

## ***Replay to anonymous Referee #2***

### ***GENERAL COMMENT***

*This is a well-written piece of work that presents a meticulous geochemical assessment of the net community production of dissolved oxygen in a cyclonic mesoscale eddy and compares it with in vitro measurements. The manuscript concludes that the irreconcilable differences between the in situ (geochemical method) and in vitro (oxygen light-dark bottle method) approaches usually observed at large spatial (103 km) and temporal (103 days) scales are also applicable to mesoscale structures (102 km and 102 days).*

*I have only one major concern with the manuscript: an individual assessment of the uncertainty of the estimation of every physical process involved in the computation of in situ oxygen changes has not been properly preformed. My feeling is that a correct evaluation of all those uncertainties would lead to an error of the estimates large enough to produce in situ NCP rates that are not significantly different from the in vitro estimate.*

We have expanded the discussion and estimation of various uncertainties in Section 3.4, including initial and final profiles, O<sub>2</sub> calibration, gas transfer velocity and mixed layer depth. These uncertainties are now included in Table 2 (appended below). In particular, we recently became aware of the gas transfer velocity formula of Ho et al. (2006, Geophysical Research Letters 33, L16611), and now use this instead of Wanninkhof (1992). The net accumulated uncertainty is not large enough to render the difference between the in situ and in vitro estimates insignificant.

#### *“3.4. Oxygen model sensitivity tests*

The oxygen model infers the NCP from the temporal change in oxygen concentration, the air-sea flux and the net advective-diffusive input. Here we examine the uncertainty in each of these estimates. In addition to providing our error estimates, this shows where improvement is most needed for making NCP estimates with this model.

The impact of the uncertainty in the initial and final mean temperature and oxygen profiles was estimated by trying different station combinations to compute the mean profiles (e.g. station 18 versus station 20 as the initial profile on 21 June), re-running both the temperature and oxygen models with the new profiles for Case 2, and computing the standard deviation of the resulting NCP estimates. The estimated 0-100 m NCP uncertainties are  $\pm 4.4$ ,  $3.3$  and  $3.2$  mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> for periods 1, 2 and 3, respectively. Thus sensitivity to our ability to accurately estimate the initial and final conditions (based on the variability of the observed profiles) is significant. The sensitivity of the air-sea flux and the advection+diffusion estimates to the mean profiles was smaller, averaging  $\pm 1$  mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>.

The air-sea flux estimate relies on several factors, the first being the O<sub>2</sub> data calibration. The air-sea diffusive flux is driven by the supersaturation, and as this is only a few percent, a small calibration error can have a large impact. According to the BATS Methods handbook (Knap et al. 1993), field precision of bottle samples using the Winkler method versus CTD profiles can vary from 0.005 to 0.03 ml L<sup>-1</sup>. We will consider here a possible systematic calibration error of 1 mmol O<sub>2</sub> m<sup>-3</sup> added to (or subtracted from) all profiles. This causes a mean uncertainty in the air-sea flux of  $\pm 3.2$  mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>, which propagates directly into the NCP estimates, though the impact on the advection+diffusion term is negligible.

Another source of uncertainty in the air-sea flux is the equation used for the gas transfer velocity. To test sensitivity, the gas transfer velocity of Ho et al. (2006) was increased and decreased by 30% in Case 2, spanning the formulas of Wanninkhof (1992) and Nightingale et al. (2000). The Wanninkhof and McGillis (1999) formula is not considered as it includes the bubble flux within it, though for a case unlike here in which the bubble flux and diffusive flux were in the same direction. The 30% uncertainty changes the average air-sea flux by  $\pm 3.5$  mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>, which again

propagates directly into the NCP uncertainty, with negligible impact on the advection+diffusion term.

Sensitivity to the bubble flux formula was examined for all Cases in all 3 periods. The Stanley et al. formula yielded a 43-day mean downward bubble flux of  $9.1 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  while the Woolf and Thorpe formula yielded  $7.1 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ . These are both close to the summer estimate at HOT of approximately  $8 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  (Hamme & Emerson 2006), and counterbalance more than half of the upward air-sea diffusive flux. This  $2.0 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  decrease in the bubble flux causes only a  $1.1 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  increase in the net air-sea flux and the NCP, because the model requires oxygen concentrations to match the observed values.

