Project: **670**

Project title: **Changes in carbon uptake and emissions by oceans in a changing climate**

Project leader: **Joachim Segschneider**

Report period: **1.3.2011 - 31.12.2015**

The project **Changes in carbon uptake and emissions by oceans in a changing climate** (EU FP7 Project **CARBOCHANGE**, www.carbochange.eu) started on 1 March 2011 and continued until February 2015. The research grant at MPI-M covered a 50% PostDoc position until October 2014.

The overall goal of CARBOCHANGE was to provide the best possible process-based quantification of net ocean carbon uptake under changing climate conditions using past and present ocean carbon cycle changes for a better prediction of future ocean carbon uptake. We improved the quantitative understanding of key biogeochemical processes (particle flux, ecosystem community structure, lateral advection) and physical processes (overturning circulation, ice cover, mixing) through a combination of observations and models. We upscaled new process understanding to large-scale integrative feedbacks of the ocean carbon cycle to climate change and rising carbon dioxide concentrations.

Specific work at MPI-MET was directed at assessing the impact of temperature dependent remineralisation on ocean-atmosphere carbon fluxes, performing pulse response function experiments with the CMIP5 model, and providing model output of CMIP5 experiments to a common project data base, including a comparison of biogeochemical model results to observations and implications for deep-sea biota.

A sensitivity experiment was performed and analysed with a comprehensive global Earth System Model (MPI-ESM) as employed for the current CMIP5 project. Temperature dependent remineralisation of detritus with a Q10 of 2 was newly introduced in this model. To be as realistically as possible with regard to future ocean warming, the experiment was forced by the temperature perturbations obtained from the MPI-ESM-LR CMIP5 RCP8.5 scenario. The same MPI-ESM-LR model with temperature dependent remineralisation was then integrated for 100 years and the carbon budget was analyzed. By comparing the CMIP5 piControl experiment and the sensitivity experiment it was then possible to analyse the effect of the temperature dependent remineralisation.

It was found that for this idealized experiment the temperature dependent remineralisation would lead to an additional release of 28 GtC over the 100 years, which could be separated into an increased flux into the atmosphere of (18.7 GtC) and an additional flux of $CaCO_3$ into the sediment of 10.2 GtC. This flux was caused by a shift from opal to calcite shell forming plankton in response to changed availability of nutrients. The flux of organic sediment was reduced by 0.9 GtC. The results indicates that temperature dependent remineralisation of organic matter, which is not currently included in CMIP5 models, will further increase atmospheric CO_2 concentrations and hence climate warming.

A further line of work was the performance of pulse response function experiments with MPI-ESM-LR, in which a pulse of 100 GtC CO_2 was released into the atmosphere and the model was integrated for a further 100 years. A parallel experiment without such a pulse was also performed. The results were sent to a common data base and compared with other models. These experiments had mainly been performed with EMICS so far. Interestingly, MPI-ESM shows a faster removal of the CO_2 pulse from the atmosphere by the terrestrial and oceanic compartments than for the EMICS.

Also the uptake of CO2 in the CMIP5 experiments was analysed for the RCP8.5 scenario in CARBOCHANGE: In MPI-ESM-LR the oceanic sink of anthropogenic carbon increases from the present day value of around 2 GtC/a, which is about one third of the current emissions, to a value of around 5 GtC/a in the year 2100, which is about one fourth of the year 2100 emissions, thus indicating a weakening of the oceanic sink for fossil fuel carbon.

Results from a model integration with the MPI-ESM-LR forced by historical atmospheric CO_2 concentrations have been compared to available present day observations. In particular, pCO_2, DIC, TA, oxygen, nitrate, phosphate and silicate have been compared to the data sets of Takahashi 2009 (pCO_2), GLODAP (DIC, TA), and WOA2010 (oxygen, nitrate, phosphate, and silicate). Quantitative metrics have been applied in this comparison (correlation coefficient, ratio of standard deviations, model efficiency, percentage model bias, root mean square error, and Bhattacharyya distance.

The above comparison demonstrated that HAMOCC as part of MPI-ESM-LR captures the general observed present day distribution of biogeochemical variables fairly well. However, the skill of the model to reproduce observations decreases with depth in both configurations (Ilyina et al., 2013).

Furthermore, a contribution was made to a comparison study of observed and simulated phosphate, distinguishing between preformed and regenerated phosphate (Duteil et al., Biogeosciences, 2012).

Finally, an experiment with the CMIP5 model setup identical to the 'historical' experiment (1850 – 2005) was performed with CFCs included as these were not part of the standard CMIP5 experiments performed at MPI-M.

Further contributions where made to a publication on the pulse response function experiments with the CMIP5 model that had been performed in 2012 (Joos et al., 2013).

