WARMING UP, TURNING SOUR, LOSING BREATH: AN INTEGRATED OBSERVING SYSTEM FOR OCEAN BIOGEOCHEMISTRY AT A TIME OF CHANGE

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ABSTRACT

Ocean biogeochemical cycles are currently undergoing fundamental changes – largely as a consequence of the addition of greenhouse gases to the atmosphere. The oceans are getting warmer, and their pH and oxygen levels are decreasing. These biogeochemical changes plus the concomitant changes in ocean circulation will lead to profound effects on some of the ocean's key services, i.e. its capability to take up CO_2 from the atmosphere and hence mitigate climate change and its provision of important ecosystem services such as food and biodiversity. Documenting, understanding, and predicting these biogeochemical changes require a concerted and sustained observational effort that includes both the continuation of well-tested approaches and the development and implementation of novel systems. Of particular importance for the former group is the sustaining and extension of (i) a surface ocean volunteer ocean ship-based observing system primarily focusing on the determination of the air-sea exchange of CO_2 and upper ocean changes in carbonate chemistry, of (ii) an interior ocean research-ship based system focusing on large-scale interior changes of the ocean's biogeochemistry (carbon, oxygen, nutrients, etc), and of (iii) time-series observations at a few selected sites, including the coastal ocean. Of particular importance for the second group are (i) the accelerated improvement, development and implementation of new observational elements on the Argo array (especially oxygen, but also bio-optical sensors), and (ii) the development, testing, and deployment of novel sensors for the ocean's carbon system. Concerted synthesis efforts involving also novel approaches for merging observations with biogeochemical models will ensure that these observational elements realize their synergistic potential.

1. INTRODUCTION

For the last 250 years, mankind has been emitting ever increasing amounts of greenhouse gases (most importantly CO_2) to the atmosphere, first primarily as a result of the clearing of forest for cropland and pasture, and since the turn of the 20th century primarily as a result of the burning of fossil fuels (IPCC, 2007). In response, atmospheric CO_2 has increased by more than 100 ppm, i.e. by more than 30%, with today's concentration of nearly 390 ppm representing a level that Earth's atmosphere likely hasn't experienced for more than 20 million years.

This accumulation of extra CO_2 and other greenhouse gases in the atmosphere has warmed the planet already by about 0.8°C since pre-industrial times (IPCC, 2007), and with atmospheric CO_2 being bound to increase further, an extra warming of at least 1.2°C will occur with high likelihood. This warming of at least 2°C will have profound effect on Earth's climate system, which will propagate into the oceans and cause changes in the physical environment that will trigger a cascade of responses in the biogeochemical systems (Riebesell et al., 2009).

By taking up over 30% of the total anthropogenic emissions of CO_2, the ocean has so far helped substantially to mitigate climate change. Without this uptake, atmospheric levels today would already have far exceeded the 450 ppm level that corresponds roughly to the maximum CO_2 level which ensures a warming guard rail of 2°C. The ocean thus has provided an invaluable service to mankind, which at a price of 20 USD per ton of CO_2 is equivalent to more than 10 trillion USD.

This service comes with a huge penalty whose ramifications are only beginning to emerge: Ocean acidification. The absorption of CO_2 from the atmosphere not only reduces the pH of the ocean, it also lowers the concentration of the carbonate ion and hence the saturation state of seawater with regard to mineral forms of $CaCO_3$. These chemical changes will affect ocean organisms, both positively and negatively (see e.g. Riebesell et al., 2009). While most studies to data have shown for pelagic calcifying groups such as coccolithophores, foraminifera, and pteropods a decrease in calcification in response to seawater acidification (e.g., Riebesell et al., 2000; Feng et al., 2008) there is also contradicting evidence (e.g., Iglesias-Rodriguez et al., 2008) and the subject remains controversial.

Global change will affect not only temperature, but also wind patterns, and evaporation and precipitation, likely causing changes in ocean circulation and mixing as well. A relatively robust projection for this century is an increase in upper ocean stratification, in part driven by upper ocean warming (low to temperate latitudes), and upper ocean freshening (high latitudes). An increase in upper ocean stratification leads to a reduced overall uptake of anthropogenic CO_2, leading to an accelerated increase in atmospheric CO_2 and surface ocean acidification, as well as to a reduced transport of oxygen from the near-surface ocean to the interior. This will amplify the loss of oxygen from the ocean induced from the warming, so that the ocean's deoxygenation resulting for example in an expansion of the oxygen minimum zones is also a relatively robust prediction for this coming century (Keeling et al., 2010). With all higher life-forms in the ocean critically depending on sufficient oxygen concentrations in the ocean, a net loss of oxygen from the ocean constitutes a severe reduction in their habitat.

These long-term biogeochemical changes occur against a background of substantial variability on time scales from days to decades, and on spatial scales from kilometres to entire ocean basins. On the one hand, these natural variations often obscure the identification of long-term trends, but on the other hand, they provide for an important laboratory for the development of an understanding of the processes underlying ocean biogeochemistry and ecosystems.

The ability to observe ocean biogeochemistry has made substantial advances in the last decade since OceanObs'99. Fundamental achievements are the establishment and extension of a global network of voluntary observing ships (VOS), the initialization of a repeat hydrography program and the implementation of a global float-based observatory. But, the changes in ocean biogeochemistry looming ahead, and our need to document, understand, and ultimately predict these changes, require us to make the next big step forward. On the one hand, this involves the continuation and strengthening of a series of well established and time-proven approaches. On the other hand, substantial advances in observational capabilities are at the cusps of our fingers, and it is fundamental to adequately support their continuing development, their testing and finally their large-scale deployment.

In the next sections, we first highlight some of key successes of ocean carbon cycle research in the past decade, then go on to describe major recent development of ocean observation capabilities and networks and finally lay out the way ahead including major implementation steps and elements.