Sensitivity to our linear MLD time series was estimated as follows. As a perturbation run, the MLD was fixed for the first 24 hours to the initial observed MLD, and then it was changed abruptly to the final observed MLD for the remainder of the period. For the opposing perturbation, the MLD was fixed to the initial MLD until switching to the final MLD in the final 24 hours. While this perturbation method is crude, it likely encompasses one standard deviation of the variability. Note that the original profiles did not show great diurnal variability (Figure 1). This yielded NCP error estimates of  $\pm 0.3$ ,  $3.5$  and  $1.1 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  for periods 1, 2 and 3 respectively, greatest for Period 2 because of its long duration and the large difference between the initial and final observed MLD. The uncertainty in the advection+diffusion term was on average  $\pm 0.4 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ .

Sensitivity to the uncertainty in the diffusivity and vertical velocities is illustrated in Table 2. While the uncertainty of any one of the vertical diffusion, vertical advection and horizontal advection terms is quite large, these estimates are not independent. Conservation of volume constrains that high horizontal advection can only exist with high vertical advection, and the observed temperature evolution constrains that vertical advection can only be high if vertical diffusion is low. These relationships cause their impacts on the oxygen budget to largely cancel. Consequently the variance in the net advection + diffusion term is much smaller than the variance in any individual term. The uncertainty in  $\kappa$  versus  $w$  causes an uncertainty in the net advection + diffusion term of  $\pm 2.3$ ,  $0.7$  and  $4.0 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  for periods 1, 2 and 3 respectively, with similar impact on NCP estimates, though only an average uncertainty of  $\pm 0.3 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  on the air-sea fluxes.

Horizontal advection of T and  $\text{O}_2$  gradients (e.g.  $u\partial\text{O}_2/\partial x$ ) was neglected in the models, which is justifiable as follows. Eight of the nine runs in Table 2 have no horizontal divergence below the mixed-layer (i.e.  $w_{grad} = 0$ ). The remaining one has very weak divergence viz. if the downwelling occurs over a 20 km radius, the outward horizontal velocity below the mixed layer at radius  $r = 20$  km is  $-w_{grad}\pi r^2/2\pi r = 4 \times 10^{-6} \text{ m s}^{-1}$ . More significant is the horizontal convergence that occurs in the mixed layer that feeds the downwelling. In the most extreme case (Period 1 Case 3) the inward horizontal velocity at 20 km radius is  $w_{max}\pi r^2/2\pi r z_{mld} = 9.5 \times 10^{-3} \text{ m s}^{-1}$ . For the temperature model, any heat gain from  $u\partial T/\partial x$  in the mixed layer is already included in the non-solar surface heat flux, which is computed as the difference between the observed heat gain and the other fluxes. For oxygen, from CTD data and underway surface measurements  $\partial\text{O}_2/\partial x$  in the mixed layer is estimated as  $5 \times 10^{-5} \text{ mmol O}_2 \text{ m}^{-4}$  (i.e. a concentration difference of  $1 \text{ mmol O}_2 \text{ m}^{-3}$  over 20 km), such that  $u\partial\text{O}_2/\partial x$  vertically integrated over the mixed layer depth ( $0.5w_{max}r \partial\text{O}_2/\partial x$ ) is  $0.28 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ . This is negligible compared to the estimates and uncertainties in Table 2.

Another simplification in the temperature model was the use of a constant solar heat flux. Variations in the solar flux indicated by the shipboard and NCEP data were estimated, but were found to be a negligible source of error relative to the other sources.

The error estimates given in Table 2 are the square root of the sum of the squares of the uncertainties related to the initial and final profiles,  $\text{O}_2$  calibration, gas transfer velocity, bubble flux, mixed layer depth and the role of advection versus diffusion. The other error sources mentioned above were estimated as negligible in comparison. Although the error estimates are considerable, the model-derived in situ NCP estimates are statistically significantly greater than the in vitro NCP estimates.”

