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Interactive comment on "Projected decreases in future marine export production: the role of the carbon flux through the upper ocean ecosystem" *by* C. Laufkötter et al.

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We wish to thank reviewer #2 for the thorough analysis of our paper and his/her thoughtful and very detailed comments, which have been very helpful and improved the quality of this manuscript. A detailed reply to each point follows below:

Reviewer Comment: Page 19943, Line 24: lower/higher - this isn't clear and confused me. Please rephrase.

Author Response: Done.

Reviewer Comment: Pg 19944, Line 23: Leung et al. (2015) show that there is some agreement on the mechanisms driving changes in NPP among the CMIP5 models within the Southern Ocean, so perhaps saying that there is no agreement on the mechanisms among the models is a bit too strong.

Author Response: We have changed the sentence to "little agreement" and cited the Leung-paper.

Reviewer Comment: Pg 19947, Line 21: Could you explain with one more sentence or so how/why aggregation and mortality are wrapped up in the same APOC term? What processes are meant to be simulated within this term (aggregation, viral lysis, other specific mortality-inducing processes)?

Author Response: We have included both aggregation and mortality in one A_{POC} term as they are first-order functions of biomass of the respective PFT, in contrast to grazing which usually depends also on grazer biomass and temperature. The term A_{POC} summarizes phytoplankton aggregation and all other forms of mortality that are modeled in the respective models. We have changed the sentence in the manuscript to: "The mechanisms by which sinking particles are formed are faecal pellet production during grazing on the phytoplankton types ($G_{POC}^{zoo_i \rightarrow phyto_j}$) and first-order biomass losses via aggregation and mortality of the different phytoplankton and zooplankton types (A_{POC}^{i}, not parameterized in all models)."

Reviewer Comment: Pg 19948, Line 21: Although defining export production as the amount of POC sinking out of 100 m depth is a common practice, it is not

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always the right way to think about export if we actually care about the amount of carbon making it down to the deep ocean. See Palevsky et al. (2016). It would be nice to mention this briefly.

Author Response: We agree and added the following sentence:

"We define particle export production (EP) as the amount of particles that sink through the 100m depth level. While this depth does not necessarily reflect the amount of carbon that reaches the deep ocean, it separates surface processes from mechanisms governing deep ocean carbon fluxes and is useful for comparing the models with each other and with observations. "

Reviewer Comment: Section 2.2, in general: I think that it would be a lot clearer if you presented all equations separately for each model with clear labels as to which model is being represented. Example 1: Equation 8 could be written out separately for BEC and PISCES, so that you can represent what happens in BEC with biomass concnetrations greater than 22 mmolC/m2 and can also add in the linear mortality term. It's a bit cumbersome to do the mental gymnastics of altering equation 8 for each different model as one reads the text. Example 2: Equation 11 could be written out separately for each model, so that there isn't as much confusion about which parameters depend on which variables differently within each model. This would make the textual explanation a lot easier to follow. fgrazPOC could have a subscript for BEC as one example. You could also denote that fgrazPOC is a function of temperature for TOPAZ as another example. I do like the way that the equations are done in Section 2.2.3.

Author Response: We use those "overview equations" as a means to underline the similarities between the models and to shorten the manuscript. The full parameters and equations are in the Appendix for readers who are interested in that level of detail.

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We have followed the reviewer's suggestion and written Eq. 8 separately for BEC and PISCES but prefer to keep Eq. 11 in the overview-form to avoid unnecessary repetition.

Reviewer Comment: Pg 19950, Lines 11-14: Here you say that aggregation grows linearly with biomass after a certain biomass concentration, but then say that there is also an additional linear mortality of phytoplankton that you ignore. I am a bit confused by this; are you referring to the same term? Also, do you justify that leaving this term out really doesn't matter? I don't see the harm in adding this linear term to the quadratic term and calling that the total mortality/aggregation, assuming that they are representing the same processes.

Author Response: We agree and we have added the linear mortality term to the equation.

Reviewer Comment: Pg 19950, Line 16: You say that aggregation increases under nutrient limitation for diatoms in PISCES, but I am unsure of what equation to look at to see how this really works. Could you point out which equations represent this phenomenon?

Author Response: Apologies - the equation is given in the parameter Table for PISCES (Table 6). We have added a reference to make this more clear.

