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The Southern Ocean's role in climate

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Vertical exchange in the Southern Ocean between the atmosphere and the surface and deep ocean has a profound influence on the oceanic uptake of anthropogenic carbon and heat, as well as nutrient resupply from the abyss to the surface. Despite this importance, the Southern Ocean, defined here as the stretch of ocean between Antarctica and approximately 30°S, remains the most poorly observed and understood part of the global ocean. Reduced uncertainties in global climate projections will be difficult to achieve without significant progress toward understanding the Southern Ocean's response to climate forcings.

Recent advances in observational and modeling capabilities have the capability to transform our understanding of the Southern Ocean and its role in climate. The global array of profiling Argo floats, combined with satellite data, has produced temperature, salinity, and pressure data with unprecedented spatial coverage. Floats equipped with biogeochemical sensors are beginning to provide the scientific community with measurements essential for studies of the carbon cycle. Numerical models are beginning to resolve spatial scales of 10-20 km, which is adequate for capturing the mesoscale dynamics that are thought to be significant in the mixing and circulation of the Southern Ocean. Finally, the development of state estimates provides us with realistic model solutions that are compatible with modern observational datasets.

Despite this progress, many challenges remain. The spatial and temporal sampling coverage in the Southern Ocean remains inadequate. Earth system models continue to have incomplete physics and biogeochemistry and thus rely on parameterizations of several important processes. Interactions between the main components of the climate system – the atmosphere, land, ocean and sea ice – tend to be poorly understood relative to processes in each of these individual components. This joint edition of the US CLIVAR and OCB newsletters includes a series of articles that highlight recent progress and identify the scientific gaps in our knowledge of the Southern Ocean's role in climate and the ocean's response to climate forcings.

Anthropogenic carbon and heat uptake by the ocean: Will the Southern Ocean remain a major sink?

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The global ocean has taken up more than a quarter of the carbon emitted from human activities (since 1750; e.g., Sabine et al. 2004) and more than 90% of the excess heat that has accumulated in the Earth system as a result of these emissions (since 1971; e.g., Church et al. 2011). Hence, the ocean is greatly mitigating the rise of global mean surface temperatures. Among all the oceanic basins, the Southern Ocean, which we define here as the vast area south of 30°S that surrounds Antarctica, is thought to play a dominant role in the uptake of anthropogenic carbon and heat (e.g., Frölicher et al. 2015, Roemmich et al. 2015). Over recent decades, the Southern Ocean has experienced significant changes such as increases in air temperature, precipitation, glacial melting and westerly winds. These changes are expected to intensify over the 21st century and have the potential to greatly impact the uptake of carbon and heat. Careful monitoring of key properties and processes in the Southern Ocean and an improved understanding of their effects on heat and carbon uptake are thus needed to assess the present and project the future of the climate system.

The Southern Ocean is one of the most remote, inhospitable places on Earth, making *in situ* observations extremely difficult to obtain. In addition, temperature and carbon concentration measured at the ocean surface are not easily linked to heat and carbon uptake. For instance, an increase in surface temperature or carbon concentration is not necessarily due to an increase in ocean uptake, but could instead be driven by an increased upward flux of heat or carbon from deep waters. Anomalies of heat and carbon due to natural climate system variability are usually referred to as *natural*. In contrast, *anthropogenic* refers to anomalies linked to human-induced climate change, either through a circulation change or a surface flux change driven by the atmosphere. The sum of natural and anthropogenic signals forms the *total* heat and carbon, which is what we measure. It is generally quite difficult to determine whether observed changes arise from the natural or the anthropogenic component. This fact together with the lack of observational data, especially in winter, leads to large uncertainties in how much anthropogenic heat and carbon the Southern Ocean is currently absorbing and how this uptake may evolve in the future.

In this article, we provide an overview of recent breakthroughs and ongoing work in understanding Southern Ocean heat and carbon uptake. We highlight remaining gaps and uncertainties, and discuss opportunities that will help address the challenges these present.

Southern Ocean dominance of global anthropogenic carbon and heat uptake

Observational analyses and numerical models both indicate that the Southern Ocean currently accounts for about 40 to 50% of the cumulative global oceanic uptake of anthropogenic carbon (Figure 1a; Sabine et al. 2004; Mikaloff-Fletcher et al. 2006; Frölicher et al. 2015). According to models, the Southern Ocean is responsible for around 75% of the global oceanic uptake of anthropogenic heat (Figure 1b; Frölicher et al. 2015). This result is consistent with recent observational estimates that show that 67 to 98% of the global ocean heat gain over the 2006-2013 period occurred in the Southern Ocean (Roemmich et al. 2015). Nonetheless, comparison to observations of heat uptake remains difficult, as observation-based air-sea heat flux estimates are problematic due to difficulties in adequately characterizing the many complex processes involved in ocean-atmosphere heat exchange (e.g., radiation, conduction, and convection). Consequently, air-sea heat flux products primarily depend on models and parameterizations. In the Southern Ocean, different products disagree on both the sign and magnitude of the climatological net heat flux (e.g., Cerovečki et al. 2011).

The storage of anthropogenic carbon and heat is better constrained by observations than the uptake. Furthermore, storage can offer insight into the uptake, as it directly depends on how much anthropogenic heat and carbon the ocean has taken up since the preindustrial era. The spatial pattern of storage also reflects the penetration of anthropogenic anomalies into the ocean interior and hence determines if anomalies are sequestered or are likely to reemerge at the surface on short timescales. In the Southern Ocean, the patterns of anthropogenic carbon and heat storage show significant differences, indicating that the redistribution of carbon in the ocean interior is driven by different processes than those governing the redistribution of heat. Several studies indicate that while anthropogenic carbon is transported much like a passive tracer, anthropogenic heat feeds back on the circulation with direct implications for heat transport into the ocean interior (Bryan and Spelman 1985; also Winton et al. 2012; Morrison et al. 2015a).

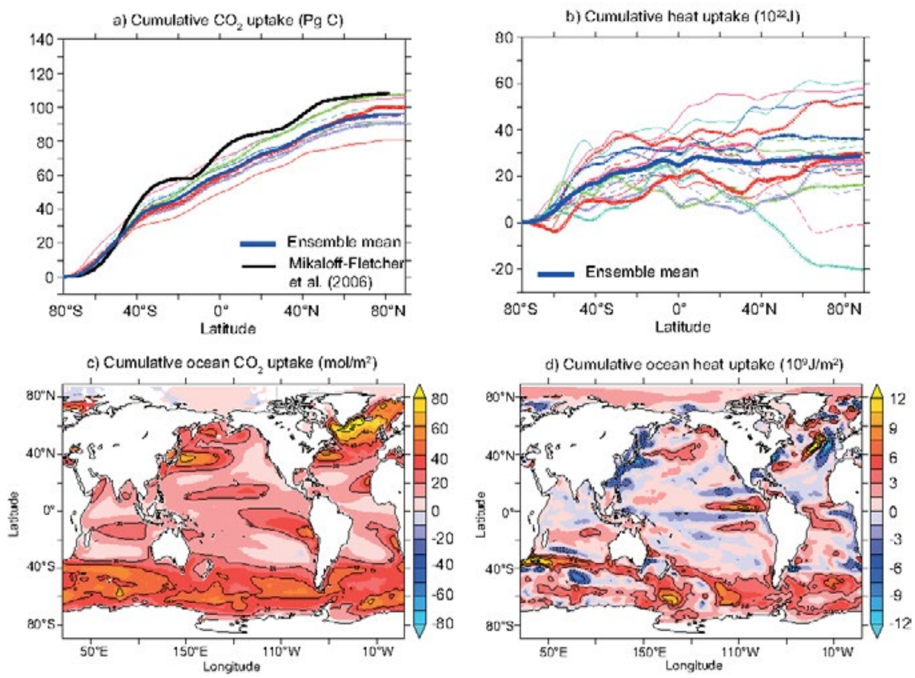

Figure 1: Oceanic uptake of anthropogenic CO_2 and heat between 1870 and 1995 simulated by a subset of CMIP5 models. (a,b) Zonal integrated cumulative ocean CO_2 and heat uptake integrated from 80°S to 90°N such that the vertical scale goes from 0 at 80°S to the total uptake at 90°N for each model. The anthropogenic carbon flux estimates from atmospheric inversions of Mikaloff-Fletcher et al. (2006) are indicated in black. (c,d) Multimodel mean in cumulative anthropogenic carbon and heat uptake. Adapted from Frölicher et al. (2015).

In addition to dominating the global oceanic uptake of anthropogenic heat and carbon, the Southern Ocean is the region where the most significant uncertainties are found. CMIP5 (Coupled Model Intercomparison Project Phase 5) models show the largest spread for both cumulative anthropogenic carbon and heat uptake in the Southern Ocean (Figure 1a-b; Frölicher et al. 2015), with a much greater intermodel spread for heat (± 71%) than for carbon (± 8%; Frölicher et al. 2015). A large portion of the differences between models can be attributed to the large internal variability in the Southern Ocean, stemming from the chaotic nature of the Earth system, which explains about half of the inter-model spread for anthropogenic carbon and of order three-quarters for anthropogenic heat in CMIP5 models (Frölicher et al. 2015). A better grasp on ocean internal variability should thus help characterizing the anthropogenic carbon and heat uptake in the Southern Ocean from climate models.

Model differences and limited observational constraints make it difficult to have confidence in the ability of climate models to represent current and future trends in carbon and heat uptake. Despite these deficiencies, both models and observations have furthered our understanding of the different processes that govern the uptake of carbon and heat in the Southern Ocean.

Mechanisms for the Southern Ocean dominance

The important role of the Southern Ocean in the global uptake of anthropogenic carbon and heat is due to its unique circulation. To maintain a high rate of oceanic uptake, ancient deep waters that are cold and uncontaminated with carbon from anthropogenic emissions need to be continuously exposed to the relatively warmer and carbon-richer atmosphere. Once anthropogenic carbon and heat have been absorbed, these waters must then be efficiently isolated from the atmosphere. In the Southern Ocean, these conditions are met through several mechanisms (see Figure 2). The vigorous wind-driven overturning circulation brings ancient deep waters to the surface at the Antarctic Divergence (~60°S; e.g., Marshall and Speer 2012; Morrison et al. 2015b). Once at the surface, these waters absorb large amounts of anthropogenic carbon and heat while being transported across the intense fronts of the Antarctic Circumpolar Current by the northward Ekman transport (e.g., Dufour et al. 2015). The subduction eventually transfers these waters into the ocean interior through the deep winter mixed layers that form around 45°S. In models, regions of strongest anthropogenic heat and carbon uptake in the Southern Ocean are generally found within two latitudinal bands around 60°S and 45°S (Figure 1c-d) suggesting that the locations of deep water upwelling and deep winter mixed layers dominate the pattern of uptake.

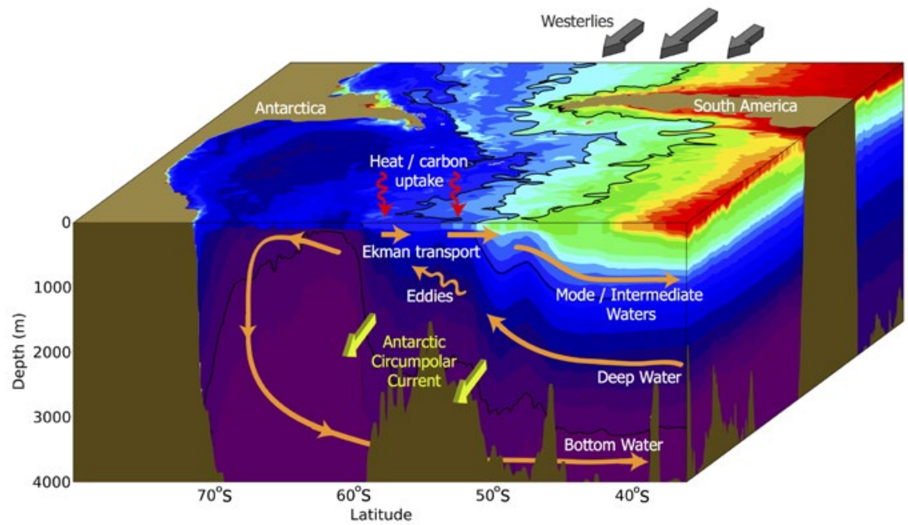

Figure 2: Schematic of the Southern Ocean circulation. A vigorous upwelling driven by powerful Westerlies brings ancient deep water that is relatively cold and rich in carbon to the ocean's surface in a region called the Antarctic Divergence. Once at the surface, much of this water is transported to the north by an intense Ekman transport across the eastward Antarctic Circumpolar Current (ACC). En route to the north, the water takes up large amounts of anthropogenic carbon and heat. At the northern boundary of the ACC, the water is subducted into the ocean interior, thus transferring anthropogenic carbon and heat to the deep ocean. Mesoscale eddies oppose the wind-driven circulation at the surface and below topographic ridges (i.e., oppose the northward Ekman flow and southward geostrophic flow, respectively) and form the main driver of the upwelling of deep waters above topographic ridges. Due to the difficulty in measuring the eddy effects in observations and in resolving them in models, the magnitude and pattern of the eddy-induced transport is still under debate, as is their resulting effect on the anthropogenic carbon and heat uptake. Adapted from Morrison et al. (2015b).

This chain of mechanisms reflects the traditional zonal-mean view of the Southern Ocean circulation that has gained wide acceptance over the past two decades. However, this paradigm has been recently questioned by studies that highlight important zonal asymmetries in the circulation (e.g., Tamsitt et al. 2015; Talley 2013; Sallée et al. 2010), impacting the pattern of uptake and subduction of anthropogenic carbon and heat. Namely, patterns of anthropogenic heat and carbon uptake show spatial structure both at the inter- and intra-basin scale, with the heat uptake being much more localized than the carbon uptake (Figure 1c-d). Sallée et al. (2012) also demonstrated that subduction of anthropogenic carbon is occurring in specific locations corresponding to formation regions of Subantarctic Mode and Antarctic Intermediate waters. These studies explore how the complex interplay between ocean and atmosphere circulation and their interactions with continents and topography sets the inter-basin differences.

Upwelling, Ekman transport, and subduction are known to be key drivers in the uptake of anthropogenic carbon and heat in the Southern Ocean (e.g., Russell et al. 2006; Mignone et al. 2006), but additional processes, like mesoscale eddies, may also play a role in regulating the uptake. Over the last decade, many studies have highlighted the importance of mesoscale eddies in the Southern Ocean circulation (e.g., Hallberg and Gnanadesikan 2006). Transport induced by eddies opposes the wind-driven circulation (Figure 2), thus reducing the rate at which deep waters are exposed to the surface (e.g., Dufour et al. 2012; Morrison and Hogg 2013). Eddies also restratify the upper ocean, reducing the subduction of light waters (Lachkar et al. 2009). Mesoscale eddy processes are thus expected to cause a reduction of Southern Ocean carbon uptake due to anthropogenic emissions. Consistent with this, models show that as mesoscale eddies are better resolved, the Southern Ocean anthropogenic carbon uptake decreases (Lachkar et al. 2007).

Contemporary trends and projected changes

Despite current limitations, models and observations have been used extensively to estimate the trends in anthropogenic heat and carbon uptake over recent decades and to project uptake over the next century. One of the key questions that needs to be addressed is whether the oceanic sink of anthropogenic carbon and heat has kept pace with atmospheric increases and how this will evolve in the future.

In the Southern Ocean, observation-based estimates and models suggest a weakening in the rate of the total carbon uptake from the 1980s to 2000s (Figure 3; e.g., Le Quéré et al. 2007; Lovenduski et al. 2007). This weakening is attributed to the intensification of westerly winds associated with positive phases of the Southern Annular Mode, which strengthens upwelling and thus brings old waters rich in carbon to the surface at a higher rate. This exposure of carbon-rich waters results in enhanced outgassing of carbon, provided that the biological pump only partially compensates the physical pump. This enhanced outgassing opposes the increasing uptake of carbon from anthropogenic emissions, hence reducing the rate of uptake of total carbon. Recent studies postulate that the rate of uptake has been reinvigorated since 2002 (Figure 3; Fay et al. 2014) possibly due to changes in the atmospheric pressure systems (Landschützer et al. 2015). The magnitude of the trend in uptake is, however, highly uncertain since it is very sensitive to the method used (Fay et al. 2014). Moreover, a robust detection of the trend in carbon uptake would require roughly two decades of continuous monthly observations with 200 biogeochemical profiling floats (Majkut et al. 2014) because of the high temporal variability (Lovenduski et al. 2015). The trend in heat uptake is even harder to estimate, with various products strongly disagreeing on the strength and pattern of the net climatological heat flux.

Over recent decades, the Southern Ocean has been experiencing significant changes that are expected to persist over the 21st century. Among those changes are increases in air temperature, precipitation, and glacial melting that strengthen the stratification of the upper ocean, and an intensification of westerly winds that strengthens the wind-driven circulation. These changes drive competing effects on anthropogenic carbon and heat uptake (e.g., Sarmiento et al. 1998, Matear and Lenton 2008), but the net effect remains unclear. Increased stratification would reduce both the flux of old waters to the surface and the subduction of newly formed waters into the ocean interior. On the other hand, increased wind-driven circulation would enhance the flux of old waters to the surface hence opposing the effect of increased stratification on carbon (e.g., Lovenduski and Ito 2009). Increased stratification and wind-driven circulation also tend to produce opposite effects on the biological drawdown of surface carbon as they both control the supply of nutrients to the surface (Matear and Lenton 2008, Hauck et al. 2015). However, to date, the anthropogenic carbon uptake does not seem to be strongly affected by the change in circulation; rather it is primarily driven by the surface flux change due to the increase in atmospheric carbon concentration (Frölicher et al. 2015). In contrast, changes in ocean circulation increase the efficacy of the ocean in taking up heat by shifting locations of the heat uptake to high-latitudes where the air-sea temperature contrast is greater (Winton et al. 2013).

Perspectives and challenges

In the past decade, we entered a new era of observations of the Southern Ocean, which will help reduce uncertainties in heat and carbon uptake and better constrain simulations. The use of autonomous profiling floats has dramatically increased the number of temperature and salinity observations in the Southern Ocean since 2000 (Argo program, http://www.argo.ucsd.edu/). Substantially more biogeochemical observations are on the horizon with the release over the next five years of roughly 200 Argo-equivalent floats equipped with oxygen, nitrate, and pH sensors (SOCCOM, http://soccom.princeton.edu/). Efforts are underway to extend the Argo array to the deep ocean below 2000 m (Johnson et al. 2015), which will provide better constraints on heat storage and abyssal circulation and, in turn, on heat and carbon uptake. On the modeling side, recent development of high-resolution climate models that are able to resolve a large portion of the ocean mesoscale eddy spectrum allows us to investigate the impact of eddies on heat and carbon uptake (e.g., Griffies et al. 2015).

