A GLOBAL SEA SURFACE CARBON OBSERVING SYSTEM: ASSESSMENT OF CHANGING SEA SURFACE CO_2 AND AIR-SEA CO_2 FLUXES.

Pedro M.S. Monteiro[(1)], Ute Schuster[(2)], Maria Hood[(3)], Andrew Lenton[(4)], Nicolas Metzl[(5)], Are Olsen[(6)], Keith Rogers[(7)], Chris Sabine[(8)], Taro Takahashi[(9)], Bronte Tilbrook[(4)], James Yoder[(10)], Rik Wanninkhof[(11)], Andrew J. Watson[(2)]

[(1)] Ocean Systems & Climate Group, CSIR (Council for Scientific and Industrial Research), Stellenbosch 7599, South Africa, Email: pmonteir@csir.co.za
[(2)] School of Environment Sciences, University of East Anglia, University Drive, Norwich, NR4 7TJ UK, Email: u.schuster@uea.ac.uk
[(3)] IOCCP (International Ocean Carbon Coordination Project), IOC - UNESCO (Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization) 1 rue Miollis 75732, Paris, France, Email: maria.hood@ioccp.org
[(4)] CSIRO (Commonwealth Scientific and Industrial Research Organisation) Marine & Atmospheric Research, Castray Esplanade, Hobart Tas 7000, Australia, Email: andrew.lenton@csiro.au; bronte.tilbrook@csiro.au
[(5)] LOCEAN-IPSL (Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques-Institut Pierre Simon Laplace), CNRS (Centre national de la recherche scientifique), Université P. et M. Curie - Case 100, 4, place Jussieu - 75252 Paris Cedex 5, France, Email: nicolas.metzl@upmc.fr
[(6)] Bjerknes Center for Climate Research, Allegaten 55 5007 Bergen, Norway Email: are.olsen@gfi.uib.no
[(7)] AOS (Atmospheric and Oceanic Sciences) Program, Princeton University, 300 Forrestal Road, Sayre Hall, Princeton, NJ 08544 USA, Email: krodgers@princeton.edu
[(8)] NOAA (National Oceanic and Atmospheric Administration) Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, USA
Email: chris.Sabine@noaa.gov
[(9)] Lamont-Doherty Earth Observatory – Columbia University, Palisades NY 10964-8000 USA
Email: taka@ldeo.columbia.edu
[(10)] Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA
Email: jyoder@whoi.edu
[(11)] NOAA (National Oceanic and Atmospheric Administration)/AOML 4301 Rickenbacker Causeway Miami, FL 33149
Email: rik.wanninkhof@noaa.gov

SUMMARY

This paper identifies the important advances of the past decade that have delivered high precision pCO_2 observations from ships of opportunity (SOOP), robust decadal climatologies of air-sea CO_2 fluxes, and uniform data through coordinated quality control and inter comparisons activities, along with standardized instrumentation and procedures. The vision for the coming decade is to build on these successes to deliver an annual assessment and understanding of the regional and global trends in CO_2 exchanges between the ocean and the atmosphere. The core challenges are the maintenance and expansion of the sampling scales and the development of robust high precision in situ sensors.

Highest priorities for the next 10 years for a global sea surface carbon observing system are:

- to deliver seasonally unbiased annual assessments of the regional and global trends in ocean – atmosphere carbon fluxes. These should comprise monthly global flux maps that are used as constraints for atmospheric inversions in order to improve the assessment of the global carbon budget, including the terrestrial component. This will form an important link between the ocean CO_2 community and the global carbon budget assessment activities of the Global Carbon project (GCP) and its inputs to the periodic IPCC assessments. In order to achieve this, the following are necessary:
- to implement an effective and integrated multi-platform pCO_2 observing network that will reduce uncertainty in regional and global CO_2 flux estimates to ± 10 - 15% of the annual mean flux;
- to advance sensor and instrument development, allowing the density of global surface ocean carbon observing networks to be increased by deployment on additional key SOOP lines, moorings, Lagrangian platforms, gliders and profiling floats.
- to understand and resolve the biogeochemical and physical mechanisms driving surface carbon, natural and anthropogenic CO_2 air-sea flux variability and long term trend sand a link to ocean acidification by incorporating a robust set of ancillary observations;
- to strengthen the capabilities of coupled climate-carbon models to forecast changes in the ocean uptake of CO_2 and the effectiveness of CO_2 emission mitigation strategies

- to further strengthen. for instance through SOCAT, the international coordination of the carbon observations, data quality control, data archiving and the development of regular products for global and regional use.

1. THE IMPORTANCE OF SEA SURFACE CARBON OBSERVATIONS

The ocean uptake of anthropogenic CO_2 emissions from fossil fuel burning, cement production, and land use changes [currently ~10Pg C y^{-1}] significantly mitigates the increase in atmospheric CO_2 [1], [2] and [3] www.globalcarbonproject.org. The oceans currently take up carbon (CO_2) corresponding to 20 to 30% of the annual anthropogenic CO_2 emissions, [2±1 Pg C y^{-1} [4], [5] and [6] and 0.30 - 0.36 Pg C y^{-1} through shelf systems [6] but this uptake is not constant in time and space [1], [2] and [7]. Emission reduction strategies aimed at capping the maximum atmospheric CO_2 concentrations at 450µatm or 550µatm require quantifying the magnitudes and understanding the causes of the changes to the ocean uptake of natural and anthropogenic CO_2 fluxes in order to evaluate the effectiveness of CO_2 emissions mitigation measures [2]. It may then be possible to evaluate the effectiveness of international cooperation to limit the extent of global warming and ocean acidification.

Air – sea CO_2 fluxes are a function of the gas transfer coefficient (k), which is primarily a function of wind speed, temperature dependent solubility (S), and the difference between the oceanic and atmospheric CO_2 concentration (ΔpCO_2), i.e. F= k.S.ΔpCO_2. In the future, in response to a changing climate, these components are expected to be impacted through physical changes in the in response to ocean warming, strengthening of ocean stratification, changes to multi-year atmospheric climate-odes such as the El Niño, the Southern Annular Mode and changes in the biological pump through ecosystem adjustments to the above [3], [9] and [10].

The goal is then to have a surface carbon sampling strategy that is comprised of a well-planned integrated network of surface pCO_2 observations, at monthly or higher timescales. These measurements of pCO_2 are required to complement the ongoing measurements of gas transfer coefficient from remote sensing. This will enable seasonally unbiased CO_2 flux to be calculated thereby reducing the uncertainty of this flux from the present 40 – 50% to 10 – 15% [3], [5] and [6]. In addition, the inclusion of a robust set of ancillary observations will provide additional insights into mechanisms driving this change. This highlights the need for a surface carbon sampling strategy, at seasonal or higher timescales, that allows a seasonally unbiased CO_2 flux to be calculated thereby reducing the uncertainty of this flux from the present 40 – 50% to 10 – 15% [3], [5] and [6].

A decadal-scale shift in the uptake of atmospheric CO_2 by the Southern Ocean may already be changing the partitioning of anthropogenic CO_2 between the atmosphere, terrestrial biosphere, and ocean [1[, [2], [8], [12] and [13]. For many regions where data are available, the seasonal to interannual variability of the air-sea fluxes appear substantial [14] and [15]. The magnitudes and the scales of both variability and the long term change in CO_2 fluxes are strongly linked to decadal changes in circulation and the resulting adjustments in the ecosystem characteristics and resultant feedbacks (Fig. 1) [3]. Understanding these feedbacks becomes particularly important in the context of the combined impacts on ecosystems from climate change and ocean acidification.