2. OBSERVING OCEAN BIOGEOCHEMISTRY: KEY SUCCESSES OF THE PAST DECADE

For decades, the main driving questions for ocean carbon cycle research has been the question of how much anthropogenic carbon the ocean is taking up from the atmosphere, where this occurs, and where this carbon is ultimately stored in the ocean (e.g. Siegenthaler and Sarmiento, 1993). Until very recently, the answers to this question were either provided by models or by indirect methods involving other tracers. In addition, little was known about seasonal to decadal variability in ocean biogeochemistry, since sampling typically has been spotty in time and space. The past decade has seen a dramatic change in these three areas. A surface ocean-based observation network has provided us for the first time with the means to obtain a climatological picture of the sources and sinks of CO_2 on a global basis, ocean interior measurements revealed how much CO_2 to the ocean has taken up since pre-industrial times and where this carbon is stored, and long-term time-series observations have demonstrated the importance of seasonal to decadal variability. The two former have provided us with two iconic maps of the ocean carbon cycle.

2.1. Ocean CO_2 flux climatology

Measurements of the surface ocean partial pressure of CO_2 provide the most powerful window into the study of fluxes of CO_2 across the air-sea interface, i.e. whether the ocean represents at a given location and time a source or sink for atmospheric CO_2. These measurements also give insights into the underlying processes, such as how much of the CO_2 exchange is driven by warming or cooling, and what the role of surface ocean biology is.

High-quality measurements of properties of the CO_2 system in surface waters started more than half a century ago during the International Geophysical Years (e.g., Keeling et al., 1965; Takahashi, 1981). For decades to come such measurements were exclusively performed from research vessels and it was only in the 1990s when autonomous surface ocean (and atmosphere) pCO_2 measurements started to be carried out from merchant vessels, often referred to as 'Voluntary Observing Ships' (VOS). Since then, the number of VOS lines with surface pCO_2 measurements has grown dramatically, forming a global network with particularly good spatial and temporal coverage along major shipping routes in the North Atlantic and Pacific.

Our current understanding of the global climatological distribution of CO_2 sources and sinks on an annual and even monthly basis was only possible because of the huge amount of data provided by the VOS network. The success of this global observatory is impressively documented in the development of the surface ocean pCO_2 climatology which started with only 2.700 data points from 1972-1992 in the North Atlantic (Takahashi et al., 1995) before it became a global climatology that

grew from 930.000 data points in its first edition (Takahashi et al., 2002) to over 3 million measurements in its most recent version (Takahashi et al., 2009). The tremendous growth of the database which essentially occurred in the decade since OceanObs'99 has allowed for a much improved robustness of the constructed CO_2 flux maps in terms of geographical coverage and resolution of the seasonal cycle (Figure 1). Key findings include the consolidation of a climatological mean flux of CO_2 into the ocean of about 1.6 ± 0.9 Pg C yr^{-1}, which, when corrected for the net outgassing of natural CO_2 driven by the input of carbon from rivers, yields a net uptake of anthropogenic CO_2 of 2.0 ± 1.0 Pg C yr^{-1} for a nominal year of 2000.

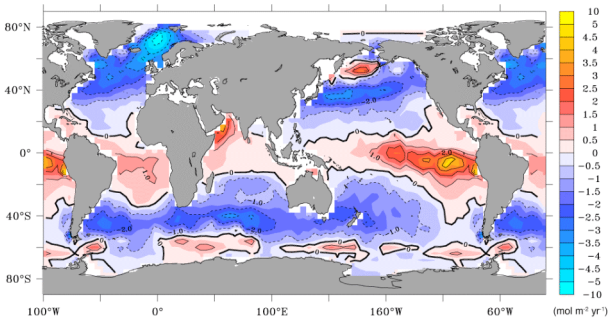

Figure 1: Map of the climatological annual mean air-sea flux of CO_2 for a nominal year of 2000 (in mol m^{-2} yr^{-1}). Positive fluxes indicate outgassing. Based on the surface ocean pCO_2 data from Takahashi et al. (2009) using a square-dependence of the gas transfer velocity on the wind speed.

The VOS-based observation approach that led to one of the icons of marine CO_2 research (Figure 1) owes its great success not only to the spatiotemporal coverage achievable by this new platform but also to international coordination and stewardship. Important activities in this context were the execution of international intercomparison exercises (e.g., Körtzinger et al., 2000) and the agreement on methods, best practices, data formats, quality control measures and data management mediated to a major extent by the International Ocean Carbon Coordination Project (IOCCP).

2.2. Inventory of anthropogenic CO_2

The detection of the accumulated anthropogenic CO_2 in the ocean on the basis of measurements of the inorganic carbon system has been a major objective of the ship-based global CO_2 survey undertaken as part of the joint WOCE/JGOFS programs in the late 1980s and early 1990s. This project resulted in an unprecedented new dataset with global coverage and the necessary high quality to make it possible to deconvolute the relatively small anthropogenic CO_2 signal against the large variability of the natural carbon system in the ocean (see e.g. Wallace, 2001).

A major accomplishment of the decade since the end of the WOCE/JGOFS program has been the completion of an international effort with the goal to produce a coherent, internally consistent data set through standardized secondary quality control procedures (the GLODAP effort, Key et al., 2004). Together with the development and refinement of anthropogenic CO_2 separation methods (e.g. the ΔC* method of Gruber et al., (1996), this data set laid the foundation for the first global estimate of the amount of anthropogenic CO_2 that the ocean has taken up since pre-industrial times (Sabine et al., 2004) (Figure 2).

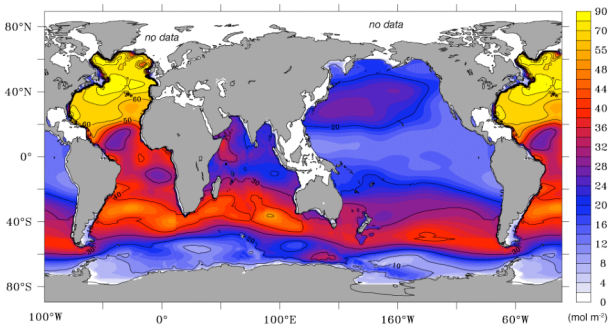

Figure 2: Map of the vertically integrated amount of anthropogenic CO_2 stored in the ocean since pre-industrial times (in mol m^{-2}). Based on Sabine et al. (2004).