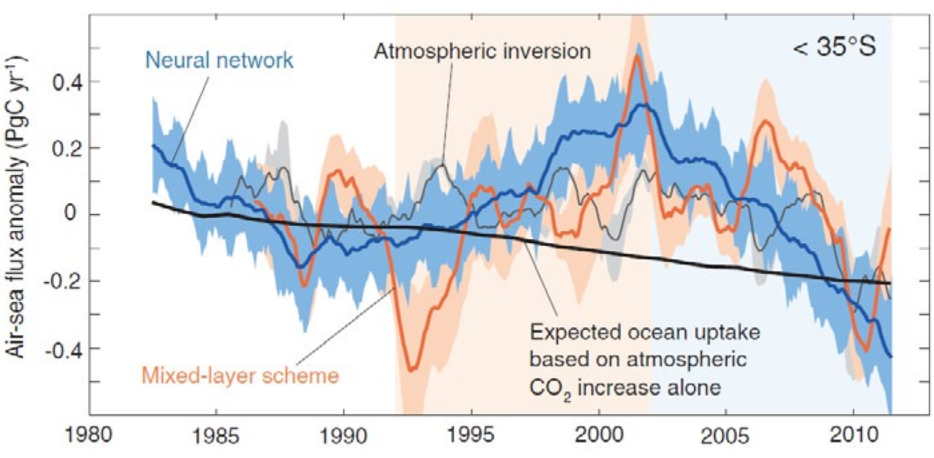

Figure 3: Evolution of total air-sea CO_2 flux integrated south of 35°S and computed as an anomaly relative to the 1980s. Negative values indicate anomalous uptake by the ocean. The flux is computed from (blue) a two-step neural network technique, (orange) a mixed-layer scheme, and (gray) an atmospheric inversion based on measurements of atmospheric CO_2. The thick black line corresponds to the expected uptake based on the growth of atmospheric CO_2 alone. Observation-based estimates show that the rate of the total carbon uptake weakened from the 1980s to 2000s but has strengthened since 2002. From Landschützer et al. (2015). Reprinted with permission from AAAS. See Landschützer et al. (2015) for more details on the methods and associated references.

Opportunities arising from new data and tools will hopefully enable the scientific community to tackle the numerous challenges that come with estimating contemporary and predicting future heat and carbon uptake in the Southern Ocean. Overall, the biggest challenges remain the improvement of data coverage and the representation of physical processes in models (Heinze et al. 2015).

Acknowledgements

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Update to "Anthropogenic carbon and heat uptake by the ocean: Will the Southern Ocean remain a major sink?"

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Dufour et al. (2015) write in the latest edition of the joint US CLIVAR and OCB newsletter about carbon and heat uptake in the Southern Ocean and ask the important question, "Will it remain a major sink in the future?" They "provide an overview of recent breakthroughs and ongoing work in understanding Southern Ocean heat and carbon uptake." However, they do not discuss some recent work about how the simulation of heat and carbon uptake in the Southern Ocean can be improved in non-eddy-resolving resolution ocean components of climate models.

Dufour et al. (2015) discuss the role of mesoscale eddies in the Southern Ocean circulation saying, "Transport induced by eddies opposes the wind-driven circulation, thus reducing the rate at which deep waters are exposed to the surface." They also suggest that the weakening of Southern Ocean carbon uptake from the 1980s to 2000s is "attributed to the intensification of westerly winds associated with positive phases of the Southern Annular Mode, which strengthens upwelling and thus brings cold waters rich in carbon to the surface at a higher rate. This exposure of carbon-rich waters results in enhanced outgassing of carbon, which opposes the increasing uptake of carbon from anthropogenic emissions, hence reducing the rate of uptake of total carbon." Can these changes in ocean circulation and carbon uptake due to stronger westerly winds be simulated correctly in the non-eddy-resolving ocean component of a climate model, in which the effects of mesoscale eddies are parameterized rather than being resolved?

All ocean models show that the equatorward surface Ekman flow increases quite linearly in response to an increase in the imposed westerly zonal wind stress maximum in the Southern Hemisphere. This increases the mean meridional overturning circulation (MOC) in the Southern Ocean, which subducts water north, and upwells water to the south, of the Antarctic Circumpolar Current. Eddy-resolving ocean models show that the eddy energy increases with the stronger zonal wind stress, and so does the eddy MOC, which opposes the mean MOC. If this eddy response is to be captured in non-eddy-resolving ocean models, then the coefficient in the eddy parameterization cannot be set as a constant. It must be dependent on aspects of the ocean circulation such that the coefficient increases when the applied zonal wind stress is increased. Farneti and Gent (2011) showed that this is exactly what happens in the GFDL CM2.1 climate model, providing that there is no artificial cap applied to the eddy parameterization coefficient. Gent and Danabasoglu (2011) showed that the eddy coefficient in the ocean component of the CCSM4 climate model also responds, and that it increases when the zonal wind stress increases. Therefore, what has come to be known as "eddy compensation" can be simulated to some degree in climate models. Whether the degree of eddy compensation in these two climate models is correct is still an open question, but they both show a significant eddy compensation effect. The fact that the non-eddy-resolving ocean components that use a variable formulation of the eddy coefficient produce a more realistic simulation over 1958 – 2007 than those with a constant coefficient has been nicely documented by Farneti et al. (2015).

Now the question is: Do climate models with a varying eddy coefficient have a different future outlook for carbon uptake in the Southern Ocean than those using a constant coefficient? Two recent papers show that the answer to this question is an emphatic yes. Lovenduski et al. (2013) use the CCSM4 ocean component forced by atmospheric observations over the period 1958 – 2007. They conclude that had a degree of eddy compensation of the increased mean MOC over this period not occurred in this model, then the rate of total carbon uptake would have reduced more strongly and by the exact mechanism outlined above and in Dufour et al. (2015). Swart et al. (2014) ran the University of Victoria climate model using both a constant and varying eddy coefficient. They showed that the reduction in Southern Ocean carbon dioxide uptake over the past 30 years using a variable coefficient is only about 40% of the reduction when a constant eddy coefficient is used. These two papers clearly show that a climate model using a constant eddy coefficient or a coefficient strongly capped at a small value in the ocean component will greatly overestimate the reduction in Southern Ocean carbon dioxide uptake in response to an increase in the Southern Hemisphere zonal wind stress.

The significant increase in the Southern Hemisphere westerlies over the past 50 years is thought to be due to increasing atmospheric carbon dioxide and the development of the Southern Hemisphere ozone hole, both of which tend to strengthen the westerlies. "As the stratosphere ozone hole recovers over the next 50 years, it is expected that the Southern Hemisphere zonal winds will not increase nearly so rapidly as they have over the past 30 years (Polvani et al. 2011). Therefore, I conclude that it is not at all certain that the effectiveness of the Southern Ocean carbon dioxide sink will decrease over the next 40 – 50 years." This quote is from a review I have written entitled "Effects of Southern Hemisphere wind changes on the MOC in ocean models" to be published in volume 8 of the Annual Reviews of Marine Science in January 2016. It is my opinion that, to paraphrase Mark Twain, reports of the future demise of the Southern Ocean carbon sink have been greatly exaggerated by climate models that use a constant ocean eddy coefficient.

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Estimating Southern Ocean air-sea fluxes from models and observations

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Air-sea fluxes determine the transfer of heat, momentum, and gas between the atmosphere and the ocean, and the Southern Ocean is at the nexus of these exchanges. Winds are critical to air-sea exchanges, and the Southern Ocean experiences some of the strongest winds in the world. Water within the oceanic mixed layer readily comes into contact with the atmosphere, and the low stratification of the Southern Ocean gives it some of the deepest mixed layers found anywhere, often extending to several hundred meters in depth (e.g., Dong et al. 2008). And cold water holds higher quantities of dissolved gas, meaning that the Southern Ocean has the potential to take up large quantities of CO_2 or O_2 from the atmosphere. Despite the central role of the Southern Ocean in the climate system, quantifying air-sea fluxes with an accuracy that is meaningful for climate studies has proved challenging.

The goal of this article is not only to highlight the main sources of uncertainties in current flux estimates but also to show what information we can learn from existing flux products for the open ocean regions of the Southern Ocean. Our focus is on heat fluxes and, to a lesser extent, freshwater and gas fluxes, all of which are less well defined than momentum fluxes and arguably more critical to understanding long-term climate processes.

Consider, for example, the challenges in determining Southern Ocean air-sea heat fluxes. The Southern Ocean is the most rapidly warming sector of the global ocean, as evidenced in Argo profiling float data from the last decade (Roemmich et al. 2015). Comparisons between historic data and modern Argo observations suggest that this warming has been persistent since early in the 20th century (e.g., Böning et al. 2008; Gille 2008). Regions of the ocean can warm either because of horizontal advection of heat within the ocean or because

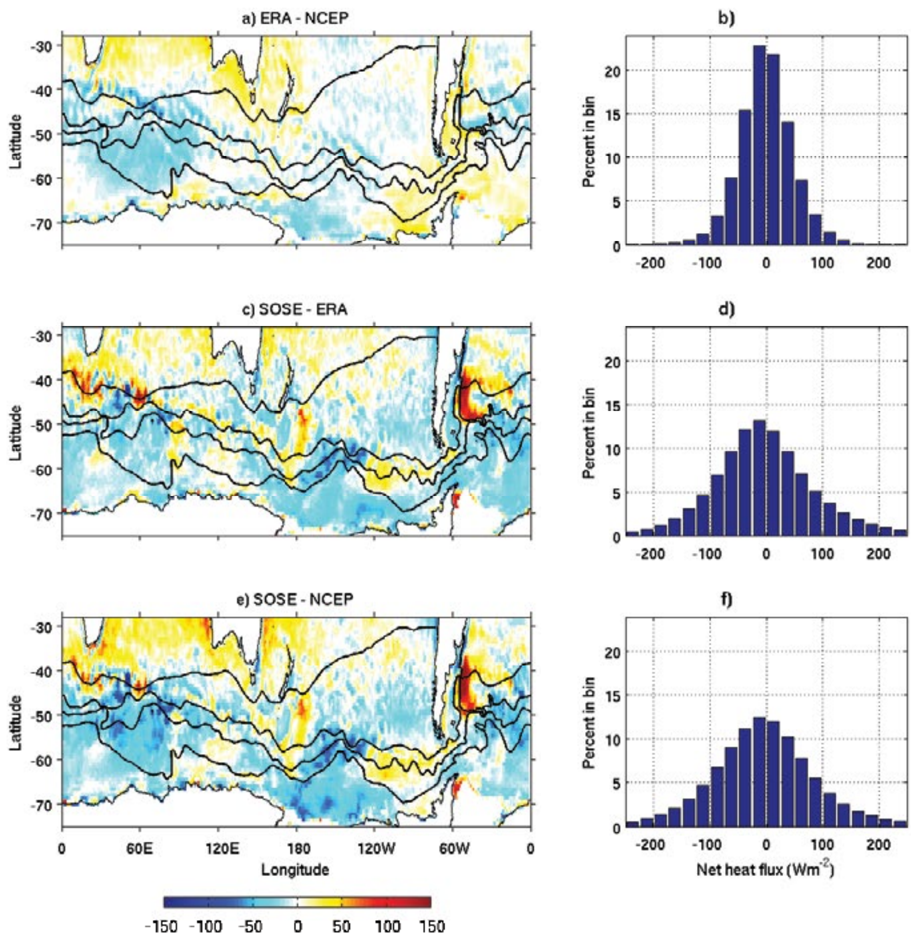

Figure 1. The difference between daily estimates of net air-sea heat flux (W m^{-2}), time averaged over years 2005 – 2010, considering only ice-free time periods, obtained from: (a) ERA-Interim (ERA) reanalysis minus National Centers for Environmental Prediction-National Center for Atmospheric Research Reanalysis 1 (NCEP), (c) the Southern Ocean State Estimate (SOSE) from SOSE iteration 100 minus ERA and (e) the SOSE minus NCEP. Positive values indicate more ocean heat loss (less ocean heat gain) by the first product relative to the second. Right-column panels show corresponding normalized histogram of daily net air-sea heat flux differences (W m^{-2}). All flux estimates have been interpolated on ERA grid. The differences are in 25 W m^{-2} wide bins, normalized to show percent of the net air-sea heat differences in each bin, where the sum over all the bins is 100%. They thus indicate the probability that the net air-sea heat difference will be in the range 12 ± 12.5 W m^{-2}. Averaged over the Southern Ocean domain shown in the figure, mean differences are: SOSE – ERA -3.4 ± 96.2 Wm^{-2}; SOSE – NCEP -4.1 ± 97.7 Wm^{-2}; and ERA-NCEP -0.6 ± 48.1 Wm^{-2}. The black contours in panels a, c, e show the climatological positions of the fronts given by Orsi et al. (1995), from north to south: Subtropical Front, Subantarctic Front, Polar Front, and Southern ACC Front.

of air-sea exchange, but growing evidence suggests that air-sea fluxes are likely to be a major player in the net increases in ocean heat content (Fyfe and Swart, personal communication). Existing data are too sparse to distinguish these processes with any real confidence. Although warming patterns extend through the water column in the Southern Ocean (e.g., Purkey and Johnson 2010), warming trends are nonetheless surface-intensified and could be explained by a net heat input to the Southern Ocean of about 0.6 W m^{-2}, roughly consistent with estimates of the global ocean energy imbalance (e.g., Abraham et al. 2013). This net heat input to the ocean sets an air-sea flux accuracy requirement that is more than an order of magnitude smaller than what we can achieve with current observational capabilities.

Challenges of measuring and modeling air-sea fluxes

Surface fluxes are difficult to measure, because they are associated with the time derivatives of upper-ocean heat content, upper-ocean kinetic energy, or upper-ocean dissolved gas concentrations. Since derivatives are inherently noisier than their time integrals, fluxes are inherently plagued by large statistical uncertainties.

In situ observation of high-latitude air-sea fluxes has proved particularly difficult for a number of reasons (e.g., Bourassa et al. 2013). The Southern Ocean is remote, with high winds, high sea states, and icing conditions. The environment makes mooring deployment difficult and leads to logistical challenges for ship and aircraft operations. Air-sea fluxes are typically computed from bulk formulae. In high-wind conditions with evolving wave conditions, even when basic meteorological variables are measured, the direct flux covariance measurements that would be needed to calibrate bulk formulae are not readily available. However, there is some promise for the future as a result of recent technological developments. These developments include wave gliders, unmanned aerial vehicles, the deployment of flux moorings in the Southern Ocean, and new concepts for obtaining high quality ship measurements, along with evolving algorithms for retrieving air-sea flux-related parameters from satellite observations and advances toward coupled data assimilation.

Model-based assessment of air-sea fluxes has also proved difficult. In Figure 1, we show the time-mean differences between three air-sea heat flux products over the 6-year interval from 2005 to 2010. Two flux products are derived from numerical weather prediction atmospheric reanalyses that are produced by the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-Interim) and by the National Center for Environmental Prediction (NCEP). The third comes from iteration 100 of the Southern Ocean State Estimate (SOSE, available from sose.ucsd.edu), which is an oceanic counterpart to the atmospheric reanalyses. SOSE uses a 4-dimensional variational assimilation approach, analogous to the methods used for numerical weather prediction and atmospheric reanalysis, and it determines air-sea fluxes that are most consistent with the constraints imposed by available ocean observations and ocean dynamics (Mazloff et al. 2010). In their time means, the three sets of fluxes differ substantially, with large-scale offsets visible in Figure 1. The atmospheric reanalyses differ from each other and SOSE shows significant departures from the atmospheric reanalyses, particularly in the Agulhas Retroflection region south of Africa, in the Brazil-Malvinas Confluence region to the east of South America, and in the region extending from Campbell Plateau south of New Zealand to the

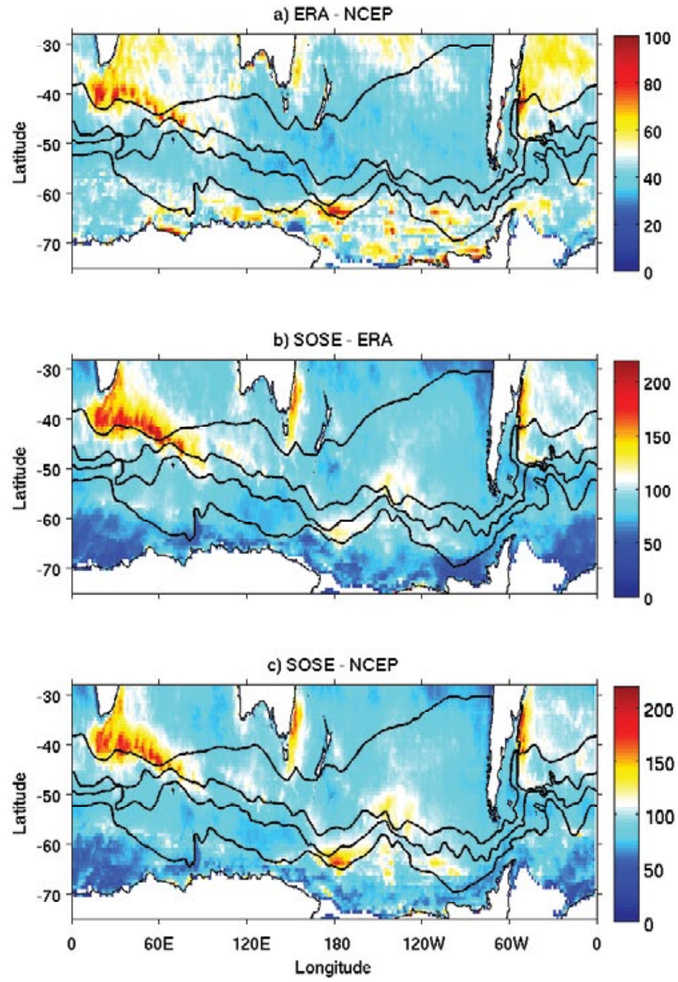

Figure 2. As in Figure 1 a, c, e, except for the standard deviation.

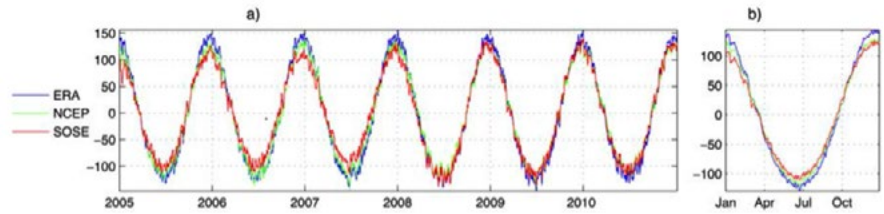

Figure 3. (a) Time series of net air-sea heat flux for the latitude range 30°- 60°S, with area and time means removed. This domain is chosen to avoid the marginal ice zones close to Antarctica and the SOSE northern boundary. (b) Net air-sea heat flux climatology obtained from time series shown in panel (a). The time-mean RMS differences are 7.8 W m^{-2} for the ERA-NCEP difference, 6.7 W m^{-2} for the SOSE-NCEP difference, and 13.3 W m^{-2} for the SOSE-ERA difference.

Eltanin-Udintsev Fracture Zones in the central Pacific. The standard deviations of the differences (Figure 2) are also pronounced in the same three regions, all of which are marked by strong topographically influenced oceanic currents with topographically generated eddy energy. In contrast to the differences illustrated in Figures 1 and 2, the amplitude and phasing of their annual cycles largely agree, as illustrated in Figure 3.

The differences suggest two major challenges to determining fluxes: one challenge is properly calibrating large-scale local mean air-sea fluxes (e.g., minimizing the large-scale patterns in Figure 1), and the second challenge is understanding the detailed physics that governs air-sea fluxes at mesoscale gradients associated with eddies and fronts (e.g., the frontal or eddy-scale differences in Figure 2).