Reviewer Comment: Pg 19950, Line 24: Could you help me more easily see how in both BEC and PISCES high and low diatom fractions allow higher aggregation than intermediate diatom fractions? I am again unsure of what equation to look at to see how this works (not equation 8, right?).

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Author Response: We have tried to explain this better. The text reads now: "In REcoM2, aggregation depends on total biomass and is independent of the diatom fraction. In contrast, in both BEC and PISCES aggregation depends on the biomass of the individual PFTs. Because of the exponential increase in aggregation at high biomass values, high or low diatom fractions can result in higher aggregation than intermediate diatom fractions in BEC and PISCES. "

Reviewer Comment: Pg 19952, Line 11-12: What does it mean mechanistically/physically for zooplankton grazing to be modeled implicitly and to be independent of zooplankton biomass? Could you add one more sentence or so to explain this more?

Author Response: In contrast to the other models, grazing does not depend on zooplankton biomass but only on phytoplankton biomass (and temperature). Therefore changes in grazing are either caused by changes in phytoplankton biomass or temperature, but not by a change in zooplankton biomass. We have extended the sentence in the manuscript: "Second, zooplankton grazing is modeled implicitly and does not depend on zooplankton biomass but only on phytoplankton biomass and temperature."

Reviewer Comment: Pg 19952, Line 12-13: This is confusing when read with Pg 19951, Line 12. The way Pg 19951, Line 12 was worded made it seem like BEC was the exception, but now we find out that TOPAZ was the exception. To clarify, I suggest listing in parentheses the name of the three models with constant fgrazPOC and taking out the word however on Pg 19951, Line 12.

Author Response: Yes. We have changed the sentence to: "..with $f \rightarrow \mathrm{POC}_{graz}$

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denoting the fraction of the grazed material that is routed to POC. $f \rightarrow \text{POC}_{graz}$ is constant in REcom2. In BEC and TOPAZ, a bigger fraction of grazed diatoms is routed to POC than grazed nanophytoplankton. In PISCES, it does not depend on food source, however a higher/lower fraction of material is routed to POC when grazed by mesozooplankton/microzooplankton. "

Reviewer Comment: Pg 19952, Line 17: You say finally to denote the last way in which TOPAZ is different on Line 12, but now you add another difference. Please tweak this wording.

Author Response: Done

Reviewer Comment: Pg 19952, Line 19: Why do you choose to compare the fractions routed to POC at 0 degrees C? Is this the average temperature at some meaningful depth?

Author Response: The difference between the partitioning of grazed material is biggest at 0°C. We have added this information, it reads now: "Finally, a much higher fraction of grazed diatoms is routed to POC (the partitioning depends on temperature, the biggest difference is at 0°C where 93% of diatoms vs. 18% of nanophytoplankton are routed to POC). "

Reviewer Comment: Pg 19952, Line 21-23: Could you add a sentence or two on how particles would mechanistically be formed via zooplankton consumption by higher trophic levels? Is this by production of fecal matter by higher trophic level biota after consuming zooplankton?

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Author Response: Yes, that includes fecal matter and also dead zooplankton carcasses. We have added a sentence: “A fraction of this biomass loss due to mortality is assumed to end up as fecal pellets from larger zooplankton as well as dead zooplankton carcasses that sink. “

Reviewer Comment: Model evaluation section: I agree with Reviewer 1 on the need for some Taylor diagrams. It would be great to see these diagrams for grazing, e-ratio, and export.

Author Response: We agree that it would be great to see a thorough statistical comparison of modeled export, e-ratio and grazing with observations. We have included a Taylor diagram of modeled export versus satellite-based export estimates, please find the figure at the end of this file. The caption of the figure reads: "Taylor diagram comparing modeled export production averaged over the 2012-2031 period with satellite-based estimates by Dunne et al. 2007 and Henson et al. 2012. The angle describes the correlation between model and satellite-based estimate, the distance from the origin is the normalized standard deviation and the distance from the point REF is the root mean squared error."
A Taylor diagram of e-ratio estimates is included in the supplement. In terms of grazing, the available measurements are unfortunately too sparse for a more statistical comparison. For example, the data presented in Calbet et al. 2004 is summarized for 9 ocean basins. Statistical metrics like correlations and normalized standard deviations calculated from 9 modeled and observed values are not very meaningful.