*On another matter, given that the authors have  $w$  and  $k$  values provided by the 3D model of Ledwell et al. (2008): i) why they do not include the oxygen model into the more realistic 3D model instead of creating a new 1D model?; ii) what would be the resulting in situ NCP if the  $w$  and  $k$  values directly provided by the 3D model were introduced rather than tuned in the 1D model?*

i) Yes, including an oxygen model in a more realistic 3D model would be interesting for future work. But the oxygen model that we use here is an inverse model, which requires many iterations for optimization, and depends on a reliable estimate of  $w$  and  $k$ , and thus iterative optimization of a physical model as well. This is much more difficult and computationally and labour intensive to do in 3D than 1D, with no guarantee of “more realistic” results. Moreover, the Lagrangian time-series data that we are examining is essentially 1D (i.e. that was the goal of the field experiment), so introducing 3D would be an unnecessary complexity. Note that our 1D model does include horizontal advection, and so should not be very different from a radially-symmetric 3D model.

ii) If we used the exact  $w$  and  $k$  values from the present 3-D model in the 1-D model, we could not accurately (enough) reproduce the observed T evolution. This indicates that the 3-D model  $w$  and  $k$  values do not agree well enough with the field data, and that it would be better to use  $w$  and  $k$  values tuned to the field data in the 1-D model itself.

#### **SPECIFIC COMMENTS**

*Section 2.1. The authors state that samples were collected for the determination of dissolved inorganic nitrogen, but only nitrate is presented. What about the distributions of ammonium and nitrite? The presence of significant concentrations of both reduced nitrogen forms, which is not unusual in isolated water parcels, could justify an extra oxygen consumption in the bottles due to the oxidation of ammonium and nitrite to nitrate by the marine nitrifiers enclosed in the oxygen flasks. In the same section, could you please describe in more detail the deck incubator, oxygen bottle volumes, number of replicates, conditioning of the incubated water (was it prefiltered?), etc..*

Unfortunately, measurements for ammonium and nitrite were made only at a few stations during these cruises so the analysis of spatial or temporal variability of nitrite and ammonium is not possible. However, in order for nitrifier bacteria to explain the extra consumption in oxygen observed in the bottles, a stimulation of these organisms activity when enclosed in flasks will be required. The stimulation of the heterotrophic versus autotrophic activity is one of the hypotheses that this manuscript proposes to explain the discrepancy between both techniques. The sentence has been modified in the methods section to clarify that dissolved inorganic nutrients refers to nitrate plus nitrite (DNN):

“Samples were collected on each CTD cast for the determination of nitrate + nitrite (DNN), oxygen and chlorophyll-a concentrations.”

A detailed description of the methods used to measure net community production based on in vitro changes in oxygen concentration has been already reported in Mouriño-Carballido and McGillicuddy (2006). The readers are pointed to this reference in the methods section, and we do not consider it necessary to duplicate the information here.

*Section 2.2.1. the temperature model is incomplete. Why you have not considered the heat loss by evaporation?*

The heat loss by evaporation is already included in the non-solar heat flux term, which includes latent, sensible and longwave radiation fluxes, plus any horizontal advective heat flux due to horizontal temperature gradients in the mixed layer. Thus the temperature model is complete.

Section 3.1. I cannot see in Figure 3 the value of  $1.6 \pm 0.1 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$  reported in the text.

This data has been corrected to:

“Maximum values of NCP were found at the surface ( $0.35 \pm 0.05 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$ ). Dramatic changes between late June and early August were observed in the upper 40 dbar, where a decrease to negative values ( $-0.5 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$ ) was observed in NCP rates.”

*In the same section, if no changes are observed in primary production measured with the  $^{14}\text{C}$  incorporation technique from the beginning to the end of the sampling period it would mean that the observed  $\text{O}_2$  changes can only be justified by a temporal evolution of the  $\text{O}_2/\text{C}$  stoichiometric ratio, which can vary from 1.0 to 1.6. In that case, what is the value of estimating NCP from in situ or in vitro oxygen measurements? Please discuss this crucial point in more detail.*

The Reviewer is mistaken that if  $^{14}\text{C}$  PP is constant “ $\text{O}_2$  changes can only be justified by a temporal evolution of the  $\text{O}_2/\text{C}$  stoichiometric ratio”. Comparison of in vitro oxygen-derived net community production (NCP) and primary production rates estimated from the  $^{14}\text{C}$  incorporation technique (PP) is not straightforward. NCP accounts for the difference between gross primary production (GPP) and total respiration (R). The excess of photosynthesis over respiration ( $\text{NCP} > 0$ ), called net autotrophy, implies a net synthesis of organic carbon that can be exported to the deep ocean or to higher trophic levels. A negative balance ( $\text{NCP} < 0$ ), named net heterotrophy, represents a net consumption of organic carbon. Under the Redfield approximation, in which autotrophic and heterotrophic processes use the same stoichiometric equation, NCP and new production (the fraction of primary production fuelled by externally supplied nitrogen) should be equivalent. Regarding  $^{14}\text{C}$  uptake, compilation of measurements carried out during the Joint Global Ocean Flux Study (JGOFS) indicated that  $^{14}\text{C}$  uptake measures net primary production (gross primary production minus autotrophic respiration) in dawn-dusk incubations (Marra, 2002). Studies comparing in vitro  $\text{O}_2$  fluxes with  $^{14}\text{C}$  production rates during JGOFS cruises determined that  $^{14}\text{C}$  productivities incubated during 24 hours were about 45% of gross carbon production rates calculated from gross  $\text{O}_2$  production (Bender et al., 1999; Laws et al., 2000). In contrast to the 24-h incubations used in the Bender and Laws studies,  $^{14}\text{C}$  incubations carried out during the EDDIES cruises are dawn-to-dusk. Therefore EDDIES  $^{14}\text{C}$  rates are likely to be closer to gross primary production than the factor of two indicated by Bender and Laws. However, it is not possible to quantify this relationship in these cruises because  $^{14}\text{C}$  and  $^{18}\text{O}$  methods have not been compared in this region. Therefore, variability in the  $\text{O}_2/\text{C}$  ratio is not necessary to explain changes in NCP without changes in PP, as an increase in the heterotrophic respiration term (bacteria + microzooplankton) could also explain this observation. In agreement with these arguments respiration rates measured on 5 Aug ( $58 \pm 8 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) were more than double the rates estimated on 22 June ( $22 \pm 7 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ ).

In addition, just because the  $^{14}\text{C}$  PP rate is constant in time doesn't mean new production is not occurring. For instance, Figure 2c Period 3 suggests new production is occurring near 100 m, likely due to diffusion (as advection is downward). This new production can occur here all summer long without any temporal change observed in  $^{14}\text{C}$  PP. Same with nitrogen fixation in the mixed layer.

The interest in estimating NCP is now discussed in the first paragraph of the Introduction:

“Net community production (NCP), the difference between gross primary production (GPP) and total respiration (R), constitutes a crucial term for comprehending the role of the marine biota as source or sink for  $\text{CO}_2$ . An excess of photosynthesis over respiration ( $\text{NCP} > 0$ ), called net

autotrophy, implies a net synthesis of organic carbon that can be exported to the deep ocean or to higher trophic levels. A negative balance ( $NCP < 0$ ), called net heterotrophy, indicates a net consumption of imported or in situ organic carbon. Under the Redfield approximation, in which autotrophic and heterotrophic processes use the same stoichiometric equation, NCP and new production (the fraction of primary production fuelled by externally supplied nitrogen) should be equivalent (Eppley & Peterson 1979). Thus NCP is also of interest as an indicator of either nitrate uptake, nitrogen fixation, atmospheric deposition or a difference between autotrophic and heterotrophic stoichiometries, i.e. non-Redfield behavior.”

