Response to Referee 2

General: The referee is thanked for their careful evaluation of the mss and specific comments on the bio-optical aspects.

Specific responses:

I have one main comment and it pertains to the predicted profiles. Given the optical conditions the author said they used, in particular the chlorophyll concentration of 0.1 mg m-3, the productivity at depth in Figure 7 appears too high. According to Morel et al. (2007) equation for the euphotic zone depth, the 1% irradiance in such waters is around 90 m. It seems, therefore, unrealistic to find such high productivity at 150 m (for some of the conditions, productivity at 150 m is about 1/3 of the maximum productivity in the water column). This could originate from an incorrect assumption about the PvE model (e.g overly high PBmax at depth or overly low Es) or an overly low attenuation coefficient.

We agree with the reviewer that the predicted productivity at depth in these profiles is too high. As part of our ongoing work modeling productivity, we have been checking the code and discovered an error in the calculation of corrected *E*par. The profiles in the paper have now been recalculated with the corrected code and the predicted productivity at 150 m is about 25% lower than before. The profile figures (Figs. 7 and 8) have been changed and there were also slight revisions to proportional effects numbers given in the text. The productivity rate at 150 m is still significant (per unit Chl) but this is consistent with the 1% depth for penetration of corrected E'_{PAR} (essentially the same as *photosynthetically utilizable radiation*, PUR, as noted by the referee below) at around 120-140 m (depending on a_{p}). The irradiance and K_{d} data comes from the worksheet provided by Cullen et al. (2012), and they independently estimate a 1% depth for E_{PUR} under the stated conditions of 120 m (using a nominal "picoplankton" a_{p}). This suggests that our bio-optical calculations are reasonable.

The reported Es are indeed relatively low in this study; it may be nice to compare with previous measurements on Synechoccocus. It may also be relevant to discuss how the photosynthesis models proposed are pertinent to estimating productivity at 150m. Generally due to photoacclimation PBmax and Es decrease with depth and sensitivity to inhibition increase, certainly the growth irradiance for the strains were nowhere near those found at these depths.

Following the reviewer's suggestion we have checked the literature but there are few other estimates of P-E parameters for *Synechococcus* cultures. Most often cited is the work of Kana et al. (1987), converting to energy units their estimates of E_{s} are 33-39 $(\mathrm{W\ m^{-2}})^{-1}$ for cultures of WH7803 grown at ca. 23 °C in the 100-160 umol $\mathrm{m^{-2}\ s^{-1}}$ range. More recently, Fu et al. (2007) estimated values of 29-35 $(\mathrm{W\ m^{-2}})^{-1}$ for WH7803 growing at 20° and 24° under normal CO_2 conditions. These are values determined using photosynthesis measured with the halogen light source of the photosynthetron. Our values for WH7803 are lower, this can be explained by the use of the more blue-enriched, and more efficiently absorbed, (compared to halogen lamp) irradiance from the Xenon lamp. The results were not included in the text for brevity, but parallel PAR only P-E curves (using essentially the same photosynthetron design as Fu et al.) were measured for each of our experiments. On average, the estimated E_S was a factor of 1.46 times higher for the P-E curve fit for the photosynthetron (halogen source) vs. the photoinhibitron (Xenon source). This brings our results in line with Fu et al. – their average = 32 $(W\ m^{-2})^{-1}$, our average for WH7803=22.9 x 1.46 =33 $(W\ m^{-2})^{-1}$.

We do acknowledge that model extrapolation below the thermocline has debatable validity (a limitation shared with most global ocean productivity algorithms).

Actions taken: In addition to the revised figures, we include new text addressing the above points on depth of the profile and extrapolation below the thermocline (1st paragraph section 3.6)

Since the in situ spectrum is efficiently absorbed by *Synechococcus* pigments, spectrally corrected PAR penetrates deeper than 100 m, and the depth at which E'_{PAR} decreases to 1% of $E'_{PAR}(0)$ is > 120 m. Thus, the model predicts significant rates of production at depths of 100-150 m. It should be kept in mind that these depths are normally below the thermocline and no attempt has been made to correct for changes in photosynthetic response related to the depth dependent decreases in temperature and photoacclimation to lower growth irradiance. Nevertheless, the profile calculations are useful to compare the overall responses implicit in the fitted models.

Specific comments

1) Methods: Could you discuss the temperature chosen for the experiments with respect to normal Synechoccocus growth conditions (distribution range). It seems to me that relatively high temperatures were selected.