Reviewer Comment: Pg 19954, Line 26 and Pg 19955, Line 4: I would caution against calling the satellite- based maps of export observational estimates or observations, but would rather them be called observationally-based, empirically-based, or satellite-based estimates due to the fact that they are

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based on observed empirical relationships rather than direct observations themselves.

Author Response: Done

Reviewer Comment: Pg 19955, Line 2: It would also be nice to see global maps of e-ratio within each of the 4 models compared to observationally-based maps of e-ratio.

Author Response: We have included global maps of e-ratio in the models in the supplementary material.

Reviewer Comment: Pg 19955, Line 16: I would again caution against using the word observations.

Author Response: Done

Reviewer Comment: Pg 19958, Line 23-24: I appreciate the separation into high and low latitudes as a starting point for understanding different mechanistic changes throughout the ocean. However, I am unsure if this is the most meaningful way of understanding how processes differ in different regions as it obscures and mashes together potentially very different trophic regimes. Have you tried looking at different ways of breaking up the ocean (namely, recreations of Figures 5 and 7) to see if it makes much of a difference? One quick starting point could be just looking at productive equatorial upwelling regions separated from the subtropics and the high latitudes. Another method would be to use

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biomes as in Sarmiento et al. (2004) and Cabre et al. (2014).

Author Response: We agree that a simple seperation into high and low latitudes mashes together potentially different tropic regimes. However, our main point here is to demonstrate how different the internal carbon fluxes in the models are and that it can lead to very different responses to climate change. Splitting the ocean into multiple biomes as in the work of Sarmiento et al. (2004) and Cabre et al. (2014) would make the paper a lot longer. But as we don't have the observations to evaluate carbon fluxes in the models, we belive that the additional information gain would be rather small.

Reviewer Comment: Pg 19959, Line 21-22: Add increase and decrease percentages for the Southern Ocean and Arctic as well.

Author Response: Done

Reviewer Comment: Pg 19960, Section 4.4: It might be nicer for this section to be written more like the previous sections; that is, by describing one model at a time, rather than by comparing between all models within the same paragraph. It is still easy to see the differences between the models this way, but makes it much easier to follow and read.

Author Response: Done, Section 4.4 reads now: "The models show substantial differences in the efficiency of the different carbon pathways, i.e. the fraction of NPP that is routed along that pathway.

In **TOPAZ** only a small fraction of NPP (8.8-26.5%) is transformed to sinking particles, and particles are exclusively formed during grazing. In the low latitudes (30°S - 30°N),

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nanophytoplankton grazing flux (5.5% of NPP) is more important than diatom grazing flux (3.3% of NPP), while in the high latitudes ($>$ 50°N/S) the diatom grazing flux (17.3% of NPP) dominates over nanophytoplankton grazing flux (9.5% of NPP).

In **REcoM2**, phytoplankton aggregation is the dominant mechanism with which particles are formed. In the low latitudes, nanophytoplankton aggregation constitudes the larger flux (25.7% of NPP is routed to POC via nanophytoplankton aggregation) while in the high latitudes diatom aggregation constitutes the larger carbon flux (45% of NPP).

In **BEC**, the nanophytoplankton grazing flux (14.0% of NPP) and to a lesser extent the diatom grazing flux (4.7% of NPP) are the largest fluxes in the low latitudes. In cold high latitude water diatom aggregation provides the largest carbon flux, about 44% of NPP is transformed to POC along that pathway.

PISCES has the most complex carbon routing among the models in this study. Zooplankton mortality (including mesozooplankton grazing on microzooplankton) provides the largest flux of carbon to particulate organic carbon in both low and high latitudes (26.4% and 23% of NPP, respectively). Grazing of nanophytoplankton is the second largest flux (16% of NPP in both high and low latitudes). The third-most important flux in the low latitudes is aggregation of DOC (12% of NPP). Aggregation of DOC is only half as strong in the high latitudes (6.7%), but diatom aggregation constitutes a large flux (9% of NPP). Finally, in PISCES zooplankton not only produce particles but also graze on particles. This reduction of particles is particularly efficient in the low latitudes, where almost a third of the formed particles are grazed again, while in the high latitudes less than ten percent of the formed particles are grazed. “

Reviewer Comment: Pg 19960, Line 23: Need to add ’and’ between the two grazing flux terms. I think that these terms should’ve been introduced and used earlier, namely when equation 11 was being explained and possibly even earlier.