Ongoing and future efforts

Despite inaccuracies in flux estimates, they nevertheless provide valuable information about the specific processes that drive air-sea exchange and show the physics that modulate seasonal to interannual variations in exchanges between the ocean and atmosphere. Flux estimates enable us to evaluate how water properties are transformed at the ocean surface, for example to form SubAntarctic Mode Water. Upper ocean budgets for heat and freshwater are determined by surface fluxes, working in tandem with diapycnal mixing, advection, and storage (Cerovečki and Mazloff 2015). Close analysis of air-sea heat fluxes suggests that in the time mean, net air-sea fluxes into the ocean are balanced by advection. In SOSE, on seasonal scales, the Indian and Atlantic Oceans appear to be governed by Ekman divergence, while the Pacific Ocean heat fluxes are balanced both by Ekman divergence and geostrophic advection (Tamsitt et al. 2015). Reduced uncertainties in surface flux estimates would allow us to refine our evaluations of upper-ocean water mass transformation processes.

A September 2015 workshop entitled "Air-Sea Fluxes for the Southern Ocean: Strategies and Requirements for Detecting Physical and Biogeochemical Exchanges" revisited the challenges associated with improving Southern Ocean air-sea fluxes. Participants identified a number of impediments to progress. Not only are air-sea fluxes difficult to measure, but they are also not currently part of the coordinated observing system, in part because the difficulty in measuring them has prevented them from being classified as Essential Climate Variables.

While Southern Ocean flux observations have historically been nearly non-existent, there are good prospects for improvements in the future. As an outcome of the September 2015 workshop, a Southern Ocean Observing System (SOOS) Capability Working Group on Southern Ocean air-sea fluxes is being established. The priorities have been fine-tuned with input from the earlier US CLIVAR High-Latitude Surface Flux and the US CLIVAR/OCB Southern Ocean Working Groups. The SOOS Capability Working Group envisions a two-pronged effort that will develop a pilot project to move towards a Southern Ocean air-sea flux observing system and at the same time to evaluate the feasibility of defining fluxes or flux-related variables as Essential Climate Variables. While we do not expect to measure fluxes with sufficient accuracy to close the upper ocean heat budgets at the 0.6 W m^{-2} level, nor do we expect equivalent levels of accuracy for CO_2 fluxes, we do think that we can unravel the processes that contribute to spatial and temporal variations in air-sea fluxes of heat, as well as freshwater, gas, and momentum.

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Observed and projected trends in Antarctic sea ice

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Antarctic sea ice extent has increased over the ~36-year satellite record, in striking contrast to the observed decline of the Arctic sea ice cover over this period (e.g., Parkinson and Cavalieri 2012). Concurrent with Antarctic sea ice expansion has been an overall cooling of the Southern Ocean surface. These trends may seem at odds with greenhouse gas-induced warming over recent decades and, disconcertingly, are not reproduced by the historical simulations of comprehensive global climate models (e.g., Turner et al. 2013; Hobbs et al. 2015). Here, we review the recent progress toward understanding the response of the Southern Ocean to climate forcing, and argue that the community's results are converging on a solution to the apparent conundrum of Antarctic sea ice expansion. We propose that while a variety of different factors may have contributed to Southern Ocean changes over recent decades, it is large-scale atmospheric circulation changes – and the changes in ocean circulation they induce – that have emerged as the most likely cause of the observed Antarctic sea ice trends.

Observations of recent Southern Ocean change

Before we delve into the possible mechanisms driving recent Southern Ocean changes, we want to describe the observations in more detail to establish a baseline that any such mechanisms must explain. Figure 1 shows sea ice concentration and sea-surface temperature (SST) trends over the era of continuous satellite observations (1979-present). While both fields show regions of increasing and decreasing trends over this period, the total sea ice extent has increased, and SSTs have largely cooled, south of the Antarctic Circumpolar Current (ACC). Notable exceptions are the regions of decreasing sea ice concentration in the Amundsen and Bellingshausen Seas, which overlie increasing SSTs – though we note that the sign of the trends in these regions has changed after about year 2000 (not shown). Although the patterns of trends in sea ice concentration and SST vary with season, the association between sea ice and SST generally prevails in every season and region (we show only the annual means here for brevity and because the signal to noise is greater than in the seasonal means). Further, we see that the spatial patterns of sea ice trends are closely mirrored by trends in SSTs that extend beyond the sea ice edge over a much larger area of the ocean – typically out to the southern flank of the ACC.

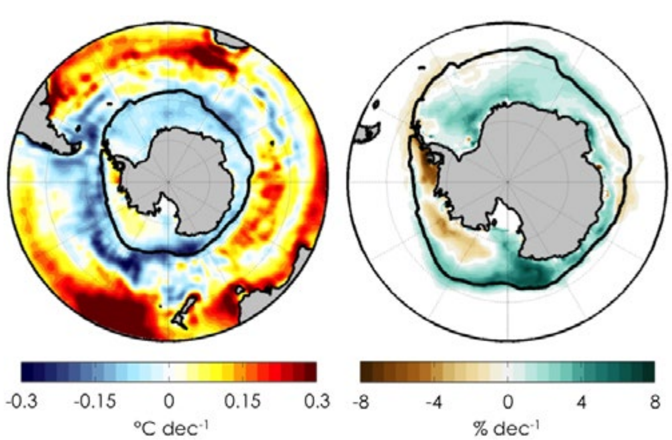

Figure 1: Linear trends of annual-mean SST (left) and annual-mean sea ice concentration (right) over 1980-2014. Sea-surface temperature is from NOAA's Optimum Interpolation Sea Surface Temperature dataset (version 2; Reynolds et al. 2002). Sea ice concentration is from passive microwave observations using the NASA Team algorithm (https://nsidc.org/data/seaice_index/archives.html).

Taking a cue from Fan et al. (2014), we see that this tight relationship between total sea ice extent and Southern Ocean SSTs (south of 50° S, the approximate latitude of the ACC) appears to hold over a much longer observational period as well (Figure 2). The sea ice cover in September of 1964 (recently recovered from the Nimbus I satellite by Meier et al. 2013) was more expansive than at any time since the start of the continuous record from passive microwave satellites – consistent with Southern Ocean SSTs that were at or near their coldest levels. In the early 1970s, an early microwave satellite and the Navy-NOAA ice charts indicated the sea ice was in between the extent in 1964 and post 1979 (see e.g., Kukla and Gavin 198; Zwally et al. 1983). Overall, the Southern Ocean has warmed slowly (by ~0.02 /decade south of 50° S) relative to the global ocean (~0.08 /decade) since 1950.

The spatial and temporal relationships in Figures 1 and 2 imply that Antarctic sea ice trends should be viewed in the broader context of trends over the whole of the Southern Ocean, and that trends in sea ice and SSTs likely share some common driving mechanisms. That is, a key constraint on any mechanism proposed to drive the observed Southern Ocean changes is that it must allow for both the characteristics of sea ice trends and the coincident patterns of large-scale SST trends, simultaneously.

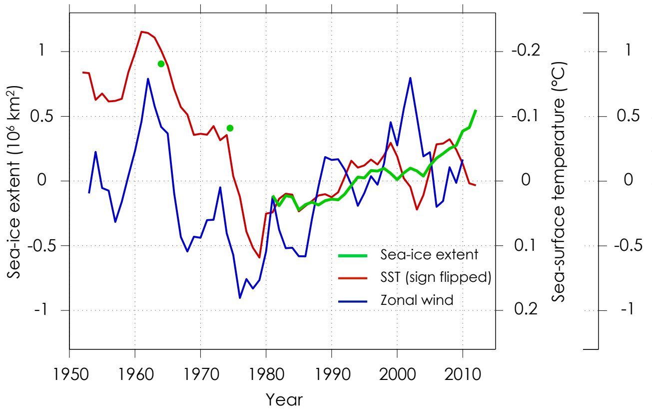

Figure 2: Time-series of anomalies in the total annual-mean Antarctic sea ice extent, annual-mean Southern Ocean SST (averaged south of 50°S), and DJF (December-January-February) zonal-mean zonal wind over 50-70°S. The sea ice extent in 1964 is the September 1964 anomaly from the Nimbus 1 satellite (Meier et al. 2013). The sea ice extent in 1974 is an average of 1973-1976 from the electrically scanning microwave radiometer (https://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html) and the Navy-NOAA Joint Ice Charts (Ropelewski, 1983). The sea ice extent from 1979 and onward is from passive microwave observations using the NASA Team algorithm (https://nsidc.org/data/seaice_index/archives.html); SST is from NOAA's Extended Reconstruction Sea-Surface Temperature dataset (version 3b; Smith et al. 2008); and zonal wind data was provided by D. Schneider from the study of Fan et al. (2014). All anomalies are taken with respect to their 1980-2010 means.

In light of the above observations, we organize the rest of our discussion around several guiding questions, which we see as relating to distinct physical mechanisms that have, together, acted to produce the observed Southern Ocean trends.

Mechanisms of delayed Southern Ocean warming

Why has the Southern Ocean been so slow to warm over the 20th century (Figure 2), relative to the global ocean and the Arctic? Recent work suggests that the primary cause of delayed surface warming is the mean divergence of seawater at the Southern Ocean surface, which is then refreshed (or buffered) by the upwelling of unmodified water from depth (Marshall et al. 2014a,b; Armour et al. submitted); hence the majority of heat taken up at the Southern Ocean surface is diverged with the mean circulation to the north, and, to a lesser extent, downward along the Antarctic continental shelf. A secondary source of delayed warming is reduced surface buoyancy loss owing to a combination of increased downward heat flux, increased precipitation minus evaporation, and reduced sea ice growth near Antarctica – each acting to increase upper ocean stratification and inhibit convection and vertical mixing, in turn reducing the upward flux of heat from warmer waters at depth (Manabe et al. 1991; Russell and Rind 1999; Gregory 2000; Kirkman and Bitz 2011).

Global climate models (GCMs) robustly simulate much slower warming and less sea ice loss over the Southern Ocean than in the Arctic under global warming (e.g., Manabe et al. 1991; Stouffer 2004; Kirkman and Bitz 2011; Li et al. 2012; Marshall et al. 2014a,b). Within GCM simulations, delayed warming of the Southern Ocean surface is seen to be a fundamental response of the ocean to anomalous surface heat and freshwater fluxes induced by greenhouse forcing. We argue that because this response is broadly consistent with observations (Armour et al. submitted), climate models seem to be adequately representing the above mechanisms of delayed Southern Ocean warming. Importantly, it is against this background of very gradual warming – rather than the rapid warming seen in the Arctic – that the mechanisms of Southern Ocean surface cooling and sea ice expansion must be understood and evaluated.

Mechanisms of Southern Ocean surface cooling and sea ice expansion

What has driven the apparent variation in Southern Ocean conditions about this gradual warming trend (Figure 2), and what has driven the recent period of surface cooling and sea ice expansion (Figure 1) in particular? One possible cause of sea ice expansion is increased freshwater input to the ocean from Antarctic ice loss (Bintanja et al. 2013) – primarily from basal melt of ice shelves – which could act to cool the sea surface via increased stratification and decreased deep ocean convection as described above. However, Pauling et al. (submitted) point out that best estimates of the current mass imbalance of Antarctica's ice sheet and shelves is at most about one-fifth the magnitude of the present-day anomaly in precipitation minus evaporation south of 50° S, relative to preindustrial, as simulated by climate models. Indeed, Liu and Curry (2010) argue that this increase in precipitation is responsible for sea ice expansion, but the question remains as to why climate models do not reproduce the observations given that they do robustly simulate increased precipitation over the Southern Ocean.

Moreover, both Swart and Fyfe (2013) and Pauling et al. (submitted) find that enhanced freshwater input to the Southern Ocean does not cause significant sea ice expansion within their simulations – even when the magnitude of freshwater flux far exceeds that applied by Bintanja et al. (2013). One important factor in the sea ice response to freshwater forcing may be the degree to which the Southern Ocean is deeply convecting. Based on the findings of Swart and Fyfe (2013) and Pauling et al. (submitted), we speculate that models that show little deep Southern Ocean convection over recent decades – consistent with observations (e.g., de Lavergne et al. 2014) – would also show little sensitivity to increased freshwater input from Antarctica. Altogether, these studies suggest that freshwater forcing is not the primary cause of the observed sea ice expansion.

Perhaps the most substantial Southern Hemispheric climate signal has been the strengthening and poleward shift of westerly winds since the late 1970s (Figure 2). This trend – often characterized as a strengthening of the Southern Annular Mode (SAM) – is thought to be primarily driven by stratospheric ozone depletion (Polvani et al. 2011a), but may also reflect natural variability (Deser et al. 2012; Thomas et al. 2015). As noted by Thompson et al. (2011), the observed correlation between SAM and SSTs on interannual timescales – wherein a strongly positive SAM is correlated with Southern Ocean surface cooling – suggests that the trend in SAM may be responsible for the observed SST and sea ice trends.

Yet, GCMs have thus far been unable to reproduce this proposed connection – perhaps, in part, due to the fact that their historical westerly wind trends are typically too weak, lack the correct seasonality, or lack the correct spatial patterns compared to the observed (Swart and Fyfe 2012; Haumann et al. 2014). This discrepancy between observed and simulated wind trends is plausibly due to a combination of (i) errors in the prescribed (or simulated) magnitude, spatial pattern (Waugh et al. 2009), or temporal resolution (Neely et al. 2014) of stratospheric ozone depletion and (ii) natural variability in SAM (Deser et al. 2012; Thomas et al. 2015).

Further complicating matters, climate models tend to show *enhanced* Southern Ocean surface warming and sea ice loss in response to ozone depletion (Sigmond and Fyfe 2010; Bitz and Polvani 2012; Smith et al. 2012; Sigmond and Fyfe 2014; Haumann et al. 2014). Clarification on this front can be gleaned from the results of Ferreira et al. (2015), who showed that two opposing sea ice trends should be expected in response to a strengthening of westerly winds: the immediate response is enhanced Ekman advection of surface waters, which transports colder waters northward and drives surface cooling south of the ACC; the longer-term response is upwelling of relative warm waters to the surface from depth, induced by anomalous wind-driven divergence of surface waters south of the maximum wind anomaly, as shown in Figure 3. Thus, while the initial response to a strengthening of westerly winds is that of surface cooling and sea ice expansion, the long-term response is that of surface warming and sea ice loss.

The timescale at which the upper ocean transitions from the fast surface cooling to the eventual warming in response to westerly wind forcing is of critical importance to sea ice trends (Marshall et al. 2014b). Yet, it differed markedly between the two models analyzed in Ferreira et al. (2015), with the comprehensive climate model in their study transitioning over just a few years, and the more idealized model transitioning over decades. The timescale appears to be largely set by the climatological meridional temperature gradient at the ocean surface, which governs the magnitude of the initial cooling, and by the temperature gradient

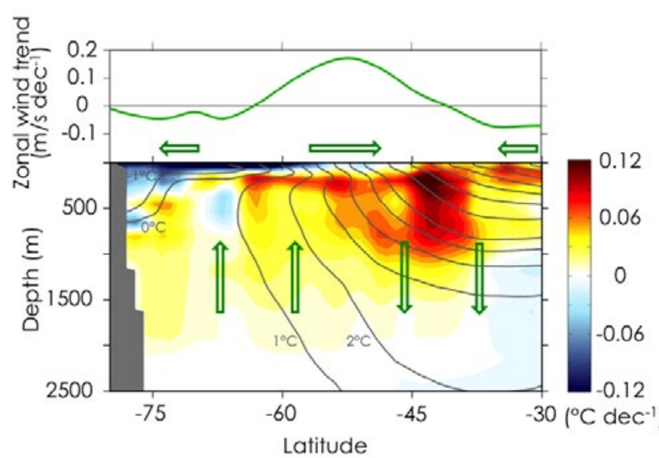

Figure 3: Trends in annual, zonal-mean ocean potential temperature and zonal-mean zonal winds over 1980-2014. Black lines are contours of the climatological zonal-mean mean ocean temperature averaged over 1980-2014. Green arrows are a schematic representation of the approximate ocean circulation that has been induced by the westerly wind trends. Generally the ocean temperature trends can be linked to anomalous advection of the ocean mean state temperature by these anomalous currents. The wind trends have driven anomalous northward surface currents that transport relatively cold waters to the north, driving surface cooling south of ~45°S. The wind trends have further driven anomalous divergence at the ocean surface, and hence anomalous upwelling, south of ~55°S; over much of this region, ocean temperature increases with depth, so this amounts to enhanced upwelling of relatively warm waters. North of about ~55°S, the winds have driven anomalous convergence, and the subsurface flow appears to be that of enhanced subduction. The annual and zonal-mean winds trends are from ERA-Interim (Dee et al. 2011).

between the sea surface and deep ocean, which governs the rate of slow warming (Ferreira et al. 2015).

It is not known what the Southern Ocean response to westerly wind trends should be, but following Fan et al. (2014) we can look to the observations since 1950 as a guide (Figure 2). As noted above, Southern Ocean SSTs have decreased concurrently with an increase in zonal-mean westerly winds since ~1980. While the wind data are sparse (see Fan et al. 2014), the time-series of zonal-mean wind shows an intriguingly strong *decrease* in strength from about 1950 to 1980, concurrent with a significant increase in SSTs and decrease in sea ice extent from 1964 to the beginning of the satellite era. We view these observations as strong evidence that the observed trends in Southern Ocean sea ice and SSTs since 1950 have been primarily driven by changes in atmospheric circulation.

These results further lead us to speculate that it may be biases in the ocean components of comprehensive climate models that are the main reason they exhibit Southern Ocean warming and sea ice loss in response to ozone depletion, which is at odds with the observed trends over recent decades. We suggest that a strong test of this mechanism would thus be the simulation of stratospheric ozone depletion within those climate models that accurately simulate the observed Southern Ocean mean state (i.e., the climatological temperature gradients in Figure 3).

Another suggestion is that the recent sea ice expansion can be explained by natural variability alone, based on GCM simulations (Polvani and Smith 2013; Zunz et al. 2013; Mahlstein et al. 2013). Yet, much of the natural variability of Southern Ocean sea ice extent in models is driven by changes in the strength of deep ocean convection (e.g., Latif et al. 2013). While variability in deep ocean convection is an intriguing mechanism for sea ice expansion, it seems inconsistent with the observations, which do not appear to reflect such changes over the satellite era. However, the possibility remains that natural variability has contributed substantial westerly wind trends over recent decades (Deser et al. 2012; Thomas et al. 2015) and, in turn, to sea ice expansion.

Mechanisms driving the observed local-scale patterns of sea ice change

What has driven the local-scale patterns of sea ice and SST trends over the satellite era? Holland and Kwok (2012) argue that winds, especially the meridional component, are the principle cause of regional sea ice trends, and that changes in sea ice advection have been a dominant factor in driving the apparent sea ice loss around West Antarctica. Trends in surface winds over the Southern Ocean also impact ocean waves, and an overall decrease in wave heights has been related to a reduction in the breakup of sea ice (Kohout et al. 2014). While local-scale wind and wave forcings appear to be factors in driving the observed pattern of sea ice trends, it is less clear how changes in sea ice motion and breakup can cause concurrent trends in SSTs. One possibility is that sea ice trends are able to modify SSTs through sea ice-ocean feedbacks (Goosse and Zunz 2014). However, such mechanisms do not account for the concurrent trends in Southern Ocean SSTs that extend far beyond the sea ice edge (Figure 1). We thus view these wind and wave height changes as the proximate causes of local-scale patterns of sea ice change, as opposed to fundamental drivers of sea ice and SST trends over the whole of the Southern Ocean.

