"Contrasting projection of the ENSO-driven $CO_2$ flux variability in the Equatorial Pacific under high warming scenario" by P. Vaittinada Ayar et al.

We first would like to thank the anonymous reviewer for her/his thorough reading and very positive and constructive comments. We tried to take them into account as much as possible. A detailed point-by-point reply to these comments is provided below. Changes in the manuscript are indicated in blue.

## Answer to Referee #1 :

### General comments :

- *Since the air-sea CO2 flux is related to three terms : ocean pCO2, air pCO2, and wind-solubility coefficient, the authors only analyze the ocean pCO2 in the manuscript. I am very interested in the role of wind-solubility coefficient and air pCO2 in explaining the divergence in two groups of ESMs. Different models might have different wind and temperature variability which might contribute to the CO2 flux variability. It is worth quantifying and discussing the wind and solubility terms. All the ESMs might use the same air pCO2, so the air pCO2 might have a very little contribution. However, it is needed to be at least discussed in the manuscript.*

  **Authors' response :** Thank you for this interesting point. We computed $k$ the gas transfer velocity multiplied by $K_0$ the solubility coefficient used to estimate $CO_2$ fluxes as F = $k * K_0$ *($pCO_{2o}$ - $pCO_{2a}$). Figure R1 represents the $k * K_0$ and surface wind anomalies for each period, group of models and ENSO phase. All the three preserved and reserved groups are able to reproduce the observed weakening in trade winds during El Niño, and vice versa during La Niña. The amplitude between ENSO phases is larger for the preserved models than the reversed ones. This can explain the higher amplitude variation between ENSO phase for the preserved models than the reverse ones (see Table 3 and Fig 5 of the article). However, for the respective groups the amplitude between ENSO phases is not changing between given the periods. This means that the wind variability can only have a marginal contribution to $CO_2$ fluxes variability and can not explain the behaviour of the reversed group models.

  Figure R1 has been added to the supplementary material and this question has been addressed in lines 243-251 of the revised manuscript as :

  In addition to surface ocean $pCO_2$, $CO_2$ flux is estimated using atmospheric $pCO_2$ and wind solubility coefficient $k * K_0$ as :

$$\text{fgco2} = k * K_0 * (p\text{CO}_{2o} - p\text{CO}_{2a}) \qquad (4)$$

  $k$ represents the gas transfer velocity and $K_0$ the solubility coefficient [cf. Wanninkhof, 2014 ]. The anomalies of surface wind and product of $k * K_0$ for each period, group of models and ENSO phase are depicted in Fig. S8 of the supplementary material. The amplitude of both anomalies

