SUMMARISING REPORT
EU FP6 Integrated Project "CARBOOCEAN" (Marine carbon sources and sinks assessment)

1. Project execution

Main project objectives of CARBOOCEAN

CARBOOCEAN IP (= CarboOcean Integrated Project) aimed at an accurate scientific as-sessment of the marine carbon sources and sinks within space and time. It focused on the Atlantic and Southern Oceans and a time interval of -200 to +200 years from now.
CARBOOCEAN was successful in determining the ocean's quantitative role for uptake of atmospheric carbon dioxide (CO2), the most important manageable driving agent for climate change..
CARBOOCEAN thus created new scientific knowledge as an essential foundation for a quantitative risk/uncertainty judgement on the expected consequences of rising atmospheric CO2 concentra-tions. Based on this judgement, it will be possible to guide the development of appropriate mitigation actions, such as management of CO2 emission reductions within a global context.
CARBOOCEAN combined the key European experts and scientific resources in the field through an integrated research effort. The effort complemented other major research programmes on oceanic, atmospheric, and terrestrial carbon cycling and was linked to these programmes.

The **ultimate goal** of Integrated Project CARBOOCEAN was to reduce the present uncertainties in the quantification of net annual air-sea CO_2 fluxes. Particular emphasis was placed on the Atlantic Ocean and the Southern Ocean as the main deep water production areas, but also the World Ocean as a whole is considered. Target was to reduce the uncertainties by a factor of 2 for the world ocean and by a factor of 4 for the Atlantic Ocean. The IP delivered description, process oriented understanding and prediction of the marine carbon sources and sinks with special emphasis on the Atlantic and Southern Oceans on a time scale –200 to +200 years from now. **Specific objectives** were:

1. Description and quantification of the CO_2 air-sea exchange on a seasonal-to-interannual scale for the Atlantic Ocean and the Southern Ocean

2. Quantification of decadal-to-centennial large-scale Atlantic and Southern Ocean carbon inventory changes

3. Quantification of the carbon sources and sinks at the European regional scale

4. Identification and understanding of biogeochemical feedback mechanisms which control marine carbon uptake and release

5. Integration of carbon observations into an integrated prognostic modelling framework

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Contractors

1	University of Bergen, coordinator	Norway
2	Université Libre de Bruxelles	Belgium
3	Alfred Wegener Institute for Polar and Marine Research	Germany
4	Leibniz-Institut für Meereswissenschaften Kiel	Germany
5	Consejo Superior de Investgaciones Cientificas	Spain
6	Laboratoire des sciences du climat et de l`environnement	France
7	Université Pierre et Marie Curie, Paris	France
8	Netherlands Institute for Sea Research	Netherlands
9	University of East Anglia	United Kingdom
10	Université de Liège	Belgium
11	Universität Bern	Switzerland
12	Max-Planck-Institut	Germany
14	Technical University Hamburg-Harburg	Germany
16	University of Bremen	Germany
45 (17)	National Environmental Research Institute/University of Århus	Denmark
18	University of Las Palmas Gran Canaria	Spain
19	Université de Bretagne Occidentale	France
20	Centre national de la recherche scientifique	France
22	University of Perpignan	France
23	Marine Research Institut	Iceland
24	Institut National de Recherche Halieutique, Casablanca	Morocco
25	Rijksuniversiteit Groningen	Netherlands
26	Netherlands Institute of Ecology	Netherlands
28	Nansen Env. and Remote Sensing Center	Norway
29	Norwegian Institute of Air Research	Norway
31	Institute of Oceanology of the Polish Acedemy of Sciences	Poland
32	University of Gothenburg	Sweden
33	MetO (UK) Hadley Centre for Climate Prediction and Research	United Kingdom
34	Southampton Oceanography Centre	United Kingdom
35	University of Essex	United Kingdom
36	FastOpt	Germany
37	Intergovernmental Oceanographic Commission of UNESCO	France
38	NILU Polska Ltd.	Poland
39	Philippe Saugier ingenieur-conseil	France
44	Trustees of Princeton University	USA

