**Biogeosciences
Discussions**

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Interactive comment on "Large-scale shifts in phytoplankton groups in the Equatorial Pacific during ENSO cycles" *by* I. Masotti et al.

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Dear Referee 1 Thank you very much for your valuable comments and suggestions. We are grateful that the referee thinks that our study contributes to our understanding of the relations between climate-driven changes in ocean dynamics and phytoplankton community structure. Please find our responses below (referee (R), author (A)).

(R) However, before the paper is published in Biogeosciences the authors first need to carry out a more detailed review of the rich history of equatorial Pacific phytoplankton composition and abundance (papers by Bidigare, Chavez, Chisolm group, Landry – JGOFS data available on line) and the results from the PHYSAT model placed in this context.

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(A) We thank referee 1 for suggesting a review of rich history of equatorial pacific phytoplankton composition and abundance. The spatial and temporal variability in phytoplankton composition (Chavez et al., 1996, Landry et al., 1996, Binder et al., 1996) and accessory pigments (Bidigare et al., 1996) studies were carried out in the context of JGOFS time series cruises. Clearly these studies present relevant information regarding changes of relative Synechococcus dominance during El Niño conditions. Our PHYSAT analysis for the Synechococcus show a decrease during early stages of the 1997 El Niño (May-Jun, SOI= -2.0, cf. Fig. 2 in the MS) and a subsequent increase in Synechococcus dominance during the mature phase of the 1997 El Niño (September-November, SOI=-3.0). This agrees with Landry et al. (1996) , who showed that Synechococcus was more numerous during the mature conditions of the 1992 El Niño (Feb-March, SOI= - 3.5) along the 140°W transect (at 12°S and 12°N), than during the weak conditions of the 1992 El Niño (August-September, SOI= -0.4). These results are also consistent with the purported 'resilience' of Synechococcus dominance as El Niño conditions mature, as we suggest in this work. This new interpretation has been included in the discussion section of the MS revised version.

(R) For example, Prochlorococcus is the dominant group along the equator in these studies yet that does not seem to be the case for PHYSAT estimates. Synechococcus appears to be overestimated by PHYSAT as well.

(A) We agree that observations along the equator domain are suggesting that Prochlorococcus is the dominant group (Binder et al., 1996, Landry et al., 1996), but it should be noted that these observation remain local and on the specific period, and it is difficult to compare with satellite observation. A comparison in space-time of PHYSAT dominant phytoplankton groups with ship-based observations is difficult because of the need for both bloom conditions and very clear skies. Unfortunately we do not have available satellite data to provide PFT estimations using PHYSAT to prove whether or not Prochlorococcus was the dominant group for this particular period and region where JGOFS time series cruises were carried out.

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(R) There is significant smaller scale spatial variability in abundances from the equator proper to a few degrees north and south that is not considered. Is this not picked up by the satellite algorithm or is the resolution of the analysis such that this effect is missed?

(A) We agree effectively smaller scale spatial variability in abundances can be possible by example in Prochlorococcus distribution (cf. fig. 7 Landry et al., 1996) whereas can be formed patches at surface that probably detected by satellite. Patches can be detected by PHYSAT at $\frac{1}{4}°$ grid cell, for example in Figure 3 in the MS, where we show the global distribution of the dominant PFT, we observe Prochlorococcus patches (green patches in the figure) during El Niño/La Niña period along EQPAC region. This is the best resolution that we have available using monthly archives and the $\frac{1}{4}°$ grid cell. Monthly archives are in fact monthly composites and can therefore rely on few daily observations not necessarily coincident with local in situ observation. We did not use weekly composites because it would have resulted in too many empty pixels. Therefore, in order to understand PFT shifts over larger scales (180°W-80°W, 10°N-10°S), we need monthly composites and at 1° grid cell resolution. This means that PHYSAT PFT signatures are not picking up smaller scale spatial variability in dominance. However, we think PHYSAT remain a useful tool to provide a general overview of the PFT distribution to understand large scale regional events like El Niño/La Niña transitions.

(R) In general there is a mismatch between the presentation of global results and the regional focus of the paper. The use of the coupled numerical model seems superfluous in the present version. To keep the coupled numerical model as part of this paper the authors should consider model results beyond estimates of nitrate concentration which surely can be predicted at least as accurately from satellite temperature. The reader is left wondering why the phytoplankton predictions from the model are not shown. The paper cries for a more detailed analysis of the processes responsible for the proposed changes in nutrients, abundance and composition. What are the temporal and spatial physical, chemical and biological dynamics in the model and the satellite time series?

