Reviewer 2

This is a fair effort. Ocean alkalinization has been talked about for some time, and as part of this discussion, specifically whether one might employ it to any effect to mitigate ocean chemistry changes in major tropical coral reef regions. Yet few (Earth system) modelling studies have been applied to atmospheric CO2 mitigation, and none previously with an explicit view on tropical coral habitat. Certainly in this respect this is a paper well worth publishing as it will set the ball rolling. The study and associated manuscript is a little minimal however and ideally I would have liked to have seen rather more details and analysis. The economic discussion is good though, and is more thorough and detailed than has been done in the few previous published modelling AOA studies.

Reply: We thank the reviewer for the thoughtful comments and suggestions.

A few specific comments and suggestions follow:

-The elephant in the room is, of course, bleaching. The authors mention it very briefly in passing in the Introduction, and again very briefly at the end of the Discussion. Rather more is needed to put the threat that OA represents into context. This could, at the minimum, be a literature-based analysis. In this respect, the Meissner et al. [2012a] paper is important. But would could either obtain their data/maps, or much better – recalculate bleaching frequencies for the regions and scenarios focussed on here. This would really put the cost/effort of regional AOA into perspective (i.e. would the reefs be likely to bleach and hence be threatened, regardless of any mitigation of ocean chemistry, or are there regions where OA is the earlier threat, or what does this say about large-scale AOA and hence substantive global pCO2 mitigation.

Reply. We have made some new efforts to better illustrate the coral bleaching status in our studied regions. Based on a literature survey we have provided some examples of coral bleaching in these regions due to thermal stress events. (Page 15 line 19 to Page 16 line 4). In fact coral bleaching incidents have been recorded for all three regions. Concerning the coral bleaching frequencies, all three regions have been reported to be coral bleaching hot spots (Teneva *et al*, (2012)). Furthermore, model predications suggest a severe increase in coral bleaching before the mid- 21st century. In the main text we write accordingly:

"Ocean acidification is only one of the stressors that corals reefs face in the future. Our study has not addressed other problems such as overfishing (Loh *et al* 2015) or thermal stress (Goreau and Hayes 1994). Coral reef bleaching, caused by thermal stress, is one of the most lethal and enduring threats to coral reefs. For example, in the Great Barrier Reef, between 11 to 83% of coral colonies were affected by large-scale bleaching due to unusually high temperatures during 1998, an El-Niño year, with the mortality rate varying between 1% and 16%

(Marshall and Baird 2000). The GB coral coverage declined by around 50% between 1985 to 2012, with 10% of the total loss attributed to coral bleaching (De'ath *et al* 2012). In the Caribbean Sea (CS), thermal stress in the year 2005 exceeded observed levels in the previous 20 years causing over 80% of corals to bleach and resulting in a 40% population loss (Eakin *et al* 2010). In the South China Sea (SC), massive coral bleaching in 1997 and 1998 affected 40% of coral colonies, but many of them recovered within a year (Waheed *et al* 2015). Model simulations have suggested that coral bleaching incidents will increase with global warming, and the threat will become more severe in the future if CO_2 emissions remain high and significant warming occurs (Frieler *et al* 2012, Caldeira 2013). According to Teneva *et al* (2012)'s model simulations, our three study areas are in coral bleaching hot spots (Goreau and Hayes 1994) with a middle to high likelihood of experiencing bleaching. Donner (2009) predicted that the 10 years' mean SST during 2090 to 2099 in our studied regions are 3.2°C (SC), 3.3°C (GB) and 3.4°C (CS) higher than those during 1980 to 2000 under a business-as-usual high CO_2 emission scenario. Given such predictions, the question arises as to whether or not regional AOA would be sufficient if CO_2 emissions remain high, e.g., warming might harm coral reefs long before acidification becomes a significant threat. "

Whether or not AOA would be useful if these areas warm as much as predicted is questionable. However, there may be situations, such as if solar radiation management (SRM) climate engineering, i.e. cloud brightening, were deployed to lower the Earth's temperature, when AOA could be useful. This is because SRM would do nothing to stop the ocean acidification threat, but could prevent thermal stress events from occurring. We have added new text to briefly discuss such a situation (Page 16, lines 4-8):

"There have been proposals to use cloud brightening (Latham *et al* 2013) to cool down surface temperatures to prevent coral bleaching and it is possible that other solar radiation management (SRM) methods may be envisaged in a similar manner. If SRM were seriously considered for this purpose when atmospheric CO_2 levels are high, AOA would be worth considering as well. "

-I appreciate that it may not be possible to do explicitly, but I would like to know something about how inter-annual variability in ocean circulation patterns and specifically ENSO, might modulate the author's projections of AOA. At the very least this requires some discussion added about how different phases of ENSO might influence of projections shown in Figure 4 and 5. But given the ocean surface in the UVic ESM is forced by climatological wind fields, it would not be impossible to substitute the applied forcing and test e.g. 'representative' El Nino vs. la Nina (although in truth they vary in strength and character).