Recent changes in atmospheric circulation patterns, and hence winds, over the Southern Ocean have been linked to teleconnections via atmospheric Rossby waves emanating from the tropical Pacific and/or Atlantic (e.g., Ding et al. 2011; Li et al. 2014; Simpkins et al. 2014; Schneider et al. 2015). Many have attributed patterns of warming and cooling in the tropics to natural variability, so perhaps we should not expect GCMs to reproduce the observed patterns of local-scale wind changes over the last few decades. Moreover, even if a simulation should randomly exhibit reasonable tropical variability, the teleconnections to the Antarctic may be poor if the location or strength of the atmospheric subtropical and mid-latitude jets is biased. Indeed, several recent studies have found fault with the ability of CMIP5 models to simulate recent decadal-scale trends in Antarctic circulation features such as the Amundsen-Bellingshausen Seas Low (Hosking et al. 2013). Given these findings, it is perhaps no great surprise that GCMs are unable to capture the local-scale patterns of Antarctic sea ice trends.

What is the future of Antarctic sea ice?

Given the inconsistencies between observed and simulated trends over recent decades, it is natural to ask, should we trust model projections of Antarctic sea ice over the 21st century? Our answer is: both yes and no. While stratospheric ozone is expected to recover, the westerly winds are likely to continue to increase in strength and shift poleward due to rising greenhouse gases alone (e.g., Kushner et al. 2001; Arblaster et al. 2011), though perhaps at a slower rate than has been observed (Polvani et al. 2011b; Bracegirdle et al. 2013; Barnes et al. 2014). We anticipate that, in time, the dominant effect of westerly wind enhancement will almost certainly be the slow, surface warming response described by Ferreira et al. (2015), which climate models seem able to simulate. Thus, although there is a wide spread in their projections, we believe that climate models are at least simulating the correct sign of the 21st century changes: a decline in the total Antarctic sea ice cover. However, natural variability in large-scale Southern Ocean winds may prove to be an important driver of sea ice trends on timescales of years to decades. Moreover, model deficiencies in simulating the spatial pattern of local wind changes, in combination with substantial variability associated with teleconnections from the tropics, may continue to preclude accurate projections of the regional patterns of sea ice trends for the foreseeable future.

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State estimation for determining the properties and sensitivities of the Southern Ocean carbon cycle

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Introduction

Regardless of complexity, the goal of data assimilation techniques is to maximize the utility of observations. The methods involve using correlation scales to project observation information in time and space. Methods using empirical or statistical models are computationally efficient and desirable for many applications. These have shortcomings, however, in that they often don't obey physical constraints and may also misrepresent correlations between forcing mechanisms. More complex mapping methods use the governing physics, represented in discrete form by a numerical model, to determine spatiotemporal correlation and cross-correlation. The complex methods also have shortcomings in that model errors still exist, and these methods are computationally expensive.

The ideal mapping method complexity will depend on the application. Determining a best estimate of the current biogeochemical–ice–ocean state incorporates all knowledge of the system, including knowledge of the physics governing the system, and thus requires a complex method. The method of choice for many science applications has become known as "state estimation". The primary difference between state estimation and "reanalysis" as performed by numerical weather prediction centers is the length of the assimilation window. Reanalyses assimilate data over a window that is less than one month and then patch the solutions together, whereas in state estimation the entire estimation period (e.g., years to decades) is assimilated in one calculation. In practice, reanalyses usually fit individual observations more closely than state estimates, but physical budgets are not closed between the sequential assimilations.

The governing physics obeyed by state estimates offers a powerful constraint allowing one to infer air-sea fluxes. Variations in ocean properties, for example inventories of heat and carbon, imply changes in fluxes. Thus by measuring ocean carbon content we are informing air-sea carbon flux, and state estimates allow one to infer this flux.

Measurements of the Southern Ocean carbon system have been greatly augmented by the deployment of biogeochemical sensors on autonomous profiling floats. Furthermore, the software to produce state estimates of the carbon budget via the adjoint method is now mature. State estimates of biogeochemical and physical ocean properties will be available in the near future. Here, we review the development of a coupled physical-biogeochemical Southern Ocean State Estimate. We then showcase the adjoint tool used to produce this state estimate by determining the sensitivity of air-sea carbon flux to ocean properties.

A biogeochemical Southern Ocean state estimate

Configuration

A Southern Ocean state estimate (SOSE; sose.ucsd.edu) is being produced at Scripps Institution of Oceanography using the machinery developed by the consortium for Estimating the Circulation and Climate of the Ocean (ECCO; http://www.ecco-group.org). For more information on SOSE and ECCO, see Mazloff et al. (2010) and Wunsch and Heimbach (2013). Here, we describe the biogeochemical SOSE configuration being used to hindcast the period 2005 to 2014.

To maximize efficiency, we utilize multi-scale optimization, in which one uses model setups of varying resolution to first optimize the large scales and then progressively smaller scales. We are currently optimizing a setup with 1/3° horizontal resolution and 52 vertical levels. The coarse state estimate will inform our first-guess solution of a 1/6° resolution setup, which will in turn be optimized and used to drive a high-resolution 1/12° setup. The vertical resolution will be increased to 104 levels for the 1/12° setup.

The domain is from 78°S to the equator. Isotropy in discretization (Mercator projection) is achieved to 30°S, and then the meridional grid size increases gradually toward the equator. Topography is prescribed using ETOPO1 (Amante and Eakins 2009), with partial bottom cells to better resolve variations in ocean depth. An atmospheric boundary layer scheme is employed where fluxes of heat, freshwater (salt), and momentum are determined by bulk formulae (Large and Yeager 2009). The atmospheric state is optimized using the adjoint method, but constrained to be consistent with the ERA-Interim reanalysis (provided by the European Centre for Medium-Range Weather Forecasts, ECMWF). Similarly, the initial conditions are optimized and constrained to be consistent with a coarse global state estimate (Forget 2010). Runoff is prescribed at the continental boundary.

The biogeochemistry component of the model is adapted from the Biogeochemistry with Light, Iron, Nutrients, and Gases model (BLING; Galbraith et al. 2010). This intermediate complexity model includes a full description of the carbon system and a simple representation of phytoplankton community production, parameterized as a function of temperature with limitation terms from deficiencies of light, iron, and phosphate. With only six prognostic variables, it is relatively computationally inexpensive to run and thus well suited for data assimilation. First-guess initial and open boundary conditions for the biogeochemical fields are derived from global climatologies (GLobal Ocean Data Analysis Project version 2 (GLODAPv2), World Ocean Atlas) and optimized using the adjoint method.

Model-observation synthesis: Determining the state estimate

Physical observations constraining the state estimate include Argo float profiles, conductivity-temperature-depth (CTD) synoptic sections, instrument-mounted seal profiles, expendable bathythermographs (XBTs), altimetric observations, microwave radiometer-observed sea surface temperature, inverted echo sounders, and bottom pressure gauges. Observations of sea ice concentration from the National Snow and Ice Data Center (NSIDC; Cavalieri et al. 1996, updated yearly) are assimilated. Biogeochemical observations come mainly from Argo floats, underway pCO2 measurements, and the GLODAPv2 calibrated data product. A collection of iron measurements for the Southern Ocean is also available (Tagliabue et al. 2012).

The adjoint method optimization, also known as 4-dimensional variational assimilation (4D-Var), is used to bring the model into agreement with the observations. Model ability to reproduce the observations is measured with a cost function, J, which is the sum over time and space of squared model-data differences weighted by a prescribed uncertainty. The weight assigned to each data point is determined by combining the measurement error with the model representation error. Optimization is sought by iteratively reducing J by adjusting the control vector, $\boldsymbol{u}$, which consists of the initial conditions and the surface boundary (atmospheric state) conditions. The adjoint model calculates the cost function gradients with respect to the controls, $\nabla_u J$, thereby increasing the efficiency of the optimization algorithm.

Examples of other biogeochemical and ecological data assimilation efforts in ocean models of varying complexity are described in Gregg (2008) and Gregg et al. (2009). It is noteworthy that coupled physical–biological models often assimilate either physical data or biogeochemical data, but rarely both (a notable exception is the study of Schlitzer (2002)). In several studies, the assimilation of chlorophyll data was shown to significantly improve the simulation (Nerger and Gregg 2007; Ford et al. 2012; Tjiputra et al. 2007). These recent studies employ Kalman filter methods for data assimilation and produce sequential reanalyses. In contrast, the state estimate we are producing is determined by running the *free* model forward in time using the adjusted control vector. In that important sense, the state estimate is dynamically self-consistent (i.e., there are no non-physical jumps in properties), and this is the primary reason the adjoint method of optimization is chosen for this work.

Assimilation of observations in SOSE will be performed with the adjoint of the coupled model, meaning that both biogeochemical and physical constraints will contribute to determining the state. Dutkiewicz et al. (2006) have shown that the adjoint methodology can be applied to a physical–biogeochemical model. Our model, though slightly more sophisticated than the one used by Dutkiewicz et al. (2006), has been made compatible with the adjoint method. As an example of what the adjoint offers, we present the results of a carbon flux sensitivity experiment in the next section.

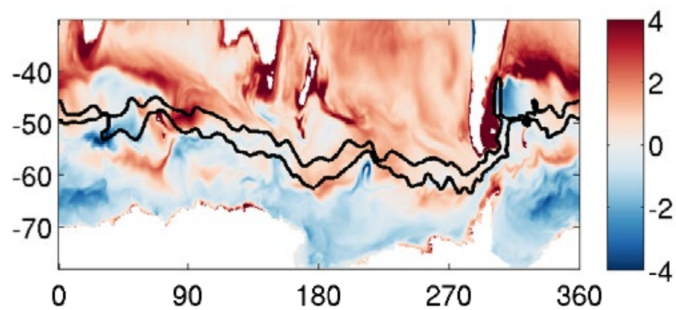

Figure 1. October mean air-sea CO_2 flux [mol m^{-2} yr^{-1}] in the model run. Positive fluxes are defined as ocean uptake (i.e., red implies an increase in oceanic carbon inventory). Black contours denote the approximate Subantarctic Front and Polar Front locations as determined in Orsi et al. (1995).

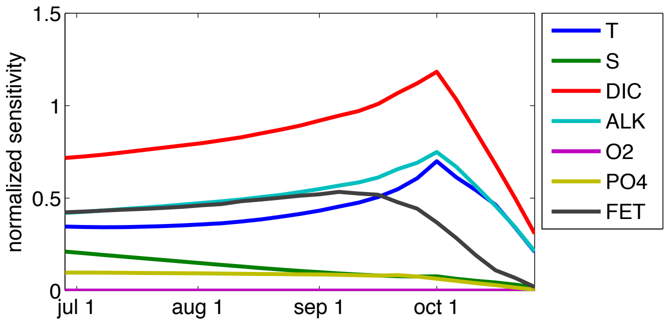

Figure 2. Temporal evolution from July 1 to October 30 of the sensitivity of October air-sea CO_2 flux poleward of 40°S to various physical and biogeochemical properties (colored lines). Sensitivity is calculated as the root-mean-square of adjoint gradients normalized by the spatially varying temporal standard deviation of the respective property.

The utility of the adjoint model: An example sensitivity experiment

The adjoint model yields the partial derivatives of a cost function with respect to model state and model inputs. In state estimation, the cost function is the weighted model-data misfit. One can, however, design a different cost function. Dutkiewicz et al. (2006) evaluate two cost functions; one being global biological productivity and the other being global air-sea carbon fluxes. They find the Pacific and Southern Oceans to be most sensitive to sustained atmospheric iron source inputs.

Following that work, we use our 1/3° setup to determine the sensitivity of October air-sea carbon exchange poleward of 40°S. The purpose is two-fold. First, we wish to demonstrate the power of the adjoint model in revealing the sensitivities of the system. Second, we wish to understand the controls on carbon flux. Fluxes themselves are challenging to observe, but knowing their sensitivities can guide how to infer them from properties that are more readily observed.

Over 50% of the variance in the air-sea carbon exchange time series in our model can be explained by the seasonal cycle (not shown). October is a time when the ocean is generally outgassing carbon to the atmosphere poleward of the Antarctic Circumpolar Current (ACC) and taking up carbon from the atmosphere equatorward of the ACC (Figure 1). This pattern is typical of the Austral spring months from September to December. The uptake is greatest in the confluence regions and downstream of land. Some uptake occurs along Antarctica.

The overall sensitivity of this October air-sea exchange to other model properties can be quantified and compared by weighting with a typical perturbation size of that property. We take the sensitivity maps (i.e., partial derivatives) of carbon flux to a property and multiply by the temporal standard deviation of that property to find how carbon is sensitive to a typical anomaly in units of carbon flux. Doing this to all prognostic variables, and then calculating the spatial root-mean-square of these normalized sensitivities, reveals that carbon flux is most sensitive to anomalies of dissolved inorganic carbon (DIC), alkalinity, temperature, and iron (Figure 2). The sensitivity maximum is on October 1, as perturbations at this time will have the greatest influence on October mean carbon flux. The decay shows how long sensitivity persists. This decay rate is

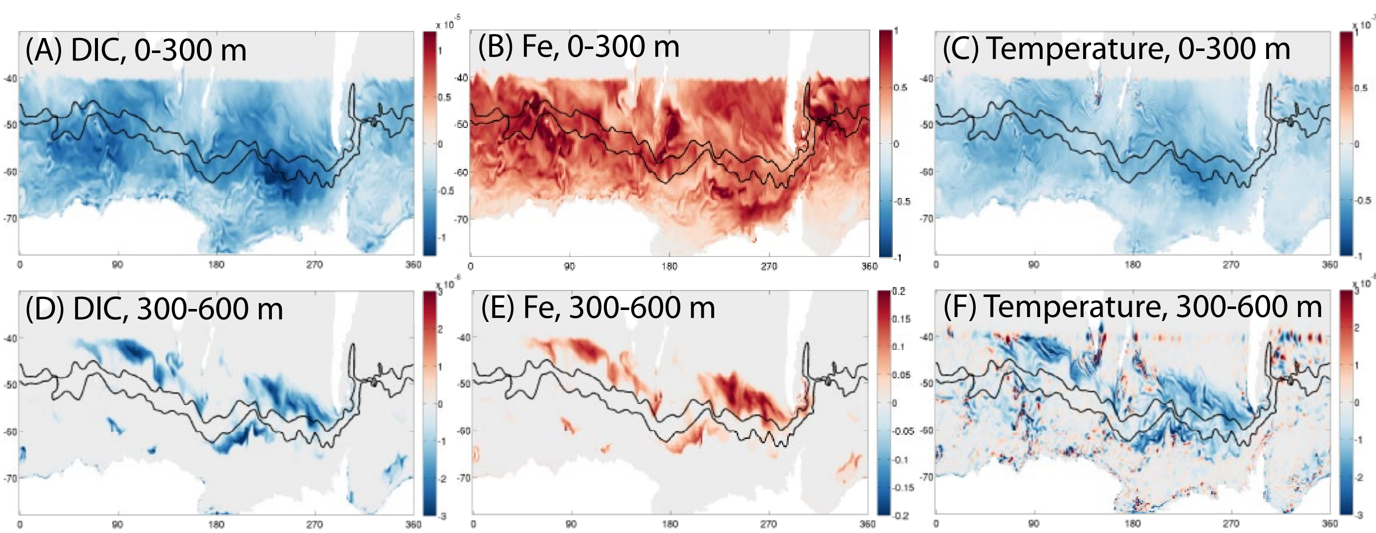

Figure 3. Spatial patterns of the sensitivity of the October air-sea CO_2 flux poleward of 40°S to DIC concentration in September (a) in the upper 300 m and (d) at depths 300 m to 600 m. The sensitivity to September iron concentration (b) in the upper 300 m and (e) at depths 300 m to 600 m. The sensitivity to September temperature (c) in the upper 300 m and (f) at depths 300 m to 600 m

similar for anomalies of alkalinity and DIC perturbations, slowest for nutrients and iron, and fastest for temperature.

The air-sea carbon flux poleward of 40°S is sensitive to September upper ocean DIC concentration almost everywhere (Figure 3a). The sign is always negative, implying adding DIC will decrease the carbon flux into the ocean, and thus increase ocean outgassing of CO2. The greatest sensitivity is found along the ACC, and particularly around the Kerguelen Plateau and in the Southeast Pacific sector. In the depth range of 300-600 m, the carbon flux is sensitive to September DIC concentration only in a few regions where there is a transport pathway to the surface (Figure 3d). These locations are primarily associated with mode water formation in the Southeast Indian and Pacific sectors. A few regions around Antarctica can also influence carbon flux. The sensitivity to alkalinity (not shown) looks qualitatively very similar to DIC, though with the opposite sign.

The sensitivity of air-sea carbon flux poleward of 40°S to September iron concentration is always positive, implying that adding iron will always increase the flux into the ocean (Figure 3b). As with DIC a sensitivity is found everywhere in the upper ocean, but the patterns are quite different. The sensitivity is strongest in the regions where the ocean is most iron-limited. Many of these locations coincide with regions of ocean outgassing in the October mean (Figure 1). An exception is a lack of sensitivity at the highest latitudes, as these are likely ice-covered and light-limited. The sensitivity at depths 300-600 m mirrors the sensitivity to DIC, as both of these are governed by the ability to be transported into the euphotic zone.

The sensitivity of air-sea carbon flux to September temperature reflects two phenomena. The first is the temperature effect on solubility, and thus the sensitivity is negative almost everywhere, implying that decreasing temperature increases carbon flux into the ocean (Figure 3c). The other is the effect of temperature perturbations on the circulation. This effect is more noticeable below the mixed layer where temperature has less impact on solubility (Figure 3f). The influence of the circulation on carbon flux poleward of 40°S is noticeable at 40°S where properties can be exchanged across the arbitrary cost function integration domain. It is also noticeable in regions where temperature anomalies can induce or enhance shelf exchanges (e.g., downstream of New Zealand) or cross-front transport (e.g., into the Argentine Basin or across the Polar Front).

The sensitivity to salinity (not shown) looks much like the sensitivity to temperature, but without the large-scale solubility component (i.e., without the relatively smooth domain-scale negative sensitivity pattern). While the sensitivity to the solubility component in temperature tends to decay rapidly, the sensitivity to circulation changes tends to grow slowly in numerous locations, as can be seen by the growing influence of salinity perturbations back in time (Figure 2).

Conclusions

Constraining biogeochemical observations to models via the adjoint method is feasible, and given the growing biogeochemical observational capabilities efforts have begun to produce state estimates of the carbon cycle. In this paper we introduced one underway state estimation effort. We demonstrate the utility of the adjoint model used in this effort by using it to map the sensitivities of the October air-sea carbon exchanges to anomalies in model state. We find this air-sea exchange is most sensitive to September anomalies of DIC, iron, alkalinity, and heat. Moderate sensitivities are also found to anomalies of macronutrients and salinity.

