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Autonomous observing platform CO_2 data shed new light on the Southern Ocean carbon cycle

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Abstract While the number of surface ocean CO_2 partial pressure (pCO_2) measurements has soared the recent decades, the Southern Ocean remains undersampled. Williams et al. (2017, https://doi.org/10.1002/2016GB005541) now present pCO_2 estimates based on data from pH-sensor equipped Bio-Argo floats, which have been measuring in the Southern Ocean since 2014. The authors demonstrate the utility of these data for understanding the carbon cycle in this region, which has a large influence on the distribution of CO_2 between the ocean and atmosphere. Biogeochemical sensors deployed on autonomous platforms hold the potential to shape our view of the ocean carbon cycle in the coming decades.

In September 1903, Dr. August Krogh measured the partial pressure of CO_2 in the surface ocean (pCO_2) on a voyage between Denmark and Disko Island, which is on the west side of Greenland. Dr. Krogh was a Nobel Prize winning physiologist and a gifted instrument and method developer who also made some of the first reproducible measurements of dissolved organic carbon in seawater [*Krogh and Keys*, 1934; *Hedges*, 2002]. On his voyage to Disko, Dr. Krogh sought to test a widely held belief of the day: that carbonic acid in seawater is in equilibrium with the atmosphere [*Krogh*, 1904]. Today, these early measurements provide a valuable benchmark to determine how much human activities have changed ocean carbon. They are shown in Figure 1, along with atmospheric CO_2 concentrations and surface water pCO_2 measurements made from on board the Ship of Opportunity (SOOP) MV *Nuka Arctica* [*Olsen et al.*, 2008] more than 100 years later. This figure illustrates the remarkable growth in ocean observing capability over the last century and the impact of rising atmospheric CO_2 on ocean carbon, which motivates these measurements.

The growth of the atmospheric CO_2 concentration is caused by emissions from industrial activities such as fossil fuel combustion and cement production and from Land Use Change, for example, the conversion of tropical forests to agricultural land. By the time Krogh carried out his measurements atmospheric CO_2 had risen from the preindustrial level of 280 parts per million (ppm) to 297 ppm. By the start of *Nuka* record shown here (2005), it was 380 ppm and in 2015 it had risen to 400 ppm [*Dlugokencky et al.*, 2016]. The increasing concerns about the effects of CO_2 on climate have led to wide recognition of the need to understand its distribution in the Earth system. CO_2 partial pressure is one of four variables that describe seawater CO_2 chemistry. It can be used to calculate the exchange of CO_2 between the atmosphere and the oceans through a bulk formula and has the advantage that it is fairly simple to measure. Ever since *Takahashi* [1961] presented the first design of a shipboard system for underway pCO_2 measurements, these have been increasingly used to observe carbon in the surface ocean. During the 1990s and 2000s, compact and robust instruments capable of operating largely unattended for months at a time were developed [*Wanninkhof and Thoning*, 1993; *Cooper et al.*, 1998; *Feely et al.*, 1998], culminating in the—later commercialized—design presented by *Pierrot et al.* [2009]. Concurrently, the number of measurements per year has risen exponentially, from around a thousand per year to more than 1 million per year from 2005 and onward [*Bakker et al.*, 2016].

While these data provide important insight on the seasonal and interannual dynamics of CO_2 partial pressure in the regions covered by each ship [e.g., *Lüger et al.*, 2004; *Olsen et al.*, 2008; *Wanninkhof et al.*, 2007], their full potential is realized by combining them in global databases. These databases can be used to estimate the global ocean sink for CO_2, which is essential for understanding the fate of anthropogenic CO_2 in the Earth system [e.g., *Le Quéré et al.*, 2016]. Throughout the 1990s and 2000s, the increasing availability of surface ocean pCO_2 measurements led to significant advances in our understanding of the climatological mean global ocean CO_2 uptake and its seasonal and regional distribution [*Takahashi et al.*, 1997, 2002, 2009]. Developments have continued this decade, in particular, with the emergence of several mapping methods that resolve interannual variations, summarized by *Rödenbeck et al.* [2015]. The output from some of these