Reply: Unfortunately the UVic model, being forced by climatological, observed wind fields, is incapable to simulate large-scale air-sea interactions due to its lack of dynamical atmosphere. Hence in the version used at GEOMAR, UVic does not feature an ENSO cycle. Furthermore, there appears to be no agreement how frequencies and intensities of ENSO will evolve in the future (Collins *et al* 2010; Guilyardi *et al* 2009). In the supplementary material (section 9, figure S14, S15) we compare the imprint of ENSO on observed SST (Reynolds *et al* 2002) and air-sea delta-pCO2 data (Landschützer *et al* 2014), respectively. Analyzing anomalies of annual mean SST and delta-pCO2 from year 1998 (El-Nino year) and year 2011 (La-Nina year) relative to a 20 year-climatology, we find only moderate differences between La Nina and El Nino dominated years in our study regions. We briefly refer to this analysis also in the main manuscript text and discuss its implications for AOA (Page 13 line 1-7):

"Second, most reported massive coral bleaching incidents are associated with El-Niño years (Aronson *et al* 2002), which are not resolved in our UVic model simulations driven by climatological winds. The observed ENSO-associated variability in our studied regions is relatively weak, as revealed by an analysis of historical SST and air-sea delta-pCO$_2$ records (supplementary figure S14 and S15). However, it is not well known how ENSO variability will develop in the future (Collins *et al* 2010; Guilyardi *et al* 2009) and thus its impact on our study region will remain another uncertainty."

-The use of the $\Omega = 3$ threshold is a relatively common device in global modelling and its previous use is well document here. Although you might note that more involved analysis suggests that no simple such threshold exists (Couce et al., Future habitat suitability for coral reef ecosystems under global warming and ocean acidification, Global Change Biology DOI: 10.1111/gcb.12335 (2013)) and that the trade-off with temperature leads to very different projects e.g. for the Eastern tropical Pacific as compared to the saturation threshold controlling assumption. However, the 500 ppm target is poorly justified and seems a rather ad hoc choice. More explanation is needed here quite why this value was adopted. It would help in this context to see fCO2 (or pCO2) maps for pre-industrial and current ocean surface chemical conditions and help put the target into perspective. Similar maps for aragonite saturation could also be usefully added, identifying the $\Omega = 3$ isopleth. Both sets of maps should have the ReefBase locations overlain. Global plots similar to the circular projection in Figures 4/5 would be fine.

Reply: Our choice of a combination of a Ω and a pCO2 threshold reflects resistance against ocean acidification from both calcifying organisms and non-calcifying organisms. The 500 μatm threshold is taken from the meta-analysis study of Wittman & Poertner (2013). This more detailed justification / explanation has been added to Page 5, lines 17 to Page 6 line 4:

"A healthy coral ecosystem usually includes a multitude of both calcifying and non-calcifying organisms. Aragonite Ω is commonly used to evaluate the impact of ocean acidification on marine calcifying organisms. Nevertheless, ocean acidification can also affect non-calcifying organisms, e.g. by reducing their metabolic rates (Rosa and Seibel 2008) or damaging their larval and juvenile stages (Frommel *et al* 2011). Concerning non-calcifying organisms, often pCO_2 is employed as a metric to evaluate impacts of ocean acidification. We therefore also consider how seawater pCO_2 will develop under increasing atmospheric pCO_2 and continuous AOA. Without AOA, annual mean surface seawater pCO_2 will follow atmospheric pCO_2 with some small time lag (e.g. Bates 2007). A meta-study of resistance of different marine taxa to elevated pCO_2 (Wittmann and Pörtner 2013) found that 50% of the species of corals, echinoderms, molluscs, fishes and crustaceans are negatively affected if seawater pCO_2 reaches high levels (between 632 to 1,003 µatm) with many species, except for crustaceans, also being significantly affected by pCO_2 levels between 500-650 µatm. Among the studied species, 57 % of echinoderms and 50 % of molluscs were negatively affected by the lowest levels of experimental pCO_2 manipulations. Since the loss of even one species, such as a keystone species, could potentially be detrimental for reef health, we chose a relatively low threshold of 500 µatm pCO_2 (as an annual average) to determine whether or not conditions were suitable for maintaining a healthy reef habitat. Moreover, by choosing a lower threshold we can better account for any variability in pCO_2 that may not be well simulated by our model. However, we must acknowledge that there are considerable uncertainties concerning such a threshold. Furthermore, these thresholds can be modulated by other environmental factors (Manzello 2015) and may not be absolutely applicable in every reef location. To avoid unnecessary complexity, the thresholds for both pCO_2 and Ω are considered here in terms of regional and annual averages."

