LETTER

Can ocean iron fertilization mitigate ocean acidification?

A letter

Long Cao · Ken Caldeira

Abstract Ocean iron fertilization has been proposed as a method to mitigate anthropogenic climate change, and there is continued commercial interest in using iron fertilization to generate carbon credits. It has been further speculated that ocean iron fertilization could help mitigate ocean acidification. Here, using a global ocean carbon cycle model, we performed idealized ocean iron fertilization simulations to place an upper bound on the effect of iron fertilization on atmospheric CO_2 and ocean acidification. Under the IPCC A2 CO_2 emission scenario, at year 2100 the model simulates an atmospheric CO_2 concentration of 965 ppm with the mean surface ocean pH 0.44 units less than its pre-industrial value of 8.18. A globally sustained ocean iron fertilization could not diminish CO_2 concentrations below 833 ppm or reduce the mean surface ocean pH change to less than 0.38 units. This maximum of 0.06 unit mitigation in surface pH change by the end of this century is achieved at the cost of storing more anthropogenic CO_2 in the ocean interior, furthering acidifying the deep-ocean. If the amount of net carbon storage in the deep ocean by iron fertilization produces an equivalent amount of emission credits, ocean iron fertilization further acidifies the deep ocean without conferring any chemical benefit to the surface ocean.

1 Introduction

Ocean iron fertilization (OIF) has been proposed by several commercial organizations as an approach to mitigate rising atmospheric CO_2 concentrations following

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John Martin's formulation of the 'iron hypothesis' (Martin 1990). Over about 20% of the surface ocean, including large parts of the Southern Ocean, the eastern equatorial Pacific, and parts of the North Pacific, low biomass and chlorophyll concentrations are observed with macronutrients go largely unutilized. These areas are termed as high-nutrient, low-chlorophyll (HNLC) regions. The proposal to fertilize the ocean with iron is based on the reasoning that adding iron to these HNLC regions would stimulate the growth of phytoplankton, and therefore enhance the biological draw-down of anthropogenic CO_2 from the atmosphere. A number of field experiments (e.g. Boyd et al. 2007; Pollard et al. 2009) and modeling studies (e.g. Sarmiento and Orr 1991; Gnanadesikan et al. 2003; Aumont and Bopp 2006) investigated the effect of OIF on plankton community dynamics and carbon sequestration. Some studies pointed out the environmental risks associated with OIF including expanded regions with low oxygen concentration, increased production of N_2O, and possible disruptions of marine ecosystems (see a review of Denman 2008 and references hereinafter).

There are a few speculations in the literature (Wayman 2008; Freestone and Rayfuse 2008) that ocean iron fertilization could help to mitigate anthropogenic ocean acidification, a process referring to the increase in ocean acidity as a result of the ocean's absorption of anthropogenic CO_2 (Caldeira and Wickett 2003). Ocean acidification would affect marine organisms and ecosystems in a variety of ways (Raven et al. 2005). For example, a decrease in the saturation state of seawater with respect to carbonate minerals (including both calcite and aragonite) would weaken the ability of corals and some other calcifying organisms to build their skeletons and reefs, posing a risk to their ecological sustainability. A decrease in ocean pH would also impact the growth, respiration, and reproduction of some marine organisms, altering the biodiversity of marine ecosystems.

In this study we investigate the effect of large-scale ocean iron fertilization on ocean acidification. To our knowledge, except for a few speculations (Wayman 2008; Freestone and Rayfuse 2008) no scientific study has addressed this issue. In a recently released report on ocean acidification, "Monaco Declaration" (Monaco Declaration 2009), it states that "Mitigation strategies that aim to transfer CO_2 to the ocean, for example by direct deep-sea disposal of CO_2 or by fertilising the ocean to stimulate biological productivity, would enhance ocean acidification in some areas while reducing it in others". But no quantitative estimates of this issue have appeared in the peer-reviewed literature. Here, from simulations by a global ocean carbon cycle model, we provide the first quantitative results that bound the effect of iron fertilization on ocean acidification.

