Simulation of global ocean acidification and chemical habitats of shallow- and cold-water coral reefs

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Abstract

Using the UVic Earth System Model, this study simulated the change of seawater chemistry and analyzed the chemical habitat surrounding shallow- and cold-water coral reefs from the year 1800 to 2300 employing RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios. The model results showed that the global ocean will continue to absorb atmospheric CO_2. Global mean surface ocean temperature will rise 1.1−2.8 K at the end of the 21st century across RCP scenarios. Meanwhile, the global mean surface ocean pH will drop 0.14−0.42 and the ocean surface mean concentration of carbonate will decrease 20%−51% across the RCP scenarios. The saturated state of sea water with respect to calcite carbonate minerals (Ω) will decrease rapidly. During the pre-industrial period, 99% of the shallow-water coral reefs were surrounded by seawater with $\Omega > 3.5$ and 87% of the deep-sea coral reefs were surrounded by seawater with aragonite supersaturation. Within the 21st century, except for the high mitigation scenario of RCP2.6, almost none shallow-water coral reefs will be surrounded by seawater with $\Omega > 3.5$. Under the intensive emission scenario of RCP8.5, by the year 2100, the aragonite saturation horizon will rise to 308 m under the sea surface from 1138 m at the pre-industrial period, thus 73% of the cold-water coral reefs will be surrounded by seawater with aragonite undersaturation. By the year 2300, only 5% of the cold-water coral reefs will be surrounded by seawater with aragonite supersaturation.

Keywords: Simulation research; Aragonite saturation state; Ocean acidification; Shallow-water coral reefs; Cold-water coral reefs

1. Introduction

Since the beginning of the industrial revolution, the CO_2 concentration in atmosphere has increased rapidly, because of human activities such as fossil fuel combustion and land use. Anthropogenic CO_2 emissions have reached 545 Pg C from 1750 to 2011 (IPCC, 2013). Not all of CO_2 emissions remain in the atmosphere, 26% of them are absorbed by the ocean and 28% are absorbed in terrestrial soil (Sabine et al., 2004). Recently, both observation and simulation studies have agreed that the ocean absorbs a large amount of CO_2, which mitigates global climate change. However, this absorption is not entirely harmless. The average pH of the sea surface has dropped from 8.2 to 8.1 since pre-industrial time, which means that the ocean hydrogen ion concentration has increased by 26% (Gattuso and Hansson, 2011). Doney et al. (2009) reported the ocean carbon chemical equilibrium formula as:

$$CO_{2(atmos)} \rightleftarrows CO_{2(aq)} + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^{2-}.$$

(1)
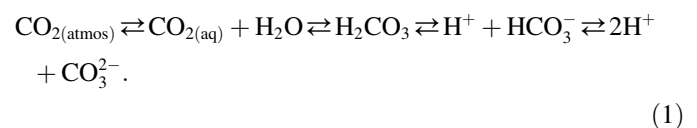
According to this equation, the increase of hydrogen ions (H^+) will result in the decrease of carbonate ions concentration (CO_3^{2-}), which will further reduce the calcium carbonate

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$(CaCO_3)$ saturation state. These changes in sea water will harm marine calcified organisms, especially the coral reefs (Doney et al., 2009; Fine and Tchernov, 2007; Fabry et al., 2008; Guinotte and Fabry, 2008). Coral reefs are an important component of marine ecosystems and are composed of aragonite (a relatively soluble mineral form of calcium carbonate). Many laboratory experiments showed that the decline of the ocean aragonite saturation state would lead to the decrease in the shallow-water coral calcification rate, because it is difficult for corals to extract calcium ions and bicarbonate ions from the surrounding seawater to form bones and shells $(Ca^{2+} + 2HCO_3^- \rightleftarrows CaCO_3 + CO_2 + H_2O)$. In addition, cold-water coral reefs also suffer from the effects of this change in the marine environment (Langdon et al., 2003). Guinotte et al. (2006) suggested that the global distribution of cold-water coral in the deep sea is limited by the surrounding seawater aragonite saturation state. Therefore, an increase in the CO_2 concentration in the atmosphere can have important influences on the marine environment and coral reef systems.

