Final publishable summary report CARBOCHANGE

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Executive summary

Currently, the oceans take up about 25 % of the CO_2 emitted annually by human activities. European research groups working in this area have made major contributions to our understanding of the oceans' carbon cycle. However, carbon uptake by the oceans is changing and many questions on the oceanic carbon sink remain unanswered.

The EU-funded 'Changes in carbon uptake and emissions by oceans in a changing climate' (http://www.carbochange.eu (CARBOCHANGE)) project was established to fill in gaps in the scientific knowledge. The initiative will update the global carbon budget with estimates for ocean carbon and air–sea CO_2 flux. The setting up of relevant procedures has enabled greater accuracy in long-term monitoring of global carbon and also facilitated prediction systems.

CARBOCHANGE has provided a more accurate picture of how unsteady the oceanic carbon sink for human-produced CO_2 really is and what changes might be expected for given future scenarios. Researchers have also made progress to establish the role of ocean carbon uptake with regard to others stressors of the marine environment.

An essential part of the CARBOCHANGE project is data collection. CO_2 and carbon measurement campaigns have been carried out, including measurements both at ocean surface level and deep below. In addition, a substantial number of model experiments have been carried out employing Earth system models – fully fledged ones as well as those of intermediate complexity.

Using data assimilation and optimising methods, the CARBOCHANGE project has systematically combined the models and observations. To date, the results include a model to quantify the effect of the temperature dependency of organic matter on atmospheric CO_2 under climate warming. A multi-model series of future climate projection scenarios has also been completed for the latest Intergovernmental Panel on Climate Change (IPCC) assessment report.

Significant progress has been made during the CARBOCHANGE project on building an original and unprecedentedly comprehensive data set on ocean carbon. The information covers the North Atlantic and Southern Oceans, as well as the Mediterranean outflow region. This data set will make clear the extent and duration of regional carbon sink variations in the context of evolving climate change.

The work of CARBOCHANGE has given new insights into the vulnerability of the ocean carbon sink for CO_2. It will contribute directly to the design and enforcement of limits to greenhouse gas emissions and a subsequent change in energy production and use. In this respect, CARBOCHANGE will make a real contribution to new research programmes such as Horizon 2020 and Future Earth.

CARBOCHANGE was a key provider to the annual updates of the global carbon budgets as coordinated by the Global Carbon Budget. The activities have been embedded in large international projects such as SOLAS (IGBP), IMBER (IGBP), and IOCCP (sponsored by SCORE and IOC).

Summary description of project context and objectives

Project context: Integrated over time from the beginning of the Industrial Revolution and intense land use change activities in the 19^{th} century, the ocean has been the major reservoir for absorbing anthropogenic excess carbon dioxide (CO_2) from the atmosphere. In the 1990s and the first decades of the current millennium about 50% of the annual human-produced CO_2 emissions to the atmosphere remained in the atmosphere, while 25% each where taken up by the land biosphere and the ocean. The temporary large terrestrial carbon sink is due to CO_2 fertilisation of plant growth. When taking into account nitrogen limitation for plant growth, the land sink could possibly be somewhat smaller. Traditionally, the ocean had been considered as a quite steady and reliable sink for anthropogenic CO_2. However, observations and ocean model results with time-dependent forcing have revealed that the ocean sink strength for carbon can vary regionally, basin-wide and globally over time. The FP6 Integrated Project CARBOOCEAN and a series of further ocean carbon projects worldwide had been major stepping stones towards the conclusion that the ocean carbon source/sink distribution is undergoing modifications and that steady-state assumptions do not apply. European research groups working on the ocean carbon cycle have made major contributions to new interdisciplinary research results on physical, chemical and biological processes that control air-ocean fluxes of carbon, including where human-produced produced carbon is stored in the ocean and how the marine uptake of carbon may change in the future. Respective research tools have been produced in the form of observational methods and networks as well as through numerical ocean models and also coupled Earth system models. But how can these observing and modelling systems be further developed and systematically combined in order to predict with more confidence and realism the ongoing and future carbon uptake by the oceans? Can earlier found considerable carbon sink strength changes in the ocean be explained through firm process attributions? What implications will the ocean's role in carbon uptake have for emission control of major greenhouse gases and for associated impacts such as ocean acidification and climate change? In order to allow for closing necessary knowledge gaps, the EU FP7 large-scale project CARBOCHANGE was implemented. CARBOCHANGE has now come to an end. All major project objectives have been achieved.

Main objectives have been: *CARBOCHANGE will provide the best possible process-based quantification of net ocean carbon uptake under changing climate conditions using past and present ocean carbon cycle changes for a better prediction of future ocean carbon uptake. The project aims at an improved quantitative understanding of key biogeochemical processes (particle flux, ecosystem community structure, lateral advection) and physical processes (overturning circulation, ice cover, mixing) through a combination of observations and models. New process understanding to large-scale integrative feedbacks of the ocean carbon cycle to climate change and rising carbon dioxide concentrations will close important knowledge gaps. An important sub-goal is to quantify the vulnerability of the ocean carbon sources and sinks in a probabilistic sense using cutting edge coupled Earth system models under a variety of emission scenarios including climate stabilisation scenarios as required for the 5th IPCC assessment report. The drivers for the vulnerabilities will be identified. The most actual observations of the changing ocean carbon sink will be systematically integrated with the newest ocean carbon models, a coupled land-ocean model, an Earth system model of intermediate complexity and fully fledged Earth system models. This will be achieved through a spectrum of data assimilation methods as well as advanced performance assessment tools.*

Main Scientific &Technological results/foregrounds

CT1 – Key processes and feedbacks, future scenarios, and vulnerabilities

Main objectives:

- The ocean CO_2 sink varies substantially in time, largely in response to changes in atmospheric CO_2 and surface forcing associated with climate variability and change. We need to know and understand the processes underlying this variability in order to be able to project reliably the future oceanic uptake CO_2 uptake under different greenhouse gas emission trajectories. Core Theme 1 contributed to this overarching objective by (i) quantifying the main physical, chemical and biogeochemical processes controlling the carbon cycle and the net air-sea exchange of CO_2 in key regions of European interest (North Atlantic, Southern Ocean, Mediterranean Sea, Canary upwelling), (ii) evaluating the feedbacks on CO_2 uptake associated with circulation changes in the these regions, (iii) assessing the role of meso-scale turbulence (e.g. eddies) in determining the sensitivity of the ocean carbon cycle to changes in atmospheric forcing, (iv) assessing the vulnerability of the future oceanic carbon sink through the use of Earth system models, and (v) identifying the processes that determine the future evolution of the oceanic carbon sources and sinks and assessing their likelihood.

Scientific highlights:

- While the analysis of surface and interior ocean carbon data permitted researchers prior to CARBOCHANGE to estimate the long-term mean ocean carbon uptake, the variability of this sink remained essentially unconstrained. Using a newly developed neural network method to extrapolate surface ocean observations of the partial pressure of CO_2 in time and space, Landschützer et al. (2014) were able to overcome this gap and to estimate the monthly variations of the global ocean carbon sink for the period 1998-2011 at 1° horizontal resolution. They found that the global uptake varies relatively little around the global long-term mean of -1.42 ± 0.53 Pg C yr^{-1}, with the equatorial Pacific dominating the variability on interannual time scales, largely associated with the variations in the El Niño/Southern Oscillation phenomenon. Accounting for steady-state riverine and Arctic Ocean carbon fluxes, their long-term mean uptake implies a mean anthropogenic CO_2 uptake of -1.99 ± 0.59 Pg C yr^{-1} over the period 1998 -2011 confirming previous estimates by IPCC.
- Observations revealed that the North Atlantic carbon sink had weakened substantially between the 1990s and the 2000s, with most of this having been attributed to a warming trend that was possibly enhanced by changes in the meridional overturning circulation. Pérez et al. (2013) analyzed ocean interior carbon observations gathered between 1997 and 2006 along the OVIDE line and used a method to separate the anthropogenic from the natural CO_2 component. This separation permitted them to show that much of the observed weakening of the CO_2 uptake in the subpolar North Atlantic was due to a reduction in the natural CO_2 component, caused by the slowdown of the meridional overturning circulation. Furthermore, this slowdown also accounted for the concomitant decline in anthropogenic CO_2 storage in subpolar waters.
- Prior to the EU-funded large-scale ocean carbon cycle projects CARBOOCEAN and CARBOCHANGE, the carbon cycle of the Arctic was essentially unknown, largely due to the very low number of observations. As a result of a sustained sampling program in the last few years, high quality data from the Arctic are becoming available to start assessing the evolution of dissolved inorganic carbon (DIC) in the subsurface water masses. Ericson et al. (2014) reported a clear trend of DIC build-up in intermediate waters. The observed evolution in DIC occurred in the absence of any increase in nutrient concentrations, suggesting that it reflects the addition of increasing levels of anthropogenic CO_2. The detailed analysis of the observed DIC changes illustrates that the Arctic Ocean is keeping up its rate of anthropogenic CO_2 sequestration, suggesting no change in the rate of deep-water formation. This also implies that this aspect of the Arctic carbon cycle currently does not provide a feedback to the global climate system
- Recent modeling studies suggested that the Southern Ocean uptake of CO_2 from the atmosphere may have stalled relative to expectations on the basis of the continuing increase in atmospheric CO_2. This was largely attributed to the observed positive trend in the Southern Annular Mode (SAM), which caused an enhanced upwelling and outgassing of natural CO_2, thereby offsetting the uptake of anthropogenic CO_2. However, these models were run at relatively low resolutions, preventing them from having eddies compensate for the wind-driven upwelling. Dufour et al. (2013) showed that the compensating effect of mesoscale eddies is quite large (perhaps a third), so that the Southern Ocean's net sea-to-air CO_2 flux is enhanced by only 0.1 Pg C yr^{-1} per standard deviation of the SAM, i.e., only about a third of the signal seen in the coarse-resolution models.
- The rise in greenhouse gases caused by humans influences and alters climate and ecosystems in a variety of ways, and the effects differ from one region to the next. Multiple climate targets are necessary in order to prevent dangerous interference with the climate system and, thus, negative social and economic effects. Steinacher et al. (2013) explored six climate targets that can have negative effects for humans and ecosystems on land and in the ocean in a probabilistic framework. They found that in order to achieve all six climate targets jointly, the emissions would have to be cut much more drastically than what is being considered under current mitigation strategies that solely focus on the reduction of global warming.

- While formal detection studies have been commonly used with regard to a number of climate-related quantities, so far no study was conducted investigating if any recent change can be detected in the global carbon sink and if this can be attributed to anthropogenic climate change. Using a modeling framework, Séférian et al. (2014) suggested that the evolution of the global oceanic carbon sink over the last decades is, as expected, dominantly attributed to rising atmospheric CO_2, and that no impact of recent climate change can be detected. In contrast, at the regional scale, and particularly in the low-latitude oceans, the influence of climate change on air-sea CO_2 exchanges appears to emerge from the internal variability, i.e., can be formally detected.

Further reading:

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- Séférian R, Ribes A, Bopp L (2014): Detecting the anthropogenic influences on recent changes in ocean carbon uptake: detecting changes in ocean carbon uptake. Geophysical Research Letters 41**,** 5968-5977. doi: 10.1002/2014GL061223.
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Contact information:

- Gruber, N., Environmental Physics Group, ETH Zürich, Institute of Biogeochemistry and Pollutant Dynamics and, Center for Climate Systems Modeling (C2SM), Zürich, Switzerland; email: nicolas.gruber@env.ethz.ch
- Gehlen, M., Laboratoire des Sciences du Climat et de L'Environnement, CE Saclay, Orme des Merisiers Bât. 712, 91191 Gif-sur-Yvette cedex, France; email: marion.gehlen@lsce.ipsl.fr

CT2 – Observing systems

Main objectives:

- Observing system of ocean carbon change, combine and critically assess the observational approaches and data to address scientific questions, identify synergies between different observing platforms and strategies, and establish an efficient and coordinated design for the ocean component of the Integrated Carbon Observing System (ICOS). The European contribution to the global network focuses primarily on the Atlantic Ocean, including the Arctic Ocean and key sectors of the Southern Ocean.
- To coordinate and conduct time-series and deep-section measurements of ocean carbon and ancillary variables. New and existing measurements are used to estimate the variability of natural and anthropogenic CO_2.
- To evaluate the carbon storage and its vulnerability in the interior ocean with respect to anthropogenic changes, oceanic circulation and biogeochemical processes, linked to model outputs and skills.

Scientific highlights:

- We have been involved in the creation and updating of the Surface Ocean CO_2 Atlas (SOCAT), a quality controlled dataset of sea surface pCO_2 (Bakker et al., 2014). These data were used in the production of the Global Carbon Budget 2014, estimating the global ocean sink to be 2.6 ± 0.5 GtC yr^{-1} for 2004 to 2013 (Le Quéré et al., 2014), with the interannual variability being estimated to be about 0.31 PgC yr^{-1} (Rödenbeck et al., 2014). Data were submitted to the UN Climate Summit meeting in 2014.
- The air-sea flux variability in the Atlantic and Arctic was studied (Schuster et al., 2013) as part of the Regional Carbon Cycle Assessment Programme (RECCAP). Results indicate a combined sea–air flux of −0.61 ± 0.06 Pg C yr^{-1} over two decades.
- In the Southern Ocean, high frequency CARIOCA measurements allowed us to estimate the net community production in the Kerguelen plume. Results indicate a strong control of the Net Community Productivity (NCP) and pCO_2 variability by the availability of iron (Lo Monaco et al., 2014).
- A global study of long-term pH trends were estimated using SOCAT v2 (Lauvset et al., 2015). In the western North Atlantic subpolar gyre, decadal pH trends were around -0.03/decade (1993 to 2014) and - 0.04/decade (2001 to 2014). The Subarctic Intermediate Waters of the North Atlantic between 1981-2008 show fast ocean acidification rate (−0.0019 ± 0.0002 yr^{-1}), 75% of which is of anthropogenic origin (Vázquez-Rodriguez et al., 2012). In subtropical North Atlantic, natural variability explains the vertical distribution of the larger pH decreases (up to -0.05 pH units), which are found within the permanent thermocline (Guallart et al., 2015).
- CO_2 uptake by the Atlantic Ocean has decreased by weakening of meridional overturning circulation. The uptake of CO_2 is predominantly anthropogenic in the subtropical gyre of the North Atlantic, while the subpolar gyre accounts almost exclusively for natural-CO_2 uptake (Pérez et al., 2013).
- The anthropogenic carbon changes in the Irminger Sea highlight a strong relationship between anthropogenic carbon and the ^{13}C Suess effect in all water masses (Racapé et al., 2013).
- At the Prime Meridian in the Weddell Gyre, CO_2 increased in bottom water with +0.12±0.05 µmol kg^{-1} yr^{-1} (van Heuven et al., 2014).
- Mesoscale eddy observations indicate near-surface suboxic/high CO_2 from the Mauritanian upwelling area into the open ocean (Karstensen et al., 2014).

Further reading:

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- Guallart EF et al. (2015): Trends in anthropogenic CO_2 in water masses of the Subtropical North Atlantic Ocean. Progress in Oceanography 131, 21-32. doi: 10.1016/j.pocean.2014.11.006.
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- Lauvset SK et al. (2015): Trends and drivers in global surface ocean pH over the past 3 decades. Biogeosciences 12, 1285-1298. doi: 10.5194/bg-12-1285-2015.
- Le Quéré C et al. (2014): Global carbon budget 2014. Earth System Science Data Discussions 7, 521-610. doi: 10.5194/essdd-7-521-2014.
- Lo Monaco C et al. (2014): Rapid establishment of the CO_2 sink associated with Kerguelen's bloom observed during the KEOPS2/OISO20 cruise. Biogeosciences Discussions 11, 17543-17578. doi: 10.5194/bgd-11-17543-2014.
- Pérez FF et al. (2013): Atlantic Ocean CO_2 uptake reduced by weakening of the meridional overturning circulation. Nature Geoscience 6, 146-152. doi: 10.1038/NGEO1680.
- Racapé V et al. (2013): Anthropogenic carbon changes in the Irminger Basin (1981-2006): Coupling $\delta^{13}C_{DIC}$ and DIC observations. Journal of Marine Systems 126, 24-32. doi: 10.1016/j.jmarsys.2012.12.005.
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- Schuster U et al. (2013): An assessment of the Atlantic and Arctic sea-air CO_2 fluxes, 1990 – 2009. Biogeosciences 10, 607-627. doi:10.5194/bg-10-607-2013.
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- Vázquez-Rodriguez et al. (2012): Observed acidification trends in North Atlantic water masses. Biogeosciences 9, 5217–5230. doi: 10.5194/bg-9-1-2012.