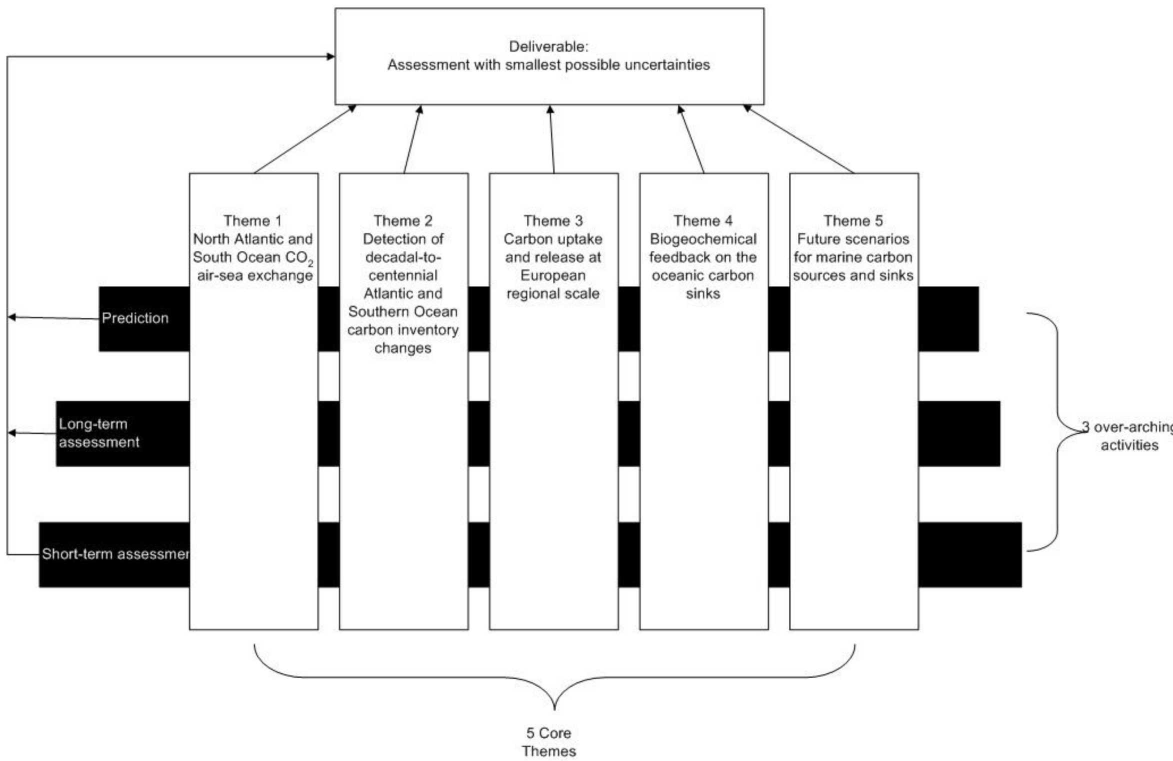
Associate members

41/ 42	GCCA of NOAAA/AOML/PML	USA
43	Pennsylvania State University	USA
45	Scripps Institution of Oceanography	USA
46	Texa A&M Research Foundation	USA
47	University of Delaware	USA
48	Carbon Dioxide Information Analysis Center	USA
49	University of Hawaii at Manoa	USA
50	Dalhousie University	Canada
51	Eidgenoessische Technische Hochschule Zuerich	Switzerland
52	National University of Ireland, Galway	Ireland

Work performed and end results – Introductive overview

Organisation structure: Core themes and work packages

The CARBOOCEAN S&T approach was based on five vertical pillars (5 core themes, CTs) and three horizontally integrating overarching scientific workpackages (WPs):



The 5 core themes which also can considered as interconnected sub-projects and the 23 work packages of CARBOOCEAN and their respective work packages were:

