

Interactive comment on “Isotopic fractionation of carbon during uptake by phytoplankton across the South Atlantic subtropical convergence” by Robyn E. Tuerena et al.

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We thank the reviewer for their time in completing this review, we believe that their input will help greatly improve the manuscript. Here we include responses to all of the comments: (1) Reviewer's comment (2) Author's comment (3) Suggested change to manuscript

(1) This paper presents data about spatial variation the carbon isotopic composition of POC and DIC in the subtropical convergence zone of the south Atlantic and authors interpret their findings in terms of CO₂ solubility (temperature) and phytoplankton physiology (cell size; growth rate). Authors conclude to an important weight of cell size and

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growth rate in setting the measured isotopic composition of the phytoplankton. They also discuss the impact of the ongoing atmospheric CO₂ increase and resulting ocean warming on future isotopic fractionation and phytoplankton isotopic composition.

The authors are rather conservative in providing information about some methods used. In particular about the following: Phytoplankton size classes as deduced from pigment assemblage. Just referring to Bricaud and Uitz seems hardly enough .. the few lines (27 to 33) at page 6 don't really enlighten this issue. The same holds for the use of Rau's diffusion model. There is no discussion whatsoever about 'why this model (which is quite complex) is selected, neither about the model parameters (including growth rate) which are mainly taken from the original Rau paper.

(2) We thank the reviewer for raising the concern that there is not enough information for the reader regarding the use of size classes and also the use of the Rau, 1996 model. We now include further information below and we suggest that this information could be included in the supplementary information for the manuscript:

Size class calculations

The size classes of phytoplankton were calculated using seven diagnostic pigments which are used as biomarkers of specific taxa as calculated from the HPLC data (see methods). The taxa can be used to estimate the proportion of micro, nano and pico-phytoplankton. This is calculated using the following formulae:

$$wDP = 1.4(\text{fucoxanthin}) + 1.41(\text{peridinin}) + 0.60(\text{alloxanthin}) + (0.35(19' - BF) + 1.27(19' - HF) + 0.86(\text{zeaxanthin}) + 1.01(\text{Chl } b + \text{divinyl} - \text{Chl } b))$$
$$f_{\text{micro}} = (1.41(\text{fucoxanthin}) + 1.41(\text{peridinin}) / wDP$$
$$f_{\text{nano}} = (0.60(\text{alloxanthin}) + 0.35(19' - BF) + 1.27(19' - HF) / wDP$$
$$f_{\text{pico}} = (0.86(\text{zeaxanthin}) + 1.01(\text{Chl } b + \text{divinyl} - \text{Chl } b) / wDP$$

The coefficients represent the average ratio between chl a and the concentration of

each diagnostic pigment, which are broadly related to taxa. This method contains caveats, which include: -pigments are shared across taxa

-cells adjust their pigments ratios in response to light/nutrient stress

-this proxy was derived for a global study to estimate phytoplankton groups from satellites, therefore, the shifts in size structure as you go from the gyres (Prochlorococcus dominated) to an upwelling system (diatom dominated) are nicely captured but the high latitudes are misrepresented.

In this dataset we transition from gyre-like to mesotrophic conditions, which we believe should be accounted for relatively accurately with this method. Bricaud et al., 2004 also found a good correspondence to the optical properties of phytoplankton, which can be viewed as an independent proxy of cell size.

Rau et al., 1996 model

On initial experiments for this work, it was found that $[CO_2(aq)]$ alone was not a suitable determinant of the $\delta^{13}C$ of POC in surface waters across the SSTC, therefore the importance of other factors needed to be examined. The Rau model is used as the intracellular carbon concentration is dependent on $[CO_2(aq)]$, cell radius, cell growth rate, cell membrane permeability to $[CO_2(aq)]$ and temperature. This therefore allows the importance of these variables to be tested.

We include a link to the MATLAB code for the model: https://github.com/mvdh7/miscellanea/blob/master/g40s_isotopes/rau1996.m

(1) Page 6, Line 15 (and also page 7, line7): It is not clearly stated how model estimates based on 'temperature alone' are obtained, except for a reference to Rau et al. 1989. Is this the same as the original Farquhar model as described by Francois et al. ? If so, that model does not consider cell size .. but you mention a constant cell size of $10 \mu m$ was used. Please clarify.

(2) Using temperature alone signifies that all other baseline numbers within the model

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construct from Rau et al., 1996 have been used apart from the variability in temperature across the SSTC (see above table). The temperature is used to reconstruct CO₂, which is used to predict variability in d¹³CPOC. All other variables within the model construct (see previous comment), are used as constants from the Rau model, therefore a constant cell size and growth rate.

(3) To investigate the spatial variability across the SSTC, [CO₂(aq)], and δ¹³CCO₂ were plotted against longitude and compared to model estimates (Rau et al., 1996, supplementary information), where we used the model constants for cell size (10µm) and reconstructing [CO₂(aq)] from temperature variability across the transect (Figure 3a and b).

(1) Page 7, Line 1 and Figure 5: authors state that cell radii were smaller in the sub-tropical waters compared to the SASW. From Figure 5 this is hardly visible.

(2) We thank the reviewer for highlighting this point, we agree that the colour plot makes it challenging to identify where the change in cell radii matches with the change in water mass. We attach a suggested amended figure with isotherms overlain for temperatures of 14 and 18 °C (Figure AC1). The smallest cell radii are within the core of the Agulhas and Brazil currents (where cell radii <8µm and temperature >18°C). The largest cell radii at the surface (excluding the Rio Plata) are within the SASW. Following on from a further comment below, we have also highlighted where stations were relative to the SSTC (north or south).

There is a significant moderate negative correlation between average cell radius and salinity (Figure AC2, Pearson's product moment correlation: $r = -0.56$, $t = -8.69$, $df = 165$, $p\text{-value} = 3.36e-15$). The lowest salinities from the Rio Plata have been removed from this (<33).

(1) Page 8 Line 6: these trends 'contrast' the global observed variability. . . They contrast in what sense?

(2) This is an important point and we recognise that our wording needs to be clearer within the revised manuscript. This comment within the manuscript is describing the global trends: when CO₂(aq) is high, ϵ_p is high (i.e. in the Southern Ocean) and in areas where [CO₂(aq)] is low such as the subtropical gyres, ϵ_p is lower (see Figure 8). In our dataset the lowest ϵ_p is where the [CO₂(aq)] is the highest (and cell size is larger), see red/pink points in Figure 8a and d.

Suggested new wording: (3) Our data contrast the global observed variability (of high ϵ_p in high [CO₂(aq)] regions such as the Southern Ocean) but are comparable to results from previous work in frontal regions where higher ϵ_p has been observed in lower [CO₂(aq)] subtropical water masses (Bentaleb et al., 1998, Francois et al., 1993).

(1) Page 8, line 21: the sentence ‘A higher growth rate increases the expression of a high ϵ_p on smaller phytoplankton’ is unclear. Please reformulate.

(2) In Rau’s 1996 model – when growth rate is higher, the effect of a variable surface area to volume ratio (or cell size) is expressed more on $\delta^{13}\text{C}_{\text{POC}}$. A higher growth rate increases the expression of a low ϵ_p on larger phytoplankton compared to lower growth rates (Fry and Wainwright, 1991). Wording changed to:

(3) A higher growth rate, such as in spring/summer blooms increases the range in ϵ_p expressed across cell sizes. For instance in fast growing blooms, larger cell sizes may have higher relative $\delta^{13}\text{C}_{\text{POC}}$ and lower ϵ_p than smaller cell sizes, compared to in low growth periods (e.g. Fry and Wainwright, 1991).

(1) Page 8 lines 20 to 27: the whole of the discussion here is highly hypothetical, and only yields a statement that waters north of the SSTC have ‘the potential to elevate growth rates’. Later in the discussion it seems the ‘potential for’ has become a solid fact (e.g. line 14 and lines 19-20 at page 9).. Also it is likely that this frontal area is influenced by N-nutrient rich AAIW and SAMW waters. Have the authors considered this? Page 9, line 20: Why would decreased light limitation lead to higher growth rates? Higher biomass and higher primary production, yes, but why higher growth rates?

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(2) The nutrient rich SAMW (500m) and AAIW (750m) waters are deeper in the water column here, but the SASW originates from the surface waters of the polar frontal zone (ultimately sourced from the UCDW) and the northwards flowing waters which have high N in comparison to the subtropical waters (Tuerena et al., 2015). The SSTC creates an environment where there is the convergence of N-limited subtropical waters and Fe-limited subantarctic waters (Browning et al., 2014). This region therefore has the potential to alleviate nutrient stress. The convergence of water masses at the SSTC can also lead to strong and swift stratification and alleviation of light limitation, which would lead to higher growth rates (Llido et al., 2005). A study of the SSTC south of New Zealand found growth rates more than double the rates within the sub Antarctic and subtropical water masses (Delizo et al., 2007). We suggest that over the broader region, growth rates here will be higher across the SSTC than in the South Atlantic gyre or in the Southern Ocean.