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Biogeochemical metrics for the evaluation of the Southern Ocean in Earth system models

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Observationally-based metrics are an important step in reducing the uncertainty in model simulations of the future climate. Especially as the community is shifting toward Earth system models with explicit carbon simulations, the need for more direct observations of biogeochemically (BGC) important parameters is essential. We present three biogeochemical metrics and discuss why they are important, the observations on which the metrics are based, and the quality and biases seen in the Earth system models' simulations. This analysis emphasizes the importance of the advent of a BGC Argo array as a critical tool for climate model assessment and refinement.

Introduction

The exchange of heat and carbon dioxide between the atmosphere and ocean are major controls on Earth's climate under conditions of anthropogenic forcing. The Southern Ocean south of 30°S, occupying just over a quarter of the surface ocean area, accounts for a disproportionate share of the vertical exchange of properties between the ocean's deep and surface waters and between the surface ocean and the atmosphere. Model simulations and observational analyses of the Southern Ocean have indicated that: 1) it may account for up to half of the annual oceanic uptake of anthropogenic carbon dioxide from the atmosphere (cf., Gruber et al. 2009, Frölicher et al. 2015); 2) vertical exchange there is responsible for supplying nutrients that fertilize three-quarters of the biological production in the global ocean north of 30°S (Sarmiento et al. 2004, Marinov et al. 2006); and 3) it may account for up to 75 ± 22% of the excess heat that is transferred from the atmosphere into the ocean each year (Frölicher et al. 2015). Unfortunately, uncertainty in these estimates and future climate projections remains high, and the carbon cycle represents one of the biggest challenges in this regard. There is an obvious need for improved observational data and model fidelity, especially as the scientific community is working toward more accurate estimates of the present and future carbon budgets.

Despite the crucial role of the Southern Ocean in the Earth system, our understanding of key underlying mechanisms remains inadequate, and the model studies that have focused on mechanisms of heat and carbon uptake to date remain highly controversial. Model uncertainty comes from incomplete physics and biogeochemistry, and from the use of parameterizations required in place of unresolved processes, such as cloud physics and stirring by mesoscale eddies. Equally important is the deficit of observational data to test the models due to the great difficulty of obtaining observations in this region. Quantifying the actual air-sea exchanges of carbon through direct observations remains beyond our capability, so we are dependent on the observations in the ocean from ships, buoys, and, most recently, the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) BGC-Argo float array. We do not have anything approaching an adequate spatial or temporal set of observations with which to definitively evaluate the biogeochemistry in Earth system model simulations. Despite significant recent advances in model development and observational coverage, it seems unlikely that modeling biases and observational gaps will be eliminated in the near future. There is an obvious need for quantitative information that would assist model validation and development and inform observational efforts on what information is most critical in this regard.

Here we describe several observationally-based data/model metrics that, with the advent of new biogeochemically-equipped floats, will be able to quantify the success of simulations and will allow for demonstrable progress and the reduction of model uncertainty in the projections of future climate. These metrics will become more robust as the coverage of the BGC-Argo array expands its scope in both space and time. Standardized metrics are especially critical for processes with large biases and inter-model differences like those that typify simulations of the Southern Ocean. We cannot expect all models to simulate all aspects of the ocean physics and biogeochemistry perfectly, so metrics should focus on processes that are most critical for the ocean's role in climate, such as heat and carbon uptake. The metrics presented here are an outgrowth of the joint US CLIVAR/OCB Working Group on the Southern Ocean Heat and Carbon Uptake, and a more complete discussion can be found in the full manuscript (to be submitted to the *Journal of Climate*).

Metrics

For this analysis, we compare a small subset of the historical simulations from the CMIP5/IPCC-AR5 archive at the Department of Energy's Program for Climate Model Diagnosis and Intercomparison (PCMDI) to the observations of surface dissolved inorganic carbon (DIC), air-sea CO_2 flux and surface pH. For each of these metrics, we discuss why the metric is important, the observations on which the metric is based, and the quality and biases seen in the Earth system models' simulations. The Earth-system models chosen for this analysis are: 1) CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada); 2) ESM2M (Geophysical Fluid Dynamics Laboratory, USA); 3) HadGEM2 (Met Office Hadley Centre, UK); 4) MIROC-ESM (Model for Interdisciplinary Research on Climate, Japan); and 5) MRI-ESM2 (Meteorological Research Institute, Japan).

Wherever possible, model simulations should be compared to actual observations. Unfortunately, ocean data and atmospheric data over the ocean rarely provide enough coverage in space or time to form a complete picture of the biogeochemistry. As a result, we will rely on atlases and reanalyses to fill in the gaps. The advent of profiling Argo-like floats equipped with BGC sensors are expected to bring a wealth of new data that can potentially revolutionize our understanding of the carbon cycle in the real ocean and dramatically improve the accuracy of the metrics discussed here.

Dissolved Inorganic Carbon

The total amount of carbon in the surface ocean, along with the pH, determines the surface pCO_2 and therefore greatly affects the air-sea exchange of carbon. Significant biases in simulated DIC will almost certainly lead to large biases in simulated uptake of CO_2 in transient forcing scenarios, and therefore the global atmospheric temperature response to these scenarios.

The gold standard of carbon data in the ocean continues to be the GLODAP dataset (Figure 1a; Key et al. 2004), although this is soon to be replaced by GLODAP v2, which is slated to become available in 2016. GLODAP data will serve as our observational benchmark for DIC and are available from CDIAC (http://cdiac.ornl.gov/ftp/oceans/GLODAP_Gridded_Data/). The other significant (and global) resource is the Takahashi surface ocean pCO_2 dataset, which is not used here for DIC. In the near future, we expect BGC-sensored floats to provide a much better resolved dataset in both space and time (seasonally) that will eventually give us an observational basis for the estimation of trends.

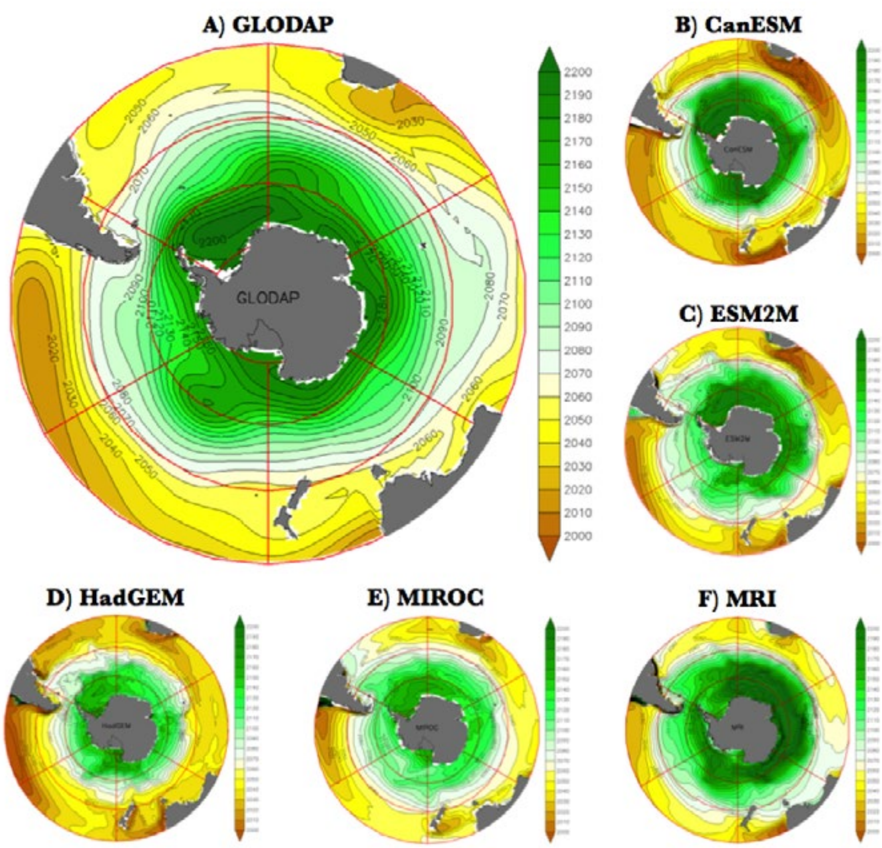

Figure 1: Surface (0-100 m) concentrations of dissolved inorganic carbon (DIC; μmol/kg) from observations (a) and model simulations (b-f). The observations are from the GLODAP dataset (Key et al. 2004), available through CDIAC. All model simulations cover years 1986-2005 from the HISTORICAL forcing scenario. Panel a) GLODAP; b) CanESM2; c) GFDL-ESM2M; d) HadGEM2-ES; e) MIROC-ESM; and f) MRI-ESM1.

Earth system models simulate significantly different amounts of total carbon, globally and in each of the different reservoirs (atmosphere, ocean, vegetation, and soil). The amount of carbon in each reservoir can potentially affect the modeled transient response (uptake or degassing) based on potentially unrealistic initial conditions. Focusing on the Southern Ocean (Figure 1), most models can simulate a general pattern of the observed surface DIC distribution, with the local maxima in the Weddell Sea and near the Ross Sea, but they also exhibit biases in simulated magnitudes of the DIC concentrations.

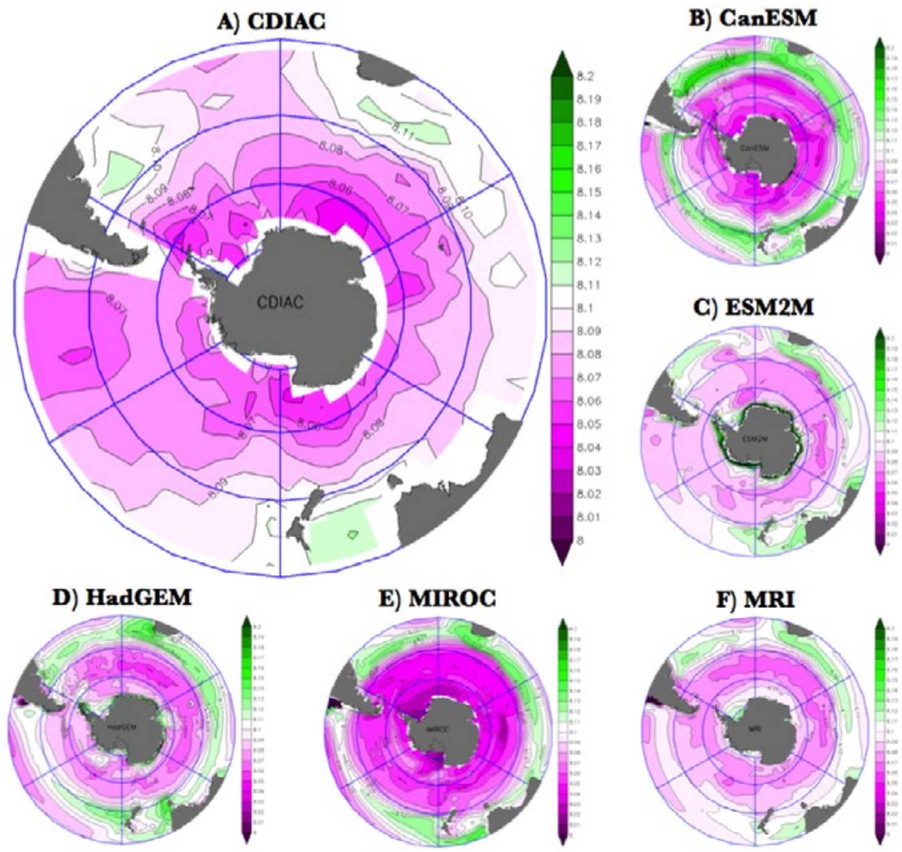

Figure 2: Annual mean surface pH from observations (a) and the model simulations (b-f). The observations are taken from the recent Takahashi et al. (2014) climatology, available through CDIAC, which has a fairly coarse 5°x5° resolution and should be indicative of 2005 conditions. The pH observations include data primarily from the GLODAP, CARINA, and LDEO databases taken from the top 50 m of the water column. Model simulations cover years 1986-2005 from the HISTORICAL forcing scenario. Panel a) CDIAC; b) CanESM2; c) GFDL-ESM2M; d) HadGEM2-ES; e) MIROC-ESM; and f) MRI-ESM1.

Surface pH

Ocean acidification, the decrease in oceanic pH due to the absorption of carbon dioxide, is an acknowledged and growing concern. Southern Ocean acidification is projected to lead to aragonite undersaturation in as little as 15 years (McNeil and Matear 2008). Monitoring and accurately simulating the Southern Ocean surface pH and its trend is critical. Small differences can potentially have large effects on simulated acidification trends as calcification rates are especially sensitive to small changes in pH. As noted above, pH influences the surface pCO_2 and carbon uptake.

The CDIAC dataset (NDP-094, Takahashi et al. 2014) is used here to provide gridded monthly surface pH data in the Southern Ocean (Figure 2a), although the BGC-Argo floats should shortly surpass these limited observations and provide depth information, as well as give us the opportunity to observe trends in real time. This new source of pH data will be essential for assessing acidification issues in the Southern Ocean, where it has been projected to become critical in as little as two decades (McNeil and Matear, 2008).

The Ekman-driven surface divergence brings old, carbon-rich, low pH water to the surface. Models generally capture this transport with some differences between the specific pH values present (Figure 2). Several of the simulations have excessively alkaline waters north of the Antarctic Circumpolar Current (ACC) and several have too acidic water in the upwelling region. Seasonal differences seen in the observations are seen in some of the simulations, but not in others (not shown), indicating that the seasonality of the upwelling is not necessarily well simulated even if the annual mean picture is more-or-less correct.

Air-Sea CO_2 Flux

The uptake of carbon dioxide by the Southern Ocean, and its subsequent removal from contact with the atmosphere is one of the most important aspects of climate change that is needed to reduce the uncertainty in future climate projections. As noted above, this flux depends on the amount of carbon in surface water, the pH and the buffering capacity, and the wind speed that controls the speed of the air-sea exchange. All of these factors are affected by anthropogenic carbon increases. Although early studies concluded that the Southern Ocean sink of anthropogenic carbon dioxide was weakening due to atmospheric warming (Le Quéré et al. 2007), more recent studies have concluded that the slowdown in the carbon uptake seen in the 1990s has ceased, and the uptake has been in-

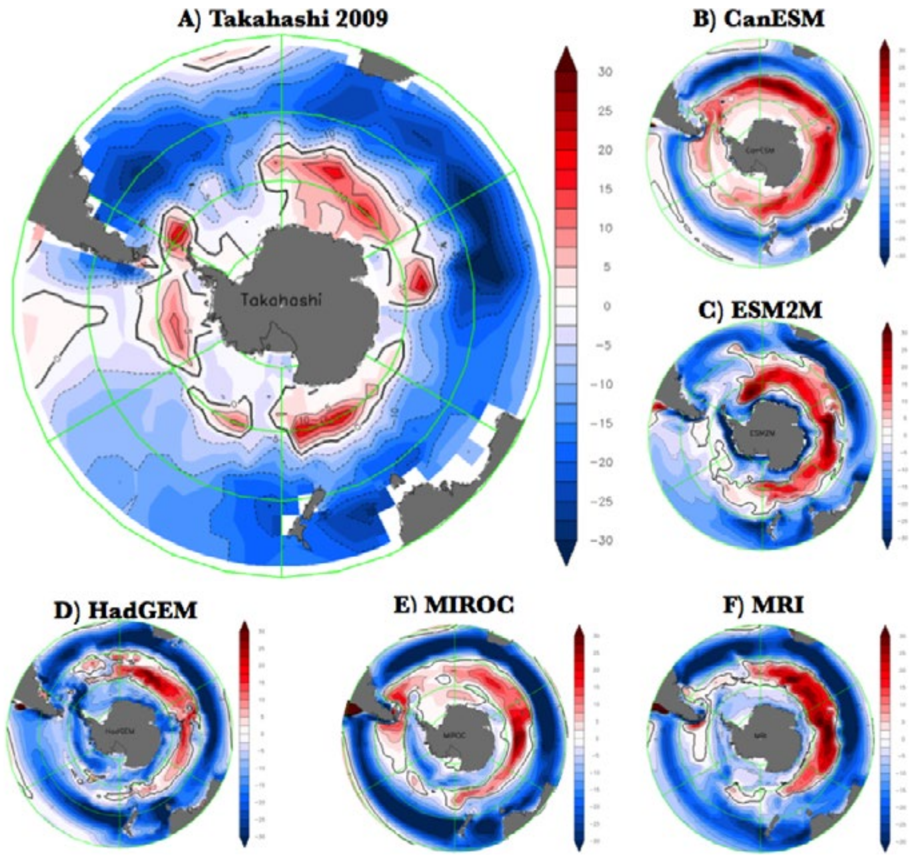

Figure 3: Annual mean surface flux of carbon (gC/m[2]/yr) from observations (a) and model simulations (b-f). The observations are from the 2009 Takahashi dataset. Model simulations cover years 1986-2005 from the HISTORICAL forcing scenario. Panel a) GLODAP; b) CanESM2; c) GFDL-ESM2M; d) HadGEM2-ES; e) MIROC-ESM; and f) MRI-ESM1. In these panels, red shading indicates degassing from the ocean into the atmosphere, while blue shading indicates uptake by the ocean.

creasing steadily since the early 2000s (Landschützer et al. 2015).

The Takahashi CO_2 flux observations shown in Figure 3a are derived from measurements of the surface ocean pCO_2, the atmospheric pCO_2, and the wind speed. Although the flux is not a direct measurement, it is likely more reliable than estimates of, for example, the total heat or freshwater fluxes.

The models generally get the pattern of CO_2 flux correct with outgassing at approximately 60°S where the upwelling of old, carbon-rich circumpolar deep water – due to Ekman divergence under the Southern Hemisphere westerlies – is most intense, and uptake at about 35°S where the Ekman convergence leads to subduction. Most of the models shown in Figure 3, however, due to their equatorward-shifted winds, overestimate both the uptake and the outgassing of carbon over the Southern Ocean.

Discussion

Consistent, observationally-based metrics are the clearest, most objective way to make progress in reducing the uncertainty in our future climate projections. We have presented some of these metrics related to the Southern Ocean biogeochemistry here. Our way forward requires two essential tracks. First, we collectively must carry out rigorous assessments of all model simulations against these and potentially other observationally-based metrics in order to evaluate the biases in the models, reduce our inter-model differences, and reduce the uncertainty in our projections of the future. Second, we need to encourage and bring about the continued expansion of the available observations. We are excited by the increasing availability of biogeochemical data from the nascent BGC-Argo efforts as well as the prospect of new data generated as part of the Southern Ocean Observing System (SOOS) efforts.

While the concept of an observationally-based metric is easy to understand, generating the datasets for those comparisons requires great care. All modeling centers should be encouraged to provide data for the comparison against the most important physical and BGC metrics, and make sure that these data are provided in standard and budget-conserving grids. While metrics are essential to the overall assessment and improvement of coupled climate and Earth system models, not every metric is relevant to every study and it remains the responsibility of the individual researcher to understand and apply the specific metrics that increase confidence with respect to individual hypotheses.

Acknowledgments

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Upcoming OCB Events

July 25-28, 2016: OCB Summer Workshop (Woods Hole, MA) (send your ideas for the summer workshop to hbenway@whoi.edu by December 7!

