Biogeosciences Discuss., 12, C8131–C8138, 2015
www.biogeosciences-discuss.net/12/C8131/2015/

Biogeosciences
Discussions
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Interactive comment on "Climate change impacts on net primary production (NPP) and export production (EP) regulated by increasing stratification and phytoplankton community structure in CMIP5 models" *by* W. Fu et al.

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Received and published: 1 December 2015

1 Reply to Reviewers, BGD November 2015

We thank the reviewers for their comments and suggestions on this manuscript. We present some general comments first and then address specific comments below. We were unaware of the Cabre et al. (2015) paper at submission, but we will compare many aspects of our results with this work in a revised manuscript. Both Cabre et al. (2015) and Bopp et al. (2013) examined the same group of CMIP 5 ocean biogeochemical models as this work. We feel this work strongly complements these two excellent papers. Bopp et al. (2013; and to some extent Cabre et al., 2015) focus more on model-mean responses, and model trends normalized to 1990s values, emphasizing similarities in the model responses to climate change. Cabre et al. (2015) also include detailed analysis of key ocean biomes and changes between the beginning and end of the century under RCP 8.5.

The emphasis in our work is partly on illustrating the wide spread across models for key biogeochemical and physical metrics from the current era, and understanding how that impacts the responses to climate change. Secondly, we wanted to identify, at the global scale, what drives the climate change responses in NPP and sinking export production. The CMIP5 ocean biogeochemical models are an increasingly important component of our climate projections (i.e. Randerson et al., 2015). Considering the vast resources committed (both human and computational), and the societal importance of predicting how the Earth system will respond to climate change, we agree with Reviewer #1 that there needs to be much more study of these models, from different perspectives. CMIP5 marks the first time ocean biogeochemistry has been included in most of these Earth System Models, and detailed documentation of model performance and results is necessary. Quantifying each model's performance relative to current-era observations, also allows for objective evaluation over time as to whether these models are improving. The target audience for this work includes the oceanographic and broader climate communities.

There are a number of new results and perspectives presented here, that are not found in previous works. Both reviewers note our novel finding that the models with the strongest positive biases in stratification for the 1990s, also show the strongest increases in stratification and the largest decreases in export production and NPP with climate change.

We present times series of the absolute values (not normalized to each model mean *for some period) key physical and biogeochemical variables, illustrating the wide inter-model spread (and comparison to observed values) in surface nutrient concentrations (Figure 5), productivity and export (Figure 8), and sea surface temperature, salinity, and surface stratification (Figure 1). We also show 2-D maps of surface nitrate for the 1990s from all the models compared with the World Ocean Atlas (Figure 7). These figures thus allow readers to examine each model's fidelity to observations for the current era, and illustrate the large spread across the models. No plots like these have appeared in prior works. Similarly, we show the 2-D spatial patterns for diatom contribution to NPP and the particle export ratio (Figures 11 and 13), and the 2d patterns of how these change with climate (Figures 12 and 14). This complements the biome by biome analysis of by Cabre et al. (2015), and illustrates the links between plankton community composition and export efficiency.*

We emphasize comparing the biogeochemical variables with stratification as a key driver, as this metric better captures high-latitude, salinity-driven climate impacts than SST alone. We also present 2D plots showing where warming and salinity changes dominate the stratification changes for each model (Figure 3), and show the spatial patterns of stratification change by the end of the century (Figure 4). Previous works have focused on the model-mean response, we highlight the similarities and the disagreements across the models in the spatial patterns of stratification change and in the dominant process driving stratification changes (temperature vs. salinity).

Our analysis of the impacts of changing stratification on biogeochemical variables utilizes the full time series from each model, rather than just comparing the beginning and end of the century. We examine how stratification impacts biogeochemistry, phytoplankton community structure, and export efficiency using 150 data points for each model (Figure 10). Rather than just one or two points per model, based on beginning and end of century, decadal time-scale means. Thus our regressions and illustrations of the similarities and differences across the models are more robust, and are more easily visualized in the plots for each model, than in previous analyses (Figure 10).

2 Anonymous Referee #1

Received and published: 29 September 2015

General comment

The paper by Fu et al. presents changes in marine productivity under a global warming scenario simulated by CMIP5 models. I think this work is meaningful because comparison of marine ecosystem variables across CMIP5 models is still limited. Their indication that models having larger biases in stratification in contemporary period show stronger stratification in future climate is important. They pointed also out that representation of community composition in models is an important factor to determine productivity response to climate change, which can be a motivation to represent marine ecosystem dynamics more realistically in CMIP models. Their analysis, however, looks crude in some aspects, and additional investigations are required before publishing.