This map reveals areas of high local accumulation, such as the North Atlantic, and the mid-latitude Southern hemisphere, and also areas, where little anthropogenic CO_2 has accumulated in the last ~250 years. The global computed inventory of 118±20 Pg C represents one of the most fundamental constraints for the global carbon cycle, equally important as the direct evidence of the accumulation of anthropogenic CO_2 in the atmosphere. Not only did this number reveal that the ocean has taken up about 45% of the total fossil fuel emissions since pre-industrial times, but also it also permitted Sabine et al. (2004) to compute the net anthropogenic CO_2 exchange of the terrestrial biosphere over this period, turning out to be a net loss of 39±28 Pg C.

2.3. The ocean's Mauna Loa curves

While the surface CO_2 network provides a constraint on the fluxes across the surface interface of the oceans, and the interior ocean network constrains the very long-term increase in the carbon content, it was the establishment of oceanic time-series for inorganic carbon that revealed for the first time how the oceanic carbon cycle truly evolves with time. The longest time-series for inorganic carbon started in the early 1980s (Keeling, 1993) near Bermuda and in 1988 was joined by a time-series near Hawaii (Sabine et al., 1995; Dore et al., 2003, Keeling et al., 2004) (Figure 3). In addition to showing a rich spectrum of variations on seasonal timescales and shorter, these long time-series also reveal unmistakingly the imprint of the oceanic uptake of anthropogenic CO_2 from the atmosphere. In fact, the surface ocean pCO_2 follows the atmospheric CO_2 increase relatively closely at both sites, reflecting the fact that the air-sea

equilibration time-scale for the surface ocean CO_2 system is about one year, substantially smaller than the characteristic time-rate of increase in atmospheric CO_2. The observations also clearly uncover the impact this uptake of CO_2 from the atmosphere has on surface ocean pH. Over the course of these 20 years, surface ocean pH at both sites have decreased by nearly 0.04 pH units.

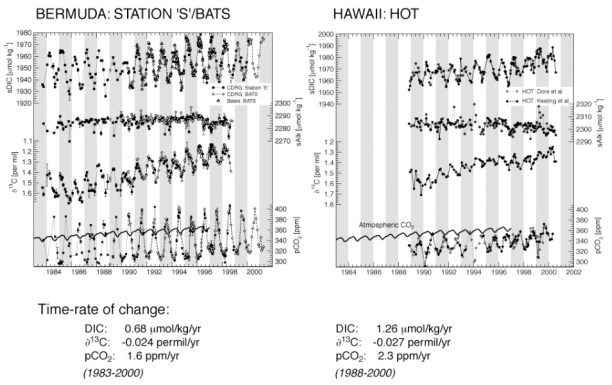

Figure 3: Long-term time-series of surface ocean CO_2 properties from an ocean site near Bermuda (a) and one near Hawaii (b). Shown are the surface ocean timeseries of dissolved inorganic carbon (DIC), oceanic pCO_2, and pH. Also shown are the atmospheric CO_2 records from nearby sites on the islands. Data are from Gruber et al. (2002) and Bates (2009) for Bermuda, and from Keeling et al. (2004), and Dore et al. (2009) for Hawaii. FIGURE NEEDS TO BE UPDATED TO INCLUDE DATA UNTIL 2009.

3. MAJOR RECENT DEVELOPMENTS

The foundations for the three major accomplishments of the past decade described above were all laid in the 1980s and early 1990s, highlighting the importance of a long-term perspective when developing an integrated observing system. These accomplishments also demonstrate the high-level of complimentary that the three approaches provide for constraining the large-scale ocean carbon system and its anthropogenic change, i.e. the surface ocean network constraining the flux across the top interface (Schuster et al. this issue), the interior ocean network constraining the long-term rate of change of carbon (and also the transport across sub-volumes) (Hood et al., this issue), and finally the time-series stations providing a temporal perspective and linking the two other approaches.

Nevertheless, these approaches are also subject to major limitations, the most important being the large spatial and temporal gaps inherent in these ship-based programs. For example, even though the most recent pCO_2 climatology of Takahashi et al. (2009) is based on more than 3 million observations, there still remain entire sub-basin areas where less than two months had been sampled over the last 30 years (Figure 4). In addition, the data set is sufficient in only a few regions to reliably determine long-term trends in surface ocean pCO_2, and in particular to reveal whether the ocean carbon system has began to move away in a substantial manner from the behavior expected for a steady-state ocean circulation, as was also implied from the largely one-time survey-time nature of the WOCE/JGOFS program.

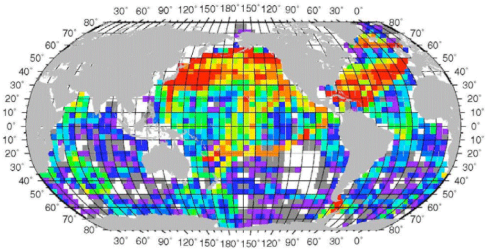

Figure 4: Number of monthly pCO2 observation per 5x5° pixels in the database used by Takahashi et al. (2009) to construct the climatology used for Figure 1. From Takahashi et al. (2009).

In recent years, important developments have occurred that permit us – given their continued support and enhanced implementation – to close these limitations and be ready for the next wave of challenges, i.e. those associated with the time-varying nature of ocean biogeochemistry.

3.1. Interannual to decadal variability in basin-scale CO_2 fluxes

The focused and intensified implementation of the surface ocean CO_2 network in recent years has permitted scientists to make the next step for certain ocean basins and not only identify regional temporal trends from the deseasonalized data, but also analyze interannual variability, e.g. in response to changes in the North Atlantic Oscillation (Fig. 5, Watson et al., 2009).