Section 3.1 now discusses the differences between  $^{14}\text{C}$  uptake and NCP:

“Primary production rates estimated from the  $^{14}\text{C}$  incorporation technique ( $^{14}\text{C}$  PP) did not change significantly from the beginning to the end of the sampling period (Ewart et al. 2008). No important changes in bacterial biomass or bacterial production were observed between cruises (Ewart et al. 2008). Particle export fluxes calculated from  $^{234}\text{Th}$  method showed a decrease in the magnitude of carbon fluxes (Buesseler et al. 2008).

Note that comparison of the in vitro NCP and the  $^{14}\text{C}$  PP measurements is not straightforward. NCP estimated gross primary production minus community respiration over 24 hours, whereas dawn-to-dusk  $^{14}\text{C}$  PP measures gross primary production minus autotrophic respiration (Marra, 2002). Since the two types of measurements available in this study are few and they were not made at the same times or locations, a precise intercomparison of both techniques can not be resolved with this dataset.”

*Section 3.2. It does not make any sense to introduce the last sentence of this section.*

Ok, the last sentence of Section 3.2 has been cut.

Table 2. Model results.  $\kappa_{deep}$  is the vertical diffusion coefficient,  $w_{max}$  and  $w_{grad}$  are vertical velocity parameters, NCP is net community production of oxygen, STD is standard deviation.  $d[O_2]/dt$ , NCP and all subsequent oxygen fluxes are in  $mmol O_2 m^{-2} d^{-1}$ . The air-sea  $O_2$  flux is defined negative upward while the diffusive and advective  $O_2$  fluxes at 100 m are defined negative downward, i.e. negative indicates a loss to the 0-100 m  $O_2$  integral. STD is computed as the square root of the sum of the error variances from various sources (see Section 3.4).

Variable (units)	21 June – 1 July				1 July – 27 July				27 July – 3 August			
	Case 1	Case 2	Case 3	Mean ( $\pm$ STD)	Case 1	Case 2	Case 3	Mean ( $\pm$ STD)	Case 1	Case 2	Case 3	Mean ( $\pm$ STD)
$\kappa_{deep}$ ( $m^2 s^{-1}$ )	$3.1 \times 10^{-4}$	$4.0 \times 10^{-5}$	$1.0 \times 10^{-5}$		$2.7 \times 10^{-4}$	$4.8 \times 10^{-5}$	$1.0 \times 10^{-5}$		$3.2 \times 10^{-4}$	$1.21 \times 10^{-4}$	$1.0 \times 10^{-5}$	
$w_{max}$ ( $m day^{-1}$ )	0	-0.53	-0.57		0	-0.46	-0.51		0	-0.38	-0.54	
$w_{grad}$ ( $day^{-1}$ )	0	0	0		0	$-3.5 \times 10^{-5}$	0		0	0	0	
$d[O_2]/dt$ , 0 - 100 m	0.6	0.6	0.6		-17.1	-17.1	-17.1		-14.9	-14.9	-14.9	
NCP, 0 – 100 m	19.3	16.0	15.6	17 ( $\pm$ 6)	-3.1	-3.3	-4.9	-4 ( $\pm$ 7)	13.9	8.4	3.6	9 ( $\pm$ 8)
Air – sea $O_2$ flux	-7.6	-8.7	-9.1	-8 ( $\pm$ 4)	-3.4	-4.3	-3.1	-4 ( $\pm$ 7)	-9.5	-9.2	-9.0	-9 ( $\pm$ 6)
Diffusive flux at 100 m	-11.1	-1.4	-0.4		-10.6	-1.9	-0.4		-19.4	-7.7	-0.7	
Advective flux at 100 m	0	-118.5	-127.4		0	-101.5	-113.4		0	-84.9	-120.3	
Horizontal advection	0	113.1	121.7		0	94.0	104.8		0	78.4	111.4	
Advection + diffusion	-11.1	-6.8	-6.0	-8 ( $\pm$ 2)	-10.6	-9.5	-9.0	-10 ( $\pm$ 2)	-19.4	-14.1	-9.6	-14 ( $\pm$ 5)