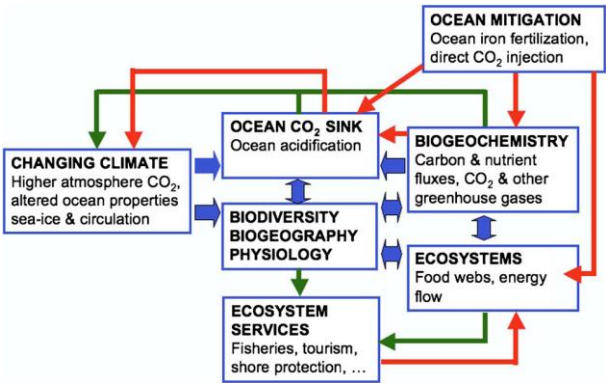


Figure 1. (From [3]): Schematic of ocean ecological and biogeochemical responses and feedbacks on climate change, including direct and indirect effects from human activities. The blue arrows indicate external forcing from changing climate and atmospheric CO_2 impacting ecological and biogeochemical processes. The green arrows indicate marine ecosystem feedbacks on ecosystem services and climate. The red arrows indicate other human perturbations on ocean systems, including fishing, habitat destruction, and deliberate carbon and climate ocean mitigation technologies.

Resolving the seasonal and interannual variability in the air-sea flux of CO_2 as well as reducing its uncertainty is a prerequisite for constraining the global carbon budget and determining how the ocean system is responding to climate variability and change. In contrast to terrestrial systems, the lower spatial variability in oceanic sources and sinks of CO_2 enables the oceanic CO_2 uptake to be quantified with greater certainty given an adequate sampling strategy [5], [6], [9], [16] and [17]. A sustained global ocean observing system for surface CO_2 could also be used in combination with atmospheric data to constrain terrestrial carbon budgets. For the foreseeable future, this "difference approach" is expected to remain a primary means to evaluate large scale terrestrial carbon fluxes [2].

Because of the sensitivity of the global economy and population patterns to climate change and the need for sustainability of key ecosystems an improved understanding of the changing marine carbon cycle has impact for stakeholders far beyond science itself, and reaches into the societal and economic realms [18] and [19]. Carbon is emerging as an important currency in determining the efficiency of economies and the value of goods and services of national and regional economies [19]. A global policy for stabilizing atmospheric CO_2 levels is requires information on carbon sources and sinks that will be increasingly translated into currency equivalents (e.g. carbon trading and carbon off-setting) and uncertainty in the ocean sink will translate into a significant uncertainty in the value of this commodity [20].

2. REQUIREMENTS OF A SURFACE OCEAN CARBON OBSERVING SYSTEM

i.) it should enable the provision of regular (monthly) and robust (10 – 15% uncertainty) CO_2 flux products that are usable to constrain atmospheric inversion-based global carbon flux estimates [1] This will support an important science – policy link between the global ocean carbon community (IOCCP – SOCAT and the IPCC through the GCP.

ii.) It should reduce the uncertainty in the global carbon exchange fluxes to make it possible to resolve interannual and decadal trends [3] and

iii.)It should comprise an integrated multi-platform observational capability to assess and validate numerical models used the understand ocean processes that modulate variability and change in the ocean uptake of CO_2 and improve forecasts of long term trends of the atmospheric CO_2 reservoir

iv.)It should return the maximum information for the investment on hardware and skills

3. THE ACHIEVEMENTS OF THE EXISTING SEA SURFACE CARBON OBSERVING NETWORK.

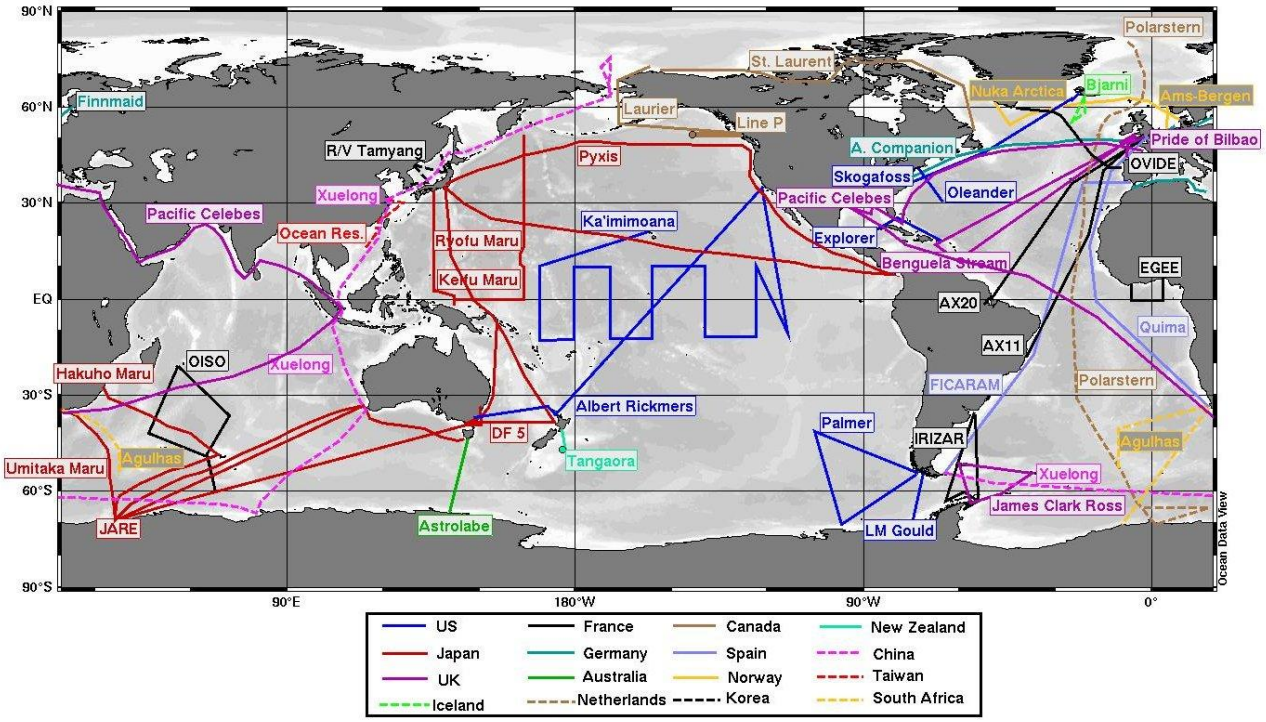
3.1 CO_2 Flux Climatologies

Sea surface carbon measurements started approximately 50 years ago during International Geophysical Year (1957 – 1958) onboard research vessels [21] and [22]. Time series of surface carbon at fixed stations began in the early 1980s in the Atlantic off Bermuda at the Bermuda Atlantic Time-series Study (BATS) and at Hydrostation 'S', and in the Pacific at the Hawaii Ocean Time-series (HOT) and Ocean Station P in the North East Pacific Ocean. Since then, a large number of surface ocean carbon measurements have been initiated at further ship based stations as well as on moorings [5] and [6]. During the 1990s, autonomous measurements of surface pCO_2 began on commercial vessels (e.g. Cooper et al. [23]. Complementing this work, limited surface pCO_2 measurements have been made from Lagrangian drifting buoys, which may be particularly useful in the Southern Ocean where few time series stations and regular VOS lines [24]. The number of routine sea surface pCO_2 measurements obtained from onboard commercial ships and research vessels (Fig. 2a) and at fixed stations (Fig. 2b), has increased significantly in response to concerns about the impacts of rapidly rising atmospheric CO_2 levels on global warming, climate, and ocean acidification.

The large number of pCO_2 measurements that have been obtained has allowed for the compilation and updates of sea surface pCO_2 climatologies [5], [6], [25] and [26]. Such studies use pCO_2 data normalized to nominal reference years in conjunction with ocean models to create global maps; each update reflects the increased number of data available (increasing from approximately one to four million). The most recent compilation by [5] and [6] includes an analysis of the long term trends in several ocean regions, which show that sea surface pCO_2 in most places has increased at a very similar rate to pCO_2 over the long term (http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/). However, on shorter timescales strong temporal trends are apparent in many regions.