Anthropogenic CO_2 emissions will decrease the ocean surface pH and the concentration of carbonate ions (Caldeira and Wickett, 2005; Orr et al., 2005; Cao and Caldeira, 2008; Steinacher et al., 2009). This development will directly affect the ocean aragonite saturation state. Aragonite saturation state (Ω) is defined as (Feely et al., 1988):

$$\Omega = \left[Ca^{2+}\right]\left[CO_3^{2-}\right] \Big/ K_{sp}^*, \qquad (2)$$

which is calculated from the calcium ion concentration ($[Ca^{2+}]$), carbonate ion concentration ($[CO_3^{2-}]$) and equilibrium thermodynamic solubility product (K_{sp}^*). The $[Ca^{2+}]$ and $[CO_3^{2-}]$ are calculated from the sea water salinity, total alkalinity (TAlk), and dissolved inorganic carbon (DIC). The solubility product K_{sp}^* is calculated based on seawater temperature, salinity, and pressure (Mucci, 1983), which is defined as the product of $[Ca^{2+}]$ and $[CO_3^{2-}]$ concentrations at the saturation state. When $\Omega < 1$ the seawater is undersaturated with respect to aragonite, while $\Omega > 1$ means it is supersaturated. The aragonite saturation horizon is defined as the depth which $\Omega = 1$. In the ocean today, the marine aragonite saturation state decreases from the surface to the depth. Thus, the water above the saturation horizon is supersaturated and the water under the saturation horizon is undersaturated.

There are numerous simulation studies about ocean acidification under various CO_2 emission scenarios. Using the ocean circulation model of the Lawrence Livermore National Laboratory, Caldeira and Wickett (2005) found that the global mean ocean surface pH would drop 0.3–0.5 at the end of the 21st century under the SRES scenario. Orr et al. (2005) commented that surface seawater would be undersaturated with respect to aragonite at the middle of the 21st century under the IS92a scenarios, which was based on the simulation results of 13 models, which would have a negative impact on polar shell plankton. In a recent research, it was found that 20% of the surface area of the Canadian Basin has been undersaturated with respect to aragonite (Robbins et al., 2013). This mismatch between observations and models is probably due to the low resolution of global models and the inability of the global models to accurately simulate sea ice. The actual speed of the decline of Arctic sea ice is faster than the forecast, because of global warming (Stroeve et al., 2007). On the basis of UVic ESCM simulation, Cao and Caldeira (2008) speculated that the ocean mean pH at high latitude would drop by more than 0.2 when the atmospheric CO_2 concentration stabilized at 450×10^{-6}, and in this case, 7% of the area of the south ocean (south of $60°S$) would be undersaturated in aragonite. Fine and Tchernov (2007) experimentally determined that Scleractinian coral would be huge, soft, and skeleton-free in acidified seawater (pH = 7.4).

Chinese scientists have conducted several studies using the global carbon cycle model simulation. For example, Xu and Li (2009) simulated the global ocean anthropogenic CO_2 uptake. Cao et al. (2014a) and Wang et al. (2014) used UVic ESCM to simulate and analyze how climate sensitivity could affect the uptake of CO_2 by the ocean under the RCP8.5 scenario. Cao et al. (2014b) analyzed the response of ocean acidification to a gradual increase and decrease of atmospheric CO_2 and found that marine ecosystems would not respond well to recover to their natural chemical habitats even if the atmospheric CO_2 content is lower than future predictions.

On the basis of the previous researches, our study used an intermediate complex earth system climate model to compare various ocean acidification rates from before the industrial revolution to the year 2300 under four CO_2 Representative Concentration Pathway scenarios (RCPs). These scenarios have been widely employed in the IPCC AR5 report. At the same time, this study also analyzed the effect of ocean acidification on both shallow- and cold-water coral reefs. Besides being a supplement to the CMIP5 multi-models prediction in the AR5 report, the work also represents the first attempt to analyze the chemical habits of cold-water coral reefs under four RCPs.

2. Model and method

2.1. Model description

Developed at the University of Victoria at Canada, the UVic Earth System Climate Model is an intermediate complexity climate model, which consists of a 3D ocean general circulation model with a spherical grid resolution of $3.6°$ by longitude and $1.8°$ by latitude with 19 vertical layers in the ocean and one-layer in the atmosphere with an energy-moisture balance. It is coupled with a sea-ice model, an atmospheric model and a land-ice model (Weaver et al., 2001). The terrestrial carbon cycle model is based on the TRIFFID land surface and dynamic vegetation scheme of Hadley Centre Met Office (Meissner et al., 2003). In addition, the ocean carbon cycle consists of a CO_2 air-sea interaction process, a marine inorganic carbon process (Orr et al., 1999) and a marine organic carbon process (Schmittner et al., 2008). The organic carbon process includes a simple marine ecosystems, which has nutrient (PO_4^{3-}, NO_3^-), interaction of phytoplankton and zooplankton and a feedback for the marine carbon cycle. This model has been widely used in numerous studies of