Sensitivity of Future Ocean Acidification to Carbon Climate Feedbacks

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Abstract. Carbon-climate feedbacks have the potential to significantly impact the future climate by altering atmospheric CO_2 concentrations (Zaehle et al., 2010). By modifying the future atmospheric CO_2 concentrations, the carbon-climate feedbacks will also influence the future trajectory for ocean acidification. Here, we use the CO_2 emissions scenarios from 4 Representative Concentration Pathways (RCPs) with an Earth System Model to project the future trajectories of ocean acidification with the inclusion of carbon-climate feedbacks. We show that simulated carbon-climate feedbacks can significantly impact the onset of under-saturated aragonite conditions in the Southern and Arctic Oceans, the suitable habitat for tropical coral and the deepwater saturation states. Under higher emission scenarios (RCP8.5 and RCP6.0), the carbon-climate feedbacks advance the onset of under-saturation conditions and the reduction in suitable coral reef habitat by a decade or more. The impact of the carbon-climate feedback is most significant for the medium (RCP4.5) and low emission (RCP2.6) scenarios. For RCP4.5 scenario by 2100, the carbon-climate feedbacks nearly double the area of surface water under-saturated respect to aragonite and reduce by 50% the surface water suitable for coral reefs. For RCP2.6 scenario by 2100, the carbon-climate feedbacks reduce the area suitable for coral reefs by 40% and increase the area of under-saturated surface water by 20%. The high sensitivity of the impact of ocean acidification to the carbon-climate feedbacks in the low to medium emissions scenarios is important because our recent commitments to reduce CO_2 emissions are trying to move us on to such an emissions scenario. The study highlights the need to better characterise the carbon-climate feedbacks to ensure we do not excessively stress the oceans by under-estimating the future impact of ocean acidification.

Key messages

– rate of OA related to land carbon uptake (climate-carbon feedback)

– sensitivity is largest for the medium emissions scenarios (RCP4.5) and for this scenario the carbon-climate feedback could significant accelerate and enhance the impact of ocean acidification. Such an acceleration OA may futher undermine the ability of marine biota to adapt to the changing environment

– need to do ESM simulations to make future OA projections (relevance to AR6) and reduce the uncertainty in the climate-carbon feedback

1 Introduction

Ocean acidification, the measurable consequence of increasing atmospheric CO_2 concentrations, has the potential to significantly impact individual marine organisms and ecosystems by reducing calcifications rates (Stojkovic et al., 2013), altering phytoplankton composition (Lohbeck et al., 2012), changing fish behavior (Munday et al., 2009) and affecting larval recruitment (Ross et al., 2011). This has the potential to significantly impact the ecosystem services that the ocean provides (Gattuso et al., 2015). Therefore accurate projections of ocean acidification are essential to assessing the future impact of ocean acidification, to setting policy that avoids or limits dangerous climate change, to managing marine resources and to guiding adaptation strategies.

Future climate-carbon cycle projections generally show global warming reduces the efficiency of carbon dioxide (CO_2) uptake by the land and ocean (Friedlingstein et al., 2006; Roy et al., 2011; Matear and Hirst, 1999). As a result, more emitted carbon stays in the atmosphere leading to additional warming (Friedlingstein et al., 2003, 2001), which represent a positive climate feedback. While these future carbon-climate feedbacks under the various emission scenarios are highly uncertain (Zhang et al., 2014; Wenzel et al., 2014), the carbon-climate feedbacks have the potential to significantly impact future climate trajectories (Zaehle et al., 2010). Studies to date have highlighted that these climate-carbon feedbacks are primarily due to changes in land carbon uptake, and have therefore focused on how the land carbon uptake may impact the future climate (Friedlingstein et al., 2006). Importantly, these carbon-climate feedbacks will also influence the future trajectory for ocean acidification because the surface ocean carbon does track the atmosphere CO_2 (McNeil and Matear, 2008). Therefore, the carbon-climate feedbacks are not only important to future climate change, they are also relevant to the future trajectory of ocean acidification and this study investigates whether future carbon-climate feedbacks have important consequences for ocean acidification. This is important as these feedbacks have not been accounted for in studies that project future changes in ocean acidification (Bopp et al., 2013). To address this gap in ocean acidification research, this

study investigates the potential for the climate-carbon feedbacks to alter the future evolution of ocean

55   acidification by using a global Earth System Model (ESM) (Phipps et al., 2011; Zhang et al., 2014).

For this study, we consider the 4 different future projections of atmospheric CO_2 of the Representative Concentration Pathways (RCPs) as provided by the CMIP5 [http://cmip-pcmdi.llnl.gov/cmip5/] based on both prescribed atmospheric CO_2 concentrations and emissions. The scenarios represent the high (RCP8.5, RCP 6.0), medium (RCP4.5) and low (RCP2.6) atmospheric CO_2 concentrations

60   pathways of the IPCC's Fifth Assessment Report (Stocker et al., 2013). We focus our analysis on how the simulated carbon-climate feedbacks influence the future ocean acidification.