2 Methods

We use an ocean general circulation and carbon cycle model (Caldeira and Wickett 2003) to study the effect of ocean iron fertilization on ocean acidification (refer to Table 1 and supplemental materials for a detailed description of the model used and simulations performed). Following previous studies (Sarmiento and Orr 1991; Gnanadesikan et al. 2003), here we simulate the effect of iron fertilization implicitly

Table 1 Simulations performed in this study

Simulation setup			
Simulation	Boundary condition	Fertilization duration	Fertilization region
A2_emis	SRES A2 CO_2 emission	None	None
A2_emis+OIF	SRES A2 CO_2 emission	2008 to 2100	Global ocean
A2_conc+OIF	CO_2 concentrations calculated from A2_emis	2008 to 2100	Global ocean

by restoring near-surface phosphate concentrations toward zero to represent the maximum possible macronutrient depletion driven by iron fertilization. The depletion of surface phosphate concentration is assumed to occur at all time over the global ocean. We emphasize that we do not intend to simulate the real-world effect of iron fertilization, which requires a comprehensive carbon cycle model including the iron cycle (e.g., Aumont and Bopp 2006). Instead, these experiments represent an upper bound of the extreme and idealized end-member case for ocean iron fertilization, which is used to demonstrate basic logic and principles relating iron fertilization and ocean acidification.

3 Results

3.1 Effects of ocean iron fertilization on atmospheric and oceanic carbon

The effect of ocean iron fertilization on atmospheric and oceanic carbon, in a manner of an idealized and extreme scenario, is given in Table 2 and Fig. 1. In our simulations under IPCC A2 CO_2 emission scenario, an extreme and sustained global iron fertilization that depletes global surface phosphate concentrations to zero all year round (A2_emis+OIF), leads to a CO_2 concentration of 833 ppm by year 2100, compared to 965 ppm in the simulation without the implementation of iron fertilization

Table 2 Main results from each simulation

Results (year 2100)							
	Carbon pool				Surface ocean chemistry		
	Fossil emission[a] (PgC)	Atm. CO_2 (ppm)	Atm. ΔC[c] (PgC)	Ocean. ΔC[c] (PgC)	pH	Aragonite saturation	Calcite saturation
Pre-industrial	0	280.0	0	0	8.18	3.53	5.43
A2_emis	1,998.0	965.3	1,457.1	540.9	7.74	1.54	2.37
A2_emis+OIF	1,998.0	832.6	1,175.8	822.2	7.80	1.71	2.61
A2_conc+OIF	2,307.1[b]	965.3	1,457.1	850.0	7.74	1.52	2.33