The growth temperatures were chosen so that the same temperatures could be used for parallel experiments on *Prochlorococcus* – which has a narrower growth temperature range than *Synechococcus*. This is now mentioned in the growth conditions section (2.1). In addition, the chosen temperatures are similar to those used in previous studies on *Synechococcus* photosynthesis (as cited above).

2) P. 19459, lines 18-19. *The graphs on Figure 3 certainly highlights an improvement with the successive models. However, as mentioned by the authors there is definitely a bias at high E*inh. Could we be seeing the "death" of the cells and only the results of a certain amount of photosynthesis at the beginning of the treatment in those cuvettes? Alternatively, would a model with a decreasing repair rate with damage past Emax be a more appropriate model? Also on this figure it seems as if the point at high E*inh has a very strong impact (higher weight perhaps?) on the fit as it is fitted better (perfectly on the latter two plots) than the ones with lower E*inh if that is the case, might it be*

relevant to remove that point or alter the weighting?

A decreasing repair rate or "death" threshold at high exposures are certainly possible responses and could account for some of the over estimates at high exposure. This is now mentioned in a new paragraph in the discussion. As far as the point with the high E^*_{inh}, We tested the fit by omitting the point and the results were virtually identical to that with the point included (the change in R^2 was in the 4th decimal place) so it does not appear to have unusually high leverage.

3) *P. 19457, the authors seem to go to great length to avoid the use of PUR irradiance. I can see that their formulation is indeed a good alternative (which it appears mathematically equivalent). Perhaps it would be nice to spell out why this choice is made here.*

The text has been revised to explain that the approach was chosen to maintain consistent energy units in the model. Admittedly, this is a matter of convenience and there is no theoretical reason why all exposure-related parameters couldn't be given in quantum units. Indeed, Cullen et al. (2012) chose to use quantum units for their calculations and show all the BWFs they use converted to these units.

Action taken: The section has been revised, the new text is given below in response to point 7.

4) *P. 19461, line 3 and 4. It may be interesting here to guide the reader as to what this means (if anything) for previously published BWFs. Would you have a recommendation for their future use?*

Under normal circumstances the weighted irradiance contributed above 300 nm is very small, e.g. see Fig. 4 in Sobrino et al. (2009), so the artifact has very little influence on the predictions of solar radiation effects using previously published BWFs.

Action taken: To the text in Section 3.3:

[The statistical leverage of data for which this bias results in a loss of fit must be small, as essentially the same R^2 was obtained for the model fit to the n=100 data set with either BWF (for BWFs in Fig. 4, difference in R^2 is ca. 0.002, results not shown).]

the text is added:

Similarly, the artifact has a nearly negligible effect on model predictions under solar exposures (in the absence of a gamma ray burst) since wavelengths < 300 nm make a very small contribution to E^*_{inh} (cf. Sobrino et al. 2009).

5) *Figure 5. I think I would prefer seeing the resulting BWFs on one plot. These figures are not very enlightening to me.*

These plots don't actually show BWFs, the lines are fitted exposure-response curves. The plots show that relative agreement between observed and predicted is different for cultures that were or were not given a pre-exposure. Since the data is from different experiments, it would be difficult to combine everything in one plot.

6) *Figure 8. Combining the two panels into one may allow for an easier comparison between the two species.*

We did consider the reviewer's suggestion but decided that having all six lines on the same plot obscured the relationship between profiles using the different spectral ranges (PAR+UV, PAR, no inhibition). So we have kept it as two panels but have moved the panels closer (dropping the second set of y-axis labels) to make it easier to compare between panels.

Minor comments

1) *title: this study is really about Synechococcus not so much pico- phytoplankton (there are quite a few other members, including eukaryotes). Perhaps dropping picophytoplankton and replacing by Synechococcus may be a more appro- priate title.*

Yes, the only picophytoplankter in this presentation is *Synechococcus*, and this focus is stated in the present title. We would prefer to retain the present format as there is a companion paper in preparation dealing with *Prochlorococcus*. In the future, hopefully we will even have a chance to work with some picoeukaryotes!

2) *P. 19453, line six: Irradiance was provided by (or something along these lines)*
3) *P. 19456, Eq. 4, the second E*inh on the top line is too close to the parenthesis, it can be confused as a multiplication at first.*
4) *P. 19457 line 3: format on reference should be fixed.*

We agree with the referee and have made all corrections as suggested. Extra space was added for Equation 4, however the format for this equation was changed from what was submitted when it was typeset. We will check the revised proofs to make sure there is enough space.