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Author Response: Done, we introduce it with Eq. 11 now.

Reviewer Comment: Pg 19964, Line 13-17: Could you include a figure to show this?

Author Response: We have included a Figure at the end of this document showing that the average depth of the maximum phytoplankton concentration changes by less than 5m between 2012 and 2100 in both low latitudes and Southern Ocean. The caption of the figure reads: " Simulated average depth of the maximum phytoplankton concentration in the different models between 2012 and 2100. Panel a) shows global values and b) and c) low latitude and Southern Ocean averages, respectively."
We did not make a seperate figure for the particle formation processes as the particle formation processes occur at the depth where the biomass is concentrated.

Reviewer Comment: Pg 19968, Line 13-14: Could you provide some examples of non-diatom large phytoplankton in the real ocean?

Author Response: Yes, the sentence reads now: " Furthermore, most models do not differentiate between large phytoplankton (e.g. dinoflagellates and other large eukaryotes) and diatoms (with TOPAZ being the only exception)."

Reviewer Comment: Pg 19968, last paragraph: This paragraph's wording and sentence order is a little confusing. I suggest the following: - Take out 'but see'. Also cite Guidi et al. (2016). - I am unsure why our previous assumption of negligible small phytoplankton aggregation consequentially leads to these fluxes constituting at most a few percent of total EP in the models. Are you saying that the model creators used this idea to purposely make aggregation for the smaller phytoplankton less? If instead you are suggesting that these fluxes

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constitute too little of total EP in the models based on the new information from Richardson and Jackson (2007), then make that clear. - I would move sentence 3 (However, contributions of pico- and nanoplankton. . .) earlier. After citing Richardson and Jackson (2007), you could then say For example, contributions of pico- and nanoplankton to total export of up to ... and THEN talk about how the models get these fluxes too low.

Author Response: We have changed the wording and structure of the paragraph to make it more clear: "Measurements of the relative contribution of phyto- and zooplankton types to the sinking particle pool are sparse. In the low latitudes, aggregation of pico- and nanophytoplankton has until recently been assumed negligible and consequentially these fluxes constitute at the most a few percent of total EP in the models in our study, with REcoM2 being the only exception. However, significant export production by pico- and nanoplankton has been inferred from inverse analysis (Richardson et al. 2007) and subsequently contributions of pico- and nanoplankton to total export of up to 33$\pm$27% have been measured by Lomas et al. (2011). In the Southern Ocean, phytodetrital aggregates can contribute up to 30% of total carbon export (measured during the initiation of the spring bloom by Laurenceau et al. 2014). The available observations suggest that the contributions of phyto- and zooplankton to particle formation are both temporally and spatially variable in the Southern Ocean, making it difficult to constrain the contribution of phytoplankton aggregation to particle formation on coarser temporal and spatial scales.Recently published metagenomic data and data on particle size distributions might be an important step forward in elucidating the complicated interplay between different members of the planktonic ecosystem and the carbon flux to depth (Guidi et al. 2016). "

Reviewer Comment: Pg 19971, Line 20: Could you give some more specific examples of what you mean by idealized simulations?

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Author Response: Yes. We have changed the sentence to: “Simulatons in which one or several of these processes are held constant would help to further explore the ballasting and temperature effects and improve our understanding of the role of temperature for the changes in e-ratio. “

Reviewer Comment: Table 3, Remin. length scale: Add in the range of remin length scales for PISCES (small POC at slowest remin rate to large POC with fastest remin rate).

Author Response: Done

Reviewer Comment: Table 4: Add in units for NPP and EP. What does the +21% mean in the grazed % of NPP column?

Author Response: Done. For PISCES, we give 57% microzooplankton grazing + 21% mesozooplankton grazing. We have edited the Table to explain this better.

Reviewer Comment: Figure 1: Make the arrowheads going from POC to Zoo, Zoo to POC (brown), Zoo to POC (gray, right), Aggregation of DOC bigger. They are hard to see right now.

Author Response: Done.

