Interactive comment on "Coastal-ocean uptake of anthropogenic carbon" by Timothée Bourgeois et al.

We thank Prof. Pierre Regnier (referee #1) and Prof. Nicolas Gruber (referee #2) for their comments and suggestions.

We first comment on 3 key topics raised by the referees, and then provide point-by-point responses for each referee. The 3 key topics are (1) the need for more information to support our proposed mechanism for lower coastal anthropogenic CO_2 uptake due to limitation by cross-shelf exchange, (2) the need to clarify our estimate of anthropogenic carbon fluxes and on the role of potential biological changes, and (3) the effect of model drift on our results.

1) Cross-shelf exchange

We concur with both referees that more information is needed to support our conclusion that it is inadequate cross-shelf exchange that reduces the coastal ocean's uptake of anthropogenic CO2 (per unit area) relative to that of the global ocean.

Following the suggestion by Referee #1, we plan to include a new figure with time series of C_{ant} uptake, C_{ant} storage, and cross-shelf export of C_{ant} (Figure 1 in this response). This new figure demonstrates clearly that simulated cross-shelf export of dissolved inorganic anthropogenic carbon (DIC_{ant}) is less than the simulated anthropogenic CO_2 uptake for the coastal ocean, implying an accumulation of DIC_{ant} in the coastal waters column during the simulation.

As suggested by the Referee #2, we will also offer more detail about the simulated coastal-ocean ocean exchange. For that, we will add the simulated water residence time for each MARCATS region to Tables 2 and 3 of the revised manuscript and we will introduce a new figure (Figure 2 in this response). These new results reveal that simulated residence times for most coastal regions are of the order of a few months or less, except for Hudson Bay, the Baltic Sea and the Persian Gulf. The latter three regions are generally more confined and we would expect longer residence times, although our model simulations were never designed to simulate these regions accurately. Generally then, our simulated residence times are shorter than what has been published for similarly defined coastal regions (see Jickells et al. (1998), Men et al. (2015)). The absence of tides and the spatial resolution used in our study do not permit to reproduce the mesoscale variability of the coastal circulation (e.g. eddies and upwellings). Depending on coastal regions, these processes may increase/decrease residence time. The comparison with these published estimates is also difficult since we average residence time estimates on extended areas.

Jickells et al. (1998)
http://science.sciencemag.org/content/281/5374/217
Men et al. (2015)
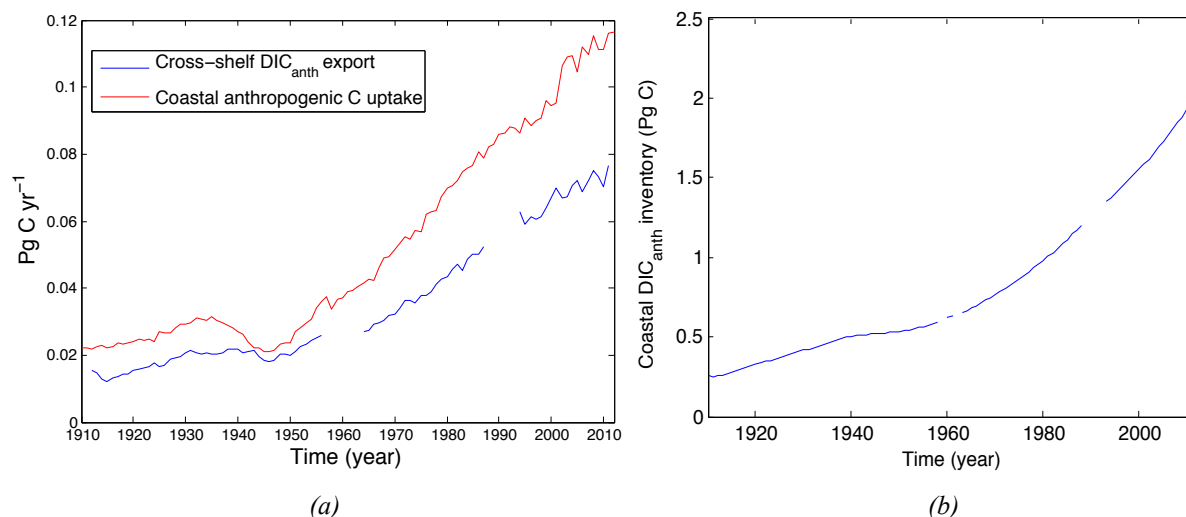http://link.springer.com/article/10.1007%2Fs10967-014-3749-y

Figure 1: Simulated temporal evolution of (a) cross-shelf export for anthropogenic dissolved inorganic carbon (DIC$_{ant}$) in blue and area-integrated anthropogenic CO$_2$ uptake for the coastal ocean in red, given in Pg C yr^{-1}, and (b) DIC$_{ant}$ inventory for the coastal ocean as Pg C. Missing years will be added in revised manuscript.
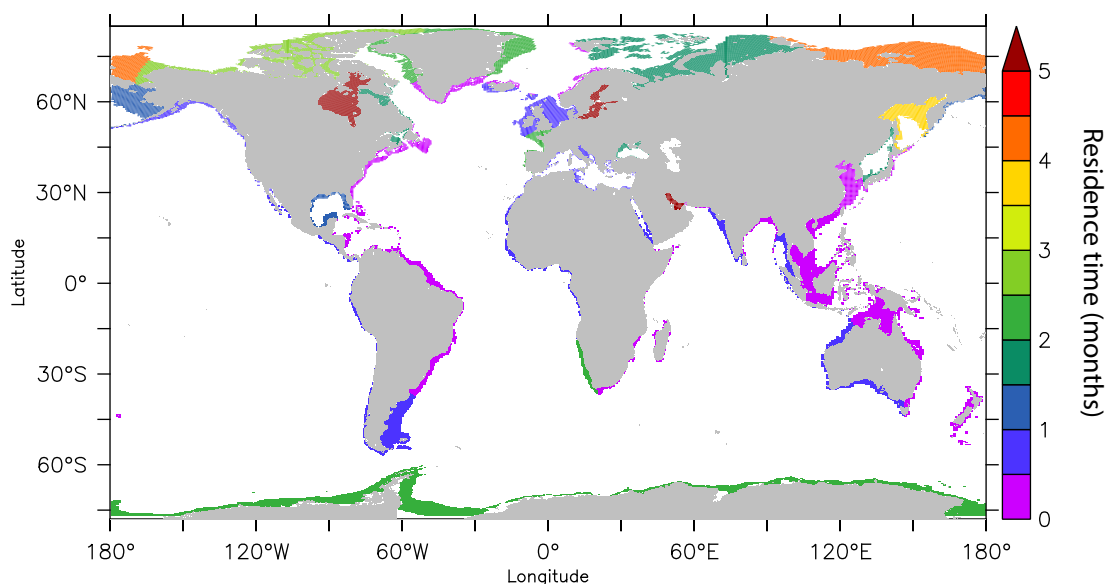

Figure 2: Global distribution of simulated residence time (month) for the global coastal ocean segmented following Laruelle et al. (2013). Results are also reported on updated Tables 2 and 3 at the end of this document.

All these points will be added to the revised manuscript.

2) Our estimate of anthropogenic carbon fluxes and the role of potential biological changes

Our method to compute anthropogenic air-sea CO$_2$ fluxes (FCO$_2$) is based on the difference between total FCO$_2$ from an historical simulation (with increasing atmospheric CO$_2$) and natural FCO$_2$ from a control simulation (i.e., with the same physical forcing but with fixed pre-industrial atmospheric CO$_2$). This method is commonly used by the modeling community to estimate anthropogenic carbon fluxes (e.g. http://ocmip5.ipsl.jussieu.fr/OCMIP/ or Bopp et al., 2015). By definition, our anthropogenic air-sea CO$_2$ fluxes only respond to increasing

atmospheric CO_2. They do not include any effect from potential changes in ocean physics or biology, because those changes are identical in the historical and the control simulations. Hence, even if surface temperature or biological fluxes (NEP or NEC) change in response to the forcing, they do not impact anthropogenic carbon uptake per se.

That said, we agree with the reviewers that potential changes in the physics and biology as well as changes in riverine input or in the interactions with the sediment may be of primary importance, would modify the distribution of total carbon and alkalinity, and hence would also modify the potential of the coastal ocean to absorb anthropogenic carbon.

These points will be discussed in more detail in the revised manuscript.

Bopp et al. (2015)
http://dx.doi.org/10.1002/2015GL065073

3) Model drift and potential implications.

We concur with both reviewers that details about model drift are important. In the original manuscript we stated the following: "At lower resolution (ORCA2), after a spin up of 3000 years, there is 0.26 Pg C yr-1 greater globally integrated sea-to-air flux, relative to results after only a 50-year spin up. Nearly all of that enhanced sea-to-air CO2 flux due to the longer spin up comes from the Southern Ocean." Unfortunately, such spin-up length is currently out of reach regarding to computation costs of our ORCA05-PISCES configuration. We emphasize though that our anthropogenic FCO_2 estimates are expected to be influenced very little by model drift because of the way anthropogenic carbon is defined ($C_{ant} = C_{total} - C_{natural}$), i.e., drift affects both C_{total} and $C_{natural}$ in the same way.

POINT-BY-POINT REPLY

- <u>Referee #1 comments</u>

The manuscript by Bourgeois et al. is the very first attempt to quantify the air-sea CO_2 flux for the global coastal ocean using a highly-resolved 3D model. The authors compare in a convincing way their model results with observational data and discuss in detail the obtained spatial variability in the air-water CO_2 exchange. The approach is well described and model results are solid; I am thus very supportive of this research. In addition, the authors have attempted a quantification of the anthropogenic perturbation on the air-sea CO_2 flux, with the key finding that the magnitude of the perturbation could be significantly smaller than previously taught. This is obviously an important result that further strengthens the value of this contribution. However, the latter aspect has several shortcomings that I believe need to be addressed fully (see in particular major comments 2) and 3) before publication.

Thanks for this positive general feedback.

Major comments

1) Uncertainties are only reported once for the anthropogenic CO_2 flux (0.1 +- 0.01). You need to explain how this uncertainty has been estimated. It is also much lower than the uncertainty on the total simulated flux (0.27 +- 0.07), which is quite surprising. More

The uncertainty on our estimate of the coastal-ocean uptake of anthropogenic carbon is defined as its interannual standard deviation over 1993-2012. This will be clarified to the revised manuscript; uncertainties will also be given for all fluxes (see updated Tables 2 and 3 at the end of our response).

Since our uncertainty values are based on the interannual variability over 1993-2012, the uncertainty on the simulated total FCO_2 is much higher than that of the anthropogenic flux. That is, the strong variability of total CO_2 flux is due almost entirely to variability in its natural component so that the variability in their difference (anthropogenic flux) is small.

Another way to estimate uncertainties for such fluxes would be to use multiple models or sensitivity tests with one model where key parameters were varied. These exercises are currently out of reach and left for future work.

We agree with the reviewer that the way we define the anthropogenic flux hampers any strict comparison with some previous estimates in which other terms are taken into account. This will be clarified in the revised manuscript, and we refer the reviewer here only to our general reply above for a first response to this comment.

We concur with the reviewer that more information is indeed needed to substantiate our proposed mechanism; we refer to the general reply (point 1, above) in which we indicate the additional figures and discussions that we will introduce in the revised manuscript.

We have also calculated the evolution of the Revelle factor for the coastal and open ocean over the historical period. While the coastal Revelle factor is 16% more than in the open ocean in 1870, that ratio evolves to being only 17% more for the last simulated decades (around 2000). Thus different rates of change of Revelle factor between the coastal and open ocean cannot solely explain the amplified anthropogenic carbon accumulation in the water column of the coastal ocean.

Finally, concerning the horizontal cross-shelf transport of water, we do not fully understand the suggestion of the referee. We have chosen to compute water residence times for each MARCATS. We refer the reviewers to our general reply for this comment.

As proposed, the main results on the model-data comparison of total fluxes will be added to the abstract and conclusion of the revised manuscript.

"To begin to better resolve coastal bathymetry" will be replaced by "to begin to better resolve coastal bathymetry and take into account the complex coastal currents" in the revised manuscript.

As the intended meaning was "cross-shelf export", "carbon export" will be replaced by "cross-shelf carbon export" to the revised manuscript to clarify this sentence.

We presume that the referee refers to page 2, line 9 rather than line 5. We agree that the "less is known" formulation for coastal-ocean air-sea CO_2 exchange is not suitable here. In the revised manuscript, the last sentence of this paragraph will be replaced by "All these

estimates suffer from high uncertainties as do those for coastal-ocean air-sea CO_2 exchange (Laruelle et al., 2014), particularly its anthropogenic component".

Page 2 line 15-16: I agree about the CO_2 switch of the coastal ocean from source to sink, but do not agree fully with the proposed attribution. Mackenzie and co-workers highlight the change in NEP (from enhanced land nutrient inputs) as one of their key driver to explain the shift (see also Regnier et al., 2013 & Bauer et al., 2013 – for reviews). Please clarify (see also major comments).

Referee #1 does well to emphasize the need to introduce the proposed role of the changing NEP and riverine nutrient inputs in the CO_2 source-to-sink shift of the coastal ocean from Mackenzie et al. (2004). This proposed mechanism will be discussed in the revised manuscript as will be that from Bauer et al. (2013) to explain the CO_2 source-to-sink shift due only to the increased physical uptake of atmospheric CO_2 (with constant NEP).

Page 3, line 20: I recommend making reference to the few published long time series of CO_2 observations (> 1 decade) for the coastal ocean. I agree nevertheless that these time series alone are sparse and short. Thus, an observation-based global extrapolation of the anthropogenic component is highly uncertain.

Two references dealing with long time series of CO_2 observations in the coastal ocean will be added in the revised manuscript (Astor et al., 2013 with 1996-2008 CO_2 data at CARIACO station on Venezuelan coasts and Ishii et al., 2011 with the 1994-2008 CO_2 data along 137°E on Japanese coasts) to support the lack of data-based estimates. To our knowledge, these are the only available time series of CO_2 data of more than a decade.

Astor et al. (2013)
http://dx.doi.org/10.1016/j.dsr2.2013.01.002
Ishii et al. (2011)
http://dx.doi.org/10.1029/2010JC006831

Page 4 line 24: calcite particles are included. This is not a satisfactory description. Please state clearly if your model accounts for calcification as this process has a potentially important impact on the air-sea CO_2 exchange (see also major comments).

We have chosen not to provide great detail on the model's calcification-related processes, which are described extensively elsewhere (Aumont and Bopp, 2006). The simulated NEC remains constant at a first order and does not respond to increasing anthropogenic CO_2. Moreover, calcification is identical in our historical and control simulations; hence, it does not affect the simulated anthropogenic carbon perturbation.

Page 4 line 29: do you mean atmospheric deposition?

Yes, "budgets" will be replaced by "deposition" in the revised manuscript.

Page 6 line 4: Assuming that land derived DOC is entirely labile is a strong assumption. The flux (0.15 PgC yr-1 from the top of my head) is also significant. Thus, the extent to which your results depend on this assumption has to be discussed.

Referee #1 is absolutely right that the representation of riverine DOC input in the model is extremely simple. Dissolved organic matter is indeed assumed to remineralize instantaneously at the river mouths, thus contributing to the DIN, DIP, DIC pools. Yet complexifying the approach will not affect our estimate of anthropogenic carbon uptake since the land-derived carbon delivery and its lability remains constant throughout simulation. We agree with the referee on the need to clarify this point in the revised manuscript.

Page 6 lines 11-19: The implication of a model outside of ' equilibrium ' has to be addressed. For instance, when you refer to a global ocean anthropogenic uptake of 2.3 PgC/yr-1, this number is obtained with a natural flux of -0,33 PgC yr-1 for the natural flux. Correct?

This is correct. We refer the reviewers to the general reply for this comment.

Page 7, section 2.4 evaluation dataset: To leave no ambiguity, did you compare your model results with LA14 using the Wanninkhoff 1992 formulation or the updated formulation?

We used Laruelle et al. (2014) estimates computed using the formulation of Wanninkhof (1992) as modified by Takahashi et al. (2009) to compare with simulated CO_2 fluxes computed using the initial Wanninkhof et al. (1992) formulation. Although the gas exchange formulation is critical for air-sea flux estimates derived from observations, it has little impact on model-derived fluxes of anthropogenic carbon (Sarmiento et al., 2002).

Sarmiento et al. (2002)
http://dx.doi.org/10.1063/1.1510279

Page 9, lines 12-14: I would say 'weak carbon sources' and 'strong carbon sinks'

We will make both of these changes in the revised manuscript.

Page 9 lines 15-25: The phrasing is misleading ('our model results tend to underestimate total carbon flux, with 76% of the simulated specific fluxes lower than the data-based estimates'), as the absolute fluxes are actually larger in the model (i.e. larger negative sinks). 'Likewise' is also not appropriate because the Arctic region is in fact the only latitudinal band where the model results predict a smaller sink than the observations. More broadly, I find that the results are quite comparable for the southern hemisphere and the low latitude regions, but that discrepancies are significantly larger in the Northern hemisphere with a stronger sink modeled for the 30-60◦ N and a weaker sink modeled for the > 60◦N latitudinal band (see also Fig 3 of LA14). Also, the fact that the areal-integrated fluxes show a weaker obs-model correlation than the fluxes per unit surface area requires discussion.

The sentence "our model results tend to underestimate total carbon flux, with 76% of the simulated specific fluxes lower than the data-based estimates" has been replaced by "our model results tend to simulate larger sinks / smaller sources than observed (i.e. 76% of the specific simulated fluxes of total carbon with lower relative values than the data-based estimates)".

"Likewise" will be replaced by "Otherwise".

Using the latitudinal distribution of natural fluxes, we can explain why carbon uptake is indeed larger in the coastal ocean. This is because upwelling zones (natural CO_2 sources) are

extremely restricted (i.e. narrow continental shelf) contrary to the CO_2 sink regions with commonly large continental shelves.

Concerning the weak obs-model correlation for area-integrated fluxes, remapping errors between MARCATS surfaces in Laruelle et al. (2014) and ours are particularly important for low area regions and reach 50% as maximums. Thus, we estimate that the model-data comparison using area-integrated FCO_2 is not adequate with such large remapping errors. We plan to delete this part of the model-data comparison and the 2nd panel (b) of the Figure 6 when revising the manuscript.

Page 10 line 14: what do you mean by 'top two regions'?

EBC and WBC are similar, they are the top two (the two largest) regions in absorbing anthropogenic carbon but their behavior differs in terms of total FCO_2. We will reformulate the sentence in the revised manuscript to clarify.

Page 10 line 25 and further: It is important to state that (to my knowledge) only LA14 accounts for the sea-ice cover in the global estimates - this is an important effect on the quantification.

We will emphasize that the Laruelle et al. (2014) is the first and only study to provide coastal observational-based FCO_2 estimates at global scale taking into account the effect of sea ice. Remarks will be added both to section 2.4 (Evaluation dataset) and to section 4.1.1 (Total fluxes).

Page 11 line 5-10: I agree that the exclusion of the proximal zone in the model assessment should have an impact on the sign of the flux under pre-industrial conditions. But what about the effect of the initialisation (the value of the sink is not reported for the coastal ocean in 1850)? Stated differently, is the global coastal ocean in equilibrium at the onset of the simulations? Regarding the proximal zone, bays, estuaries, deltas, lagoons are indeed sources of CO_2 (see Laruelle et al., 2013 for the latest synthesis), banks should be too (a reference would be useful), but I am not sure about what is meant by ' marine wetlands '. If this refers to marshes and mangroves, they are then believe to be sinks for atm CO_2 (see Cai, 2011, Regnier et al., 2013, Bauer et al., 2013). Thus, clarification is required here.

Certainly, the coastal ocean is not at equilibrium when the simulation is initialized in 1870. This is an important point addressed in our previous responses.

"Marine wetlands" will be replaced by "salt marshes and mangroves" in the revised manuscript to clarify the sentence and "banks" will be added to the revised manuscript. Those regions are included in the proximal zone that is generally known as a carbon source although some parts of it may be sinks.

Page 11, section 4.1.2 first paragraph: I believe that regional scale studies have attempted an estimation of the anthropogenic CO_2 uptake in EBUS. If true, they should be included in the discussion.

We have searched but fail into find regional-scale studies that provide estimates of anthropogenic CO_2 uptake in EBUS regions. Estimates of anthropogenic carbon content in the water column have been published for instance for the California current region by Feely

et al. (2008) but we do not found any regional estimates of anthropogenic CO_2 uptake from the atmosphere.

We do not understand Referee #1's remark to tone down the sentence on line 21-22. Our affirmation that Wanninkhof et al. (2013) exploit coarse-resolution model and data is valid. According to our model, the extrapolation technique used by Wanninkhof et al. (2013) overestimates the anthropogenic carbon uptake of the coastal ocean. We plan to leave the sentence as is.

We choose to design the section 4.2 to highlight contrasts between the coastal and the open ocean whereas 4.1.1 is specifically focused on coastal total FCO2. As the first two paragraphs of the section 4.2 deal with coastal vs. open ocean comparison, we suggest letting the paragraphs as is. To clarify the aim of section 4.1, we will rename it as "Comparison with previous coastal estimates".

Our assumption of the instantaneous remineralisation of all land-derived DOC into DIC impacts natural FCO_2 (and total FCO_2) but has no effect on simulated anthropogenic FCO_2. One of the potential of this assumption would be a total CO_2 sink reduction, shown for the Amazon plume for instance. In our model, river alkalinity input is equal to the initial riverine DIC input. But when riverine DOC is remineralized to DIC, that does not affect simulated ocean alkalinity. This point will be clarified in the model description.

The latitudinal distributions of anthropogenic CO_2 fluxes are indeed similar between the coastal and open ocean. In particular, we note that this similarity is prominent in the Southern Ocean: Antarctic shelves and adjacent open ocean waters are very much alike. Following the Laruelle et al. (2014) definition of the Antarctic Shelves, the bathymetry of this coastal region is deeper than the other MARCATS regions. Its mean bathymetry is around 500 m against 160 m for the global coastal ocean. This mitigates the contrast between coastal and open ocean processes in the Southern Ocean. This explanation will be added to the revised manuscript.

We insist that the Revelle factor does affect the anthropogenic CO_2 flux (e.g., Sabine, 2004, Nature). This fact can be demonstrated with simple equilibrium calculations. For example, using CO2SYS-Matlab, if we increase the xCO_2 from 280 to 400 ppm in equilibrium with two surface water masses at 2°C and 20°C each having a total alkalinity of 2300 ueq kg^{-1}, the corresponding increases in DIC_{ant} are 55 and 73 umol kg^{-1} (while the Revelle factor increases by 2.2 and 1.3, respectively). Clearly the Revelle factor influences anthropogenic carbon uptake.

In the criticized sentence, we will add "anthropogenic carbon" so that its revision will read as follows: "That finding is consistent with the lower simulated specific fluxes of anthropogenic carbon into the coastal ocean". The differences between coastal and global ocean highlighted by the referee in Figure 5 are mainly due to natural fluxes.

Sabine et al. (2004)
http://dx.doi.org/10.1126/science.1097403

Page 13 lines 23-24: The chemical factors are presented as independent of the physical factors controlling the air-sea CO_2 exchange. However, based on the model construct, I feel that the higher Revelle factor for the coastal ocean precisely results from the physics of the coastal zone, with a progressive accumulation of DIC due to weaker cross-shelf export than CO_2 air-sea exchange.

At the beginning of the historical simulation, the Revelle factor is already 16% larger on average, for the coastal ocean relative to the global ocean. And at the end of the simulation it remains about the same, 17% larger. We agree though that cross-shelf transport is inadequate to allow the coastal ocean to take up as much CO_2 per unit area as for the global ocean average.

Figure 8: I assume that fluxes refer to total anthropogenic fluxes, i.e. organic plus inorganic carbon – please clarify.

Yes, the flux in Fig. 8 refers to anthropogenic flux. And that corresponds only to an inorganic flux. The model does not account for the anthropogenic perturbation to the organic carbon pool (see general reply).

Spelling

Page 1, Line 10-11: rephrase – this sentence is odd

Initial sentence:
Yet only 4.5% of that (0.10 Pg C yr^{-1}) is absorbed by the global coastal ocean, i.e., less than its 7.5% proportion of the global ocean surface area.

New sentence:
Yet only 0.1 Pg C yr^{-1} is absorbed by the global coastal ocean. That represents 4.5% of the anthropogenic carbon uptake of the global ocean, less than the 7.5% proportion of coastal-to-global ocean surface areas.

Page 2 line 4: remove 2nd 'relative'

Done.

Page 4 line 25: not sure that 'model' can be used as a verb

In the revised manuscript, we will replace "explicitly models" with "explicitly accounts for".

Page 10 line 19: remove 'that'

OK.

Page 14 line 14: remove 'of'

Line 13: We point out a missing "carbon" after the word "anthropogenic". It will be corrected in the revised manuscript.

"offshore transport of carbon" is replaced by "offshore carbon transport".

Page 14 line 24-25: parenthesis wrongly placed

Fixed.

- <u>Referee #2 comments</u>

1 Summary

Bourgeois et al. use an eddy-permitting global ocean biogeochemistry model to investigate the relative contribution of the ocean margins to the uptake of anthropogenic CO_2 from the atmosphere. They find that these regions take up a disproportionally low amount of anthropogenic CO_2, i.e., only 4.5% relative to this regions areal contribution of 7.5%. The authors suggest that it is the limited degree to which the anthropogenic CO_2 is transported and mixed offshore that leads to this low uptake. These results are in stark contrast to earlier studies based primarily on a few point observations that suggested a very high coastal ocean uptake of CO_2 from the atmosphere.

Thanks for this nice feedback.

2 Evaluation

Understanding and predicting the future evolution of the oceanic sink for atmospheric CO_2 is of paramount importance for determining how much CO_2 we can emit in the coming decades without exceeding any climate target. While our confidence in the net exchange fluxes of CO_2 over the open ocean has increased substantially in recent years thanks to better observations and novel methods to interpret these data, our ability to constrain the fluxes along the continental margins has not increased commensurably. The existing observational constraints are still relatively weak and associated with sizeable uncertainties. By far the most extensive and detailed assessment to date by Laruelle et al. suggested a relatively small global net uptake of atmospheric CO_2, but their data-based approach did not permit them to separate this net flux into its "natural" and "anthropogenic" components.

Thus the study by Bourgeois et al. is much welcomed as it brings a consistent global perspective to the problem. Their model-based approach is far from perfect, owing to many issues ranging from its still coarse resolution to the limited of consideration of several processes that are of relevance in coastal systems (e.g., limited consideration of benthic processes), but by using - for the first time - an eddy permitting 3D model, it is a big step up from previous model based approaches that used highly simplified models. I particularly like that the authors spend a considerable amount of effort in order to assess their model's performance against observations and that they run two parallel simulations in order to determine the anthropogenic CO_2 uptake explicitly. The paper is overall well written, adequately illustrated and referenced. The discussion is generally thorough and the conclusions supported by the provided evidence including an appropriate consideration of the caveats. All in all, this is a very good study that is well suited for publication in Biogeosciences. However, before giving the green light, I would like the authors to consider my concerns regarding important model shortcomings.

- Model drift: The model's drift is quite substantial, and I am not entirely convinced that the authors have fully considered the implications when discussing their results. I think the drift is large enough that it cannot be ignored.

Please see our general response.

- Reflective bottom boundary: The model's lower boundary is assumed to "reflect" any settling organic matter back into the water column in remineralized form. Thus, this model does not incorporate any delayed response of remineralization nor any other benthic remineralization process of relevance such as benthic denitrification etc. This is a rather important omission, as these processes influence coastal biogeochemistry in many shallow marginal seas. I thus recommend to address and discuss this issue in somewhat more detail and to give it better consideration.

We agree the referee on the need to give better consideration on that point for the model-data comparison.

In the revised manuscript, we will better describe the version of the model used in this study: in particular, we will indicate that part of the settling organic material is indeed reflected back in the water column in remineralized form, whereas part of it is buried to compensate for the riverine input.

In the new version of PISCES (PISCES-v2, Aumont et al. GMD, 2015), to be used in subsequent studies, water-sediment interactions are considered using the meta-model of Middelburg et al. (1996), which allows computation of sediment denitrification. It also explicitly represents conservation of calcite in the sediment as a function of the saturation levels of the overlying waters.

In the revised manuscript, we will also discuss some shortcomings of such representation on our results, referring for example to the work of Krumins et al. (2013) and Soetaert et al. (2000).

Krumins et al. (2013)
http://dx.doi.org/10.5194/bg-10-371-2013
Soetaert et al. (2000)
http://dx.doi.org/10.1016/S0012-8252(00)00004-0

- Coastal-open ocean exchange: This issue is actually addressed a bit more than the other two in the current version, but I still consider it worthwhile to assess the implications of this shortcoming in more detail.

See general reply (1) above.

3 Recommendation

I recommend acceptance of this manuscript with minor revisions.

4 Minor comments

Abstract, line 10: "absorbed by the coastal ocean": I suggest to define also in the abstract how the authors define the "coastal" ocean.

We agree on the need to explain our definition of the coastal ocean in the abstract. We will add "Here we define the coastal zone as the continental shelf area, excluding the proximal zone" in the abstract of the revised manuscript.

p1, line 15: "the ocean naturally mitigates..." I am not sure why the authors use the expression "naturally" here. I suggest deleting it.

We agree. "Naturally" will be deleted.

p5, line 5, equation 2: The authors still use a coefficient of 0.30, while there are numerous studies that have shown that this coefficient needs to be lowered in order to close the oceanic C14 budget. It's time to change, no?

Referee #2 is certainly correct. In future work, we will switch to using the revisited value of the coefficient (0.25) from Wanninkhof (2014, Limnol. Oceangr.), which is the new standard being adopted for the Ocean Model Intercomparison Project (OMIP). Here, we estimate that our 20% larger coefficient will lead to errors in anthropogenic carbon uptake of about 2% based on the study by Sarmiento et al (1992), who showed that a doubled coefficient increased anthropogenic carbon uptake by only 10%.

p5, lines 17 to 25: By neglecting the oceanic uptake of anthropogenic CO2 over the period 1750 until 1870, the authors underestimate the total anthropogenic uptake by about 10% or so. This should be taken into consideration more explicitly. I also suggest to avoid the use of the term "preindustrial" when referring to 1870.

In the revised manuscript, we will clearly define what we mean by preindustrial, prior to 1870, but that that operational definition does indeed neglect small changes between 1750 and 1870, resulting in about a 10% underestimate in our results.

Our integrated air-sea flux of -0.33 Pg C/yr is actually comparable to the 0.45 Pg C yr^{-1} outgassing because at equilibrium the model should indeed have the same value as the latter. That is, its delivery of riverine carbon to the ocean minus sedimentary burial is the same number. We will clarify this point in the revised manuscript.

We think that the general patterns in the FCO_2 would remain similar after a long spin up, except for the Southern Ocean where the drift is concentrated. Please see our general reply for more details.

Remapping errors are particularly important for low area regions and reach 50% as maximums. Thus, following this comment and the next ones on Table 2 and Figure 6b, we agree Referee #2 that the model-data comparison using area-integrated FCO_2 is not adequate with such large remapping errors. We plan to delete this part and the 2nd panel (b) of the Figure 6 when revising the manuscript.

Referee #2 offers a plausible explanation for this discrepancy. Another cause for discrepancy might be the instantaneous remineralisation of the entire land-derived DOC into DIC. We will mention these possibilities in the revised manuscript.

We agree. In the revised manuscript, there will be much new discussion on the subject offshore transport, as indicated in our general reply above.

Good point. We agree. Please see our comment below regarding Fig. 6, for which we plan to delete the 2nd panel (b) when revising the manuscript.

Because the simulated ocean uptake of anthropogenic carbon is estimated from the difference of our 2 simulations, it bears only a very weak signature of climate (interannual, decadal) variability. The drop of uptake in the 1940s is hence clearly coming from the pause of atmospheric CO_2 growth during that period. We have checked this simulated drop by comparing it to all CMIP5 historical simulations, based on the recent paper from Bastos et al. (2016) in *Biogeosciences Discussions* in which the authors focus on the 1940s CO_2 plateau. The figure below indicates that our simulation is broadly consistent with the CMIP5 coupled simulations in terms of its response to the stall in atmospheric CO_2 during the 1940s (see also Figure 4 from Bastos et al., 2016). As indicated in Bastos et al. (2016), "The anomalies in ocean CO_2 uptake present multi-decadal variations which are consistent between the 16 models and are due to the ocean response to the atmospheric CO_2 forcing. In particular, during the plateau of the 1940s, most models estimate lower ocean uptake because of the slow-down of the anthropogenic perturbation".
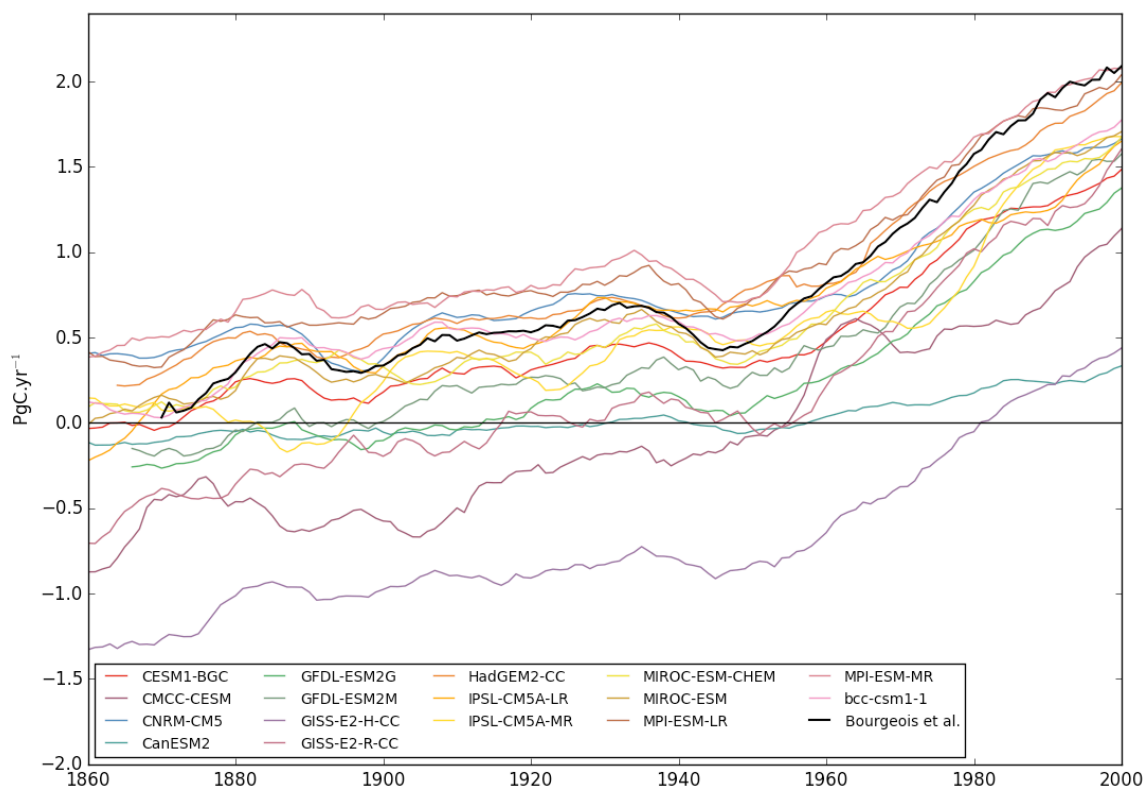
Figure 3: Ocean uptake of anthropogenic CO_2 simulated by the group of CMIP5 models and comparison with our model results (black line).

Bastos, A., Ciais, P., Barichivitch, J., Bopp, L., Brovkin, V., Gasser, T., Peng, S., Pongratz, J., Viovy, N., and Trudinger, C.M. (2016). Re-evaluating the 1940s CO_2 plateau. Biogeosciences Discussions 1–35 (http://www.biogeosciences-discuss.net/bg-2016-171/)

We agree. We will remove Figure 6b from the revised manuscript.

Here are some that we propose to improve the manuscript, independent from the reviewers' comments

- Update Figs. 3d and 5 of the submitted manuscript to remove previously unnoticed errors in zonal mean calculations.

- Update Fig. 2 of the submitted manuscript by replacing time series for global ocean to time series for open ocean (see the updated figure at the end)

- Add Jens Terhaar to the author list as he provided the residence-time calculation.

- Reduce file size and enhance of figure details for Figs. 3a, 3b, 3c, 3e, 3f, and 4 of the submitted manuscript.

- Add following link http://katirg.github.io/CO2airsea/ to permit access to a data visualization to that nicely illustrates results.

Table 2. MARCATS regions as described by Laruelle et al. (2013, 2014), along with means for data-based fluxes of total CO_2 from LA14 during 1990-2011 as well as simulated anthropogenic and total CO_2 fluxes, and residence time during 1993–2012. Abbreviations are included for North (N), South (S), East (E), West (W), Eastern Boundary Current (EBC); Western Boundary Current (WBC), sea-to-air flux of total carbon (FCO_2^{tot}), anthropogenic carbon (FCO_2^{ant}). Surface areas indicated as 'from LA14' actually differ slightly from those published in LA13 as they have been modified for subsequent computations (Goulven G. Laruelle, personal communication, January 2015).

N°	System Name	Class	Surface (10^3 km²) Model	Surface (10^3 km²) LA14	FCO_2^{tot} (mol C m^{-2} yr^{-1}) Simulated	FCO_2^{tot} (mol C m^{-2} yr^{-1}) LA14	FCO_2^{tot} (Tg C yr^{-1}) Simulated	FCO_2^{tot} (Tg C yr^{-1}) LA14	FCO_2^{ant} Tg C yr^{-1}	FCO_2^{ant} mol C m^{-2} yr^{-1}	Residence time (month)
1	N-E Pacific	Subpolar	397	350	-2.29 ± 0.17	-1.61	-10.935 ± 0.823	-6.775	-2.16 ± 0.23	-0.45 ± 0.05	0.83 ± 0.23
2	Californian Current	EBC	118	208	-0.34 ± 0.10	-0.05	-0.477 ± 0.148	-0.135	-0.50 ± 0.13	-0.35 ± 0.09	1.00 ± 0.23
3	Tropical E Pacific	Tropical	152	183	-0.12 ± 0.05	0.09	-0.222 ± 0.095	0.192	-0.65 ± 0.10	-0.36 ± 0.05	0.51 ± 0.09
4	Peruvian Upwelling Current	EBC	138	143	1.44 ± 0.80	0.65	2.386 ± 1.325	1.073	-0.64 ± 0.15	-0.39 ± 0.09	0.72 ± 0.15
5	Southern America	Subpolar	1126	1190	-1.51 ± 0.13	-1.31	-20.460 ± 1.705	-18.715	-6.28 ± 0.74	-0.46 ± 0.05	0.65 ± 0.05
6	Brazilian Current	WBC	475	484	-0.33 ± 0.08	0.10	-1.872 ± 0.479	0.567	-1.95 ± 0.29	-0.34 ± 0.05	0.26 ± 0.06
7	Tropical W Atlantic	Tropical	479	488	0.86 ± 0.10	0.07	4.934 ± 0.551	0.394	-1.50 ± 0.31	-0.26 ± 0.05	0.20 ± 0.02
8	Caribbean Sea	Tropical	303	358	0.10 ± 0.10	0.81	0.366 ± 0.348	3.460	-1.12 ± 0.14	-0.31 ± 0.04	0.32 ± 0.03
9	Gulf of Mexico	Marginal Sea	469	532	-0.79 ± 0.11	-0.33	-4.478 ± 0.633	-2.100	-1.81 ± 0.16	-0.32 ± 0.03	1.01 ± 0.15
10	Florida Upwelling	WBC	545	591	-2.25 ± 0.21	-0.38	-14.692 ± 1.351	-2.723	-4.29 ± 0.36	-0.66 ± 0.05	0.39 ± 0.02
11	Sea of Labrador	Subpolar	576	638	-1.27 ± 0.18	-1.72	-8.808 ± 1.244	-13.172	-2.19 ± 0.21	-0.32 ± 0.03	1.20 ± 0.35
12	Hudson Bay	Marginal Sea	998	1064	0.31 ± 0.29	n.d	3.757 ± 3.423	n.d.	-0.99 ± 0.46	-0.08 ± 0.04	51.22 ± 22.75
13	Canadian Archipelago	Polar	1001	1145	-0.52 ± 0.06	-1.02	-6.234 ± 0.748	-13.986	-1.03 ± 0.21	-0.09 ± 0.02	2.82 ± 0.46
14	N Greenland	Polar	544	602	-0.97 ± 0.15	-0.61	-6.333 ± 1.000	-4.400	-1.67 ± 0.33	-0.26 ± 0.05	2.38 ± 0.44
15	S Greenland	Polar	238	262	-3.35 ± 0.44	-3.81	-9.564 ± 1.259	-11.972	-2.45 ± 0.53	-0.86 ± 0.19	0.48 ± 0.09
16	Norwegian Basin	Polar	141	162	-2.87 ± 0.23	-1.72	-4.855 ± 0.396	-3.342	-1.02 ± 0.15	-0.60 ± 0.09	0.31 ± 0.10
17	N-E Atlantic	Subpolar	1020	1073	-2.16 ± 0.12	-1.33	-26.501 ± 1.419	-17.165	-6.52 ± 0.59	-0.53 ± 0.05	0.93 ± 0.11
18	Baltic Sea	Marginal Sea	324	364	0.30 ± 0.07	0.51	1.184 ± 0.288	2.245	-0.05 ± 0.03	-0.01 ± 0.01	17.37 ± 9.52
19	Iberian Upwelling	EBC	251	267	-1.13 ± 0.12	0.04	-3.393 ± 0.352	0.122	-0.82 ± 0.10	-0.27 ± 0.03	2.31 ± 0.54
20	Mediterranean Sea	Marginal Sea	423	529	-0.24 ± 0.06	0.62	-1.196 ± 0.327	3.925	-1.52 ± 0.12	-0.30 ± 0.02	0.72 ± 0.09
21	Black Sea	Marginal Sea	131	172	-0.24 ± 0.11	n.d.	-0.375 ± 0.174	n.d.	-0.28 ± 0.03	-0.18 ± 0.02	1.60 ± 0.48
22	Moroccan Upwelling	EBC	177	206	0.18 ± 0.12	2.92	0.385 ± 0.263	7.220	-0.71 ± 0.07	-0.33 ± 0.03	0.67 ± 0.14
23	Tropical E Atlantic	Tropical	225	259	0.09 ± 0.08	-0.06	0.239 ± 0.208	-0.174	-0.52 ± 0.05	-0.19 ± 0.02	0.59 ± 0.09
24	S W Africa	EBC	300	298	0.43 ± 0.40	-1.43	1.544 ± 1.448	-5.103	-2.14 ± 0.28	-0.59 ± 0.08	2.17 ± 0.55
25	Agulhas Current	WBC	189	239	-1.20 ± 0.09	-0.58	-2.730 ± 0.206	-1.664	-1.21 ± 0.12	-0.53 ± 0.05	0.13 ± 0.01
26	Tropical W Indian	Tropical	46	68	-0.06 ± 0.08	1.00	-0.031 ± 0.044	0.815	-0.09 ± 0.03	-0.16 ± 0.04	0.20 ± 0.04
27	W Arabian Sea	Indian Margins	82	92	0.35 ± 0.04	1.14	0.342 ± 0.043	1.257	-0.31 ± 0.04	-0.31 ± 0.04	0.12 ± 0.04
28	Red Sea	Marginal Sea	158	174	0.24 ± 0.03	0.16	0.460 ± 0.065	0.330	-0.28 ± 0.02	-0.15 ± 0.01	0.57 ± 0.15
29	Persian Gulf	Marginal Sea	208	233	0.04 ± 0.08	n.d.	0.092 ± 0.203	n.d.	-0.31 ± 0.04	-0.12 ± 0.02	24.67 ± 12.09
30	E Arabian Sea	Indian Margins	298	317	0.21 ± 0.12	0.67	0.749 ± 0.427	2.555	-1.07 ± 0.15	-0.30 ± 0.04	0.67 ± 0.15
31	Bay of Bengal	Indian Margins	197	203	-0.69 ± 0.12	-0.22	-1.641 ± 0.276	-0.530	-0.74 ± 0.09	-0.31 ± 0.04	0.43 ± 0.11
32	Tropical E Indian	Indian Margins	727	763	-0.06 ± 0.07	-0.02	-0.482 ± 0.569	-0.170	-1.78 ± 0.17	-0.20 ± 0.02	0.50 ± 0.04
33	Leeuwin Current	EBC	81	117	-2.05 ± 0.15	-0.98	-2.010 ± 0.148	-1.379	-0.58 ± 0.07	-0.60 ± 0.07	0.56 ± 0.16
34	S Australia	Subpolar	392	436	-1.37 ± 0.18	-1.14	-6.438 ± 0.859	-5.983	-1.29 ± 0.14	-0.27 ± 0.03	0.74 ± 0.25
35	E Australian Current	WBC	98	130	-1.74 ± 0.18	-1.09	-2.036 ± 0.205	-1.695	-0.58 ± 0.08	-0.50 ± 0.07	0.37 ± 0.04
36	New Zealand	Subpolar	263	286	-1.23 ± 0.16	-1.25	-3.882 ± 0.498	-4.274	-1.64 ± 0.23	-0.52 ± 0.07	0.49 ± 0.04
37	N Australia	Tropical	2278	2292	-0.29 ± 0.11	0.44	-7.872 ± 3.114	12.120	-6.19 ± 1.00	-0.23 ± 0.04	0.38 ± 0.03
38	S-E Asia	Tropical	2130	2160	-0.29 ± 0.07	-0.91	-7.344 ± 1.908	-23.609	-5.01 ± 0.72	-0.20 ± 0.03	0.49 ± 0.05
39	China Sea and Kuroshio	WBC	1132	1129	-1.99 ± 0.15	-1.41	-27.046 ± 1.991	-19.100	-6.13 ± 0.72	-0.45 ± 0.05	0.32 ± 0.01
40	Sea of Japan	Marginal Sea	233	147	-3.07 ± 0.17	-3.47	-8.613 ± 0.475	-6.113	-1.44 ± 0.18	-0.51 ± 0.06	1.64 ± 0.24
41	Sea of Okhotsk	Marginal Sea	933	952	-1.66 ± 0.07	1.31	-18.623 ± 0.761	14.955	-4.00 ± 0.34	-0.36 ± 0.03	3.52 ± 1.38
42	N-W Pacific	Subpolar	1025	1000	-1.85 ± 0.14	-0.70	-22.760 ± 1.726	-8.419	-2.99 ± 0.52	-0.24 ± 0.04	1.48 ± 0.59
43	Siberian Shelves	Polar	1848	1889	-0.47 ± 0.10	-0.90	-10.499 ± 2.117	-20.322	-1.09 ± 0.28	-0.05 ± 0.01	4.10 ± 0.64
44	Barents and Kara Seas	Polar	1559	1680	-0.75 ± 0.14	-1.60	-14.176 ± 2.585	-32.225	-2.05 ± 0.43	-0.11 ± 0.02	1.58 ± 0.46
45	Antarctic Shelves	Polar	2452	2936	-0.90 ± 0.14	-0.15	-26.630 ± 3.989	-5.381	-20.30 ± 2.18	-0.69 ± 0.07	2.08 ± 0.29

Table 3. Weighted mean of simulated and data-based sea-to-air CO_2 fluxes and simulated residence time for each MARCATS class, excluding the Sea of Okhotsk (see text). Abbreviations are included for Eastern Boundary Current (EBC) and Western Boundary Current (WBC).

| Class	Sea-to-air CO_2 flux ($mol\,C\,m^{-2}\,yr^{-1}$)			Residence
	Total (LA14)	Total (model)	Anthropogenic (model)	time (month)
EBC	0.12	-0.12 ± 0.16	-0.42 ± 0.03	1.52 ± 0.22
Indian margins	0.19	-0.07 ± 0.05	-0.24 ± 0.02	0.49 ± 0.04
Marginal Seas	-0.56	-0.92 ± 0.07	-0.29 ± 0.01	10.34 ± 3.50
Polar Margins	-0.88	-0.84 ± 0.06	-0.32 ± 0.03	2.18 ± 0.20
Subpolar Margins	-1.23	-1.61 ± 0.07	-0.36 ± 0.02	0.92 ± 0.16
Tropical Margins	-0.10	-0.15 ± 0.06	-0.22 ± 0.02	0.42 ± 0.03
WBC	-0.80	-1.65 ± 0.08	-0.48 ± 0.03	0.31 ± 0.01
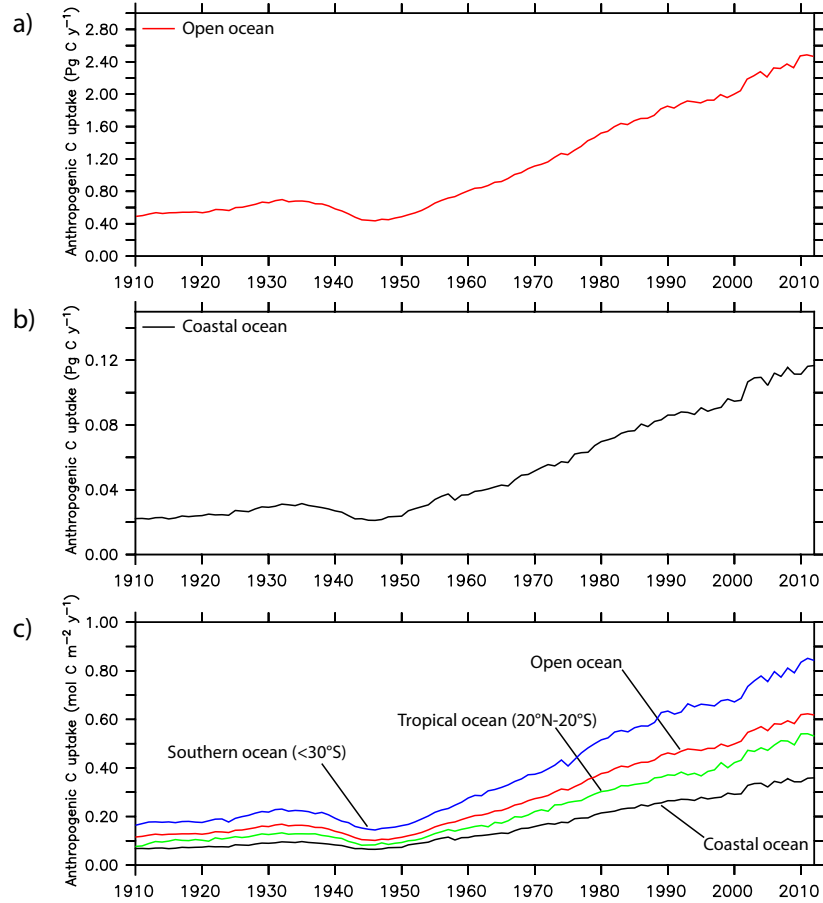
Figure 2. Simulated temporal evolution of area-integrated anthropogenic carbon uptake for (a) the global ocean and (b) the coastal ocean. (c) Analogous evolution of anthropogenic carbon uptake for the global ocean, the coastal ocean, the Southern Ocean, and the tropical oceans, but given as the average flux per unit area.