(A) We agree that model predictions of phytoplankton functional groups might be useful to compare with PHYSAT PFT distributions. In our study, we use the model output to explain possible environmental processes that might explain the PFT shifting observed by PHYSAT. Ideally, we would be able to compare the PFT distributions from PHYSAT (i.e., Prochloroccocus, Synechococcus, nanoeucaryotes and diatoms) to those predicted by the model. However, such global models typically do not include such a diversity of PFTs, particularly for the smaller phytoplankton classes. The NEMO-PISCES model includes a generic separation between large, silicifying diatoms and smaller, non-silicifying nanophytoplankton. Accordingly, any shifts between smaller PFTs (synechococcus, prochloorococcus and nanoeucaryotes) cannot be compared as they would all be present in the 'nanophytoplankton group in the model. On the other hand, a comparison of shifts in diatom dominance from NEMO-PISCES and PHYSAT during La Niña periods was recently performed (Gorgues et al., 2010). In the context of our study, we used NEMO-PISCES to examine likely spatio-temporal changes in the physio-chemical properties of the region that cannot be assessed using PHYSAT. Once we can persuade ourselves that the model is reasonably representing the temporal evolution of ocean physics (e.g. see T° comparison between satellite and NEMO-PISCES model in Fig. 7), we can examine what changes in environmental variables may be the bottom up forcing of the shifts in PFT measured by PHYSAT. While only NO3 changes are presented in this study (see results presented in section 4 in the MS), we did in fact examine a suite of environmental parameters from NEMO-PISCES, such as PO4, Fe, mixed layer depth and euphotic depth. Our preliminary analysis showed that nutrients exhibited more significant changes over periods of interest. For example during the strong 1997-1998 El Niño condition Fe and NO3 concentrations decreased by a factor of 1.6 and 2.4 respectively (cf. Fig. R1) compared to a $\sim$10% decrease/increase in the mixed layer or euphotic depth. Our eventual focus on NO3 is also supported by the fact that i) regional-mean PO4 concentrations show almost similar inter-annual variations than NO3 in the 180°W-80°W, 10°N-10°S region, but with a much smaller relative amplitude (+- 20% for PO4 concentrations vs

+- 100% for NO3 concentrations) ii) mean Fe concentrations during early state of the El Niño condition show a decrease simultaneous to NO3 and PO4 in the 180°W-80°W, 10°N-10°S region, and iii) although regional NO3/Fe present decoupling episodes at inter-annual scales in the 180°W-80°W, 10°N-10°S region, NO3/Fe show almost similar inter-annual variations in the core of the PFT variability region (140°W-100°W, 10°N-10°S, see results presented in section 3, Fig. 6 in the MS). Moreover, figure R2 shows the NO3, PO4 and Fe anomaly in the 140°W-100°W, 10°N-10°S region. As can be seen, NO3, PO4 and Fe show almost similar inter-annual variation, except during mature El Niño conditions (September 1997 to March 1998) when a decoupling between Fe and NO3 seems to appear. This agrees with the NO3/Fe decoupling shown to occur at the decadal time-scale and in the eastern part of the EQPAC region (150°W-90°W, 2°N-2°S) (Rodgers et al., 2008). In the 180°W-80°W, 10°N-10°S region it is clearly NO3 that controls/limits productivity in NEMO-PISCES model and we therefore focus on the 180°W-80°W, 10°N-10°S region where NO3 appears to be a more representative nutrient to explain any PFT variability.

We will introduce these new comments to clarify the choices of nutrients control/limitation in the methods section of the MS revised version and figure R1,R2 will be included as supplemental material. We think this will aid in better understanding how and why we chose to use the NEMO-PISCES model.

Specific comments: (R) Several of the figures (3, 5, 6, 7) are very difficult to read given their size and the labels (A) Acknowledged and addressed in the revised MS. New figures were reproduced.

(R) The authors mix in results from other geographical regions when the focus is on the equatorial Pacific. Stick to the topic.

(A) Other geographical regions (e.g. Atlantic Ocean) were included to obtain a comparative overview of PFT variability in another tropical region. We also think this helps to illustrate the consistency between the two PHYSAT processing algorithms.

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(R) SOI values / identification of strong/moderate El Niños (p. 2528 l. 4-8 ie. data&methods) should be in the results when first using the SOI; the OCTS/SeaWiFS comparison (p. 2529 l.22-27 results) should be in data and methods when introducing the satellites.