Reviewer Comment: Figure 4: A vertical line at 0% change in each subplot would help. From this, it looks like NPP changes are driving export changes

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a lot more within PISCES and REcoM2. In all of the models, however, it looks like the zonal variations in export change match (i.e., are correlated with) those in NPP change. In PISCES, it looks like NPP and e-ratio changes are very well anti-correlated, while in TOPAZ they are somewhat well- correlated. What might be some reasons behind this?

Author Response: We have added a 0% change line.

Reviewer Comment: Figure 5: I think the images of the phytoplankton and zooplankton in a) are not necessary here and are instead kind of distracting.

Author Response: Thanks for the feedback, we have removed the images.

Reviewer Comment: Figure 7 caption: Zooplanktonmortality should be two words. Change comma to a period after fluxes are given in percent of total NPP.

Author Response: Done.

Reviewer Comment: Figure 7: I found it very confusing for the largest fluxes to have red arrows. I think that the size of the flux should just be represented by the width of the arrow, so that you can immediately tell which fluxes are largest by that alone. The fact that the arrows are red and then the numbers denoting the changes are red, too, is another cause for confusion. Thus, just leaving those numbers red, while making all of the flux arrows black will be clearer. Make arrowheads larger, as they are sometimes invisible. Why are there dashed arrows for REcoM2 high latitudes? As Reviewer 1 noted, TOPAZ high latitude

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grazing arrows are on top of the zooplankton box unlike the other diagrams, and it would be nice to have titles at the top of each column saying low latitudes and high latitudes.

Author Response: Done, thanks for the feedback.

Reviewer Comment: Conclusions: It would be nice to mention the role of physics (both model-resolved and those occurring on scales smaller than the models can resolve) in driving EP and caveats of leaving physical effects out of this analysis. See Omand et al. (2015), for example. It would also be nice to see where the largest differences between models lie and to thus speculate on what may be the biggest source of uncertainty for projecting future EP changes (at least among the models analyzed here). Is it in p-ratios, s-ratios, or NPP? Mechanistically, is it grazing efficiency, aggregation efficiency, aggregation/mortality functional form, temperature dependence, etc.?

Author Response: We have included the following sentences in the conclusions: "Our analysis focuses on the differences in the biogeochemistry models, a detailed analysis of the role of circulation is beyond the scope of this work. We acknowledge that changes in ocean circulation play an important role in driving future export production, both on large and small scales (e.g., Najjar et al. (2007), Omand et al. (2015). Future work should try to quantify the differences in physics, for instance by using modeling frameworks in which one biogeochemistry model can be coupled to different circulation models (e.g., Allen et al. (2010). " Regarding the biggest source of uncertainty, we have added the following: "The most uncertain process among the models analysed in this work is the change in particle formation (p-ratio), where models don't even agree on the direction of change. Mechanistically, this is caused by large differences in the inclusion and parameterization of phytodetritus, zooplankton faecal pellet production,

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zooplankton mortality losses and particle aggregation dynamics on particle formation rates. “

Reviewer Comment: Technical Corrections: Pg 19947, Line 24: Change ’(DOC), moreover’ to ’(DOC). Moreover,’ Pg 19948, Line 19: length misspelled Pg 19949, Line 17-18: Change to: We use the terms grazing efficiency and aggregation efficiency to describe the fraction of NPP that is transformed into particles via grazing and aggregation processes, respectively. Pg 19951, Line 12: ’four models, however in’ should be ’four models. However, in’ or with a semi-colon rather than a period. Or change to ’four models, while in BEC fPOCgraz is larger for grazed diatoms compared to grazed nanophytoplankton.’ Pg 19951, Line 21: It might be clearer to say Pj dependence here, instead of just P-dependence. Pg 19952, Line 16: ’particle formation, however ...’ should be ’particle formation. However, . . .’ Pg 19953, Line 24: Suffers should be suffer. Pg 19970, Line 8: Change ’if they capture the processes how particles are formed’ to ’if they capture the processes dictating how particles are formed’ or something like this. Table 1: GFDL-ESM2M should be under the CMIP5 project. Table 3 caption: Change from a comma to a period after ’Agg’ is short for aggregation.

Author Response: Done

Interactive comment on Biogeosciences Discuss., 12, 19941, 2015.