CT1: North Atlantic and Southern Ocean CO_2 air-sea exchange on a seasonal-to-interannual scale
CT2: Detection of decadal-to-centennial Atlantic and Southern Ocean carbon inventory changes
CT3: Carbon uptake and release at European regional scale
CT4: Biogeochemical feedbacks on the oceanic carbon sink
CT5: Future scenarios for marine carbon sources and sinks

WP1: Prediction towards Sustainable Development (overarching WP)
WP2: Annual Assessment (overarching WP)
WP3: Long Term Assessment (overarching WP)
WP4: Atlantic observing system, VOS, time series (CT1)
WP5: Southern Ocean observations and processes (CT1)
WP6: Model-based Flux assessment (CT1)
WP7: Mooring Development (CT1)
WP8: Ocean Interior data collection and documentation (CT2)
WP9: C_{ant} quantification and decadal changes in carbon inventory (CT2)
WP10: Oxygen and carbon profiling floats (CT2)
WP11: Model performance assessment and initial fields for (CT2 and CT5)
WP12: Regional assessment for the North Sea (CT3)
WP13: Regional assessment for the West-Mediterranean (CT3)
WP14: European Integration (CT3)

WP15: Physical-chemical feedbacks at high latitudes (CT4)
WP16: Biological feedbacks (CT4)
WP17: Coupled climate carbon cycle simulations (CT5)
WP18: Feasibility study on purposeful carbon storage (CT5)
WP19: Data and information management (overarching activity)
WP20: Management of the project (overarching activity)
WP21: Training (overarching activity)
WP22: Dissemination, exploitation and management of knowledge (overarching activity)
WP23: Review and assessment of progress and results (overarching activity)

Description of methodologies and approaches employed

CARBOOCEAN was one of the climate relevant *Integrated Proejcts* in the EU's 6th Framwork Programme. As such an *IP*, CARBOOCEAN was supposed to look at its topoc, the marine carbon sources and sinks, from all relevant angles in a broad and comprehensive way. Already from the planning phase on, CARBOOCEAN researchers aimed at pursuing all relevant methods and approaches in order to fulfil the project's objective. The three main methodological pillars of CARBOOCEAN were observations, process studies, and model simulations. These three basic methodological types were pursued in all 5 core themes, i.e., CARBOOCEAN was "integrative" within each of its core themes already and brought observational and modelling scientists close together, with many benefits for mutual understanding and merging of measurements with model approaches.

Observational methods: The backbone of CARBOOCEAN research have been observations. We carried out a cutting edge surface ocean sea surface CO2 observing programme using a network of voluntary observing ships (VOS lines), which can be deemed extremely successful due to the high accuracy measurments now available for autonomous fCO2 measurements. For deep sections and 3-D measurements, highest accuracy data were obtained from water samplers and subsequenet analyses in the laboratory. In oceanic regions, where notoriously bad coverage with ships exists, in particular the Southern Ocean, also automated drifters were used, such as the CARIOCA buoys. In situ measurements were complemented with satellite observations including ocean colour sensors, which proved especially useful for estimating the biological contribution to regional and temporal changes in sea surface fCO2 due to biological carbon uptake and release. Development work on new oxygen floats was carried out which brings this technique close to operational use. The systematic oxygen measurements in the ocean are of extreme use as they contribute to an overall budgeting approach from which also the biological carbon sources and sinks on land can be estimated (given good coverage and quality of atmospheric O_2/N_2 measurements). A number of time series station was included in CARBOOCEAN: Station M (Mike, Norwegian Sea), DYFAMED (Mediterranean Sea), and ESTOC (subtropical North East Atlantic, off Canary Islands). Repeated reoccupations of the Straint of Gibraltar and the North Sea established a much more solid view about the role of these European regional seas in the carbon cycle. Further, work on an automated deep sea whinch, which also contributes to novel automated deep sea measurements of ocean carbon variables, was supported in the first two years of CARBOOCEAN. Atmospheric CO2 (and at one station also atmospheric O2/N2) measurements were carried out in the North Sae (oil/gas platform F3 and a Wadden Sea station) as well as the southern tip of Greenland (Ivituut), which helped to improve top down estimates of carbon fluxes over the larger European area.

