

Influence of mitigation policy on ocean acidification

D. Bernie,¹ J. Lowe,² T. Tyrrell,³ and O. Legge³

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[1] This study quantifies the relative impact on future ocean acidification of different aspects of global climate change mitigation policies, such as the year that global emissions peak, how fast they reduce after their peak, and the long term minimum emissions that are possible. Relative to a scenario where emissions peak in 2016 and then decrease by 1% per year, further emissions reductions to 2, 3 and 4% per year lead to the same impact minimum pH (by 2100) if emissions peak 10, 15 and 17 years later respectively. Over the same time scale, non-mitigation scenarios lead to a decrease of global mean surface pH of 7.67 to 7.81. Strong and urgent mitigation, emissions peaking in 2016 and reducing by 5% per year, are shown to limit this minimum to 8.02. Minimum pH over longer timescales, the next 500 years, is largely determined by the minimum emission level that is attainable, owing to its relation with cumulative emissions. **Citation:** Bernie, D., J. Lowe, T. Tyrrell, and O. Legge (2010), Influence of mitigation policy on ocean acidification, *Geophys. Res. Lett.*, 37, L15704, doi:10.1029/2010GL043181.

1. Introduction

[2] Anthropogenic emissions of CO₂ have increased atmospheric concentrations from 280ppm to approximately 390ppm, higher than any time in at least the last 800,000 years [Lüthi *et al.*, 2008]. While around 40 ± 8% of recent emissions have remained in the atmosphere, contributing to global warming, an estimated 32 ± 6% is sequestered in vegetation and an estimated 27 ± 5% of emissions absorbed by the ocean [Houghton, 2003; Canadell *et al.*, 2007] limiting the global warming impact of CO₂ emissions. The uptake of CO₂ by the ocean, however, increases the acidity of the ocean.

[3] Modelling and observational studies suggest that the absorption of CO₂ by the ocean has already decreased the pH of the ocean surface by 0.1 since 1750 [Orr *et al.*, 2005]. This rate of change is faster than any during the last 55 million years [Pearson and Palmer, 2000]. While the resultant changes in carbonate chemistry are well understood, the biological impacts of increasing acidification on marine organisms, ecosystems and biogeochemistry are all less clear [Intergovernmental Panel on Climate Change (IPCC), 2007] though it is widely believed that increasing acidity, as well as reduced CaCO₃ saturation, may signifi-

cantly affect marine organisms and the biogeochemical processes that they mediate. Adverse affects on marine organisms and degradation of ocean habitats may also disrupt marine ecosystems and detrimentally affect the coastal societies that depend on them. Such impacts will have a significant duration (centuries) due to the long time scale of recovery of atmospheric CO₂ and ocean pH [Frölicher and Joos, 2010].

[4] Previous studies of future ocean pH have used non-mitigated emissions scenarios and idealised CO₂ stabilisation scenarios [Steinacher *et al.*, 2009; Orr *et al.*, 2005; Cao and Caldeira, 2008; Caldeira and Wickett, 2005] or the magnitude and time scale of future CO₂ release [Zeebe *et al.*, 2008]. In this study we quantify acidification under a range of emissions scenarios and analyse what aspects of global emission reduction scenarios have most impact of future acidification. The key feature of this study is the explicit relation of future pH to aspects of global climate change mitigation policy. Key policy questions which this study seeks to inform include the relative importance of how soon emissions reduction start and how rapid those reductions are. Estimates are presented of how much future acidification can be avoided with a range of different global climate change mitigation scenarios. The impact on acidification of the long term minimum emission level that is reached is also examined.

2. Methodology

[5] In order to avoid prohibitive computational costs, a coupled carbon-cycle general circulation model (GCM) is first used to examine a limited set of idealised emissions scenarios. Traceability is then established between the complex model and a simple ocean carbon cycle model (SCM), which is then used to greatly expand the number of different emissions scenarios examined. The SCM is not a replacement for the complex model, but a tool for extrapolation and developing understanding that allows particular policy relevant questions to be addressed quickly.