The structure of the paper is as follows. In the next section we briefly describe the ESM model used and the simulations performed. In the subsequent section, we present the results from the historical simulation and the future simulations. We show the climate-carbon feedbacks accelerate ocean

65   acidification in all future emissions scenarios. Importantly, it is in the low and medium emissions scenarios where ocean acidification is most impacted by the carbon-climate feedbacks. For these low and medium emissions scenarios, the ocean acidification is sensitive to the additional CO_2 in the atmosphere provided by the carbon-climate feedbacks. This has important policy relevance because the recent global commitments to reduce our greenhouse gas emissions seek to put us on

70   the low to medium emissions path to avoid dangerous climate change but it may underestimate the consequences for ocean acidification.

2   Model Description

In this study we used the CSIRO Mk3L Carbon Ocean, Atmosphere, Land (COAL) Earth System Model (ESM)(Buchanan et al., 2016) The COAL components include ocean and land biogeochem-

75   istry (Matear and Lenton, 2014; Zhang et al., 2014), which exchange CO_2 with the atmosphere and enable investigating carbon-climate interactions within an Earth System model. The atmospheric resolution of 5.6° by 3.2°, and 18 vertical layers, and land carbon component has the same horizontal resolution as the atmosphere

The land module (CABLE) with CASA-CNP (Wang et al., 2010; Mao et al., 2011) simulates the

80   temporal evolution of heat, water and momentum fluxes at the surface, as well as, the biogeochemical cycles of carbon, nitrogen and phosphorus in plants and soils. For this study, we use the land module that includes carbon, nitrogen and phosphate cycles with spatially explicit estimates of nitrogen deposition held constant from Dentener (2006). The simulated (Zhang et al., 2014) geographic variations of nutrient limitations, major biogeochemical fluxes and pools on the land under the present

85   climate conditions are consistent with published studies (Wang et al., 2010; Hedin, 2004).

The ocean component of the Earth System Model has a resolution of 2.8° by 1.6°, and 21 vertical levels. The ocean biogeochemistry is based on Matear and Hirst (2003); Buchanan et al. (2016), and simulates the evolution of phosphate, oxygen, dissolved inorganic carbon and alkalinity in the ocean.

This ocean biogeochemical model was shown to realistically simulate the global ocean oxygen and
90 phosphate cycles (Duteil et al., 2012) and the present day distribution of dissolved inorganic car-
bon and alkalinity in the ocean (Matear and Lenton, 2014; Buchanan et al., 2016). The simulations
presented here use the standard the ocean BGC formulation presented in Matear and Lenton (2014).

2.1 Model simulations.

The ESM was spun-up under preindustrial atmospheric CO_2 (1850: 284.7 ppm) until the simulated
95 climate was stable (2000 years) (Phipps et al., 2012). Stability was defined as the point where the
linear trend of global mean surface temperature over the last 400 years of the spin-up was less than
0.015°C per century.

From the spun-up initial climate state, the historical simulation (1850 - 2005) was performed using
the historical atmospheric CO_2 concentrations as prescribed by the CMIP5 simulation protocol. For
100 the historical period, the atmospheric CO_2 affects both the radiative properties of the atmosphere and
the carbon cycle (Zhang et al., 2014). From year 2006, 4 different future projections were made using
the atmospheric CO_2 concentration pathways of RCP8.5, RCP6, RCP4.5 and RCP2.6 as provided by
the CMIP5 [http://cmip-pcmdi.llnl.gov/cmip5/]. The simulations made with prescribed atmospheric
CO_2 are subsequent called concentration pathway (CP) simulations.

105 The future simulations were repeated using the CO_2 emission scenarios that were used by the
Integrated Assessment Model to generate the future atmospheric CO_2 concentrations used in the
RCPs. We subsequently refer to these simulations as the emission pathway (EP) simulations. EP
simulations have prescribed atmospheric carbon emissions, and the atmospheric CO_2 is determined
by considering how much carbon is absorbed by the land and ocean in our ESM. For each of the
110 EP scenarios, the radiative forcing of non-CO_2 gases was converted into equivalent CO_2 and added
to the simulated atmospheric CO_2 to maintain the same radiative forcing of non-CO_2 greenhouses
gases as used in the corresponding CP simulation but this additional CO_2 was not seen by the land
and ocean carbon modules. From the difference between the EP and CP simulations we quantify the
carbon-climate feedbacks, and we use these differences to investigate how carbon-climate feedbacks
115 influence the future atmospheric CO_2 concentration and ocean acidification.

The future carbon-climate feedback simulations made with RCP8.5 and RCP2.6 were discussed
by Zhang et al. (2014) with a focus on how the feedbacks increased warming due to reduced carbon
uptake by the land. Zhang et al. (2014) showed the EP simulations had less than 0.4°C more global
surface warming than the corresponding CP simulations by 2100. Here, we have added the RCP4.5
120 and RCP6 scenarios and focus our study on ocean acidification.

In all our simulations, the vegetation scenario used by Lawrence et al. (2013) remained unchanged
over the simulation period following the CMIP5 experimental design. We also neglected changes
in anthropogenic N deposition over the simulation period, because of the large uncertainty in the
future deposition rate and the small impact it has on net land carbon uptake (Zaehle et al., 2010).