Process studies and methods used therein: Carbon cycle modelling and generally biogeochemical modelling as such are still a kind of "soft modelling" when compared with purely physical climate models, which rely on"first principels" such as Newton's 2nd law, the theorems of thermodynamics, and other fundamental quantitative laws. In order to improve the models, which are used for predictions of the marine carbon sources and sinks, a better process understanding and a better quantification of these processes through mathematical equations is needed. During CARBOOCEAN two experiments (one large, one smaller) were carried out with so called "mesocosms" (at the respective facilities at Espegrend, near Bergen, Norway). In the mesocosms technique, natural seawater volumes including their plankton communities are enclosed by big plastic containers, in which under quasi-natural conditions perturbation experiments are carried out, e.g., by increasing the CO2 partial pressure in these "bags" and thus simulating a high CO2 world. The chemical and biological state variables, and biological production rates in these experiments were continuously measured and analysed later on. Next to mesoosm experiments, also perturbation experiments on biota were carried out in the laboratory, e.g., for flow through experiments on calcium carbonate dissolution under varying CO2 partial pressure or pH value. In a feasibility study on deliberate injection of human-produced CO2 into the deep water column, a pressure chamber (Technical University of Hamburg-Harburg) was employed, which allowed to study in detail the near field of CO2 and methane dispersion close to an injection site and the respective droplet rise rates of liquid CO2 and methane.

Modelling methods: A hierarchy of modelling tools and modelling methods were used. A number of prognostic physical-biogeochemical ocean general circulation models were used in stand-alone mode, i.e. by forcing them with atmospheric data. These models usually have a "slab atmosphere" included, however, in order to predict (or prescribe) atmospheric CO2 concentrations. A number of 5 fully coupled Earth system models (LSCE, MPI, Hadley Centre/UK MetO, NCAR/Bern, BCM-C) including interactive carbon cycle climate modules were employed for future scenarios beyond the observational record. These scenarios mostly were run until year 2100, but some of them were carried out longer until 2200 and beyond. Next to these forward models, also a "data driven" inverse models of the global ocean with different complexity (Reiner Schlitzer, AWI Bremerhaven; Sara Mikaloff Fletcher et al., Princeton and other institutes) were used for quantification of air-sea and ocean-interior carbon fluxes. Data assimilation methods were used in particular to interpolate between the VOS line measurements for obtaining basin-wide carbon fluxes for the Atlantic Ocean, including so-called neural network methods. Inventories of carbon, which entered the ocean as a consequence of rising atmospheric CO2 concentrations due to human-produced CO2 emissions, were estimated employing a range of different approaches including the ΔC^* method, TrOCA, TTD, and further approaches. These techniques are listed here under modelling, though this type of analyses is extremely close to the observational data themselves.

The general approach of CARBOOCEAN was to combine earlier and new observations, process studies, and models for an overall assessment of carbon sources and sinks on a regional and global scale. The links between modellers and experimentalists was carried out at the work package level, the core theme level, and also through the overarching work packages. The overall 6 large project meetings (each with around 100 key specialsists on marine carbon cycling; kick-off meeting plus 5 annual meetings including the final meeting; each meeting over 3-5 days) brought together scientists from the various methodological approaches and different disciplines, so that a fruitful integration of the new knowledge could be achieved. This new knowledge merged into a broad variety of data and model products as well as a comprehensive list of peer reviewed publications. The project data management proved to be extremely useful for a handing over of the CARBOOCEAN data to the next generation of projects and neighbouring projects, which whom we closely collaborate (such as the European project on ocean acidification EPOCA under EU's FP7).