2.1. Simple Model

[6] A SCM comprising 3 vertically stacked boxes, developed and validated by Chuck *et al.* [2005], has previously been used to examine future impacts of CO₂ emissions [Tyrrell *et al.*, 2007]. The SCM calculates carbonate chemistry, air-sea gas exchange of carbon, the organic and inorganic carbon pumps and other standard aspects of ocean carbon cycle models. It contains dissolved inorganic carbon and alkalinity as dynamic state variables from which other carbonate system parameters are calculated. The model is forced using global average near surface air temperature and atmospheric CO₂ concentration inputs from scenarios developed by the AVOID programme (<http://www.avoid.uk.net/>) to provide advice on mitigation and avoiding

¹Met Office Hadley Centre, Exeter, UK.

²Met Office Hadley Centre, Department of Meteorology, University of Reading, Reading, UK.

³National Oceanography Centre, Southampton, University of Southampton, Southampton, UK.

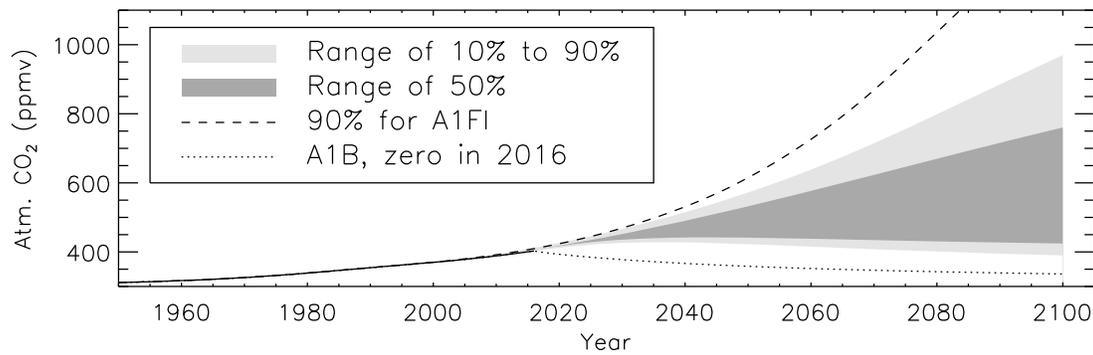


Figure 1. Atmospheric CO₂ concentrations pathways from the emissions scenarios used to force the simple model. The runs use an A1B baseline with different years of peak emissions (2016 to 2030), post peak emissions reduction rate (1 to 5%) and the long term minimum emissions). The range of the central expectation of CO₂ concentration from these scenarios is shown in dark grey, with the range of the 10th and 90th percentiles in light grey. Two extreme scenarios were used to expand this range further; the IPCC SRES A1FI scenario and a scenario based on the SRES A1B scenario peaking in 2016 when emissions are reduced to zero. The 90th and 10th percentiles are shown respectively for these two extreme concentration pathways.

dangerous climate change to the UK government. Probabilistic projections of atmospheric CO₂ concentrations for each emissions scenario are produced using the MAGICC simple climate model [Wigley and Raper, 2001] in the same way as Lowe *et al.* [2009]. In order to translate this probabilistic data into a form that could be used by the SCM to examine ocean pH, the 10th, 50th and 90th percentiles of the CO₂ concentration and temperature for each scenario were examined.

2.2. Complex Model: HadCM3LC

[7] The GCM used in this study, HadCM3LC, couples the HadCM3 climate model [Gordon *et al.*, 2000] to ocean and terrestrial carbon cycle models. The terrestrial component is formed from the dynamic global vegetation model TRIFFID [Cox, 2001] coupled to the land surface scheme MOSES [Cox *et al.*, 1999]. The ocean component is the Hadley Centre ocean carbon cycle model, HadOCC, which contains a four-component nutrient–phytoplankton–zooplankton–detritus (NPZD) ecosystem model that simulates the effects of light penetration, alkalinity, and (nitrate) nutrient availability. HadOCC is described and the quality of its simulation examined by Palmer and Totterdell [2001].

