

## ***Interactive comment on “Carbon export and sequestration in the southern Benguela upwelling system: lower and upper estimates” by H. N. Waldron et al.***

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### Authors' Comments:

The comments made by both anonymous reviewers have been welcome additions to some of our thinking in respect of this paper. The paper emanated from a presentation at a Deep Ocean Exchange with the Shelf (DOES) workshop held in Cape Town and was an attempt to synthesize the three studies relating to carbon export that have been conducted in the Benguela Upwelling System. Bearing this in mind, it was inevitable that “the estimates had been reported previously... and [don't] add much in terms of new results” (Anon Referee #1). The same referee stated that the “paper is not par-

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ticularly well written. . .” I admit that there were a few minor transgressions (pointed out by the referee) that have been corrected; overall I consider the paper to have been competently written by someone with a clear command of the English language. This, however, is a subjective opinion, as was the referee’s I presume.

We address the more specific points of the two referees below:

Anon reviewer #1:

The referee is quite correct to state that shelf-recycled nitrate (which enhances the South Atlantic Central Water (SACW) nitrate concentration) should not be included in the estimate of annual potential new production. This premise follows the thinking of Roemmich (1989) (Mean transport of mass, heat, salt and nutrients in southern California coastal waters: implications for primary production and nutrient cycling. Deep-Sea Res, 36, 1359-1378,) who distinguished between imported and locally produced nitrate. The paper has been corrected so that annual potential production due to nitrate (C) is the sum of annual potential new production, “Ca” (derived from pathway “A” SACW) and shelf re-cycled nitrate, “Cb” (pathway “B”). The component of annual potential new production that sinks over the shelf (pathway “E” is bi-furcated into pathways “F” and “B.” to reflect a sink and re-cycling respectively. The above changes have been included in a new figure 1 and incorporated in the text.

With respect to “a significant fraction [of potential new production] that is advected offshore but doesn’t sink below the thermocline. Why is this not accounted for?” –

Pathway “D” accounts for the amount of potential production due to nitrate that is advected offshore and was obtained from integrated nitrate values occurring seaward of the shelf edge. It is assumed that once a short-lived bloom finds itself outside the system boundary it will die or be consumed by secondary producers. In either case it will sink (either as dead material or faecal pellets) and enter the “twilight zone” where it is assumed to be exported (and sequestered) carbon. Note that the remaining fraction of potential new production due to nitrate that sinks over the shelf is divided between

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“F” (incorporated in shelf sediments) and “B” (the shelf re-cycling nitrate loop). It is suggested that a proportion of “F” may be transported off-shelf and sequestered in continental slope sediments. This is analogous to the bottom nepheloid layer described by Swart and is shown as a dashed arrow in figure 1. The algebraic relationship between the network of nitrate pathways balances the various sources and sinks.

Lines 18-19. New text introduced to take into account that the open ocean is not always nutrient limited.

P.1174, Line 21-22. The seasonal and sub-seasonal terms to which former and latter refer are now made unequivocally apparent.

P.1174, Line 24. Toggweiler now spelt correctly.

P. 1174, Line 25. Falkowski et al. (1983). “When inferring carbon export the concept of “new production” doesn’t work well for coastal systems.”

Falkowski’s work in the Mid-Atlantic Bight identified two problems in this respect:

1. The pulse-storage nature of phytoplankton growth and re-mineralization negates the steady state assumption.
2. Anthropogenic inputs of nitrogen (eg ammonium) from estuaries constitute “new nitrogen.”

The Waldron et al. paper is addressing pathways of nitrate at the annual scale. The pulse-storage problem (even at the annual scale) is taken into account by the pathway that re-cycles nitrate over the shelf “B.” Our study makes no attempt to directly link event-scale estimates of new production (from say  $^{15}\text{N}$  uptake) with carbon export but provides nitrate transport pathways between offshore and shelf and shelf sediments over the annual time-scale. Riverine and estuarine inputs of nitrogen to the Benguela are negligible since the area is arid with few rivers. Our study related to the region well south of the Orange River but in any event, fresh water inputs could not compete with the 2Sv estimate of SACW transport (Stramma and Peterson, 1989).