For example, sea surface pCO_2 increases measured in the North Atlantic over the last decade or so, have been higher than the atmospheric pCO_2 increase [27], [28], [29] and [30]. Similarly, in the Southern Ocean oceanic pCO_2 growth rates have been observed to be equal or greater than the atmospheric rate [4], [5] and [31]. Similarly there are areas of the ocean, such as the Bering Sea, in which the surface ocean pCO_2 growth rate is below the mean atmospheric rate, suggesting an intensifying sink [5], [6] and [32]. Feely et al [33] observed large-scale decadal increases in the sea-air fluxes of CO_2 in the Equatorial Pacific after the 1998 Pacific Decadal Oscillation regime shift. The differences between these regional studies and the global scale assessments by [5] and [6] emphasize the sensitivity of the results to sampling and assessment scales.

Despite an important increase in the density of the observational network, whole regions or basins are still not adequately covered by ship-based (SOOP/VOS) observations and other platforms. This is highlighted in Fig. (3) which depicts the mean pCO_2 observed and the gaps of the global SOOP – LDEO data set for 2007. Basin-wide and global sea surface pCO_2 and air-sea flux maps are often estimated using a variety of interpolation methods including algorithms relating sea surface pCO_2 [34] to physical (SST/SSS) properties [35], satellite-



OceanSITES – meteorological

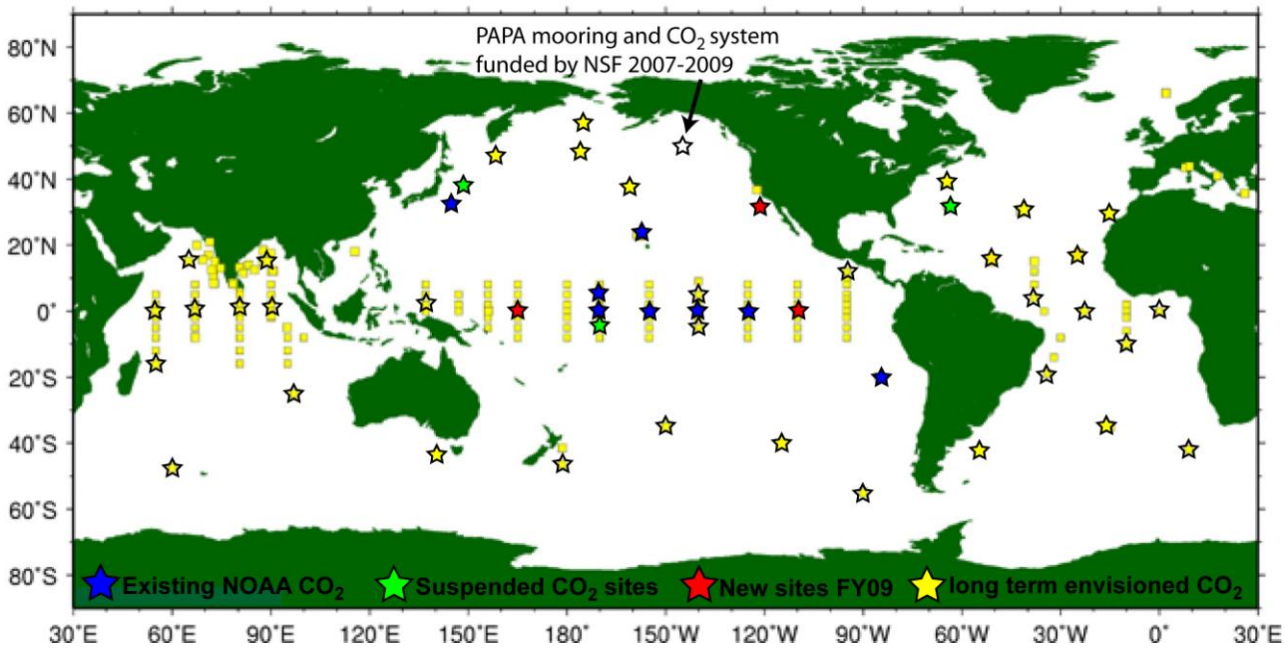


Figure 2. Locations where routine surface carbon measurements are presently undertaken, (A) the SOOP/VOS programme along the lines of commercial and research ship routes, and (B) at time-series stations. (Source: http://www.ioccp.org

derived parameters and reanalysis products [36], [37], [38] and [39] and neural network approaches [34] and [40].Algorithms have been developed and applied to calculate particulate carbon [41] and [42] and coloured organic matter in near-surface waters from satellite measurements of water-leaving radiance. The accuracy of these measurements will depend on many factors including sensor characteristics such as the number of spectral bands and their calibration, as well as an accurate atmospheric correction of the radiances measured and recorded by the satellite sensor. SeaWiFS, MODIS-Aqua and MERIS instruments have been successfully used for these measurements. Although the overall accuracy and precision is not as good as can be measured with *in situ* measurements, the advantage is the broad spatial and frequent temporal coverage provided by the satellite sensors. Future sensors are expected to have more spectral bands and other characteristics that will lead to improved calculations of sea-surface particulate carbon and coloured organic matter. These remote-sensing products will become important adjuncts to the objective of understanding how surface ocean physics and the biogeochemistry are responding to global warming and altering both anthropogenic and natural uptake fluxes of CO_2 by the ocean.

These proxy approaches and other emerging ones will be investigated using modelling platforms as part of the Surface Ocean CO_2 Atlas (SOCAT) activities to derive and improved basis for a comprehensive re-construction of the pCO_2 variability. Parts of the SOCAT data set will form a strong basis for model validation. Numerical models [10], [16], [17] and [44], are emerging as an effective way to optimize the spatial and temporal sampling scales of surface pCO_2. It is the synoptic capabilities of numerical models that allow us to develop and test different sampling strategies, in the present day and under a changing climate, that will be if we are to achieve the goal of 10 – 15% uncertainty levels in CO_2 fluxes. One example of this approach entails combining the signal-to-ratios with Fourier transforms to show that in different regions a trade-off exists between temporal and spatial sampling, and this can be exploited to formulate a strategy that returns the maximum information for minimal sampling effort (Fig. 4) ([16] and [17].

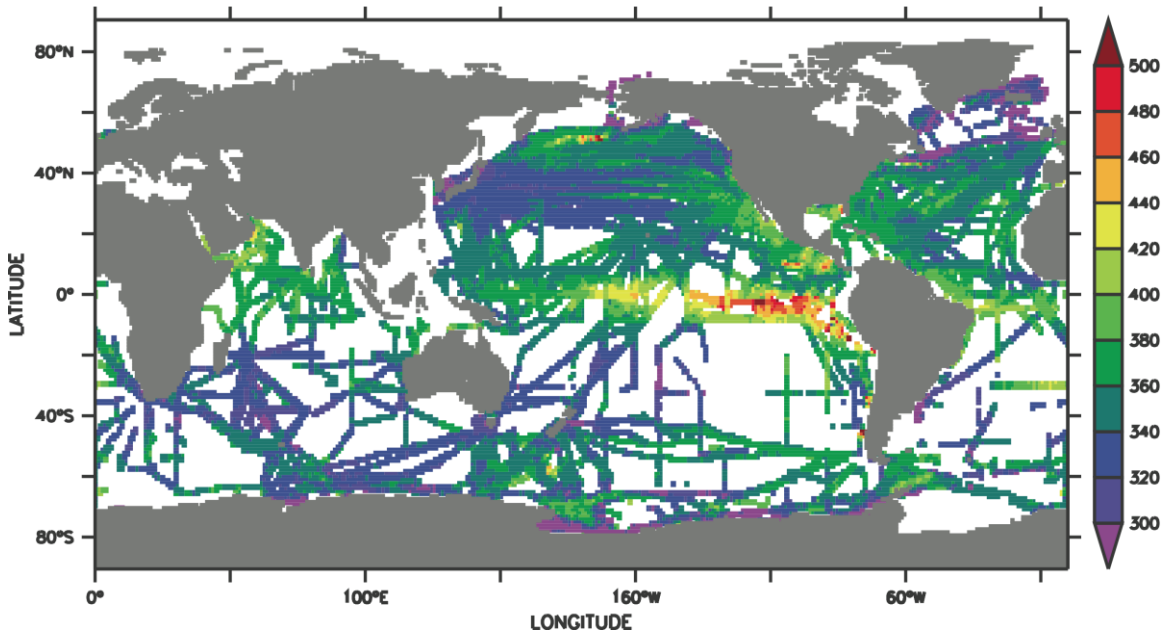


Figure 3: The mean value of oceanic pCO_2 from all seasons in the period 1991-2007, illustrating the regions that remain under-sampled with respect to CO_2 as calculated from the LDEO observational database

