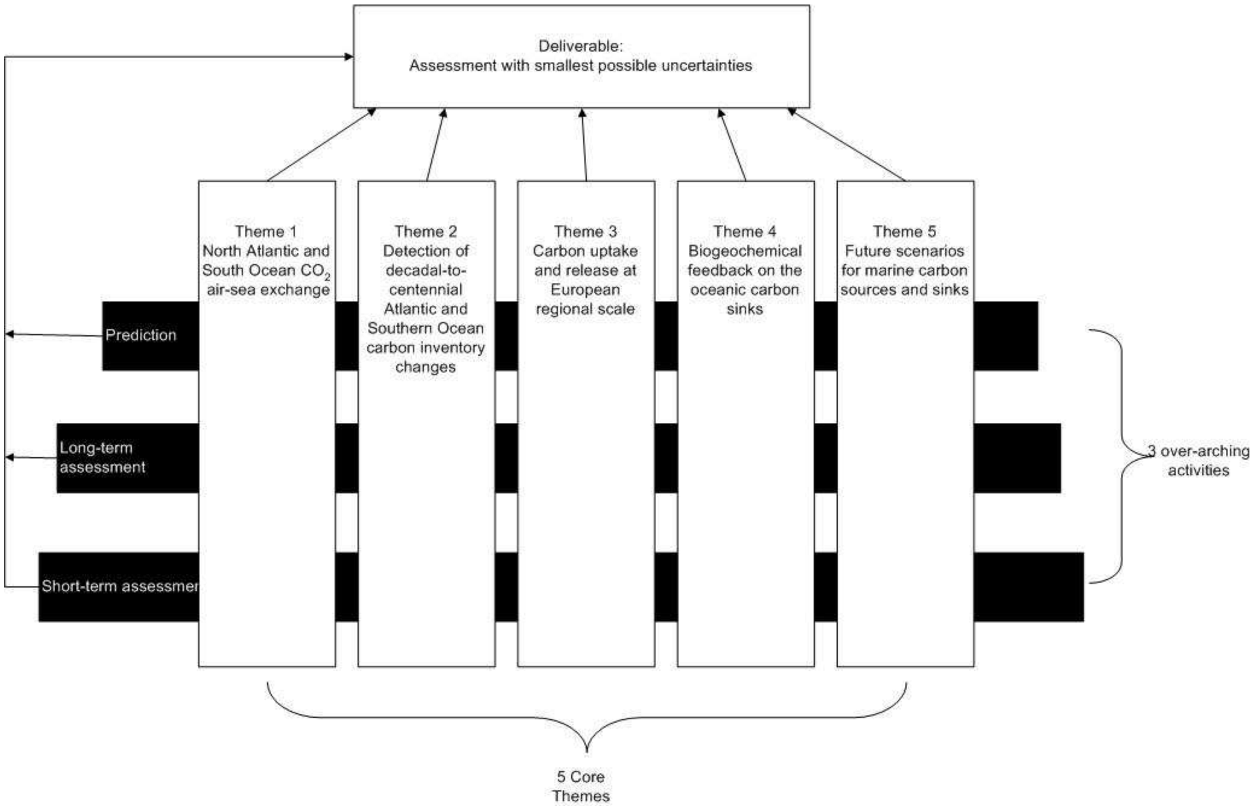
CARBOOCEAN
Core theme (CT) and Work package (WP) fact sheets

Summary of highlights

The CARBOOCEAN S&T approach through five vertical pillars (5 core themes) and three horizontally integrating overarching scientific activities:



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
WP5: Southern Ocean observations and processes
WP6: Model-based Flux assessment
WP7: Mooring Development
WP8: Ocean Interior data collection and documentation
WP9: C_{ant} quantification and decadal changes in carbon inventory
WP10: Oxygen and carbon profiling floats
WP11: Model performance assessment and initial fields for
WP12: Regional assessment for the North Sea
WP13: Regional assessment for the West-Mediterranean
WP14: European Integration
WP15: Physical-chemical feedbacks at high latitudes
WP16: Biological feedbacks
WP17: Coupled climate carbon cycle simulations
WP18: Feasibility study on purposeful carbon storage
WP19: Data and information management
WP20: Management of the project
WP21: Training
WP22: Dissemination, exploitation and management of knowledge
WP23: Review and assessment of progress and results

Core Theme 1: North Atlantic and Southern Ocean CO_2 air-sea exchange on a seasonal-to interannual scale

Tasks/background

- The North Atlantic and the Southern Ocean are thought to be key regions for uptake of "anthropogenic" carbon dioxide. This core theme was directed at constraining the air-sea fluxes in these regions by co-ordinated observations, and understanding the processes giving rise to the fluxes, and the factors that may cause them be variable.
- Studies using the distribution of atmospheric measurements suggest larger variability in the ocean uptake/release than do ocean models. By improving the observation and the modeling of these fluxes, we had the objective of helping to resolve this question.
- The North Atlantic is a well-travelled and accessible ocean where for example commercial ships could provide useful observing platforms which we exploited fully. The Southern Ocean is remote and more data-poor, and here we made the fullest use of autonomous instrumentation and remote sensing.

Highlights

- We set up The "CarboOcean North Atlantic Observing system". This was the first time that a co-ordinated observing network has been used to observe air-sea CO_2 exchange over an entire ocean basin.
  - New data handling and integration techniques had to be developed to interpret the unprecedented coverage of high-quality data that we generated using this network.
  - We have discovered that the North Atlantic exhibits strong year-to-year variability, with indications that the yearly flux is controlled by regional climate.
  - We are able to specify the flux with high resolution in both time and space, to an annual precision better than 10%.
- Using instrumented drifting buoys, research and Antarctic supply ships we returned substantial coverage of the carbon observations in the Atlantic and Indian sectors of the Southern Ocean.
  - The sink for CO_2 in the Indian sector was remaining steady or declining slightly, in agreement with recent studies interpreting atmospheric observations there.
  - New estimates of the productivity at Southern Ocean frontal regions using in-situ drifters
  - New description of the role of sea ice in the Weddell sea in modulating the air-sea flux of CO_2 there.
- New data interpretation methods included the extension of assimilation methods both for physical and biogeochemical data into models, to better simulate the carbon cycle. New models include a time-dependent adjoint formulation and high resolution eddy resolving models.

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Core theme 2: Detection of decadal-to-centennial ocean carbon inventory

Tasks/background of Core Theme 2:
Emissions of CO_2 to the atmosphere have increased atmospheric pCO_2 and caused, on the global scale, an increased flux of CO_2 into the ocean. This causes the dissolved carbon concentration within the ocean interior to increase. Core Theme 2 works on using data from the ocean interior to estimate this CO_2 sink strength. In addition, the Core Theme investigates new technological approaches to measuring carbon-related parameters in the ocean interior as well as how these data can be compared to models of the same process.

Highlights:
CarboOcean led an enormous, international collaboration to assemble all available carbon data from the ocean interior, apply data quality control procedures, and make the data public. Data from 188 cruises or projects collected by 15 countries between 1977 and 2006 were made public. The resulting database is a major step forward in our ability to quantify the oceanic carbon sink.

At the same time, CarboOcean used the data to estimate the total amount of fossil-fuel carbon contained within the Atlantic Ocean and the rate at which it has increased over the past decades.

A new class of autonomous, drifting float that can measure dissolved oxygen with high accuracy was developed by CarboOcean investigators, and tested in a region of low oxygen concentrations off the West African coast. These floats are now commercially available from a European manufacturer. Their future deployment can be used to keep track of oxygen decreases in the deep ocean resulting from climate change as well as assist the estimation of the ocean carbon sink.

Further reading:

CARINA: a consistent carbon-relevant data base for the Arctic, Atlantic and Southern Oceans
Editor(s): T. Tanhua, A. Olsen, M. Hoppema, and V. GouretskiIn open discussion and accessible via:
http://www.earth-system-science-data.net/index.html

Data: http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html

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CT 3: "Carbon uptake and release at European regional scale" fact sheet

Tasks/background of the CT

- to understand seasonal variability of the pCO_2 in the North Sea employing a N-S VOS line crossing the transition from the shallow one-layer southern North Sea to the deep two-layer northern North Sea characterized by strong seasonal gradients,
- to establish North Sea carbon budgets and assess their variability based on the preceding 2001-2002 and two new CARBOOCEAN cruises in 2005 and 2008.
- to estimate Mediterranean carbon fluxes and Mediterranean/Atlantic carbon exchange through the Strait of Gibraltar.
- to assess the concentration of anthropogenic CO_2 in the West Mediterranean.
- to constrain the marine and terrestrial European carbon balance relying on CO_2 data from surface waters and marine air in the North Sea, and from cruises in NW Mediterranean Sea,
- to develop emission reduction scenarios and related socio-economic effects.

Highlights

- Carbon fluxes in the North Sea are highly variable in space and time and are strongly controlled by natural and anthropogenic impacts originating from land, Baltic Sea, Atlantic Ocean and atmosphere.
- Generation of Alkalinity (A_T) in shallow sediments enhances CO_2 uptake in the North Sea (Fig. 1), which might be fulled by organic matter production in the Wadden Sea as implied by CO_2 uptake there (Fig. 2).

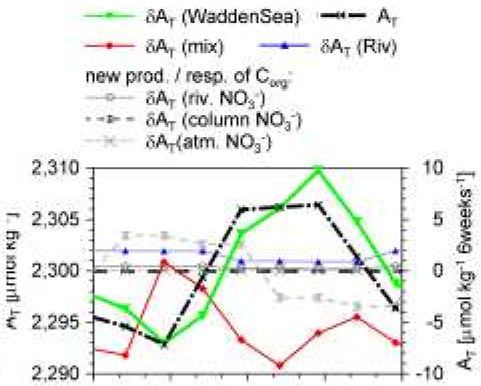

Figure 1: Shallow sediments (green line) release Alkalinity from anaerobic processes, in a similar order of magnitude to rivers (blue line) (Thomas et al., 2009).

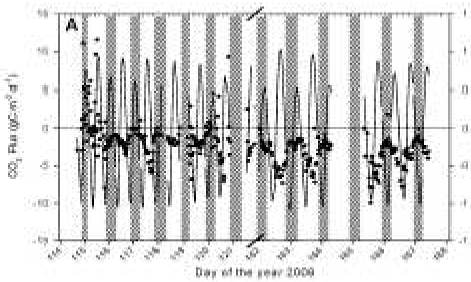

Figure 2: CO_2 fluxes at a permanent monitoring station at the Wadden Sea (Zemmelink et al., 2009). The average CO_2 uptake is $1.9gCm^{-2}day^{-1}$. For the entire Wadden Sea, this would amount to $0.8GMOL\ C\ day^{-1}$. Annual A_T release by the Wadden Sea is $70GMOL\ AT\ yr^{-1}$, which requires approx. 90GMOL organic carbon per year.

- The Mediterranean Sea receives anthropogenic CO_2 from and exports Alkalinity to the North Atlantic Ocean.
- Atmospheric observations have been used to constrain the oceans role in the European carbon balance (Fig. 3).

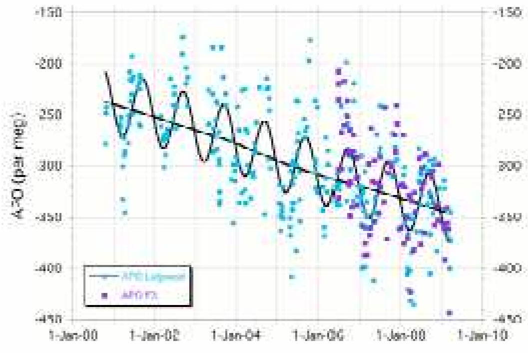

Figure 3: Mirroring oceanographic CO_2 uptake by combined atmospheric oxygen and CO_2 measurements (APO), made on a gas rig in the North Sea (F3) and at a Wadden Sea station (Lutjewad) (Luijkx et al., 2009). The integrative investigation of atmospheric and oceanographic processes is one of the key tasks and achievements of CT3, leading to a comprehensive European carbon balance.