(1) Page 9, Lines 16-20: increase cell size reduces the expression of a high ep as shown by the higher $\delta^{13}\text{C}_{\text{POC}}$ and lower ϵ_{p} ..). It seems to me the data points rather fit the general trend of $\delta^{13}\text{C}$ and ep, and highlighted offset mentioned, appears weak.

(2) The data points fit the trend to a lesser degree than expected for $[\text{CO}_2(\text{aq})]$. Note the red-pink points in 8a have a higher than predicted $[\text{CO}_2(\text{aq})]$ at the given latitude (40-50°S) and a lower than predicted $\delta^{13}\text{C}_{\text{CO}_2}$. It would be intuitive therefore to predict that the $\delta^{13}\text{C}_{\text{POC}}$ produced would be lower than the average trend, but is in fact higher. ϵ_{p} is also lower than predicted with all of the cell radii $>10\mu\text{m}$.

(1) Though this is not the subject of this paper, it is interesting to see this decrease of $\delta^{13}\text{C}$ DIC also in cold North Atlantic waters. What is the explanation for this phenomenon? The lower $\delta^{13}\text{C}$ in the North Atlantic and Southern Ocean is related to circulation and the relative extent of photosynthesis and respiration of nutrients and carbon within surface waters. In the low latitude ocean, nutrients and DIC are much lower in the surface ocean from downwelling and the uptake of nutrients and regeneration at depth, therefore $\delta^{13}\text{C}_{\text{DIC}}$ is higher in the lower latitudes compared to the higher

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latitudes. The concentrations of DIC and nutrients are higher in the Southern Ocean compared the North Atlantic (more upwelling), therefore the $\delta^{13}\text{C}_{\text{POC}}$ is lower relative to the North Atlantic.

(1) Page 10, line 5: “.. predicting increases in ε_{p} and decreases in $\delta^{13}\text{C}_{\text{POC}}$ “. Figure 9 rather shows increasing temperature would result in decreased ε_{p} and increased $\delta^{13}\text{C}_{\text{POC}}$.. On page 12, line 5.

Although an increase in temperature in the figure shows an increase in $\delta^{13}\text{C}_{\text{POC}}$ and a decrease in ε_{p} , this will have very little effect compared to the predicted changes in carbon availability and cell size. To give an example:

A 2°C change in SST from 14 to 16°C would increase $\delta^{13}\text{C}_{\text{POC}}$ from -23.9‰ to -23.3‰. That is the predicted change over ~200yrs (IPCC). Over this time period atmospheric CO₂ would increase from pre-industrial to 500ppm which would decrease $\delta^{13}\text{C}_{\text{POC}}$ to -26‰ (at 14°C) and -25.5‰ (at 16°C). Decreasing cell radius from 10µm to 8µm would decrease $\delta^{13}\text{C}_{\text{POC}}$ further to -27‰ (14°C) and -26.5‰ (16°C).

Therefore a 2°C increase in SST with the expected rise in atmospheric CO₂ would decrease $\delta^{13}\text{C}_{\text{POC}}$ from -23.9‰ to -25.5‰ and would decrease further if the average cell size decreased.

(1) Page 12: the authors conclude to the significance of their findings for future studies of $\delta^{13}\text{C}$ in food web studies. They could add that this also extends to future studies about the fate of plankton organic matter in the deep ocean. In that aspect an useful paper that can be cited is the one by Cavagna et al., BG 10, 2013 “Water column distribution and carbon isotopic signal of cholesterol, brassicasterol and POC in the Atlantic sector of the S.O.”

(2) We thank the reviewer for this useful addition, and we will include this line of thought in the amended manuscript.

Minor things: (1) Page 4 line 6: 50 ml of 100% HgCl₂ were added; I guess you mean

50 μ l ..? (2) Correct, this has been amended (3) and 50 μ L of 100% HgCl₂ added

(1) Page 10, line 11: the wording 'physiological status' is rather vague.. can you specify more ?

Changed to: (3) including the physiological dependencies of phytoplankton on light and nutrients and their ecological diversity

(1) Figures 4 and 5: mark the waters located north and south of the SSTC (2) Now amended: green triangles have been added to the figures to mark the SSTC (see Figure AC1 and AC3).