2.3. Emission and Concentration Scenarios

[8] As a result of exploiting pre-existing simulations, the input scenarios differ in the GCM and SCM simulations. To aid understanding of the role of the carbon cycle, HadCM3LC is forced with prescribed emissions of CO₂ in line with the IPCC SRES A2 business-as-usual (BAU) scenario [IPCC, 2000] from 2000 to 2100 but *without* emissions of any other greenhouse gases. With this simulation as a basis, further runs were performed starting from 2012, 2050 and 2100 in which; i) the atmospheric CO₂ concentration is held constant at that years level from the basis run; ii) the emissions are reduced to zero and the CO₂ concentration allowed to vary freely. These 6 integrations then extended for another 100 years.

[9] The SCM was used to examine over 100 different multi-gas mitigation scenarios designed to systematically examine different aspects of mitigation policy. These sce-

narios cover a range from large and rapid global emissions reductions, to smaller and later emissions reductions.

[10] Using the IPCC SRES A1B scenario as a baseline, the aspects of emissions reductions policy that are examined are the i) year in which global emissions peak [2016 to 2030]; ii) the post-peak year-on-year reduction rate [1% to 5%] and; iii) the long term minimum emissions that are attainable [6 (low), 11 (default) or 16 (high) GtCO₂e/yr, expressed in terms of the equivalent emission of CO₂ as per their Kyoto gas global warming potential. These emissions floors have a split between CO₂ and non-CO₂ gases such that the CO₂ emissions for the low, default and high floors are 0, 5.13 and 10.26 GtCO₂/yr. For comparison global emissions in 1990 and 2009, expressed as a CO₂ equivalent, were 36 and 51 GtCO₂e/yr respectively. While the years of peak emissions were chosen to reflect possible urgent or delayed action, the post-peak reduction rates are limited to 5% following den Elzen *et al.* [2007]. Long term minimum emissions, from here on referred to as the emissions floor, are based on the work of the UK Committee on Climate Change (<http://www.theccc.org.uk/>). Multi-gas emissions and reductions include all Kyoto gases. The ratio of non-CO₂ and CO₂ used to estimate the emissions pathways of non-CO₂ species is that of the IPCC SRES B1 scenario as this assumes a future in which environmental concerns are of high priority, which we judge consistent with mitigation scenarios where emissions peak between 2016 and 2030.

[11] In addition to these plausible mitigation scenarios, two extreme scenarios were examined to extend the range of the results. One of these is the lower 10th percentile of the CO₂ and temperature distributions of a scenario where emissions are set to zero in 2016. The other extreme case is the upper 90th percentile from an SRES A1FI emissions scenario. The CO₂ concentrations from all scenarios are shown in Figure 1.

[12] The use of multi-gas scenarios to force the SCM and CO₂-only for the GCM is considered relatively unimportant for ocean pH since atmospheric CO₂ concentration is the main driver of changes in ocean pH, with a smaller impact from temperature. As such the CO₂ only scenarios are omitting only the impact of the additional warming from non-CO₂ gases on carbonate chemistry and as noted by