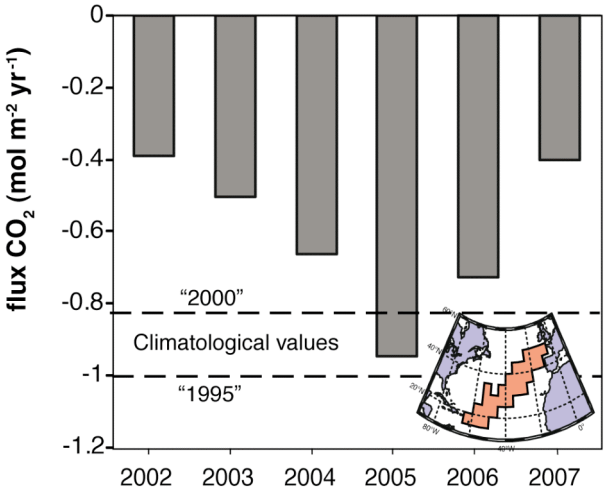

Figure 5: Time-series of the net air-sea CO_2 flux in the eastern North Atlantic (see map in inset). Adapted from Watson et al. (2009).

3.2. Decadal variability in the ocean's interior

Until today, ship-based hydrography has remained the only method for obtaining high-quality measurements with high spatial and vertical resolution of a wide range of physical, chemical, and biological parameters over the full ocean water column, and in areas of the ocean inaccessible to other platforms. Despite the tremendous advances in other observational approaches, the classical hydrography has not become obsolete owing to these unique properties.

Following the success of the WOCE/JGOFS global hydrographic survey, which among numerous other important outcomes formed the basis for the construction of an unprecedented global-scale inventory of anthropogenic CO_2 in the ocean (Sabine et al., 2004), a repeat hydrography program for carbon and carbon-relevant parameters was mounted under the umbrella of the 15-year CLIVAR program and through coordination by IOCCP. Following a post-WOCE period characterized by lack of formal global organization and perhaps visibility the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP - http://www.go-ship.org/) was launched only a few years ago (Hood et al., this issue).

The global repeat survey is carried out with a select subset of WOCE hydrographic sections and scheduled to be completed in 2012. The field program is presently completed to about 75%. First results show profound secular change in ocean properties ranging for example from warming and freshening via increasing storage of total/anthropogenic carbon (Figure 6, Sabine et al., 2008; see also Sabine and Tanhua, 2010) to widespread ocean deoxgenation (Keeling et al., 2010). These trends are superimposed on large natural variability on a wide range of time scales. Of these, sub-decadal/decadal variability associated with the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), or the Southern Annular Mode (SAM) are most prominent examples. These results clearly both the strong need for decadal hydrographic survey as ultimate "groundtruthing" and reference occupations and the integration of this approach with other observing system elements, such as the Volunteer Observing Ship Program (3.1), Argo profiling float program (3.3) and the time-series stations all providing complementary information.

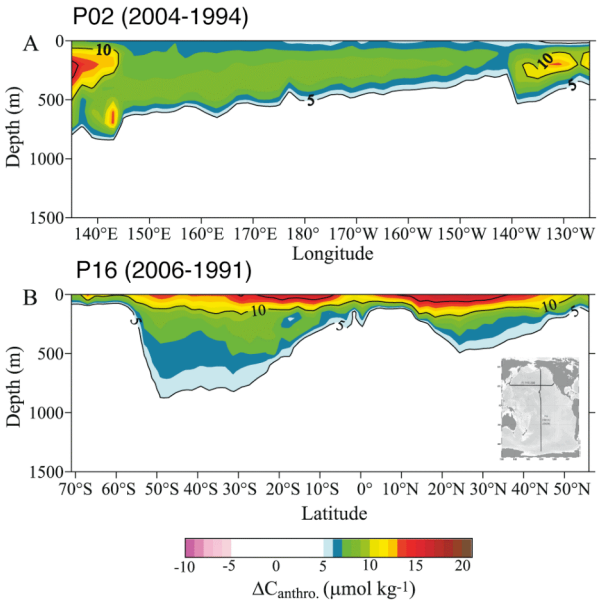

Figure 6: Change in anthropogenic CO_2 along two long sections in the Pacific Ocean. (a) Change in anthropogenic CO_2 along the zonal section P02 in the North Pacific between 1994 and 2004. (b) Change in anthropogenic CO_2 along the meridional section P16 in the central Pacific between 1991 and 2006. Anthropogenic CO_2 was determined using an eMLR approach. See map inset for locations of the cruises. Modified from Sabine et al. (2008).

3.3. A synoptic view of the ocean's oxygen variability

Since OceanObs'99, the ARGO float program has perhaps become one of the greatest successes of physical oceanography revolutionizing ocean observation and providing for the first time a global synoptic observatory for the ocean's interior (Freeland et al., this issue). The scientific value of the ARGO float array is not only documented in the many important research products from intended use of the data provided but perhaps just as well in the widespread use of the ARGO data by other communities and for a multitude of other purposes in a way certainly not anticipated by the founding fathers. The ready availability of the quality controlled ARGO data have proved to be open doors for ocean scientists seeking information on physical properties of the ocean. This growing user base also brings in new ideas for future expansion of the scope of the ARGO mission.

The development of float and sensor technology now provides observational capabilities that were not even contemplated when ARGO was created a decade ago. Among the many different measurements made from and sensors tested on profiling floats (e.g., wind, rainfall, oxygen, nitrate, bio-optical properties etc., see also Claustre et al., this issue) oxygen is perhaps the most advanced and promising candidate for inclusion into the ARGO mission (Gruber et al., this issue; Johnson et al., 2009). There are many scientific reasons for undertaking detailed global-scale measurements of the

temporal evolution of the ocean's oxygen distribution (Gruber et al., this issue). The wide-spread phenomenon of ocean deoxygenation (Keeling et al., 2010) as discovered by classical hydrographic surveys (3.2) in itself provides a strong research imperative for the biogeochemical community. To date, over 200 floats with oxygen sensors have been deployed resulting in new scientific insights into the interplay between physics, chemistry, and biology in the ocean (Figure 7, Körtzinger et al., 2004; Riser and Johnson, 2008) as well as methodological insights into the possibilities and current limitations of float-based oxygen measurements (Körtzinger et al., 2005).

