2.1.3 Research Topic A3: Present and Future CO_2 Uptake

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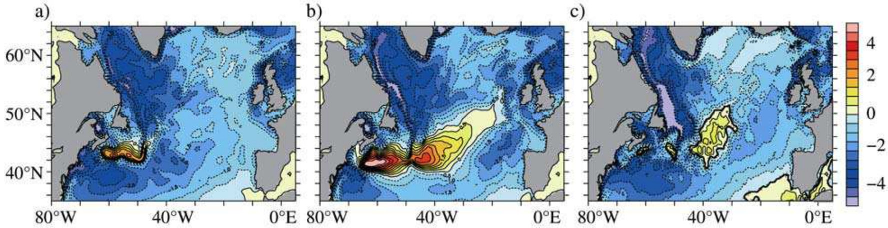
1. Summary / *Zusammenfassung*

An assessment of the fate and future evolution of the oceanic CO_2 uptake is of central importance for projections of both climate change and of changes in oceanic ecosystems. Modeling the coupled system of ocean circulation and biogeochemistry has become a key tool for understanding the principle physical and biological mechanisms which govern the ocean carbon cycle and its variability. The reliability of model-based projections of anthropogenic changes is still severely hindered, however, by strong model dependencies on the representation of many poorly constrained processes, both in the physical and in the biogeochemical system. We propose to advance this field by exploring novel approaches of combining model simulations with oceanic measurements, with the objective of the identification and improved representation of the critical processes governing circulation and carbon cycling in the ocean. Building on the combined expertise and activities of the participating groups in ocean circulation and carbon cycle modeling on the one hand and in modern aspects of inverse modeling and optimization theory on the other hand, the JRG will explore innovative methods for assimilating data in three-dimensional ocean carbon-cycle models to systematically assess and reduce model uncertainties as a key step toward reliable determinations of natural variability and anthropogenic changes in the physical and biogeochemical properties related to current and future oceanic CO_2 uptake.

Die Prognosen sowohl von Klimaänderungen als auch von Veränderungen ozeanischer Ökosysteme hängen entscheidend von der zukünftigen Entwicklung der ozeanischen CO_2-Aufnahme ab. Während das Verständnis der dabei beteiligten Mechanismen durch gekoppelte Modelle der ozeanischen Zirkulation und Biogeochemie sehr befördert worden ist, sind quantitative Modellprognosen durch Defizite in der Darstellung der beteiligten Prozesse noch sehr eingeschränkt. Die Nachwuchsgruppe wird durch innovative Ansätze in der Modell-Daten-

Synthese, aufbauend auf einer Kombination der Expertise in hochauflösender Ozeanmodellierung am IFM-GEOMAR und in modernen Methoden nichtlinearer Optimierung am Zentrum für Numerische Simulation der CAU Kiel, einen neuen Weg beschreiten, der über eine verbesserte Darstellung der kritischen Prozesse zu belastbaren Aussagen über Veränderungen in den physikalischen und biogeochemischen Eigenschaften des Ozeans führt.



Annual mean air-sea CO_2 exchange in three different models in mol C/m^2/yr. Negative values (blue) denote uptake of CO_2 by the ocean. The figure demonstrates how a typical bias in the physical model affects CO_2 uptake: a wrong pathway of the North Atlantic Current off Newfoundland in a model with low resolution (b) leads to a large and unrealistic release of carbon by the subpolar North Atlantic. In a corrected model using simple data assimilation schemes (a) this bias is reduced, and the simulation is similar to a simulation with drastically increased resolution (c) (a and b from Eden and Oschlies 2006).