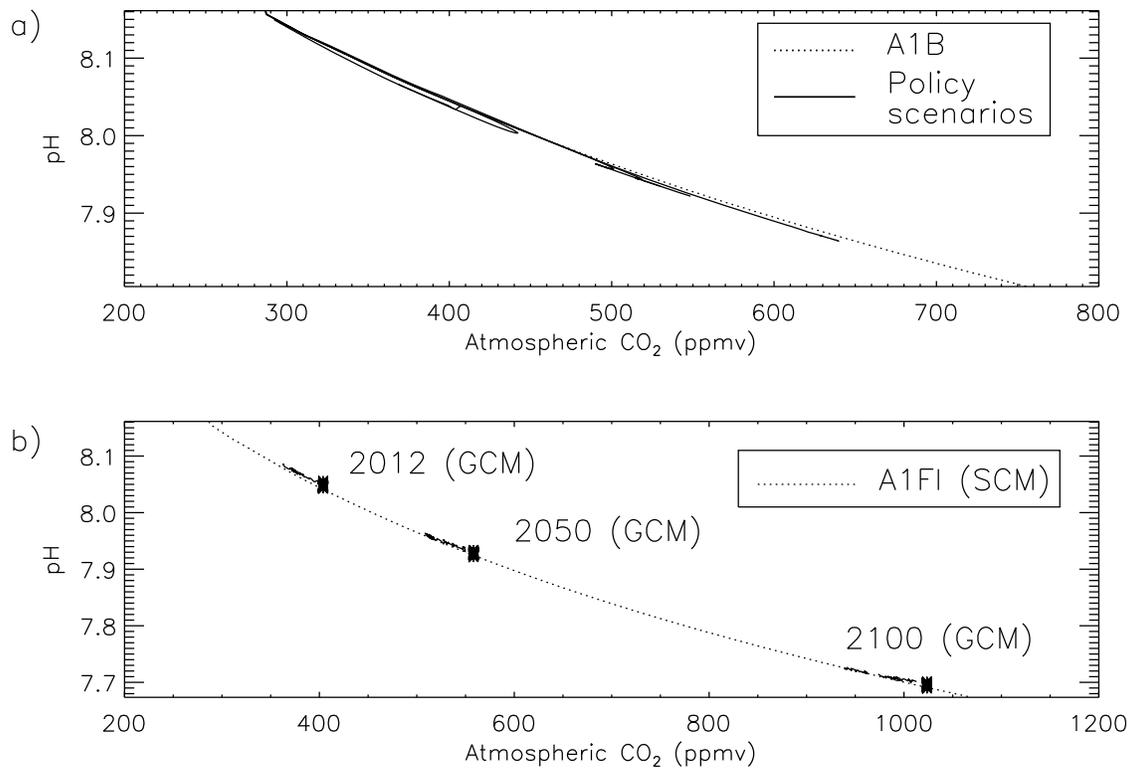


Figure 2. (a) Atmospheric CO₂ concentration and ocean surface pH from the simple model for a representative range of mitigation scenarios and the A1B baseline common to each. (b) As Figure 2a for the IPCC SRES A1FI scenario SCM simulation and the zero emission and stabilisation runs with HadCM3LC. The stabilisation runs are the “blocks” at constant CO₂.

McNeil and Matear [2007] and Cao *et al.* [2007], temperature plays a much smaller role in pH than CO₂ concentration.

3. Traceability Between Complex and Simple Models

[13] As atmospheric concentrations of CO₂ change, the resultant difference in the partial pressure of CO₂ between the atmosphere and ocean produces a flux of CO₂ between the atmosphere and ocean, reducing this difference. This adjustment happens rapidly in the SCM experiments (as in reality, where the gas exchange timescale of CO₂ is less than a year [Müller *et al.*, 2008, and references therein]) and results in an ocean surface pH that closely tracks the prescribed changes in atmospheric concentrations. Figure 2a shows the relation between these two parameters from several of the scenarios shown in Figure 1. The close match in pH at a particular concentration level in the different scenarios, despite the different emission, concentration and temperature pathways, shows that the relationship between global mean ocean surface pH and atmospheric CO₂ concentration in the SCM is largely independent of concentration pathway. A small deviation from the relation (<0.01 pH units) is present in Figure 2a as atmospheric CO₂ declines in some scenarios after a peak in emissions. This is likely a consequence of the effects of temperature changes on dissociation constants and CO₂ solubility. The impact of temperature on pH via these two factors largely cancel each other out and so, as noted in section 2.3, temperature changes have a very small impact on pH compared to

atmospheric CO₂ concentration. Similar surface ocean carbonate ion concentrations were also obtained at the same atmospheric CO₂ levels in different scenario runs of the NCAR CSM1.4-carbon model [Gattuso *et al.*, 2009, Box 5], even though carbonate ion concentration is less independent of global warming [Cao *et al.*, 2007]. Though it must be noted that other studies have found a significant path dependency in the Arctic [Frölicher and Joos, 2010].

[14] The relation of atmospheric CO₂ concentration in ppmv, [CO₂], and ocean surface pH in the SCM is well approximated by the cubic polynomial:

$$pH = 8.5541 - 0.00173 \times [CO_2] + 1.3264 \times 10^{-6} \times [CO_2]^2 - 4.4943 \times 10^{-10} \times [CO_2]^3 \quad (1)$$

Global mean pH produced from the complex model experiments are shown in Figure 2b along with the A1FI based scenario from the SCM. There is a close match between the CO₂ concentration and pH over the scenario space examined. The SCM can, in this respect, be said to demonstrate useful skill in reproducing the global mean results of the GCM. The high CO₂ “blocks” in Figure 2b show the evolution of the stabilized CO₂ experiments over time and shows that there is little further change of pH in these runs.