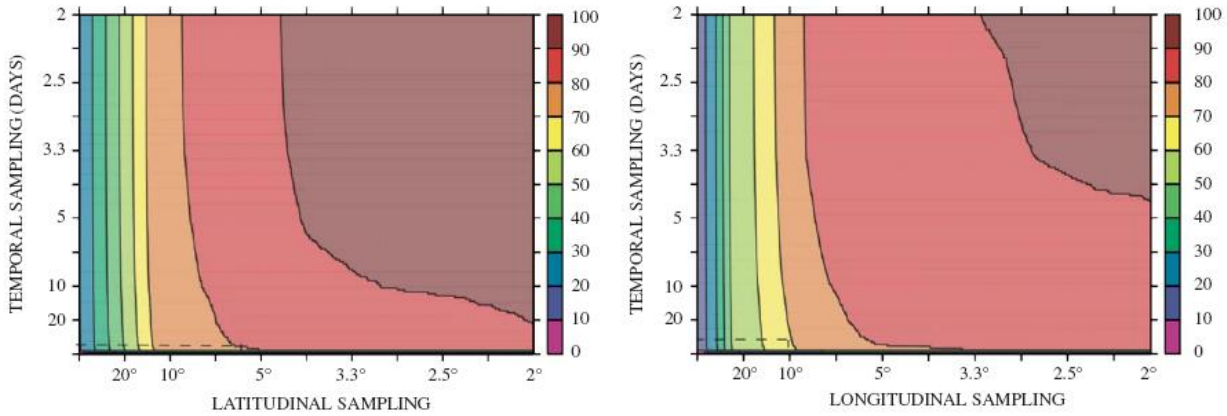


Figure 4: From Lenton et al., [17]: North Atlantic signal-to-noise ratio (SNR) estimated from the 2D Fourier transform for latitude and longitude, the sampling points are marked on each figure, the units are percent of maximum SNR returned.

3.2 International Science Coordination

The International Ocean Carbon Coordination Project (IOCCP), (http://www.ioccp.org) co-sponsored by UNESCO's Intergovernmental Oceanographic Commission and the Scientific Committee on Oceanographic Research was initiated in 2003. The IOCCP has fostered the development of the existing global network of ocean carbon observations for research through technical coordination and communication services, international agreements on standards and methods, advocacy, and links to the global observing systems. This effort applies to surface carbon research as well as ocean interior carbon storage and transport. In the 6 years since its inception, IOCCP has held 17 workshops or meetings and has published and/or co-sponsored the publication of 16 reports, guides, and strategy and best practices documents, many of which have been used by national or regional programs to aid in project planning and international coordination. This successful coordination mechanism will significantly aid international collaboration over the next decade.

3.3 Data Management and Stewardship

The central data archive for the international carbon research community is the Carbon Dioxide Information Analysis Centre (CDIAC, http://cdiac.ornl.gov/, Oak Ridge, Tennessee, USA), which began archiving surface CO_2 data in 1982. Efforts to include all nations' measurements are continuing and improving. CDIAC is recognised as the primary repository for ocean carbon data and metadata. All nations should be encouraged deposit surface CO_2 data with CDIAC in future.

The Surface Ocean CO_2 ATlas (SOCAT) was initiated by SOLAS & IOCCP in 2007, and is a community effort to deliver a uniform format, quality controlled data base of all available surface ocean pCO_2 measurements. This was the outcome of a CO_2 community meeting (Surface Ocean CO_2 Variability and Vulnerability: SOCOVV) in Paris ([45].

Data handling is carried out by the Bjerknes Centre for Climate Research in Bergen, in collaboration the LAS group at PMEL and CDIAC. It is being developed with rigorous 1st and 2nd level data Quality Controls (QC) and presently contains more than 7 million measurements of surface CO_2 data, whenever possible recomputed to fCO2 following Dickson et al. [46] from approximately 2100 cruises from 1968 to 2007. The QC of these data is being carried out by regional groups working on the Pacific, Atlantic, Indian, and Southern Oceans, and in coastal regions. Regional groups began their work in January 2009, aiming to finish their work by mid -2010. The community intends to maintain SOCAT beyond that, adding new data which will be QC'd and incorporated in future releases.

The combined efforts of IOCCP, CDIAC and SOCAT have helped many international groups to work together to develop a unified database of surface fCO_2 for the oceans. This has provided a strong and tested framework to continue the work in the next decade. Only surface fCO_2 measurements are now included in the database. To provide a more comprehensive data set for research on physical and biological controls on surface CO_2 the community should consider establishing a companion database, which should include available total dissolved inorganic carbon (DIC), alkalinity (TA) and pH data from the surface ocean. This will also aid the 2nd level QC of pCO_2 data.

4. LIMITATIONS OF THE EXISTING SEA-SURFACE CARBON OBSERVING NETWORK

Ocean climatologies of CO_2 fluxes of [5, 6 and 26] have been a very important achievement in recent decades. However, as these are synthetic results in which all scales of variability are normalised to a reference year and hence they cannot be used to explore interannual

variability in CO_2 fluxes. They particularly exclude El Niño years which are an important source of interannual variability in Ocean – Atmosphere CO_2 fluxes [5 and 6]. Efforts to determine the interannual variability in the CO_2 fluxes (and pCO_2) has started in the tropical Pacific [33] and [47], North Atlantic [15] and South Indian [31], but most areas lack sufficient data and synoptic global scale assessments are not possible without with models [27].

The global maps in show where routine measurements of surface carbon are now made by commercial ships and research vessels (Fig. 2a), and at time series sites (Fig. 2b) The contrasting regional density of surface fCO2 observations from repeat SOOP/VOS lines are shown in Fig. (3), which highlights areas of elevate sampling and those where routine measurements are sparse or non-existent. One of the best covered regions is the North Atlantic, although most coverage has been recent (Fig. 5a) and the timing of the measurements show that the seasonal cycles are not evenly sampled with potential to alias estimates of the variability (Fig. 5b).

Despite this, the North Atlantic remains the best covered ocean basin due to international collaborative programs like the EU funded CAVASSOO and CARBOCEAN programs. Sustaining these collaborative programs and fostering similar international efforts in other basins is needed to ensure adequate and continuous coverage of measurements in both time and space.

The parameters most often measured on ships and moorings are surface pCO_2, sea surface temperature and salinity. However, these parameters alone are not sufficient to determine biogeochemical and physical drivers of the variability in the surface carbon cycle and air-sea flux, or the effects of the carbon cycle on ocean acidification. Important additional ocean surface parameters for routine measurement include total dissolved inorganic carbon, total alkalinity, dissolved nutrients, dissolved oxygen, carbon isotopes of the dissolved inorganic carbon, and phytoplankton biomass and production ([9], [48] and [49].

The uncertainty of CO_2 flux estimates depend significantly on the parameterization of the gas transfer rate models [50]. Re-assessment of global constraints on gas transfer velocities based on ^{14}C [51] and [52], and field studies and syntheses of gas transfer relationships with wind based on deliberate tracer studies have converged on consistent findings within an uncertainty of 10 %. Larger differences are observed with previous studies, and between micrometeorological CO_2 flux studies but it is not clear if methodological biases are contributing to this [53] and [54]. The gas transfer wind speed relationships should be applied consistently to the corresponding wind fields. Mixing and matching gas transfer-wind speed relationships with different wind products can easily double the uncertainty. Locally and on time scales of days to weeks, significant deviations from canonical relationships are apparent, due to impacts of other forcing and inhibiting factors such as bubble entrainment, thermal gradients and surface films. For the estimates of uncertainties in CO_2 fluxes on regional to global scales based on air-water pCO_2 differences a 10 % uncertainty can be used with a realization that this is likely an optimistic assessment. Further process studies quantifying gas exchange under different conditions and linking the gas transfer to environmental forcing are needed for full characterization of the uncertainty in air-sea CO_2 fluxes due to uncertainties in the gas transfer velocity.

The observational needs for ocean acidification research and monitoring are addressed by Feely et al., [55] and the utilization of data from repeat hydrography measurements that are discussed by Hood et al., [56] can greatly aid the process of resolving biogeochemical/physical processes influencing surface carbon and air-sea flux variability. The costs and personnel required to build, test and deploy instrumentation for surface carbon measurements is limiting the expansion of the global surface carbon network, especially while it remains primarily dependent on National funding programmes. Access to suitable platforms such as SOOP remains challenging both because the ships only ply certain routes and obtaining access to the ships. A considerable investment is needed in research and development of sensors and alternative platforms like drifters, wave riders, and robotic boats over the next decade to reduce costs, strengthen the benefits and provide the spatial and temporal coverage needed to resolve the seasonal and interannual variability in carbon fluxes for all ocean basins in Byrne et al., [57]. This is a critical step to address the existing gaps in the SOOP coverage.

5. THE STRATEGY FOR THE NEXT 10 YEARS

The goal is the detection and attribution of seasonal, interannual and decadal trends in both the ocean natural carbon cycle and uptake of anthropogenic CO_2. The scientific, technological and global coordination capability demonstrated over the past 10 years coupled with the expected progress show that it should be possible to achieve this goal over the next decade. Moreover, through its contribution to enabling annual global carbon budget assessments this will help policy makers setting global CO_2 emissions targets, assess their effectiveness, assess the evolution of ocean acidification and support periodic IPCC reviews.

a) To reduce the uncertainty of CO_2 air-sea fluxes on regional and ocean basin scales, and ultimately on a global scale to 10 – 15%. Although this level of

uncertainty is being achieved in specific ocean basins such as in the North Atlantic [27] the Equatorial and the North Pacific progress will depend on studies of optimal observing system design optimize and multi- platform and parameter integration [17] Further sensor and platform development to lower the costs of long term sampling while maintaining long-term accuracy of the measurements and strengthened global coordination of the science and the sustainable funding of long term observations.

b) To create an adequate, integrated and sustained observational network to observe trends and variability in sea surface pCO_2 and air-sea CO_2 flux in response to the increasing atmospheric CO_2 burden and climate variability. This strategic goal is necessary if the first goal is to be achieved in the coming decade.

In order to determine the regional air-sea flux of CO_2 to within 10 – 15% of the mean annual flux (Sweeney et al., 2002) recommend evenly spaced and regular sampling in the northern North Atlantic of 5 to 9 samples per year every 1500 km, in the temperate North Atlantic 6 samples per year every 1500 km, in the temperate North Pacific 9 samples per year every 200 to 600 km, in the equatorial Pacific 15 samples per year every 200 km, and in the polar South Pacific every 300 km in summer to every 800 km in winter. Recent modelling approaches to optimize sampling scales showed that in the Southern Ocean, the CO_2 air-sea flux can be determined to within ± 0.1 Pg C yr^{-1} with regular 3-monthly sampling at a spatial resolution of 3^o meridionally and 30^o zonally [16], and that > 80% of the CO_2 air-sea flux variance can be captured in the North Pacific and in North Atlantic, with a 3-monthly sampling frequency at a spatial resolution of 6^o meridionally and 10^o zonally [17]. For the Indian Ocean (50˚E - 120˚E, 30˚N - 40˚S); Lenton (in prep) determined that sampling 20° (E-W) x 3°(N-S) every 3 months, this was sufficient to constrain the air-sea CO_2 fluxes to < 20% of total flux. These proposed minimum surface CO_2 sampling scales, depicted in Fig. 6 superimposed on the present VOS activity (cf. Fig. 2a), provide an indication of the gap between existing and required sampling to achieve the vision set out in this CWP. This sampling resolution is not feasible based on SOOP alone but is probably achievable using a similar modelling based approach to integrate a range of different platforms. These recommendations for sampling in time and space are for the open ocean areas, not coastal areas, where sampling strategies must be different due to the much higher variability encountered. This is addressed by Borges et al., [58] who set out the strategies for dissolved inorganic carbon in coastal environments. Achieving these goals for both ocean and coastal systems will form part of the ongoing scientific and coordination activities of the SOCAT network and the IOCCP (www.ioccp.org).

The global observational network needs to work towards expanding and technologically enhancing routine carbon measurements in the ocean surface. This includes a combination of existing platforms such as commercial and research vessels, fixed stations which presently provide the only high quality data to moorings, buoys and floats. Most recently, gliders, robotic boats, and wave-propelled surface platforms increasingly offer long range autonomy to enable basin wide pre-determined transects at a frequency that will resolve the seasonal cycle provided sensors can be downscaled while maintaining accuracy and long-term stability. Reliable sensors on autonomous platforms remain an important area of R&D and until they are available the global surface carbon observation network will need to aim at strengthening the reliable and high

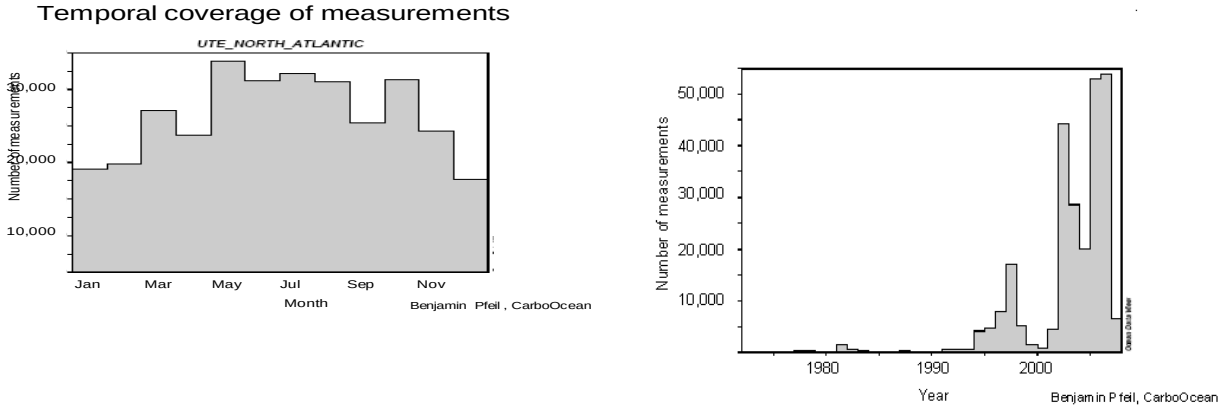


Figure 5: (A) Number of surface pCO2 measurements per year in the North Atlantic. (B) Number of surface pCO_2 measurements per month in the North Atlantic. (Benjamin Pfeil, CABOOCEAN, pers. comm.).