We have also included new maps of surface aragonite saturation and pCO_2 with a new color scale that shows the locations of the Ω = 3 and pCO_2=500µatm isopleths more clearly (figure.1) with reefbase location overlain. Hopefully, this better illustrates the targeted thresholds and how they would change, to the detriment of coral reef ecosystems, without AOA.

- In the Discussion, the amount of Ca(OH)2 required to meet the carbonate chemistry targets in each region is compared and discussed. Various factors that might explain differing applications targets are discussed ... but no area. Firstly, when the authors use the word 'amount' this is completely total area dependent. They probably mean application density or flux ('rate of flow of a property per unit area'), but should say that. Even in terms of mean flux, all other things being equal, the larger the area, the proportionally smaller the circumference vs. the area, and one would hence expect lower mean flux is required.

Reply: Sorry for the confusion. We have revised this section to better differentiate between how much was added to each area in total and what the regional mean lime input flux was stated in Page 13, line 24-26.

- General: A little clarification is needed surrounding the absence of Ca2+ as an explicit tracer in the ocean. The authors are very open about this and at one point make an estimate of to what degree this might matter. A few places in the text still refer to adding ”Ca(OH)2” in the model ... which of course they are not ... (rather: (OH−)2).

Reply: There are two complementary definitions of TA. The well known one by Dickson (1981) reflecting on the excess of proton acceptors over proton donors with respect to the proton conditions defined at pK=4.5, and the more recent definition regarding the ‘explicit conservative form of total alkalinity’ by Wolf-Gladrow, Zeebe, Klaas, Körtzinger, Dickson (2007, mar. Chem. 287ff): $[Na^+]+2[Mg^{2+}]+2[Ca^{2+}]+[K^+]+2[Sr^{2+}]+ \ldots . -[Cl^-]-[Br^-]-[NO_3^-]-\ldots$ $TPO_4+TNH_3-2TSO_4-THF-THNO_2 = TA_{ec}$ (equ. 32 of Wolf-Gladrow *et al.* 2007).

Considering AOA by $Ca(OH)_2$ in terms of addition of OH- is in line with the definition of Dickson (1981). However, since the elements of the Dickson equation do not behave conservatively, considering the addition of OH- is not the most straightforward approach. Consider for example the impact of mixing of two water samples, one with and one without a certain Ca(OH)2 addition would give a non-linear mixing line (TA vs. OH-). Considering instead the addition of Ca2+ in the context of the explicit conservative form of TA, appears more straightforward. In particular, the mixing line (TA vs. Ca^{2+}) is linear. If we could measure Ca2+ with sufficient precision, we could then perfectly detect the added amount of alkalinity from the difference of Ca2+ measurements before and after the addition.

In particular the consideration of the effect of mixing on TA and Ca^{2+}, respectively, clarifies why one does not need an explicit Ca^{2+} tracer. That is, among other reasons, why the explicit conservative form of TA is so helpful.

Abstract: ”unprecedented carbon chemistry states”. Unprecedented’ how? In terms of what carbon chemistry variable, or all of them? Is this unprecedented spatially? As meaning ’never done or known before’ you infer never seen in any of Earth history. Perhaps some clarification is needed.

Reply: Sorry for the confusion. We have revised this sentence into:
“Beyond preventing local acidification, regional AOA, however, results in locally elevated aragonite oversaturation and pCO_2 decline”

- Section 1 / 1st paragraph: for the threats to tropical coral reefs – please reference the primary literature (experimental and observational studies) rather than global model studies that implicitly already assume the threat is true (and instead go on to quantify it). Similarly, at the end of the paragraph you cite a perspectives on a paper rather than the paper and its results directly – at the very least you might cite both.

Reply: In page 2 line 18, “Goreau and Hayes 1994, Cooper *et al* 2008, De’ath *et al* 2009” are added as observational proofs for our argument. Also, some of the studies already cited in this paragraph are experimental evidence instead of model results. i.e. Gattuso *et al* 1998, Langdon and Atkinson 2005.