(A) Acknowledged and addressed in the revised MS. New comments were added to introduce SOI values in the results section. However we think that OCTS/SeaWiFS comparison (p. 2529 l.22-27) in the results section is useful to help explain and illustrate the consistency between the two PHYSAT processing algorithms. Therefore, we do not think it appropriate to move the OCTS/SeaWiFS comparison from the results to methods section.

(R) Fig. 3 is referred to as climatology when it really isn't – OCTS is based on 1996-97 and SeaWiFS on 1999 ie El Niño vs. La Niña

(A) We agree with the reviewer. As described in the results section, figure 3 illustrate a global distribution of the dominant PFTs each month and it is not climatology, we correct the figure legend. We also change the word 'climatology' by 'global distribution each month' throughout the revised MS.

(R) – OCTS is based on 1996-97 and SeaWiFS on 1999 ie El Niño vs. La Niña - which the authors acknowledge, but still use it as "basic comparison" between the two satellites. If it's just to say that OCTS has more missing data, a simple number (average percentage of missing values per month for each) should be enough. If they do want to compare, then use all SeaWiFS years rather than just the 1999 La Niña. Same should be done for fig. 4.

(A) In section 3.1 we show a comparison of OCTS 1996-1997 and SeaWiFS in 1999 (cf. figure 3) essentially because we aimed to examine whether OCTS PFT detections were comparable at the global scale with SeaWiFS. To support this, we needed to compare monthly global PFT distribution from OCTS with one typical SeaWiFs year. We did not use the climatology, as we needed to compare monthly products from the equivalent

PHYSAT composition procedure. Figure 4 show a comparison by each PFT obtained from OCTS and SeaWiFs in 1999. The choice of 1999 was because this year seems representative of the SeaWiFS PFT climatology as shown in figure R3. In the figure R3 we show a comparison between the monthly areal coverage (in percentage) by each PFT obtained from SeaWiFs in 1999 and SeaWiFS climatology (between 1997-2007). To better clarify our choice of 1999, we introduce these new comments in the section 3.1 of the MS revised version and figure R3 will be included as supplemental material.

(R) Authors should complete Fig. 3 discussion before moving on to Fig. 4 (refer to Fig. 3 very briefly p.2529, then Fig. 4, and come back to Fig. 3 p. 2531). (A) Acknowledged and addressed in the revised MS.

(R) Why is there no impact on phyto composition in 2002-03 when nitrate concentration decreases rather significantly?

(A) We show that significant changes in PFT have been observed during transitions from non-El Niño to El Niño conditions when they are associated with strong and 'rapid' changes in nutrients (where NO3 relative shift is used as index, cf. Fig. 7 in the MS). This is the case for the transitions to the 1997 and the 2006 El Niño events, where the NO3 relative shift reduces by 4.5μM month-1 and 2.6 μM month-1 respectively. The transition to the 2002-2003 El Niño is accompanied by a much smaller reduction of NO3 relative shift (1.0 μM month-1) and is therefore not associated with a change in PFT dominance. This might suggest a certain threshold the relationship between the NO3 shift and changes in PFT dominance. Also, in the transition to the 1997 and 2006 El-Niños the NO3 relative shift changes from conditions that are favourable for plankton growth (i.e. positive values) to conditions that are unfavourable (i.e. negative values), while in the transition to 2002-2003 the NO3 relative shift does not change sign (i.e. low negative to slightly more negative values) and is less likely to cause significant changes in PFT.

(R) The arguments about synechococcus linked with NO3 do not seem valid – they

show that Syn concentration/numbers increase with NO3 but NOT that their dominance increases – ie. that they increase more than others.

(A) As described in the paragraph above Synechococcus dominance decays quickly when strong and 'rapid 'decrease in NO3 are observed. In the opposite sense, even if an increase of NO3 will produce a favorable condition for the growth of Synechococcus and consequently increase in Synechococcus abundance, this NO3 increase does not necessarily guarantee Synechococcus dominance. Indeed, NO3 will be available not only for Synechococcus but also for others phytoplankton communities e.g. Prochlorococcus, nanoeucaryotes, and eventually diatoms. These others phytoplankton communities will be also able to increase their abundance and PFT dominance would depend of the ability of specific communities to grow faster that others.

(R) The argument seems based on half-saturation constants (p. 2536 l.12) but this reviewer could not find the values in the Veldhuis 2005 paper.

(A) Acknowledged and addressed in the revised MS. Now, we cite the original reference and new references are cited to confirm the high N dependency of Synechococcus. The new sentence is reproduced hereafter.