[a]Cumulative fossil-fuel emission from pre-industrial to year 2100
[b]SRES A2 CO_2 emission plus emission credit produced by the increase in net carbon storage in the deep ocean due to ocean iron fertilization
[c]ΔC is the change in atmosphere and/or ocean carbon storage relative to the pre-industrial values ($1PgC = 10^{15}$ g carbon)
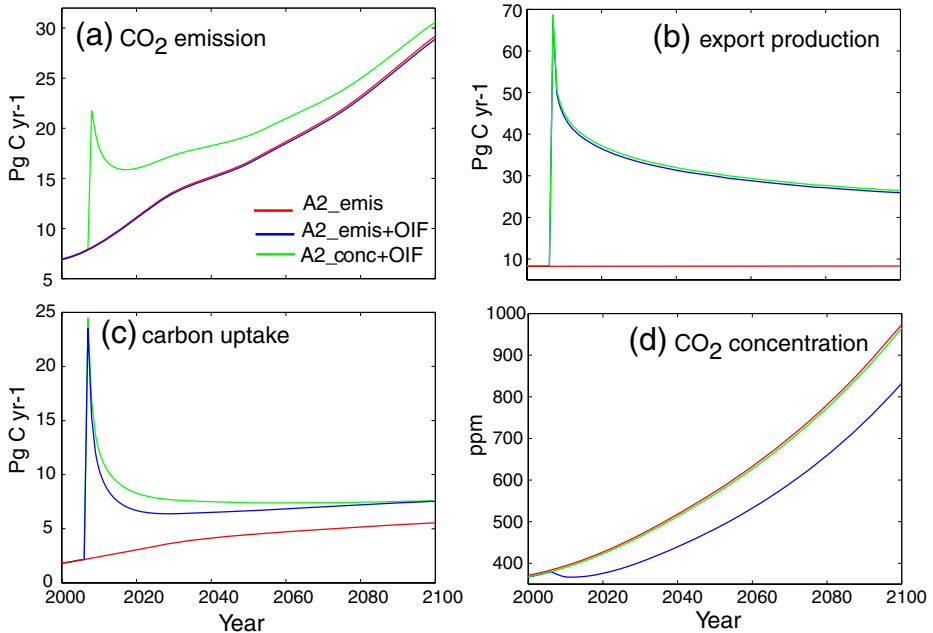
Fig. 1 Simulated temporal evolution of CO_2 emission (**a**), export production (**b**) (the amount of the sum of particulate and dissolved organic carbon exported across 75 m in the model), carbon uptake (**c**), and atmospheric CO_2 concentrations (**d**) for simulations with/without iron fertilization (refer to Table 1 for simulation setup). For CO_2 emissions, A2_emis result is the same as A2_emis+OIF. For export production, A2_emis+OIF result is the same as A2_conc+OIF. For CO_2 concentration, A2_emis result is the same as A2_conc+OIF (These lines are plotted slightly apart for better visibility). Here, the effect of ocean iron fertilization is represented by restoring global surface phosphate concentrations to zero all year round, which places an upper bound on the maximum effect of iron fertilization

(A2_emis). (The model does not include a terrestrial biosphere and the implicit assumption underlying modeled CO_2 concentrations is a neutral terrestrial carbon uptake). On the other hand, if the amount of net carbon storage in the deep ocean by iron fertilization produces an equivalent amount of emission credits, resulting in an equivalent increase in CO_2 emissions with no change in CO_2 concentration, this extreme global fertilization scenario (A2_conc+OIF) would generate a CO_2 emission credit of 309 PgC during this century. We note that both the reduction in atmospheric CO_2 concentration and the emission credits generated by iron fertilization shown here represent an upper bound maximum effect of iron fertilization. Any real ocean iron fertilization project would have effects of substantially smaller magnitude.