125 To account for possible drift in the simulated climate and carbon pools, a control simulation with
the atmospheric CO_2 held constant at 284.7 ppm was performed over the simulation period, 1850 to
2100. Drifts in climate and carbon pool sizes were small (less than $0.015°C$ century^{-1} and 5 Pg C
century^{-1}), and correcting the future scenarios with the control simulation had negligible impact on
the future projections of ocean acidification and ocean warming.

3 Results

3.1 Historical Period

An assessment of the simulated carbon and climate was made in Zhang et al. (2014); Matear and
Lenton (2014); Buchanan et al. (2016) and here we briefly comment on the simulation over the his-
torical period (1850 - 2005). Mk3L-COAL simulates the historical climate well, as compared to the
135 models used for earlier IPCC assessments (Phipps et al., 2011; Pitman et al., 2011). Over the his-
torical period, the global averaged surface warms by $0.57° \pm 0.07°C$ (Zhang et al., 2014), which is
comparable to the observed value of $0.76° \pm 0.19°C$ (Trenberth et al., 2007). The simulated land and
ocean uptake were 85 ± 1 PgC and 116 ± 1 PgC, respectively compared to observed land and ocean
estimates of 135 ± 84 and 135 ± 25 (Zhang et al., 2014). The simulated response of the land carbon
140 cycle to increasing atmospheric CO_2 and warming is consistent with those from the Coupled Model
Intercomparison Project Phase 5 (CMIP5) (Zhang et al., 2014). While the acidification of the ocean
was also comparable to other CMIP5 simulations (Matear and Lenton, 2014; Bopp et al., 2013). For
1995, we compare the annual mean surface ocean carbonate ion concentration to the concentrations
estimated for the 1995 from the carbon, alkalnity (Key et al., 2004), temperature and salinity (Boyer
145 et al., 2009) observations (Figure 1). The simulated values are generally consistent with the obser-
vations with a slight over-estimate in the simulated carbonate ion concentration in the mid-latitudes.
The model also under-estimates the carbonate ion concentration off northeast Australia but recent
analysis of the observations in this region showed the GLODAP (Key et al., 2004) derived values
were too high and our ESM simulation is consistent with this recent data compilation (Lenton et al.,
150 2015).

3.2 Future Response

For the future, the ESM simulated reduced uptake of carbon by the land and higher atmospheric
CO_2 in the EP simulations compared to the corresponding CP simulations (Figure 2). For reference,
the emissions simulations with just a C-based version of our land model produced atmospheric CO_2
155 concentrations that nearly tracked the corresponding CP scenarios (Zhang et al., 2014). However,
with nitrogen and phosphorus limitation on the land, the land carbon uptake was reduced (Zhang
et al., 2014) and by the end of the simulations had 17, 31, 54 and 80 ppm more CO_2 in the atmo-
spheric in the EP simulations (RCP2.6, 4.5, 6, and 8.5 respectively) than in the corresponding CP

simulations. With higher atmospheric CO_2 concentrations, the EP simulations have higher global
160   averaged surface temperature (Figure 3) and increased oceanic uptake of CO_2 (Figure 4 than the
corresponding CP simulations.

The higher atmospheric CO_2 translated into higher CO_2 in the surface ocean. To quantify ocean
acidification impacts we show the carbonate ion concentrations in the surface water for both the CP
and EP simulations (Figure 5). Figure 5 illustrates how rising atmospheric CO_2 impacts the carbon
165   chemistry of the surface ocean. Two ways to gage the ocean acidification impacts in the surface
water are where aragonite becomes chemically unstable or corrosive (aragonite saturation state of
less than 1) and where aragonite saturation declines to less than 3, an approximate threshold for
suitable coral reef habitat (Hoegh-Guldberg et al., 2007). In Figure 5, the white lines denote annual
mean aragonite saturation state values of 1, and the purple lines the annual mean aragonite saturation
170   state values of 3.0. A quick way to assess the ocean acidification impact is by how the white and
purple lines differ between RCP scenarios (e.g. difference down a column) and how the carbon-
climate feedbacks alters the surface chemistry changes (i.e. differences along a row). As one goes
to higher future emissions scenarios (e.g. RCP2.6 to RCP8.5) the atmospheric CO_2 concentrations
increase and the white lines move towards the equator and the regions of surface water in which
175   aragonite is chemically unstable expand. In contrast, as one goes to higher emissions scenarios the
suitable regions for coral reefs shrink. In the RCP6 and RCP8.5 scenarios, there are no suitable coral
reef regions by 2100 and a substantial portion of the polar Southern and Northern hemisphere have
surface water corrosive to aragonite in agreement with previous studies (Ricke et al., 2013; Sasse
et al., 2015). When the carbon-climate feedbacks are accounted for (EP simulations) there is a further
180   expansion of aragonite under-saturated surface water, and the area suitable for coral reefs is further
compressed.

Figure 6 shows more clearly how climate-carbon feedback alters the rate of ocean acidification.
The figure shows how the global surface areas of aragonite undersaturation (a) and suitable coral reef
habitat (b) change with time for the various scenarios. The EP scenarios are always more negative
185   (hashed lines) than the corresponding CP simulations.