[15] Both SCM and GCM display the expected close relationship between the global mean atmospheric concentration of CO₂ and ocean surface pH, despite a significant difference in complexity of the two models. Increases and decreases in atmospheric CO₂ concentrations lead to readily

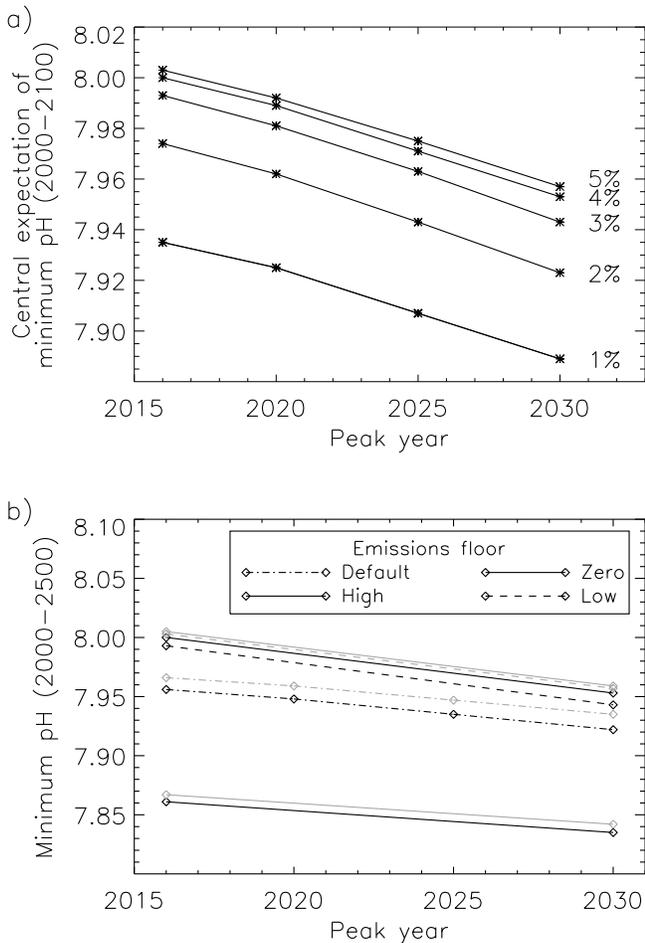


Figure 3. (a) Minimum global mean surface pH (2000–2100) as a function of peak year and post-peak reduction from the simple climate model using scenarios with the default emissions floor. (b) As Figure 3a but for minimum pH to 2500, with grey lines showing post peak reductions of 5% and black lines showing 3%.

predictable changes in ocean pH with only small discrepancies between the two, such as the presence of inter-annual variability of the ocean pH in the GCM. Although expected in a model of such complexity, it is still small (a standard deviation of 0.0024) compared to the change due to atmospheric CO₂ concentrations (see Figure 2b).

4. Impacts of Mitigation Policy on Acidification

4.1. How Much Acidification Can Mitigation Avoid?

[16] We here compare pH from two non-mitigation scenarios from the IPCC SRES, A1B and A1FI, to that from mitigation scenarios. Ocean surface pH has already dropped by ~0.1, from 8.16 in 1750 to 8.07. We find that an A1FI scenario would further decrease pH to 7.67 [7.74–7.57] by 2100 (where the square brackets indicate the 10th and 90th percentile values). For A1B pH would reach 7.81 [7.86–7.71]. These pH minima during the next century are 3.9 to 5.4 times the current change in ocean pH since 1750 and are likely without precedent in the last 21 million years [Pearson and Palmer, 2000], a period over which many

oceanic organisms have evolved to survive in a narrow range of pH.

[17] In an aggressive mitigation scenario, with global emissions peaking in 2016 and a post-peak reduction of 5% per year to a low long-term emissions floor, pH can be limited in its decrease to 8.02 [8.04–7.96] by 2100. This represents slightly less than a doubling of the change in pH since the pre-industrial era.