August 1-4, 2016: Joint GEOTRACES-OCB Workshop on Internal cycling of trace elements in the ocean (Lamont-Doherty Earth Observatory, Palisades, NY)

Recent Activities

Workshop report: Biological, ecological and biogeochemical implications of the iron availability mosaic in the California Upwelling Zone

May 19-21, 2015 (Univ. N orth Carolina, Chapel Hill)

Benjamin Twining (Bigelow Laboratory),
Adrian Marchetti (Univ. North Carolina, Chapel Hill),
Kim Thamatrakoln (Rutgers Univ.)

On May 19-21st, 2015, a workshop was held at University of North Carolina--Chapel Hill to synthesize the results of measurements and experiments conducted during an interdisciplinary cruise to the California Upwelling Zone (CUZ) in July 2014 (Fig. 1). The cruise, led by Ken Bruland (Professor Emeritus, UC Santa Cruz), represented his final expedition as chief scientist and involved 34 scientists from the US and Canada. Funding for the cruise was provided through an NSF Accomplished-based Renewal grant to Bruland (NSF OCE-1259776), who assembled a synergistic and multidisciplinary team of scientists to study the biological, ecological and biogeochemical implications of the mosaic of iron availabilities in the CUZ. Funding to Adrian Marchetti (UNC; NSF OCE-1334935) and Ben Twining (Bigelow Laboratory; NSF OCE-1334632) and to Kim Thamatrakoln (Rutgers University; NSF OCE-1333929) and Mark Brzezinski (UC Santa Barbara; NSF OCE-1334387) to study the molecular, physiological and ecological implications of iron and silicon availability in diatoms, also supported core sampling and experimental activities during the cruise.

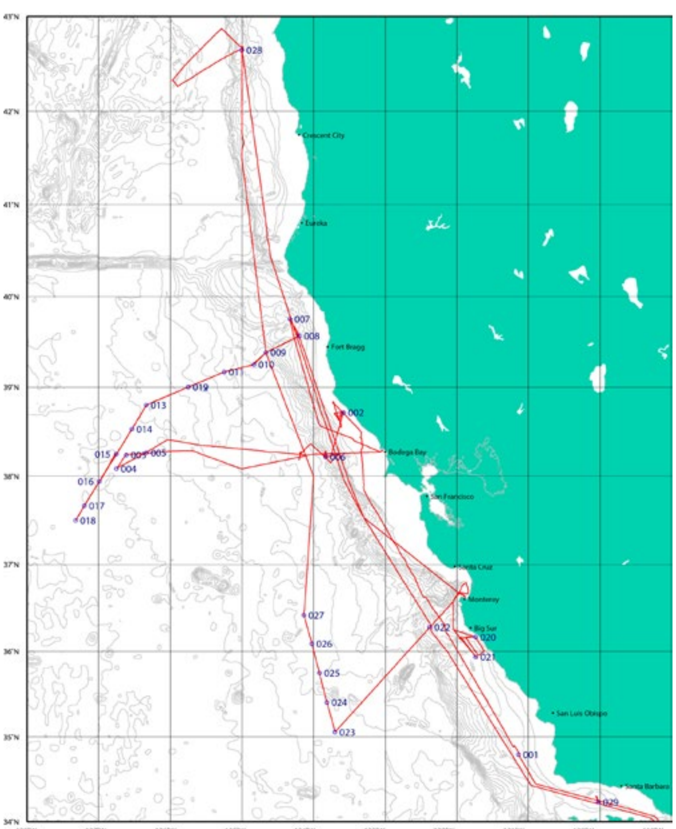

Figure 1. Cruise tracks in California Upwelling Zone (CUZ)

Major research objectives of the cruise included studying seawater iron chemistry and the effects of iron limitation on the marine ecosystem (spanning from viruses to zooplankton) and the resulting influences on biogeochemical cycles in the region. A unique aspect of the cruise was the unprecedented number of real-time, multidisciplinary oceanographic measurements. Using high-frequency measurements of iron and macronutrient concentrations, photosynthetic efficiency, and community composition (via FlowCam and SeaFlow flow cytometers), participants were able to sample waters experiencing vary-

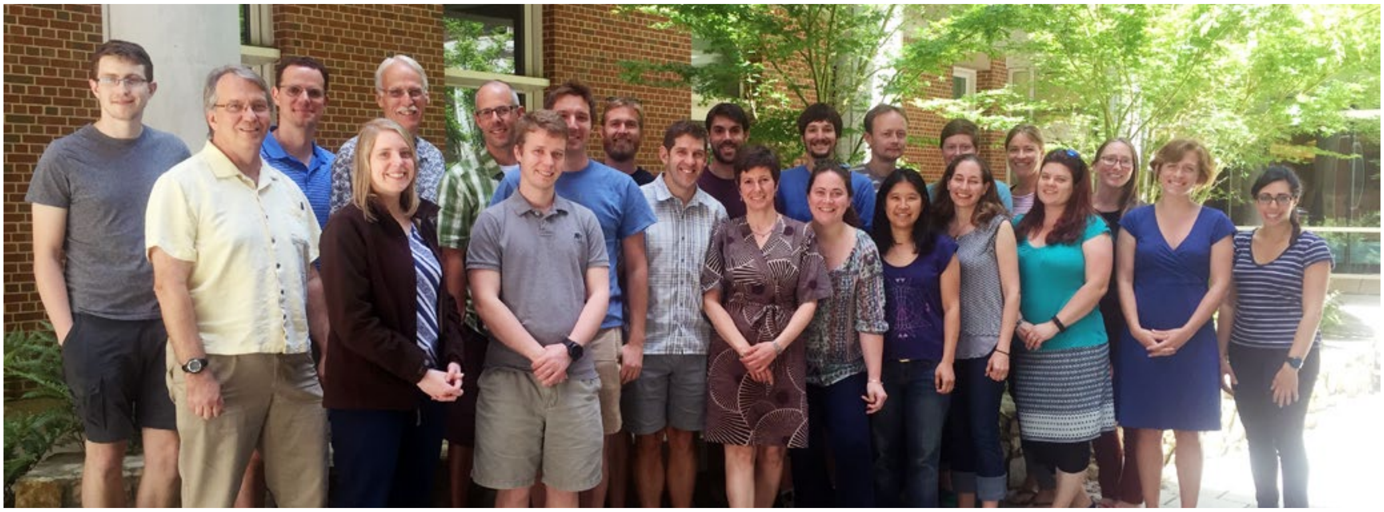

Figure 2. Workshop participants

ing degrees of iron stress (determined using both biological and chemical measurements) to support a wide range of iron-based studies.

Project activities were directly in line with OCB themes and research priorities, including improved understanding of environmental sensitivities of biogeochemical cycles and marine ecosystems, and molecular-level responses of marine organisms to their changing environment. Funding support from OCB enabled more than three quarters of the cruise participants to attend and participate in this post-cruise workshop (Fig. 2). OCB provided partial travel support and covered accommodation expenses for all early career scientists, which included faculty, post-docs, and graduate students.

The first day of the meeting focused on presentation and discussion of data characterizing biological and chemical conditions, starting with an overview of the physical and biogeochemical context of the cruise presented by Ken Bruland. Distributions of dissolved trace metals (Claire Parker, UC Santa Cruz) and particulate trace metals (Ben Twining) were presented, along with measurements of dissolved metal speciation into colloidal (Jessica Fitzsimmons, Texas A&M) and ligand-bound (Rene Boiteau, WHOI; Kristen Buck, Univ. South Florida) fractions. Spatial gradients of picoplankton (Sophie Clayton, Univ. Washington), microplankton (Tawnya Peterson, Oregon Health & Science Univ.), and bacteria and viruses (Kim Thamatrakoln) were presented, as well as data on phytoplankton photophysiology (Fedor Kuzminov, Rutgers Univ.) and autotroph molecular diversity (Sebastian Sudek, MBARI). The afternoon was dedicated to breakout and plenary discussions and synthesis of field data.

Day two focused on the presentation and discussion of data collected from the numerous deckboard incubation experiments. Incubations were designed to test the physiological and molecular responses of plankton to changing environmental conditions, and consisted of various manipulations, including altering the availability and chemical forms of iron, exposing the community to various light conditions (low light/ambient light or UV/dark) or $p\mathrm{CO_2}$ levels (present/future), or increasing silicon concentrations. Data were presented on the responses of dissolved iron and copper speciation (Kristen Buck), phytoplankton metal quotas (Ben Twining), and short- and long-term iron and carbon uptake kinetics (Maria Maldonado and Carolyn Duckham, Univ. British Columbia). These data were paired with measurements of the molecular physiological responses of incubated phytoplankton to altered metal availability (Natalie Cohen, UNC; Dreux Chappell, Old Dominion Univ.). The impacts of phytoplankton responses on micro- and macronutrient biogeochemistries were also examined (Adrian Marchetti; Mark Brzezinski). The third day of the meeting included additional discussion and integration of biological and chemical data in order to understand the physiological and ecological responses of the communities to the dynamic physical and chemical environment.

Throughout the duration of the workshop, research findings from the cruise were shared and the group discussed ways to combine data to provide holistic assessment of iron-related dynamics within the CUZ that would not be achieved through any single dataset alone. Several synthetic papers resulting from workshop discussions are planned, and research groups have coordinated abstract submissions to the upcoming 2016 Ocean Sciences Meeting in New Orleans. Workshop participants are extremely grateful to OCB for their financial support.

A Report from the 2015 OCB Summer Workshop

July 20-23, 2015 (Woods Hole, MA)

Heather Benway (OCB/WHOI)

The 10th annual Ocean Carbon & Biogeochemistry summer workshop, sponsored by NSF and NASA, convened 200 participants from July 20-23, 2015 at the Woods Hole Oceanographic Institution in Woods Hole, MA. This year's summer workshop featured three plenary sessions. The first plenary session *Atmospheric Nutrient Deposition: Impacts on Marine Ecosystems and Biogeochemical Cycles* featured an overview of natural and anthropogenic sources of atmospheric nutrients, followed by a series of talks on oceanic ammonia emissions, stable isotope tracers of anthropogenic nitrogen, a new field study on anthropogenic nitrogen deposition in coastal waters of the eastern US, and impacts of atmospheric nutrient deposition and aerosols on biogeochemistry and marine ecosystems. The second plenary session *Studying Spatial and Temporal Variability in the Ocean with Shipboard and Autonomous Platforms* was organized by members of the OCB Ocean Time-series Committee (OTC). Speakers in this session highlighted scientific insights gained from combined shipboard and autonomous measurement approaches in open-ocean, coastal, and high latitude systems. A community discussion during this session focused on ways to expand current time-series capabilities, including sensor development and testing, leveraging and/or augmenting existing assets, and increased coordination and intercomparison across time-series. The third plenary session *Evolving Views on Physical, Ecological, and Biogeochemical Underpinnings of Plankton Blooms* was organized into four parts. *Part 1. Overview of Habitat Conditions that Promote Blooms* kicked off with an overview of bloom properties and mechanisms, followed by talks on the physical processes underlying bloom formation and the meso- and submesoscale dynamics of blooms and how they evolve. *Part 2. Types and Detection of Blooms* included presentations on bloom formation by different organisms (coccolithophores, diatoms, *Trichodesmium*, etc.) and various means of detecting blooms, including satellite remote sensing, shipboard, and automated instruments such as ice-tethered profilers. Presenters in *Part 3. Biogeochemistry and Ecology of Phytoplankton Blooms* focused on the biogeochemical and biological processes that take place within a bloom, including aggregation and export of material, how nutrient sources and settings (low- vs. high-nutrient) drive blooms of different phytoplankton (e.g., diatoms vs. dinoflagellates), and the dynamics of grazing (predation) in bloom systems. Presenters in *Part 4. Bloom-Induced Changes in Plankton Ecology* explored the role of gelatinous zooplankton (i.e., jellyfish) blooms in the biological pump and the use of -omics data to explore responses of different marine bacteria to phytoplankton blooms.

In addition to the plenary and poster sessions, this year's workshop included several community updates, activities, and discussions. Bob Anderson (Lamont-Doherty Earth Observatory) spoke about recent development in the GEOTRACES Program, including an upcoming joint GEOTRACES/OCB workshop in 2016 focused on internal cycling of trace elements in the ocean. Oscar Schofield (Rutgers Univ.) spoke about recent developments with the Ocean Observatories Initiative (OOI) and fielded questions from the audience. Galen McKinley (Univ. Wisconsin) provided an update on the Coastal CARbon Synthesis (CCARS) activities, including a coastal carbon science plan. Igor Kamenkovich (Univ. Miami) shared recent activities and findings of the joint US CLIVAR/OCB working groups *Southern Ocean Heat and Carbon Uptake* and *Oceanic carbon uptake in the CMIP5 models*. He also provided a report from the December 2014 US CLIVAR/OCB workshop *Ocean's Carbon and Heat Uptake: Uncertainties and Metrics*. Maria Tzortziou (City Univ. New York) gave an update on the NASA Arctic scoping study *Arctic-COLORS.* There were reports from international partner programs and initiatives IMBER and Future Earth (Eileen Hofmann, Old Dominion Univ.) and IOCCP (Laura Lorenzoni, USF). NASA, NSF and NOAA program managers provided agency updates. BCO-DMO (Biological and Chemical Oceanography Data Management Office) staff provided one-on-one meetings and group training sessions for workshop participants. Graduate students gave short presentations on their research interests and also participated in an informal lunch discussion about careers in interdisciplinary science with former and current members of the OCB SSC. WHOI also arranged a research funding panel discussion for postdocs and students to meet agency managers.

Immediately following the OCB Workshop, several OCB participants attended a scientific planning discussion for the next Decadal Survey of Earth Science organized by the NASA Ocean Biology and Biogeochemistry (OBB) Program to discuss the critical observational needs and priorities of the OBB community.

For more information, including links to plenary talks and webcast footage, please visit the workshop website or contact Heather Benway.

OCB Scoping Workshop Report: Trait-based Approaches to Ocean Life

October 5-8, 2015 (Waterville Valley, NH)

Organizers:
Andrew Barton (Geophysical Fluid Dynamics Laboratory, Princeton University) and Stephanie Dutkiewicz (Massachusetts Institute of Technology)

Steering Committee:
Ken H. Andersen (Technical University of Denmark), Øyvind Fiksen (University of Bergen), Mick Follows (Massachusetts Institute of Technology), Colleen Mouw (Michigan Technological University), Nick Record (Bigelow Laboratory for Ocean Sciences), Tatiana Rynearson (University of Rhode Island)

Marine ecosystems are rich and biologically diverse, often composed of thousands of competing and interacting species with a vast range of behaviors, forms, and life histories. This great ecological complexity presents a formidable barrier to understanding how marine ecosystems are structured and controlled, but also how they respond to natural and anthropogenic change. The "*trait-based approach to ocean life"* is emerging as a novel framework for understanding the complexity, structure, and dynamics of marine ecosystems, but also their broader significance. Rather than considering species individually, organisms are characterized by essential traits that capture key aspects of diversity. Trait distributions in the ocean emerge through evolution and natural selection, and are mediated by the environment, biological interactions, anthropogenic drivers, and organism behavior. Because trait variations within and across communities lead to variations in the rates of crucial ecosystem functions such as carbon export, this mechanistic approach sheds light on how environmental variability impacts marine ecosystems, biogeochemical cycles, and feedbacks to climate and society.

87 scientists, including 18 students, 22 postdoctoral scholars, scientists, program managers, and foundation representatives convened for the Ocean Carbon and Biogeochemistry (OCB) scoping workshop Trait-based Approaches to Ocean Life in Waterville Valley, NH, USA on October 5-8, 2015. The workshop included theoreticians, numerical modelers, experimentalists, satellite oceanographers, and microbial biologists, with many participants spanning multiple disciplines. Organisms from marine viruses, bacteria, plankton, jellyfish, and fish were represented. Invited speakers shared recent developments in trait-based science from terrestrial systems (Professor Hans Cornelissen, Vrije Universiteit Amsterdam), marine fisheries (Professor Simon Jennings, Centre for Environment, Fisheries and Aquaculture Science, and University of East Anglia), zooplankton (Professor Thomas Kiørboe, Technical University of Denmark), phytoplankton (Professor Elena Litchman, Michigan State University), and molecular ecology (Professor Sonya Dyhrman, Columbia University). Contributed talks and plenary discussions centered on coherent themes:

- Measuring and detecting traits
- Biogeography of traits
- Linking observations and models
- Size as a master trait
- Role of physics on setting and linking traits
- Contributions to cross-cutting principles in marine ecosystems
- Contributions to climate science and biogeochemical cycles
- Contributions to policy
- From the gene to the ecosystem

In addition to the plenary program and linked poster sessions, numerous small group discussions and "chalk talks (informal lab-group style presentations) were held to maximize participant interaction.

The workshop showcased numerous examples of how the trait-based approach to ocean life provides a powerful, reductive framework for understanding the complexity and dynamics of marine ecosystems, and pinpointed areas for further development in the coming years. It also highlighted the inherent multi-disciplinary nature of the trait-based approach, encompassing species groups from bacteria to fish, as well as diverse methodological approaches. The workshop encouraged the development of meaningful interactions between modelers/theorists and scientists making or aggregating fundamental trait observations. These new lines of communication between methodological perspectives have facilitated the development of a common "trait" language.

The workshop highlighted the need for robust investment in making and aggregating individual lab-, field-, or satellite-measured trait observations. Such meta-analyses provide a powerful tool to unveil relationships between traits and their environment. Trait-based models and theory readily incorporate this meta-analytical perspective to develop global representations of species biogeography and formulate testable hypotheses that link traits to ecosystem structure, function, and fundamental controlling mechanisms. Improved cyber-infrastructure (e.g., data and model repositories) and a culture of data sharing, curation, and stewardship will produce more effective linkages throughout the field and across methodological perspectives.

In addition to building a strong interdisciplinary network for scientists studying trait-based approaches to ocean life, numerous tangible workshop outcomes are forthcoming. First, a detailed workshop summary report will be shared with OCB and the broader scientific community. Second, the workshop served as an incubator for several review and synthesis papers, including:

- A review of the roles of ocean circulation on setting trait distributions
- A synthesis of marine ecosystem model techniques
- A perspective on trait-based modeling of viruses
- An examination of how the principal trait-based research questions vary across spatial and temporal scales, from the gene to the globe.

Finally, several new data and model stewardship efforts were proposed, including a global plankton trait database (to be linked to Encyclopedia of Life and World Register of Marine Species, or WoRMS) and a trait-based model repository and inter-comparison project.

The organizers thank the OCB Program, the Simons Foundation, and the Gordon and Betty Moore Foundation for their support.