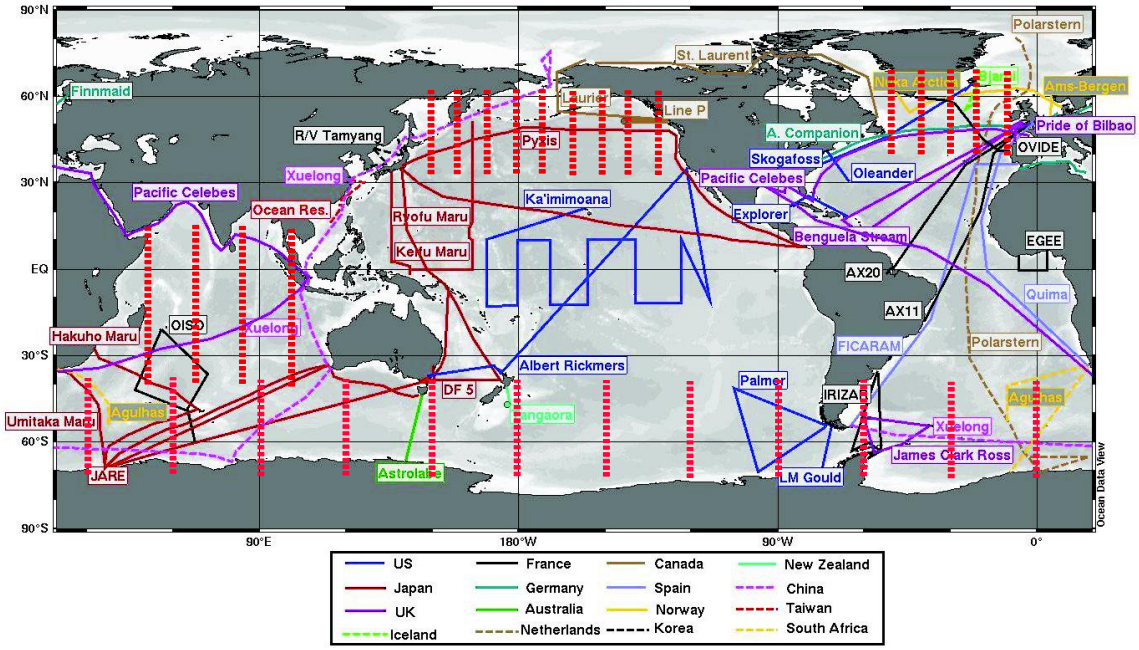


Figure 6: The spatial scales of sampling derived from the Lenton et al 2006, 2009 SNR modelling approach, required from a quarterly VOS programme to resolve the seasonal cycle superimposed on the existing network of VOS observations. It provides an indication of the scaling up required particularly in low sampling areas such as the South Pacific and Southern Oceans.

quality underway systems. Voluntary observing ships (VOS), both commercial and research ships, are able to cover the ocean basins where shipping routes or repeat research lines occur and these will continue to provide stable reference data to check autonomous sensors. In order to cover all ocean basins at the required frequency of sampling, emphasis is needed on the development/deployment of a new generation sensors and platforms. Recent and future advances in this area of sensors and systems for marine CO_2 observations are addressed by Byrne et al., [58].

c) To determine the biogeochemical / physical drivers of seasonal to interannual variability, including the resolution of the sensitivity of these drivers to climate change.

Net regional ocean–atmosphere CO_2 fluxes will be impacted at seasonal, interannual and decadal scales by adjustments of ocean physics to climate change, surface ocean carbon load, including ocean acidification and ocean interior biogeochemistry. Understanding the response of the ocean biogeochemistry and natural carbon fluxes to changes in stratification and wind stress is likely to emerge as a key gap in attempts to define required emission reduction strategies and evaluation of their effectiveness. This will require collection of ancillary variables such as DIC and TA, stable isotope ratios of DIC, oxygen, nutrients, underway high spatial resolution surface ocean productivity indices of carbon export fluxes and biomass [48] In addition remotely sensed data such as chlorophyll, SST, altimetry, wind speed should be systematically collocated with the in situ pCO_2 data. Improved ship based bio-optical and carbon flux proxy observations will close the gap between ocean colour and carbon fluxes which could improve the constraints on the biological pump in biogeochemical models. Observations need to focus on resolving the seasonal cycle, in order to enable the detection of other scales of variability, and to ensure that sampling density is sufficient to remove any potential seasonal biases.

d) To strengthen forecast numerical model capabilities, including those used to constrain the ocean-land partitioning of carbon.

The confidence in forecasting capabilities of coupled climate-carbon models to predict the future evolution of atmospheric CO_2 and the changing role of the ocean carbon cycle will be based to a significant extent the ability of these models to reproduce historical climate change. This assessment can only be made if high quality data sets are available. In addition such data sets will be required for data assimilation for both parameter and state estimation of the global carbon cycle and its components. These dataset in addition to air-sea CO_2 fluxes and oceanic pCO_2 should include a wide range of ancillary both biogeochemical and physical observations. This effort is expected to lead to increased cooperation between the global and regional scale modelling and the observational communities including the efforts in WCRP to constrain heat, momentum, water vapour fluxes that can be tied to air-

sea CO_2 fluxes. Models need to dovetail with observational programmes in order to not only advise on optimized sampling strategies but also to insure that data is produced at scales that are key to reducing the uncertainties of model projections.

e) Strengthened International Coordination

The successes of the several regional research programmes and the coordination efforts of the IOCCP provide a strong basis for developing a global network of surface carbon observations. However, there are still many nationally funded observational programmes that have not contributed to the international effort. In order to achieve the scientific and societal impact, and to develop an optimal observing network within a decade all national and regional programmes need to adhere to, and support, a single global CO_2 observational strategy, coordinated internationally, with agreements on routine data sharing and data archiving, and supported by product development activities such as SOCAT. This will require a significant outreach to assure adherence to best practices, training in operation. Also the benefits of data sharing at local to global scale need to be well articulated. Protocols and safeguards should be implemented that data is properly acknowledged and shared.

6. SUMMARY

Highest priorities for the next 10 years are

- to deliver seasonally unbiased annual assessments of the regional and global trends in ocean – atmosphere carbon fluxes. Through its contribution to enabling global carbon flux assessments this will help policy makers, setting global CO_2 emissions targets, their effectiveness, ocean acidification and IPCC reviews. This will be achieved by,

- implementing an effective and integrated multi-platform global surface ocean carbon observing network that will reduce uncertainty in regional and global CO_2 flux estimates to 10 – 15% of current values (Globally ≈ 2 Pg C yr^{-1})

- exploring and exploiting ongoing advances in sensor, instrument and platform development, that will allow the density of global surface ocean carbon observing networks to be increased. Such platforms may include additional moorings, Lagrangian platforms, , surface wave driven platforms, gliders and profiling float improved understanding of the biogeochemical / physical mechanisms driving surface ocean fCO_2, air-sea flux variability and ocean acidification by increasing the number of ancillary observations;

- provide data that will better constrain of coupled climate carbon models in their ability to forecast changes in the ocean uptake of CO_2 and the effectiveness of CO_2 emission mitigation strategies to further strengthen the international coordination of carbon observations, data quality control, data archiving and the development and dissemination of regular products for global and regional use.

8. REFERENCES

1. Le Quéré et al., 2009. Trends in sources and sinks of carbon dioxide Nature Geoscience doi:10.1038/ngeo689.

2. Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A. & Marland, G. (2007). Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Nat. Acad. Sci*. USA **104**, 10288-10293.

3. Doney, S.C., Tilbrook, B., Roy, S., Metzl, N., Le Quéré, C., Hood, M., Feely, R.A. & Bakker, D. (2009a). Surface-ocean CO_2 variability and vulnerability. *Deep-Sea Research II*, doi:10.1016/J.dsr2.2008.12.016.

4. Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A., Ono, T. & Rios, A. F.: (2004). The oceanic sink for anthropogenic CO_2, *Science* **305**, 367-371, 2004.

5. Takahashi, T., S C. Sutherland, R.Wanninkhof, C. Sweeney, R.A. Feely, D. Chipman, B. Hales, G. Friederich, F. Chavez, A. Watson, D. Bakker, U. Schuster, N. Metzl, H.Y. Inoue, M. Ishii, T. Midorikawa, C. Sabine, M. Hoppema, J. Olafsson, T. Amarson, B. Tilbrook, T. Johannessen, A. Olsen, R. Bellerby, Y. Nojiri, C.S. Wong, B. Delille, N. Bates and H. De Baar. (2009). Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-air CO_2 Flux over the Global Oceans. *Deep-Sea Res II*, doi:10.1016/j.dsr2.2008.12.009.

6. Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D., Hales, B., Friederich, G., Chavez, F., Watson, A., Bakker, D., Schuster, U., Metzl, M., Inoue, H.Y., Ishii, M., Midorikawa, T., Sabine, C., Hoppema, M., Olafsson, J., Amarson, T., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R., Nojiri, Y., Wong, C.S., Delille, B., Bates, N.& De Baar, H. (2009). Corrigendum to Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-air CO_2 Flux over the Global Oceans (DSRII). *Deep-Sea Res I*, doi:10.1016/j.dsr.2009.07.007.

7. Chen C.T.A. & Borges, A.V. (2009). Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2. *Deep-Sea Research II*, doi:10.1016/j.dsr2.2009.01.001.

8. Le Quéré, C., Rodenbeck, C., Buitenhuis, E.T., Conway, T.J., Lagenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., Heimann, M. (2007). Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science* **316**,1735–1738

9. Bender, M., Doney, S., Feely, R.A., Fung, I., Gruber, N., Harrison, D.E., Keeling, R., Moore, J.K., Sarmiento, J., Sarachik, E., Stephens, B., Takahashi, T., Tans, P. & Wanninkhof, R. (2002). A Large-Scale CO_2 Observing Plan: *In Situ* Oceans and Atmosphere (LSCOP), National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, 201.

10. Doney, S.C., Lima, I., Feely, R.A., Glover, D.M., Lindsay, K., Mahowald, N., Moore, J.K. & Wanninkhof, R.: (2009b). Mechanisms governing interannual variability in the upper ocean inorganic carbon system and air-sea CO_2 fluxes: Physical climate and atmospheric dust. *Deep-Sea Res. II*, doi:10.1016/j.dsr2.2008.12.006.

11. Friedlingstein, P, Dufresne J.-L., Cox, P.M. & Rayner, P. (2003). How positive is the feedback between climate change and the carbon cycle? *Tellus* **55B,** 692–700.

12. Rayner P.J., Scholze, M., Knorr, W., Kaminski, T., Giering, R. & Widmann, H. (2005). Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS). G*lobal Biogeochemical Cycles*, **19**, GB2026, doi:10.1029/2004GB002254.

13. Böning, C.W., Dispert, A., Visbeck, M., Rintoul S.R.& Schwarzkopf F.U. (2008). The response of the Antarctic Circumpolar Current to recent climate change. *Nature Geoscience* **1**, 864 - 869 doi:10.1038/ngeo362

14. Rodgers, K.B., Sarmiento, J.L., Aumont, O., Crevoisier, C., de Boyer Montégut, C. & Metzl, N. (2008). A wintertime uptake window for anthropogenic CO_2 in the North Pacific, *Global Biogeochem. Cycles*, 22, GB2020, doi:10.1029/2006GB002920.

15. Schuster, U. et al. (2009). Trends in North Atlantic sea-surface fCO_2 from 1990 to 2006. *Deep-Sea Research II*, doi:10.1016/j.dsr2.2008.12.011

16. Lenton, A., Matear, R. J., and Tilbrook, B.: Design of an observational strategy for quantifying the Southern Ocean uptake of CO_2, *Global Biogeochem. Cycl.*, **20**, doi:10.1029/2005GB002620, 2006.

17. Lenton, A., Bopp, L. & Matear, R. J. (2009). Strategies for high-latitude northern hemisphere CO_2 sampling now and in the future, *Deep-Sea Res. II*, doi:10.1016/j.dsr2.2008.12.008.

18. Canadell, J.G., Ciais, P., Cox, P. and Heimann, M. (2004). Quantifying, Understanding and Managing the Carbon Cycle in the Next Decades. Climate Change. 67(2-3): 147 – 160.

19. Raupach, M.R. & Canadell, J.G. (2008). *Observing a vulnerable carbon cycle*. *In*: Observing the Continental-Scale Greenhouse Gas Balance of Europe (eds. H. Dolman, R. Valentini, A. Freibauer), Springer, Berlin, pp. 5-32.

20. Scholes, R.J., Monteiro, P.M.S, Sabine, C.L. & Canadell, J.G. (2009). Systematic long-term observations of the global carbon cycle, *Trends in Ecology and Evolution*, doi:10.1016/j.tree.2009.03.006.

21. Keeling, C.D., Rakestra. N.W. & Waterman, L. S.: (1965). Carbon Dioxide in Surface Waters of Pacific Ocean .1. Measurements of Distribution, *Journal of Geophysical Research* **70**, 6087-98.

22. Takahashi, T. (1961). Carbon dioxide in the atmosphere and in Atlantic Ocean water. *Journal of Geophysical Research*, **66,** 477-494

23. Cooper, D.J., Watson, A.J. & Ling, R.D. (1998). Variation of pCO_2 along a North Atlantic shipping route (U.K. to the Caribbean): A year of automated observations. *Marine Chemistry* **60**, 147-164

24. Boutin, J., Merlivat, L., Henocq, C., Martin, N. & Sallee, J.B. (2008). Air–sea CO_2 flux variability in frontal regions of the Southern Ocean from Carbon Interface OCean Atmosphere drifters. *Limnol. Oceanogr.* **53**(5, part 2), 2062–2079

25. Takahashi, T., Olafsson, J., Goddard, J.G., Chipman, D.W. & Sutherland, S.C. (1993). Seasonal Variation of CO_2 and Nutrients in the High-Latitude Surface Oceans: a Comparative Study, *Global Biogeochem. Cycles* **7**(4), 843–878.

26. Takahashi, T., Sutherland, S.C., Sweeney, C., Poisson, A., Metzl, N., Tilbrook, B., Bates, N., Wanninkhof, R., Feely, R. A., Sabine, C., Olafsson, J. & Nojiri, Y. (2002). Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Res. II*, **49**, 1601-1622.

27. Le Quéré, C et al., Two decades of ocean CO2 sink and variability. *Tellus*. 55B, 649–656

28. Schuster, U. & Watson, A.J.W. (2007). A variable and decreasing sink for atmospheric CO_2 in the North Atlantic, *Journal of Geophysical Research*, **112,** doi:10.1029/2006JC003941.

29. Corbière, A., Metzl, N., Reverdin, G., Brunet, C., & Takahashi, T. (2007). Interannual and decadal variability of the oceanic carbon sink in the North Atlantic subpolar gyre. *Tellus* **59B**, 168-178.

30. Lefevre, N., Watson, A.J., Olsen, A., Ríos, A.F., Pérez, F.F. & Johannessen, T. (2004). A decrease in the sink for atmospheric CO_2 in the North Atlantic. *Geophysical Research Letters*, 31, L07306, doi:07310.01029/02003GL018957.

