Biogeosciences Discuss., 5, S3322–S3328, 2009
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5, S3322–S3328, 2009

Interactive Comment

Interactive comment on "Imminent ocean acidification projected with the NCAR global coupled carbon cycle-climate model" *by* M. Steinacher et al.

M. Steinacher et al.

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We would like to thank both reviewers for their constructive comments. We have followed their suggestions in most cases. Please find below the detailed response (bold/italic font) to the comments of anonymous referee 3 (normal font).

As the Arctic Ocean is a key area for the timing ocean acidification, I would appreciate to receive a bit more information on how well sea ice cover in general is handled by the model. Can the authors add figures of sea ice cover (thickness and/or compactness), comparing the present state with observations, and giving model results for the future (e.g. at years 2050 and 2100)?

A figure on sea ice has been added as discussed below.

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Interactive Discussion

Discussion Paper

- P 4354 l 22: cause (not causes)
- P 4356 l 12: Currently, however, . . . (shift the "however")

Done.

- P 4357 l 25: next to Heinze (2004), you could add the references: Gehlen et al. (Biogesciences, 4, 505-519, 2007), Ridgwell et al. (Biogeosciences, 4, 481-492, 2007)

Both references have been added.

- P 4359 l 14-16: please, give a reference for the sea ice characteristics of the NCAR model and discuss these with a figure (see main comment above).

We have added a new figure (Fig. 13) showing the sea ice extent for the years 2000 (model and observations) and 2100 (model only). Further the text on page 4359, line 14-16 has been extended:

"The model is known to simulate too much ice in the Northern Hemisphere (Weatherly et al., 1998). In particular the ice cover is too extensive in the North Pacific and North Atlantic. There is some contribution to the excess annual mean ice volume through larger-than-observed summer sea ice concentrations in the Arctic Ocean. The simulated preindustrial ice covered area in the Arctic Ocean is about 10% (summer) to 5% (winter) larger than estimated by Walsh (1978). The decreasing trend in summer sea ice cover during the last few decades is captured by the model but less pronounced. In the year 2000 the simulated ice covered area is about 40% (summer) to 10% (winter) larger than observed. Further, maximum thickness in the Arctic occurs against the Bering Strait, not against the Canadian Archipelago as observed (Weatherly et al., 1998)."

Further the text about future changes in Arctic sea ice cover in the results section (P 4369, l 19-24) has been stated more precisely:

"The summer sea ice extent in the CSM is 10-40% higher than observed by 2000 (Fig. 13). The reduction in sea ice cover is at the lower end of the range of projections for

the 21th century. More specifically, the simulated decrease from 2000 to 2100 in the A2 scenario is only slightly larger than the rapid reduction observed during the last decade. Holland et al. (2006) project abrupt reduction in summer Arctic sea ice and near ice-free conditions by 2040 for the SRES A1B scenario, whereas in our SRES A2 simulation summer sea ice cover remains above 70% of the total Arctic Ocean surface until about 2050. The simulated winter ice cover declines only little and remains larger than the observed present-day ice cover throughout the simulation. If the projections of rapid summer sea ice decline are true, the projected effects we see on the Arctic carbonate system will be even more pronounced than seen in the CSM simulations."

- P 4359 l 25: CaCO3:orgC export ratio 0.07 may be relatively low; how does this compare to other studies/data analyses?

The $CaCO_3$:POC export ratio of $R = 0.07$ falls within the range R = 0.06-0.08 suggested by Yamanaka and Tajikais (1996) and $R = 0.06 \pm 0.03$ given by Sarmiento et al. (2002). It is at the lower end of the range $R = 0.07 - 0.10$ given by Jin et al. (2006). Kwon and Primeau (2008) optimized the parameters of an OCMIP-2 biogeochemistry model using observation-based estimates of PO_4 from World Atlas 2001 as well as TA and DIC from GLODAP. They obtained the $CaCO_3$:POC export ratio of $R = 0.081 \pm 0.008$. Thus the reference OCMIP-2 value of $R = 0.07$ is still consistent with recent estimates, but at the lower end of the suggested ranges. The following sentence has been added on page 4359, line 25: *A ratio of 0.07 is within (Yamanaka and Tajika, 1996; Sarmiento et al., 2002) or at the lower end (Jin et al., 2006; Kwon and Primeau, 2008) of the range given by others.*

- P 4361 and throughout: silicic acid is now usually reported as $Si(OH)_4$; PO_4 could be written PO_4^{3-}.