Further readings (e.g. publications, book chapters, web pages...)

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- Huertas. I.E., Rios, A.F., García-Lafuente, J., Makaoui, A., Rodríguez-Gálvez, S., Sánchez, A., Orbi, A., Ruiz, J., Perez, F. (2009) Anthropogenic and natural CO2 exchange through the Strait of Gibraltar. Biogeosciences 6: 647–662.
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- and APO climatology, Atmos. Chem. Phys. Discuss., 8, 20113-20154, 2008.
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CT 4: "Biogeochemical feedbacks on the oceanic carbon sink"

Tasks/background of the CT

Rising atmospheric CO2 levels since the beginning of the industrial revolution and induced warming drive profound changes of the physical and chemical ocean. Temperature driven changes in ocean circulation and stratification lead to large scale changes in vertical marine carbon and nutrient distributions. As a consequence marine ecosystems are altered in their structure and functioning. These changes will ultimately affect the efficiency of the ocean for uptake and removal of carbon lastingly from exchange with the atmospheric reservoir. *The approach adopted within CARBOOCEAN relied on the integration of experimental studies and modeling.* Experimental studies proved particular useful for identifying new feedback processes and unraveling their physiological basis. They gave rise to novel process parameterizations which after implementation into global biogeochemical ocean models allowed a first order quantification of feedback loops. The **principal objective** were to:

- identify key regions
- analysis and identify important geochemical and biogeochemical processes feedbacks between atmospheric CO2
- derive quantitative relationships to be used in global biogeochemical ocean models

Highlights

Key regions

Modifications in the strength of the physical C pump are particularly large at high latitudes due to the combination of physical (temperature, river run-off, ice cover, mixed layer depth, circulation), and chemical changes (Revelle Factor) in a warming climate.

- CarboOcean allowed a first order quantification of the effect a sea ice free Arctic ocean during summer on air-sea exchange of CO2. The later being under-saturated with respect to atmospheric CO2, it would need an uptake corresponding to about 1 ‰ of the global anthropogenic emission to get to saturation.
- The anthropogenic carbon dioxide inventory of the Arctic Ocean is about 2 600 Tg C which is approximately ~2% of the global inventory even if the Arctic Ocean volume is only ~1%.
- A model study provided evidence for a saturation of Southern Ocean CO_2 sink has since 1981, meaning that the CO_2 sink has not increased in spite of the fact that the CO_2 emissions increased by 40%.

Important processes

Targeted processes studies highlighted key processes underlying oceanic biogeochemical feedback mechanisms to atmospheric CO2.

- Laboratory experiments suggested that the C and N fixation of the cyanobacterium *Trichodesmium* is affected by CO_2 concentrations with higher rates at projected future CO2 values.
- A parameterization of the temperature dependency of dissolved and particulate organic C suitable for implementation to large scale biogeochemical models was derived from a extensive experimental data set.

Feedback quantification by means of global ocean modeling

CarboOcean allowed to quantify known feedback mechanisms (e.g. calcification feedback) and to identify new processes (e.g. export stoichiometry).

- Reduced calcification in response to rising atmospheric CO_2 and changes in ocean chemistry (ocean acidification) leads to a rather modest increase of the cumulative CO_2 uptake of 6 Gt C over 140 years. This is close to negligible in view of current and expected anthropogenic CO_2 emissions. The increased uptake might be largely compensated for by a decrease in the efficiency of the biological pump going along with a decrease of ballasting of particulate organic C fluxes and thus shallower remineralisation.
- Results from a CarboOcean mesocosm experiment suggest an enhanced C drawdown at higher than present atmospheric CO_2 levels, with an increase of the stoichiometric ratio C:N from 6 at low to 8 at high CO_2. The effect of CO_2 sensitive C:N stoichiometry on atmospheric CO_2 levels could amount to a cumulative excess uptake of 34 Gt C by the year 2100 (IPCC SRES-A2 scenario)

- The first ever high latitude mesocosm, at Ny Ålesund, Svalbard, showed that changes in stoichiometry may not always result in increasing sequestration of carbon in the ocean. Nutrients and energy flow was shown to channel through bacteria at the expense of phytoplankton resulting in less organic carbon sequestration with increasing stoichiometry of dissolved organic matter supply

EPOCA (European Project on Ocean Acidification), a CarboOcean 'spin-off': While the CarboOcean project proposal mentioned research targeting effects of ocean acidification on C fluxes, it became evident that an independent project would be needed in order to address impacts of changes in carbonate chemistry on ocean biota. The overarching goal of EPOCA is to achieve a better prediction of ocean acidification and its consequences.

Further readings

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- Gehlen, M., R. Gangstø, B. Schneider, L. Bopp, O. Aumont, and C. Ethé , The fate of pelagic $CaCO_3$ production in a high CO_2 ocean: a model study2007, *Biogeosciences*, 4, 505–519
- Heinze C., 2004, Simulating oceanic $CaCO_3$ export production in the greenhouse, *Geophysical Research Letters 31(L1638)*: doi:10.1029/2004GL020613.
- Jutterström, S., and L.G. Anderson. Uptake of CO_2 by the Arctic Ocean in a changing climate, *Mar. Chem*., accepted pending revisions.
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- Thingstad T.F. et al., 2008. Counterintuitive food web response to organic carbon enrichment in an arctic pelagic ecosystem, *Nature* 455: 387-390, doi:10.1038/nature 07235
- EPOCA webpage: http://www.epoca-project.eu/

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CARBOOCEAN

CT 5 "Future scenarios for marine carbon sources and sinks"

Tasks/background of Core Theme 5

- We need to know the marine CO_2 sink under future CO_2 emissions from fossil fuel burning, land use, and other sources. The conditions will be quite different from know, as we expect the emissions and the atmospheric CO_2 concentrations raise further (from pre-industrial 278 μatm to 387 μatm today and possibly to 500 μatm at 2030).
- Coupled ocean-atmosphere-land physical-biogeochemical climate models (so called Earth system models) were employed in order to predict future marine CO_2 uptake. These models are among the most complex computer codes which have been developed by human brains. As there is still a considerable difference between various models we have used the 5 key European model systems in order to predict future marine CO_2 uptake and atmospheric CO_2 concentration under given emission scenarios.
- In order to build up expertise on technical mitigation options, the core theme has also developed knowledge on spreading of CO_2 which gets injected under high pressure into the water column.

Highlights

- All models show that the overall carbon cycle climate feedback is positive (i.e. re-enforcing climatic change). In the past IPCC report (4th assessment report, 2007) mostly physical models have been used. The use of coupled Earth system models, which take the carbon cycle climate feedback into account, shows that climate change will be stronger as anticipated from purely physical models.
- The carbon cycle climate feedback still varies between the different models, which can be attributed to the different process descriptions in the models (e.g., representations of ocean circulation, gas exchange as well as biological carbon cycling).
- In view of potentially high droplet rise rates for artificially injected human-produced CO_2 into the water column, the spreading of CO_2 injected into the deep-sea back into shallower layers may be relatively quick. This underlines that direct CO_2 injection into the water column is most probably not a useful mitigation option.

Further readings

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- Bigalke, N.K. et al., 2008, Experimental investigation of the rising behavior of CO_2 droplets in seawater under hydrate-forming conditions, Environmental Science & Technology, 42(14), 5241-5246.

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WP 1: “Prediction towards Sustainable Development” (Overarching WP)

Tasks/background of Work Package 1

- Since the onset of the industrial revolution, mankind has increasingly released CO_2 to the atmosphere which significantly contributes to human induced climate change. The atmospheric CO_2 content would even be higher if it was not for that at present about 25% of annual CO_2 emissions are absorbed by the ocean.
- The goal of WP1 is to summarise the new knowledge on marine carbon sources and sinks for scientists and policy makers. WP 1 of CARBOOCEAN builds on all core themes of the projects.

Highlights:

- CARBOOCEAN has shown that overall emission targets for human-produced CO_2 have to be corrected towards smaller emissions, because of the positive carbon cycle climate feedback, ocean acidification, and the potential for a weakening of important marine carbon sink areas.
- CARBOOCEAN had aimed at strongly reduced uncertainties in ocean-atmosphere CO_2 fluxes, especially for the North Atlantic. For specific regions, seasons, and years this goal has been reached through the North Atlantic carbon observing system. On the other hand, a number of key processes which influence carbon uptake by the oceans have been newly identified, which have not yet been fully quantified. Therefore, the future prediction of marine CO_2 uptake is still associated with significant uncertainties. CARBOOCEAN in any case has contributed to estimate these uncertainties more realistically.

Further readings

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WP 2: “Short term Assessment” (Overarching WP)

Tasks of WP 2

1. Compilation of air-sea exchange fluxes for carbon dioxide (CO_2) for the Atlantic Ocean basin, its polar extensions, the European coastal seas and the exchanges with the European continent for the year 2005 (annual mean, seasonal).
2. Integration of this estimate into large scale global estimates.
3. Critical evaluation of relevant methods.
4. Comparison to earlier annual/seasonal CO_2 air-sea flux estimates.

Highlights

- Operation of an Atlantic Carbon Observing Network on Voluntary Observing Ships (VOS), autonomous moorings and time series stations from 2005 to 2009.
- Observations of surface water pCO_2 (partial pressure of CO_2) in the Southern Ocean on repeat cruises and research cruises, as well as by 6 autonomous CARIOCA drifters (83 months of hourly pCO_2 measurements).
- *In situ* surface water CO_2 measurements in the Arctic Ocean, the North Sea, and the western Mediterranean Sea and the Atlantic Ocean.
- Collection of high quality, continuous, atmospheric CO_2 and O_2 (oxygen) data at four sites around the North Sea and the North Atlantic Ocean.
- Weekly and monthly maps of air-sea CO_2 exchange coefficients for several gas transfer parameterisations and QSCAT satellite wind speed since 1999 (available on ftp.ifremer.fr).
- Critical evaluation and application of multiple linear regression and neural network techniques for interpolation of pCO_2 data, using remotely sensed and ocean reanalysis data.
- Assessment of seasonal and interannual variation of pCO_2 in the North Sea along two VOS routes. The North Sea is an annual sink for atmospheric CO_2 along these transects.
- The surface water pCO_2 distribution in August 2005 for the North Sea.

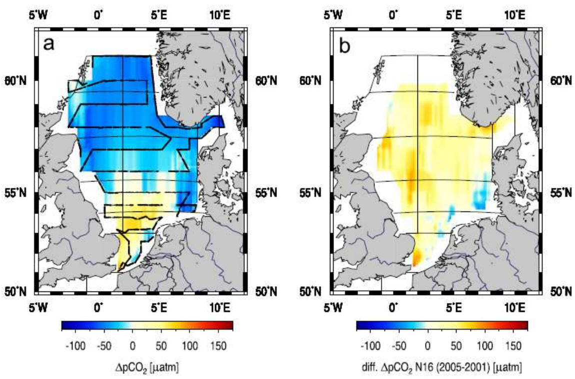
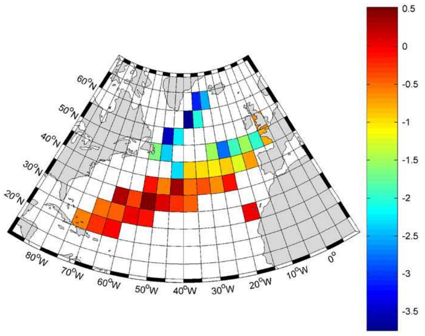


Fig. 1: a) The pCO_2 difference between water and air, ΔpCO_2(w-a), for August-September 2005 and b) the change in ΔpCO_2(w-a) from August 2001 to 2005 for the North Sea (Thomas et al., 2007).