Degree to which the objectives were reached

The specific scientific project objectives had been:

1. **Description and quantification of the CO_2 air-sea exchange on a seasonal-to-interannual scale for the Atlantic Ocean and the Southern Ocean:**
   Operational goal was: An observing system for surface marine CO_2 in the Atlantic will be implemented. Methods for diagnosing and predicting the Atlantic and Southern Ocean CO_2 sinks through combination of in situ measurements, satellite data, and models will be developed.
   Delivery: *Short term assessment of net air-sea CO_2 fluxes.* This goal has been fully achieved. North Atlantic and Southern Ocean surface ocean observing systems have been established over the planned time period. The respective data have been analysed, model computations

have accompanied this analysis, and data assimilation methods have been used to combine the measurements with model simulations. Key publications describe the variability of the fluxes in the North Atlantic and the Southern ocean (e.g. Watson et al., 2009; Le Quéré et al., 2007, and Metzl, 2009). Key contributions to the international surface ocean CO2 data base SOCAT have been made.

2. **Quantification of decadal-to-centennial large-scale Atlantic and Southern Ocean carbon inventory changes:**
   Operational goal was: The Atlantic and Southern Ocean carbon sink, and its decadal change, will be quantified through highest accuracy measurement of the changing inventories of inorganic carbon and carbon-related tracers. Atlantic and Southern Ocean data will be integrated into a coherent global data base. The ability of prognostic models to represent the observed changes for a reliable nowcast will be assessed.
   Delivery: *Large scale assessment of the ocean carbon storage.*The objective has been fully reached. The CARINA data set on Atlantic carbon data (with special focus on North Atlantic and Southern Ocean) was compiled and published in special issue of *Earth System Science Data* (e.g. Tanhua et al., 2010). New inventory estimates on the oceanstorage of human-induced carbon were provided. Simulation models of the ocean carbon cycle have been compared with the ocean data (but also atmospheric CO2 data) and intercompared (e.g. Schneider et al., 2008).

3. **Quantification of the carbon sources and sinks at the European regional scale:**
   Operational goal was: The variability of carbon uptake and release as well as the exchange of marginal seas with both the land and the open Atlantic Ocean will be described. A pilot study on establishing a closed carbon budget for Western Europe combining the marine, terrestrial, and atmospheric compartments will be carried out in cooperation with the CarboEurope IP.
   Delivery: *Assessment of the western European contribution to the oceanic CO_2 uptake.* All these goals have been fully achieved. The role of the North Sea in the natural and humanly perturbed carbon cycle was seasonally observed and analysed as well as new processes in shallow seas influencing the carbon cycle have been identified (e.g., Thomas et al., 2007; Thomas et al., 2009). The link between the Mediterranean Sea and North Atlantic carbon cycles has been quantified (e.g., Aït-Ameur and Goyet, 2006; Huertas et al., 2009).

4. **Identification and understanding of biogeochemical feedback mechanisms which control marine carbon uptake and release:**
   Operational goal was: The quantitatively important feedbacks between CO_2 partial pressure and other carbon cycle variables will be identified and analysed. Quantitative descriptions that can be used in models will be derived. Key regions for feedback processes will be identified and strategies to monitor the evolution of feedbacks will be developed
   Delivery: *Assessment of the role of biogeochemical feedbacks for oceanic CO_2 uptake.* The objective has been fully achieved. New estimates of Arctic ocean carbon uptake have been established (e.g., Jutterström and Anderson, under revision). Mesocosm ecxperiments on changes in biological carbon cycling in a high CO2 world have been carried out and resulted in new suggestions for process parameterisations (e.g. Riebesell et al., 2007). A series of modelling studies have successfully shown the potential for quick changes of the oceanic environment due to human-produced carbon down to the ocean floor (e.g., Gehlen et al., 2008).

5. **Integration of carbon observations into an integrated prognostic modelling framework:**
   Operational goal was: Best possible science-based projections of ocean carbon sink behaviour for scenarios of future energy use and climatic change will be developed. The initial conditions for the scenarios will be compiled through a combination of observational data and modelling. The models will include formulations of new biogeochemical feedback mechanisms. Data collection and model simulations will be coordinated in particular with marine carbon cycle research activities in the US.