(1) Figure 7: the full red line is not specified (2) See edited figure (Figure AC4)

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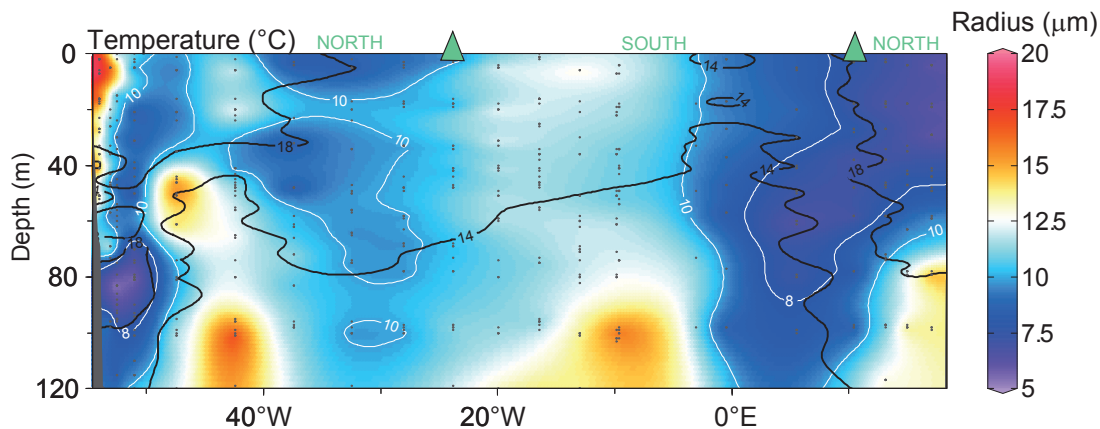


Fig. 1. Figure AC1. Average cell radius across the SSTC (white contours show cell radius of 8 and 10 μm). Black contours show temperatures of 14 and 18 $^{\circ}\text{C}$. Green triangles mark the subtropical front.

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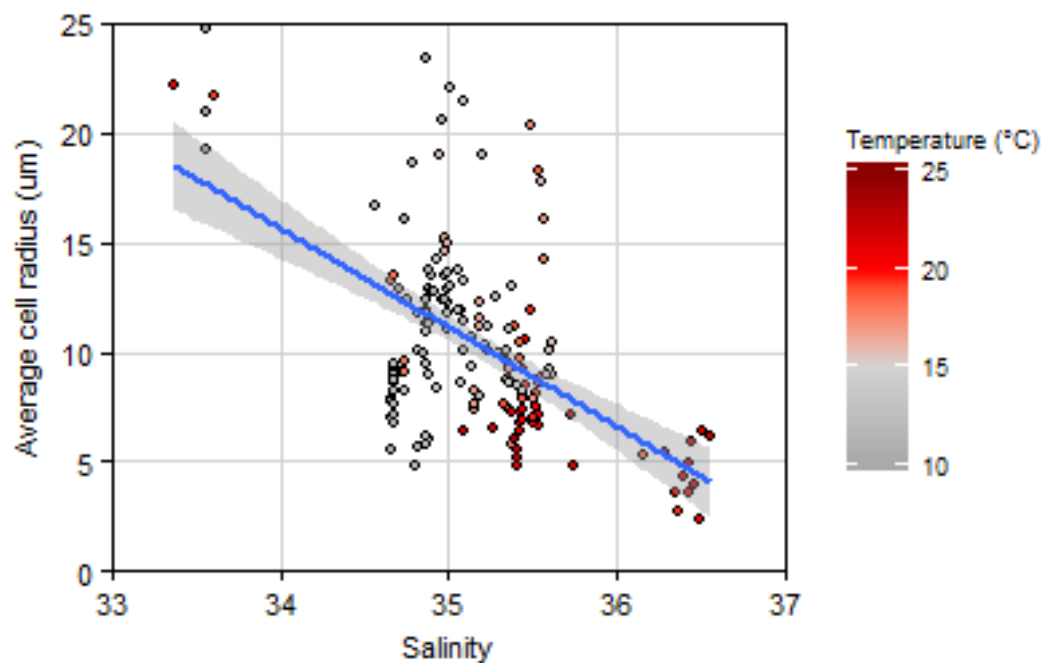


Fig. 2. Figure AC2. Correlation between average cell radius and salinity, with temperature as colour.