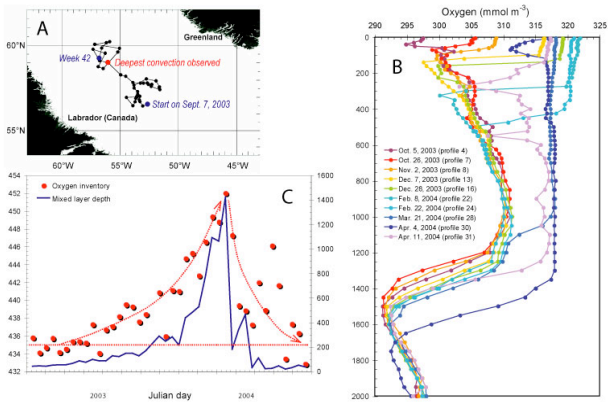

Figure 7 (a) Float track in the central Labrador Sea Gyre, showing positions of weekly surfacing between deployment on 7 September 2003 and profile 42 on 26 June 2004. (b) Selected vertical oxygen profiles. (c) Temporal development of the oxygen inventory (in the upper 1400 m) and mixed-layer depth, based on 42 weeks of measurements. Dotted red lines represent the build-up and decay of the oxygen inventory in the convection region relative to an assumed background concentration of the surrounding waters. From Körtzinger et al. (2004).

To date, two types of dissolved O_2 sensors have been employed on profiling floats: (i) the SBE-IDO from SeaBird Electronics (Seattle/WA, USA) which is an electrochemical sensor (Clark electrode), and (ii) the model 3830 oxygen optode from Aanderaa Instruments (Bergen, Norway) which is an optical sensor that operates on the principle of fluorescence quenching. Owing to the very stringent requirements for the sensors in terms of accuracy/precision, long-term drift, and response time both sensors do not currently meet all these requirement and exhibit their individual strengths and weaknesses. Overall, the optode principle with its high precision and excellent long-term stability (Tengberg et al., 2006) appears to be the more promising candidate providing the current limitations in initial accuracy and response time can be overcome.

3.4. Data assimilation in ocean biogeochemistry

The last few years have seen the advent of various methods to merge biogeochemical observations and models in order to provide optimal estimates for certain properties, fluxes, and rates (c.f. Brasseur et al., 2009). These approaches include the use of a Green's function approach to use ocean interior carbon data to constrain air-sea CO_2 fluxes of both natural and anthropogenic CO_2. This approach naturally links the ocean interior with the surface ocean based networks. In fact, a recent comparison between the two fully independent estimates revealed a remarkable level of agreement, with the exception of the region south of about 30°S (Figure 8).

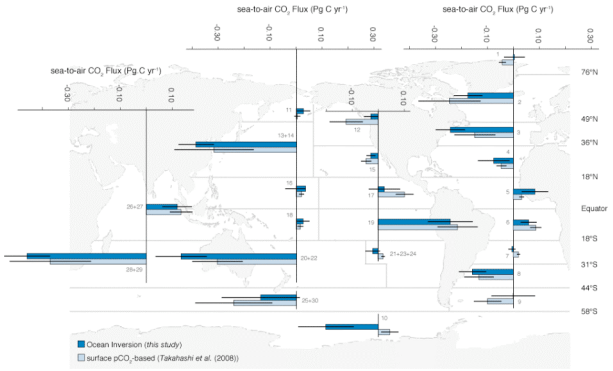

Figure 8: Comparison of the contemporary air-sea CO_2 flux between the pCO_2 based estimate of Takahashi et al. (2009) and the ocean inversion-based estimate of Gruber et al. (2009). Adapted from Gruber et al. (2009).

Other approaches based on Kalman filters (Gerber et al., 2009), adjoint methods (Schlitzer, 19xx), and many other techniques have been developed, especially with regard to assimilating surface ocean chlorophyll (c.f. Brasseur et al., 2009), but data limitations and the complexity arising from the interactions of physics, biogeochemistry, and ecology have prevented rapid progress.

4. THE WAY AHEAD: THE NEXT DECADE OF OBSERVING OCEAN BIOGEOCHEMISTRY

4.1. Introduction

The fundamental changes in ocean biogeochemistry that are already under way, and the much more profound changes that likely are looming ahead require a concerted effort in order to *determine, understand, and predict these changes*. Both the changes in the ocean's carbon cycle associated with the uptake of anthropogenic CO_2 from the atmosphere and the additional changes expected from the interactions of the natural carbon cycle with climate justify the continuation and extension of the ocean carbon observing networks. But also the more recently recognized biogeochemical changes associated with ocean acidification and the loss of oxygen (deoxygenation) warrant attention, as their impacts on marine ecosystems and services might be very large. Thus an ocean observing network for ocean biogeochemistry has the following specific objectives:

4.2. Objectives

- To determine, understand, and predict the past, present, and future oceanic sink for anthropogenic CO_2
- To determine, understand, and predict the past, present, and future changes in the oceanic carbon system resulting from climate change, and ocean acidification.
- To determine, understand, and predict the past, present, and future changes in dissolved oxygen

The biogeochemical changes occur globally requiring that these objectives need to be met on a global level. Regional differences are expected, however, justifying regionally enhanced efforts, such as in coastal regions (see e.g. Borges et al. (this issue)). The accuracy with which these objectives need to be reached needs to commensurable with the task at hand. For example, in its implementation plan, the IMBER-SOLAS joint research group on the ocean carbon cycle states that it aims to determine the oceanic uptake, transport, and storage of anthropogenic CO_2 with an accuracy of about 10%, i.e. 0.2 Pg C yr^{-1} (IMBER-SOLAS, 2006). With regard to the surface ocean fluxes, IMBER-SOLAS specified an objective of "constraining net annual ocean-atmosphere CO_2 flux at the scale of an ocean basin to <0.2 Pg C yr^{-1}" while Monteiro et al. (this issue) suggest a relative accuracy of "± 10 - 15% of the annual mean flux". No specific quantitative targets have been specified yet for ocean acidification, while for oxygen, only the expected accuracy of the sensors has been set yet (Gruber et al., this issue).