2016 Ocean Sciences Meeting

OCB at Ocean Sciences 2016

OCB will have an exhibit booth at the upcoming 2016 Ocean Sciences Meeting (February 21-26 2016, New Orleans, LA), so please come by and visit us! There will be a **poster on the OCB Program entitled** *Advancing Ocean Science Through Coordination, Community Building, and Outreach* **(paper number AH24A-0049)**, which will be presented on Tuesday, Feb. 23 from 4-6 pm as part of the session *Updates, advancements, and projections on the state of the ocean carbon cycle SOCC): How the ocean is "SOCC"ing it to us!*

Town Hall Meetings

Below is a sampling of town halls that may be of interest to the OCB community. For a complete list of town hall meetings, please visit http://osm.agu.org/2016/town-halls/

Monday, February 22

Towards a standard, user-friendly chemical speciation model for seawater and estuarine waters
TIME: 12:45-1:45 pm
LOCATION: Ernest N. Morial Convention Center, 228-230

Deep Ocean Stewardship Initiative (DOSI)
TIME: 6:30-7:30 pm
LOCATION: Ernest N. Morial Convention Center, 228-230

Wednesday, February 24

The Future of Biogeochemical Ocean Time Series
TIME: 6:30-7:30 pm
LOCATION: Ernest N. Morial Convention Center, 225-227

Thursday, February 25

Launch of the 2nd International Indian Ocean Expedition (IIOE-2)
TIME: 12:45 - 1:45
LOCATION: Ernest N. Morial Convention Center, 225-227

Opportunities to strengthen your science (and proposals) using GEOTRACES data
TIME: 6:30-7:30 pm
LOCATION: Ernest N. Morial Convention Center, 228-230

North Atlantic-Arctic News

In April 2014, NSF and the European Commission cosponsored a workshop on the coupled North Atlantic-Arctic System to identify critical research questions, discuss common research interests, and explore areas of potential collaboration. Participants included scientists across multiple disciplines from Canada, the EU, and the US, as well as representatives from ocean-relevant US and EU government agencies. The science plan that emerged from this workshop was finalized in May 2015. In October, NSF released a Dear Colleague Letter to provide guidance for US scientists who will request support from the NSF Division of Ocean Sciences (OCE) and Division of Polar Programs (PLR) over the next 18 months to conduct research related to the workshop goals in collaboration with scientists from Canada and/or the European Union.

Community Announcements

Science and outreach

- *Eos* opinion piece on the need to strengthen carbon cycle science in support of policy
- **New OCB slide deck** *Temporal and Spatial Perspectives on the Fate of Anthropogenic Carbon: A Carbon Cycle Slide Deck for Broad Audiences - also download accompanying explanatory notes (doi:10.1575/1912/7670)*
- *Integrating Carbon Cycle Research into Decision-Making Processes - Report from the fifth biennial meeting of the North American Carbon Program (NACP) Principal Investigators Meeting*
- IMBER IMBIZO IV "Marine and human systems: Addressing multiple scales and multiple stressors" keynote talks posted
- GEOTRACES special issue in Marine Chemistry
- GEOTRACES Education/Outreach Webinar Series
- New movie on ocean change developed for the general public
- Submit ideas for topics related to SOLAS science and society (view report from SOLAS Open Science Conference) by **January 6, 2016**
- 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
- SOCAT version 3 now available, submit data for SOCAT version 4 by **December 31**
- NASA Carbon Mapper (beta version) has been released
- NSF report *America's Future: Environmental Research and Education for a Thriving Century*
- LDEO Database V2014 published at CDIAC

- Future Earth's Pop Up webinars focus on communication tools to help scientists engage with a wider audience
- New NAno-Raman Molecular Imaging Laboratory (NARMIL) established at Stony Brook University

Science planning and policy

- Draft of the Update to the 2012-2021 USGCRP Strategic Plan is available for public review until **January 30**
- EarthCube Oceanography and Geobiology Environmental 'Omics (ECOGEO) Research Coordination Network Workshop 1 Report (November 2015)
- Workshop report from joint US CLIVAR/OCB workshop *Ocean's Carbon and Heat Uptake: Uncertainties and Metrics* now available
- View North American Coastal Carbon Science Plan
- International North Atlantic-Arctic science plan now final and NSF has released a Dear Colleague Letter encouraging proposals seeking proposals for collaborative international North Atlantic-Arctic research
- Southern Ocean Observing System (SOOS) Progress report (2011-2014)
- Ocean policy brief *Intertwined ocean and climate: implications for international climate negotiations*
- NASA EXPORTS Science Definition team selected
- Arctic-COLORS (Arctic-COastal Land Ocean inteRactions) science plan

Ocean Time-Series News

Instrumenting our oceans for better observation: A training course on biogeochemical sensors

(June 22-July 1, 2015, Kristineberg, Sweden)

Laura Lorenzoni[1], Toste Tanhua[2] and Heather Benway[3]

[1]University of South Florida, College of Marine Science, St. Petersburg, FL. USA

[2]Helmholtz Centre for Ocean Research Kiel (GEOMAR), Kiel, Germany

[3]Woods Hole Oceanographic Institution, Woods Hole, MA. USA

The importance of globally distributed marine biogeochemical observations has been highlighted in recent years in light of issues of global, regional, and local climatic and societal relevance[1,2,3]. While our current global ocean observing framework provides a wealth of data, there are still large spatial and temporal gaps in coverage, making it difficult to observe patterns of change in the ocean and associated climatological and ecological feedbacks, as well as impacts on ecosystem services. A truly integrated global ocean observing system includes shipboard, autonomous, and satellite components, and should actively involve all nations with a coastline, including developing nations, so that they directly benefit from and contribute to ocean observations.

Over the past decade, the oceanographic community has identified an urgent need for expanded observational coverage in space and time, which has accelerated the development and deployment of autonomous biogeochemical and biological sensors. Autonomous platforms have greatly expanded the footprint of our current observational network, contributing to an improved scientific understanding and capacity to address societal needs concerning the availability of marine resources. To contribute to the ongoing development and expansion of autonomous capabilities in the ocean, the International Ocean Carbon Coordination Project (IOCCP), with support from the Ocean Carbon and Biogeochemistry (OCB) Program, the Royal Swedish Academy of Sciences (KVA), IOC-UNESCO, the Scientific Committee on Oceanic Research (SCOR), the Gordon and Betty Moore Foundation, NSF and NASA, held a 10-day international training course on autonomous biogeochemical sensors. Course participants, consisting mostly of relatively experienced sensor users, tackled issues of basic usage of the technology to data reporting, standards and protocols. The course took place from June 22-July 1, 2015 at the Sven Lovén Center for Marine Sciences in Kristineberg, Sweden. The objectives of the course were to 1) teach best practices for biogeochemical sensors in general, and for selected types of sensors in particular, with the aim of improving the quality of data currently generated by such sensors; 2) collate the collective wisdom of participants and instructors on best practices of operation of biogeochemical sensors and distill this into a document; and 3) work on data reduction practices for sensor data, including reporting format and requirements (e.g., meta-data, accuracy and precision estimates, etc.).

The biogeochemical variables considered for this course were oxygen, nitrate, pH and pCO_2, which were chosen based on sensor maturity, deployment, and commercial availability. Participating sensor manufacturers included Seabird Scientific, Sunburst, Aanderaa, and Contros. Course participants engaged in lectures in a classroom setting, as well as hands-on activities with the sensors. Course topics included sensor calibration and validation, sensor interfacing, biofouling, sensor mechanical functioning and detection principles, and data management and quality control. The outcome of this course will be a document that contains all of the knowledge acquired throughout the 10 days. This document will be completed during the first quarter of 2016 and will be available to the entire community with the aim of perfecting and expanding the usage of autonomous biogeochemical sensors.

While the final course document will contain all of the details regarding the intensive 10-day experience, there were several salient comments and recommendations from the participants and lecturers. One of the most pressing discussion topics was the sustainability of observing systems. As infrastructural costs rise, the usage of ships for oceanographic observations will be limited, and while sensors cannot replace shipboard observations, autonomous platforms should be implemented more widely, especially in the open ocean, to ensure a sustained set of biogeochemical measurements. With limited funding for ocean research and observations, it is important to consider that 1) the sustainability of the system ultimately depends on the utility and quality of data being generated; and 2) international collaboration is essential in the development of a truly integrated, globally accessible ocean observing system.

A global biogeochemical sensor network that fills in current geographic and temporal gaps in coverage would greatly improve our global ocean observing framework and capacity to monitor changes in marine biogeochemical cycles and ecosystems. Such a network might leverage and/or be integrated with existing sampling programs. Several existing observing networks focus exclusively on physical variables, and while augmentation of these physical networks with biogeochemical sensors would be useful, real progress in understanding the complex interplay between physical, biogeochemical, and biological processes necessitates a movement toward a truly integrated observing system, in which physical, biological, and biogeochemical components are simultaneously incorporated at the design stage. Remote sensing platforms also represent a critical component of an integrated global ocean observing system that can fill spatiotemporal gaps in *in situ* observational coverage and guide deployment of autonomous platforms. Conversely, high-quality *in situ* measurements are critical for validating satellite data and models. Thus, it is important that the data being generated by autonomous sensors are consistent and trustworthy. The quality of such measurements depends on the set-up and performance of the sensors/platforms with time and the selection of a specific sensor for a particular measurement. Sensor suitability will depend on the question(s) being asked: What do you need? How good is good enough? This requires knowledge of a sensor's limitations, as well as a robust understanding of the environment in which it will be deployed, which also underscores the importance of detailed metadata. Reporting as many parameters and specifications about the sensor as possible will improve the chances of data use and intercomparison by other users. It is important to remember that a sensor is not measuring a biogeochemical variable directly, but a proxy. Accurate and thorough reporting of data is important, including values that appear below detection or negative, as removing these (left censoring) could introduce biases. Most importantly, data accessibility to scientists and decision makers will not only advance our scientific understanding of the ocean system, but will provide important information to support responsible management of our marine resources and thus ensure continued support for these critical observing systems.

Biogeochemical sensors have the capacity to become the new eyes of oceanography, greatly expanding our spatial and temporal observational coverage of the ocean. A key challenge is to develop an educated and experienced community of users of this technology. This course has provided a new layer of information and "know-how" regarding best practices of autonomous biogeochemical sensor deployment. Course participants will further expand our collective ocean observing capacity by sharing their newly gained knowledge with colleagues and students. The 'best-practices guide' to be published as a result of the course will also facilitate more widespread usage of autonomous sensors, providing an informational resource accessible to all, and that together with other existing documentation will set universal guidelines for sensor standardization procedures, data QC protocols, and the emergence of an autonomous biogeochemical sensor network.

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2. Johnson, K. S., et al. 2009. Oceanography, 22(3), 216-225.

3. Lorenzoni, L., Benway, H. M. (Editors), 2013. Report of Global intercomparability in a changing ocean: An international time-series methods workshop, November 28-30, 2012, Ocean Carbon and Biogeochemistry (OCB) Program and International Ocean Carbon Coordination Project (IOCCP), 61 pp.

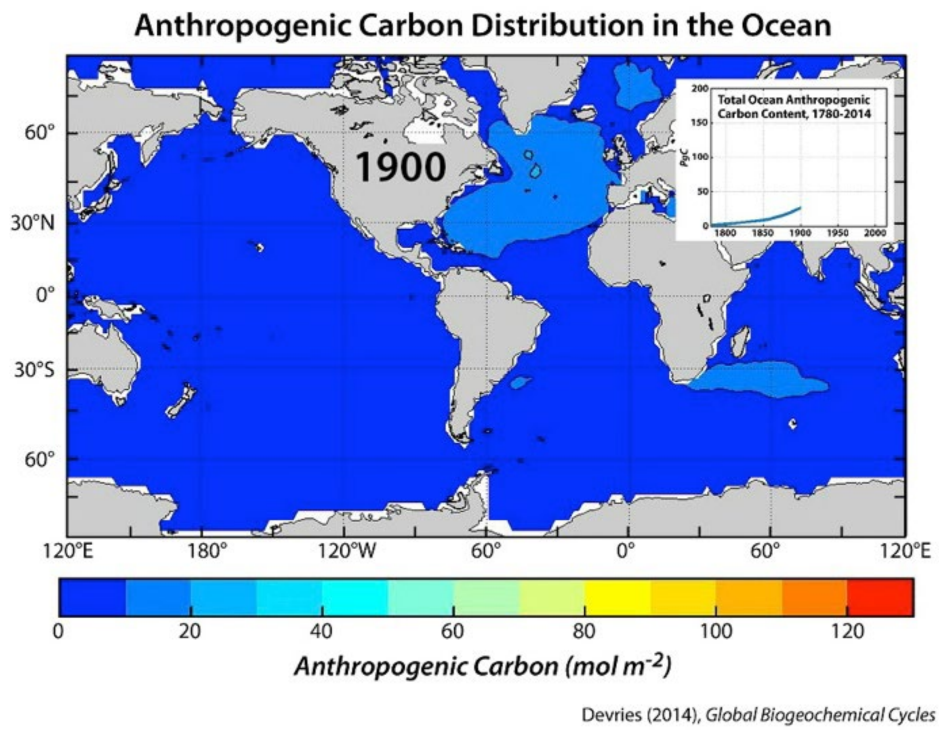
OCB Ocean Time-series Committee (OTC) to Convene Town Hall at 2016 Ocean Sciences Meeting—*The Future of Biogeochemical Ocean Time-series*

February 24, 2015 at 6:30 pm
Ernest N. Morial Convention Center, 225-227

Monitoring ocean change requires a sustained, globally distributed network of observatories that integrates shipboard, autonomous, and remote sensing platforms. Data intercomparability within such a network is facilitated by universally established guidelines and methodological approaches, a commitment to data sharing, and improved coordination and communication across sites and programs. This town hall, organized by the US Ocean Carbon and Biogeochemistry (OCB) Program's Ocean Time-series Committee, will convene interested ocean scientists to share outcomes of recent time-series activities and coordination efforts and gather community feedback on mechanisms to strengthen this international network.

Education

OCB releases new teaching/outreach slide deck on anthropogenic carbon in the ocean



The OCB Project Office recently worked with OCB scientists to develop a slide deck to inform broader scientific, as well as general audiences about the role of the ocean in the global carbon cycle, including key sinks and sources of anthropogenic carbon and how they have evolved through time and space. The slide deck features **1) animations of anthropogenic carbon sources and sinks throughout the industrial era** based on Khatiwala et al. (2009, 2013); and **2) map-based animations of anthropogenic carbon uptake and storage in the ocean over time** from DeVries (2014). The slide deck also has an accompanying **pdf with explanatory notes** and key points to highlight when presenting the slides. We hope you find this to be a useful resource. The links in the citation below will take you to the Powerpoint and accompanying notes. Please share with your colleagues.

Slide Deck Citation

Ocean Carbon and Biogeochemistry Program (2015). Temporal and Spatial Perspectives on the Fate of Anthropogenic Carbon: A Carbon Cycle Slide Deck for Broad Audiences with explanatory notes. Contributors: S. Khatiwala, T. DeVries, J. Cook, G. McKinley, C. Carlson, H. Benway. doi:10.1575/1912/7670.

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Khatiwala, S., T. Tanhua, S. Mikaloff Fletcher, M. Gerber, S. C. Doney, H. D. Graven, N. Gruber, G. A. McKinley, A. Murata, A. F. Rios, C. L. Sabine (2013). Global ocean storage of anthropogenic carbon. Biogeosciences 10, 2169-2191, doi:10.5194/bg-10-2169-2013.

1865 THE UNIVERSITY OF MAINE

Ocean Optics Summer Course Information

Calibration & Validation for Ocean Color Remote Sensing

July 6 - 31, 2015

OCB supports student participation in the University of Maine Ocean Optics Summer Course

Kevin Williams, II (Florida A&M Univ.)

Kevin received his B.S. in Natural Resources and Environmental Management with a minor in Sustainability from Ball State University in Muncie, Indiana. A 2013 Morris K. and Stewart L. Udall Scholar and 2013 Benjamin A. Gilman International Scholar, Kevin spent the spring of 2013 in Costa Rica, where he studied sustainable development in unison with current socioeconomic and environmental issues in the province of Sarapiqui. He is currently enrolled in the M.S. program at Florida A&M University, School of the Environment. His research topic is the effectiveness of activated green infrastructure in remediating contaminant loading via agricultural runoff that can contribute to *Microcystis* blooms.

"The Ocean Optics Summer Course gave me the tools I needed to enhance my thesis and add value to my graduate coursework at my home institution. The combination of lectures from distinguished instructors, fieldwork, lab training, and peer interaction all occurring at the Darling Marine Center offered an ideal learning community that will benefited my academic and professional goals. I want to integrate what I learned at DMC into my thesis research, demonstrating how ocean color remote sensing can be coupled with laboratory analysis for multi-disciplinary HAB mitigation research. As ocean color remote sensing continues to develop, I can take the knowledge from this program and be a part of the next generation of marine scientists using ocean optics as an integral part of studying aquatic ecosystems."

Ian Brosnan (Earth Science Division, NASA Ames Research Center)

Ian Brosnan is a STEM Presidential Management Fellow in the Earth Science Division at NASA Ames Research Center. He completed his Ph.D. at Cornell University, where he applied advanced acoustic telemetry techniques and individual-based modeling in studies of early marine survival and migration of juvenile Pacific salmon. He received his Master's in Marine Affairs from University of Washington, where he studied governance and security in a changing Arctic. Prior to entering the School of Marine Affairs, he served as an active duty U.S. Coast Guard officer, holding positions as a military diver, Commanding Officer of the Coast Guard cutter COBIA, and liaison to members of Congress. He continues to serve in the Coast Guard Reserve

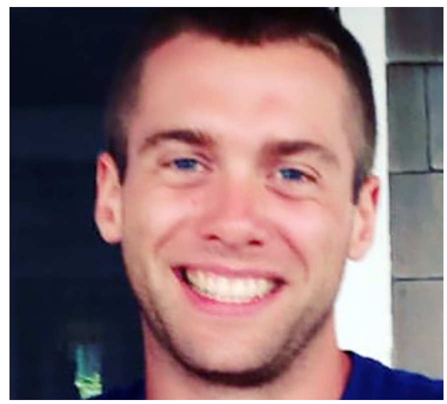
"Attending the 2015 Calibration and Validation of Ocean Color Remote Sensing course was a truly great experience. The depth, breadth, and quality of instruction was superb, and while the pace of the class was intense, I had great classmates who made

each day, and the many long nights, a real pleasure. The instructor's efforts to bring a truly international class with diverse scientific backgrounds really paid off. I am new to ocean color research, and NASA, so I am very grateful to have had this opportunity to build new relationships with potential collaborators, and expand my technical expertise."

Cael Barry (Massachusetts Institute of Technology/Woods Hole Oceanographic Institution)

Cael is a graduate student in the MIT-WHOI Joint Program, and is working on mathematical aspects of ocean ecology and bio-physical interactions with Mick Follows and Amala Mahadevan. Cael also enjoys reading instead of sleeping like it's fifth grade, or playing accordion like it's Romania.

"I adored the optics course, finding it one of the best experiences of graduate school thus far. Between delving deep into the theory of ocean optics at all levels with caring experts, and getting daily hands-on practice with a range of essential methods used in optics, the course gave me a strong foundation in the ocean optics discipline and the inspiration to incorporate it into current and future research."



Ben Lambert (Massachusetts Inst. Technology)

Ben Lambert is a graduate student in the MIT-WHOI Joint Program where he studies microbial ecology under advisors Heidi Sosik and Roman Stocker. Prior to the Joint Program, Ben received a B.Sc. in Civil and Environmental Engineering from the University of Alberta. Currently he is working as an academic guest in the department of Civil, Environmental, and Geomatic engineering at ETH Zurich.

"The Ocean Optics summer course was the best educational experience I've ever had. I've never participated in a course that was so well structured and covered so many topics with such depth. The combination of theory and hands-on work was an incredible way to develop new skills."