5) *P. 19457 line 8: Pigment absorbance: I think you mean "Irradiance weighted chlorophyll specific absorption for the photoinhibitron"... 6) P. 19457 line 9: Pigment absorbance: I think you mean "phytoplankton absorption coefficient"... also add units (m-1)*

The text has been revised to use the suggested terminology, adding the terms "chlorophyll-specific spectral" on line 9, units are given which are the same as for a_p

7) *P. 19457, line 5: I don't like the use of PFD for an irradiance (in quantum units). I think the symbol should remain some variant of E. Perhaps a superscript could details that it is in quantum units. . . but this may just be my personal preference!*

Following the referee's suggestion, we now use E^{Q} to denote irradiance in quantum units.

Actions taken in response to points 3 and 7: The text in this section is now revised as follows:

A factor is applied to underwater PAR to correct for spectral differences of model PAR vs. the filtered xenon irradiance used to measure photosynthesis. Irradiance weighted chlorophyll-specific absorption for the photoinhibitron, a_{PI} (m^2 mg Chl^{-1}), was calculated by weighting the phytoplankton chlorophyll-specific spectral absorption coefficient ($a_{\mathrm{p}}(\lambda)$, m^2 mg Chl^{-1}) with the average photoinhibitron spectrum, as photon flux, $E_{PI}^{Q}(\lambda)$,

$$a_{PI} = \sum_{400nm}^{700nm} a_p(\lambda)\cdot E_{PI}^{Q}(\lambda)\cdot\Delta\lambda \Bigg/ \sum_{400nm}^{700nm} E_{PI}^{Q}(\lambda)\cdot\Delta\lambda \tag{5}$$

The calculation was based on photon (quantum) flux (E^Q) since photosynthesis is a quantum process. The wavelength resolution (Δλ) was 1 nm. A similar calculation was performed for the underwater profile to obtain the irradiance weighted absorption of in situ irradiance, $a_{\mathrm{IS}}(z)$ (m^2 mg Chl^{-1}):

$$a_{IS}(z) = \sum_{400nm}^{700nm} a_p(\lambda)\cdot E^{Q}(0^-,\lambda)\cdot e^{-K_d(\lambda)\cdot z}\cdot\Delta\lambda \Bigg/ \sum_{400nm}^{700nm} E^{Q}(0^-,\lambda)\cdot e^{-K_d(\lambda)\cdot z}\cdot\Delta\lambda \tag{6}$$

Finally, a corrected PAR irradiance for the photosynthesis model was calculated as

$$E'_{PAR}(z) = E_{PAR}(z)\frac{a_{IS}}{a_{PI}} \tag{7}$$

For consistency with previous usage of the BWF/P-E model, the corrected PAR is in energy units.

8) *P. 19462, line 12: Capital "B" on the superscript. 9) P. 19465, line 8. Please check spelling on both pigments. 10) P. 19465, line 8. Typo on weights.*

All corrected, spelling on pigments was checked and is correct.

References cited in response:

Fu, F.-X., Warner, M. E., Zhang, Y., Feng, Y., and Hutchins, D. A.: Effects of Increased Temperature and CO2 on Photosynthesis, Growth, and Elemental Ratios in Marine

Synechococcus and Prochlorococcus (Cyanobacteria), Journal of Phycology, 43, 485-496, 10.1111/j.1529-8817.2007.00355.x, 2007.

Kana, T. M., and Glibert, P. M.: Effect of irradiances up to 2000 μE m^{-2} s^{-1} on marine Synechococcus WH7803–II. photosynthetic responses and mechanisms, Deep-Sea Res., 4, 497-516, 1987b.

Attachments: Revised Figures 7 and 8.