We thank the reviewer for the comments. We agree that more comparative studies across the CMIP5 models are warranted.

Specific comments 1. Controlling factors other than stratification In this paper, the authors focused mainly on relationship between marine biogeochemical variables and stratification. Although high correlations between these variables (Fig. 10) highlight an importance of stratification, other factors, changes in light availability and temperature increase, can contribute to the simulated production changes. In p. 12869 L. 13-16, the authors concluded that increased stratification and nutrient stress are the dominant control on the production change in comparison with changes in light and temperature. There is, however, no analysis supporting this argument.

In our discussion, we focus on the global scale response, where increasing stratification is the dominant factor leading to decreasing NPP and export. We also acknowledge that temperature and light can also impact the response to climate change, particularly in the polar-regions. We will clarify and expand this discus-

sion section in a revised manuscript. In fact, the three limiting factors, stratification, light and temperature are not independent. Stratification, as a function of temperature and salinity, is closely related to MLD and thermocline depth. Stratification also affects nutrient supply and light availability. At high latitudes, light can often be a limiting factor for phytoplankton growth. The changes in light are largely associated with ice retreat and changes in MLD. Enhanced stratification and shoaled MLD increase light availability and can result in higher production (Sarmiento et al. 2004; Bopp et al. 2005; Doney 2006; Steinacher et al. 2010). However, increased stratification leads to reduced nutrient supply and PP in many regions, which dominates the global response (Bopp et al. 2005; Cabre et al., 2015). We show that the stratification metric captures both the temperature-driven changes that dominate at low to mid-latitudes, and the salinity-driven changes at higher latitudes. On a global scale, over the full 1850-2100 time period, the changes in NPP and EP are more highly correlated with the changes in stratification, than with the changes in SST (r2 0.72 for stratification-NPP and 0.66 for SST-NPP). The relationship between the change of PAR and PP was shown to be significant only in the sea-ice covered area of south hemisphere by Cabre et al. (2015). We will reference the Cabre et al. (2015) analysis of the role of light, particularly in the sea-ice biome dynamics, and more quantitatively examine the potential roles of light and temperature in driving NPP and EP climate-change response at the global scale in a revised manuscript.

2. Spatial pattern of production change The authors mainly discuss changes in globally averaged variables. Discussions for changes in spatial patterns can strengthen their argument. For example, although they argue that stratification is the main driver decreasing productivity, the spatial patterns of changes in stratification (Fig. 4) and NPP by diatoms (Fig. 12) are quite different. How do the authors explain this discrepancy? From my view, there are some characteristic responses in the spatial pattern of NPP change among models. In the complicated models (GFDLs, IPSLs and CESM), the responses of NPP by diatoms show decrease in the northern high latitudes, small increase in tropics and subtropics, and modest increase in the Southern Ocean (Fig. 12). In the simpler models, on the other hand, show decrease in the northern high latitudes and increase in tropics and subtropics. What controls such different response?

One key factor driving the different response we document is the stronger declines in surface nutrients and increasing nutrient stress in the high northern latitudes, and the resulting shifts in plankton community composition. We will add additional discussion on the spatial patterns of diatom productivity and how it changes with climate across the models in a revised manuscript. The response of the %NPP by diatoms depends on several factors, including whether they were a small or large component of the community initially. As the reviewer notes, and we address in the paper, the largest decreases are seen in areas with high diatom production initially and large increases in stratification, particularly in the Northern Hemisphere. In the Southern Ocean, the winds that drive upwelling strengthen in these models, influencing iron supply, a point we will make more fully in the revised manuscript. Cabre et al. (2015) also address the asymmetry in the biogeochemical response to climate change. We will bring this and other relevant previous work into the revised discussion (i.e. Marinov et al., 2013; Moore et al., 2013, others. . .).

Minor comments and questions 1. Add units (kg/m3?) in p. 12886 Fig. 4.

The unit will be added.

2. What is the definition of the particle export ratio?

Particle export ratio is defined as the sinking production flux out of the euphotic zone to net primary production in this work (Dunne et al., 2007). The broader term, export ratio, should also include the export of dissolved organic matter, which we do not address here. We will clarify this in the revised manuscript.

3. p. 12897 Fig. 15 Are these regression slopes statistically significant? If so, please

write it, and also describe what significant level is used.

The slopes are plotted when the correlation is significant at >95% level, we will note this in revised manuscript.

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