The mitigation in atmospheric CO_2 concentrations or the gain in allowable emissions is achieved at the cost of storing more anthropogenic CO_2 in the deep ocean. By year 2100, about 40% of fossil-fuel CO_2 is stored in the ocean in both simulations involving iron fertilization, compared to a value of 27% in the simulation without it (Table 2).
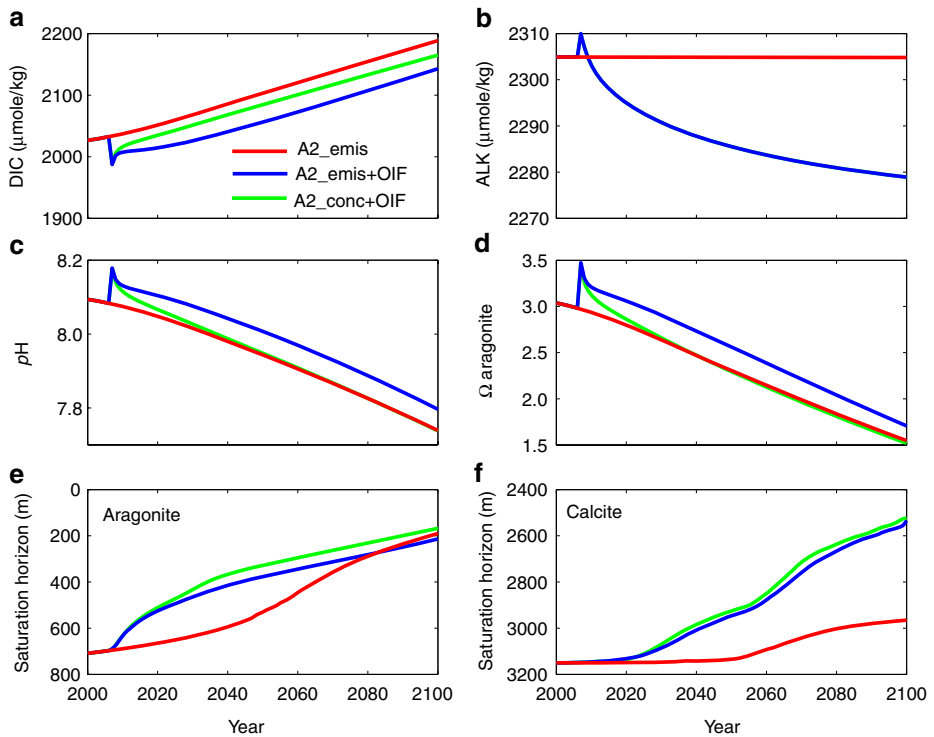
Fig. 2 Simulated temporal evolution of global mean surface-ocean dissolved inorganic carbon (DIC), alkalinity (ALK), pH, saturation state of aragonite ($\Omega_{aragonite}$), and saturation horizon of aragonite and calcite with/without iron fertilization (refer to Table 1 for simulation setup). The saturation state of seawater with respect to aragonite ($\Omega_{aragonite}$) and calcite ($\Omega_{calcite}$), two major forms of calcium carbonate, is defined as the ion product of the concentrations of calcium and carbonate ions divided by the stoichiometric solubility product. For ocean alkalinity, the A2_emis+OIF result is the same as the A2_conc+OIF case. Here, the effect of ocean iron fertilization is represented by restoring global surface phosphate concentrations to zero all year round, which places an upper bound on the maximum effect of iron fertilization

3.2 Effects of ocean iron fertilization on surface ocean acidification

Our simulations show that ocean iron fertilization, even in the extreme scenario by depleting global surface macronutrient concentration to zero at all time, has a minor effect on mitigating CO_2-induced acidification at the surface ocean (Table 2, Figs. 2c, d and 3). When iron fertilization is implemented to mitigate atmospheric CO_2 concentrations, it diminishes near-surface ocean acidification by delaying changes in global surface ocean chemistry by about a decade. By year 2100 in the simulation with iron fertilization, global surface pH decreases by 0.38 units from a pre-industrial value of 8.18, compared with a decrease of 0.44 units in the scenario without fertilization. On the other hand, when iron fertilization is implemented to generate carbon credit, it has a negligible effect on surface ocean chemistry.
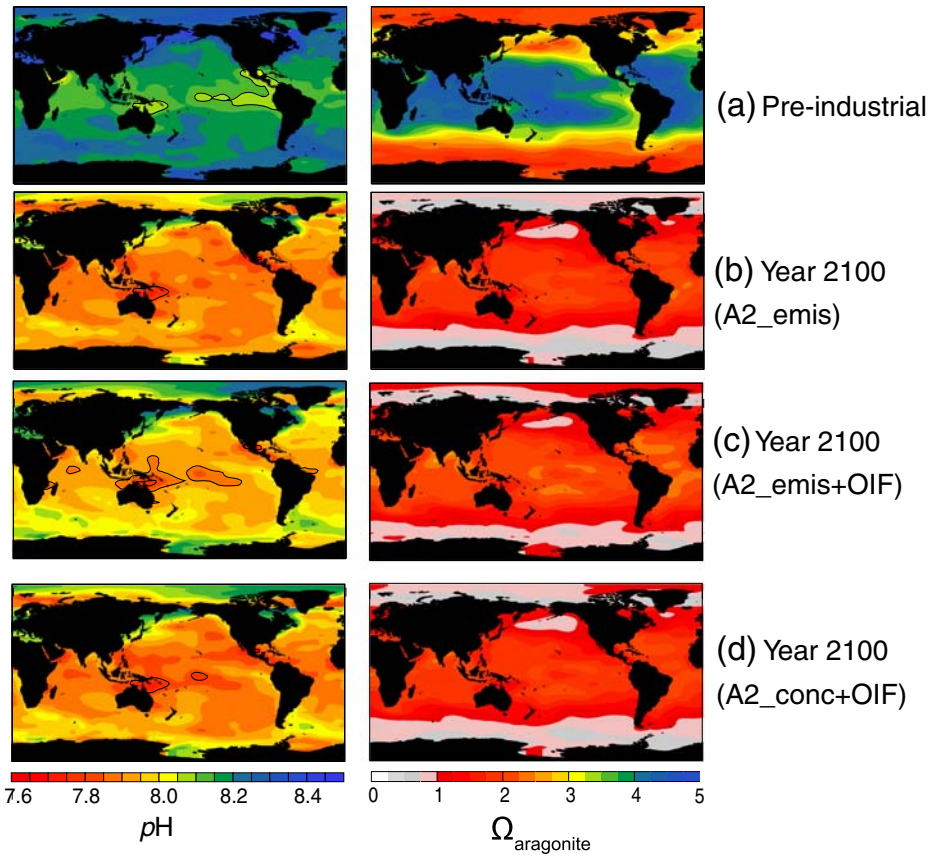
Fig. 3 Simulated surface ocean pH and saturation state of aragonite ($\Omega_{aragonite}$) in pre-industrial time and year 2100 for the simulation with/without iron fertilization (refer to Table 1 for simulation setup). By comparing surface ocean chemistry at the end of this century with that at pre-industrial time, it is shown that ocean iron fertilization, even implemented to achieve the upper bound of its maximum effect, has a minor effect on mitigating surface ocean acidification caused by anthropogenic CO_2 emissions

