

CALCITE AND ARAGONITE UNDERSATURATION UNDER RISING ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS AND GLOBAL WARMING

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INTRODUCTION

Increasing atmospheric CO₂ concentrations lowers oceanic pH and carbonate ion concentrations, thereby decreasing the level of saturation of calcium carbonate [Feely *et al.*, 2004]. This acidification will eventually lead to undersaturation and dissolution of calcium carbonate in parts of the surface ocean. Besides affecting the global carbon cycle, these changes threaten marine organisms that form their exoskeletons out of CaCO₃, which are essential components of the marine food web [Orr *et al.*, 2005]. We investigate magnitude and pattern of ocean acidification due to increasing atmospheric CO₂ concentrations and global warming, both for the recent past and the near future, using the reduced complexity, Bern 2.5-D physical-biogeochemical climate model and a series of CO₂ emission scenarios and CO₂ stabilization profiles provided by the Intergovernmental Panel on Climate Change (IPCC). The focus of the study is on the impact of global warming and induced ocean circulation changes on the projected oceanic pH and carbonate ion reductions.

MODE

The cost-efficient, Bern 2.5-D physical-biogeochemical climate model [Marchal *et al.*, 1998] is used, which has previously been applied to study global warming – marine carbon cycle feedbacks [Joos *et al.*, 1999, Plattner *et al.* 2001]. The model consists of a zonally averaged, dynamic ocean model, coupled to an atmospheric energy balance model with an active hydrological cycle, and includes representations of the marine and terrestrial carbon cycles. Sediment processes are neglected. CO₂ fertilization of the terrestrial biosphere is taken into account by a logarithmic dependence of net primary production on elevated atmospheric CO₂. Model setup and simulations are as described in detail in Plattner *et al.* [2001]. Radiative forcing from observed historic and projected future atmospheric CO₂, non-CO₂ greenhouse gases and aerosols is taken into account [see Joos *et al.*, 2001, for details]. Ocean acidification results for the historic period are broadly consistent with basin- to global-scale averages from observation-based estimates. Simulated future projections are comparable to results from more comprehensive ocean general circulation models [Orr *et al.*, 2005]. The efficiency of the Bern 2.5-D climate model allows to run a large number of IPCC carbon emission and CO₂ stabilization scenarios, covering the full range of available IPCC projections until year 2100 or year 2500, respectively. This permits to investigate past and future oceanic changes on timescales from decades to several centuries, and to estimate the sensitivity of the results to model setup, atmospheric CO₂ concentrations, and applied radiative forcing.

RESULTS AND DISCUSSION

The observed historic and the projected future atmospheric CO₂ increase causes large worldwide reductions in surface pH and carbonate ion concentration and thus in the saturation states of calcite and aragonite. The degree of modeled changes is almost exclusively determined by the projected level of atmospheric CO₂ concentrations. Estimated pH changes since preindustrial times for the present are close to 0.1. For stabilization of atmospheric CO₂ at 1000 ppm (scenario WRE1000), corresponding to the upper end of atmospheric CO₂ levels applied, and year 2100 (year 2500), high latitude surface pH is

projected to decrease by up to 0.35 (0.65) compared to the preindustrial state. The largest changes in CaCO_3 saturation states in all scenarios occur in the tropical surface ocean, with reductions of up to 115 mmol m^{-3} by 2100, and of over 160 mmol m^{-3} by 2500 in WRE1000; however, these tropical waters always remain saturated in our simulations. Conversely, in the high southern latitudes, undersaturation with respect to aragonite occurs near the end of the 21st century, with the timing being dependent on the CO_2 history. In the WRE1000 case, all northern and southern high latitudes become undersaturated in both calcite and aragonite after 2100. These changes also extend well below the sea surface, leading to undersaturation throughout the water column at high latitudes, and substantial shoaling of the calcite and aragonite saturation horizons.

The contribution of global warming and induced ocean circulation changes to the changes in oceanic pH, carbonate ion concentration, and saturation states is small when compared to the effect from the anthropogenic CO_2 increase itself. Global warming slightly moderates changes induced by anthropogenic CO_2 (by 10% at most) for all scenarios. With warming, CO_2 solubility is reduced which in turn reduces oceanic CO_2 uptake and increases the carbonate ion concentration. Global warming also delays undersaturation with respect to both aragonite and calcite by about 25 years in Southern Ocean and North Atlantic surface waters. In the extreme case of a complete shutdown of the North Atlantic Deep Water formation after 2100 and a large-scale reorganization of the global thermohaline circulation in scenario WRE1000, undersaturation becomes largest in the North Atlantic Ocean by the end of year 2200, due to the associated changes in surface salinity.

Modeled changes in marine biology have a minor impact on ocean acidification levels and carbonate saturation states in all scenarios. However, the representation of marine biology in the ocean carbon cycle component of the Bern 2.5D model is very simplistic. We expect that the projected large-scale changes in oceanic conditions will have a large impact on ecosystem structure and biodiversity, particularly at high latitudes, with substantial consequences not only for marine life but also for the cycling of carbon and other biogeochemically important elements.

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