Response to review comments on "Global carbon budgets estimated from atmospheric O_2/N_2 and CO_2 observations in the western Pacific region over a 15-year period"

Anonymous Referee #1:

We would like to thank the anonymous referee #1 for his/her helpful comments and suggestions on our paper. We have revised the manuscript as is described in the following. The referee's comments are in *blue italics*, and the modifications are shown in red.

First, we would like to mention about the GCP-reported data used in this paper. In the original manuscript, we used fossil fuel emissions, atmospheric accumulation, and global sink estimates taken from Global Carbon Budget 2017 reported by GCP (Le Quéré, et al., 2018). However, the updated data of Global Carbon Budget 2018 (Le Quéré, et al., 2018) is now available. So, we have used the updated GCP data for recalculating the global carbon budgets in the revised manuscript. Since the fossil fuel-derived CO_2 emission rates have been slightly downwardly revised, the ocean and land sinks based on the APO data have been slightly decreased. But the changes are at most 0.1 PgC yr^{-1}. Consequently, this change has affected very little the conclusion of the original manuscript.

Reply to minor comments:

1) The uncertainties of F and Z_eff should be presented explicitly somewhere in themain text and/or Tables. Did the authors assume the uncertainty of 100% for Z_eff following Keeling and Manning (2014)? Also, for those readers not familiar with O2/N2 studies, it would be better to present the representative values of alpha_F for the period 1998-2016 or the respective values for the periods in Table 2.

In response to the suggestions about the uncertainties from both Referee #1 and #2, to clarify how we calculated the uncertainties associated with the sink estimations, we have added the following paragraph after the first paragraph in section 3.2.:" The uncertainties in the parameters used for the carbon budget calculation (Eqs. (6) and (7)), which are also listed in Table 2, are briefly discussed here. Note that in this study the estimated uncertainties are ±1σ. Since the ocean outgassing effect is rather speculative, we assumed that the values of Z_{eff} for the individual periods had ±100% uncertainties in accordance with previous studies (e.g. Manning and Keeling, 2006; Tohjima et al., 2008). We adopted uncertainties of ±5% for the fossil fuel-derived CO_2 emission rate and ±0.2 PgC yr^{-1} for the atmospheric CO_2 increasing rate from Le Quéré, et al. (2018). As for the uncertainties of the observed APO changing rates, we adopted the standard deviations among the sites shown in Fig. 7 (±0.37 per meg yr^{-1} for longer than 10 years and ±0.54 per meg yr^{-1} for 5 years). The estimated uncertainty of the O_2/N_2 scale stability (±0.45 per meg yr^{-1}) discussed in Section 2. 3, the uncertainty of the O_2/N_2 span sensitivity (±3%), and the uncertainty in the global averaged APO associated with the limited atmospheric sampling (±0.2 PgC yr^{-1}) discussed in Nevison et al. (2008) were also included in the calculation of the uncertainties in ΔAPO. The uncertainties of α_B and α_F were ±0.10 (Keeling and Manning, 2014) and ±0.04 (Tohjma et al., 2008), respectively. Finally, these uncertainties were propagated to the ocean and land sink uncertainties in accordance with Eqs. (6) and (7)."

Additionally, we have added a column for the values of α_F in Table 2 and a description of the uncertainties in the footnote. Following these changes, Table 2 has been modified as follows:

Table 2. Comparison of global carbon budgets based on APO with those from GCP[a,b]

	Atm.	Fossil	Sink of this study	Sink of GCP[d]

Period	ΔAPO [c]	CO_2 [d]	fuel [d]	α_F [e]	$Z_{eff}/1.1$ [f]	Ocean	Land	Ocean	Land	Imb.
1998-2016	-10.3(0.91)	4.45	8.28	1.38	0.52	2.57(0.71)	1.26(0.89)	2.24	1.46	0.13
2000-2016	-10.3(0.91)	4.45	8.48	1.38	0.54	2.55(0.73)	1.48(0.91)	2.27	1.48	0.29
2003-2016	-9.9(0.91)	4.58	8.83	1.38	0.52	2.35(0.73)	1.90(0.93)	2.34	1.55	0.36
2000-2004	-8.8(0.94)	3.93	7.11	1.40	0.59	2.23(0.76)	0.94(0.90)	2.01	1.30	−0.14
2004-2008	-9.2(0.96)	4.08	8.21	1.38	0.33	1.97(0.62)	2.17(0.82)	2.18	1.74	0.22
2008-2012	-10.4(0.98)	4.19	9.05	1.37	0.54	2.54(0.77)	2.31(0.97)	2.32	1.85	0.68
2012-2016	-11.6(1.06)	5.36	9.65	1.37	0.71	3.05(0.90)	1.25(1.09)	2.55	1.26	0.49

[a]Figures are given in units of per meg yr^{-1} for ΔAPO, mol mol^{-1} for α_F, and PgC yr^{-1} for the others.
[b]Figures in parentheses represent the uncertainties.
[c]ΔAPO is based on the data from HAT, COI, and cargo ships (40°S-30°N). The uncertainty in parentheses includes the uncertainty associated with the observations, stability in the O_2/N_2 scale, uncertainty derived from limited sampling, and uncertainty in the O_2/N_2 span sensitivity (see text).
[d]These figures are computed from the dataset summarized by the Global Carbon Project (GCP). The uncertainties are ±0.2 PgC yr^{-1} for the atmospheric CO_2 and ±5% for the fossil fuel emissions, ±0.5 PgC yr^{-1} for the ocean sinks, and ±0.9PgC yr^{-1} for the land sinks (Le Quéré, et al., 2018).
[e]The uncertainties for α_F are ±0.04 mol mol^{-1} (Tohjima et al., 2008).
[f]The values of Z_{eff} include both global ocean warming and anthropogenic nitrogen deposition effects, and the uncertainties are assumed to be ±100% (see text).