5. IMPLEMENTATION

5.1. Preamble

The proposed integrated network to tackle the above objectives consists of a combination of well-tested and new emerging elements. Together, they will bring a step change in our ability to observe the biogeochemical changes, commensurate with the challenge imposed on ocean biogeochemistry. In particular, the following elements are envisioned:

- Surface ocean network
- Interior ocean network
- Time-series stations network
- Lagrangian network

Data from these observing systems need to be subjected to careful quality control and data assembly procedures, requiring dedicated support of such facilities. Sustained synthesis activities involving also novel data-model integration approaches are envisioned to realize the complimentary strengths of the four main observing elements. Finally, dedicated efforts are needed to realize the full potential of newly emerging technological approaches, particularly with regard to the development and deployment of stable, low-power sensors on Lagrangian platforms.

5.2. Surface ocean network

The primary means for observing the air-sea fluxes of CO2 (objectives 1 and 2) is a surface ocean network built on the existing collaborative VOS network. Thus the sustaining and extension of this network is tantamount, since only through a continuation of this large international effort further new insight into scales of internal variability and its driving physical and/or biological factors can gained.

Despite all the effort and success the fact must not be overlooked that in many pixels of the climatology the seasonal cycle is not resolved and even white spots still exist on the global CO_2 flux map (e.g. subtropical southeast Pacific, Figure 4). This deficit is mostly due to the more or less complete lack of shipping routes in these regions. Fostering the establishment of additional VOS lines in a coordinated and strategic way in undersampled regions will therefore significantly enhance the network and improve regional flux estimates in these areas. In particular, Monteiro et al. (this issue) suggest an intensification of the observing network to a net density of about 3-monthly sampling at a spatial resolution of about 3-6° meridionally and 10-30° zonally depending on the ocean basins.

These proposed minimum surface CO_2 sampling scales, depicted in Fig. 9 superimposed on the present VOS activity provide an indication of the gap between existing and required sampling to achieve the vision set out by Monteiro et al. (this issue). Areas of high variability, such as the coastal ocean, will require higher frequency sampling, part of which can be achieved from benefiting from coastal survey ships and ferries (see Borges et al., this issue).

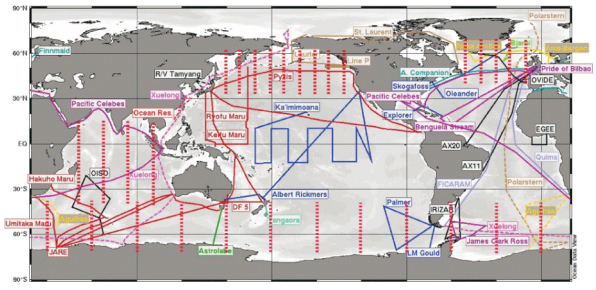

Figure 9: Map showing the recommended spatial sampling density for the surface ocean network (red dots) superimposed on the existing VOS-based network. In order to reach the stated objectives, these lines would have to be sampled roughly 4-times a year. From Monteiro et al. (this issue).

Such an extension of the VOS network, however, is not suitable in regions where commercial shipping routes

are absent (e.g. Southern Ocean, tropical southeast Pacific). Here, the pCO_2 observatory can only be extended by integration of other autonomous platforms such as moorings and surface drifters. While this is now reasonably feasible with existing sensor and platform technology even under harsh environmental conditions (Boutin et al., 2008; Körtzinger et al., 2008), profiling floats and gliders as the most advanced Langrangian platforms (CWP) are essentially out of reach with current CO_2 sensor technology (Byrne et al., this issue). A major focus therefore needs to be placed on the development and improvement of suitable CO_2 sensors employing novel technology.

5.3. Interior ocean network

Long-term changes in the ocean's interior biogeochemistry away from the upper 20 m are currently accessible only by a ship-based observing approach (see Hood et al., this issue). This is particularly the case for the documentation of the long-term changes of the ocean carbon system, for which there does not (yet) exist suitable sensors for long-term deployment on Lagrangian floats. Thus, in order to determine the oceanic uptake, transport, and storage of anthropogenic CO_2 in the ocean (objective 1), and for documenting the long-term changes in the ocean's oxygen and carbonate systems (particularly in the deep ocean below the reach of most Lagrangian floats) (objective 2), regular research ship-based surveys with a set of highly standardized measurements are needed.

To reach these objectives, Hood et al. (this issue) suggest an observing program with a roughly 10 year repeat cycle with several meridional and zonal cruises per basin (Figure 10, see also www.go-ship.org/)

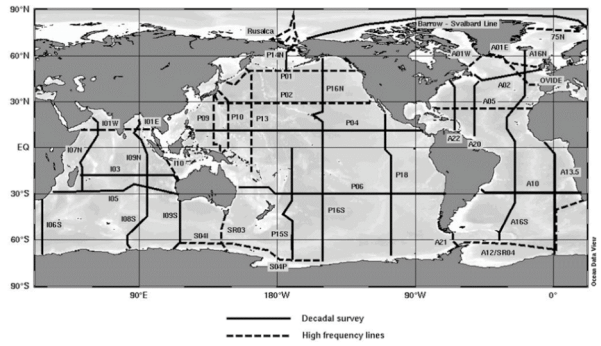

Figure 10: Map showing the recommended spatial sampling density for the interior ocean network. A temporal sampling frequency of 10 years is recommended for the decadal survey sections (solid), while the high-frequency sections should be re-sampled every two to three years. From Hood et al. (this issue).

This shipboard-based approach for determining long-term changes in the ocean's biogeochemistry benefits strongly from the many synergies that can be realized with the wealth of additional parameters that can be measured from a ship, especially the large suite of (physical and biogeochemical) tracers (e.g. CFCs, radiocarbon and other isotopes) as well as the organic components of the ocean carbon cycle (particulate and dissolved organic carbon).