Contact information:

- Prof. Andrew J Watson FRS, University of Exeter, UK; email: Andrew.Watson@exeter.ac.uk
- Prof. Aida F. Rios, CSIC, Spain; email: aida@iim.csic.es

CT3 – Data model integration

Main objectives/background:

- The overall objective of CT3 was the integration of observations with models including systematic model calibration.
- Specific goals were (i) to establish model systems for projections towards climate stabilization and global synthesis by *calibrating ocean carbon models* and *Earth system models of intermediate complexity* with respect to observations, (ii) to quantify the magnitude and distribution of carbon sources and sinks in the ocean in the *past* (over the industrial period and the recent past) and *present* by *data-model integration*, and (iii) to determine specific governing carbon system parameters, inventories, and fluxes relevant *for improved quantification of the ocean carbon cycle under ongoing and future climate change* and as input for studies on the impact of large scale *ocean acidification*.

Scientific highlights:

- CT3 was very successful as evidenced by 40 publications published in, in press in, or submitted to peer-reviewed journals. CT3 members provided a synthesis of CMIP5 model results concerning ocean acidification and deoxygenation published in the Working Group I Summary for Policy Maker and in the Synthesis Report of the 5th IPCC Assessment. The theme contributed results to the international RECCAP effort.
- Five state-of-the art data assimilation schemes are operational in CT3 and were successfully applied in a range of applications, including optimal parameter estimation for a 3-d dynamic ocean model and for an ecosystem model, the quantification of parameter sensitivities against a whole range of in-situ ocean data over millennial time scales and for a range of biogeochemical models, the determination of export and water column dissolution of calcium carbonate, the assimilation of surface ocean pCO_2 data from the SOCAT database, and atmospheric CO_2 data to estimate air-sea carbon fluxes.
- Thanks to Core Theme 3, it has now become a standard to analyze multi-model results in ocean carbon cycle work. Highlights are (i) the multi-model, model-data, and model-model intercomparison studies and model evaluation for a very broad set of variables (pCO_2, DIC, TA, oxygen, nutrients, and anthropogenic CO_2, and pH), (ii) the quantification of preindustrial air-sea carbon fluxes using inverse and forward methods, (iii) the application of radiocarbon data to assess deep ocean model performance and a study that demonstrates how the distribution of ocean interior radiocarbon starts to mimic those of anthropogenic CO_2, (iv) the application of detection-attribution methodology to changes in dissolved oxygen and carbon, (v) a multi-model analysis that quantifies the link between NAO and the carbon cycle in the North Atlantic, (vi) a weighted mean "best" assessment of projected 21st century changes in the fugacity of O_2, CO_2, pH and $CaCO_3$ saturation, and (vii) the determination of regional trends in surface ocean pCO_2, on variability of the marine biogeochemical system and feedbacks. CT3 scientists developed the standard software package to compute inorganic carbon chemistry. CT3 scientists demonstrated that the anthropogenic influence on marine carbon trends is detectable using formal, state-of-the-art, statistical methods. CT3 scientist demonstrated that changes in the marine system are earlier detectable in biogeochemical than physical variables, calling for a continued and long-term effort to monitor biogeochemical variables.
- We expect a long-lasting legacy of CARBOCHANGE CT3 work with benefits for the scientific community and, by providing policy-relevant information on ocean carbon, for decision makers and the public. Notably, the model archives and protocols further developed in CARBOCHANGE lay the ground for the planned Coupled Model Intercomparison, Phase 6 (CMIP6) towards the IPCC Assessment Report 6, with strong involvement of CT3 scientists in CMIP6. The work performed on data assimilation is expected to be integrated into complex seasonal-to-decadal climate prediction systems. CT3 scientist are leading a special issue on data assimilation across different EGU Copernicus journals permitting to convey CT3 advances to the wider community.

Further reading (selection):

- See http://carbochange.b.uib.no/data/publications/ for CARBOCHANGE publications.
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Contact information:

- Fortunat Joos, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland; email: joos@climate.unibe.ch
- Nicolas Metzl, Institut Pierre Simon Laplace, Universite P. et M. Curie, Paris, France; email: Nicolas.Metzl@locean-ipsl.upmc.fr

WP1 – Biochemical processes and feedbacks

Main objectives:

- To quantitatively assess the magnitude of biological feedbacks on the ocean uptake of CO_2 by changes in vertical fluxes of organic carbon, testing as well as validating new model parameterizations, and producing model output that will be used in model-model intercomparison.
- To assess the role of lateral fluxes of carbon into the open ocean for variations in air-sea carbon fluxes, integrating models and observations. By doing so, WP1 (as part of CT1) contributes to the identification of physical and biological as well as biogeochemical processes which govern the oceanic carbon source/sink and to the improvement of the capability of large scale ocean C cycle models to reproduce observed variability of the ocean C cycle and forecast its future evolution.

Scientific highlights:

- A number of possible biological feedbacks on the carbon cycle have been studied within WP1, of which only a few examples are listed here. These studies have enabled comprehensive multi-model studies on the future role of the biological pump, e.g. Hauck et al. (2015). One important highlight is a study on the sensitivity of modeled carbon fluxes to the description of sinking rates and remineralization processes in models (Kriest and Oschlies, 2013), which shows that model configurations with benthic burial simulate global oxygen well over a wide range of possible sinking flux parameterizations, making the model more robust with regard to uncertainties about the remineralization length scale. Based on a combined metric of dissolved tracers and biogeochemical fluxes, two model descriptions of burial have been identified as suitable candidates for further experiments and eventual model refinements.

- The role of the offshore transport of organic carbon and nutrients on the carbon cycle in the Canary and Californian upwellling was studied in a series of papers (e.g. Lachkar and Gruber, 2013). These show amongst other results that distribution and transport of the inorganic carbon (i.e., DIC) in the Canary CS is to the largest extent dominated by the local physical circulation, i.e., the coastal upwelling and subsequent offshore transport: in the nearshore domain, almost all of the upwelled and laterally advected DIC is transported offshore of 100 km, while only about 2% is removed either via air-sea gas exchange of CO_2 or via biological production. Similarly, in the offshore domain, roughly 80% of laterally advected DIC is transported to the open ocean further offshore of 800 km, while about half of the remaining 20% of DIC sinks through the euphotic zone and half is removed biologically, through air-sea gas exchange or transported to the north. A study on the exchange of nutrients and (anthropogenic) carbon between the Mediterranean and the Atlantic (e.g. Flecha et al., 2012) has further given insight into the role of marginal seas and coastal regions for the carbon balance in the Atlantic.

Further reading:

- Flecha S, Pérez FF, Navarro G, Ruiz J, Olivé I, Rodríguez-Gálvez S, Costas E, Huertas IE (2012): Anthropogenic carbon inventory in the Gulf of Cádiz. Journal of Marine Systems 92, 67-75. doi: 10.1016/j.jmarsys.2011.10.010.
- Hauck et al. (2015): A multi-model study on Southern Ocean CO_2 uptake and the role of the biological carbon pump in the 21st century. Global Biogeochemical Cycles, submitted.
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Contact information:.