For under-saturate aragonite surface water, the EP simulations all display a similar evolution to the
corresponding CP simulations but with a more rapid onset of under-saturate conditions. For RCP8.5,
the EP simulation leads the CP simulation by about 5 years. For RCP6, the EP simulation leads the
CP simulation by about 10 years. For RCP4.5 the lead is nearly 20 years. While for RCP2.6 there
190   is a similar 20 year lead in the emissions simulation but the area of under-saturation water is small
due to the low atmospheric CO_2 which makes quantifying the lead uncertain. Further, in the RCP2.6
scenario the atmospheric CO_2 starts to decline after 2050 (Figure 2) because the scenario has nega-
tive emission sin the second half of the century. Associated with the declining atmospheric CO_2 is a
reduction in surface ocean acidification (Figure 6b) hence, in this scenario there is a small reduction
195   in the area of under-saturated water by the 2100 from the maximum value in 2060s. The simula-

tions show that it is in the mid to low emissions scenarios (RCP4.5 and RCP2.6) the differences between emissions and concentration driven simulations are most pronounced and hence where the carbon-climate feedbacks are most significant.

For the surface ocean area suitable for coral reefs the evolution of the EP simulations are similar to the corresponding CP simulations but again they lead the CP simulations. The more rapid onset of ocean acidification produces the largest difference in the RCP4.5 scenario where by the end of the century the suitable area for coral reefs in the EP simulation (18%) is less than half the CP simulation (37%). Under the high emissions scenarios (RCP 6.0 and 8.5) their is no suitable habitat for coral reefs by 2100 with the time of disappearance occurring 15 and 6 years earlier in the EP simulation than the CP simulation for RCP6 and RCP8.5, respectively. With the highest emission scenario (RCP8.5) there is such a large and rapid release of CO_2 to the atmosphere that ocean acidification impacts are so substantial that the differences between the emission and concentration simulations are similar but with a slight acceleration in the EP simulation.

The differences between the EP and CP simulations extend into the ocean interior. By 2100, the EP simulations show shallower depth of where the aragonite goes under-saturated (referred to as aragonite saturation horizon) than the corresponding CP simulations (Figure 7). For the RCP2.6, the difference is generally smaller because the rate of CO_2 rise is slow and the penetration of carbon is not very different between the two EP and CP simulations. However, for the other emissions scenarios the differences between the EP and CP simulations are substantial particularly in the Southern Ocean and North Pacific (Figure 7b,c,d). Under the RCP4.5 scenario, it is in the Southern Ocean where the EP simulated aragonite saturation horizon is more than 400 m shallower than the CP simulation. In this scenario, the surface water does not become under-saturated with respect to aragonite (Figure 5b) but the sub-surface water does and the slight increase in the uptake of carbon in the EP simulation is sufficient to significantly shoal the aragonite saturation horizon. Such a shoaling of the aragonite saturation horizon would have a detrimental impact on calcifying organisms such as pteropods inhabiting the Southern Ocean (Comeau et al., 2012). The RCP8.5 and RCP6.0 scenarios also display areas where the aragonite saturation horizon is more than 400 m shallower in the EP simulation than the CP simulation. In both these scenarios, most of the Southern Ocean surface water is under-saturated with respect to aragonite (Figure 5c,d) with the largest shoaling occurring just outside of the Southern Ocean, where anthropogenic carbon taken up in the Southern Ocean is stored (Groeskamp et al., 2016). As more anthropogenic carbon is transported into the ocean interior in the EP simulations, it is these regions where the carbon is stored that show the greatest shoaling of aragonite saturation horizon. The changes in the aragonite saturation horizon in the Southern Hemisphere could also be very important to future viability of deep water corals found in regions like south of Australia (Thresher et al., 2011; Guinotte and Fabry, 2008).

4 Conclusion and Discussion

Here we employ an ESM to investigate the potential consequence of the climate-carbon feedbacks on the future evolution of ocean acidification. With the emissions driven (EP) simulations, we show the climate-carbon feedback can significantly influence the future rate of ocean acidification. Therefore accounting for carbon-climate feedbacks is important in projecting future ocean acidification impacts and trajectories.

The other salient point is the that the carbon-climate feedbacks have the greatest impact under the medium to low emissions scenarios (RCP4.5 and RCP2.6). For RCP4.5 scenario, the carbon-climate feedbacks nearly double the area of under-saturated surface water, and halves the surface water suitable for coral reefs by the end of the century. While less dramatic, the RCP2.6 scenario shows the carbon-climate feedbacks reduce the area suitable for coral reefs by 40% and increase the area of under-saturated surface water by 20%. If we aim to track a low emissions scenario (Anderson and Peters, 2016) then we are on a path where the carbon-climate feedbacks can have the most impact on ocean acidification and there is a pressing need to better quantify the impact to ensure we avoid the most negative consequences of ocean acidification. This may ultimately require faster reductions in CO_2 emissions and the need to consider ways to increase negative emissions (Lackner, 2016). Here is another area where ESM simulations can help assess the benefits and consequences of different strategies to enhance carbon sinks (Lenton et al., 2017).