A high N dependency of Synechococcus has also been observed in laboratory studies. For example, the Synechococcus half-saturation constant for ammonium uptake (2.6 μM N) is 2.6 times higher than for other pico-phytoplankton species (Timmermans et al., 2005). Other laboratory studies suggest that Synechoccocus utilizes a full range of N sources, including nitrate, nitrite, ammonium, urea and amino acids (Moore et al., 2002). As a result of its N-rich phycobilisomes, Synechoccccus also requires more N compared to Proclorococcus (Moore et al., 2002) and has a higher overall cellular N demand (Bertilsson et al., 2003; Heldal et al., 2003). On the other hand, Prochlorococcus has low cellular N requirements (Bertilsson et al., 2003; Heldal et al., 2003) and is extremely abundant in oligotrophic N-poor waters (Partensky et al., 1999). A higher requirement for N for Synechococcus, relative to other PFTs, would result in

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greater limitation of Synechococcus growth rates under the depleted N conditions that typify El Niño events.

(R) Why not look at N:P (p. 2537) with PISCES?

(A) Because of CPU cost of PISCES model, PISCES uses fixed C:N:P stoichiometry for phytoplankton uptake and organic matter production (it is not the case for Fe and Si); denitrification and N-fixation are the only processes that could be potentially decouple N and P in the model. As such, PISCES does not represent the complete variability in oceanic N:P ratios that might be anticipated. However work to improve the N:P modeling in PISCES is underway (work in progress by Laurent Bopp and Alessandro Tagliabue; Tagliabue et al., in review, Global Biogeochem. Cycles).

Technical comments: (R) - p. 2525 l.20-25: there are 2 different considerations that are treated together: phytoplankton have different C-fixation efficiency as we as different nutrient requirement. Not clear, re-write.

(A) Acknowledged and addressed in the revised MS. The new sentence is reproduced hereafter.

Photosynthetic performances and nutrient demands differ between different phytoplankton groups. For example, diatoms are twice as efficient as typical equatorial picoplankton (e.g., Prochlorococcus and Synechococcus) in carbon fixation, despite having a higher nutrient demand (e.g., Veldhuis et al., 2005; Sarthou et al., 2005). In this context, it is unsurprising that the composition of the phytoplankton community also changes during ENLN transitions (Chavez et al., 1999).

(R) - p. 2534 l.14: a space missing (NO3is) (A) Acknowledged and addressed.

(R) - fig. 4: Synetochococcus or I don't know what in the caption... (A) Acknowledged and addressed.

(R) - fig. 5: I'd change the scales, especially for Pros/Dia. Maybe add the SOI somewhere in Fig. 5e/g. (A) Acknowledged and addressed. We change scales for Pro/Dia.

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in the new version of the figure.

Reference cited in this answer to comments from referee 1:

Bidigare, R.R., and Ondrusek, M.E.: Spatial and temporal variability of phytoplankton pigment distributions in the central equatorial Pacific Ocean, Deep-Sea Research II 43, 809–833, 1996.

Binder, B.J., Chisholm, S.W., Olson, R.J., Frankel, S.L., and Worden, A.Z.: Dynamics of picophytoplankton, ultraphytoplankton and bacteria in the central equatorial Pacific, Deep-Sea Research II 43, 907–931, 1996.

Bertilsson, S., Berglund, O., Karl, D. M., and Chisholm, S. W.: Elemental composition of marine Prochlorococcus and Synechococcus: Implications for the ecological stoichiometry of the sea. Limnol. Oceanogr., 48, 1721–1731, 2003. Chavez, F.P., Buck, K.R., Service, S.K., Newton J., and Barber, R.T.: Phytoplankton variability in the central and eastern tropical Pacific. Deep-Sea Research II 43, 835–870, 1996.

Gorgues, T., Aumont, O., and Rodgers, K. B.: A mechanistic account of increasing seasonal variations in the rate of ocean uptake of anthropogenic carbon, Biogeosciences, 7, 2581-2589, doi:10.5194/bg-7-2581-2010, 2010.

Heldal, M., Scanlan, D. J., Norland, S., Thingstad, F., and Mann, N. H.: Elemental composition of single cells of various strains of marine Prochlorococcus and Synechococcus using X-ray microanalysis. Limnol. Oceanogr. 48: 1732–1743, 2003.

Landry, M.R., Kirshtein, J., and Constantinou, J.: Abundances and distributions of picoplankton populations in the central equatorial Pacific from 12°N to 12°S, 140°W. Deep-Sea Res. II 43: 871-890, 1996.