Done.

- P4361, end: Please, describe a bit more in detail, how the production and export of $CaCO_3$ and POC are modeled (parameterisations)

BGD
5, S3322–S3328, 2009

Interactive Comment

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Interactive Discussion

Discussion Paper

The description of the biogeochemical ocean model on page 4359 lines 24-28 has been expanded:

"Biological productivity is modulated by temperature, surface solar irradiance, mixed layer depth, and macro- and micronutrients (PO_4^{3-}*, and iron). Following the OCMIP-2 protocols (Najjar et al., 2007), total biological productivity is partitioned 1/3 into sinking particulate organic matter (POC) flux and 2/3 into the formation of dissolved or suspended organic matter, where much of the latter is remineralised within the model euphotic zone. A constant export ratio of* $CaCO_3$ *to POC of 0.07 and constant Redfield ratios were used (Anderson et al., 1994). A ratio of 0.07 is within (Yamanaka and Tajika, 1996; Sarmiento et al., 2002) or at the lower end (Jin et al., 2006; Kwon and Primeau, 2008) of the range given by others. Below the compensation depth of 75 m, 90% of the POC is remineralized within the first 1000 m, following a power-law parametrisation (Martin et al., 1987) and* $CaCO_3$ *is assumed to decrease exponentially with a depth scale of 3500 m. Any flux of POC or* $CaCO_3$ *reaching the sea floor is remineralized instantaneously. There is no feedback between changes in saturation state, pH or other carbonate chemistry variables and the biological carbon cycle implemented."*

- P 4362 l 5: "reasonably well" is soft wording, can you find an alternative description?

The sentence has been changed to: *"The modeled values and spatial pattern for* Ω_{arag} *and* $[\mathrm{CO}_3^{2-}]$ *(averaged over the years 1990-1999 in the transient simulation) are compared with the data-based estimates in all major ocean basins."*

- P 4362 l 9: Please, give the reference for Taylor diagrams to facilitate the use/understanding of this for non-modellers

The reference has been added to caption of Fig. 2 (Taylor, 2001).

- P 4364 l 3: Please give a reference for the Revelle factor for the non-carbon-cycle people

The references Revelle and Suess (1957) and Takahashi et al. (1993) have been

BGD

5, S3322–S3328, 2009

Interactive Comment

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Interactive Discussion

Discussion Paper

included.

- Figures 5 and 6: please, adjust color scale to better resolve undersaturation

The color scales of Figures 5, 6, and 7 have been adjusted to better distinguish between undersaturation (blue) and oversaturation (geen to red).

- P 4369 l 9: The ACIA report chapter 9, see: http://www.acia.uaf.edu/pages/ scientific.html describes a potential change in biological carbon cycle due to sea ice retreat away from the Arctic shelves and associated shift of highly productive regions along the marginal ice zone to deeper waters (with particulate fluxes of carbon and nutrients deeper down into the water column). Do you see such changes in your model results as well? (see Box 9.10, page 505)

Biological productivity and export of POC is enhanced in the Arctic Ocean during the transient SRES A2 simulation. In most areas that are permanently ice-covered in the year 2000 and become ice-free during summer by 2100, POC export increases by 1-6 mg m^{-2} day^{-1}, in the Kara Sea by up to 8-15 mg m^{-2} day^{-1}. The largest increase in POC export of 12-60 mg m^{-2} day^{-1} can be found south-east of Svalbard, a region with relatively high productivity and which is already ice-free during summer in the year 2000. The region along the marginal ice zone in the Greenland and Barents Seas with POC export of 6-15 mg m^{-2} day^{-1} moves northward by about 2°-5° by 2100. Although we see an increase in productivity and POC export related to sea ice retreat in the Arctic, the specific process described in the ACIA report cannot be observed in our coarse resolution model and therefore we will not discuss it in the main text.

- P 4369 l 16: "corresponds" instead of "correspond"

Done.

Additionally, a reference to a recent review paper (Doney et al., 2009) has been added at page 4355, line 26.

BGD

5, S3322–S3328, 2009

Interactive Comment

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Interactive Discussion

Discussion Paper

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Interactive comment on Biogeosciences Discuss., 5, 4353, 2008.

BGD

5, S3322–S3328, 2009

Interactive Comment