31. Takahashi,T., Sutherland, S.C., Feely, R.A., Wanninkof, R., 2006. Decadal change of the surface water pCO2 in the North Pacific: a synthesis of 35 years of observations. J.Geophys.Res.111,C07S05

32. Feely, R.A., Boutin, J., Cosca, C.E., Dandonneau,Y., Etcheto, J., Inoue, H., Ishii, M., Le Quéré, C., Mackey, D.J., McPhaden, M., Metzl, N., Poisson, A. & Wanninkhof, R. (2002). Seasonal and interannual variability of CO_2 in the equatorial Pacific. *Deep-Sea Res. II* **49**, 2443–2469.

33. Friedrich, T. & A. Oschlies (2009). Neural-network based estimates of North Atlantic surface pCO_2 from satellite data: A methodological study, *J. Geophys. Res*., **114**, C03020, doi:10.1029/2007JC004646.

34. Metzl, N., Poisson, A., Louanchi, F., Brunet, C., Schauer, B. & Brès, B. (1995). Spatio-temporal distributions of air-sea fluxes of CO_2 in the Indian and Antarctic Oceans: a first step. *Tellus* **47B**, 56-69.

35. Lee, K., Wanninkhof, R., Takahashi, T., Doney, SC.,& Feely, R.A. (1998) Low interannual variability in recent oceanic uptake of atmospheric carbon dioxide. *Nature*. **396**, 155-159

36. Cosca, C. E., R. A. Feely, J. Boutin, J. Etcheto, M. J. McPhaden, F. P. Chavez, and P. G. Strutton (2003), Seasonal and interannual CO2 fluxes for the central and eastern equatorial Pacific Ocean as determined from fCO2-SST relationships, J. Geophys. Res., 108(C8), 3278, doi:10.1029/2000JC000677.

37. Olsen, A., Triñanes, J.A. and Wanninkhof, R. (2004) Sea–air flux of CO2 in the Caribbean Sea estimated using in situ and remote sensing data. *Remote Sensing of Environment*: 89, (3): 309-325

38. Chierici, M., Olsen, A., Johannessen, T., Trinanes, J. & Wanninkhof, R. (2009). Algorithms to estimate the carbon dioxide uptake in the northern North Atlantic using shipboard observations, satellite and ocean analysis data. *Deep-Sea Research II*, doi:10.1016/j.dsr2.2008.12.014.

39. Telszewski, M., Chazottes, A., Schuster, U., Watson, A.J., Moulin, C., Bakker, D.C.E., Gonzalez-Davila, M., Johannessen, T., Kortzinger, A., Luger, H., Olsen, A., Omar, A., Padin, X. A., Rios, A., Steinhoff, T., Santana-Casiano, M., Wallace, D. W. R. & Wanninkhof, R.: Estimating the monthly pCO_2 distribution in the North Atlantic using a self-organizing neural network, *Biogeosci. Disc*. **6**, 3373-3414.

40. Stramski, D., Reynolds, R.A, Kahru, M. & B.G. Mitchell. (1999). Estimation of particulate organic carbon in the ocean from satellite remote sensing. *Science* **285**: 239-242.

41. Behrenfeld, M.J., Boss, E., Siegel, D.A. & Shea, D.M. (2005). Carbon-based productivity and phytoplankton physiology from space. *Global Biogeochemical. Cycles*, **19**, GB1006, doi:10.1029/2004GB002299.

42. Siegel, D.A., Maritorena, S., Nelson, N.B. & Behrenfeld, M.J. (2005): Independence and interdependencies of global ocean color properties; Reassessing the bio-optical assumption. *Journal of Geophysical Research*, **110**, C07011, doi:10.1029/2004JC002527.

43. Thomas, H., Prowe, A.E.F., Lima, I.D., Doney, S.C., Wanninkhof, R., Greatbatch, R.J., Schuster, U. & Corbiere, A. (2008). Changes in the North Atlantic Oscillation influence CO_2 uptake in the North Atlantic over the past 2 decades, Global *Biogeochem. Cycl.*, **22**, doi:10.1029/2007 GB003167.

44. Metzl, N., Tillbrook, B., Bakker, D., Le Quéré, C., Doney, S., Feely, R., Hood, M. and R. Dargaville. (2007). Global Changes in Ocean Carbon: Variability and Vulnerability. *EOS*, 88, N 28.

45. Dickson, A.G., Sabine, C.L., Christian, J.R. (Eds.), (2007). Guide to best practices for ocean CO_2 measurements. PICES Special Publication 3

46. Ishii, M., et al. (2009). Spatial variability and decadal trend of the oceanic CO_2 in the western equatorial Pacific warm / freshwater. *Deep-Sea Research II*, doi:10.1016/j.dsr2.2009.01.002.

47. Behrenfeld, M.J., Westberry, T.K., Boss, E.S., O'Malley, R.T., Siegel, D.A., Wiggert, J.D., Franz, B.A., McClain, C.R., Feldman, G.C., Doney, S.C. & Moore, J.K. (2008). Dall'Olmo, G. Milligan1, A. J. Lima, I. and Mahowald N. Satellite-detected fluorescence reveals global physiology of ocean phytoplankton. *Biogeosciences Discuss.*, **5**, 4235–4270.

48. Cassar, N., Barnett, B.A., Bender, M.L., Kaiser, J., Hamme, R.C., Tilbrook, B. (2008) Continuous O_2/Ar measurements in the sea surface mixed layer by Equilibrator Inlet Mass Spectrometry (EIMS). *Analytical Chemistry*, in press.

49. Wanninkhof, R., Asher, W.E., Ho, D.T., Sweeney, C.S. & McGillis, W.R. (2009). Advances in Quantifying Air-Sea Gas Exchange and Environmental Forcing, A*nnual Reviews Mar. Science*, **1,** 213-244, doi:10.1146/annurev.marine.010908.163742.

50. Sweeney, C., Gloor, E., Jacobson, A.R., Key, R.M., McKinley, G., Sarmiento, J.L. & R. Wanninkhof (2007). Constraining global air-sea gas exchange for CO_2 with recent bomb C-14 measurements. *Global Biogeochemical Cycles* **21**, doi:10.1029/2006GB002784.

51. Naegler, T. (2009). Reconciliation of excess ^{14}C-constrained global CO_2 piston velocity estimates, *Tellus* B, doi:10.1111/j.1600-0889.2008.00408.x.

52. Miller S., Marandino, C., d. Bruyn, W. & Saltzman, E.S. (2009). Air-sea gas exchange of CO_2 and DMS in the North Atlantic by eddy covariance, *Geophys. Res. Lett*., **36**, L15816, doi:10.1029/2009GL038907.

53. McGillis, W.R., Dacey, J.H., Ware, J.D., Ho, D.T., Bent, J.T., Asher, W.E., Zappa, C.J., Raymond, P.A., Wanninkhof, R. & Komori, S. (2007). *Air-water flux reconciliation between the atmospheric CO_2 profile and mass balance techniques*, in Transport at the Air Sea Interface, Measurements, Models and Parametrizations, edited by C. S. Garbe, *et al*., pp. 181-192, Springer, Berlin, Heidelberg.

54. Feely, R. & Co-Authors (2010). "An International Observational Network for Ocean Acidification" in these proceedings (Vol. 2), doi:10.5270/OceanObs09.cwp.29.

55. Hood, M. & Co-Authors (2010). "Ship-Based Repeat Hydrography: A Strategy for a Sustained Global Program." in these proceedings (Vol. 2), doi:10.5270/OceanObs09.cwp.44.

56. Byrne, R. & Co-Authors (2010). "Sensors and Systems for In Situ Observations of Marine Carbon Dioxide System Variables" in these proceedings (Vol. 2), doi:10.5270/OceanObs09.cwp.13.

57. Borges, A. & Co-Authors (2010). "A Global Sea Surface Carbon Observing System: Inorganic and Organic Carbon Dynamics in Coastal Oceans" in these proceedings (Vol. 2), doi:10.5270/OceanObs09.cwp.07.