3.3 Effects of ocean iron fertilization on deep ocean acidification

Iron fertilization causes more carbon to be sequestered into the ocean interior (Table 2), accelerating acidification of the deep ocean. This can be seen in the distribution of pH (Fig. 4) and the shoaling of saturation horizons (the depth below which seawater is undersaturated with respect to calcium carbonate) of aragonite (Fig. 2e) and calcite (Fig. 2f). The effect of iron fertilization on deep-ocean chemistry is most pronounced in the Southern Ocean, as can be seen from its effect on both pH (Fig. 4) and aragonite saturation horizon (Fig. S1). The accelerated deep-ocean acidification is of concern given the evidence that deep-sea organisms are highly sensitive to even modest pH changes (e.g., Seibel and Walsh 2001). Again, we note that the results presented here represent an upper bound on the maximum effect of iron fertilization.
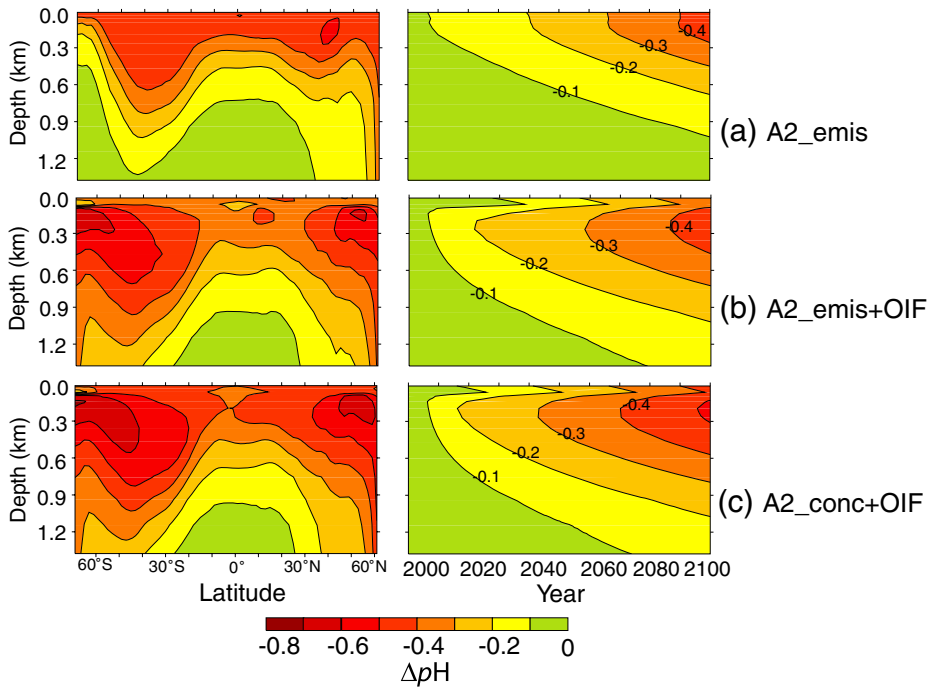
Fig. 4 (*Left panels*): simulated latitude-depth distribution of changes in *p*H (relative to pre-industrial values) in year 2100. (*Right panels*): simulated horizontal mean Δ*p*H as a function of year and depth (refer to Table 1 for simulation setup). It is shown here that ocean iron fertilization accelerates deep-ocean acidification