Delivery: *Assessment of future marine CO_2 uptake kinetics based on models and data.*This goal has also been fully achieved. Fully fledged Earth system models have been used to predict regional as well as global air-sea fluxes from the pre-industrial over the present until year 2100 (e.g., Roy et al., manuscript to be submitted). Longer term studies including stabilisation scenarios have been carried out with a simplified model (e.g., Plattner et al., 2008). The overall positive feedback of the carbon cycle on climate change has been corroborated.

Further, the project achieved a dissemination to policy makers (e.g. Schulze, Heinze et al., 2009) including members of the European Parliament (Heinze and Volbers, 2007; Heinze et al., 2009b), to schools (via the Carbo-Schools Programme, CarboSchools, 2006, 2008) and to the general public (CARBOOCEAN info-film on DVD and broadcast on TV, CARBOOCEAN, 2009). The project was instrumental to initiate further research projects and coordinating activities (such as the European FP7 project on ocean acidification EPOCA and the EU FP7 coordination action COCOS). The instrument Integrated Project has extremely well worked for the European carbon cycle community and has contributed to the competitiveness of the European Research area in this field. The international collaboration, in particular with he US through partner Princeton University was indeed extremely fruitful. Towards the end of CARBOOCEAN, important review/progress overview papers have been published together with US partners (Le Quéré et al., 2009; Sabine and Tanhua, 2010).

Achievements of the project in relation to the state-of-the-art

The CARBOOCEAN achievements represent themselves the cutting edge in the state-of-the-art in marine carbon cycle research on the domains of interest of the project. They are embedded in the international research community and have triggered new collborations and fostered existing collaborations. The record of peer reviewed publications form the CARBOOCEAN IP documents the high standard of the research results (including papers in *Nature* and *Science*). To illustrate this, we give below for each core theme examples, where CARBOOCEAN research has lead to new knowledge which will have also considerable effect beyond the project end and which IS shaping our present research questions as well as new up-coming research directions.

1. At basin wide/regional scale the air-sea CO2 fluxes are interannually more variable than thought before (e.g., Schuster et al., 2009; Watson et al., 2009; Metzl, 2009, Le Qu***éré*** et al., 2007) especially in regions of vertical downward mixing of water close to saturation with respect to the atmospheric CO2 concentration. This new knowledge will help to re-design coming ocean observotaries for carbon (such as initiated through the the ESFRI programme in ICOS – Integrated Carbon Observing System, e.g., Ciais et al., 2009). This new finding also is fundamental in our general understanding of ocean carbon cycling: The ocean sink is not as reliable and steady at least at regional level as many analysis methods (assuming steady state conditions) expect. In some way the finding of highly variable air-sea CO2 fluxes represents a paradigm shift in global carbon cycle research. The analysis of VOS line data for establishing basin wide fluxes (e.g., Telszewski et al., 2009) is currently also tested for the Pacific Ocean as CARBOOCEAN supported PhD student M. Telszewski started a post-doc position in Japan. The link between a temporarily decreasing Southern Ocean carbon sink and stratospheric ozone is a completely new aspect of Earth system science underlining the need for truly coupled multi-reservoir Earth system models. CARBOOCEAN researchers are also partners in the newest sea surface fCO2 climatology as produced under US lead authorship with amny international contributors (Takahashi, et al., 2009). The CARBOOCEAN work on the North Atlantic and Southern Ocean complement ideally the work by international colleagues on the Pacific Ocean and particularly the El Nino/Southern Oscillation associated changes in air-sea carbon exchange.

2. The most comprehensive highest accuracy consistent carbon cycle tracer data set for the Atlantic available to date is the CARINA data set which consists of a large number of pre-CARBOOCEAN data, data sampled during CARBOOCEAN, and many data stes from international colleagues.