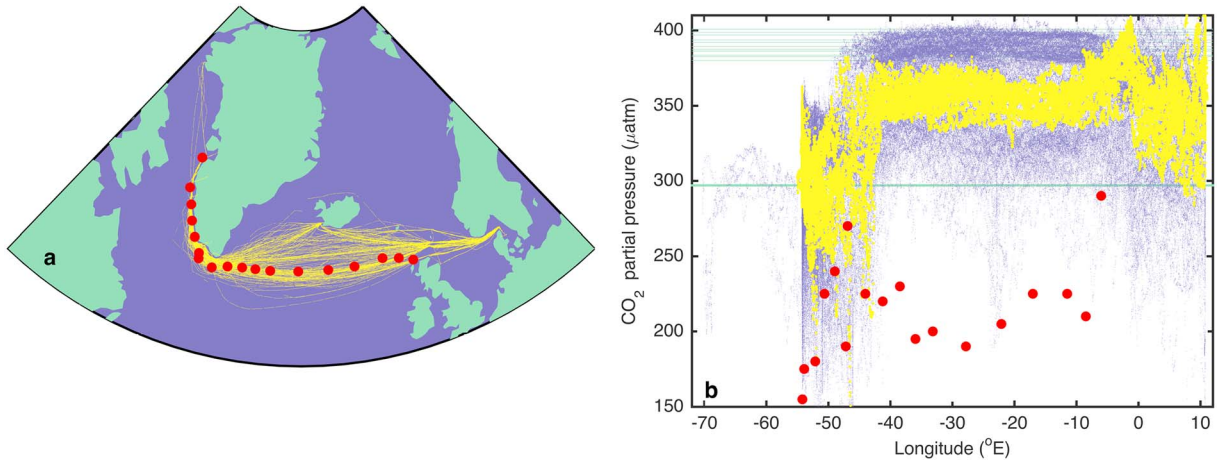

Figure 1. Subpolar North Atlantic surface water pCO_2 measurements. (a) Location of pCO_2 measurements obtained by *Krogh* [1904] (red circles) and on board the SOOP MV *Nuka Arctica* in the period 2005–2015 (yellow points). (b) Surface seawater pCO_2 versus longitude. The red circles show the *Krogh* [1904] data; blue points show all data obtained from onboard *Nuka*, and yellow points show its September measurements. The thick green line shows atmospheric pCO_2 in 1904, while the thin lines show values in 2005–2015.

is now included in the annual assessments of global and regional CO_2 sources and sinks prepared within the framework of the Global Carbon Project. These annual global carbon budgets [e.g., *Le Quéré et al*., 2016] are among our most efficient opportunities to communicate the state of the global carbon cycle and the need for —and the efficiency of—emission cuts to policy makers and society at large.

A fundamental challenge for all of these mapping efforts is the large gaps in the records of actual pCO_2 observations that underpin them. In the Northern Hemisphere, the installation of pCO_2 instruments onboard SOOPs now ensures regular observations over large swaths of the ocean, but a similar network has yet to be established in the Southern Hemisphere. In the Southern Ocean, the availability of observations is in particular poor (Figure 2), as they are only collected at specific supply routes or during research cruises. This leads to large sampling biases in both time and space as the former covers only limited regions and the latter takes place almost solely in summer. The lack of other shipping activities means that it is not even possible to establish an adequate SOOP network. This is the major hurdle to exact quantifications of the magnitude of this CO_2 sink, which is among the largest on Earth, its variability and trends, and its climate change sensitivity.

Williams et al. [2017] present the first results of a groundbreaking project designed to overcome this issue. By deploying approximately 200 Bio-Argo floats in the Southern Ocean, the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project aims to provide near-continuous data coverage of Southern

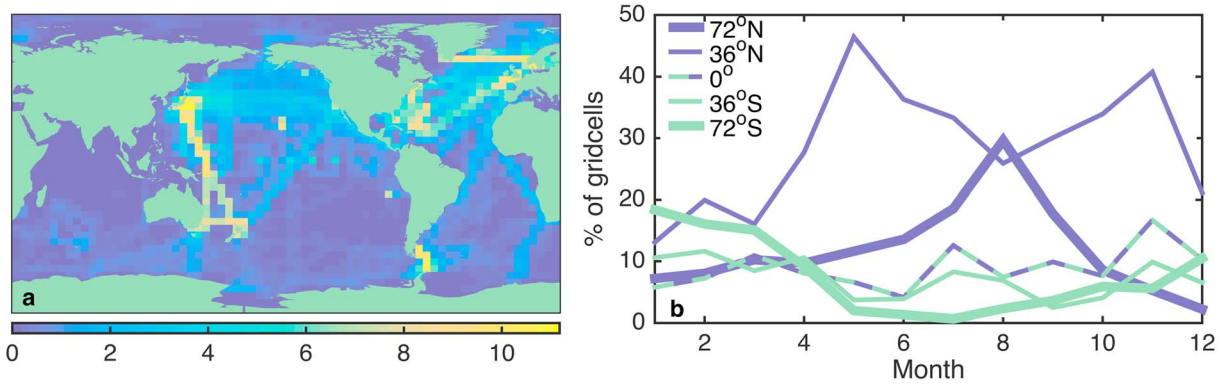

Figure 2. Surface ocean pCO_2 observing network coverage based on data extracted from SOCATv4 [*Bakker et al*., 2016]. (a) Average number of months per year with pCO_2 data in 4° latitude × 5° longitude grid cells for the period 2005–2015, the period when the number of available data exceeds 1 million per year. (b) The fraction of 4° × 5° grid cells with data, in 36° wide latitude bands, per month in the example year 2014, the year with most observations in SOCATv4 (1.7 million). Center latitudes for the five bands are given in the legend. The figure includes only SOCAT flags A–D data.

Ocean biogeochemistry. Since 2003, the global Argo array has transformed the way we observe the structure and heat content of the global oceans by deploying thousands of Argo floats [*Riser et al*., 2016]. These floats drift at their so-called parking depth around 1000 m, but every 10 days they plunge into the deep before ascending all the way to the ocean surface. On their way they collect vertical profile temperature and salinity data. When the floats surface, they transmit these data to global data assembly centers for wider distribution to the science community, before they return to their parking depth.