- Melchor González Dávila, Universidad Libre de Gran Canarias; melchor.gonzales@ulpgc.es
- Christoph Völker, Alfred Wegener Institut Helmholz-Zentrum für Polar- und Meeresforschung; christoph.voelker@awi.de

WP2 – Physical processes and feedbacks

Main objectives:

- A comprehensive understanding of physical processes and feedbacks is mandatory for the projection of carbon fluxes in the earth system in a warming world. To this end, this WP assessed quantitatively (i) the feedback of climate change on the oceanic uptake of CO_2 by changes in physical processes in the North Atlantic Ocean, including the Arctic Ocean and Nordic Seas, and the Southern Ocean, and (ii) the role of small-scale processes involved in the feedbacks (e.g. eddies) and their representation in carbon-climate models, and guided the development of improved subgrid-scale parameterisations.

Scientific highlights:

- The application of novel techniques based on an analysis of observations with neural networks by Landschützer et al. (2013, 2014) yielded a quantitative estimate of carbon uptake in the Atlantic and globally. Complementary global modeling work by Resplandy et al. (2013) with a suite of CMIP5 configurations (which among other differences featured differing representations of small-scale processes) showcased the importance of mode and intermediate waters as destinations of anthropogenic carbon. This importance was traced back to (i) the large outcrop area-to-volume ratio of mode (and intermediate) waters and (ii) to the declining contribution of higher latitude oceanic carbon uptake sites in a warming world with reduced meridional overturning (Pérez et al., 2013). However, not all results obtained were stringently consistent. For example, Zunino et al. (2013) report that, based on extensive analysis of oceanic carbon transports, the subpolar North Atlantic may well be a site of increased (and not decreased) carbon uptake. We speculate that the remaining inconsistencies are associated to the high spatial and temporal variability of local processes driving air-sea carbon exchange such as e.g. shown by Wåhlström et al. (2012).

Further reading:

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Contact information:

- Andreas Oschlies, GEOMAR, Germany: email: aoschlies@geomar.de
- Leif Anderson, University of Gothenburg, Sweden; email: leifand@chem.gu.se

WP3 – Future scenarios under different emission curves and vulnerability analysis

Main objectives:

- To assess the vulnerability of oceanic carbon sources or sinks with respect to future emission scenarios and associated climate change projections, on different time-scales (from multi-decadal to multi-centennial) through the use of Earth system models of variable complexity (ESMs and EMICs).
- To identify the processes responsible for the simulated future changes in carbon sources and sinks and develop methods to determine the probability density distributions of their future evolution.

Scientific highlights:

- A multi-model study of the vulnerability of ocean sources and sinks showed that the 5 models considered agreed well, globally, on the ocean CO_2 uptake and on the sensitivity of uptake to atmospheric carbon and to climate, but showed significant differences regionally. Even under the heavy-mitigation RCP2.6 scenario the ocean continued globally to be a sink for anthropogenic CO_2 until 2100, though in the last two decades some regions were sources. The last IPCC report relies on these simulations (5 CARBOCHANGE models out of ~10 world-wide) for assessing the future evolution of the ocean carbon sink.
- It has been shown that changes in the Southern Ocean water mass distribution and properties affect the future effect of climate change on air-sea CO_2 fluxes (Séférian et al., 2012). A simple box model was used to emulate an Earth System Perturbed Parameter Ensemble to show that the main cause of the “peak and decline” of ocean CO_2 uptake in the North Atlantic seen by models during the 21st century is the increasing atmospheric pCO_2 interacting with the background chemical gradient and the northwards transport of carbon.

- Bopp et al. (2013) studied the evolution of the carbon-related ecosystem stressors pH and net primary production (NPP).
- Segschneider and Bendtsen (2013) examined the effect of temperature-dependent remineralisation of organic material on ocean pCO_2.
- The Bern3D-LPJ model ran a suite of 5000 model simulations (spin-up and historical) and a 1000-member subset to run 22 scenarios to year 2300. Results inferred allowable carbon emissions under multiple climate targets (Steinacher et al., 2013), which were lower than under any single target.
- For the first time, detection and attribution methods were applied to air-sea carbon fluxes to detect if an anthropogenic climate signal is detectable on the evolution of the ocean carbon sink (Séférian et al., 2014). It was shown that the evolution of the global sink over the last decades can be understood without invoking climate change, rising atmospheric CO_2 being the prominent driver, but regionally climate change's influence on air-sea fluxes can be detected in the low-latitude ocean.

Further reading:

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Contact information:

- Ian Totterdell, Met Office, U.K.; email: ian.totterdell@metoffice.gov.uk
- Laurent Bopp, CEA/LSCE; email: laurent.bopp@lsce.ipsl.fr

WP4 – Surface observing system

Main objectives:

- To establish a network of observations to track trends in atmosphere-ocean carbon fluxes in critical regions: (i) set up and evaluate a network of observations to track trends in ocean-atmosphere carbon fluxes, (ii) support and improve the observing network of Voluntary Observing Ships (VOS) and moorings in the North and Tropical Atlantic, (iii) use research vessel transects and drifter studies to build up a decadal picture of the Atlantic and Indian sections of the Southern Ocean, and (iv) undertake high-precision atmospheric measurements of CO_2, O_2, and N_2.

Scientific highlights:

- The coordination of 9 VOS observing ship lines, one marine and two atmospheric stations in the Atlantic and Southern Ocean observational network, were successfully maintained; high quality measurements of sea surface CO_2 and related parameters, as well as atmospheric CO_2, O_2, CH_4, and N_2 were submitted.
- WP4 had been involved in the creation of the Surface Ocean CO_2 Atlas (SOCAT), and its two releases to date (Bakker et al., 2014), providing a publically available, global, quality controlled dataset of sea surface pCO_2.

- WP4 collaborated in the production of the Global Carbon Budget 2014, estimating the global ocean sink to be 2.6 ± 0.5 GtC yr^{-1} for 2004 to 2013 (Le Quéré et al., 2014), with the interannual variability being estimated to be about 0.31 PgC yr^{-1} (Rödenbeck et al., 2014); data were submitted to the UN Climate Summit meeting in 2014.
- The air-sea flux variability in the Atlantic and Arctic was studied (Schuster et al., 2013) as part of the Regional Carbon Cycle Assessment Programme (RECCAP). Results indicate a combined sea–air flux of −0.61 ± 0.06 Pg C yr^{-1} over two decades.
- In the Southern Ocean, the high frequency of CARIOCA measurements has allowed us to estimate the net community production in several places in the Kerguelen plume. Results support the hypothesis of a strong control of the Net Community Productivity (NCP) and pCO_2 variability by the availability of iron (Lo Monaco et al., 2014).
- A global study of long-term pH trends have been estimated using SOCAT v2 (Lauvset et al., 2015). In the western North Atlantic subpolar gyre, decadal pH trends were around - 0.03/decade (1993 to 2014) and - 0.04/decade (2001 to 2014).

Further reading:

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Contact information:

- Dr. Ute Schuster, University of Exeter, UK; email: U.Schuster@exeter.ac.uk
- Dr. Jacqueline Boutin, Université Pierre et Marie Curie, France; email: jb@locean-ipsl.upmc.fr

WP5 – Deep ocean, time series, choke points

Main objectives:

- Coordinate and conduct time-series and deep-section measurements of ocean carbon and ancillary variables. New and existing measurements are used to estimate the variability of natural and anthropogenic CO_2.
- Evaluate the carbon storage and its vulnerability in the interior ocean with respect to anthropogenic changes, oceanic circulation and biogeochemical processes, linked to model outputs and skills.

Scientific highlights:

- A new carbon budget for the Nordic Seas; little air-sea exchange of anthropogenic CO_2 (C_{ant}) within the Nordic Seas; all C_{ant} there is due to the Atlantic inflow.
- CO_2 uptake by the Atlantic Ocean has decreased by weakening of meridional overturning circulation.
- During the past two decades, the uptake of CO_2 is predominantly anthropogenic in the subtropical gyre of the North Atlantic, while the subpolar gyre accounts almost exclusively for natural-CO_2 uptake.