CARBOOCEAN was instrumental in bringing this data set to life (e.g., Key et al., 2009; Tanhua et al., 2010). The data set complements nicely the GLODAP data set compiled under guidance of R.M. Key (Key et al., 2004). Bob Key from Princeton University was a central figure also in the compilation of CARINA. An effort similar to CARINA has now started also in the circum-Pacific Asian-American communities under the name PICES and will lead together with CARINA to a world wide extreme high quality carbon data set. This data set will have to be updated also in future due to the transient nature of the marine carbon cycle. CARBOOCEAN also provided new estimates on Atlantic inventories of excess carbon due to the anthropogenic carbon perturbation. The high latitude oceans can well have a considerably higher amount of anthrpogenic carbon stored in their water column than previously estimated (Vázquez-Rodríguez et al., 2009). Inverse computations of intra-ocean fluxes and air-sea carbon fluxes through international-US efforts were supported by contributions from CARBOOCEAN (Mikaloff Fletcher et al., 2006, 2007).

3. The contribution of European regional seas to the Atlantic and European carbon budget was significantly better quantified than through previous efforts. The seasonal analysis of an entire regional seas basin (the North Sea, Thomas et al., 2005) and the systematic seasonal reccoupation of the Starit of Gibraltar hydrographic cross section (Huertas et al., 2009) with marine carbon measurements can be regarded as milestones towards a systematic quantification of the carbon fluxes along the land-ocean continuum. A series of new process and case studies has indicated new processes through re-mineralisation of shallow organic sediments and associated alkalinity release (Thomas et al., 2009) and new procdures for biogeochmemical pH computations (Hofmann et al., 2008, 2009). Borges and Gypens (2010) have shown that in the discussion about ocean acidification, eutrophication in the coastal seas has an even stronger impact on the carbonate system and hence must be taken into account in continental seas carbon cycling. CARBOOCEAN scientists have contributed to the new international text book (Liu et al., 2010) on carbon and nutrient fluxes in continental margins.

4. The dependence of nutrient utilisation by biota on increase in ambient CO2 partial pressure (and associated pH decrease and decrase in calcium carbonate saturation) as resulting from Riebesell et a. (2007) has triggered a new line of research on non-stoichiometric carbon cycle midelling, where the assumed “Redfield concept” of constant ratios of $P:N:C:\Delta O_2$ in most biogeochemical ocean models is abandoned. It is under discussion, whether the relationship as deduced from mesocosm experiments can be transferred to other situations and regions or not. If yes, it could include a potentially significant feedback to rising CO2. In any case a process on re-thinking older established concepts in marine biogeochemical understanding has been started now, and has, e.g., lead to a new interface between Earth system models and the marine paleoclimatic sedimentary record (Heinze et al., 2009) which can help to solve the issue in future by looking at past changes of the Earth system. Gehlen et al. (2008) could show, how quickly the sea surface signal of ocean acidification is transferred to the deep ocean where high CO2 water is starting to dissolve marine calcium caronate sediments. This study complements nicely earlier studies with coarser models on the long-term negative feedback induced by sediment dissolution carried out by US researcher Archer (2005). Further, a cutting edge summary and description on the term “alkalinity” was published (Wolf-Gladrow et al., 2007) which will enter the scientific literature as classic paper on this often not unambiguously discussed carbon cycle tracer (see discussions in Rakestraw, 1949; Dickson, 1992).

5. A new isopycnic physical-biogeochemical carbon cycle model was developed based on the existing modules MICOM and HAMOCC (Assmann et al., 2010) and implemented into a new Earth system model (Tjiputra et al., 2010). Next to the isopycnic ocean model version used at GFDL Princeton (GOLD model), this is the only isopycnic ocean Earth system model currently available and hence very useful in intercomparisons such as the CMIP5 programme in view of the 5th IPCC Assessment Report of Working Group 1. Systematic predictive scenarios with 4 comprehensive Earth system models have provided hindcasts (since the onset of industrialisation) and future projections (under assumptions of an SRES A2 emission scenario) for global as well as regional air-sea carbon fluxes which will enter the RECCAP analysis of the Global Carbon Project (Roy et al., to be submitted) in the years to come.

Overall, the European carbon cycle community has provided through the Integrated Project CARBOOCEAN new knowledge which is key for further studies. All CARBOOCEAN PIs gratefully acknowledge the contribution form the European Commission for their scientific work during 2005-2009 and hope to build on further joint work in near future to continue the fruitful partnership on a European and world wide level.

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