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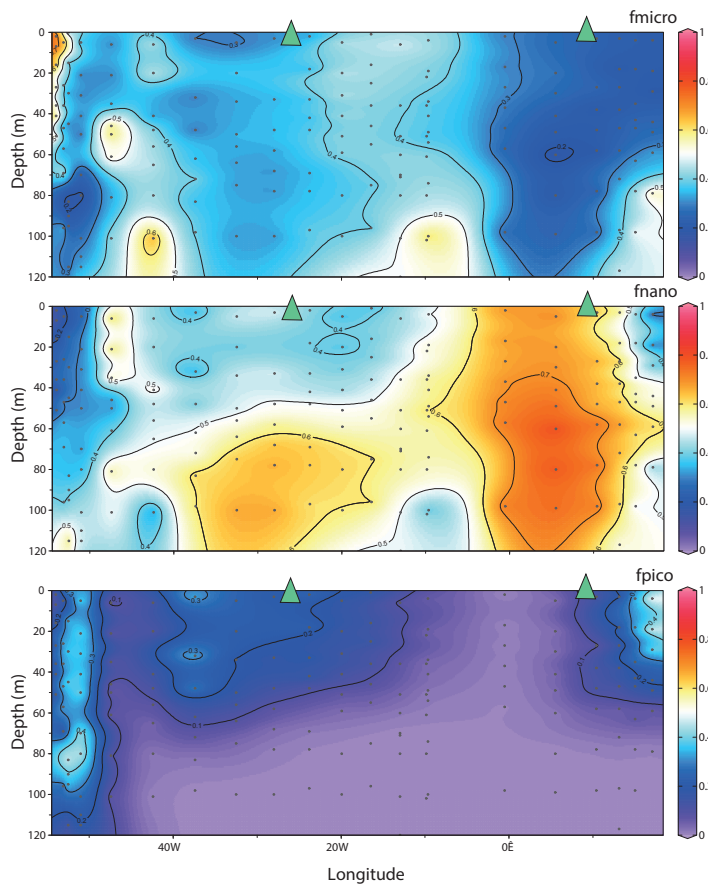


Fig. 3. Figure AC3.

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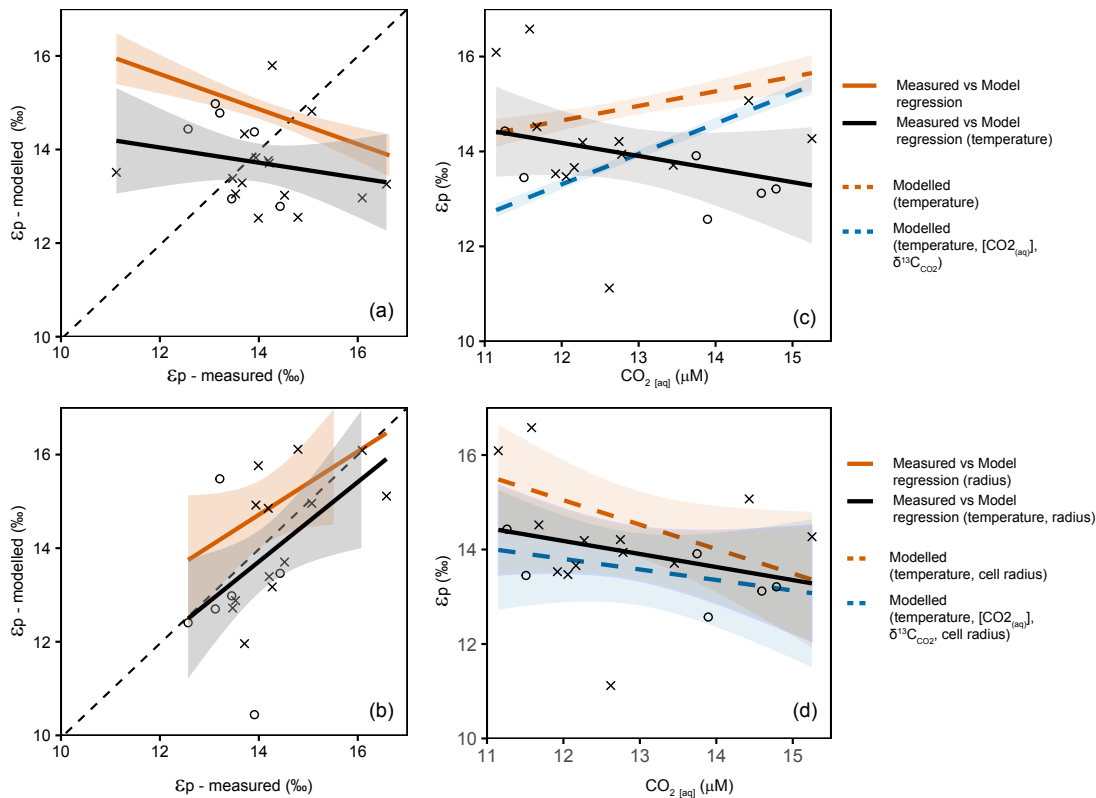


Fig. 4. Figure AC4.

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