- The C_{ant} changes in the Irminger Sea highlight a strong relationship between anthropogenic carbon and the ^{13}C Suess effect in all water masses.
- High C_{ant} storage rate in the western South Atlantic is caused by low but significant C_{ant} concentrations combined with the large volume of Antarctic Bottom Water.
- Large accumulation of C_{ant} in the western basin of the North Atlantic is due to the conveyer role of the Deep Western Boundary Current.
- At the Prime Meridian in the Weddell Gyre, CO_2 increased in bottom water with +0.12±0.05 μmol kg^{-1} yr^{-1}. Near the Antarctic Peninsula, full equilibration occurs with atmospheric C_{ant}: Ice cover is not a major impediment for uptake of C_{ant} in this ice-covered area.
- Direct pH observations in the North Atlantic over the period 1981-2008 highlights that the Subarctic Intermediate Water has the fastest ocean acidification rate (-0.0019 ± 0.0002 yr^{-1}) and that 75% of this pH decrease is of anthropogenic origin.
- In the subtropical North Atlantic, natural variability, mostly due to a decrease in oxygen levels, explains the vertical distribution of the larger pH decreases (up to -0.05 pH units), which are found within the permanent thermocline.
- Observations and model results confirm that pH changes in the Atlantic Ocean are dominated by the anthropogenic component (rates of -0.0015 to -0.0020 yr^{-1} in surface waters). In contrast, in mode and intermediate waters, anthropogenic and natural components are similar.
- In the Weddell Sea, significant trends of increasing nutrients in the surface layer were found, caused by increasing rate of upwelling of subsurface water in the last 20 years.
- All deep water masses in the Weddell Sea are getting older and less ventilated on a decadal time scale. This is caused by the mixing component of deep and abyssal waters: the Warm Deep Water.
- The compilation of various data- and model-derived estimates gives a “best estimate” of the inventory of anthropogenic CO_2 in the ocean in 2010 of 155 PgC with an uncertainty of ±20%, in collaboration with WP8.
- No clear trend can be detected from the CO_2 data collected at the PIRATA time series at 6ºS 10ºW over the period 2006-2013.
- At CVOO station, mesoscale eddies were observed which carried near-surface suboxic/high CO_2 from the Mauritanian upwelling area into the open ocean. Respiration rates in eddies are 3-5 times higher than elsewhere in the open Atlantic Ocean.
- Significant decreasing annual trend of -0.0056±0.00008 in the Mediterranean pH was accompanied by a rise of pCO_2 of 5.8 µatm from 2012 to 2014.
- Knowledge about the storage and variability of carbon in the Atlantic Ocean and its adjacent regions has been advanced through multiple publications in the peer-reviewed literature.
- Carbon and ancillary data collected at cruises in the Atlantic Ocean and its adjacent regions were included in the data product GLODAPv2 which can be freely exploited by the scientific community.

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Contact information:

- Aida F. Ríos, CSIC, Instituto de Investigaciones Marinas. c/Eduardo Cabello, 6, 36208 Vigo, Spain; email: aida@iim.csic.es
- Mario Hoppema, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany; email: Mario.Hoppema@awi.de

WP6 – Systematic model calibration using observational data

Main objectives:

- Design and development of mathematical robust calibration (data assimilation) systems for ocean carbon cycle, coupled ocean-terrestrial carbon cycle and intermediate complexity models of the Earth system (EMICS).
- Calibration of the different models and parameters for data constrained reconstruction of carbon and related tracers on different time scales by the developed data assimilation systems.

Scientific highlights:

- Encouraging proof-of-concept results with state-of-the-art optimisation techniques on various time scales have been obtained:
  1. Results from the MICOM-HAMMOCC data assimilation run using SOCAT data show that posterior uncertainties in the estimated net ocean surface fluxes are reduced at measurement locations but remain high elsewhere.
  2. Assimilation of one year of atmospheric CO_2 observations by a 4D-Var system around the coupled MITgcm-DIC / BETHY ocean-terrestrial carbon cycle model has shown to substantially improve the posterior seasonal cycle of atmospheric CO_2 as well as the monthly net surface exchange CO_2 fluxes.
  3. A 1-D version of PISCES has been calibrated against Chlorophyll data (in-situ and remotely sensed) at two stations over one year.
  4. The parameterisation of the $CaCO_3$ dissolution within a water column has been calibrated within the UBERN EMIC by a Monte Carlo type approach. This has led to a significantly improved representation of alkalinity in the ocean and revealed a shortcoming in the TA*-CFC age method.
  5. The Transport Matrix Method was successfully applied together with a range of ocean biogeochemical models with varying complexity to quantify parameter sensitivities against a whole range of in-situ ocean data over millennial time scales.
- As the computing power is increasingly available, the findings obtained in EMICs will have a chance to be integrated into ESMs of higher complexity and higher spatial-temporal resolution.
- The work performed in WP6 also has good perspectives of integration into complex seasonal-to-decadal climate prediction systems (for example the NorCPM). They will then have the opportunity to be included in CMIP6 scenarios and, thus, have large societal impacts.

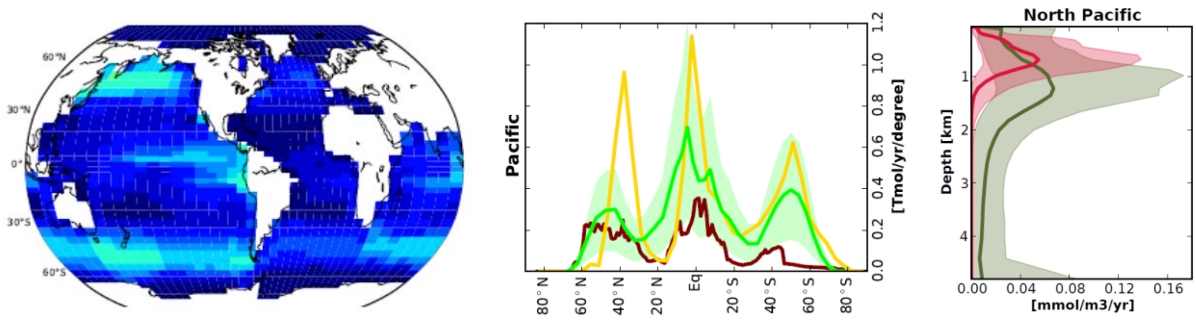

Figure WP6.1: The cycling of calcium carbonate ($CaCO_3$) in the ocean as constrained by assimilating alkalinity data in the Bern3D Monte Carlo framework. (Right) Map of export production of $CaCO_3$ and (middle) zonally integrated export for the Pacific (green) as compared to estimates by other studies, and (left) dissolution of $CaCO_3$ within the water column for the North Pacific and for the mineral form of calcite (green) and aragonite (red) (Battaglia et al., in preparation).

Further reading:

- Battaglia G, Roth R, Steinacher M, Joos F (2015): A Monte-Carlo type assimilation of alkalinity data to constrain modern ocean $CaCO_3$ export and dissolution, in preparation
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Contact information:

- Laurent Bertino, Mohn-Sverdrup Center / NERSC, Thormøhlensgate 47, N-5006 Bergen, Norway; email: laurent.bertino@nersc.no

WP7 – Data-model and model-model comparison

Main objectives:

- WP7 aimed to compare simulated and data-based estimates of ocean carbon and related biogeochemical tracers. Comparison included ocean carbon cycle models, both when coupled within Earth system models (CMIP5) and when forced by atmospheric data (reanalyses).

- WP7 scientists used multiple models along with data to (i) quantify the changing ocean carbon sink, (ii) assess carbon-climate feedbacks, and (iii) detect and attribute effects from climate change.