4 Discussion and conclusions

The results presented here provide an upper bound on the maximum effect of ocean iron fertilization, which is simulated in the model by depleting near-surface phosphate concentrations to zero all year round over the global ocean. We recognize that the magnitude of the effect of ocean iron fertilization presented here will not be achieved in the real world. Iron fertilization, if implemented in reality, is most likely to occur in the Southern Ocean, and its effect on carbon uptake and ocean chemistry would depend on the complex interplay between carbon and iron biogeochemistry, ecosystem response, and ocean dynamics (Boyd et al. 2007). An in-depth analysis of how these processes affect iron fertilization and ocean acidification would require detailed measurements from observations and model simulations using comprehensive marine ecosystem and carbon cycle models including an iron cycle.

We analyze extreme cases to illustrate basic logic and principles relating iron fertilization and ocean acidification. Our results show that ocean fertilization can at best play a minor role in mitigating surface ocean acidification. If this fertilization is used to generate credits that will allow greater carbon dioxide emissions, there may be no benefit to upper ocean chemistry. In all cases, ocean fertilization would lead to greater acidification of the deep ocean.

Our results have broader implications for carbon emission "offsets" schemes. If carbon is removed from the atmosphere and stored in, for example, a forest, and no carbon "offset" is generated (i.e., the storage does not lead to greater emissions), then the storage of carbon in the forest will tend to result in lower atmospheric CO_2 concentrations, less warming, and less ocean acidification. However, if the storage of carbon in the forest generates a carbon "offset" that leads to greater fossil-fuel emissions, then the storage of carbon in the forest may provide economic benefits by allowing greater amounts of energy to be derived from carbon-emitting sources, but will provide no direct benefit to lowering atmospheric CO_2 concentrations, diminishing warming, or reducing ocean acidification. Similarly, if the storage of carbon due to direct ocean carbon sequestration is used to generate emission credit, ocean carbon sequestration will provide no benefit to surface ocean acidification. Of course, intermediate cases are imaginable in which each ton of carbon stored in the ocean through iron fertilization produces less than 1 ton of carbon credit, or where the existence of the ocean fertilization option somehow leads to the negotiation of more stringent limits on carbon emissions generally. Therefore, whether the carbon storage benefits the environment or the economy depends on the socio-political context in which carbon storage occurs.

In summary, our study demonstrates, that ocean iron fertilization can only slightly mitigate surface ocean acidification caused by anthropogenic CO_2 emissions, and at the expense of accelerated acidification in the deep ocean. In the context of a carbon-emission offset scheme, ocean iron fertilization could lead to further acidification of the deep ocean without mitigating surface ocean chemistry change. Small-scale fertilization experiments can be useful to help understand the role of nutrients in marine biogeochemical cycles. However, as suggested by our simulations ocean iron fertilization is unlikely to be effective for either climate or ocean chemistry mitigation. If ocean iron fertilization is implemented in generating carbon credits which lead to a corresponding increase in fossil-fuel emissions, it would cause further pollution to the deep ocean without conferring any environmental benefit.

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