The vulnerable ocean: Decadal changes in the North Atlantic carbon and oxygen cycles

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Abstract
Repeat measurements of the interior North Atlantic have revealed surprisingly large changes in its oxygen and inorganic carbon content over the last few decades, primarily located at mid-depth and associated with intermediate and mode waters. While some of the inorganic carbon changes are due to the oceanic uptake of anthropogenic CO2, the oxygen changes and the remainder of the inorganic carbon changes are driven by some combination of variations in ocean circulation/mixing and variations in the ocean's biological pump. Presently available analyses suggest that most of the changes are physically driven, owing to a climatically forced slowdown of the ventilation and circulation of these mode and intermediate waters. In the presence of a continuing biological pump, this led to a rapid consumption of the available oxygen and the buildup of anomalous inorganic carbon. We will present updated analyses on the basis of a newly available data base of North Atlantic oxygen and carbon observations as well as new model-based results. In particular, we will investigate how the simultaneous measurements of oxygen and inorganic carbon can help us to extract the mechanisms responsible for these changes as well as better elucidate that component of the inorganic carbon changes that is due to the uptake of anthropogenic CO2. A better understanding of these components and processes are crucial for improving our ability to assess the vulnerability of the ocean in this century, especially since the observed changes are remarkably congruent with the changes that model projections suggest for a warming world. The ocean interior, and particularly its oxygen content, may therefore act as the miner's canary bird of anthropogenic climate change.
Variation in atmosphere-ocean fluxes of CO₂ in the Atlantic and Southern Oceans: first results from the Carbo-Ocean observing system

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CO₂, air-sea flux, variability, observing system

Abstract
Core Theme 1 of Carbo-Ocean IP is the first time that an effective network to monitor air-sea fluxes of CO₂ has been set up to cover entire ocean basins with adequate spatial and seasonal time resolution. In the North Atlantic the project has instrumented five commercial shipping routes and one research supply ship, as well as two time series stations, to measure surface pCO₂ and the associated variables required to monitor the flux. Our priority is to be able to monitor how the North Atlantic CO₂ sink varies seasonally, inter-annually and interdecadally. This will enable us to understand better the ocean carbon cycle and the factors causing variation on these time scales. It enables us to test our current models and understanding of these processes; finally it helps to constrain global and Continental scale budgets of CO₂ by adding valuable constraints to atmospheric inversion estimates of these fluxes.

Though the observing system has only been in place for a year, it is already giving valuable information that can be compared to more isolated historical records. Comparison with such records confirms that the north Atlantic sink for CO₂ varies strongly and coherently over large regions from year to year. Over the period from the mid-nineties to the present, there has been a sharp decline in the North Atlantic sink for atmospheric CO₂ between about 20N and 60N -- we estimate about 0.25 Pg C yr⁻¹, more than 50% of the net sink in the region.

We are also active in the South Atlantic and Southern Ocean with a valuable data coverage from these more remote areas. In the Southern Ocean substantial measurement effort has been put into using drifting instrumented buoys. These have shown that there is considerable variation in air-sea fluxes on seasonal time scales, dominated by changes in sea-surface pCO₂ there.
Temporal changes of the CO$_2$ system in the North Sea and the North Atlantic Ocean