As a contribution to the Global Carbon Project, an NCEP driven model experiment was performed using repeated NCEP cycles and historical atmospheric CO_2 concentrations from 1750 to 2012. Seasonal fields on a 1x1° grid and annual mean sums of atmosphere – ocean CO_2-fluxes were delivered for the years 1959 to 2012 to the GCP data base. Interestingly, these values are about 25% lower than in the coupled model, which will be further investigated (Le Quéré et al, 2014, 2015).

A further computation was performed to adjust the oceanic carbon inventory to a revised value based on recent observations from GLODAP (Global Data Analysis Project). The estimate for the global inventory was changed from the old estimate of 38500 GtC to 36800 GtC, and the coupled model MPI-ESM was integrated for 40 years to provide an updated model carbon inventory.

CARBOCHANGE work resulted in numerous publications (see references below). and on a poster at the workshop celebrating the 25th anniversary of DKRZ as well as on a CARBOCHANGE project meetings in Norwich (Li et al., Internal- and intra-model variability in CMIP5 interactive carbon cycle projections of fossil fuel CO_2 invasion into the ocean; and an oral presentaion at the EGU.

Moreover, a contribution to a feedback analysis based on the CMIP5 idealized experiments was made (Schwinger et al., 2014) and the effect of ocean acidification on deep-sea biota in the North Atlantic (Gehlen et al., 2014)

Publications with contributions from CarboChange:

Le Quéré C. et al. (47 co-authors incl **J. Segschneider**), 2015. Global Carbon Budget 2014. Earth System Science Data, 7(7):47-85. DOI: 10.5194/essd-7-47-2015

Gehlen, M. R. Séférian, D. O. B. Jones, T. Roy, R. Roth, J. Barry, L. Bopp, S. C. Doney, J. P. Dunne, C. Heinze, F. Joos, J. C. Orr, L. Resplandy, **J. Segschneider**, J. Tjiputra, 2014. Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk. Biogeosciences, 11(23):6955-6967. DOI: 10.5194/bg-11-6955-2014

Schwinger, J., J.F. Tjiputra, C. Heinze, L. Bopp, J.R. Christian, M. Gehlen, T. Ilyina, C.D. Jones, D. Salas-Mlia, **J. Segschneider**, R. Séférian, I. Totterdell, 2014. Non-linearity of ocean carbon cycle feedbacks in CMIP5 earth system models. J. Clim., DOI: 10.1175/JCLI-D-13-00452.1

Le Quéré C. et al. (47 co-authors incl **J. Segschneider**), 2014. Global Carbon Budget 2013. Earth System Science Data, 6, 235-263.

V. Cocco, F. Joos, M. Steinacher, T. L. Frölicher, L. Bopp, J. Dunne, M. Gehlen, C. Heinze, J. Orr, A. Oschlies, B. Schneider, **J. Segschneider**, and J. Tjiputra, 2013. Oxygen and indicators of stress for marine life in multi-model global warming projections. Biogeosciences., 10, 1849-1868.

Joos, F. et al. (28 co-authors incl. **J. Segscneider**), 2013. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis, Atm. Chem. Phys., 13, 1-31.

Ilyina, T. K. D. Six, **J. Segschneider**, E. Maier-Reimer, H. Li, and I. Nunez-Riboni, 2013. Global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth system model in different CMIP5 experimental realizations, J. Adv. Mod. Earth Syst., 5, 1–29.

Jones, C., E. Robertson, V. Arora, P. Friedlingstein, E. Shevliakova, L. Bopp, V.Brovkin, T. Hajima, E. Kato, M. Kawamiya, S. Liddicoat, K. Lindsay, C. Reick, C.Roelandt, **J. Segschneider**, and J. Tjiputra, 2013: 21st Century compatible CO_2 emissions and airborne fraction simulated by CMIP5 Earth System models under 4 Representative Concentration Pathways. J. Climate, 26, 4398-4413. doi:10.1175/JCLI-D-12-00554.1

Segschneider, J. and J. Bendtsen (2013). Temperature-dependent remineralisation in a warming ocean increases surface pCO2 through changes in marine ecosystem composition. Global Biogeochemical Cycles, 27, 1214-1225.

Duteil, O., W. Koeve, A. Oschlies, O. Aumont, D. Bianchi, L. Bopp, E. Galbraith, R. Matear, J.K. Moore, J. Sarmiento, and **J. Segschneider**, 2012. Preformed and regenerated phophate in ocean general circulation models: can right concentrations be wrong? Biogeosciences, 9, 1-12.

Impact of temperature dependent remineralisation in a warming ocean on the global carbon cycle (CARBOCHANGE – BMBF Project 670)

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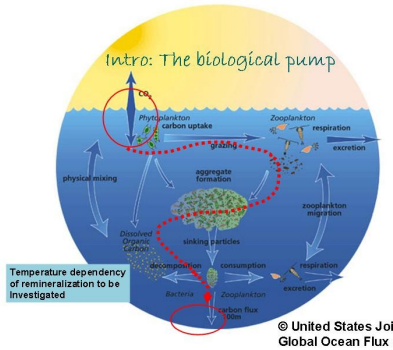
Motivation

The biological pump exports carbon from the atmosphere to the subsurface ocean (see right)

How will this change in a warming ocean?

- Observations demonstrate temperature dependency of remineralization of organic matter (Bendtsen et al., submitted) $Q_{10} \approx 2.5$
- → rise in temperature (due to climate change) will increase remineralisation rate
- but: increased remineralisation will increase near surface nutrient levels with a potential for a negative feedback by increased production
- what is the net effect of increased remineralization on the carbon budget and air-sea exchange?



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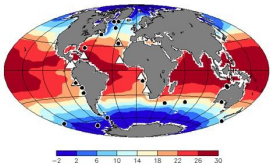
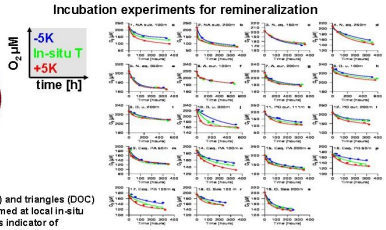
The experimental basis

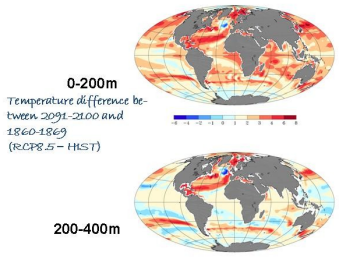


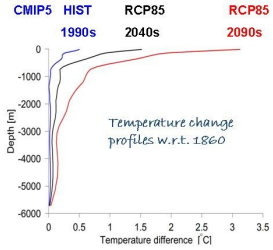
Water samples were taken at locations indicated by bullets (POC) and triangles (DOC) around the world (see map). Incubation experiments were performed at local in-situ temperature and +/- 5 °C. Oxygen consumption was measured as indicator of remineralization and a fit was made in order to determine Q_{10} rates (lines).

Incubation experiments for remineralization

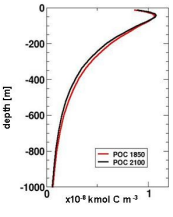


Projected temperature changes (CMIP5) and experiment setup





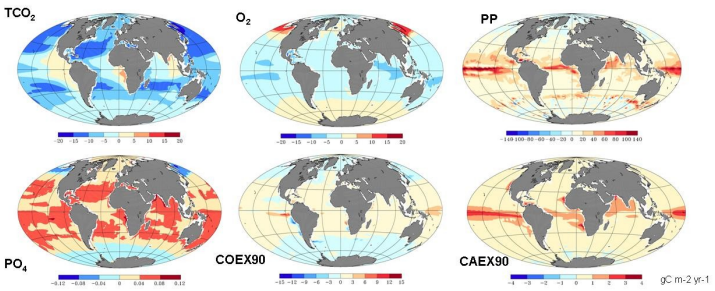
Change in remineralization profile of POC



Experiment set-up

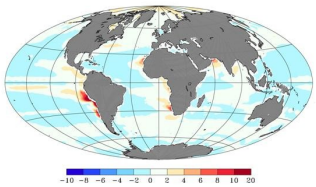
Basis: CMIP5 piControl (MPI-ESM-LR)
Identical experiment set up but:
Temperature perturbation field from RCP85 2090-2100 used for remineralization only (!)
with a Q_{10} of 2 (POC and DOC)
Integrated for 100 years
Differences with identical years from piControl

Impact on biogeochemistry

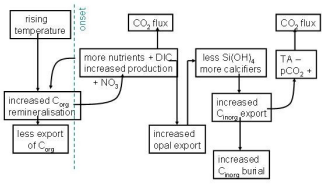


Change in global inventories by year 100	[Pg C]	Accumulated change in ocean boundary fluxes by year 100	[Pg C]
TCO_2	-27.95	Air-sea CO_2 exchange	18.66
Detritus	-0.06	Sedimentation of $CaCO_3$	10.22
$CaCO_3$	0.05	Sedimentation of organic carbon	-0.87
Phytoplankton	0.02		
Zooplankton	0.03		
Dissolved organic carbon	0.27		
Total	-27.63		28,01

Impact on pCO_2 [ppm]



Flowchart of processes



- Temperature dependent remineralisation has an impact on carbon budget
- Increase of pCO_2 mainly in regions of high biological production
- Decrease in oligotrophic regions
- Net loss almost 0.3 GtC/a
- Calcite export plays significant role
- Role of alkalinity needs to be further investigated
- Going from sensitivity exp. to absolute T-dependent remineralisation requires tuning/new spinup

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