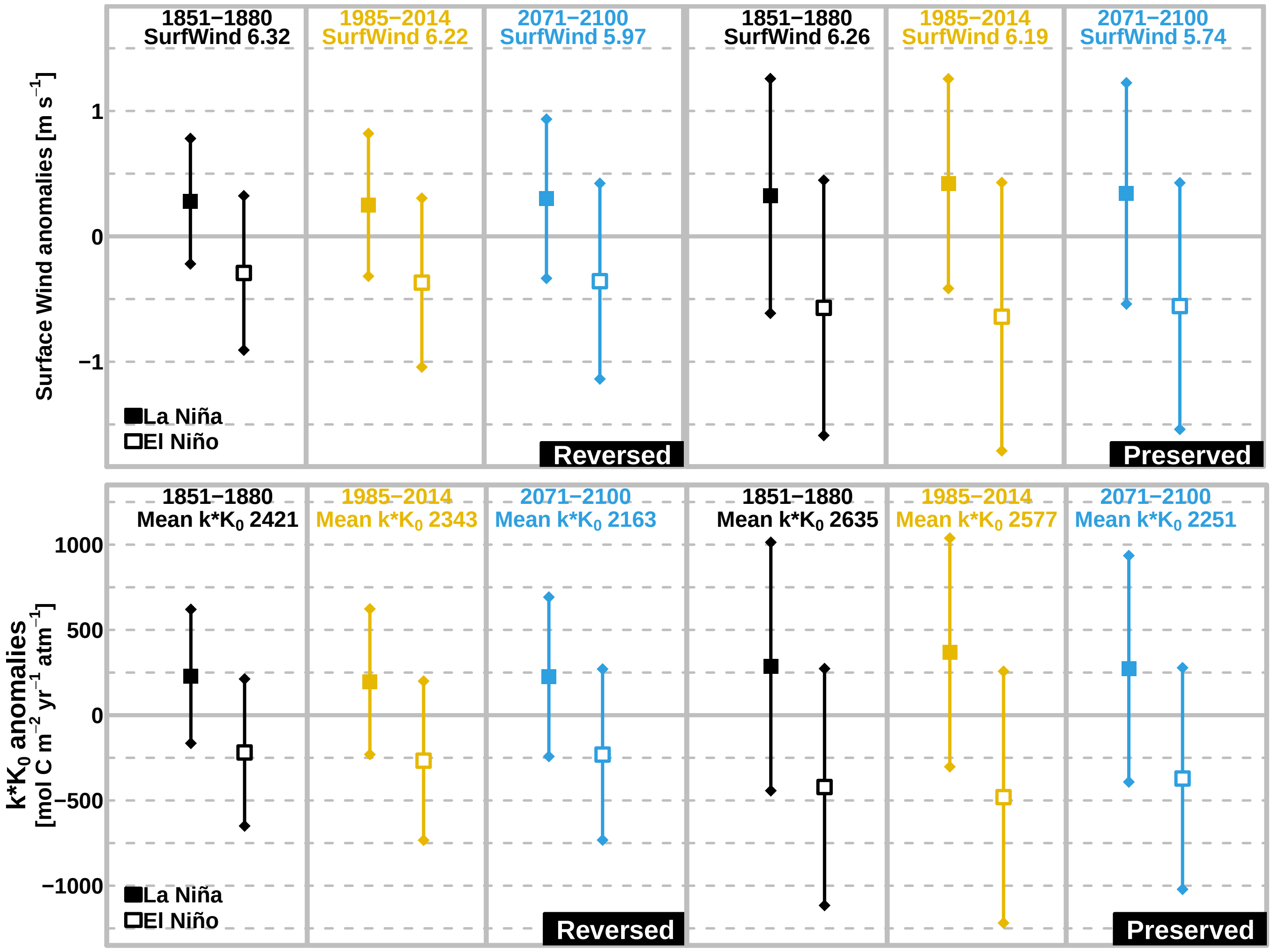


FIGURE R1 – El Niño and La Niña surface wind (*top* in m s$^{-1}$) and $k * K_0$ (*bottom* in mol C m$^{-2}$ yr$^{-2}$ atm$^{-1}$) mean anomalies for the reversed (*left*) and preserved (*right*) ESMs over the early historical (1851-1880), contemporary (1985-2014) and future (2071-2100) periods in the EP domain. Vertical bars represents ± one s.d. of the anomalies for the respective periods, groups of models and ENSO phases.

between ENSO phases is larger for the preserved models than the reversed ones, which partly explains the higher amplitude of $CO_2$ flux variability variation between ENSO phase for the preserved models than the reverse ones (see Table 3 and Fig. 5). However, for the respective groups the amplitudes between ENSO phases are not changing between given the analysed periods. This means that the wind variability can only have a marginal contribution to $CO_2$ fluxes variability and can not explain the behaviour of the reversed group models.

- *Ocean $pCO_2$ is sensitive to four terms : temperature, DIC, alkalinity, and salinity (Takahashi et al., 1993). The authors only discuss the temperature and DIC. Although the DIC is dominant in the ocean $pCO_2$ variability, the alkalinity has a very large compensation. The alkalinity might partly contribute to the model divergence. In addition, the precipitation probably changes a lot under global warming (Cai et al., 2015), this might drive a relatively large variability of alkalinity and salinity in the future. It would be convincing if the author could discuss/quantify the contribution of alkalinity and salinity to the model divergence ?*

**Authors' response :** Thank you this comment. In order to address this, similar figure as Figure 7 of the article has been reproduced for SSS vs. salinity normalised ALK (ALKs). Except, this time we did one figure by group and period given the important increase of temperature and DIC from early historical to the future (cf. revised Figure 7 of the article). This figure shows a higher SSS and ALKs for reversed models than the preserved ones. For both groups, the ALKs and SSS changes are very small from one period to another indicating a limited sensitivity of $pCO_2$ to salinity and alkalinity. Besides, the amplitude between ENSO phases is small for salinity and alkalinity (respectively <.2 psu for SSS and $< 6.5$ µmol eq $L^{-1}$ for ALKs).