5.4. Time-series Stations

The gap in space and time that emerges between the upper ocean and the interior ocean observing systems can be optimally filled with a time-series station approach, which builds on the successful time-series programs that have been established at a handful of places around the world. In this approach, a suite of sites are sampled at relatively high frequency and throughout the full water column using a combination of moorings and ship-based surveys. For the open ocean, this approach has been organized through the OceanSites initiative (see www.oceansites.org/, Send et al., this issue), while no such coordinated effort exists for the coastal ocean, though this is highly recommended (see Borges et al., this issue).

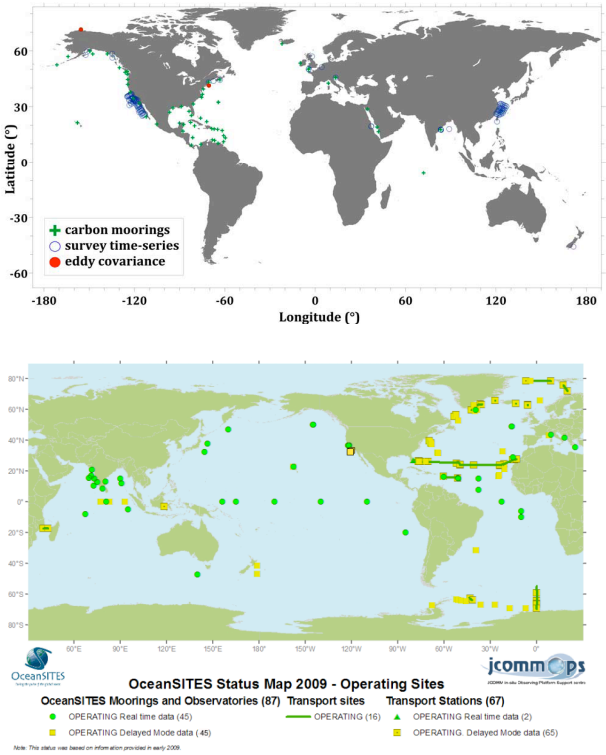

Figure 11: Map showing the current status of (a) coastal and (b) opean ocean time-series sites. In (b) only those stations from the TAO/TRITON/PIRATA/RAMA arrays are shown that include biogeochemical measurements. From Borges et al. (this issue) and Send et al. (this issue).

Particular strengths of the time-series approach are its ability to focus on the processes driving the observed changes as well as the possibility to obtain measurements across the entire frequency domain of interest, e.g. from seconds to years. Time-series sites are also ideal testbeds for testing new approaches and instruments, including the possibility to measure the

air-sea flux of CO_2 directly using eddy co-variance methods.

5.5. Lagrangian Observation Systems

A Lagrangian observing system of sufficient spatial and temporal density represents an almost ideal system for observing upper ocean biogeochemical variability on seasonal to interannual time-scales. However, the lack of suitable sensors has limited this approach so far mostly to oxygen and biooptics (see e.g. the CWP by Gruber et al. (this issue) for an ARGO-oxygen program and the CWP by Claustre et al (this issue) for a bio-optical ARGO program).

With regard to ARGO-Oxygen, the technology for a full-fledged deployment is nearly ready, but some further action is still required to solve remaining problems with sensor characteristics (e.g., response time) and calibration (initial accuracy). In order to overcome these limitations, a two step implementation has been proposed (Gruber et al., this issue). The pilot phase consists of a two pronged approach where on the one side the already deployed oxygen floats (so far more than 200 of them) are carefully analyzed and synthesized, and where on the other hand a new set of oxygen float is deployed in a suitable area. Such a pilot phase would serve several functions. Firstly, it can be used to solve the remaining problems and open questions on technological and data issues. Secondly, it will help to develop tools and approaches necessary for analysis and interpretation of the huge amount of data to be produced by an ARGO-Oxygen program. And thirdly, it would provide for higher visibility of this new observational approach which may help generate support for its full implementation (see Gruber et al., this issue for details).

The details of such a pilot phase would still have to be defined. An important question that needs to be addressed is the regional focus of the pilot study which provides for scientifically interesting spatiotemporal oxygen dynamics, the possibility for ground-truthing exercises through existing hydrographic survey and time series, the existence of prior data and system understanding, and finally a large range in oxygen concentrations.

Following and building on the results of a successful pilot phase a global implementation of the ARGO-Oxygen program is envisioned. Although a detailed analysis has not yet been carried out de-correlation length scales could be expected to be similar to those of temperature possibly requiring the entire ARGO observatory of ~3.000 float to be equipped with oxygen sensors.

A global float-based oxygen observatory would provide insight into ocean climate change and biogeochemistry which is also of great interest for the understanding of dynamics and changes in the ocean's carbon system. Eventually, however, direct carbon observations from floats are desired. This is currently not feasible because of the lack of carbon sensors meeting the stringent requirements for float applications. Membrane-based pCO_2 sensors have been tested on floats (Körtzinger, pers. comm). The results are promising but limited so far by the comparatively long time constants of available pCO_2 sensor technology. Sensors for pH that are based on ion-sensitive field effect transistor (ISFET) technology and capable of long-term operation, are now being tested in the laboratory and on surface moorings where they show great potential for future float applications (Martz et al., submitted). In any case, the ARGO-Oxygen program will provide the operational knowledge and tools to implement a possible future ARGO-Carbon program which despite some promising first work is much further down the road at this time.

Gliders, about more than 100 of which are now being operated, represent a further development of the floats' buoyancy engine technology which combines profiling measurements with the possibility to follow a predetermined path. As such gliders are no longer Lagrangian platforms. Since the glider platform is rather comparable in terms of requirements for sensors and since a glider-based observation approach can be usefully combined with a float observatory a short side view on the utility of gliders is warranted. Glider observations could be nested into a float array where high spatiotemporal resolution and/or a narrow regional focus is required or where float observations need to be extended horizontally, e.g. towards the continental slope or onto the shelves. The ARGO float observatory would then provide the larger picture and boundary information for the focussed glider studies which makes gliders a potentially very useful extension of the ARGO approach in key regions.

