Response to the referee #3's comments on "Importance of El Niño reproducibility for reconstructing historical CO2 flux variations in the equatorial Pacific" by Watanabe et al.

Thank you very much for invaluable comments and suggestions on our original manuscript. We would like to answer the questions given by the referee and to describe how we have revised our manuscript point by point. In addition, following the comment we received personally from the National Oceanographic Centre, UK. (The supplement of the reply to referee #1 includes their comments and our replies), we have combined Section 3.2 and 3.3 in the original manuscript and reorganized. We think the revised manuscript is now more readable. We hope that the revised manuscript meets your approval and will be more suitable for publication in the journal.

Reply to General comments:

(Referee #3) "This study is an important contribution for understanding ENSO and carbon fluxes variations in the equatorial Pacific. The authors have investigated the processes in regulating the relationship between ENSO and carbon fluxes in assimilations with nudging ocean temperature and salinity based on two MIROC models, i.e., OLD MIROC-ESM and NEW MIROC-ES2L. They demonstrated that the ability of model in producing correct amplitude of ENSO is crucial for reproduction of the air-sea CO2 flux variations in coherence with ENSO. Both the storyline and the writing are clear. However, there are still some unclear aspects listed as below, I would expect the authors further clarify them and improve the manuscript.

Thank you very much for your comments. We have reviewed the entire manuscript and revised it in accordance with the comments.

1. It is exciting to see the NEW model shows promising results of the anticorrelation between ENSO and air-sea CO2 flux, which the OLD model couldn't capture well especially the magnitude of ENSO. As revealed by Dong et al. (2016), most CMIP5 models could not capture the relationship right. It would be helpful to have some discussion on which key model developments do improve the representation of ENSO magnitude in the NEW model? A paragraph of discussion on this will provide advices for other modeling centers.

The important model improvements in MIROC-ES2L was not stated in the original manuscript. We have added the description on it in Lines 185–194 in the revised manuscript. In brief, one is implementation of an updated plume model for cumulus convection with multiple cloud types where lateral entrainment rate varies vertically depending on the surrounding environment. The other is reduction of numerical diffusion by introducing highly-accurate tracer advection scheme in the ocean and by increasing vertical resolutions.

2. ENSO is an air-sea coupled system, it involves both ocean and atmosphere processes. In this study, both OLD-assim and NEW-assim only nudge ocean temperature and salinity, the atmosphere ran freely without any data nudging. I have couple of questions here: i) Does the IAU apply to every ocean level including the ocean surface? ii) How is the atmosphere part for instance winds treated? As the ocean part has strong nudging, the atmosphere should be adjusted accordingly, the mismatch of ocean and atmosphere would cause some spurious circulation. iii) Why is this spurious upwelling only found in the OLD-assim? iv) Is the spurious upwelling obvious in the climatological mean state in OLD-assim comparing with the OLD? A comparison of climatology in the nudged data and the model free runs will help understand this point. v) Would a different assimilation method, e.g., including atmospheric circulation nudging, end up with a different conclusion?

i) In this study, the observed temperature and salinity are assimilated into the ocean models at depths between the sea surface and 3000 m. To state this, we have rewritten Lines 103–104 in the revised manuscript as follows:
”In addition, the IAU was applied at depths between the sea surface and 3000 m, with the values of $\tau = 1$ day and $\alpha = 0.025$ (Tatebe et al., 2012).”

ii) In the atmosphere, data assimilation is not used. To clarify this, we have added the following sentence in Line 107 in the revised manuscript:
“Also, any atmospheric observations/reanalysis are not applied.”
The ocean temperature and salinity observations were assimilated into ESMs and the atmosphere responds to them.