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P. 1175, Line 2-3. The authors are indeed saying that despite their limited areal extent the margins account for a large fraction of total productivity.

P. 1175, Line 7. Changed to north east USA.

P.1175. Line 15. Made more apparent that we are referring to Chen et al.

P. 1175. Line 20. Text changed - The southern Benguela upwelling system is an good system to explore this question because the terrestrial POC and nutrient input to the shelf system is insignificant and CO<sub>2</sub> sink will therefore depend mostly on ocean – shelf exchange of the different carbon fractions (Monteiro, 2009; Santana-Casiano et al., 2009).

P. 1175. Line 26-27. Amended to southern Benguela focus.

P. 1176. Line 18. Now reads “upwelling source water nitrate.

P. 1176. Line 20. Shallow system new production discussed earlier. Potential new production represents the potential primary production that can be attributed to available nitrate. It assumes the complete assimilation of all available nitrate and therefore represents the maximum possible new production.

P. 1177. Line 10. Re-formatted.

P. 1177. Line 15-19. This part of the methodology has been more fully described.

P. 1177. Line 20. The years from which these numbers were derived is now given.

P. 1177. Line 23. SACW spelt out fully.

P. 1177. Line 24. The nitrate enhancement due to interaction between SACW and shelf waters now fully described.

P. 1178. Line 3. The percentage of annual potential production due to nitrate that is locally re-cycled on the shelf is now presented arithmetically.

P. 1179. “Gate Hypothesis” now described in amended text.

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P. 1179. Line 2. Amended so that the “this study” is made apparent.

P. 1179. Line 6-7. Amended in revised text.

P. 1179. Line 26-28. Now stated that - The model was a simple Ekman flux calculation forced by equatorward wind stress that persisted for periods longer than the inertial oscillation period (Monteiro, 1996).

P. 1180. Line 8. Explained more fully - The fluxes shown in Figure 3 are million tons carbon per year ( $=\text{TgCy}^{-1}$ ). The blue arrows represent dissolved inorganic carbon (DIC), the magenta arrows represent nepheloid fluxes of particulate organic carbon (POC) and the dotted green arrows represent fluxes of dissolved organic carbon. The results show that there is a substantial import of DIC but, by comparison, lesser exports of POC and DOC. The fluxes calculated from measurements and an Ekman model indicate that 1340 mTons DIC per year are transported from the outer to inner shelf (C2 to B2) but only 117 mTons per year are upwelled (B2 to B1). In order to compare equivalent fluxes between the Waldron and Monteiro approaches:

P. 1180. Line 12-14. Comment addressed above. Detail of the calculations contained in referenced Monteiro publication(s).

P. 1180. Line 23. Amended

P. 1180. Line 24. Amended to read “Swart’s study.”

P. 1181. Line 11-12. R-squared values given.

P. 1181. Line 19. This refers to the decay rate of organic material.

P. 1181. Line 24. It is now made unequivocally apparent that this study refers to Swart’s study.

P. 1183. Line 11. The meaning of potential new production is given above (P. 1176. Line 20). New production *per se* means the new production that actually occurred rather than the maximum possible (potential new production). *Per se* means by (or in)

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itself (intrinsically).

Anon Reviewer #2.

This reviewer echoed some of the points raised by Anon Reviewer #1 and are therefore addressed in the paragraphs above. It is correctly stated that the three methods are very different. In this respect it is rewarding that the estimates can be argued to fall in the same order of magnitude. The confusion relating to the (apparent) inclusion of the northern Benguela has been removed.

The reviewer's comments re terminology have been addressed under Anon Reviewer #1.

The same applies re POC advected offshore. With respect to errors, we have included the 'range' and, in Swart's equations, the r-squared.

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