Kelsey Bisson (Univ. California, Santa Barbara)

Kelsey is a 3rd year PhD student in marine science at the University of California in Santa Barbara. Her research seeks to understand how remotely sensed surface ecosystem characteristics influence the fate of carbon transport from the euphotic zone into the mesopelagic. She employs global data analysis and crafts models to address the broad question 'what controls the fate of CO2 in the global ocean?'. Her current research focuses on understanding the plankton ecosystem within the surface ocean and she intends to model settling particle dynamics in the mesopelagic next.

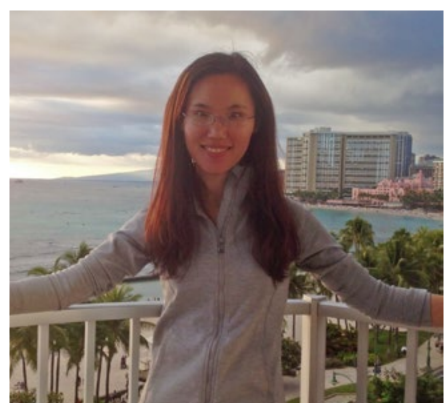
"This course brought me up to speed on the intellectual culture surrounding ocean optics while teaching me the fundamentals of understanding and applying optical techniques to study the ocean. It gave me an enormous appreciation for the history of the field while energizing me about the contributions to be made to extend our understanding beyond current limitations. The instructors are charismatic and passionate; their energy is truly contagious and it was a huge pleasure & honor to learn from them. The setting in Maine is remote in a way that promotes full immersion learning while including good things dock jumps and campfires. My peers in the class are diverse in their interests and skills, which sustained interesting conversation and development. Overall it was a truly luminous time."

Jason Hopkins (Bigelow Laboratory)

Jason's interest in the ocean stems from a 12 year career as a submariner in the Royal Navy. On leaving the service he went to the University of Southampton to study for a BSc Oceanography at the National Oceanography Centre, Southampton. After graduating in 2011 he continued as a post-graduate student at the Graduate School National Oceanography Centre studying for a PhD in Biological Oceanography which he received in 2015. Since then Jason has moved to Maine and is a post-doctoral researcher at Bigelow Laboratory for Ocean Sciences under the guidance of Dr. Barney Balch. Jason's current research interests focus on the use of satellite derived data, in particular particulate inorganic carbon data, to understand the long term, global impact of coccolithophores, a phytoplankton that create an outer shell of intricate calcium carbonate plates.

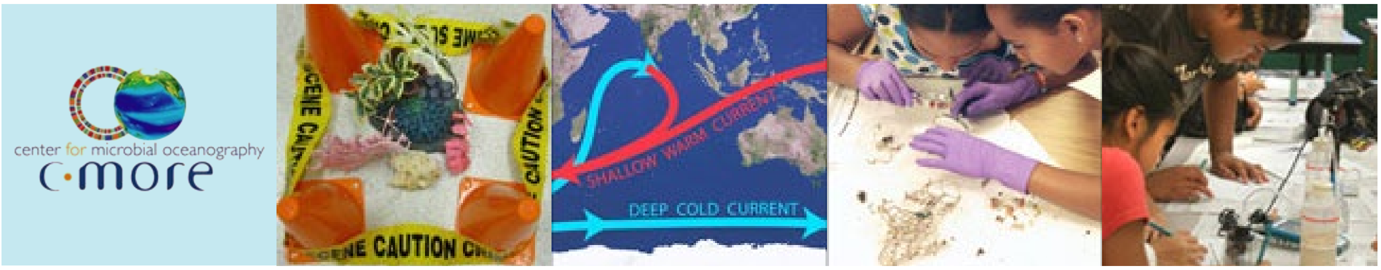
"Long days, hard work but a course that has already changed the way I have approached my work." For me this pretty much sums up the four weeks of the Ocean Optics Summer Course 2015. Having come from a biological oceanography background where I had just interpreted satellite data, the course provided me with the knowledge and tools to be able to critically evaluate my research from a totally different perspective. I have already applied some of the lessons learned directly to my research and the practical experience I gained from the course has enabled me to contribute much more to the discussions and work that is undertaken in our lab. There were many highlights from the course including meeting and being taught by some of the leaders in the field, practical hands on experience working with different instruments and making new friends from around the world. My thanks go to the organisers and instructors for giving their time to share their knowledge, NASA and University of Maine for sponsoring the course, the other students and OCB for helping with travel costs. I cannot recommend this course highly enough for anyone wanting to pursue a career involving optical oceanography."

Guoqing Wang (Univ. Massachusetts Boston)



Guoqing Wang works on the biological optical oceanography and remote sensing. She holds a master degree in Physical Oceanography from South China Sea Institute of Oceanography, Chinese Academy of Science. In July 2012, as one of the 16 students, she attended the summer lecture series provided by International Ocean-colour Coordinating Group in Villefranche-sur-Mer, France. Now she is pursuing her Ph.D degree at University of Massachusetts, Boston with her work focusing on remote sensing of phytoplankton pigments. Guoqing's current interests include remote sensing, marine science, phytoplankton and remote sensing-based ocean primary productivity study.

"The summer course was a great training opportunity. Almost all critical models and concepts in this field were covered. The faculty members were top scientists in this field who were very generous to share their stories and research experiences with us. They were very patient and willing to answer our questions. They responded to our feedback and adjusted the course accordingly. The faculty provided training on almost all of the instruments used to collect in situ data. And I gained a lot of experience collecting and analyzing my own data from these instruments and applying the data in my project. The classmates were amazing. I learned a lot from them in our collaboration and daily lives. We become good friends from then on. All of the training I got during this course was valuable for me in pursuing my career in ocean color and remote sensing research. I would like to say that this is one of the best courses for young students in ocean color and remote sensing. I would be more than happy to recommend this course to other students who are interested and dedicated in this field."



OCB hosts four C-MORE Ocean 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.

Ocean Acidification News

3rd US Ocean Acidification Principal Investigators Meeting

June 9-11, 2015 (Woods Hole, MA)

by Heather Benway (OCB Project Office) and Jeremy Mathis (OCB Ocean Acidification Subcommittee)

The 3rd US Ocean Acidification Principal Investigators Meeting took place June 9-11, 2015 at the Woods Hole Oceanographic Institution in Woods Hole, MA. The meeting, which was organized by the OCB Ocean Acidification Subcommittee (OCB-OA) and the OCB Project Office and funded by NSF Biological Oceanography, convened 107 scientists who are currently working on funded ocean acidification (OA) projects at their home institutions. The scientific program for the 3-day PI meeting was structured to maximize opportunities for PIs to present their most recent work and to facilitate as much participant interaction as possible. Each day started with an overview "tutorial" presentation that broadly encompassed the plenary topics for that day, followed by a series of plenary talks organized by theme. Each themed plenary session included 3-4 talks and concluded with a group discussion to exchange ideas and highlight challenges and emerging priorities in that specific area of ocean acidification research.

The meeting opened with an introduction by OCB-OA co-chair Jeremy Mathis and an update from the Interagency Working Group on Ocean Acidification (IWG-OA) and agency representatives from NSF (David Garrison, NSF Biological Oceanography) and NOAA (Libby Jewett, NOAA Ocean Acidification Program) on federal ocean acidification activities and documents, including the reauthorization of the Federal Ocean Acidification Research and Monitoring (FOARAM) Act and the Strategic Plan for Federal Research and Monitoring of Ocean Acidification. The scientific program for day 1 kicked off with a tutorial on applications and limitations of boron-based paleo-proxies for OA in corals and foraminifera, followed by three themed plenary sessions: ***1) Paleo-responses and geochemical proxies***: This session featured talks on modern geochemical proxies for CO_2 system parameters, Laser Ablation (LA)-ICPMS-based trace element measurements to document larval bivalve exposure to OA, and boron-based reconstructions of OA across the Paleocene-Eocene Thermal Maximum (PETM). Discussion focused on the need for a multi-pronged experimental approach that includes proxy validation efforts (sediment traps, plankton tows, etc.), detailed studies of biomineralization effects (especially for B proxies), and a combination of multi-parameter lab, field, and modeling experiments. There was also an important recognition of the challenges of working in "deep time" (e.g., PETM, Permian-Triassic extinction) when dating of sediments is difficult, there are fewer constraints on ocean chemistry (e.g., [Ca]), and many of the calcifiers that existed during those time periods are no longer present in the modern ocean. ***2) Single/multiple species response to ocean acidification and cross-ecosystem comparisons***: This session started with an overview talk on the geographically varying responses of coral reef systems to ocean acidification, followed by research talks on other organisms' responses to ocean acidification, including squid, pteropods, and shrimp. This group discussed the value of cross-ecosystem comparisons and leveraging "natural laboratories" with natural swings in pH and other variables. The group also discussed the increased number of organisms represented in OA studies over the past 2-3 years and the need to strike a balance between breadth of organisms represented in our studies and depth of our understanding of an individual organism's response to OA. ***3) Carbonate chemistry***: This session started with an overview talk on carbonate dissolution kinetics followed by focused talks on OA-driven carbonate mineral dissolution in different regions of the world's oceans (Bering Sea, Southern Ocean, California Current System, Bermuda, etc.) and effects of OA on iron availability in upwelling waters off the California coast. This plenary group discussion emphasized the importance of moving the community as a whole toward state-of-theart CO_2 system measurements and access to high-quality CRMs, which will require investment in capacity building efforts (e.g., training in measurement techniques and data quality control procedures, laboratory intercomparison studies, etc.).

Day 2 opened with a tutorial on organism response to OA over longer time scales focusing on genetic and evolutionary time scales, followed by three themed plenary sessions: ***4) Multiple stressor responses***: This plenary session included a series of talks on the combined effects of contemporary environmental stressors such as ocean warming, acidification, and hypoxia on marine animals and plants, including benthic foraminifera, fish, corals, and eelgrass. The group discussion focused on the design and inherent challenges of ocean acidification experiments with multiple variables and identifying "model" marine organisms (easy to grow/breed in the lab, established genotypes, etc.) for such experiments. ***5) Evolution and adaptation:*** This plenary session opened with an overview presentation on plasticity and evolutionary responses to OA, followed by more focused talks on coral and fish plasticity and the evolutionary history of coral biomineralization. The group discussion following this plenary session included further consideration of model marine organisms that are already or close to being fully sequenced (e.g., coral species, sea urchins, oysters, and other commercially important species) and consideration of OA effects on fitness (egg quality and fecundity, life history strategies, etc.), which is the key link between biological response and adaptation potential. The group also discussed the importance of archiving samples and data from these experiments. ***6) Temporal perspectives on ocean acidification:*** This session featured a series of presentations on ocean acidification time-series from the California Current Ecosystem, Moorea, and Palmer Long Term Ecological Research (LTER) sites. After the plenary talks, participants discussed key criteria for effective OA monitoring and how LTERs could be incorporated into the Global Ocean Acidification Observing Network (GOA-ON), including valuable process studies, core sets of chemical and biological measurements on compatible time/space scales, an integrated (shipboard, autonomous, satellite, etc.) measurement approach to be able to capture multiple scales of variability, and adequate investment in modeling and data assimilation efforts to maximize the return on our investments in OA monitoring efforts. Furthermore, paleo- and historical data sets from existing LTER and time-series sites can help broaden our temporal perspective of climate and ocean variability at these sites. Another key process that should be considered in the development of OA observing criteria is dissolution, which is still poorly understood. In addition to anthropogenic CO_2 uptake by the ocean, there is a need to quantify and differentiate impacts of other processes that induce acidic conditions (e.g., wastewater effluent, organic carbon remineralization, etc.). The group brainstormed sustained funding mechanisms for long-term OA time-series and mesocosm studies, which are often more realistic for studying individual and community-scale responses to OA. Further development and deployment of new microsensors would be helpful for mesocosm work.

Day 3 opened with a tutorial on spatial and temporal patterns of CO_2 system changes (pH, aragonite saturation state) throughout the world's oceans, followed by three themed plenary sessions: ***7) Feedbacks between seawater chemistry and organisms:*** This session included a talk on the impacts of OA on dissolution of coccoliths as they pass through copepod guts, a talk exploring links between microbial DMS production and OA, and a talk on cellular level responses to OA in different coral species, including regulation of proton pumps and metabolism. The group emphasized the need to better constrain key processes such as dissolution, coupling of benthic ecosystems and seawater chemistry, and predator-prey impacts on CO_2 system chemistry. They also discussed challenges of working in systems that experience high amplitudes of variability (e.g., coastal systems) and scaling up disparate measurements to achieve basin-/global-scale understanding. ***8) Ecosystem modeling of ocean acidification:*** This session started with an overview of the ecosystem modeling approaches being used in OA research, followed by two focused talks, one on the use of integrated assessment models to explore OA impacts on commercially important fisheries and the other on the use of a biogeochemistry/ecosystem model to explore responses of different phytoplankton types (coccolithophores, diatoms, diazotrophs, *Synechococcus*, etc.) to OA. The group discussion focused on key processes that are currently not well represented in models, including parameterization of sinking flux and incorporation of atmospheric sources (dust, rain, etc.) of trace elements (e.g., Fe) that limit productivity in many regions of the ocean. Future recommendations for experimentalists to more readily integrate data into models include more experiments on key fishery organisms and different life stages of organisms, and growth experiments (as function of pH, nutrients) to help inform functional group representation. With regard to fisheries management, it could also be useful to develop a tool based on the model for scenario testing by managers. ***9) Technological advances to support ocean acidification research:*** The final plenary session of the meeting opened with an overview of recent OA technological developments and community activities, including intercomparison activities and training workshops and best practices publications on autonomous CO_2 system sensors. Other presenters in this session highlighted new developments in OA research, including newly emerging *in situ* sensors for total alkalinity (TA) and dissolved inorganic carbon (DIC); new drone technology for monitoring OA in the Pacific-Arctic region; satellite-based measurements and products (e.g., particulate inorganic carbon, PIC) for OA research, and the application of targeted metaproteomics for examining microbial response to OA. Following the presentations, the group discussed these and other new technology on the horizon.

Meeting materials and talks are posted on the workshop website. Following this meeting, the NOAA OA Program held a 1-day NOAA OA PI meeting on June 12 (also in Woods Hole, MA). More information about the NOAA meeting is available via the NOAA OA Program Office.

Ocean Acidification Updates

- Special issue of *Oceanography* magazine *Emerging Themes in Ocean Acidification Science* based on discussions at the 2013 Ocean Acidification PI meeting
- 3rd Report on Federal Funded Ocean Acidification Research and Monitoring Activities (April 2015)
- A plea to ocean scientists regarding ocean acidification terminology
- 4th International Symposium on the Ocean in a High-CO_2 World (May 3-6, 2016, Hobart, Tasmania Australia)
- 3rd Global Ocean Acidification Observing Network (GOA-ON) Science Workshop (May 8-10, 2016, Hobart, Tasmania Australia)
- Congratulations to the Wendy Schmidt Ocean Health X-Prize winners!
- Stay up to date with activities/news from **regional coastal ocean acidification networks**:
  - Southeast Ocean and Coastal Acidification Network (SOCAN)
  - Northeast Coastal Ocean Acidification Network (NECAN)
  - California Current Acidification Network (C-CAN)
- Recommended new version (3.0.11) of the R package seacarb for calculating seawater carbonate system parameters. Includes useful functions for ocean acidification research
- Ocean Acidification International Coordination Centre (OA-ICC)
  - OA-ICC ocean acidification bibliographic database
  - OA-ICC news feed
  - OA-ICC biological response to ocean acidification data compilation

Calendar

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

2016	
January 26-29	EMBO Symposium *A New Age of Discovery for Aquatic Microeukaryotes* (Heidelberg, Germany)
February 1-5	Second Mares Conference Marine Ecosystems Health and Conservation (Olhão, Portugal)
February 1-4	2016 Gulf of Mexico Oil Spill and Ecosystem Science Conference (Tampa, FL)
February 9-12	Species on the Move International Conference (Hobart, Australia)
February 21-26	2016 Ocean Sciences Meeting (New Orleans, LA) Abstracts due September 23!
March 12-18	3rd Biennial Arctic Observing Summit (Fairbanks, AK)
May 3-6	4th Oceans in a High CO_2 World Meeting (Hobart, Tasmania Australia)
May 8-10	3rd GOA-ON Science Workshop (Hobart, Tasmania Australia)
May 23-27	48h International Liege colloquium on Ocean Dynamics Submesoscale Processes: Mechanisms, implications and new frontiers (Liège, Belgium)
May 23-25	2016 Paleo AMOC Workshop Connecting Paleo and Modern Oceanographic Data to Understand AMOC over Decades to Centuries (Boulder, CO)
June 5-10	ASLO 2016 Summer Meeting (Santa Fe, NM)
June 12-17	Gordon Research Conference: Biologically-driven ocean carbon pumps (Hong Kong, China)
June 19-24	13th International Coral Reef Symposium (Honolulu, Hawai'i)
June 26-July 1	Goldschmidt 2016 (Yokohama, Japan)
July 16-17	Ocean Global Change Biology Gordon Research Seminar (Waterville Valley, NH)
July 17-22	Ocean Global Change Biology Gordon Research Conference (Waterville Valley, NH)
July 24-29	Gordon Research Conference *Unifying ecology across scales* (Biddeford, ME)
July 25-28	2016 OCB Summer Workshop (Woods Hole, MA)
August 1-4	Joint OCB/GEOTRACES workshop: Internal Cycling of Trace Elements in the Ocean (Palisades, NY)
August 10-17	IMBER ClimECO5 Summer School (Natal, Brazil)
August 31-September 4	1st Altimetry for Regional and Coastal Ocean Models Workshop (Pilot ARCOM Workshop) (Lisbon, Portugal)
September 6-9	2nd International workshop on Air-Sea Gas Flux Climatology (Brest, France)
September 19-23	CLIVAR Open Science Conference: Charting the course for future climate and ocean research (Qingdao, China)
October 23-28	Ocean Optics 2016 (Victoria, BC Canada)

2017	
August 13-18	Goldschmidt 2017 (Paris, France)
August 20-25	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)
- **Rolling submission:** Call for proposals for the DISCOVERY Yacht program, matching oceanographic researchers with privately owned vessels - The International SeaKeepers Society
- Learn more about NOAA's Small Business Innovation Research (SBIR) Phase 1 Solicitation for Fiscal Year 2016

January 7	NASA ROSES 2015 Ocean Biology and Biogeochemistry Letters of Intent due
January 28	Simons Foundation proposal deadline: Mathematical Modeling of Living Systems
February 1	NSF preliminary proposal deadline for new LTER site
February 15	NSF Ocean Technology and Interdisciplinary Coordination, Chemical Oceanography, and Biological Oceanography proposal deadlines (note NSF Dear Colleague Letter on North Atlantic-Arctic science)
March 3	NASA ROSES 2015 Ocean Biology and Biogeochemistry full proposals due
August 2	NSF full proposal deadline for new LTER site
August 15	NSF Chemical Oceanography, and Biological Oceanography proposal deadlines (NSF Dear Colleague Letter on North Atlantic-Arctic science)
October 18	NSF Arctic Research Opportunities (NSF Dear Colleague Letter on North Atlantic-Arctic science)

OCB News

is an electronic newsletter that is published by the OCB Project Office. Current and previous issues of OCB News can be downloaded from: www.us-ocb.org/publications/newsletters.html

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