

***Interactive comment on* “Estimating the storage of anthropogenic carbon in the subtropical Indian Ocean: a comparison of five different approaches” by M. Álvarez et al.**

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We appreciate the positive review and comments. We also appreciate the careful style revision. Following, we clarify some of the referee comments.

It appears that the main goal of this manuscript is to verify the much used DeltaC* method to determine anthropogenic CO₂ in the oceans. It is not just "a comparison exercise between different data-based techniques for estimating CANT ..." (page 733), It is clear that the DeltaC* method is the most widely used and accepted method to estimate CANT in the ocean, so any comparison should discuss it and probably use it as a reference (as we did). Our manuscript is a comparison exercise not a work on the weakness and strengths of the DeltaC * method, this has already been done

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in Matsumoto and Gruber (GBC, 2005). Our main aim is to obtain the best or more sounded estimate of the CANT inventory in the subtropical Indian Oc. Our work of course verifies (or tries to verify) the DeltaC* method, but as much as does with the others, for example, the OCCAM model is disregarded for the deep and bottom waters or the IPSL method for upper waters. The manuscript compares all methods but is not an exercise to completely reject the DeltaC* method. Additionally, this work enables the modelling community to compare their CANT simulations with more than just one number (usually the DeltaC* method) and their associated error.

At different places in the manuscript it is stated that the carbon-based methods (like DELTA C*) are not valid in the surface layer. In Fig. 8 the computed inventory with this method is much smaller than that of other methods and certainly smaller than the 7 mol m⁻² taken to be the value for the surface layer and based on OCCAM and the TTD method. This is a misunderstanding and it will be accordingly corrected in the text. Carbon-based methods are unable to estimate CANT in the upper surface mixed layer because of the photosynthetic activity in this layer and the seasonal variations. However, in the text we use the term surface to refer equally to the mixed layer and to waters between the 0 m and neutral density equal to 26.5. We will clarify this.

However, in Fig. 10 the DELTA C* method is surprisingly the method that fits well within the upper and lower boundaries set by theoretical considerations, while OCCAM and TTD are less good. What does this mean for the general estimation of the inventory? A lower estimate for the surface layer would bring the optimal estimate of the inventory very close to that obtained with the DELTA C* method. Figure 1 refers to samples deeper than 200 meters, with T_{pot} higher than 5°C and CFC-12 ages less than 30 years, in fact, it comprises the upper (from 200 m to 26.5), SAMW and half of the AAIW layers as defined in figure 5, but not the upper mixed layer where carbon-based methods are unable to estimate CANT. The DELTAC* method is comprised between the theoretical range of CANT values expected, this is the reason to support it for the CANT inventory estimation in the SAMW layer. This point has been clarified in section

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8.3. The TTD and OCCAM methods do give CANT estimates for the mixed layer so the surface layer (from 0 m to 26.5) CANT inventory is preferentially estimated using their values, which are practically equal!.

Manuscript longitude: we do agree that the manuscript is rather long but there is no way to avoid this as we wanted to discuss all the points raised in the discussion, specially the disequilibrium and the relation of CANT estimates with tracers.

The figures have been redrawn, improving the axes descriptions.

Minor comments:

The style and typo corrections have been incorporated in the new text. Following are some specific comments:

1. About the TIC accuracy: in the new version of the manuscript this section is shortened and the reader is referred to the appendix. Regarding all the details about the TA, pH and TIC analysis and quality control, it is true that they would better fit in a cruise report but at the time of writing it (at the end of the cruise) we did not have much time to perform all the calculations and checking, and additionally, we did not have the TIC direct analysis, they were sent to R. Wanninkhof. There is a wealth of bibliography about quality control and internal consistency of CO₂ analysis on board, and much effort have been done to compile basin-wide quality CO₂ data (e.g., the GLODAP project). For any CO₂ researcher the information given in our manuscript is worthy, although within an appendix. The CD139 Indian Oc. section is included in a recent intercomparison project, CARINA, papers dealing with the data quality treatment and data corrections for all the biogeochemical variables will be submitted to the Earth System Science Data journal. Regarding our confidence in our own data: all the information given in our manuscript is part of a logical reasoning to find any internal inconsistency within the CO₂ data and check all the possibilities. The initial statement was that our TA and pH data was reliable because they were in agreement with the directly measured TIC. However, we took into account that few coulometric

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TIC measurements were available so we proceed to perform the crossover analysis, first within the NADW core, but as they were nearly inconclusive, we continued with the rest of cruises on the eastern IO. In this way, we were certain that the calculated TIC data needed a correction, which at the beginning we were reluctant to apply. We have reduced section 2, referring the reader to the corresponding appendix.

2. Section 7.1: yes, details about the DeltaCbio and CT280 calculations given in the methods section are repeated here with the aim of being clearer and avoid the reader (mostly for non specialists in estimating CANT using carbon-based methods) to go back to the corresponding section. I think it is better to keep the explanations.