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Abstract
The carbon cycle of the North Sea, a NW European Shelf sea, has been investigated in detail in 2001/2002 covering the North Sea by a 90 stations grid during all four seasons. Underway measurements of the partial pressure of CO$_2$ (pCO$_2$) complemented the station sampling. In 2005 the 90 stations and surface waters have been resampled again during the same period in summer in order to investigate the temporal variability of the carbon and related nutrient cycles. The atmospheric pCO$_2$ increased from approximately 364ppm in 2001 to 375ppm in 2005, however, the pCO$_2$ observations reveal that the surface water pCO$_2$ increased at a higher rate. This in turn means that the partial pressure difference, being the driver of the CO$_2$ air-to-sea flux, decreased. Similar trends have recently been reported by others for the open North Atlantic Ocean. While necessarily assuming the North Sea carbon cycle to be in steady-state during the initial evaluations of the 2001/2002 data, the consideration of the recent 2005 data allows us to identify an increase of the water column DIC inventory from 2001 to 2005, this in addition to the CO$_2$ exported to the North Atlantic Ocean via the continental shelf pump mechanism. The results will be extrapolated to the entire North Atlantic Ocean employing a global ocean carbon model. Several hypotheses will be compared for the discrepancy between the rates of increase of the atmospheric and surface water pCO$_2$, in order to define the most likely explanation.
Biological and physico-chemical ocean feedbacks to rising atmospheric CO₂: The case of ocean acidification.

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Abstract
Rising atmospheric CO₂ since the beginning of industrialization and the resulting modification of climate forcing drives profound changes in the ocean. These changes impact on ocean physics, chemistry and biology, which all in turn feed back to atmospheric CO₂ increase. CarboOcean aims at an improved quantification of biological and physico-chemical oceanic feedbacks to atmospheric CO₂ increase, as well as their future evolution. Our approach relies on the synergy between in situ observations, experimental and modelling studies. I will exemplify our approach with focus on ocean acidification and the fate of future marine calcification. In the modern ocean, CaCO₃ is produced by a variety of organisms: e.g. coccolithophores (calcite), pteropods, corals (aragonite). Biocalcification takes place in supersaturated waters and strongly depends on the level of supersaturation. Unmitigated ocean acidification will trigger a decrease in calcification, ultimately threatening the existence of calcifiers and causing major changes to marine ecosystems. Calcification feeds back on atmospheric CO₂ by decreasing alkalinity and increasing pCO₂ of waters. The magnitude of the feedback associated with changing calcification is still under debate. The response of marine biota to elevated pCO₂ was studied in controlled experiments. They served as a basis for the parameterization of calcification as a function of saturation, which was implemented to the biogeochemical ocean model PISCES. To investigate the response of marine calcification to ocean acidification and to quantify its impact on air-sea exchange of CO₂, model experiments were carried out with an atmospheric pCO₂ increasing from 1xCO₂ (pre-industrial state) to 4xCO₂, with a 1% per year increase. Model results indicate a strong decrease of calcification (-28%) in response to rising atmospheric CO₂, along with an increase of pelagic carbonate dissolution from 60 to 75% of net calcification, but a moderate impact on air-sea fluxes.
Climate feedback on the marine carbon cycle in CarboOcean Earth System Models

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Keywords
Earth System Modelling, marine carbon cycle, anthropogenic carbon uptake, climate feedback

Abstract
To estimate the climate feedback on the carbon cycle within CARBOOCEAN, Earth System Models comprising an atmospheric, land biosphere and soil, and an oceanic component including the marine carbon cycle are forced with 20C3M and SRES A2 CO₂ emissions from 1860 to 2100. In one of the experiment streams the climate is kept at a fixed pre-industrial state while CO₂ increases, in the other it is allowed to evolve freely in response to the CO₂ emissions. The difference between the two experiments can be used to estimate the climate sensitivity of the terrestrial and marine carbon cycle. Since the uptake of the land biosphere is higher in the non climate feedback experiments, resulting in a lower pCO₂, the effect of higher temperature and higher atmospheric pCO₂ in the climate feedback experiments are counteracting with regard to the oceanic carbon uptake. Note that this is an important difference from concentration driven experiments to derive climate sensitivity. The climate carbon feedback is positive for all models (higher atmospheric pCO₂ in the feedback experiments) but varies strongly in magnitude. The reasons for these discrepancies are not a priori clear due to the complex structure of the earth system models but will be investigated in more detail in the near future by identifying the response of the individual components (land biosphere/ocean) and the different marine carbon pumps (physical, biological, and alkalinity counter pump).