- Section 2 / 5th paragraph – the issue of local/reef-scale ocean chemistry (and e.g. diurnal cycles) vs. mean open ocean conditions is discussed well later, but you should still add in this caveat in at the end of this paragraph where you define the Ω threshold you are going to use.

Reply: In page 5 line 9, the sentence is now rewritten:

" Critical coral habitat threshold values of ambient aragonite Ω ranging from Ω = 3 (Meissner *et al* 2012b), Ω = 3.3 (Meissner *et al* 2012a), to Ω = 3.5 (Ricke *et al* 2013) have been used in recent climate change studies, acknowledging that these represent regional mean values and that local reef-scale carbonate chemistry may display large diurnal fluctuations also in healthy reefs. Ignoring sea surface temperature as a regulator of coral reef habitats may be a further simplification (Couce *et al* 2013). "

- Section 3 / 1st paragraph – remind us here what ’GB’, ’CS’, etc stand for.

Reply: They are now written out in full length (Page, 6, line 19-21).

- Section 4 / 2nd paragraph – at the end some minerals are listed and the concern stated that ’adding significant amounts of calcium ...’, which for calcite and aragonite is slightly spurious as large amounts of alkalinity are already being added, with the proportional change in [CO23− orders of magnitude more important than adding Ca2+. The potential side effect re. carbonate precipitation is already well addressed earlier. Apatite seems highly unlikely given the low surface [PO34−] or it would already be precipitating out of much of the deeper water column. Gypsum I could buy.

Reply: Thank you for pointing this out. We have deleted this argument from the new version of the main text.

Reference list

Collins M, Soon-Il A, Cai W, Ganachaud A, Guilyardi E, Fei-Fei J, Jochum M, Lengaigne M, Power S, Timmermann A, Vecchi G, Wittenberg A 2010 The impact of global warming on the tropical pacific ocean and El Nino *Nature Geosci* 3:391-7

Cooper T F, De'Ath G, Fabricius K E, and Lough J M 2008 Declining coral calcification in massivePorties in two nearshore regions of the northern Great Barrier Reef *Glob. Change Biol* **14**, 529-38

De'ath G, Fabricius K E, Sweatman H and Puotinen M The 27-year decline of coral cover on the Great Barrier Reef *Proc. Natl. Acad. Sci. U. S. A.* **109**, 44

Dickson A G 1981 An excat definitation of total alkalinity and a procedure for the estimation of alkalinity and totoal inorgnic carbon from titration data *Deep sea Res.* **28A,** 609-623

Donner S D 2009 Coping with commitment: projected thermal stress on coral reefs under different future scenarios. *PLoS One* **4** e5712

Eakin C M *et al* 2010 Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005 *PLoS One* **5**(11)

Goreau T J and Hayes R L 1994 Coral Bleaching and Ocean “Hot Spots” *Ambio* **23** 176–80

Guilyardi E, Wittenberg A, Fedorov A, Collins M, Wang C, Capotondi A, von Oldenborgh G, and Stockdale T 2009 Understanding El-Nino in ocean-atmosphere general circulation models, progress and challenges. *Bull Am Meterol Soc* **90**:325-40

Latham J, Kleypas J, Hauser R, Parkes B and Gadian A 2013 Can marine cloud brightening reduce coral bleaching? *Atmos. Sci. Lett.* **14** 214–9

Reynolds R W, Rayner N A, Smith T M, Stokes D C and Wang W 2002 An improved in situ and satellite SST analysis for climate *J. Clim.* **15** 1609–25

Teneva L, Karnauskas M, Logan C a., Bianucci L, Currie J C and Kleypas J a. 2012 Predicting coral bleaching hotspots: The role of regional variability in thermal stress and potential adaptation rates *Coral Reefs* **31** 1–12

Waheed Z, Benzoni F, van der Meij S E T, Terraneo T I and Hoeksema B W 2015 Scleractinian corals (Fungiidae, Agariciidae and Euphylliidae) of Pulau Layang-Layang, Spratly Islands, with a note on Pavona maldivensis (Gardiner, 1905) *Zookeys* **2015** 1–37

Wittmann A C and Pörtner H-O 2013 Sensitivities of extant animal taxa to ocean acidification *Nat. Clim. Chang.* **3** 995–1001

Wolf-Gladrow D A, Zeebe R E, Klaas C, Körtzinger A and Dickson A G 2007 Total alkalinity: The explicit conservative expression and its application to biogeochemical processes *Mar. Chem.* **106** 287–300