2. State-of-the-art

Observational compilations of the ocean's inorganic carbon inventory indicate that the ocean may have taken up about half of the total anthropogenic CO_2 emissions created since the beginning of the industrial period (Sabine et al. 2004). Due to the required, basic assumptions, current estimates involve uncertainties of at least 20% in anthropogenic CO_2, particularly in regional distributions (Wanninkhof et al. 1999). Quantitative understanding of oceanic uptake and carbon cycling has been aided by ocean circulation models coupled to certain types of carbon chemistry (Maier-Reimer and Hasselmann 1987, Tanhua et al. 2006). Model comparison studies reveal, however, large inter-model differences in the regional patterns of storage and fluxes of anthropogenic CO_2 (Orr et al. 2001). These appear to be partly related to biases which are typical of coarse-resolution ocean models (Doney et al. 2004, Eden and Oschlies 2006) and partly to the simplified treatment of biogeochemical processes which are of potential importance for the carbon cycle, but are poorly constrained by observations (Aumont et al. 1999, LeQuere et al. 2000, Wetzel et al. 2005). Recent research has begun to explore inverse methods for optimizing biogeochemical model parameters (Fasham and Evans 1995, Schartau et al. 2001), but has thus far, however, primarily focused on one dimension, thus overlooking the effects of lateral advection and mixing (Oschlies and Schartau 2005).

3. Previous and on-going work of the proponents

The project builds on the combined expertise in high-resolution ocean circulation and biogeochemical modeling at IFM-GEOMAR as well as in modern algorithms in numerical mathematics and computer science at the Interdisciplinary Center for Numerical Simulation (ICN) and is strongly aided by expertise provided by the observational groups at IFM-GEOMAR in the determination and interpretation of biogeochemical properties related to the anthropogenic carbon signal. Ocean model development has a long history in Kiel, witnessed by the leading role of the proponents in major international panels, e.g., of WCRP modeling groups. Modeling activities have contributed to the German CLIVARmarine and DEKLIM programs and are involved in SFB 460, DFG FG 432, and the EU projects NOCES, CARBOOCEAN and DYNAMITE. On-going projects at ICN include research into modern algorithms in numerical mathematics and computer science, in particular based on expertise in combinatorial and continuous optimization gained in DFG GK 357 Efficient Algorithms and Multiscale Methods and DFG Priority Program 1126 Algorithmic Aspects of Large and Complex Networks.

4. Objectives

The objective of the research proposed here is to quantify the present and future uptake of anthropogenic CO_2 by the global ocean, pathways into the ocean, and interactions with the biogeochemical system. The research program will build on and be embedded in continuing developments in coupled physical-biogeochemical modeling carried out at IFM-GEOMAR, in particular within the context of the Kiel Climate Model System (KCMS). Linkage with expertise at ICN will provide the critical means for refining modeling capabilities through the exploration of novel algorithms for large-scale optimization problems. ICN will thus provide the framework for an iterative reduction of model uncertainties, particularly in relation to simulations of biogeochemical components and air-sea gas exchange. The specific objective of the JRG is to contribute to the project’s goal of an improved determination of the ocean’s CO_2 uptake, by exploring advanced methods of constraining numerical simulations through the assimilation of both physical and biogeochemical data. This represents, in the context of three-dimensional carbon cycle models, a grand challenge of vastly increased complexity. In combination with the activities of the proponents at IFM-GEOMAR and ICN, the project will thus embark on these objectives:

(1) the application and assessment of innovative methods in assimilating data in three-dimensional ocean carbon-cycle models; exploration and utilization of modern algorithmic methods for optimizing model simulations of ocean variability and future change.

(2) the refinement of the KCMS hierarchy by identifying the critical physical and biogeochemical processes governing simulations of the oceanic carbon cycle as well as through systematic combinations of model dynamics and relevant data for the last decades;

(3) a determination of the mechanisms and rates of changes in the ocean’s biogeochemical properties, as driven by ocean-atmosphere variability on seasonal to interdecadal time scales;

(4) a determination of the impact of anthropogenic climate changes, such as higher stratification and lower levels of mixing, more frequent El Niño episodes, the slowing of Atlantic overturning, a decrease in Arctic sea ice, etc., on oceanic CO_2 uptake and marine biogeochemical cycles.

The A3 ocean modeling program is closely related to the climate modeling in A4; together these projects will contribute to various other Cluster projects by providing model simulations of the earth system, quantifying the natural variability and range of future changes in various physical and biogeochemical properties (e.g., circulation, temperature, CO_2 uptake), as required in A1, A2, A5, A7 and B1. A3 research will heavily rest on the infrastructure and tools provided by research platform P1 and interact with the observing system capabilities provided by P4; together with A4 it will contribute to the development of the comprehensive “Kiel Climate Model System” provided and maintained through P1.

5. References

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