3. TTD method: this method has been clarified, specially the air-sea disequilibrium issue, please read the new section below. Particular changes about the referee answer are highlighted. The previous last paragraph of this section was deleted in this new version. New text: The TTD method used here to estimate CANT concentrations is that described by Waugh et al. (2004, 2006). We assume that CANT is an inert passive tracer (with a well known atmospheric history), and that the transfer of inorganic carbon from the atmosphere to the ocean can be determined by using the empirical relations between surface salinity and alkalinity (e.g. Brewer et al., 1986) and the inorganic carbon chemistry. Thus, with only observations of salinity, temperature and tracer, the oceanic CANT input function for each water sample can be determined. We used CFC-12 data to determine the TTDs of the water samples using the time-dependent saturation described in Tanhua et al. (2008) and we have assumed that the disequilibrium of carbon between the atmosphere and the surface ocean did not change during the last few hundred years. The latter assumption is possibly the single largest single source of error for the CANT TTD calculation; other sources of errors are discussed in Waugh et al. (2006) and Tanhua et al. (2008). For instance, uncertainties in the Delta-gamma ratio propagates to uncertainties in CANT TTD and is dependent on CFC concentrations and Delta-gamma ratio; the CANT TTD estimate is relatively insensitive to errors in the Delta-gamma ratio for CFC-12 levels higher than 0.5-0.6

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pmol kg⁻¹ and to errors in the Delta- ratio for moderate to large mixing (Delta-gamma higher than 0.75). The TTD method is also sensitive to uncertainties on the CFC saturation state at the time of water mass formation; the biasing effect is larger for CFC-12 concentrations larger than about 450 ppt due to the low atmospheric increase rate in recent times (Tanhua et al., 2008).

4. page 746 clarification: we said: This is probably a consequence of the reduced coverage of our section, which is not representative for light waters (situated above 600 dbar along the CD139 section). We comment: Disequilibrium values following Gruber et al (GBC 1996) should be calculated with a basin-wide data base in order to get a representative data set for each density range. Taking just the CD139 data to calculate the disequilibrium for light waters (less than 26.8) yields completely unrealistic results, the maximum number of data for any density bin is only 6 samples. I agree that the phrase needs rewording:

Instead of: Figure 4 presents the three DeltaCTdis set of values (original SAB99 values and those obtained from our data) by density intervals. DeltaCTdis values calculated with our own data for sigma less than 26.8 should be disregarded since they show inconsistency with SAB99 values. This is probably a consequence of the reduced coverage of our section, which is not representative for light waters (situated above 600 dbar along the CD139 section). =>

Now is written: Figure 4 presents the three DeltaCTdis set of values (original SAB99 values and those obtained from our data) by density intervals. DeltaCTdis values calculated with our own data for sigma less than 26.8 should be disregarded due to the reduced density of samples with these characteristics (situated above 600 dbar along the CD139 section).

5. p 747 lines7-8: this part of the text was rewritten: Old text The vertical pCFC-12, pCCI4 and CANT distributions along with some reference neutral density levels are shown in Figs. 5 and 6. In deep layers below $\sigma_{\theta}=27.7$ where no CANT is expected to be

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detected (according to CFC-12 levels, but not to those of CCl₄, see Fig. 5a) and where DeltaC* method is used to calculate DeltaCTdis, CANTSAB99 values are 0+/-3 umol kg⁻¹, within the limit of detection of the method.

New text

The vertical pCFC-12, pCCl₄ and CANT distributions along with some reference neutral density levels are shown in Figures 5 and 6. In deep layers below density=27.7, no CANT is expected according to CFC-12 levels (Fig. 5a), here the DeltaC* method is used to calculate DeltaCTdis, and CANTSAB99 values are practically null, 0 plus minus 3 umol kg⁻¹, which is less than the limit of detection of the method. However, according to CCl₄ levels CANT is expected in this layer. In this sense, CANT IPSL and TrOCA estimates range from 0 to 10 umol kg⁻¹,8230;..

6. p 749 about CANT in the surface layer: As previously explained this is a misunderstanding because it was improperly explained in the text, which has been corrected. New text: The initially calculated CANT values are randomly modified by plus minus 5 umol kg⁻¹. A set of 100 perturbations are done for the five methods, finally a mean and standard deviation for the total and layer CANT inventory is calculated, the standard deviation for each layer is weighted by the layer contribution to the total section area. Inventories are shown in Figure 8 and Table 1. The SAB99 method estimates the lowest total inventory compared with any other method (Fig. 8, Table 1), even with OCCAM which seems to underestimate CANT in deep and bottom layers (Fig. 7). Discrepancies and similarities arise when inventories are studied by layers. Biological processes in the upper mixed layer (comprised within the surface layer here defined) occurring during the cruise prevent the use of carbon-based methods (SAB99, TrOCA and IPSL), for example when AOU is negative. TTD and OCCAM do provide CANT estimates in this layer by circumventing the direct use of biogeochemical variables: TTD relies on CFC ages that are more precise in upper, younger waters; OCCAM accounts for surface circulation and air-sea CO₂ equilibrium, and its upper waters are less affected by uncertainties in model physics and chemistry. Interestingly, the mean

specific inventories for the upper layer from TTD and the OCCAM are similar, around 7 molC m⁻² (Table 1). Within the SAMW layer, all methods, except IPSL, agree within plus minus 2 molC m⁻². Within AAIW, IPSL is again high, TTD and TrOCA agree and OCCAM and SAB99 are lower.

7. p 749 about CANT perturbations: CANT estimates are randomly perturbed in plus minus 5 umol kg⁻¹ in order to get an error value for the total water column inventory.

8. First paragraph of the discussion: We meant to say that all methods have some uncertainties; they do yield better (more reliable) estimates in different conditions, areas of the ocean or water masses.

9. p755 about the surface layer: Corrected text: Upper surface waters, shallower than about 200 dbars, occupy a small fraction of the whole water column. Carbon-based methods are unable to properly correct for biological activity and therefore unable to estimate CANT (Fig. 8, Table 1), while TTD is based on tracer distributions independent of biological activity, but affected by seasonality; and OCCAM assumes CO₂ air-sea equilibration, which is not always true. Despite the uncertainties, we consider TTD and OCCAM more reliable in the surface layer, and therefore the inventory here would be 7 plus minus 0.2 molC m⁻².

10. Figure 3. We have now taken every 4th data, this is explained in the figure caption.

11. Accuracies have been added for the oxygen and nutrient analysis within the data section.

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