- Monthly and annual surface water pCO_2 and CO_2 air-sea flux maps for the North Atlantic Ocean for 2004, 2005 and 2006.
- Revised monthly and annual climatological surface water pCO_2 and CO_2 air-sea flux maps for part of the Southern Ocean Subantarctic Zone.
- Detection of multi-annual to decadal trends in surface pCO_2 and oceanic CO_2 for the North Atlantic Ocean, the North Sea and the Southern Ocean. Oceanic CO_2 uptake may well have decreased over the past 20 years in the northern North Atlantic Ocean and the southwestern Indian Southern Ocean.



Fig, 2: The change in the annual mean sea–air flux (mol m^{-2} $year^{-1}$) from 1990 to 2006 (Schuster et al., 2009). The negative values indicate a decrease in oceanic CO_2 uptake for the northern North Atlantic Ocean.

- Identification of mechanisms for long-term trends in oceanic CO_2 uptake. An increase in Southern Ocean wind speeds possibly due to a decrease in the stratospheric ozone content could reduce the Southern Ocean CO_2 sink, while the North Atlantic Oscillation might be a factor in the variation of the North Atlantic CO_2 sink.
- The seasonally ice-covered Weddell Sea acts as an important CO_2 sink upon ice melt.
- A disappearance of summer-time sea ice coverage in the central Arctic Ocean would result in marine CO_2 uptake of 0.001 Pg C yr^{-1}.
- Atmospheric CO_2 uptake of 0.030 Pg C yr^{-1} by the Barents Sea is exported into dense, intermediate modified Atlantic Waters.
- Contribution to a global climatology for surface water pCO_2 and CO_2 air-sea fluxes.
- Contribution to a revised mass balance of carbon on the continental shelves. Continental shelves act as sinks (0.33-0.36 Pg C yr^{-1}) and near-shore ecosystems as sources (~0.50 Pg C yr^{-1}) for atmospheric CO_2.
- Safe storage of and public access to marine CO_2 data via the CarboOcean data base.
- A key contribution to the Surface Ocean CO_2 Atlas (SOCAT).
- Completion of several PhD theses.

Further reading

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Thomas et al. (2008) GBC 22: GB4027.
Watson et al. (2009) Science, in rev.

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Work Package 3 “Long Term Assessment” (overarching WP)

Tasks/background of the WP

- Establish the framework for repeated anthropogenic CO_2 (Cant) inventory quantification within the Atlantic Ocean basin, including its polar extensions and the European marginal seas.
- Create interfaces between CARBOOCEAN activities and related international activities in order to permit global ocean inventory estimates.

Highlights

- Thorough comparison of existing methods for estimation of anthropogenic CO_2 completed (Vázquez-Rodríguez et al., 2009);
- New approaches for estimation of anthropogenic CO_2 proposed (Tanhua et al., 2007);
- 1st and 2nd level quality control of huge CARINA database completed
- CARINA data currently under review (or preparation) for publication in *Earth System Science Data*; 8 manuscripts/data sets submitted, approx. 11 further manuscripts/data sets to follow;
- Application of individual methods for estimation of anthropogenic CO_2 applied regionally (e.g., Jutterström *et al*., 2008), basin-wide (e.g., Steinfeld *et al.*, 2009; Tanhua et al., 2009) or globally (e.g., Velo *et al.*, submitted).

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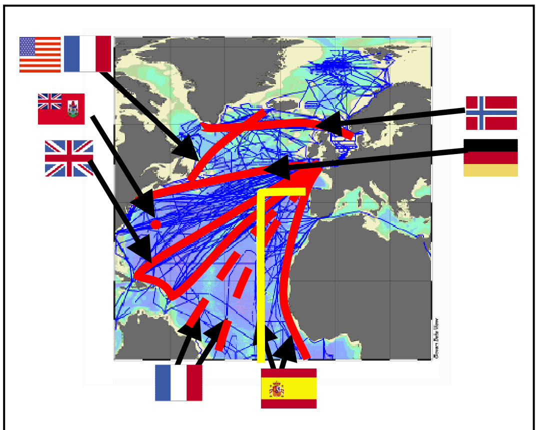
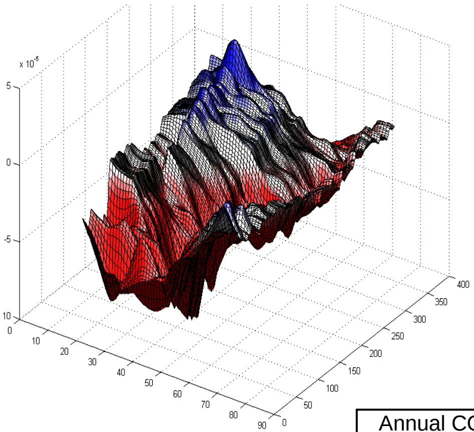
WP 4: North Atlantic Observing system

Tasks were:

- To set up an integrated observing network for surface ocean air-sea fluxes of CO_2 in the North Atlantic, based on voluntary observing ships and time series stations.
- To collect and interpret observations from this network during the period 2005-2008, in order to define air-sea fluxes to the best precision, accuracy and resolution allowable. Our aim was for accuracies ~10%, and for seasonal or better time resolution.
- To document the magnitude and variability, both in time (seasonal and inter-annual) and space of North Atlantic air-sea CO_2 fluxes, reporting maps of fluxes at intervals through the project.



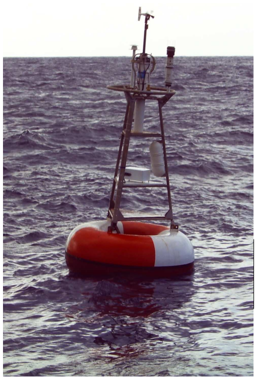
Observing network



Annual CO_2 flux mapping for the N. Atlantic

Highlights

- The network confirmed that the North Atlantic net sink for CO_2 is variable from year to year, and strongly indicates the variability is decadal in nature with a long-term decline, linked to climate variability in the region.
- The network achieved all its aims: it represents the first basin-scale observing system for marine carbon, with observations cross-calibrated and reported to a central data management facility, producing basin-wide mappings. Our efforts resulted in a huge expansion of the number and quality of observations in the North Atlantic.
- Effective Methods were developed to allow the carbon observations to be used to construct maps of fCO_2 and fluxes, by the use of satellite and reanalysis products mapped with regression or neural net techniques.
- Among many regional firsts in the North Atlantic were:
  - Time series estimates of the seasonal cycle, and variability from the 1990s to the 2000s, showing large changes and decadal decline in uptake in the Northwest Atlantic, Northeast Atlantic, and along a shipping route from Europe to the West Indies.
  - New time series were established on moorings in the tropical Atlantic and the Eastern subtropical gyre.



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WP 5: “Southern Ocean observations and processes”

Tasks/background of the WP

- To assess the air-sea CO_2 flux and its space and time variability in specific sink regions of the Atlantic and Indian sectors of the Southern Ocean.
- To understand processes responsible for the variation of air-sea CO_2 fluxes.
- To provide inputs for estimating air-sea CO_2 fluxes at regional and monthly time scales to constrain atmospheric inverse modelling.

Highlights

- Monitoring of surface CO_2 parameters in the Atlantic and Indian sectors of the Southern Ocean (open ocean and coastal regions) from ships and by CARIOCA drifters.

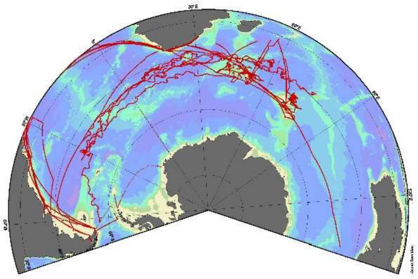

Fig. 1: Location of fCO_2 (fugacity of carbon dioxide) measurements acquired since 2005

- The rate of increase of the fugacity of CO_2 in Indian Ocean surface waters was similar or above to that of atmospheric CO_2 (1991-2007)

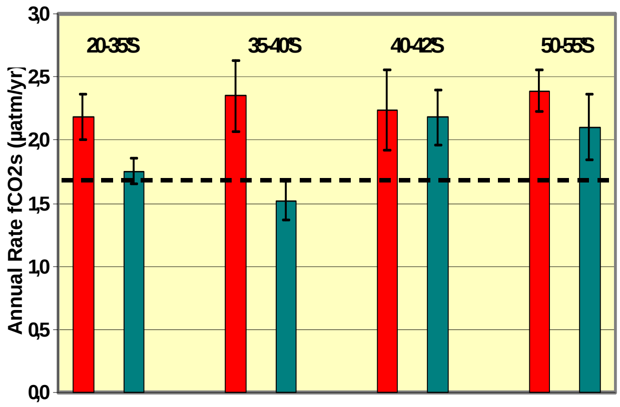

Fig. 2: Summer-time (red) and winter-time (dark green) trends of surface water fCO_2 (µatm/yr) in four regions in the Indian Ocean (1991-2007). The average trend is 2.1 (+/- 0.3) µatm/yr.

- New in situ estimates of net community carbon production from CARIOCA drifters in frontal regions of the Southern Ocean.
- High surface water fCO_2 below Weddell Sea sea-ice was a result of upwelling and entrainment of ‘old’ carbon-rich Warm Deep Water into the winter mixed layer. During and upon ice melt, biological activity rapidly reduced surface water fCO_2 by up to 100 µatm, thus creating a sink for atmospheric CO_2.

Further readings

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- Boutin et al. ,2008. LO 53 : 2062-2079.
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WP 6: "Model-based Flux Assessment"

Tasks/background of the WP

The objectives of this workpackage were (1) to improve methods to interpolate surface measurements of ocean pCO_2 to provide basin-wide seasonal maps, and (2) to better quantify and test our understanding of air-sea CO_2 fluxes by improving ocean models and initiating related data assimilation activities.

Highlights (take home messages) [can be supported by 1-2 photos, graphs etc.]

Interpolation:

LSCE (Partner 6) collaborated with UEA (Partner 9) to jointly implemented an adaptative neural-network (nonlinear) scheme to make monthly pCO_2 maps for the North Atlantic from the CarboOcean pCO_2 data and other routine measurements including temperature, salinity, mixed-layer depth (Telszewski et al., 2009)

IFM-GEOMAR (Partner 4) used a high-resolution (1/12°) North Atlantic regional ocean model simulations as a test-bed to evaluate the ability of their neural-network approach to reproduce maps of surface pCO_2 fields. For a simulated VOS and satellite coverage corresponding to the year 2005, their mapping scheme yielded basin-wide RMS errors of 20 µatm. Estimated errors were reduced to 16 µatm when simulated surface temperature and salinity were used to locally estimate surface pCO_2 via a neural network at the observed ARGO positions in the North Atlantic in 2005.

Assimilation:

AWI (Partner 3) tested their first implementation of a time-dependant scheme for their adjoint model in order to assess the annual cycle of air-sea CO_2 fluxes and new production from hydrographic and biogeochemical data. Annual mean preindustrial air-sea CO_2 fluxes were inferred using ocean-interior carbon data in a CFC- and ^{14}C-calibrated global model (Schlitzer , 2007). Monthly CO_2 fluxes were estimated in a time-dependent model by fitting the model to seasonal nutrient and carbon data. Misfits with carbon data were reduced by 60%; however, resulting air-sea CO_2 fluxes depend strongly on model export production. Additional assimilation of satellite chlorophyll data appears necessary to better constrain particle export and the overall carbon budget of the upper ocean.

LSCE (Partner 6) led the French Green Mercator project (http://mercator-vert.ipsl.jussieu.fr), which has made 2º, ½ º, and ¼º simulations in a North Atlantic regional model without assimilation, which are now being compared to analogous simulations with assimilation of physical data (altimetry and in-situ hydrographic data).

LSCE (Partner 6) has assimilated remotely sensed ocean Chl a as well as observed nitrate, silicate, and POC at 5 JGOFS time-series stations into a 1-D version of the ocean model ORCA/PISCES in order to simultaneously tune 48 model parameters, finding substantial improvement in simulated Chl a, particularly in the North Atlantic and Southern Oceans (Kane et al., 2009).

The UK Met Office (Partner 33) has modified the FOAM operational model to assimilate oceanic pCO_2 data, with the long-term gaol to improve simulations of seasonal-to-interannual variability of the air-sea CO_2 flux. Mixed-layer DIC and total alkalinity fields are adjusted to nudge simulated surface ocean pCO_2 towards the observed values. Early results show a significant reduction in average RMS error (difference of model and observations) across the North Atlantic.

Predictive model improvements:

LSCE (Partner 6) improved horizontal resolution of global biogeochemical ocean simulations to explicitly account for the role of ocean eddies, a key feature of ocean dynamics that can heavily influence ocean biogeochemistry. Dynamic ocean model simulations (at 2º, ½ º, and ¼º-degree horizontal resolution) were made within the DRAKKAR high-resolution modeling consortium; these versions of the dynamic model (NEMO) were evaluated and coupled to the biogeochemical model (PISCES); they are now being compared in terms of how simulated interannual variability in air-sea CO_2 fluxes varies with model resolution and different sets of atmospheric forcing.

Further reading

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WP 8: "Ocean interior data collection and documentation"

Tasks/background of the WP8

- To assemble and report an observational data base of measurements of carbon and carbon-related properties in the ocean interior through collection, merging and reporting of new and historical data.

Highlights

-WP8 led an international data assembly effort which involved:
-International collaboration to assemble existing data, perform quality control and produce a publicly-available, internally consistent dataset for three main regions: Arctic Mediterranean Seas, Atlantic Ocean and Southern Ocean. The entire product is referred to as the CARINA project (Carbon in the Atlantic Ocean)
-The database include three merged data files including observations from 188 cruises or projects conducted between the years 1977 and 2006, and involving ships from 15 countries including the USA, Canada, Japan, New Zealand, Australia.
-Custom on-line collaboration tools and software were developed for performing the quality control and consistency checks. These tools are now being used by US, Canadian and Japanese researchers who are assembling a data set for the Pacific Ocean.
-The descriptions of the data, and the procedures used for consistency-checking are being published as 20 papers in a peer-reviewed journal (a special issue of Earth System Science Data). These papers are citable, will be indexed in the Science Citation Index and will help to assure that the groups responsible for making data available are given appropriate credit
-The CarboOcean approach to data assembly and reporting is likely to set a new standard for collaborative data reporting with appropriate professional recognition of this important activity.

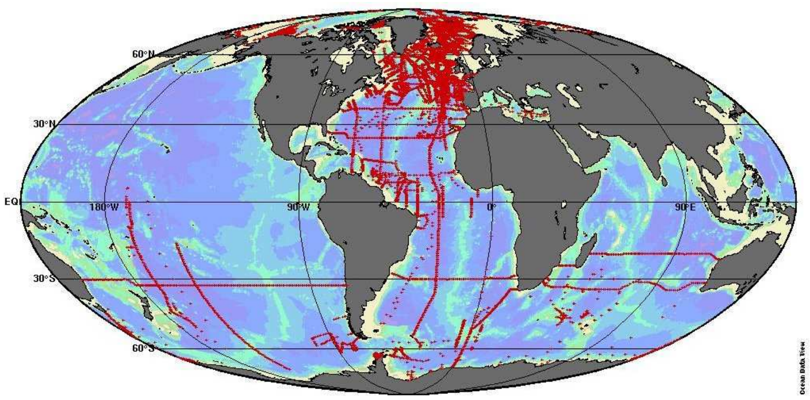

Fig. 1: The locations of stations which are now included in the CARINA database.

Further readings

-ESSD - Special Issue
-CARINA: a consistent carbon-relevant data base for the Arctic, Atlantic and Southern Oceans
Editor(s): T. Tanhua, A. Olsen, M. Hoppema, and V. Gouretski
-In open discussion and accessible via: http://www.earth-system-science-data.net/index.html

Data

http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html

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CARBOOCEAN

WP 9: “C_{ANT} quantification and decadal changes in carbon inventory”

Tasks/background of the WP9

- To establish optimal methods to assess anthropogenic CO_2 inventories and its temporal change.
- To apply these methods in combination with existing and new highest accuracy data in order to quantify the inventory of anthropogenic CO_2 in the Atlantic and Southern Oceans.

Highlights

- Very good agreement between most recent methods are found along the whole Atlantic, except for the ΔC* method which produce inventories five times lower in the Southern Ocean and 40% higher in the Artic Ocean.

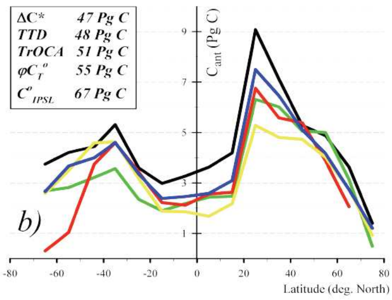


Fig. 1. The total inventories (Pg C) for the same domain and latitude band resolution. The inlayed box gives the integrals of the presented total inventories for each method in the Atlantic Ocean south of 65ºN.

- Contemporary and preindustrial air-sea fluxes of natural and anthropogenic carbon remain uncertain in the Southern Ocean according to the quantification using an Ensemble Kalman Filter Assimilation into the Bern3D model

- C_{ANT} inventory was 54 ±8 Pg C for the Atlantic Ocean for 1994 using 5 selected sections and a combination of the five methods.

- Using the whole CARINA data for the Atlantic south 65ºN a total inventory of 55 PgC was obtained for 1994.

- The temporal increase of C_{ANT} inventory between 1997 and 2003 (12%) follows that given by the atmospheric.

- Strong reduction, of about three times, in the C_{ANT} inventory between high and low NAO scenarios in the Irminger Sea related with the water mass formation.

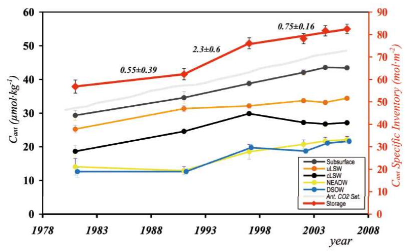
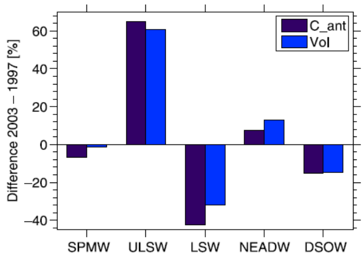


Fig. 2: Temporal evolution (1981–2006) of the average Cant (μmol kg^{-1}) stored in the subsurface layer (dark grey line), uLSW (orange line), cLSW (black line), NEADW (yellow line) and DSOW (blue line). The continuous grey line shows the 100% Cant saturation of water masses in equilibrium with the atmosphere over time. The evolution of the specific inventory (in mol Cm−2) of Cant in the Irminger basin is given by the thick red line, and its values can be read on the right-hand y-axis. The numbers above this line stand for the rates of increase of Cant storage (in mol Cm^{-2} yr^{-1}) for the time periods (from left to right) of 1981–1991, 1991–1997 and 1997–2006, respectively.



- Temporal variation in the water mass formation in the North Atlantic has a very strong impact in the C_{ANT} storage rates.

Fig. 3: Relative changes of volume and Cant inventory (all values time-corrected toward 2003) between 1997 and 2003 within the northwest Atlantic. In the case of a steady state ocean, both differences should be zero

Further readings

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- Jutterström, S. et al. Evaluation of anthropogenic carbon estimates in the Arctic Ocean (to be submitted)...

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WP 10 “Oxygen and carbon profiling floats”

Tasks/background of the WP

- Development of standard oxygen float model PROVOR CTS3 DO with Seabird CTD and Aanderaa oxygen optode
- Development of prototype float model PROVCARBON with Seabird CTD, Aanderaa oxygen optode and Wetlabs transmissometer;
- Execution of a dedicated field experiment using six of the newly developed floats;
- Evaluation of the viability of a float-based oxygen observatory;
- Model simulations to explore the magnitude and location of predicted oxygen concentration changes over the next 100-200 years resulting from global change and associated circulation/biogeochemistry changes.

Highlights

- There is a growing body of observation and model-based evidence that ocean deoxygenation is a near-ubiquitous phenomenon which is driven by global (climate) change that needs to be addressed by dedicated future research;
- Oxygen floats are now fully operational and commercially available in Europe;
- A float-based global oxygen observatory is technically feasible;
- An international community-driven effort is underway to promote the addition of an oxygen component to the ARGO programme.

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WP 11: "Model performance assessment and initial fields for scenarios"

Tasks/background of Work Package 11:

- Physical, chemical, and biological oceanographers have developed highly complex coupled physical-biogeochemical global ocean circulation models. These models are used within complete climate models for simulations of past, present, and future climate. These models need to be validated against observations.
- The availability of newly constructed observational data bases make the model performance assessment with respect to observations attractive and feasible. As not many time series of marine carbon observations are available, an assessment on how well ocean carbon models reproduce variability is still limited but certainly has improved through the CARBOOCEAN work.

Highlights:

- All oceanic carbon cycle circulation models reproduce the basic features of oceanic carbon cycling well (the global "conveyor belt circulation", outgassing at upwelling areas).
- The models are capable of realistically modelling marine anthropogenic carbon inventories as a whole, though regional discrepancies from observations remain.
- Ocean carbon models reliably simulate the ongoing ocean acidification as such, while still details on the biogeochemical consequences and impacts need consideration and improvements.
- Time dependent tests of ocean carbon cycle models for, e.g., reproducing interannual variability (El Nino Southern Oscillation type variations), are crucial and can reveal the real ability of models to simulate the interplay of inorganic and organic carbon cycling processes correctly.
- Models forced with time dependent data as derived from observations can encouragingly simulate the patterns of decadal changes in regional carbon cycling though amplitude and phase of the simulated changes still need improvement.

Further reading:

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WP 12: “Regional assessment for the North Sea”

Tasks/background of the WP:

to understand the carbon cycling in the North Sea using field data and simulations.
to understand interactions between North Sea, atmosphere, land and northeast Atlantic Ocean.
to assess the North Sea's role in integrated, hemispheric carbon budgets.

Highlights:

- The CO_2 system in the North Sea reveals high variability in time and space.
- Variability is caused by climatic processes, by the North Atlantic Ocean and by terrestrial, i.e., riverine and Baltic Sea inputs, all of which are variable themselves.
- Anaerobic processes in sediments generate Alkalinity in similar order of magnitude as riverine inputs. Alkalinity from anaerobic processes contribute up to 25% to overall CO_2 uptake by the North Sea and play an important role in controlling the pH.
- The role of eutrophication in controlling carbon cycle in shallow areas has been better understood.
- Interannual fCO_2 variability is large and controlled mainly by biology and SST.

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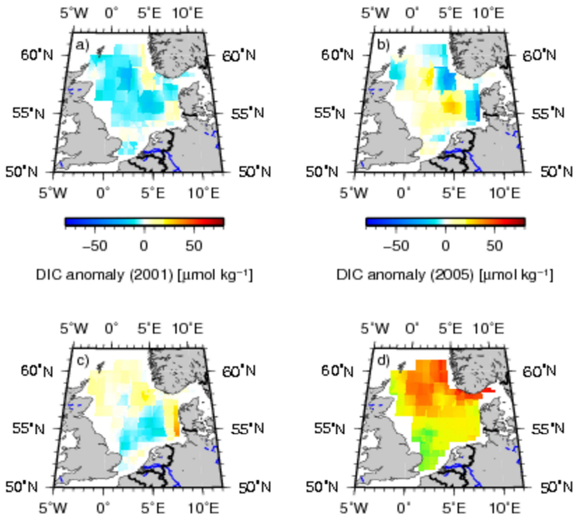
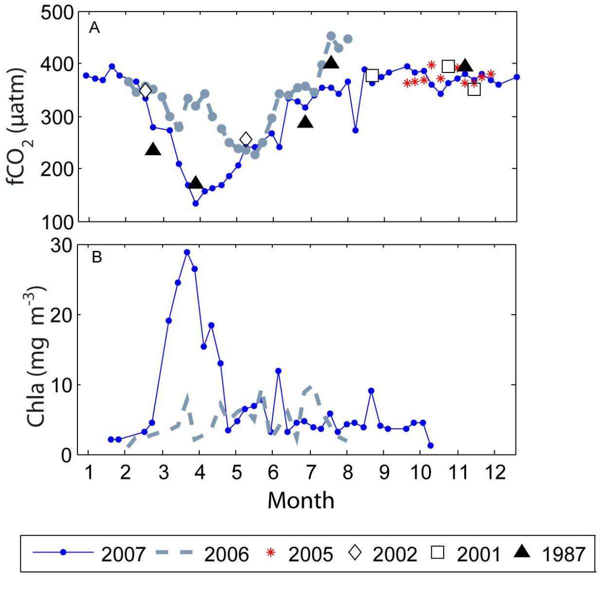


Figure 1: Variability of the surface dissolved inorganic carbon (DIC) in the North Sea between 2001, 2005 and 2008 (a-c), relative to the average (d).

Figure 2: Interannual variability of A) surface fCO_2 between 1987, 2001-2002, 2005-2006 and 2006 B) SeaWiFS chlorophyll-a between 2006 and 2007 in the southern North Sea.



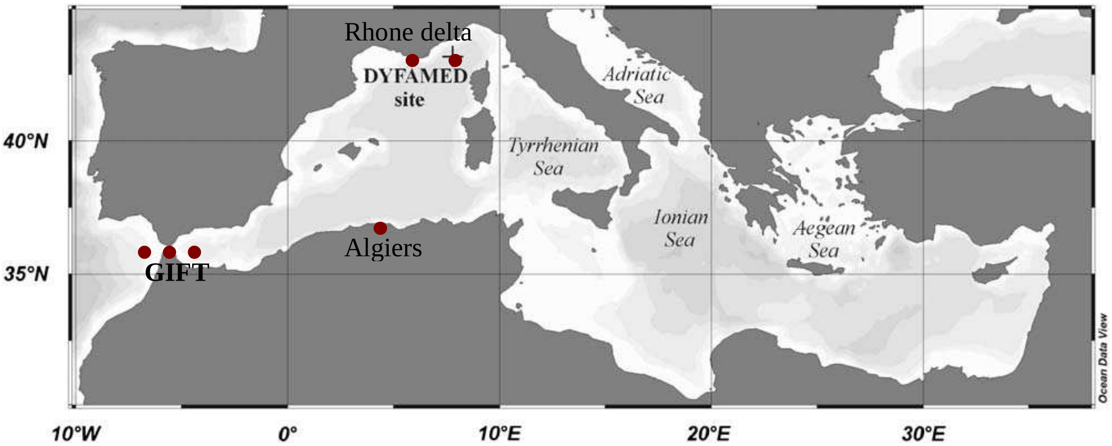
WP 13: “Regional Assessment for the West-Mediterranean”

Tasks of WP13:

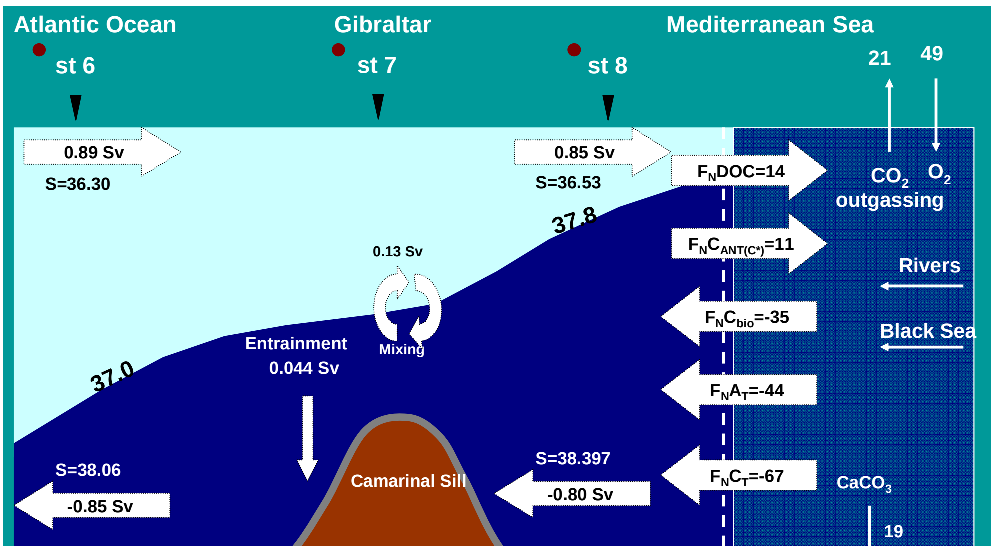
- To create the data sets, measurement systems and model set-ups as prerequisite for a quantitative estimate of Mediterranean carbon fluxes and Mediterranean/Atlantic carbon exchange through the Strait of Gibraltar.
- To assess the concentration of anthropogenic CO_2 in the West Mediterranean.

Highlights:

- Generation of databases: (DYFAMED, Gulf of Lion-Rhone delta–off Algiers, West Mediterranean, GIFT-GIbraltar Fixed Time series)

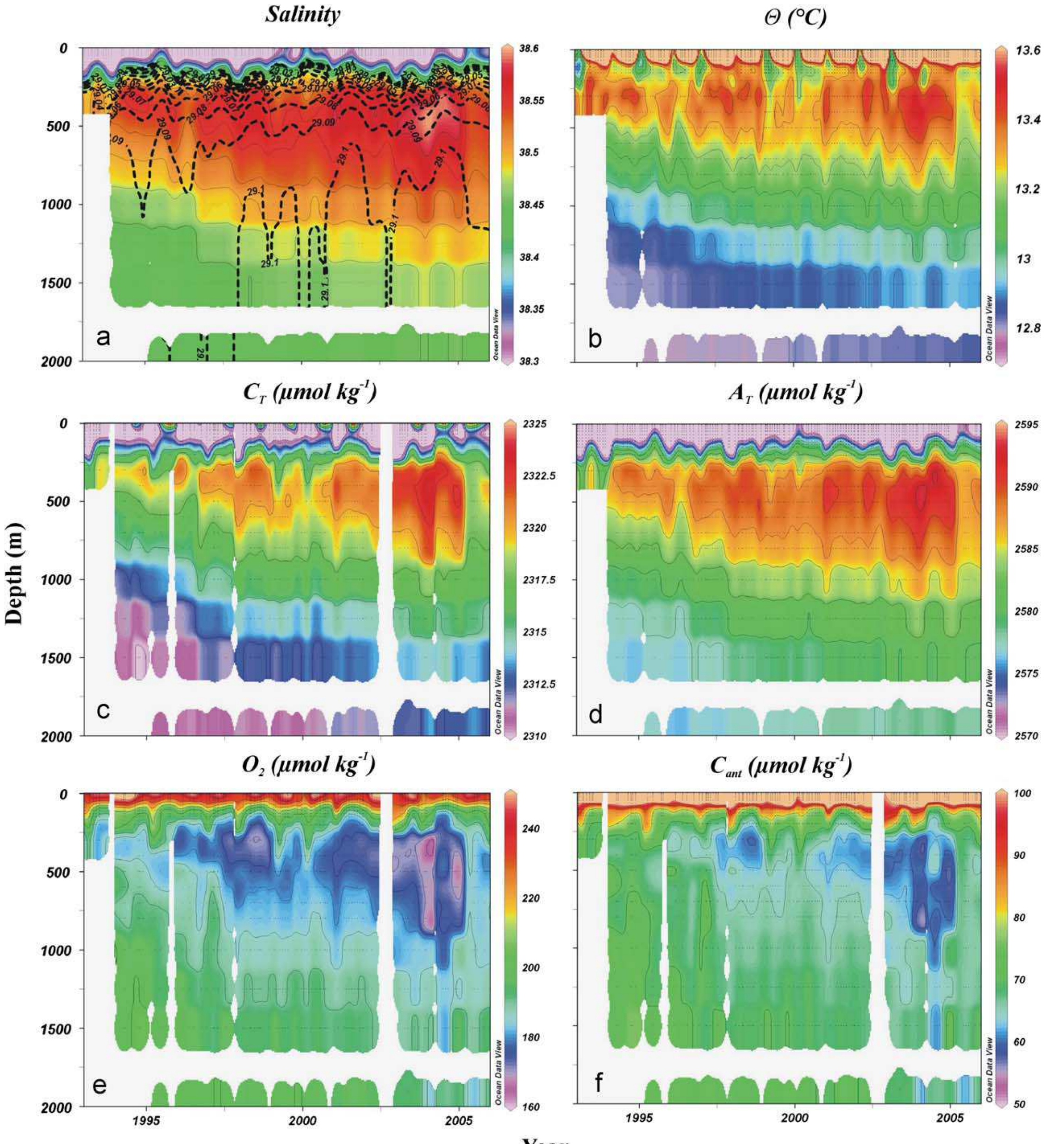


- Quantitative estimate of the carbon exchange between the Mediterranean Sea and the North Atlantic through the Strait of Gibraltar



CARBON FLUXES THROUGH THE STRAIT OF GIBRALTAR

DOC: disolved organic carbon; C_{ANT}: anthropogenic carbon; A_T: total alkalinity; C_T: total inorganic carbon; C_{bio}: inorganic carbon resulting from remineralization of organic matter; S: salinity



Temporal evolution of the properties at the DYFAMED site. a) salinity and σ_θ (isolines); b) potential temperature (θ); c) total dissolved inorganic carbon (C_T); d) total alkalinity (A_T); e) dissolved oxygen (O_2); and f) anthropogenic CO_2 (C_{ant}).

Further readings:

- Touratier F, Goyet C (2009) Decadal evolution of anthropogenic CO_2 in the northwestern Mediterranean Sea from the mid-1990s to the mid-2000s. Deep-Sea Research I, 56: 1708-1716.
- Huertas IE, Rios AF, García-Lafuente J, Makaoui A, Rodríguez-Gálvez S, Sánchez A, Orbi A, Ruiz J, Perez F (2009) Anthropogenic and natural CO_2 exchange through the Strait of Gibraltar. Biogeosciences 6: 647–662.

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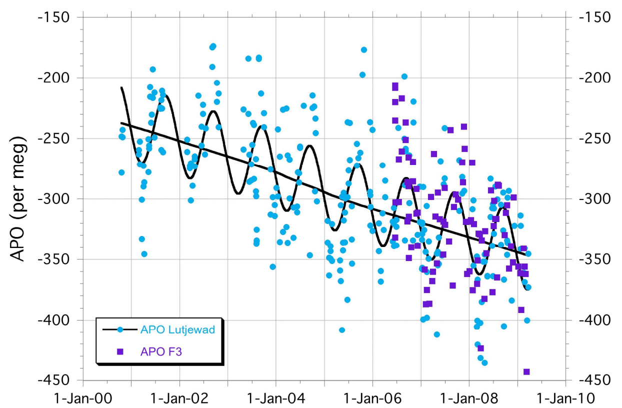
WP 14: “European Integration” fact sheet

Tasks/background of the WP

- To incorporate the European coastal seas into the European carbon budget, *in concreto* by:
  - Extending the atmospheric monitoring network with a platform station in the North Sea.
  - Establishing an atmospheric modelling framework for continental Europe including the regional seas.
  - Providing first estimates on air/sea CO_2 fluxes in European regional seas including uncertainty estimates.
- To evaluate the sensitivity of terrestrial carbon flux estimates with respect to prescribed CO_2 air-sea fluxes in an inverse modelling approach.
- To design scenarios for reduction of atmospheric emissions and discharges of carbon compounds for the year 2010, and 2020.

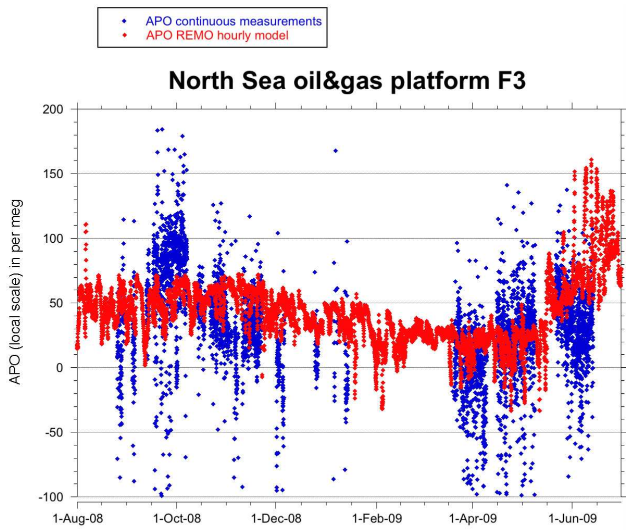
Highlights

An atmospheric monitoring station has been successfully established on the F3 oil and gas platform, 200 km off the Dutch coast (we sincerely acknowledge the support by the oil companies NAM/Shell and GdF!). This station provides continuous measurements of atmospheric O_2 and CO_2, as well as remote control air flask filling for laboratory analysis of various atmospheric tracers (again CO_2 and O_2, but also methane, CO, isotopes of CO_2). Together with the existing Dutch coastal station Lutjewad, the flask record is now 9 years long. Combined O_2 and CO_2 measurements yield the specific oceanic tracer Atmospheric Potential Oxygen (APO). Its long year trend points at an average sink of the global ocean of around 2.8 PgC/yr over this period.



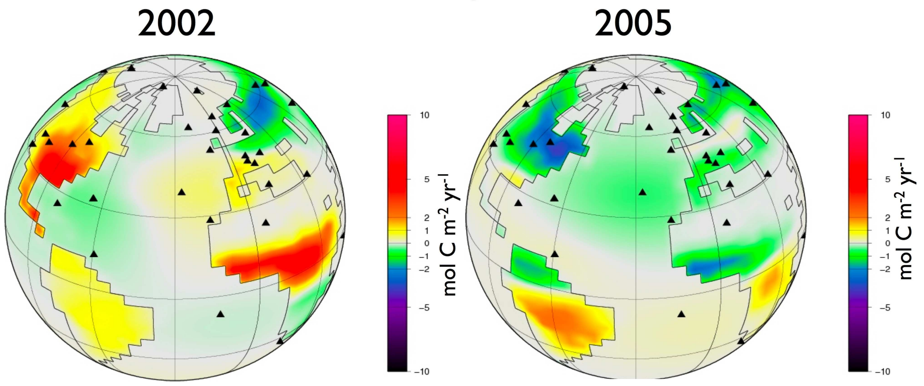
Model simulations of APO were performed using the regional model REMO (55 km x 55 km horizontal resolution) on a semi-hemispheric domain (north of 30° N). The individual components of APO form oceanic exchange processes and fossil fuel combustion were transported separately in the model. The oceanic APO component was based on APO fluxes that were derived using an inversion technique (Rödenbeck et al, 2008). The fossil fuel component was based on a temporally and spatially resolved dataset (J. Steinbach MPI-BGC, personal communication), which was derived from a combination of high-resolution CO_2 emissions (EDGARV3.2 inventory, Olivier et al., 2001) with information on fuel type based on UN energy statistics and fuel-mix specific oxidative ratios.

APO simulation results for 2006 are compared with continuous observations at F3 for August 2008 to July 2009 in the adjacent figure. Although this is not a consistent comparison it indicates that the variability of APO is underestimated and the seasonal cycle is shifted in the simulations. These deficiencies

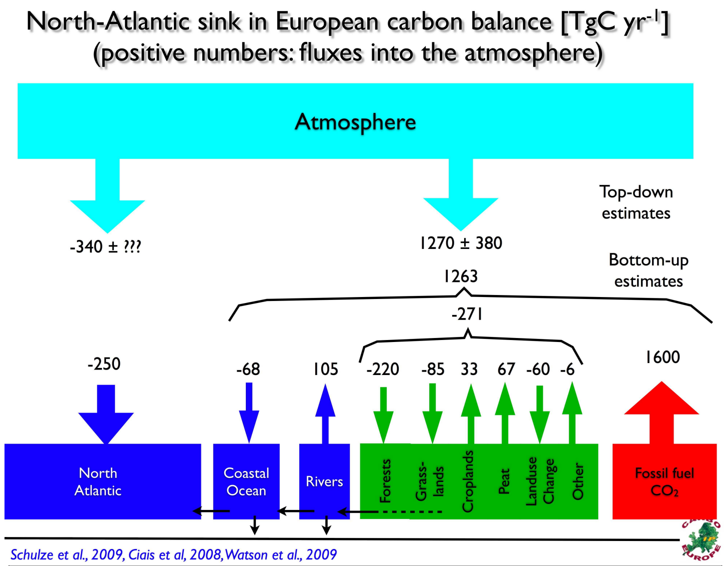


in the model simulations are probably due to the underestimation of the spatial and temporal variation in the oceanic APO source. Since long term time series of atmospheric O_2, and hence APO, have not been available in the North Sea or even in the North Atlantic, the inversion was not very well constrained in this region.

The first inverse modeling attempts for the N. Atlantic region have been produced. In spite of the severe undersampling of the region, and the presence of only CO_2 records, the inversion is already able to show remarkable interannual variability. Its results form the first top-down carbon sink estimate of the N. Atlantic, and as such are valuable comparison and validation material for the bottom-up work in CarboOcean's Core Theme 1. The reliability of the inverse results will be greatly enhanced by the establishment of more (coastal) N.Atlantic stations, and by the incorporation of APO into the inversion. The latter is, of course, only useful, if there are stations actually measuring that tracer, preferably continuously. Establishing more of those stations deserves the ocean community's full attention.

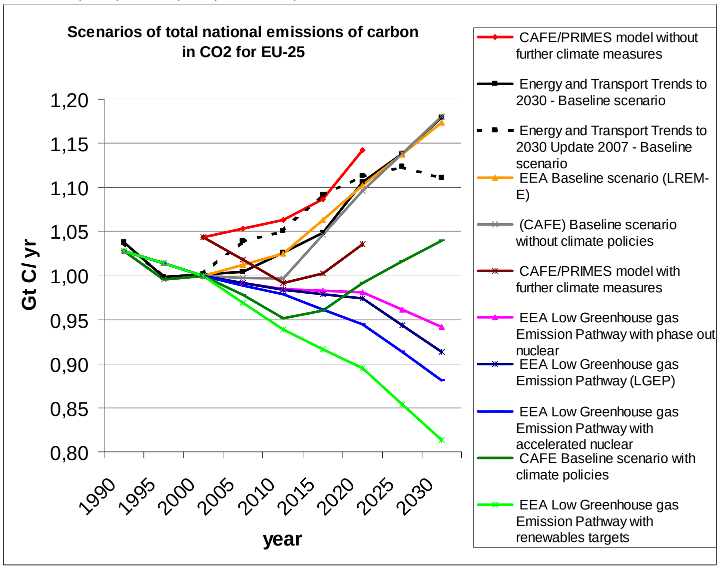


The main findings of CarboOcean as a whole, together with those of CarboEurope-IP, have been bundled in the "Integrated assessment of the European and North Atlantic Carbon Balance " booklet (available through the EU on-line bookstore). From these data, it is possible to compose the shown diagram, a simplified sketch of the European Carbon balance.



Scenarios for CO_2 emission of the EU-25 to 2030 have been designed. Apart from several baseline scenarios, also so-called policy target (POT) scenarios have been developed. Only the EEA Low Greenhouse gas Emission Pathways lead to reduction of greenhouse gas emissions. The only one leading to substantial reduction, including extensive renewable energy systems, would lead to extra costs of about 0.6% of the EU GDP.

Scenarios for CH_4 emission to 2030 in the EU-25 show that the significant reduction of European emission until 2000 is expected to extend in the near future. Differences between EEA scenarios with existing and additional climate measures are small, and substantial reductions will be reached by all of the scenarios.



Further readings

-I.T. Luijkx et al. AMTD 2, 1693-1724, 2009
-C. Sirigniano et al. ACPD 8 (6) 20113-20154, 2008
-C. Rödenbeck et al. Tellus, 60B, 685-705, 2008

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WP 15: "Physical-chemical feedbacks at high latitudes"

Tasks/background of the WP

- To evaluate the correlation between sea-ice cover, biogeochemical properties as well as river runoff distribution with partial pressure of CO2 in the northern North Atlantic and the Arctic Ocean.
- To model the reactions of the carbon system to current fluctuations and changes of climate (temperature, wind stress, precipitation, and ice cover) in the Southern Ocean and to evaluate the model skill by comparison with observations.

Highlights

- One of the major achievements and challenges has been the collection of new high quality data from ice-covered Arctic Seas, including several cruises crossing the marginal ice zone of the Barents Sea and cruises to the central Arctic Ocean in 2005 and 2007 as well as to the Siberian shelf seas in 2008. These collected data have been quality controlled and together with historic data from the Arctic Ocean submitted to the CarboOcean data base, thus building a legacy for the future.
- The surface waters of the central Arctic Ocean is under-saturated with respect to atmospheric carbon dioxide to a degree that if the summer sea ice coverage disappear an uptake corresponding to about 1 ‰ of the global anthropogenic emission is needed to get to saturation.
- By evaluating data collected from the Laptev and East Siberian Seas in the summer of 2008 an excess of DIC equal to $10 \cdot 10^{12}$ g C was computed for the whole water column, an excess that is hypnotized to be caused by terrestrial organic matter decomposition.
- The anthropogenic carbon dioxide inventory of the Arctic Ocean is about 2 600 Tg C which is approximately ~2% of the global inventory even if the Arctic Ocean volume is only ~1%.
- In the Barents Sea there is an uptake of carbon dioxide from the atmosphere equal to 30 Tg C yr^{-1} which is exported the Arctic Ocean into the intermediate dense modified Atlantic Waters.
- Coupled physical and biogeochemical model computations for the Southern Ocean has elucidated the role of iron for primary production. The uptake of iron and silica by phytoplankton, and how these influence the physiology of the cell has been shown with the phytoplankton physiology being validated by comparison with laboratory results of the cellular C:N and Si:N ratios dependence by various external factors, such as iron limitation, Si:N ratio in the medium, etc.
- The model reproduces Southern Ocean chlorophyll distribution very well and also produces a belt of elevated Si:C drawdown around Antarctica as observed.
- Runs with inter-annually variable forcing and with idealized climate change scenarios generally show relatively small reactions in the Southern Ocean primary productivity, indicating that the increased nutrient upwelling under higher and southward shifted winds are compensated by other changes, such as deeper mixed layers.

Further readings

- Jutterström, S., E. Jeansson, L.G. Anderson, R. Bellerby, E.P. Jones, W.M. Smethie Jr., and J.H. Swift, Evaluation of anthropogenic carbon in the Nordic Seas using observed relationships of N, P and C versus CFCs. *Prog. Ocean.*, 78, 78-84, doi: 10.1016/j.pocean.2007.06.001, 2008.
- Jones E.P., L.G. Anderson, S. Jutterström, and J.H. Swift, Sources and Distribution of Fresh water in the East Greenland Current. *Prog. Ocean.*, 78, 37-44, doi: 10.1016/j.pocean.2007.06.003, 2008.
- Tanhua T., E.P. Jones, E. Jeansson, S. Jutterström, W.M. Smethie Jr., D.W.R. Wallace, L.G. Anderson, Ventilation of the Arctic Ocean: mean ages and inventories of anthropogenic CO2 and CFC-11, *J. Geophys. Res.*, 114, C01002, doi:10.1029/2008JC004868, 2009.
- Anderson L.G., S. Jutterström, S. Hjalmarsson, I. Wåhlström and I.P. Semiletov, Out-gassing of CO_2 from Siberian Shelf Seas by terrestrial organic matter decomposition, *Geophys. Res. Lett.*, in press.
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Richard Bellerby (Richard.Bellerby@gfi.uib.no); Christoph Völker (Christoph.Voelker@awi.de)

WP 16: “Biological feedbacks”

Tasks/background of the WP
The **main objective** of WP16 was to estimate the strength of feedbacks between increasing atmospheric CO_2 and air/sea fluxes induced by biogeochemical processes.

Highlights

- **CO_2 – effects on marine biota:** The first CARBOOCEAN mesocosm experiment (PeECE III) carried out at the Espegrend facility near Bergen (Norway) in 2005 confirmed earlier studies suggesting a slight increase in organic C production under future CO_2 concentrations. The detailed analysis of carbon to nutrient drawdown during the mesocosm experiment revealed an enhanced C drawdown at higher than present atmospheric CO_2 levels, with an increase of the stoichiometric ratio C:N from 6 at low to 8 at high CO_2 (Riebesell et al., 2007). The effect of CO_2 sensitive C:N stoichiometry on atmospheric CO_2 levels was investigated in a model study following the IPCC SRES-A2 scenario. By the year 2100, *the associated negative feedback to atmospheric CO_2 amounted to 15µatm or an additional C uptake by the ocean of 34 Gt C (Oschlies et al., 2008).*
  The existence of such a negative feedback is conditioned by the export of excess C below the euphotic layer. A mesocosm study targeting an Arctic pelagic ecosystem highlights that this prerequisite is not always satisfied (Thingstad et al., 2008). Under conditions of bacterial production limited by the availability of organic C, the addition of excess labile C might shift the system towards enhanced bacterial production, in other words recycling, at the expense of phytoplankton. The routing of C through the bacterial loop resulted in an overall decreased C sequestration.
  The improved apprehension of biogeochemical feedbacks to atmospheric CO_2 mediated by ecosystem responses requires a detailed understanding of the coupling between C and nutrient cycles, as well as the interaction across the different levels of the foodweb (autotrophy – heterotrophy).
- **CO_2-dust-N_2 fixation:** According to laboratory experiments, the carbon and nitrogen fixation of the cyanobacterium *Trichodesmium* in semi-continuous batch cultures proofed to be affected by CO_2 concentrations with higher rates at projected future CO2 values.. This might have important implications for future element cycling and ultimately affect the strength of the biological carbon pump and hence atmospheric CO_2. (Barcelos et al., 2007)
- **Temperature controlled biological feedbacks:** The temperature sensitivity of remineralisation of organic carbon is a poorly constrained parameter of global ocean biogeochemical models. Participation in a circumnavigating cruise in 2005-6 gave the opportunity to measure the temperature sensitivity on water samples from all major ocean basins. This data set was completed with water samples collected during the PeECE III mesocosm experiment. It provided a first experimental basis for deriving a parameterisation of the temperature sensitivity in terms of a Q10-factor for dissolved and particulate organic matter. A sensitivity experiment was made with MPI-OM1/HAMOCC5 by increasing the remineralisation rate by 30% and 50% for POC and DOC, respectively, corresponding to an increase in ocean temperature of 3° C. *Increasing the remineralisation rates resulted in a reduced ocean uptake of 28 PgC during a 100-year period compared to a control simulation.*
- **Carbonate production – dissolution feedback:** The data base on $CaCO_3$ fluxes as recorded by sediment traps and compiled during the FP5 project ORFOIS was used to evaluate the pelagic dissolution rate of carbonate particles. The description of $CaCO_3$ dissolution kinetics was updated in the global ocean biogeochemical model NEMO/PISCES. The model computes a carbonate budget in line with current estimates. In order to quantify the carbonate production feedback on rising atmospheric CO_2, simulations were performed with an atmospheric pCO_2 increasing at a rate of 1% per year from the pre-industrial level to 4 times this value. Carbonate *production decreased by 27% in response to the pCO_2 increase.* Over the same period, export decreased by 29%. *The effect of reduced calcification leads to a total increase of the cumulative CO_2 uptake of 6 GtC over time which is close to negligible in view of current and expected anthropogenic CO_2 emissions.*
- **Particle flux attenuation feedback:** A global dataset of sediment trap data was compiled with 5000 entries on particulate organic carbon (POC) and mineral fluxes from experiments ranging between 50 m to 6800 m depth. Preliminary analysis showed a strong correlation between POC fluxes and mineral

fluxes over the whole depth range covered by the data, indicating that mineral fluxes determine POC fluxes in the ocean. Results show consistently higher efficiencies for POC export in systems dominated by calcium carbonate producers. Estimates of particulate inorganic carbon (PIC) to POC rain ratios based on this new analysis of sediment trap data are close to 0.06 mol mol-1 similar to recent estimates based on oceanic tracer distributions.

Further readings

- Barcelos e Ramos, J., H. Biswas, K. G. Schulz, J. LaRoche, and U. Riebesell (2007). Effect of rising atmospheric carbon dioxide on the marine nitrogen fixer Trichodesmium., *Global Biogeochem. Cycles*, 21 21: GB2028, doi:10.1029/2006GB002898
- Gehlen, M., R. Gangstø, B. Schneider, L. Bopp, O. Aumont, and C. Ethé , The fate of pelagic $CaCO_3$ production in a high CO_2 ocean: a model study2007, *Biogeosciences*, 4, 505–519
- Heinze C., 2004, Simulating oceanic $CaCO_3$ export production in the greenhouse, *Geophysical Research Letters 31(L1638)*: doi:10.1029/2004GL020613.
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- www.tos.org/oceanography/issues/issue_archive/.../21.3_euroceans.pdf
- Mesocosm webpage http://peece.ifm-geomar.de/index2005.htm

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WP 17: **"Fully coupled climate/ocean carbon cycle simulations"**

Tasks/background of the WP

- **Development**: To provide standard set ups of coupled carbon-climate models
- **Simulations** : To provide predictions of ocean carbon sources and sinks for a standard emission (A2) scenario 2000-2200
- **Analysis** **:** To determine important feedback processes – key regional areas in the response of oceanic carbon cycle to climate change

Highlights

- All 5 CARBOOCEAN models show a positive climate-carbon feedback in the next 100yrs: from **+20 ppm to +200 ppm in 2100** for the A2 scenario (range similar to Friedlingstein et al. 2006)
- The response of air-sea carbon uptake to climate change is similar at the global scale amongst the different models (**from -16 PgC/yr to -24 PgC/yr**), but varies markedly at the regional level.
- For all models, **the Southern Ocean and the N. Atlantic** are key regions in explaining the negative effect of climate change on air-sea carbon uptake.

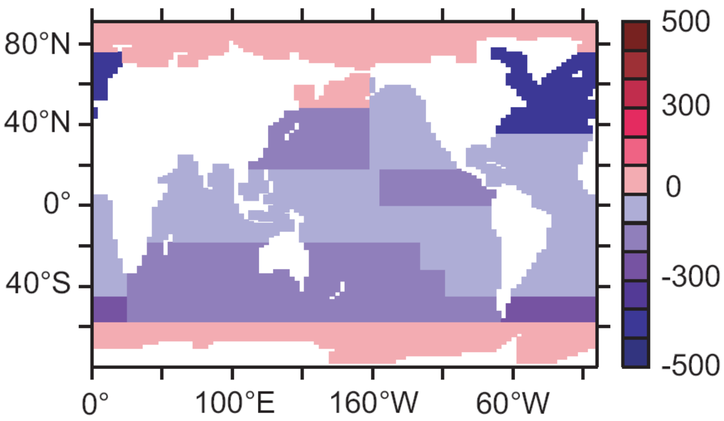

Fig. 1: Regional model-mean (NCAR,IPSL,BCCR,MPIM) **vulnerability of carbon uptake to climate change** (gC/m2/°C). Negative values indicate a decrease of carbon uptake per degree of global warming due to anthropogenic climate change (Roy et al. in prep).

- Several additional effects / processes have been tested and quantified: role of **ozone hole** on carbon uptake in the SO, impact of **other greenhouse gases and aerosols** on carbon-climate feedback, impact of changing **dust deposition**, role of **phytoplankton shifts**, role of **greenland** melting, **long term commitment** of carbon emissions, …

Further readings

- **Climate/Carbon Feedbacks:** Friedlingstein et al. JClim 2006, Plattner et al. JClim 2007, Tjiputra et al. GMDD 2009
- **Comparison of CARBOOCEAN models:** Schneider et al. BG 2008, Steinacher et al. BGD 2009, Roy et al in prep.
- **Additional Effects / Processes investigated:** Bopp et al. GRL 2005, Swingedouw et al. GRL 2006, Tagliabue et al. BG 2008, Cadule et al. GRL 2009, Lenton et al. GRL 2009, Froehlicher et al. sub.

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WP 18: “Feasibility study on purposeful carbon storage”

Tasks/background of the WP

In 2005, the IPCC launched a special report on Carbon Capture and Storage (CCS), which summarized rationale and potential techniques of separation of CO_2 and subsequent injection into geological reservoirs or the deep ocean in order to mitigate the rise of atmospheric CO_2 levels. It thus appeared mandatory to enhance the knowledge of the consequences of the suggested injection schemes in the framework of the Core Theme “Future Scenarios” within the CARBOOCEAN IP. WP 18 addresses the question how liquid CO_2 injected into the marine environment will propagate in the ocean interior, and which kind of physical, chemical and biological interactions could be expected. To do so, the WP covers research and links approaches of very different scales, ranging from the transfer reactions at the interface between concentrated CO_2 phase and seawater to the large scale transport of injected CO_2 after dissolution by global ocean circulation. Over the last 5 years, the emphasis of potential marine CO_2 storage options has changed from mid- or deepwater injection towards sub-seafloor injection, and most of the scientific progress obtained within this WP can directly be related to the risk assessment of such schemes.

Selected highlights

- The laboratory-based experimental investigation of the upward motion of CO_2 droplets rising in seawater at P,T-conditions within and outside the hydrate stability field (HSF) revealed a distinct bimodal velocity distribution. This observation is due to the ability of the CO_2 to form hydrate at the droplet/seawater interface resulting in a dramatic change of the hydrodynamic boundary conditions. The results are significant to modeling the vertical pattern of dissolution of liquid CO_2 released into water depths of less than 2500 m, either from purposeful midwater injection or accidentally seeping from sub-seabed storage sites. The results end a long-lasting controversy of the parameterization of CO_2 droplet rise rates in existing models.
- Laboratory investigation proved that dissolution of methane hydrates exposed to a flow of undersaturated seawater at conditions inside the HSF is limited by the transfer of mass, and a simple equation to assess the dissolution from such hydrates as a function of P,T, gas concentration in seawater, and current velocity close to the seafloor was established. Based on earlier findings of similarities in the behavior of methane and carbon dioxide hydrates in an open ocean flow field, a similar behavior appeared predicable at the interface between carbon dioxide hydrate and seawater. However, very recently, experiments for CO_2 under hydrodynamic and thermodynamic conditions akin to deep-sea disposal scenarios revealed a CO_2 transfer rate which differs from (i) the methane hydrate film analogue, (ii) CO_2 droplets, and (iii) values used to date in numerical CO_2 lake models. The reasons of this unexpected finding are still being evaluated.
- The capability to model the propagation of the CO_2-field around a CO_2 droplet emission site or around a gravitational stable injection of liquid CO_2 has been steadily and considerably enhanced over the course of the CARBOOCEAN project. Enhancements include, amongst others, the mathematical description of polydisperse bubble plumes, the inclusion of hydrate formation and its impact on solubility and the introduction of advanced description of turbulent mixing and lateral exchange. The improvement of the near-field (< 10 km scale) description of CO_2 and CO_2-enriched water is mandatory to estimate the effectiveness of marine purposeful CO_2 storage, as well as to assess the size of areas of potential biological damage.
- The investigation of a natural hydrothermal site where liquid CO_2 (diluted by a smaller fraction of methane and toxic hydrogen sulfide) is emanating from the seafloor in the Okinawa Trough was performed with leading scientists of WP 18. The field work in a water depth of 1600 m revealed a change in phase behavior (from liquid to gas) of the CO_2 when larger fractions of the other gases were present, and the ability of the macrofauna typical for hydrothermal systems to sustain chemoautotrophic life even in the presence of CO_2-dominated seepage sites. At the same time, it became apparent that sediments in equilibrium with a liquid CO_2 phase were basically devoid of any life, even extremophilic microbes, apparently because the high CO_2 partial pressure hamper the gain of energy from respiratory processes and interfere with certain enzymatic reactions. The overall aim of this research was to use one

of the very few liquid CO_2 emitting sites worldwide as a natural laboratory to assess the impact of leakage from a deep –sea subsedimentary CO_2 storage site.

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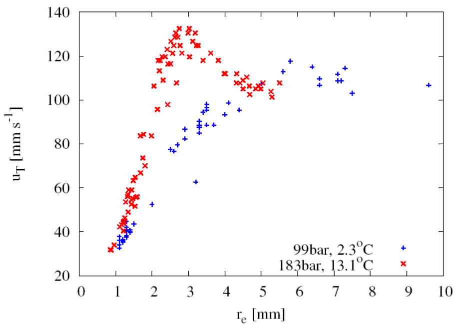
<td>
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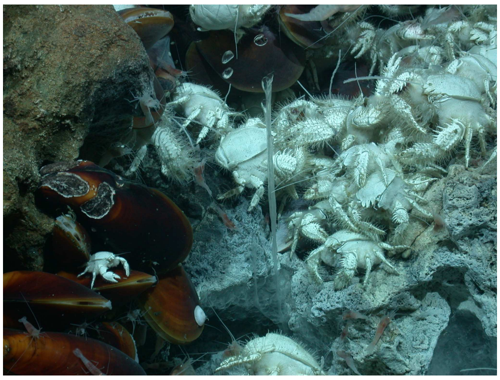
<td></td>
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<td>Steady state velocities of CO_2 droplets rising in seawater at P,T conditions within (blue) and outside (red) HSF at identical □□.</td>
<td>Natural liquid CO_2 emitting site, with in situ hydrate formation, and surrounding makrofauna living in symbiosis with chemoautotrophic bacteria</td>
</tr>
</table>

Further readings

- Bigalke, N.K., G. Rehder, G. Gust: Experimental investigation of the rising behavior of CO_2 droplets in seawater under hydrate forming conditions. Environ Sci Technol, 42(14), 5241-5246, 2008.
- Bigalke, N.K., G. Rehder, G. Gust: Methane hydrate dissolution rates in undersaturated seawater under controlled hydrodynamic forcing. Mar Chem doi:10.1016/j.marchem.2009.09.002, 2009.
- Enstad L. I., Rygg K., Alendal G. and Haugan, P. M.,Dissolution of a CO_2 lake, modeled by using an advanced vertical turbulence mixing scheme", Int. J. Greenhouse Gas Control, 2, 511-519, doi:10.1016/j.ijggc.2008.04.001, 2008.
- http://io-warnemuende.de/fs-sonne-2008.html

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WP 19: “Data and information management”

Tasks/background of the WP

- Provide a continuous data and information management

Highlights

- Data from more than 1000 surveys carried onboard from research vessels and voluntary observing ships was archived at different World Data Centers
- CARBOOCEAN data management served as a hub for data request and services (>2000 requests) from CARBOOCEAN scientists, related EC funded and national funded projects, data centers and interested scientists worldwide
- CARBOOCEAN data portal was launched - a Google like search engine for data and metadata archived at different World Data Centers
- Creation of data packages (CARINA by CT2 and SOCAT)
- Input database for Surface Ocean CO_2 Atlas (SOCAT) was compiled by the CARBOOCEAN data management office with help from Are Olsen (BCCR).
  SOCAT is the world largest surface CO_2 database with more than 7,5 million measurements covering four decades divided over 2150 cruises.

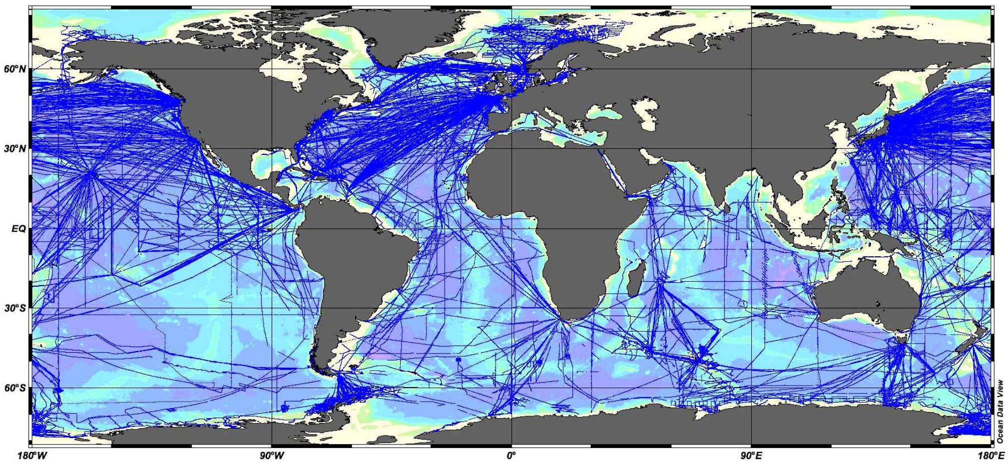

Fig. 1: Overview of SOCAT

Further readings

- SOCAT: http://www.socat.info
- CARBOCOEAN data portal: http://dataportal.carboocean.org/
- CARINA: http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html

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WP 21: “Training”

Tasks/background of the WP

TRAINING (coordinated by Janusz Pempowiak, WP21 leader)

- to train young researchers working on the project in theories and methodologies to make them better prepared for the integrated CARBOOCEAN research approach and specific research tasks
- to invite external young researchers to participate in courses to help advance research in this area (invitees would have to cover respective travel costs by own funds);
- to provide easy access to the educational material
- to encuradge exchange of ideas among young reserchers

CARBOSCHOOLS (tasks coordinated by Philippe Saugier, CarboSchools educational coordinator, www.carboschools.org)

- support to on-going & starting projects
- website, booklet translations, revision of materials, etc.
- support to emerging regional projects (continuation of LSCE + developments foreseen in Warnemünde & in Vigo)
- networking with sister initiatives: connection with ACCENT , IGLO , CRBOEUROPE

Highlights (take home messages)

- CarboOcean PhD students statistics :45 altogether, 23 CO founded, most listed at web-page (http://carboocean.iopan.gda.pl), for the breakdown by country see fig.1 , by gender
- CarboSchool proposal was accepted as an independent, 1mln Euro, EUFP7 founded project (www.carboschools.org)
- six publications were awarded diplomas in CO contest for the best CO related publication, authored by PhD students affiliated to CarboOcean

Detailed information on TRAINING and CARBOSCHOOLS can be found at:

- Training- http://carboocean.iopan.gda.pl
- CarboSchools- www.carboschools.org

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WP 22: “Dissemination, exploitation and management of knowledge“

Main tasks/background of the Work Package (WP22)

- To organize and carry out dissemination of knowledge created by CarboOcean beyond project partners and to a wider community and potential users
- To document, archive, and conserve project results and deliverables

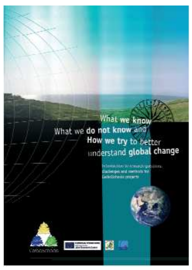
Highlights

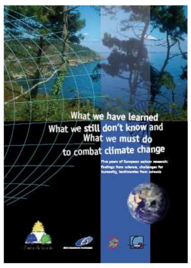
- **CarboOcean information film**: Putting CarboOcean results into a wider perspective

now available on DVD (50 min, in English)

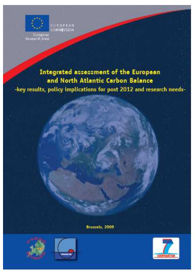
- **CarboSchools project:** Started in 2004 and funded by CarboEurope and CarboOcean projects to link researchers from several leading carbon science laboratories in Europe with secondary schools. CarboSchools has been funded by the Science in Society programme of the EU since 2008 with a target of ca. 100 schools involved. Since 2008, EPOCA, a new EU research project on ocean acidification, has been joining forces with CarboSchools
(together with WP21)

Two educational booklets available





- **Carbon assessment report:** Latest key research results and policy implications (together with WP1)



EU publication (141 pages)

Further readings

- **Project web side:** Publicly available project information at http://carboocean.org
- **Carbon assessment report:** Schulze, E.-D., Heinze, C., Volbers, A., Gash, J., Freibauer, A., Kentarchos, A. (2008). Integrated assessment of the European and North Atlantic Carbon Balance- key results, policy implications for post 2012 and research needs; 137 pages. 2008.3008, Luxembourg:

Office for official publications of the European Communities, ISBN: 978-9279-07970-2, available at: http://ec.europa.eu/research/environment/pdf/carbon_balance_report.pdf

- **CarboSchools booklet I**: "What we know, what we do not know and how we try to better understand global change" (an introduction to research questions, challenges and methods for CarboSchools projects), available at http://www.carboschools.org
- **CarboSchools booklet II**: "What we have learned, what we still don't know and what we must do to combat climate change" (synthesis of latest CarboOcean research and what kind of actions can be taken by individuals in their daily life and work to reduce their CO_2 emissions), available at http://www.carboschools.org

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