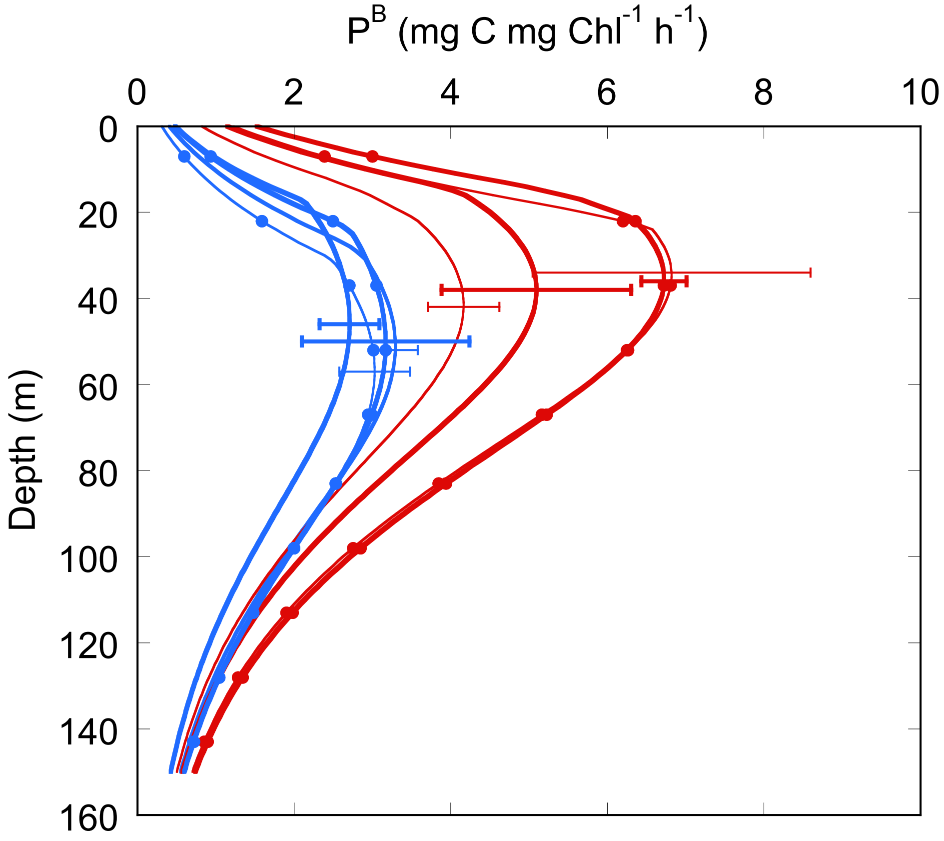

Figure 7. Predicted profiles of biomass specific productivity (P^B) for a test set of water column optical conditions (noon, summer solstice, 15° S latitude, oligotrophic bio-optics, etc) based on fitted BWF_{Emax}/P-E models estimated from experiments with *Synechococcus* strains WH8102 (lines with no symbols) and WH7803 (lines with circles) for each of four growth conditions, 20°C (blue), 26°C (red), medium PAR (thin line), high PAR (thick line). The line is the average profile (n=3) for replicate experiments, horizontal bars indicate simple standard deviation of P^B estimates from replicate experiments at the depth of peak average productivity.

Neale et al. bg-2013-505 Revised Figure 8.

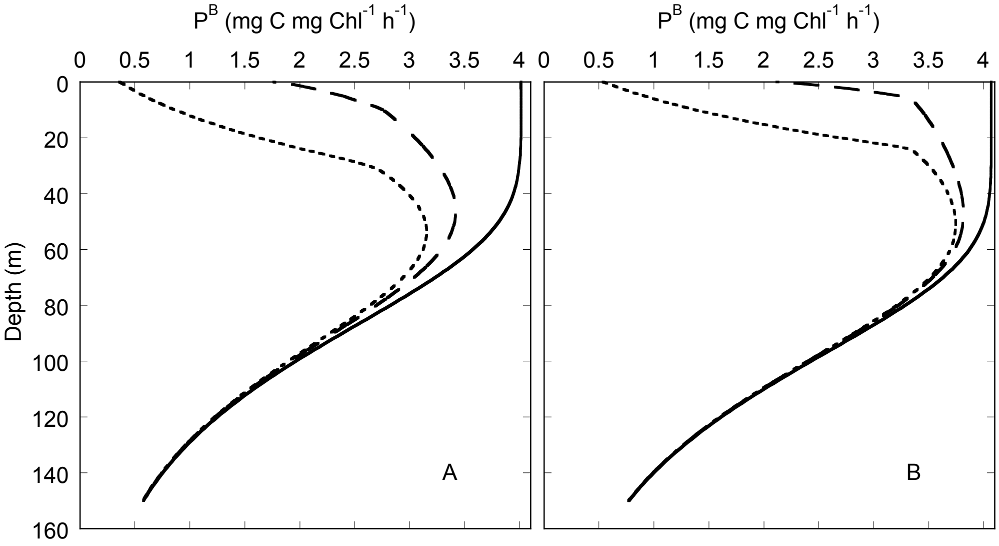

Figure 8. Depth profiles of productivity as predicted using the BWF$_{E\mathrm{max}}$/P-E model evaluated with the P-E equation and no inhibition (solid line), with only inhibition by PAR (e_{PAR}) included (long dashes) or with full UV+PAR inhibition (short dashes). The curves in panel A show the average response by *Synechococcus* (ML 20° cultures, WH8102 and WH7803 combined), in panel B is shown predicted response based on a fit of the BWF$_{E\mathrm{max}}$/P-E model to the photoinhibitron data for the diatom *Thalassiosira pseudonana* (strain 3H) grown at comparable growth irradiance and temperature [from Sobrino et al. (2009)].