4.2. Influence of the Level of Action and the Time Action Starts

[18] Minimum pH is an useful metric for determining the success of mitigation measures. Figure 3a illustrates the relative importance of post peak emissions reduction rate and the year of peak emissions on the minimum global mean ocean surface pH from 2000 to 2100 in scenarios using the default emissions floor.

[19] Delaying the peak in global emissions has a roughly linear effect on the peak acidity up to 2100, while the avoided acidification from increased post-peak reduction rate starts to level off as reductions approach 5% per annum.

[20] An important conclusion that can be drawn from this is that commitment to stronger reductions at a later date can allow for a delay in peak emissions while still reaching the same pH minimum. For example, increasing post-peak reduction rates from 1% to 2% allows the peak year to be around 10 years later. Similarly, increasing reductions in emissions from 2% to 3% allows a delay of another 5 years, while moving from 3% to 4% adds another 2 years.

[21] The emissions floor has little impact on the minimum pH out 2100 (not shown), as the mitigation scenarios only reach their floor values, if at all, shortly before 2100. As a result the integrated difference in emissions owing to the different floor values is small compared to that due to the variation in peak emissions year and post-peak reduction rate. On longer time scales the integrated difference in emissions between floor values is important to CO₂ concentration and pH. Figure 3b shows the minimum pH reached by 2500 as a function of the year of peak emissions. The minimum values over this timescale are here dominated by the emissions floor with little sensitivity to the peak year and post-peak reduction rate.

5. Discussion and Conclusions

[22] This study finds that the minimum global mean ocean surface pH by 2100 in mitigation scenarios is influenced by both the peak year of emissions and plausible post-peak reduction rates. Longer-term acidification (out to 2500), as with global mean temperature, is largely determined by the long-term level of emissions reductions that are possible, as this dominates the cumulative emissions in mitigated emissions scenarios [Allen *et al.*, 2009].

[23] Global mean surface pH without mitigation is projected to decrease to between 7.67 and 7.81 by 2100. With aggressive mitigation (peak emissions in 2016 and a post-peak emissions reduction of 5% per year to a low value long-term minimum emissions) this could be limited to 8.02, roughly a doubling the current acidification. This minimum is likely to occur after the 21st century, in line with previous studies of non-mitigation scenarios [Caldeira and Wickett, 2005].

[24] It is noted that the duration of commitment to significant acidification may be large (several centuries) in line with [Caldeira and Wickett, 2005; Frölicher and Joos, 2010]. This study finds that the long term level of acidification reached is largely dependent upon the long term emissions levels attained, though stronger and more immediate action can limit the levels reached this century.

[25] Whilst this study has highlighted the significance of different aspect of mitigation policy for the minimum ocean surface pH over the coming 100 and 500 years, there are a number of methodological limitations. Regional differences highlighted in other studies relating to the Arctic [Steinacher et al., 2009; Frölicher and Joos, 2010], which are omitted in our large scale study, indicate that this sensitive area will undergo acidification faster than the global mean. Consequently specific inferences for the ecology of the Arctic cannot be drawn from this study. Model resolution also restricts our examination of coastal regions which are highly variable. Acidification in coastal regions is strongly influenced by both the deposition of sulphur and nitrogen as well as coastal dynamics [Doney et al., 2007]. Finally it is also acknowledged that global mean surface pH may not provide insight to changes in pH at depth throughout the global oceans for which other metrics are more appropriate [Caldeira and Wickett, 2005; Orr et al., 2005].

[26] These limitations acknowledged, the present study of basin scale acidification and mitigation policy, which would not have been computationally feasible with a fine resolution coastally resolved GCM, is an informative study of the potential to avoid impacts of anthropogenic climate change through mitigation efforts.

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D. Bernie, Met Office Hadley Centre, Fitzroy Road, Exeter EX1 3PB, UK. (dan.bernie@metoffice.gov.uk)

O. Legge and T. Tyrrell, National Oceanography Centre, Southampton, University of Southampton, Waterfront Campus, European Way, Southampton SO14 3ZH, UK.

J. Lowe, Met Office Hadley Centre (Reading Unit), Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK.