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Interactive comment on "Model constraints on the anthropogenic carbon budget of the Arctic Ocean" *by* Jens Terhaar et al.

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Response to Referee #1

We thank both referees for their comments and suggestions. The manuscript will be revised to thoroughly address each point. Generally the plan is as follows:

(1) The description of the simulations analyzed in our study will be improved by adding more details concerning (a) how the different simulations (ORCA2, ORCA05, and ORCA025) were made, making it clear that each of these has its own control simulation, (b) how CFC-12 was simulated, and (c) how carbon transport was estimated at

the boundaries of the Arctic Ocean.

(2) The discussion section will be expanded to provide more detail about (a) the effect of increasing resolution in ocean models found by other modeling studies and (b) the mechanisms influencing changes in air-sea CO_2 fluxes in the Arctic between the different resolutions, including a discussion of the role of sea-ice. Additional analysis will also be included to show how the different configurations compare to each other in terms of the global-ocean inventory of anthropogenic carbon.

During the review period, we also discovered an issue with our CFC-12 simulations (initialization to non-zero concentrations). Hence we have rerun all CFC-12 simulations (as will be detailed in the revised manuscript). Furthermore, we have used the opportunity to complement the ORCA05 C_{ant} perturbation simulations with analogous simulations for the ORCA2 and ORCA025 configurations (each initialized in the beginning of 1958 with output from the last time step in 1957 of the ORCA05 C_{ant} perturbation simulation and run until 2012). With these updated simulations, the model-data CFC-12 comparison has been improved (to be discussed in Sections 3.2 and 4.1) as have been the corrections for the estimated C_{ant} fluxes at the boundaries (both lateral and at the air-sea interface). The figures and tables of the revised manuscript will be updated accordingly. Despite these improvements, the Conclusions of our study remain the same.

In the following we address their concerns point by point.

Referee # 1

1) Overview

Terhaar et al. ask: what effect does model resolution have on simulated Arctic Ocean anthropogenic CO_2 storage and acidification? The answer: increased model resolution shows higher regional storage by up to 25%, moving the inventory closer to data-based estimates, and increased acidification with faster shoaling of the aragonite saturation horizon. This is an interesting and useful question, and the study has been well-designed to answer it. The results and their interpretation seem sensible, although as mentioned below, a robust uncertainty analysis is critically lacking. The manuscript is interesting and easy to read. The Introduction is very well-written and Methods are clear. Results and Discussion are succinct, but in places the Discussion in particular could be developed further to provide more insight. Many of the questions below are really prompts in this direction.

Reply: Thank you very much. In the revised manuscript, we will strive to address these concerns in detail.

2) Scientific questions

Reviewer Question 1 — The highest-resolution model is "still not eddy resolving" (3-28 i.e. page 3, line 28). Does that mean that you would expect further changes still with yet higher resolution? Would you expect the anthropogenic CO_2 inventory to increase even more?

Reply: Without actually making higher resolution simulations, one can of course never be certain. However, we would agree with Referee #1 that the anthropogenic carbon

inventory in the Arctic Ocean would probably increase if the model resolution were refined even further. The C_{ant} inventory increases by 0.38 Pg C between ORCA2 and ORCA05 and by 0.27 Pg C between ORCA05 and ORCA025, so we may not have reached the nearly flat part of the asymptote. Further enhancement of resolution could further increase the inventory via the combined effects of improved bathymetry, increased coastal water velocities, and enhanced surface-to-deep transport of passive tracers from brine formation on Arctic shelves. Concerning the latter, even higher model resolution might well lead to higher C_{ant} concentrations in the Canada basin and to refining the chimneys of higher CFC-12 concentrations in the Canada basin, which are observed but only barely resolved in ORCA025 (page 10, lines 23-24). We will add these considerations in section 4.4 of the revised manuscript.

Reviewer Question 2 — The monthly averaging process introduces an error of 27% for the lowest-resolution model (7-20). This is a similar magnitude to the difference in anthropogenic CO_2 inventory between the different resolutions, which is your most important result. Does this error being the same size as the 'signal' not significantly reduce your confidence in the results (i.e. differences between resolutions)?

Reply: Our error estimate of 27% applies only to the ORCA2 transport of C_{ant}, calculated separately at each of the 4 boundaries of the Arctic Ocean from monthly-average model output (offline), an important point raised by Referee #1 for which we should have been clearer. That offline calculation error is smaller at higher resolution (e.g, 4% with ORCA025). Moreover, it does not apply to our estimates of C_{ant} inventory, the cumulative air-sea C_{ant} flux, and the total lateral flux, all of which are calculated online in the model and for which associated calculation errors are negligible.

This key point will be clarified in the revised manuscript.

Reviewer Question 3 — You note that overestimation of sea-ice cover should reduce

air-sea CO_2 exchange (9-14). There are a number of observational studies that attempt to quantify this effect. Can these be used to quantify your statement?

Reply: Our overestimation of sea-ice extent is less than 3%. Thus it is of second order when estimating the C_{ant} air-sea flux. There are studies that have estimated the effect of declining sea-ice on air-sea fluxes of total carbon (Bates et al. [2006], Cai et al. [2010]), but they do not agree on whether the flux will increase due to increasing biological activity or decrease due to higher stratification and increases in riverine organic carbon. Because these studies focus on the air-sea flux of total CO_2 (natural + anthropogenic), we cannot use them to extract the response of only the anthropogenic component, the focus of our study.

Reviewer Question 4 — Section 3.4: my impression was that the primary reason to expect model resolution to influence the anthropogenic CO_2 inventory was because of better representation of circulation features. Therefore the increase in lateral flux, being a function of circulation, is expected – but the simultaneous increase in the air-sea flux does not seem so intuitive. Indeed if additional anthropogenic CO_2 is being transported into the region from elsewhere we might expect this to increase total dissolved inorganic carbon and thus reduce net air-to-sea CO_2 flux. Do you have a conceptual explanation for what is driving the air-sea flux increase with resolution?

Reply: Two mechanisms may explain the increase in the air-sea flux with resolution: (1) higher resolution increases the amount of C_{ant} that is advected into the Arctic Ocean through the Fram Strait via subsurface currents, which does not substantially affect surface C_{ant} concentrations nor hence air-sea exchange of anthropogenic carbon and (2) higher resolution enhances deep-water formation in the Arctic Ocean , mainly in the Barents Sea as shown in the CFC-12 profiles (Figure 7), which reduces surface C_{ant} and thus enhances the air-to-sea flux of anthropogenic carbon.

We will add this explanation to Section 4.4 of the revised manuscript.

Reviewer Question 5 — In order to declare that two things are 'not statistically different' (14-12) you must also provide the statistical information that were used to demonstrate this.

Reply: In the revised manuscript, the corresponding sentence will be changed to 'The simulated air-sea flux falls within that assigned uncertainty range for the data-based estimate.'

Reviewer Question 6 — Does the increase in resolution alter lateral anthropogenic CO_2 fluxes primarily because of the representation of circulation (1) inside the Arctic Ocean, (2) at its boundaries/interfaces, (3) in the non-Arctic global ocean, or (4) everywhere?

Reply: We tried to address this question in Section 4.4 of the submitted manuscript, but we only discuss circulation differences inside the Arctic Ocean and at its boundaries. We showed that increasing resolution from ORCA2 to ORCA05 affects mainly the circulation at the boundaries (1) while the change from ORCA05 to ORCA025 affects mainly circulation inside the Arctic Ocean (2).

For more insight into the role of the global ocean (outside the Arctic), we have now calculated the total C_{ant} inventory for the global ocean with all three resolutions (see below). Globally the three resolutions agree within 3%. This agreement is much tighter than that for the Arctic Ocean C_{ant} inventory. This new comparison suggests a weak role of the non-Arctic global ocean on the Arctic Ocean C_{ant} budget (3)(4), although resolution-dependent changes in regions adjacent to the Arctic Ocean's lateral boundaries (e.g., in the North Atlantic) may well have an effect. These considerations will be added to section 4.4 of the revised manuscript.

Reviewer Question 7 — You note that for computational reasons we cannot routinely run these models globally at high resolution, but if only one region of the model needed

to be at high resolution to achieve your results, would it be possible to strike a balance with a hybrid resolution model?

Reply: Certainly such approaches, using for example the nesting tool of NEMO (AGRIF, Debreu et al. [2008]) as in Duteil et al. [2014] would be an interesting option. Unfortunately, this nesting tool is known to not work well in ice-covered regions nor with the biogeochemical model PISCES. Hence we leave this for future work as will be mentioned in the Conclusion of the revised manuscript.

Reviewer Question 8 — Some of the notes about possible future work on CFC-12 and the TTD parameters in the Conclusions would probably be more suited to the Discussion.

Reply: We are considering to move these notes to the Discussion.

Reviewer Question 9 — No other studies have been mentioned that have attempted to answer this same question for the Arctic Ocean, but there have been other investigations of the effect of increased model resolution in various contexts. Do these provide any insights that would be useful in interpreting your results?

Reply: In terms of ocean biogeochemistry, most studies on the effect of resolution have focused on the impacts of mesoscale to submesoscale structures on phytoplankton and productivity (e.g., Lévy [2008], McGillicuddy [2016]). Other studies have investigated the role of increased model resolution on transient tracers (Lachkar et al., [2007]) and on carbon and oxygen (Duteil et al., [2014]), but they have focused on other regions (Southern Ocean and the tropics). Therefore it is difficult to transfer their findings to the Arctic Ocean. Some discussion on other studies focusing on the role of model resolution will be include in the Discussion of the revised manuscript.

3) Figures

Reviewer Question 10 — Use of red vs green (e.g. Fig. 3) with no difference in line style can render these lines indistinguishable to colorblind readers.

Reviewer Question 11 — The blue-green-yellow-red color scale used on transect plots (e.g. Fig. 4) is not perceptually uniform, leading to visual artifacts such as false boundaries.

Reviewer Question 12 — Depth should be positive going down into the ocean (Figs. 4 and 6).

Reply: These suggestions for improving the style and colors will be implemented in the revised manuscript.

4) Technical/grammatical notes

Reviewer Question 13 — There is inconsistency in usage of past and present tenses in the Methods.

Reply: The Methods section will be improved to avoid this inconsistency in the revised manuscript.

Reviewer Question 14 — The contexts in which the word 'though' is used are highly colloquial and, to me, not suited for scientific writing (2-12, 14-29, 15-8).

Reply: We will avoid the use of the word 'though' in the revised manuscript.

Reviewer Question 15 — Suggested corrections:
1-6 eddy-admitting
2-3 consequences for
4-30 following Moore et al.
10-24 (Fig. 6) ?
11-21 Arctic Ocean basins
15-33 reword this sentence to indicate the direction of the effect

Reply: The manuscript will be revised according to these suggestions. For 15-33 we will write "Thus model resolution also affects the time at which waters become undersaturated with respect to aragonite with higher resolutoin producing greater shoaling."

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