Scientific highlights:

- During this project, there were many contributions to WP7 from numerous partners. Here, we highlight only a few aspects of WP7; a synthesis of the full list of WP7 studies is given in the 3 periodic reports.
- Model simulations were made by multiple groups and output submitted to a common model archive (WP9). That was heavily exploited to compare and evaluate models. This joint effort allowed comparison and evaluation of multiple ocean carbon cycle models to become commonplace, with WP7 scientists leading virtually all efforts (OCMIP5). During CARBOCHANGE, WP7 produced >30 publications for peer-reviewed journals.
- Much of WP7's focus was on global comparison and evaluation of Earth system models. For instance, WP7 directly contributed to the IPCC AR5 report comparing changes in ocean pH under different emission scenarios calculated as multi-model means. WP7 scientists acted as authors of the same report. WP7 also showed that anthropogenic trends in some biogeochemical variables emerge sooner than for physical variables.
- Data-model comparison in WP7 revealed the marked benefit of installing a denser regional observational network of surface-ocean pCO_2 to evaluate the climate-carbon feedback in lower latitudes, where there is a strong signal-to-noise ratio. Other WP7 studies used multi-tracer observations of physical and biogeochemical variables to detect changes in the marine system linked to ENSO variability. Multiple Earth system models were used to attribute observed changes in ocean oxygen to external forcing rather than to internal ocean variability. Potential systematic biases in ocean radiocarbon simulations were evaluated to better assess if modelled deep-water ages and ventilation are realistic.

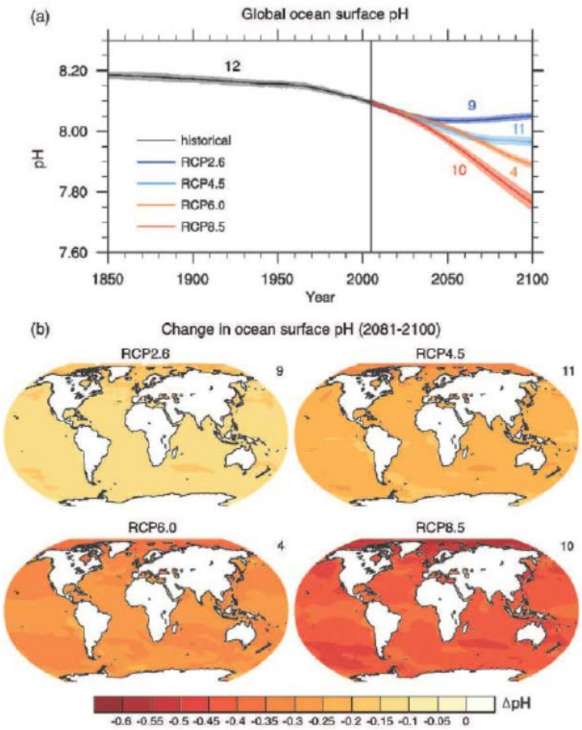

Figure WP7.1: The WP7 synthesis for the IPCC AR5 WG1 Technical Summary (Figure TS.20) with projections of surface-ocean pH from the CMIP5 Earth system models: (a) mean and range for the time series (1850-2100) under 4 scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5, and (b) maps of the mean model result averaged over 2081-2100 relative to the 1986-2005 average for each scenario. Numbers (top right of each map) indicate the number of models used to calculate multi-model means.

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Contact information:

- Toste Tanhua, GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany; email: ttanhua@geomar.de
- James C. Orr, LSCE/IPSL, Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, Paris, France ; email: James.Orr@lsce.ipsl.fr

WP8 – Global synthesis and outreach to policy makers

Main objectives:

- Prepare annual releases of air-sea CO_2 fluxes for the global ocean and by basin.
- Release of the Surface Ocean CO_2 Atlas.
- Merge the GLODAPv1 and CARINA datasets into a unified, consistent dataset.
- Report on vulnerability of the oceanic CO_2 sink.

Scientific highlights:

- The 2011 to 2014 Global Carbon Budgets have provided annual estimates for 2010 to 2013 of ocean carbon sink and an estimate of trends in the sink from 1959 to 2013 based on up to seven ocean biogeochemistry models combined with observations.
- The annual Global Carbon Budgets are publicized widely, well beyond the science community.
- Versions 1 and 2 of the Surface Ocean CO_2 Atlas (SOCAT) were made public in 2011 and 2013 (www.socat.info). Version 2 brings together 10.1 million quality-controlled, surface ocean fCO_2 (fugacity of CO_2) values from 1968 to 2011 for the global oceans and coastal seas. Version 3, with more data than version 2, will be released in 2015. Automated data upload will increase the frequency of future SOCAT releases.
- Scientific applications of SOCAT include: 1) quantification of the ocean carbon sink and 2) ocean acidification and their temporal and spatial variation, 3) validation of ocean carbon models and coupled climate carbon models, and 4) provision of constraints for atmospheric inverse models used for estimating the land carbon sink.
- The 2013 and 2014 Global Carbon Budgets use

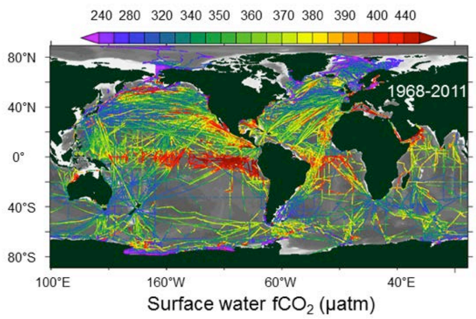

Figure WP8.1: Observations in the Surface Ocean CO_2 Atlas version 2 (from Bakker et al., 2014).

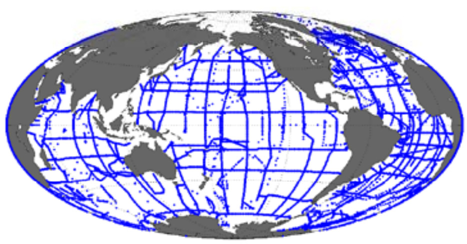

Figure WP8.2: Data distribution in GLODAPv2.

SOCAT-based methods for an assessment of the variability in the ocean carbon sink and to provide confidence on the model results.

- A recent, independent, initiative, the Surface Ocean pCO_2 Mapping Intercomparison (SOCOM) evaluates 14 data-based surface ocean CO_2 gridded products, nine of them using SOCAT.
- SOCAT is cited in at least 73 peer-reviewed, scientific publications, 4 high-impact reports, 5 book chapters and 1 PhD thesis.
- The pre-release version of the Global Ocean Data Analysis Project version 2 (GLODAPv2.beta) contains data from 775 surveys from 1972 to 2013, including the data from CARINA and GLODAPv1. The final version will be published by June 2015.
- A global atlas of ocean carbonate variables was prepared using GLODAPv2.beta.
- Coupled climate carbon simulations from 1850 to 2100 for a range of concentration pathways, along with other Coupled Model Intercomparison Project 5 (CMIP5) simulations, have been exploited to derive: (1) the vulnerability of regional anthropogenic carbon sinks to future climate change, and (2) the vulnerability of marine ecosystems to future climate change through changes in carbon-related marine ecosystems stressors.
- The scientific, open-access journal Earth System Science Data is developing a new type of paper series, called 'living data', in response to the Global Carbon Budget and SOCAT efforts.
- The SOCAT and GLODAPv2 synthesis products represent a (live) milestone in coordinating international researchers, for the delivery of publicly accessible and uniformly quality-controlled datasets, for marine carbon and ocean acidification research and for informing (inter-)national government policy and climate negotiations. Given the importance of such products for science and policy, it is essential that the high-quality collection, documenting and archiving of marine carbon measurements and synthesis activities, such as SOCAT and GLODAPv2, continue.
- An outreach leaflet on the ocean carbon sink in the Global Carbon Budget has been published. (http://carbochange.b.uib.no/files/2015/02/2015_GCP_SOCAT-_CarboChange_leaflet.pdf)
- Results from CARBOCHANGE ocean models where used in the 5th Assessment of the Intergovernmental Panel on Climate Change (IPCC), namely in Chapter 6 Figure 6.14, and in the calculations presented in Table 6.1 and 6.4.