Here we have only considered ocean acidification impacts but the carbon-climate feedbacks also leads to faster global warming, this would accelerate the impacts like ocean warming and deoxygenation (Cocco et al., 2013). For our simulations, the carbon-climate feedbacks on these impacts were small (ocean surface water less than 0.25C) but these impacts are synergistic (Bopp et al., 2013) and although they may be small they will further stress the ocean ecosystems with potential importance consequences to future livelihoods coastal nations (Mora et al., 2013). As aragonite staturation state is also controlled by temperature (Mucci, 1983), there is a weak increase in saturation state with increased ocean warming but this affect is very small and cannot offset the decrease in saturation state due to enhanced ocean carbon uptake.

A key conclusion of the our study is that carbon-climate feedbacks may be important to future ocean acidification and getting a better quantification of the feedbacks are essential. This has been recognized by World Climate Research Program (WRCP) who identified *Carbon Feedbacks in the Climate System* as one their Grand Challenges (https://www.wcrp-climate.org/grand-challenges/gc-carbon-feedbacks). Here, we have presented simulations with only one ESM, but our simulations are consistent with previous evaluations of the climate-carbon feedbacks. To express the long-term sensitivity of land carbon storage to future climate warming (γ_L in PgC K^{-1}) is used quantified the carbon loss per unit temperature change (Friedlingstein et al., 2003). The differences in γ_L simulated by ESMs is highly variable and remains a key uncertainty in climate projections of the 21st century (Friedlingstein et al., 2006; Booth et al., 2012). Recent analysis using the short-term variability to

constrain the model simulations reduces the range of γ_L to 44 ± 14 PgC/K^{-1} (Wenzel et al., 2014), which overlaps with the probability density function derived from the C4MIP models (53 ± 17
270 PgC/K^{-1}) (Cox et al., 2013). For the ESM used in this study we estimated γ_L was 34 PgC/K^{-1} comparable to the best estimate of what the response should be. A sensitivity study (Booth et al., 2012) with a single land carbon model showed a range of climate-carbon feedbacks on atmospheric CO_2 of 461 ppm (669 to 1130 ppm) by year 2100 with A1B scenario (Nakicenovic et al., 2000) scenario. This range exceeds the range in atmospheric CO_2 from the 4 RCP emissions scenarios
275 considered in this study (420 to 936 ppm). Booth et al. (2012) demonstrates that climate-carbon feedbacks could be an important player in the future evolution of ocean acidification and more ESM projections are needed to realistically assess the carbon-climate feedbacks on ocean acidification.

The large differences in the climate-carbon feedbacks are not only a key uncertainty in climate projections (Friedlingstein et al., 2006; Booth et al., 2012) they are also a key uncertainty in future
280 ocean acidification projections. Therefore for both climate projections and ocean acidification there is a pressing need to improve our ability to simulate the climate-carbon feedbacks. Even with the small climate-carbon feedbacks shown here (less than 100 ppm change by the end of the century) the impact on the future rate of ocean acidification were still significant and make the ocean even more vulnerable than what was provided by the recent ocean acidification assessment (Aze et al.,
285 2014).

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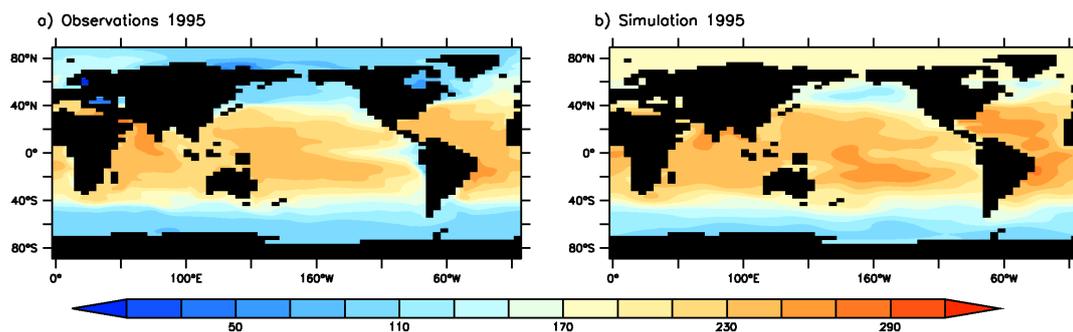
Figure 1. Surface ocean carbon ion concentration (μmol kg^{-1}) a) from observations of dissolved inorganic carbon and alkalinity (Key et al., 2004) and annual mean surface temperature and salinity (Boyer et al., 2009); b) simulated for 1995
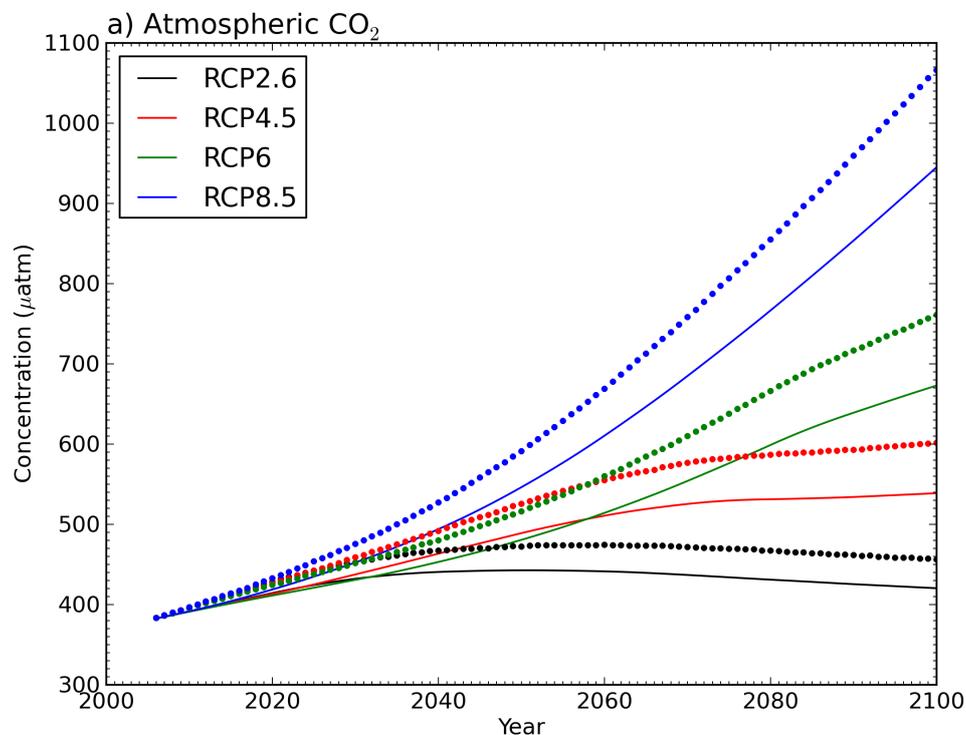
Figure 2. For the various RCP scenarios, the atmospheric CO$_2$ prescribed for the CP scenarios (solid lines) and simulated by the ESM for the corresponding EP scenarios (dotted lines).
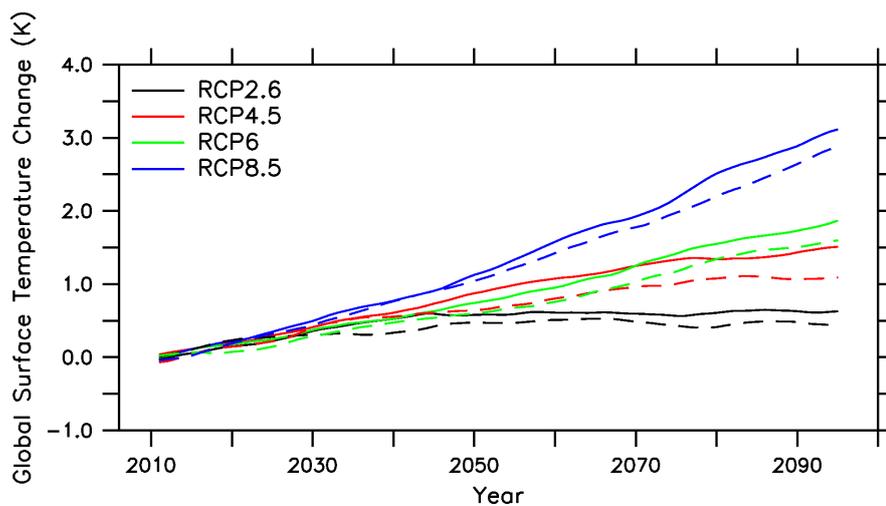
Figure 3. For the various RCP scenarios, the global annual averaged surface temperature change in Kelvin from

the present-day for the EP (dotted) and CP (solid lines) simulations.
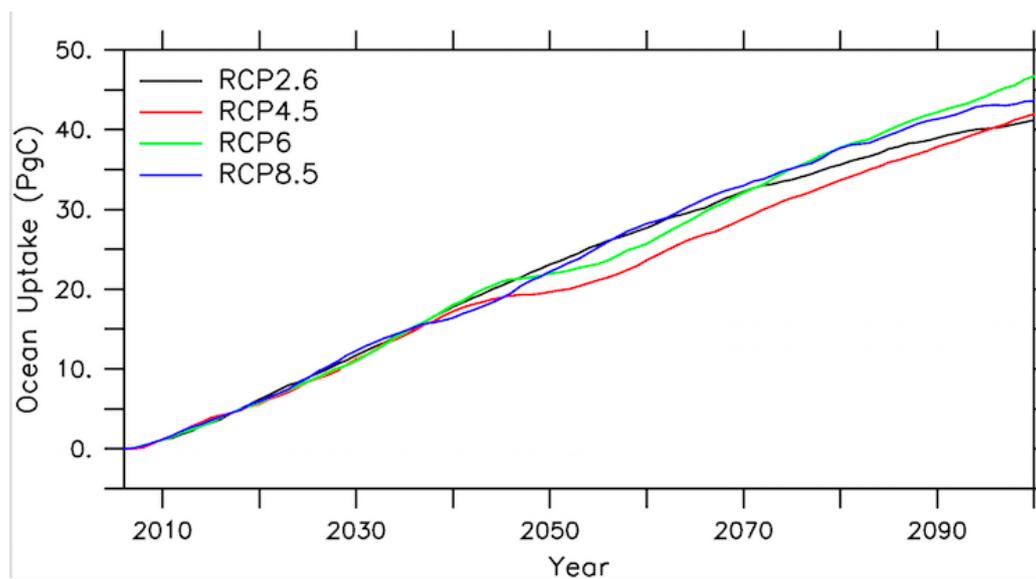
Figure 4. For the various RCP scenarios, the global annual difference in oceanic uptake of CO_2 (PgC y^{-1})

between the EP and the corresponding CP simulations.
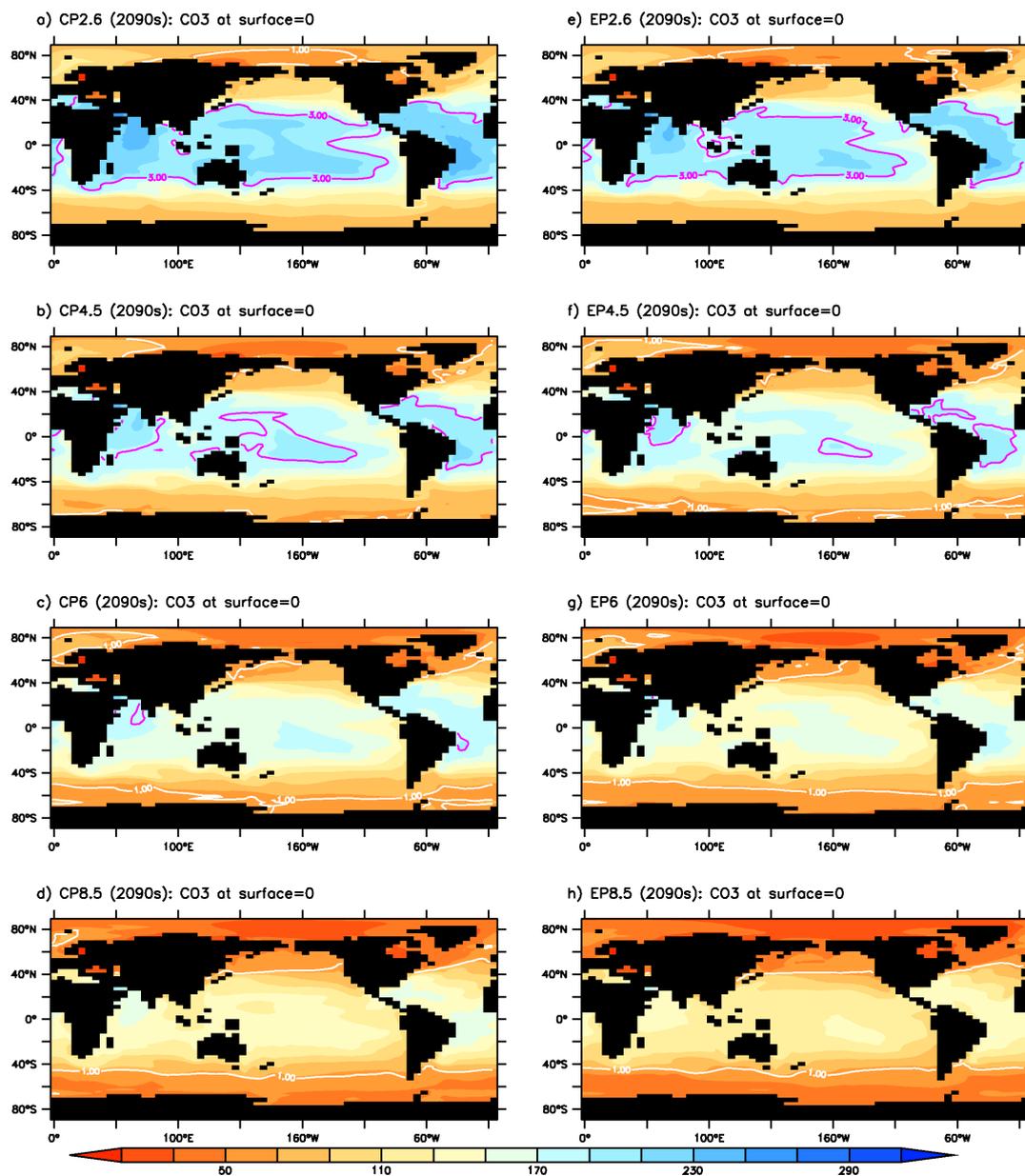
Figure 5. For the various RCP scenarios, the surface ocean carbon ion concentration (μmol kg^{-1}) for the decade of the 2090s for CP simulations (left column): a) RCP2.6, b) RCP4.5, c) RCP6, and d) RCP8.5; the same scenarios for the EP simulations (right column) e) RCP2.6, f) RCP4.5, g) RCP6 and RCP8.5. In the figures, the white contour lines denote where aragonite saturation state equals one and the area with carbonate ion concentrations less than this line would be corrosive to aragonite. The purple contour lines denote aragonite saturation state of 3 and the regions enclosed by the purple lines reflect the regions suitable for coral reefs.