2) The discussion on the evaluation of the needed interval to suppress the temporal variability in Z_eff is useful in deriving reasonable interannual variations in CO2 sinks from O2/N2 observations. The needed interval was estimated to be 5 years in the paper, and the authors used the ocean heat storage of 0-2000 m layer to estimate Z_eff based on the gas flux / heat flux ratio reported by Keeling and Garcia (2002). However, I think the circulation time of ocean deep layer water is much longer than 5 years. Please explain why the authors have considered the use of heat storage of 0-2000 m to be more reasonable than that of 0-700 m. I suppose there is an implicit assumption in the analysis that the ocean circulation and oxygen concentration are in steady-state from the surface to the deep layer. However, temporal variations found in the 5-years average Zeff in Table2 suggest that the ocean is not in steady-state.

There are several evidences of an increase in the ocean heat content, suggesting that the present ocean is not in steady-state. The changes in both the heat and O_2 contents of the ocean depend on net air-sea exchanges of the heat and O_2. Considering the similarity between heat and gas regarding the air-sea exchange, we can assume that the air-sea O_2 flux is proportional to the air-sea heat flux (O_2 flux/heat flux = constant). Under this assumption, we can evaluate the O_2 outgassing flux if we know the total increase in the ocean heat content. In previous studies, ocean heat content data for the 0-700 m layer were used to evaluate the O_2 outgassing fluxes. However, Levitus et al. (2012) revealed that a much deeper layer significantly contributed to the ocean heat storage: about one third of the heat storage of the 0-2000 m layer is stored in the 700-2000 m layer. Therefore, we used the data for the 0-2000 m layer in this study following the study of Keeling and Manning (2014). These explanations are given in the fourth paragraph of Section 2.5.
In addition to the gradual ocean warming, there are large inter-annual variations in the air-sea heat exchange, which are attributed to an imbalance of the large seasonality in the air-sea heat fluxes. These inter-annual variations in the air-sea heat fluxes are considered to cause rather large inter-annual variations in the air-sea gas exchanges. In this study, we conclude that the 5-year average would to some extent, but not completely, suppress such interannual variability. These explanations are also given in the fourth paragraph of Introduction.

3) I think it may be helpful for the reader to note the differences in land and ocean CO2 uptakes expected from the 3% difference in the span sensitivity between NIES and SIO. Has the conclusion about the comparison of the CO2 uptake reported by the present study with those by GCP changed significantly due to the difference in the span sensitivity?

A 3% higher span sensitivity, which corresponds to the SIO oxygen span sensitivity, results in an approx. 0.3 PgC yr^{-1} increase and decrease in the ocean and land sinks, respectively. These changes, although not negligible, have not changed significantly the conclusion about the comparison of the CO_2 sinks between this study and those of GCP. To clearly state the influence of the difference in the span sensitivity, we have added the following sentences after the last sentence of the second paragraph (the third paragraph in the revised manuscript) in section 3.2.: "A 3% higher span sensitivity of the O_2/N_2 measurements, which corresponds to the difference in the span sensitivity between SIO and NIES (section 3.1), would result in an increase and decrease of 0.27 PgC yr^{-1} in the ocean and land sinks, respectively, for the three long periods. Although these changes would enlarge the differences in sinks between GCP and this study, the differences are still not significant given the uncertainties of both this study and GCP."

4) The authors have compared land and ocean CO2 sinks estimated in the present study with those obtained by GCP, with and without the imbalance sinks added. It seems to me that the authors conclude that the differences between the present study and GCP are reduced, both for land and ocean CO2 sinks, by adding the "total" imbalance to the respective sinks. However, I actually think we can only add the imbalance to the land and ocean CO2 sinks based on an appropriate differential distribution. I understand it would be difficult to suggest the best distribution due to uncertainties of the estimated CO2 sinks, but I would like to hear the authors' thoughts on this.

We cannot draw any certain conclusion about how to partition the budget imbalance between ocean and land sinks because of the large uncertainties associated with the sink estimation of this study, as Referee #1 also pointed out. Nevertheless, the differences in the sinks between the estimates of this study and those of GCP correspond to the best estimation of the partioning of the budget imbalance. Since the budget imbalances seem to increase after 2007 in the pentad averages, we have added a discussion about the partitioning of the imbalances in the revised manuscript. Consequently, we have added one paragraph after the fourth paragraph in section 3.3. to read as: "Shown as discrepancies between the pentad sinks of GCP with and without budget imbalances (Fig. 8), the magnitude of the budget imbalances seems to increase after 2007. For the pentad sinks centered on 2007, 2008 and 2009, the ocean and land sinks of this study agree with those of GCP without and with the budget imbalances, respectively. For the pentad sinks between 2010 and 2014, both the ocean and land sinks of this study are plotted between those of GCP with and without the budget imbalances. Although we cannot show any definitive partitioning of the budget imbalance between ocean and land sinks because of a rather large uncertainty associated with the sink estimations, the above results seem to suggest that the budget imbalances are allocated to land sinks for the former period and to both sinks for the latter period."

5) P3, line 32: A literal error ": : :heat content,." should be corrected.

The literal errors have been corrected.

6) P7, line 19: I think the unit of Z_eff is not TgC yr-1 but PgCyr-1 in this context.

The unit of Z_{eff} has been corrected to "PgC yr^{-1}".

7) References: Please consolidate the format of references. For example, some journal titles are written in Italic and the others are not.

We have consolidated the format of references.

8) Caption in Fig.7: The phrase "changing ratio" should be changed to "changing rate".

"changing ratio" has been changed to "changing rate".