The Bio-Argo version of these floats is equipped with additional biological and biogeochemical sensors such as oxygen, nitrate, chlorophyll, backscatter, and pH. Similar to pCO_2, pH is one of the four variables that describe seawater CO_2 chemistry. The others are dissolved inorganic carbon (DIC) and total alkalinity (TA). Knowledge of two enables full determination of all species. For instance, if DIC and TA are known, the pCO_2 and pH can be calculated. Sensors for seawater CO_2 chemistry are typically too bulky and power consuming for deployment on Argo floats. Although there has been a strong push for the development of pCO_2 sensors suitable for long-term deployment on Argo floats [*Byrne et al*., 2010], they are not yet available. To overcome this, *Williams et al*. [2017] take advantage of the fact that pH is the seawater CO_2 chemistry variable that covaries most strongly with pCO_2 and demonstrate that combined with an estimate of TA furnished by an empirical algorithm, the data recorded by the Deep-sea DuraFET pH sensors [*Johnson et al*., 2016] on the SOCCOM Bio-Argos enable Southern Ocean surface pCO_2 to be calculated to an accuracy of 10 microatmospheres (μatm).

Variations in Southern Ocean are widely regarded as being not only among the large drivers of interannual variations of the present global ocean CO_2 sink [*Landschützer et al*., 2015; *Lovenduski et al*., 2008; *Le Quéré et al*., 2007] but also largely responsible for the reduction of atmospheric CO_2 during the ice ages that have occurred regularly the past few million years [e.g., *Toggweiler et al*., 2006]. Hence, even though the uncertainty of the pCO_2 estimates of 10 μatm is large compared to the 2 μatm obtained by current shipboard underway measurements [*Pierrot et al*., 2009], the SOCCOM Bio-Argo program represents a very clever strategy to obtain sorely needed data from a remote but important region. These floats can sample in regions and at times where no ships operate, either because there are no regular shipping routes or because it is simply too dangerous. They are also far less expensive to deploy and maintain and can provide much more regular data than the occasional research cruises. For example, using data from less than a handful floats, *Williams et al*. [2017] show how we now need to revise existing estimates of pCO_2 in the very important upwelling regions south of the Polar Front. We can only imagine the insight that will be offered by the analyses of the data from the entire fleet of SOCCOM floats. This project holds the potential to shape our view on carbon cycle variability and underlying processes in the years to come.

In the absence of viable carbon capture and storage options [*Smith et al*., 2015], the 2° target puts strong constraints on the remaining CO_2 emissions quota [*Jackson et al*., 2015]. CO_2 emissions are now a "scarce commodity" and have to be managed as such. In addition to—or rather as part of—scientifically based verification systems for nationally reported emissions, trends and efficiencies of natural sources and sinks need to be constrained at a level beyond what is currently achieved in order to measure the effectiveness of mitigation and energy policies. There is also a need for better constraints on the magnitude of climate-carbon cycle feedbacks to vetted climate and emission targets. Combined with the emerging issue of potential detrimental ecosystem effects of ocean acidification, this increases the requirements of the ocean carbon observing system. The scientific challenges that lie ahead for the ocean carbon community include separation of anthropogenic from natural fluxes, delineation of the variability from the trends in each of these components, and identification of the drivers [*Marotzke et al*., 2017], ideally on interannual—at least on decadal—timescales. This can only be achieved on the basis of an observing system that measures more homogenously, more frequently and a wider range of variables. The development of an extensive array of autonomous platforms equipped with seawater CO_2 chemistry sensors, to complement the existing surface [*Bakker et al*., 2016] and interior [*Olsen et al*., 2016] networks, will be a critical step for realizing such a transformative change in ocean observing.

Although the SOCCOM Bio-Argo floats and other emerging technologies [e.g., *Fiedler et al*., 2013] certainly represent major advances in the correct direction, there is still a long stretch ahead. Accurate assessment of the ocean carbon cycle, its trends, and its variability require high-precision data free from bias. Case in point, comparisons between the *Krogh* [1904] data with those obtained from *Nuka* indicate that a remarkable change in the Subpolar North Atlantic carbon cycle has taken place over the past 100 years (Figure 1b), but the

potentially large but unquantified bias of the *Krogh* [1904] data prohibits any really firm conclusions. Two μatm is currently regarded as the target accuracy for surface ocean pCO_2 measurements; this allows quantification of regional fluxes to 0.2 gigatonnes of carbon per year [*Bender et al*., 2002] and is also comparable to the expected annual trends from anthropogenic CO_2 uptake. A network for resolving the ocean carbon sink on interannual timescales cannot be based on less accurate sensors. With 5 times larger uncertainty, the large value of the data presented by *Williams et al*. [2017] is mainly a result of the fact that they were retrieved in a region and at a time that is more or less devoid of other measurements. In the heavily sampled North Atlantic, for instance, they would add very little, if any, knowledge to our understanding of the carbon cycle. Increasing the precision and reducing the potential for bias must be the main priorities in the years to come.

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