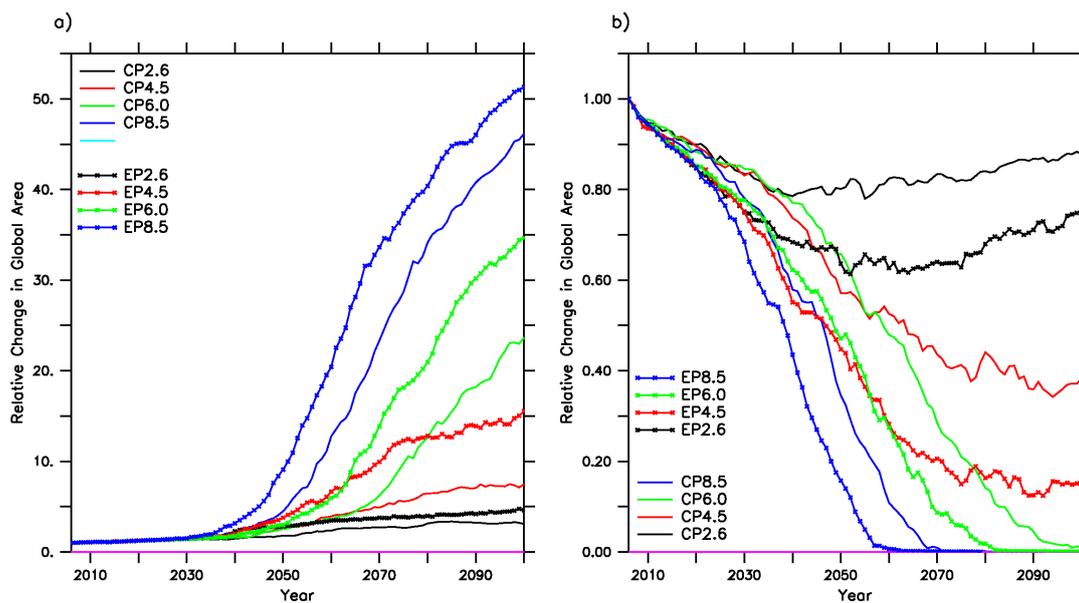
Figure 6. For the various RCP scenarios, the concentration simulations (CPs) and their corresponding emission driven simulations (EPs): a) Change in area of surface water with aragonite saturation state less than 1 relative to the area in 2005; b) Change in area of the surface water suitable for coral reefs (aragonite saturation state greater than 3) relative to the area in 2005.
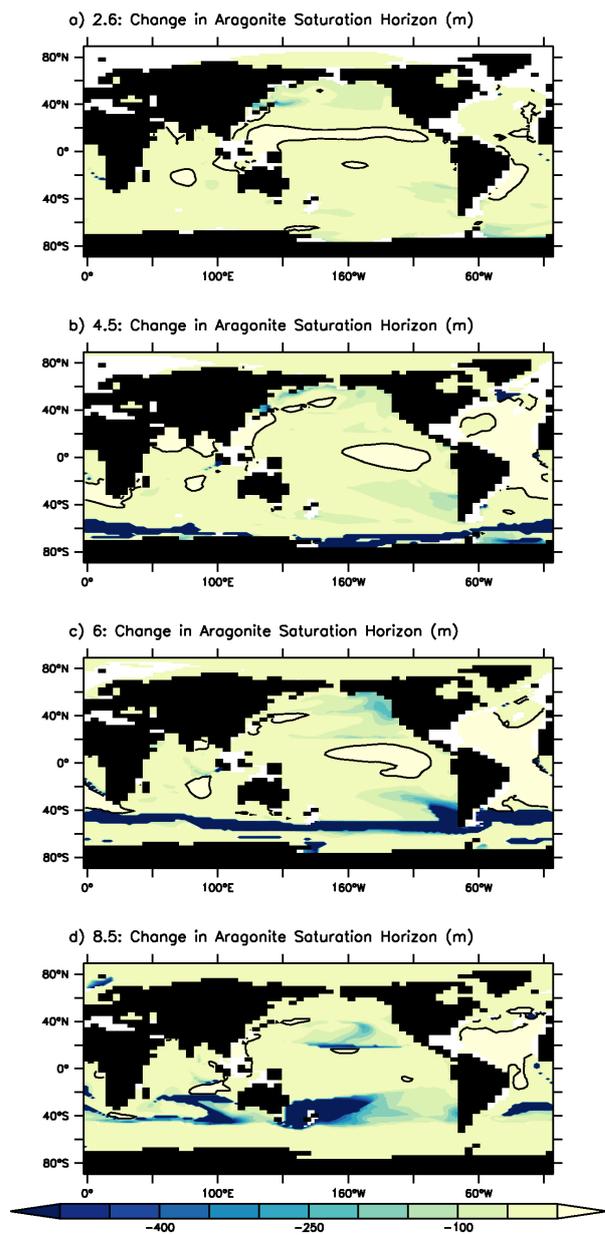
Figure 7. For the year 2100, the change in the depth of the aragonite saturation horizon between the emission simulations (EPs) and the concentration simulations (CPs) for: a) RCP2.6; b) RCP4.5; c) RCP6; and d) RCP8.5