Further reading:

- Bakker DCE et al. (2014): An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). Earth System Science Data 6, 69-90. doi:10.5194/essd-6-69-2014.
- Bopp L et al. (2013): Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models Biogeosciences 10, 6225–6245. doi:10.5194/bg-10-6225-2013.
- Heinze C et al. (2014): The ocean carbon sink – impacts, vulnerabilities and challenges. Earth System Dynamics Discussions 5, 1607-1672. doi:10.5194/esdd-5-1607-2014.
- Landschützer P et al. (2014): Recent variability of the global ocean carbon sink. Global Biogeochemical Cycles 28, 1-23. doi:10.1002/2014GB004853.
- Lauvset SK et al. (2015): Trends and drivers in global surface ocean pH over the past 3 decades, Biogeosciences 12, 1285-1298. doi:10.5194/bg-12-1285-2015.
- Le Quéré C et al. (2013): The global carbon budget 1959–2011, Earth System Science Data 5, 165-185. doi:10.5194/essd-5-165-2013.
- Le Quéré C et al. (2014): Global Carbon Budget 2013. Earth System Science Data 6, 235-263. doi:10.5194/essd-6-235-2014.
- Le Quéré C et al. (2014b): Global carbon budget 2014. Earth System Science Data Discussions 7, 521–610. doi:10.5194/essdd-7-521-2014.
- Moriarty R et al. (2015): Global Carbon Budget: Ocean carbon sink. Outreach leaflet by the Global Carbon Project, the Surface Ocean CO_2 Atlas and CARBOCHANGE. 6 pp.
- Pfeil B et al. (2013): A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). Earth System Science Data 5, 125-143. doi:10.5194/essd-5-125-2013.
- Resplandy L et al. (2013): Role of mode and intermediate waters in future ocean acidification: analysis of CMIP5 models. Geophysical Research Letters 40, 3091-3095. doi:10.1002/grl.50414.
- Rödenbeck C et al. (2014): Interannual sea-air CO_2 flux variability from an observation-driven ocean mixed-layer scheme. Biogeosciences 11, 4599-4613. doi:10.5194/bg-11-4599-2014
- Sabine CL et al. (2013): Surface Ocean CO_2 Atlas (SOCAT) gridded data products. Earth System Science Data 5, 145-153. doi:10.5194/essd-5-145-2013.
- Séférian R et al. (2014): Detecting the anthropogenic influences on recent changes in ocean carbon uptake. Geophysical Research Letters 41, 1-10. doi: 10.1002/2014GL061223.
- Sitch S et al. (2015): Recent trends and drivers of regional sources and sinks of carbon dioxide. Biogeosciences 12, 653-679, doi:10.5194/bg-12-653-2015.
- Tjiputra JF et al. (2014): Long-term surface pCO_2 trends from observations and models. Tellus B 66, 23083, doi:10.3402/tellusb.v66.23083.
- Wanninkhof R et al. (2013): Global ocean carbon uptake: Magnitude, variability and trends, Biogeosciences 10, 1983–2000. doi:10.5194/bg-10-1983-2013.

Contact information:

- Corinne Le Quéré, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK; c.lequere@uea.ac.uk
- Are Olsen, Uni Research and Geophysical Institute, University of Bergen, Norway; are.olsen@gfi.uib.no
- Dorothee Bakker, Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK; d.bakker@uea.ac.uk

WP9 – Data and information management

Main objectives:

- Providing continuous data management for observational and model output data.
- Yearly updates for the SOCAT (Surface Ocean CO_2 Atlas) input database.

Scientific highlights:

- Data from more than 400 surveys carried out onboard research vessels and voluntary observing ships was archived at different World Data Centers (PANGAEA and CDIAC).
- Public release of SOCAT and lead on the first SOCAT paper.
- The data management office assembled, archived, and published SOCAT data files for version 1 and 2 (more than 4400 data files).
- SOCAT Version 3 has been assembled and will be released in 2015.
- Contribution to the data package GLODAP Version 2.
- International advise on data management for various initiatives: UNESCO/SCOR's International Ocean Coordination Project (IOCCP), Global Ocean Acidification Observing Network (GOA-ON).
- Data contribution to the Global Carbon Project for the Global Carbon Budget 2014.

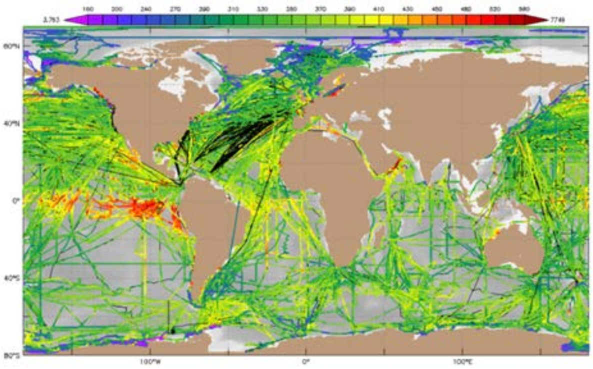

Figure WP9.1: Overview of the distribution of the expected data for SOCAT V3.

Further reading:

- Bakker DCE et al. (2014): An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). Earth System Science Data 6, 69-90. doi:10.5194/essd-6-69-2014.
- Le Quéré C et al. (2014): Global carbon budget 2014. Earth System Science Data Discussions 7, 521–610. doi:10.5194/essdd-7-521-2014.
- Pfeil B et al. (2013): A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). Earth System Science Data 5, 125-143. doi:10.5194/essd-5-125-2013.
- Sabine CL et al. (2013): Surface Ocean CO_2 Atlas (SOCAT) gridded data products. Earth System Science Data 5, 145-153. doi:10.5194/essd-5-145-2013.

Contact information:

- Benjamin Pfeil, University of Bergen, Geophysical Institute / Bjerknes Centre for Climate Research, Allégaten 70, N-5007 Bergen, Norway; email: benjamin.pfeil@uib.no

WP10 – Management of the project

Main objectives:

- management of communication and collaboration with and between partners
- review and assessment of scientific results with regard to assuring high-quality-research, consistency with the defined project tasks and monitoring schedules
- outreach to policy makers and the general public
- reporting to the European Commission
- financial administration with regard to allocation of funds between beneficiaries and project activities

Management highlights:

- Management tasks were carried out successfully during the course of the project.
- The project has fully achieved its major objectives.
- Outreach highlights within WP10 include the following:
    1. Organization of a panel debate at the International Carbon Dioxide Conference, Beijing, China, 6 June 2013: 'Shaping tomorrow's carbon cycle research'
    2. Organization of a science-policy event at the final CARBOCHANGE project meeting, Bergen, Norway, 20 January 2015: '10 years of ocean carbon and climate research in Bergen'
    3. Compilation of an EU-brochure: 'EU-funded research on the Carbon Cycle'
    4. Publication of 2 outreach/review papers
    5. Preparation of other outreach material (flyers, posters, website) and (co-)organization of annual project meetings

Further reading:

- www.carbochange.eu
- http://carbochange.b.uib.no/media-centre/project-information-material/
- Heinze C (2014): The role of the ocean carbon cycle in climate change. European Review 22, 97-105. doi: 10.1017/S1062798713000665.
- Heinze C, Meyer S, Goris N, Anderson L, Steinfeldt R, Chang N, Le Quéré C, Bakker DCE (2014): The ocean carbon sink - impacts, vulnerabilities, and challenges. Earth System Dynamics Discussions 5, 1607-1672. doi: 10.5194/esdd-5-1607-2014.