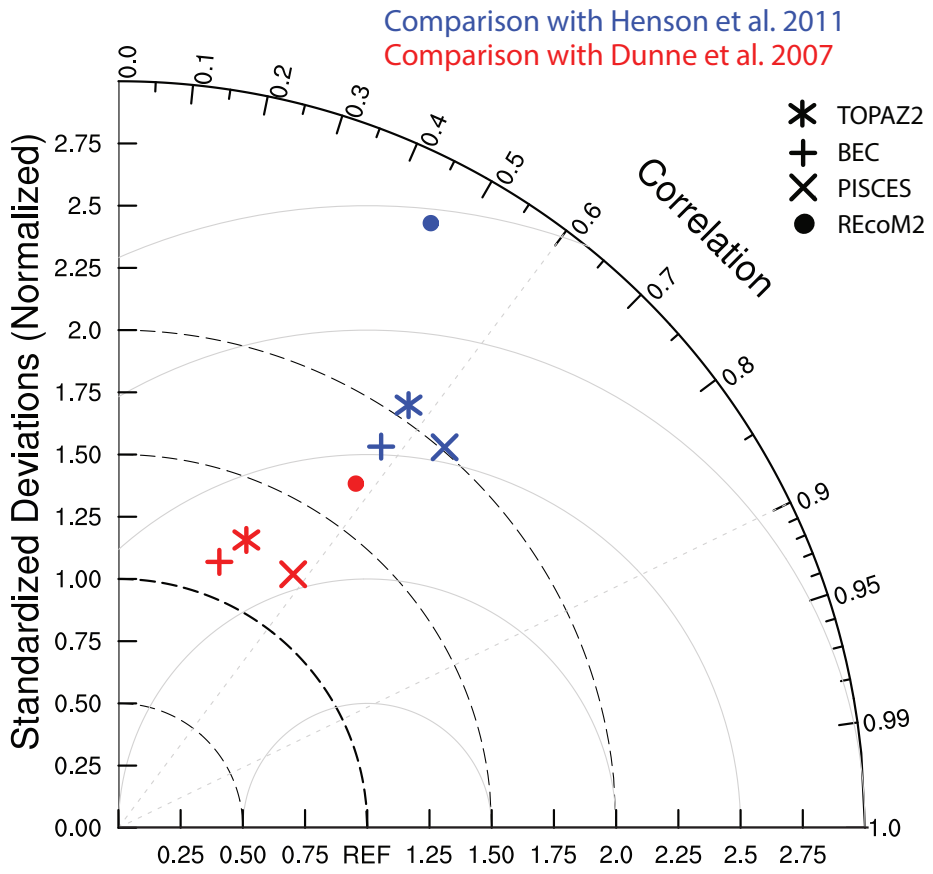

Fig. 1.

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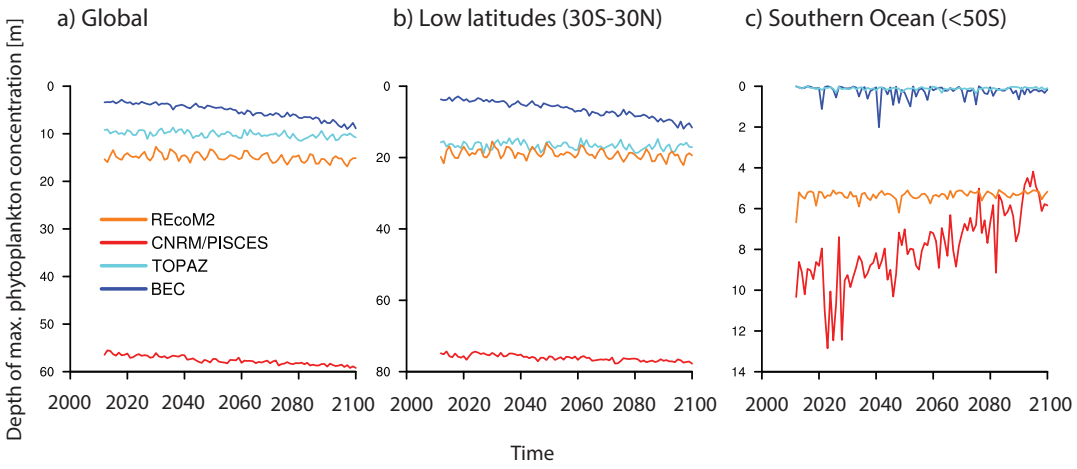

Fig. 2.

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