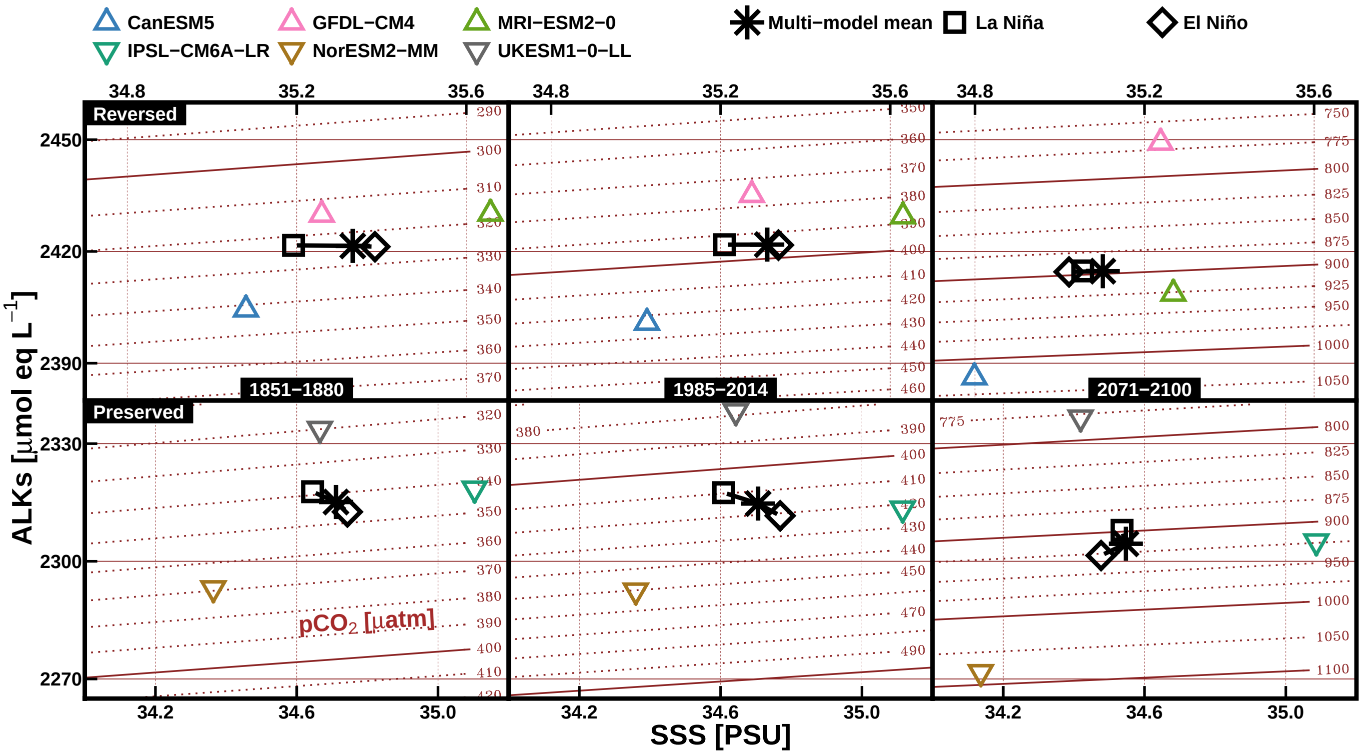


FIGURE R2 – Mean SSS (in psu) versus mean ALKs (in µmol eq $L^{-1}$) over the early historical (1851-1880), contemporary (1985-2014) and future (2071-2100) periods in the EP domain simulated by all reversed and preserved ESMs (*top* panels, circle markers). The multi-model mean values of SSS and ALK (asterisk markers) from each ESM group together with their respective mean values during La Niña (square markers) and El Niño (diamond markers) are also depicted for the three periods. Isolevels of $pCO_2$ for varying SSS and ALKs are given in the background and are computed from period and group specific SST and DICs muti-model average.

Figure R2 has been added to the supplementary material and this has been addressed in lines 276-283 of the revised manuscript as :

TAKAHASHI et al., 1993 also mention $pCO_2$ sensitivity to alkalinity and salinity. A similar figure as Fig. 7 but for the mean states of SSS against ALKs is given in supplementary Fig. S10. Given the important increase of temperature and DIC from early historical to the future period (cf. Fig. 7) one panel per model group and period is produced. This figure shows higher SSS and ALKs for reversed models than the preserved ones. For both groups, the ALKs and SSS changes are very small from one period to another indicating a limited sensitivity of $pCO_2$ to future changes in salinity and alkalinity. Besides, the amplitude between ENSO phases is small for salinity and alkalinity (respectively <.2 psu for SSS and $< 6.5$ µmol eq $L^{-1}$ for ALKs). Therefore the relative contribution of ENSO-induced salinity and alkalinity changes to $pCO_2$ is smaller than temperature and DIC changes.