5.6. Technological Advances

A common trait of most observational approaches is their current limitation by the availability of sensors and systems for *in situ* observations of marine carbon dioxide system variables (Byrne et al. this issue). Depending on the observational platform under consideration different parameters of the CO_2 system may be of highest interest and very different requirements for sensors/systems emerge. It is obvious for example that pCO_2 measurements from a VOS are much easier to implement than from a surface drifter or even a profiling float. The stage of development is therefore fastly different for the various applications:

- For VOS operations, elaborate and reliable pCO_2 systems with classical gas-water equilibration and subsequent NDIR CO_2 detecion are available and will not be further considered here.
- For Lagrangian surface drifters, pCO_2 systems based on a colorimetric method that are fully integrated into drifter systems are commercially available (e.g., CARIOCA system: Lefèvre et al., 1993) and have

provided high-quality data even under harsh environmental conditions (e.g., Boutin et al., 2008).

- For Eulerian sub-surface observations (moorings), pCO_2 and pH sensor with long endurance and good precision are commercially available (e.g., SAMI system: DeGrandpre et al., 1995) and also have provided high-quality data even under harsh environmental conditions (e.g., Körtzinger et al., 2009).
- For Langrangian platforms (profiling floats, gliders) currently no fully suitable carbon sensor is available. First test with current membrane-based pCO_2 sensors show some promise but also major shortcomings. For pH, the emerging ISFET technology holds significant promise but again major work has to be done before such sensors are operational for sub-surface Lagrangian platforms (Martz et al., submitted).

With autonomous platforms making impressive progress, the need for carbon sensors akin to the oxygen optode (that is: small size, robust, low power requirement, long-term stable, high precision) is becoming more and more pressing. Major emphasis should therefore be placed on sensor development. This includes both the improvement of existing methods and systems for higher performance and the introduction of new technologies. In these development activities the important role of sensor intercomparison (ideally under realistic operation conditions) and rigorous assessment of precision and accuracy employing reference measurements and/or consistency tests on the basis of discrete measurements of other CO_2 system parameters.

5.7. Data requirements, assembly & syntheses

For most biogeochemical application, especially those undertaken to reach the objectives set out in 4.2, a delayed data mode approach is entirely sufficient. Since the primary objectives are associated with changes in the ocean's biogeochemistry, ensuring the highest data quality is much more important than real-time availability of the data.

Data assembly and initial quality control procedures have already been developed for the surface ocean and interior surface ocean networks, while such procedures are in development for the Lagrangian networks. It is recommended that these successful data assembly centers in the respective networks are sustained and equipped to handle the biogeochemical data.

The accurate determination of long-term changes often requires secondary data control procedures, which need to be supported and sustained as well.

5.8. Model and data integration

The intensification of the observing networks for ocean biogeochemistry (and also for bio-optics, see Claustre et al, this issue) opens the great potential for moving this field from a data-limited into a data-rich era, providing excellent opportunities for making a big step forward with regard to the use of models to synthesize data, and to develop and apply sophisticated data-model fusion procedures, i.e. data assimilation similar to those that have emerged in recent years for ocean physics. In particular, such procedures will permit researchers to interpret the large amounts of data in their spatial and temporal context, and to turn concentration measurements into quantitative rate estimates over large regions of the ocean. Achieving an integrated system will require substantial effort in this area. Some of the proposed pilot studies would represent ideal test beds for making rapid progress.

5.9. Integration across observing elements

In principle, the different observational approaches can be regarded as stand-alone initiatives with their own rationales, objectives, analysis tools and synthesis products. In fact, this has been the path followed historically, event though many investigators in the marine carbon arena are often involved in more than one approach. Overcoming this separation is a clear objective of the biogeochemistry community for the next decade.

Clearly, the various approaches probe the marine carbon cycle from different perspectives but they still study the same entity. A good example is the surface ocean network that aims to pin down the net air-sea flux of CO_2 on a global grid at monthly resolution as precisely as possible. Any regional net CO_2 sink/sources, however, by necessity have to match changes in the interior ocean carbon storage and/or regional carbon transport divergences. Thus, the surface and interior ocean network elements are thus providing important complementary information.

The combination of time series, surface and interior observing elements also make for a most complete description of regional carbon characteristics and dynamics. Eulerian time-series can provide high temporal and vertical resolution (1-D) which allows to observe and identify scales of temporal variability and reliably detect secular trends. A surface ocean VOS line that ideally would run through the time-series location would great benefit from the understanding of surface ocean dynamics gained at the time-series but at the same time put the latter into a great regional picture. Mechanistic understanding derived from time-series observations could thus be applied on regional basis. Similary, 1-D time-series data provide high synergistic potential when combined with a repeat hydrography section running through the same location. As a further example, a strong case can be made that the spatiotemporal distribution of oxygen observed by a full ARGO-Oxygen program will aid in the interpretation of sparse data from repeat hydrographic surveys.

These examples document the need to coordinate the observational systems and foster synthesis efforts that

combine the data from the different systems. This way synergies can be achieved on issues such as the assessment of data quality and consistence, the complementarity of spatial and temporal resolution and coverage, or independent proof of fundamental understanding. It is worthwhile to note that this complementarity not only applies to the observation systems describes here but also to other existing observatories, e.g. the strong link between an ARGO-Oxygen program and the atmospheric oxygen network which could improve the atmospheric O_2/N_2 constraint on the oceanic uptake of anthropogenic CO_2.

6. CONCLUSION

The fundamental changes in ocean biogeochemistry that we expect to occur for the 20th century leave us no option but to renew and expand our efforts to observe ocean biogeochemistry. Time-tested approaches and technologies are ready to tackle this challenge. But also new technologies and approaches need to be pushed strongly, opening new doors for making a step change.

These efforts cannot and should not occur in isolation, but in close collaboration with the other observing elements of the ocean, in particular those focusing on the ocean's physical state and those focusing on transport and mixing. Many synergies can also be expected with the emerging observing capabilities for ocean ecosystems (e.g. Claustre et al. plenary paper).

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