Contact information:

- Christoph Heinze, Geophysical Institute / University of Bergen and Bjerknes Centre for Climate Research / Uni Research Climate, Bergen, Norway; email: christoph.heinze@uib.no
- Stefanie Meyer, Geophysical Institute / University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway; email: stefanie.meyer@uib.no
- Friederike Urbassek Hoffmann, Geophysical Institute / University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway; email: friederike.hoffmann@uib.no
- Hege Dysvik Høiland, University of Bergen, Bergen, Norway; email: hege.hoiland@uib.no

Potential impact, exploitation of results, and main dissemination activities

Final results: Key results of the CARBOCHANGE project are optimal process descriptions and realistic error margins for future ocean carbon uptake quantifications with models making simultaneous use of the available observational evidence. Observations: We have now an unprecedentedly comprehensive ocean carbon data set available, especially for the North Atlantic, for the Southern Ocean as well as for the Mediterranean outflow region. This fully quality checked data set will elucidate the extent and duration of regional carbon sink variations in the context of evolving climate change and will be of extreme usefulness for further generations as a benchmark for following the progressing ocean carbon sink. The systematic combination of complex physical-biogeochemical models with observations provides three key results: (a) We now know in a more objective way, how good our predictive models can reproduce observations and where specific model strengths/weaknesses can be identified in the context of many different models. Here, we can mention persisting deficiencies, particularly in the simulation of vertical water movements and related biogeochemical fluxes. (b) Nevertheless, we have made comprehensive progress in producing improved objectively and dynamically interpolated fields of the observations, in particular for the surface ocean. (c) We included improved process descriptions in models and tested methods to calibrate free parameters in these process descriptions through systematic combination with field observations. CARBOCHANGE has provided key contributions to annual updates of the global carbon budgets through specifically delivering ocean carbon and air-sea CO_2 flux estimates. Through establishing the relevant procedures for such updates, a further detailing of global carbon long-term monitoring and predicting system has been facilitated. Further, we now know with more confidence than 4 years ago how unsteady the ocean carbon sink for human-produced CO_2 really is and what changes we may expect for given emission scenarios in the future when anthropogenic climate change will have progressed in a more pronounced way. Finally, we have established the role of ocean carbon uptake in the context of other stressors of ocean ecosystems.

Potential impacts and use of the results (including socio-economic impact and the wider societal implications of the project): CARBOCHANGE results are, among other target groups, especially important for the interdisciplinary climate change research community, for the global change impact community (researchers, public agencies etc.) and for decision makers designing and implementing appropriate climate mitigation as well as adaptation measures. CARBOCHANGE delivered calibrated future evolutions of ocean pH and carbonate saturation as required by the research community on ocean acidification. The synthesis on the time history of atmosphere-ocean carbon fluxes' past, present and future (globally as well as regionally) has fed into the results of transcontinental RECCAP project and other initiatives. Observations and model results will merge into GEOSS/GEO and also GOOS (Global Ocean Observing System) through links with other European and worldwide on-going projects, especially also through the newly established GOOS Biogeochemistry Panel. CARBOCHANGE has contributed to the preparation and establishment of the marine branch of the European Research Infrastructure ICOS, and the CARBOCHANGE legacy in terms of observations, models, and methodology development will continue to be of key use for ICOS. Results of the project have been summarised for policy makers and the interdisciplinary research community as well as the public at large through targeted outreach papers. The new knowledge on the vulnerability of the ocean carbon sink for CO_2 under evolving climate change provides a direct input into designing and enforcing greenhouse gas emission limitations and a respective change in energy production as well as energy use. Within this context, CARBOCHANGE has provided concrete input to emerging new research programmes such as "Horizon 2020" and "Future Earth".

The CARBOCHANGE consortium has been very active in disseminating their scientific results and achievements. At the end of April 2015, 135 peer-reviewed publications acknowledging CARBOCHANGE had been published, thereof ~60% being open access publications. In addition, 3 book chapters, 12 doctoral theses, 10 master theses, and 2 bachelor theses had been achieved in association with the project. Twelve studies are still under discussion in various journals. Beyond that, CARBOCHANGE beneficiaries have registered 643 other dissemination activities (Figure 1). Peer-reviewed publications of CARBOCHANGE have been cited in the 5th IPCC Assessment Report (especially in chapter 6 of the WG1 report). Two chapters of the 2nd edition of the "WOCE book" (Siedler, G., Griffies, S., Gould, J. and Church, J. (Eds.): Ocean Circulation and Climate, 2nd Ed. A 21st century perspective, Elsevier) have been written by CARBOCHANGE authors – these chapters will contribute also to education of new oceanographers over the years to come. CARBOCHANGE has organised a side event at the 9th International Carbon Dioxide Conference (Beijing, June 2013) on future carbon cycle research need with comprehensive participation from the international carbon dioxide community (ocean, land, atmosphere). The accompanying EC-brochure "EU-funded research on the carbon cycle" was compiled by the CARBOCHANGE project office.

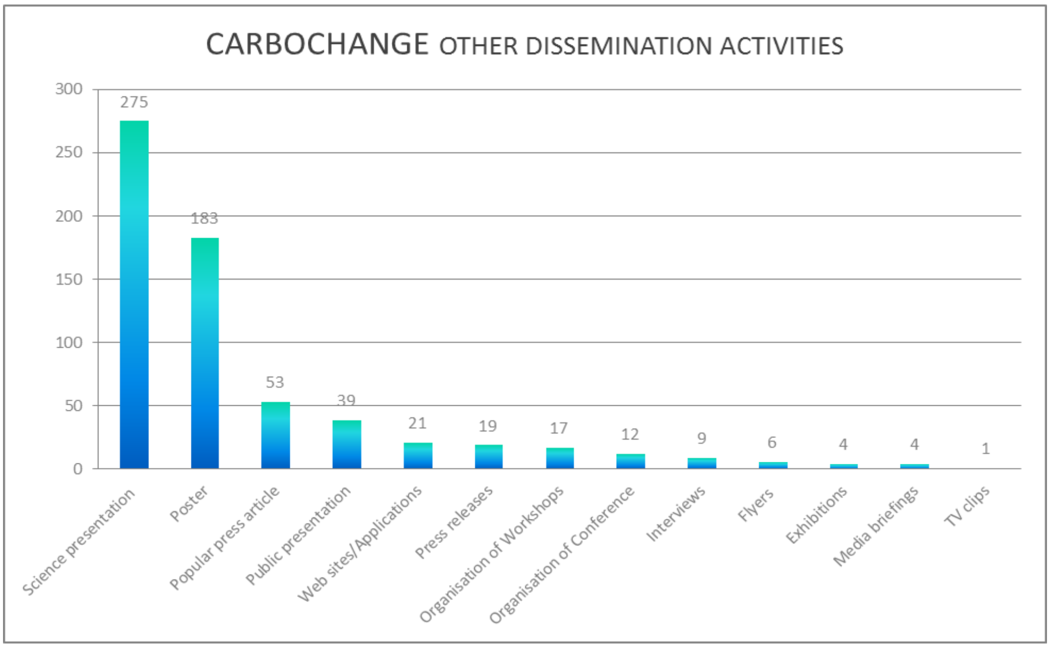

Figure 1: CARBOCHANGE other dissemination activities between 2011 and 2015 (in total: 643). In addition, the project co-funded 135 peer-reviewed publications, 3 book chapters, 12 doctoral theses, 10 master theses, and 2 bachelor theses. Twelve studies are still under discussion in various journals.

CARBOCHANGE dissemination highlights included (i) the contribution of several consortium members to the annual updates of the Global Carbon Budget, (ii) the contribution of several consortium members to the 5th IPCC Assessment Report, (iii) a panel debate at the International Carbon Dioxide Conference on "Shaping tomorrow's carbon cycle research" (Beijing, China, 6 June 2013), (iv) a science-policy event at the final CARBOCHANGE project meeting on "10 years of ocean carbon and climate research in Bergen" (Bergen, Norway, 20 January 2015), (v) two outreach/review publications to policy makers and the wider public (Heinze, 2014, European review, doi: 10.1017/S1062798713000665; Heinze et al., 2014, ESDD, doi: 10.5194/esdd-5-1607-2014), (vi) a combined GCP-SOCAT-CARBOCHANGE leaflet (beneficiary no. 25, UEA, http://carbochange.b.uib.no/files/ 2015/02/2015_GCP_SOCAT-_CarboChange_leaflet.pdf), and (vii) the website (www.carbochange.eu) that also contains a FAQ site with a list of contact researchers sorted according to topic as well as a data portal site.

Address of public project website and relevant contacts

website: www.carbochange.eu (http://carbochange.b.uib.no/)

contact: Prof. Dr. Christoph Heinze, Geophysical Institute / University of Bergen and Bjerknes Centre for Climate Research / Uni Research Climate, Allégaten 70, N-5007 Bergen, Norway, email: christoph.heinze@uib.no, phone: +47 55 58 98 44, fax: +47 55 58 98 83