- *Line 245-247. The authors found two differences between two group of ESMs (Large increase of surface DIC and lower range of DIC changes). Fig.9 could show the large increase in surface DIC. However, I could not see a figure showing the lower range of DIC changes during ENSO phases. I would suggest one such figure in the main text or supporting information.*

  **Authors' response :** Figure 7 has been modified replacing DIC by salinity normalised DIC (DICs) to better see the DIC changes during ENSO phases. The range of DIC changes during ENSO phase goes from 30.26 to 19.45 µmol C $L^{-1}$ for reversed models and from 44.87 to 34.00 µmol C $L^{-1}$ for preserved ones.

  This has been adressed in lines 268-269 of the revised manuscript as :
  (from early historical to future period, the absolute change of surface DICs between both ENSO phases evolves from 30.26 to 19.45 µmol C $L^{-1}$ for reversed models and from 44.87 to 34.00 µmol C $L^{-1}$ for preserved ones)

- *Fig. 9. Except for surface DIC difference between preserved and reversed models, I also see the difference in subsurface DIC (e.g., 200-300 m) between two groups of ESMs. What is the role of subsurface DIC difference in the model CO2 flux-ENSO relationship divergence ? Why is the subsurface DIC also different in the two groups of models ?*

  **Authors' response :** Vertical DIC gradient is a key factor driving ENSO related $CO_2$ flux variability throughout the vertical column. The reversed ESMs simulate higher historical DIC making them more biased than the preserved ones, but both groups have similar vertical profile. As stated in the article, the increase of future DIC below 100m is similar in both groups. But we noted that there is a higher DIC increase in the upper ocean for the reversed ESMs, leading leading to a stronger reduction in vertical DIC gradient and thus contributes to a less ENSO-induced surface DIC variability in the reversed ESMs. The difference in the subsurface DIC between both groups is likely associated with the bias in the respective alkalinity mean state (see also new supplemental figure S11). Model-dependent bias in interior alkalinity can arise from the different formulations of particulate inorganic carbon formation and dissolution in each model (Planchat et al., in prep.).

  This has been adressed in lines 311-315 of the revised manuscript as :
  Indeed, vertical DIC gradient is a key factor driving ENSO related $CO_2$ flux variability throughout the vertical column. The reversed ESMs simulate higher historical DIC (yellow lines in first row of Fig. 9) making them more biased than the preserved ones, but both groups have similar vertical profile. Bias in the interior DIC may be associated with the simulated mean alkalinity state (Supplementary Fig. S9 and S11), which is likely associated with variation in particulate inorganic carbon formulation in ESMs (Planchat et al., in prep., 2022).

**Minor comments :**

- *Line 41-43. The tropical Pacific ocean CO2 flux anomaly is not only related to the upwelling strength but also related to the poleward Ekman transport driven by easterly trade wind. One more* *reference (Liao et al., 2020 GBC) is suggested.*

**Authors' response :** This has been added in lines 45-46 of the revised manuscript as :
In addition, $CO_2$ flux anomaly variability in the tropical Pacific is also related to the poleward Ekman transport driven by the easterly trade wind [Liao et al., 2020].

- *Line 80. What is the re-grid method ?*

  **Authors' response :** Bilinear interpolation is used as re-griding method. This has been clarified in line 85 of the revised manuscript.

- *Line 91. The ENSO variability is usually an interannual variability ranging from 3 to 7 years. Could the author plot the total CO2 flux and CO2 flux anomaly at a sample point to show how well is the detrend method ? Could the detrend method remove the decadal variability ?*

