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Modelling ocean acidification in the Nordic and Barents Seas in present and future climate

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ABSTRACT

An ecosystem model, NORWECOM.E2E including a module for the carbonate system, has been used to investigate the effects of rising atmospheric CO_2 and climate change on the ocean's acid–base state in the Nordic and Barents Seas. Using the 20C3M control run and the A1B emission scenario, a downscaling of the GISS-AOM global climate model has been used to force the ecosystem model for a reference (1981–2000) and a future climate (2046–2065) simulation respectively. The simulations demonstrate how the saturation state of seawater with respect to aragonite will evolve, with a shoaling of the saturation horizon of approximately 1200 m in the Nordic Seas, and a large increase in area extent of under saturated surface waters. The simulated pH change in the surface water is −0.19 from 2000 to 2065, while the model estimates an almost doubling of the CO_2 air–sea flux in the Barents Sea increasing the uptake from 23 to 37 gC m^{-2} yr^{-1}. The main driver for the modelled changes in surface fCO_2 is the change in DIC, with only minor contributions from temperature, salinity and total alkalinity.

1. Introduction

The average pH of the surface waters of the global oceans has decreased from approximately 8.2 before the onset of the industrial revolution to a present average of approximately 8.1 (Caldeira and Wickett, 2003; Orr et al., 2005). This ocean acidification is a result of the dissolution of CO_2 corresponding to approximately 1/3 of the CO_2 released to the atmosphere from combustion of fossil fuels, industrial cement production and by changes in land use (Canadell et al., 2007; Sabine et al., 2004). Compared to paleo-geological estimates of previous undulations in ocean carbon chemistry, the current ocean acidification is extremely rapid (Honisch et al., 2012). Moreover, the present concentration of CO_2 in the atmosphere far exceeds the peaks reached during the glacial changes the last 650,000 years, and probably the last 20 million years (Pearson and Palmer, 2000).

The eastern part of the Nordic (Norwegian, Iceland and Greenland) Seas is dominated by Atlantic water entering through the Faroe-Scotland Channel, across the Iceland Faroe Ridge, and via the North Icelandic Irminger Current through the eastern Denmark Strait (Blindheim and Østerhus, 2005). The North Atlantic drift passes the two deep basins of the Norwegian Sea and then separates into an eastern branch entering the Barents Sea between Norway and Bear Island and a western branch, which forms the West Spitsbergen Current. Most of the West Spitsbergen current enters the Arctic Sea, but a part is deflected in the Fram Strait and mixed with Arctic water leaving the Arctic Ocean (Rudels et al., 2012). The Arctic and Polar water forms the east Greenland current, and is partly recirculated over the deep basin of the Greenland Sea. Approximately midway between the continental shelf breaks of Norway and Greenland a row of sea-mounts formed by the Jan Mayen Ridge, the Mohn Ridge and the Knipovich Ridge governs the general shape of the Arctic front where the warmer eastern and colder western water masses meet (Rossby et al., 2009). The Norwegian Coastal current is a minor part of the circulation system and carries a major component of Baltic Sea water.

The surface water from the North Atlantic entering the Nordic Seas is presently equilibrated with atmospheric CO_2 and carries small or zero capacity for further uptake in the Nordic Sea region (Olsen et al., 2006). A time course of carbon chemistry from Ocean Weather Station Mike (OWSM) (66 N, 2E, see Fig. 1) demonstrated an annual pH change of −0.001 pH-units $year^{-1}$ in surface water between 2001 and 2005 (Skjelvan et al., 2008). This change in pH was mainly due to temperature increase, and demonstrates that to analyse future seawater carbon chemistry we need to take into account an array of climate influenced variables such as temperature, salinity and currents, in addition to anthropogenic CO_2.

A large proportion of marine life forms incorporate calcium carbonates in body armour such as shells, exoskeletons and claws, and ocean acidification leads to less favourable conditions for the formation of these minerals. Current surface seawaters are generally supersaturated with respect to calcium carbonates, but saturation state decreases when

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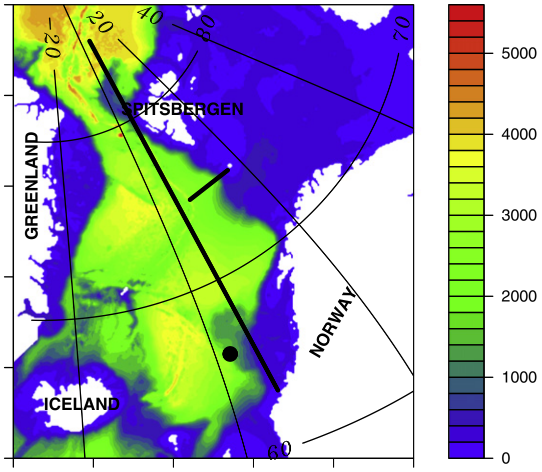

Fig. 1. Model bathymetry in meters. Thick solid East–west line is the Bjornøya West section in Fig. 4, the North–south line is the section used in Fig. 9, while the filled circle is the position of OWSM (66 N,2E).

more CO_2 is dissolved in the water. A decrease in the carbonate concentration will affect the survival of calcifying organisms, and when the carbonate concentration reaches a critical level the seawater will become corroding for the calcifying organisms (Roleda et al., 2012). A decrease in pH reduces the saturation state, Ω, of calcium carbonate minerals such as aragonite and calcite. When Ω is larger than 1.0 the seawater is supersaturated with respect to $CaCO_3$, while for values below 1.0 the seawater is corrosive to $CaCO_3$. Changes in saturation state with respect to these minerals are therefore important for understanding how ocean acidification might impact future ecosystems. Of the two pure mineral forms of calcium carbonate, calcite is more resistant to acidification than aragonite. However, in biogenic materials these forms will be diversified, for example by replacement of calcium by alternative divalent cations (Ries, 2011b), and incorporation organic materials in variable proportions. These modifications will all influence the solubility of biological chalk armours. For simplicity we will discuss the saturation state of aragonite, from which the stability of other forms can be at least crudely inferred.