Moore, L. R., Post, A. F., Rocap, G., and Chisholm, S. W.: Utilization of different nitrogen sources by the marine cyanobacteria Prochlorococcus and Synechococcus. Limnol. Oceanogr. 47: 989–996, 2002.

Rodgers, K. B., Aumont, O., Menkes, C., and Gorgues, T.: Decadal variations in equatorial Pacific ecosystems and ferrocline/pycnocline decoupling, Global Biogeochem. Cycles, 22, GB2019, doi:10.1029/2006GB002919, 2008.

Timmermans, K.R., van der Wagt, B., Veldhuis, M.J.W., Maatman, A., de Baar, H.J.W.: Physiological responses of three species of picophytoplankton to nitrogen, phosphorus, iron and light limitation. J. Sea Res. 53: 109-120, 2005.

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NO$_3$ (µM)   Fe (nM)
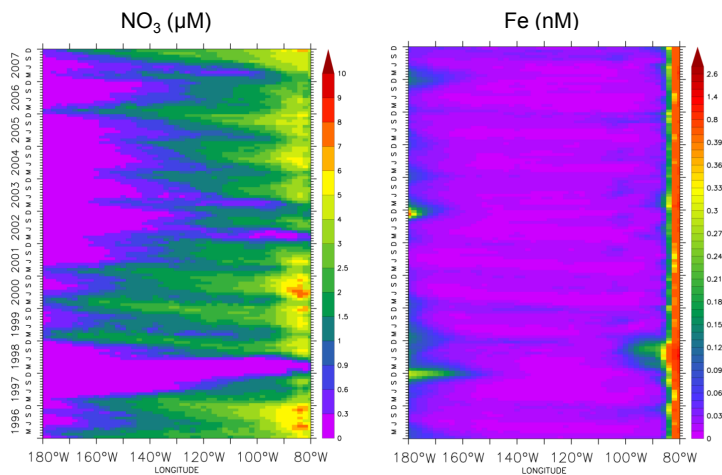
Fig. R1. Longitude-time plots of the NO$_3$ (left panel) and Fe (right panel) concentration in the Equatorial Pacific region (10°N-10°S) over 1996- 2007.

Fig. 1.

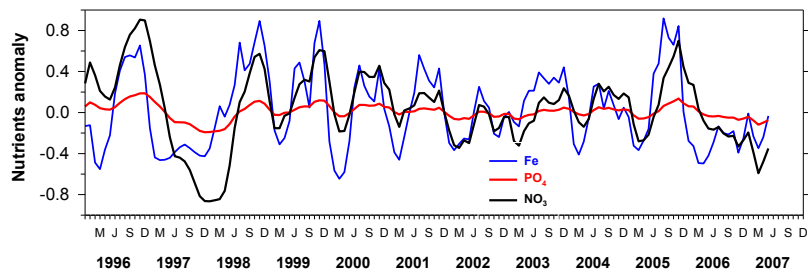Fig. R2. Anomaly of nutrients in the core of the PFT shift region (140°W-100°W, 10°N-10S) during ENSO cycles.
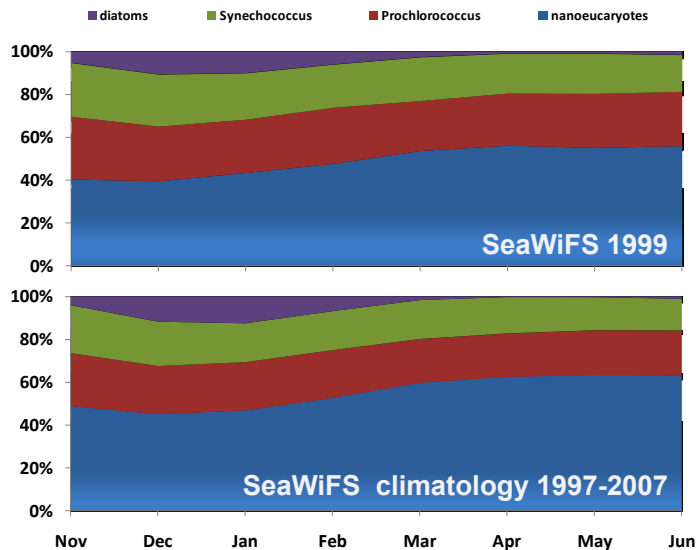
Fig. 2.

Fig. R3. A comparison of the monthly areal coverage (in percentage) by each PFT obtained from SeaWiFS 1999 year (upper panel) and SeaWiFS climatology between 1997-2007 (bottom panel).

Fig. 3.