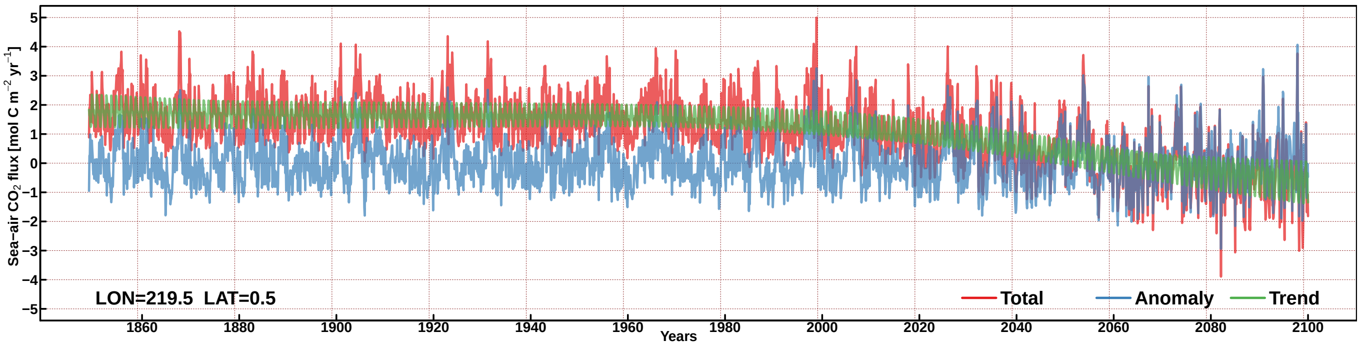


FIGURE R3 – Example of sea-air $CO_2$ flux (in mol C m$^{-2}$ yr$^{-1}$, *bottom*) total, anomaly and trend extracted at a NorESM1-MM grid-point.

**Authors' response :** From the example in Figure. R3, it shows that our detrending method remove the long-term (greater than multi-decadal) trend and preserve both interannual and decadal variability.

- *Line 100. Why do you use 1981-2010 as the climatological period instead of 1985-2014 which is the contemporary period defined in the manuscript.*

  **Authors' response :** The 1981-2010 climatology has been chosen because this is the usual climatological period chosen by institute providing Niño3.4 index. See for instance,
  https ://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/
  https ://climate.copernicus.eu/charts/c3s_seasonal/c3s_seasonal_plume_lfpw ?facets=undefined&time =2022050100,0,2022050100&type=plume&area=nino34.
  The 1985-2014 is chosen given to availibility of $CO_2$ flux observation (1982-2015).

- *2 Caption. What is the observed data of SST and CO2 flux ? I know the authors state them in the method section. However, it would be clearer for the readers if the authors could detail them in the caption. For example, SST is JRA.*

  **Authors' response :** Done.

- *3. Why do the authors use 5N-5S instead of 2N-2S ? This is not consistent with the method section.*

  **Authors' response :** That was a typo, thank you for noticing this. It is $\pm 2°$ and we have corrected this in the revision.

- *What is the CMIP6 ensemble anomalies one standard deviation ?*

  **Authors' response :** Fig. 2 and 3, it represents the CMIP6 inter model ensemble standard deviation of the different variables during El Niño and La Niña phase.

- *Line 379. The text reads like Liao et al. (2021) selected the model subjectively and got a partial and biased conclusion. Actually, Liao et al., (2021) use a strict and reasonable constrain method to select the model. The results are physically rational and convincing. I would suggest rephrasing the words. A suggested way would be : "With a strict constrain method based on contemporary observations, the model tends to show a weaker future CO2 flux anomalies during ENSO phases (Liao et al., 2021)."*

  This has been rephrased in lines 417-418 of the revised manuscript as :
  However, using models selected based on their contemporary period performances, Liao et al., 2021 found weaker future $CO_2$ flux anomalies during ENSO phases.

- *Lines 381-382. The increasing Revelle factor and ocean pCO2 sensitivity to temperature would be a general result in my opinion. This point is discussed by many studies. I would rephrase or delete this point.*

  This has been added in lines 420-421 of the revised manuscript as :
  This result is consistent and reaffirms findings from previous studies (e.g, Liao et al., 2021 ; Gallego et al., 2020 ; Hauck and Völker, 2015) ;

# References


Liao, Enhui, Resplandy, Laure, Liu, Junjie & Bowman, Kevin W. (**2020**). "Amplification of the Ocean Carbon Sink During El Niños : Role of Poleward Ekman Transport and Influence on Atmospheric CO2". Global Biogeochemical Cycles. Vol. 34. no. 9, e2020GB006574.

Liao, Enhui, Resplandy, Laure, Liu, Junjie & Bowman, Kevin W. (**2021**). "Future Weakening of the ENSO Ocean Carbon Buffer Under Anthropogenic Forcing". Geophysical Research Letters. Vol. 48. no. 18, e2021GL094021.

Takahashi, Taro, Olafsson, Jon, Goddard, John G., Chipman, David W. & Sutherland, S. C. (**1993**). "Seasonal variation of $CO_2$ and nutrients in the high-latitude surface oceans : A comparative study". Global Biogeochemical Cycles. Vol. 7. no. 4, p. 843-878. eprint : https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/93GB02263.

Wanninkhof, Rik (**2014**). "Relationship between wind speed and gas exchange over the ocean revisited". Limnology and Oceanography : Methods. Vol. 12. no. 6, p. 351-362.