The surface waters of the Arctic Ocean with low temperature and high natural concentrations of inorganic carbon is expected to become under saturated with respect to aragonite within few decennia (Steinacher et al., 2009). The central Baltic Sea, which supplies a large component of the Norwegian Coastal Current, has been reported to be under saturated with respect to aragonite during wintertime (Tyrrell et al., 2008). However, recently initiated monitoring of the carbon chemistry in the Norwegian Coastal current off Southern Norway showed that during 2010 the surface water aragonite saturation state varied between 1.6 and 1.9 throughout the year (Chierici et al., 2012), so the local minimum in the Baltic seems not to be carried across the Skagerrak at present.

Studies of biological consequences of ocean acidification indicate that large groups of organisms will meet with stress or reduced success rate in seawater with reduced pH and carbonate concentration (Fabry et al., 2008). Biomineralisation of protective body parts enforced with calcium carbonates is energetically favourable in seawater over saturated with respect to the major principal calcium carbonates (Ries, 2011a, b) and the saturation horizon for aragonite and calcite is shoaling globally (Feely et al., 2004). In the Arctic Ocean, with already high natural content of dissolved inorganic carbon, the surface waters are already under saturated in some areas parts of the year, especially over the continental shelves (Chierici and Franson, 2009; Steinacher et al., 2009). Under saturated waters may restrict the success of calcifiers, notably the types that rely on seawater pH for calcification (Ries, 2011a). In addition, all life processes are intimately influenced by pH, and a disturbing number of negative physiological effects of ocean acidification on marine life forms have been demonstrated (Fabry et al., 2008).

Investigating such processes can only partly be done from observations, and one cannot measure into the future. Therefore numerical models have become an important tool to better understand and predict the consequences of ocean acidification. To simulate all these processes in requisite detail is a significant challenge and requires a relatively complex coupled hydrodynamic ecosystem and carbonate model, and several models have been used to assess the state of the carbonate system in present climate and to forecast its future state under different emission scenarios (Artioli et al., 2012; Feely et al., 2009; Orr et al., 2005). Global oceanic models show significant spatial variability in the Polar regions, in particular the Arctic, exhibiting more vulnerability because of temperature effects (Steinacher et al., 2009), thus any attempt to evaluate future ecosystem consequences of CO_2 emissions will need predictions at regional scale of development of ocean carbon chemistry, along with knowledge of biological responses. Bellerby et al. (2012) modelled both present and future climate ocean acidification in the Arctic with a focus on the Spitsbergen region, and compared the results with extrapolation of mesocosm experiments in an Arctic fjord. The purpose of the present paper is to investigate the consequences of rising atmospheric CO_2 and climate change on the ocean's carbonate system in the Nordic and Barents Sea with the NORWECOM.E2E ecosystem model. Downscaled physics from a global climate model is used to force the regional biogeochemical model including a submodule for the carbonate system in the areas considered. Two periods, a control and a future climate, have been simulated. After a description of the climate and downscaled physical models, the biogeochemical model is presented. To initialise the carbonate submodule, fields of dissolved inorganic carbon (DIC) were derived using data collected during the joint Knorr and Oden survey of the Nordic Seas in 2002 (Olsen et al., 2010). The method for deriving these fields is presented together with data from OWSM (for position see Fig. 1) used to validate the control run. Finally, results from the simulations have been compared to published data and other model studies.

2. Material and methods

2.1. ROMS/GISS

The regional coupled ice-ocean numerical model, which here serves the biophysical model with variables as salinity, temperature and velocity is the Regional Ocean Modeling System (ROMS), described in Shchepetkin and McWilliams (2005). ROMS is a three-dimensional baroclinic ocean general circulation model (OGCM) and uses topography-following generalised sigma coordinates in the vertical, which ensures high vertical resolution also in shallow and well-mixed areas. This regional model is run on a stretched orthogonal curvilinear grid with an average resolution of 10 km, covering the Arctic and the Atlantic down to about 20° S (Melsom et al., 2009). In the vertical, the model has 40 generalised sigma levels with a distribution that enhances resolution towards the surface and the bottom (Song and Haidvogel, 1994).

The regional model is downscaled from the global Goddard Institute for Space Studies Atmosphere–Ocean Model (GISS AOM). Daily mean sea level pressure, surface air temperatures, surface winds, surface specific humidity, downward long- and short wave radiation at the surface, and precipitation values from the global GISS AOM (GISS-G) are here combined with appropriate sea surface values from the regional ROMS (GISS-R) in accordance with (Fairall et al., 2003) to provide atmospheric forcing for the GISS-R model.

The GISS-R simulations have been performed for two periods, 1981–2000 representing the present climate (20C3M) and 2046–2065 representing the future scenario (A1B) (IPCC, 2007). The first five years is considered as spin-up, and the remaining 15 years are used in