iii) Here, we describe the anomalies during El Niño periods, while the opposite applies during La Niña periods. In OLD, the ENSO signal is weaker than the observation, so that the correction term on the governing equation of the ocean temperature forces to raise the equatorial water temperature in order to realize observed temperature variations. The warming due to data assimilation procedure reduces density, leading to

enhancement of upward vertical velocity at the depth of thermocline. In NEW, on the other hand, because amplitudes of the equatorial temperature anomalies are larger than in OLD and are closer to observations, the correction term in NEW-assim arisen from the assimilation procedure was kept small enough not to cause spurious enhancement of upward vertical velocity. To describe in more detail the mechanism by which upward vertical velocity in the equatorial Pacific in OLD-assim enhances during El Niño periods, we have rewritten Lines 230–237 in the revised manuscript as follows:

"In OLD, the temperature variations associated with ENSO at the depth of the thermocline in the eastern equatorial Pacific is smaller than observed (see Figure 3b and 3c), so that the correction term forces to raise the equatorial water temperature by 0.16 $\times 10^{-6}$ °C s^{-1} during El Niño periods in order to realize observed temperature variations (Figure 5b). The wind feedback in OLD-assim is 0.48 m s^{-1} K^{-1} (Table 3), which is the same as in OLD, and the map of the wind speed anomalies shows a similar pattern to that of the OLD (Figure S3e–h); however, the warming due to data assimilation procedure during El Niño periods reduces density, leading to low-pressure anomalies. This results in anomalous cyclonic circulation and convergence, and thus enhancement of upward vertical velocity at the depth of the thermocline (Figure 5d)."

iv) In this study, the observed temperature and salinity anomalies are assimilated into the ocean models at depths between the sea surface and 3000 m, which was not described in the original manuscript. Therefore, the climatological mean states of ocean temperature and salinity with assimilation are same with those without assimilation. In order to clarify that the observed anomalies are assimilated into the model in this study, we have added the following sentences in Lines 100–103:

"For $X^a(0)$ and $X(0)$, we used anomalies from monthly mean climatology during 1961–2000 in observations and models, respectively. Such a scheme often called 'anomaly assimilation' or 'anomaly initialization' is used in many previous studies (e.g., Smith et al., 2007; Keenlyside et al., 2008; Pohlmann et al., 2009; Li et al., 2016, 2019; Sospedra-Alfonso and Boer, 2020)."

v) Different assimilation techniques could make the model correlate better with the observations. Further investigation is required to identify the best suitable method and why. However, we think if the model itself does not perform well, the assimilation process leads to an unnatural circulation, as in OLD-assim in this study.

3. Line 32: "…warm by 1.5C within ~20 years…" -> "…warm by 1.5C within ~20 years relative to the preindustrial state"

Corrected. (Line 49 in the revised manuscript)

4. Line 87: “This remainder..” -> “The remainder. . .”

Corrected. (Line 67 in the revised manuscript)

5. Combining Fig. 5 and Fig. 7, Fig. 6 and Fig. 8 will help readers for the comparison of OLD and NEW.

Following the comment, Figures 5 and 7 (Figures 6 and 8) in the original manuscript have been combined into Figure 4 (Figure 5) in the revised manuscript.

6. Line 234-236: “In this research, the same simple data assimilation scheme is incorporated into two ESMs, OLD in which the ENSO amplitude is about half the observed value and NEW with improved reproducibility of ENSO.” Is this statement of ENSO amplitude based on the free runs of the two models? It would be helpful to add panels of ENSO amplitude in the free runs with OLD and NEW models in Fig. 1.

We have added Table 2 in the revised manuscript, that shows the intensity and period of ENSO in NEW, OLD, and observations. We have also added Figure S2 showing the timeseries of the detrended NINO3-SST and NINO3-CO2F anomalies simulated by one ensemble member in OLD and NEW and that derived from the observation.

7. Line 237: “. . .is consistently represented. . .” here needs to be rephrased to make it clearer, e.g., the anticorrelation relationship between SST and CO2F. ”

In order to state the results of this study more concisely and clearly in Discussion and Summary section, its first paragraph has been totally rewritten and the relevant sentence has been modified as follows:
”In the case where the ocean temperature and salinity observations were assimilated into the other ESM with rather realistic ENSO representation, anticorrelated relationship between SST and CO2F was reproduced.” (Lines 259–260)