Supplement of

Time varying changes and uncertainties in the CMIP6 ocean carbon sink from global to regional to local scale

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S1. Model selection

The data used in this study was accessed through the PANGEO CMIP6 catalogue on Google Cloud (https://storage.googleapis.com/cmip6/cmip6-zarr-consolidated-stores.csv), and cross verified against data published on the Earth System Grid Federation (ESGF, https://esgf-node.llnl.gov/search/cmip6/). Sixteen models submitted at least one realization for historical, ssp126, ssp245, and ssp585 scenarios (Table S1). Three models were excluded, leaving 13 total models in our analysis.

Among these, NorESM2-MM was excluded because the same realization was not available for all three scenarios.

BCC-CSM2-MR was excluded because it showed sink values that were three orders of magnitude larger than other models. To make sure this is not an issue with the uploaded dataset to google cloud, the historical dataset was downloaded directly from ESGF and yielded the same results. The units according to the published metadata are kg m^{-2} s^{-1} of carbon, but may be in error.

CNRM-ESM2-1 was excluded because the historical model results are out of the range of uncertainty of the observation data over 1960-2020 from the Global Carbon Project of 2021 (Friedlingstein et al., 2021) by a large offset (lower pink line in Fig. S1).

Institution	Model(s)	Main Reference(s)	Realization(s)
Beijing Climate Center (China)	BCC-CSM2-MR	Wu et al. (2019); Xin et al. (2019)	Excluded
National Center for Atmospheric Research (USA)	CESM2 [1] , CESM2-WACCM [1]	Danabasoglu et al. (2020)	r1i1p1f1, r1i1p1f1
Norwegian Earth System Model (Nowrwegen)	NorESM2-LM [2], NorESM2-MM	Tijiputra et al. (2020)	r1i1p1f1, excluded
Institut Pierre Simon Laplace (France)	IPSL-CM6A-LR [3]	Boucher et al. (2020)	r1i1p1f1
Institute for Numerical Mathematics (Russia)	INM-CM4-8 [4], INM-CM5-0 [4]	Volodin et al. (2017,2018)	r1i1p1f1, r1i1p1f1
JAMSTEC, NIES, AORI, U. of Tokyo (Japan)	MIROC-ES2L [5,6]	Hajima et al. (2020)	r1i1p1f2
Max Planck Institute for Meteorology (Germany)	MPI-ESM1-2-HR [7,8], MPI-ESM1-2-LR [9]	Mauristen et al. (2019)	r1i1p1f1, r1i1p1f1
Met Office Hadley Center (UK) and Natural Environment Research Council (UK)	UKESM1-0-LL[10,11]	Sellar et al. (2019) Williams et al. (2017)	r1i1p1f2
Canadian Centre for Climate Modelling and Analysis (Canada)	CanESM5 [12] CanESM5-CanOE [12]	Swart et al. (2019a) Christian et al. (2021)	r1i1p1f1, r1i1p2f1
Geophysical Fluid Dynamics Laboratory (USA)	GFDL-ESM4 [13,14]	Held et al. (2019)	r1i1p1f1
CNRM-CERFACS (France)	CNRM-ESM2-1	Voldoire et al. (2019);	excluded

[1] Danabasoglu (2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h)

[2] Øyvind et al. (2019a, 2019b, 2019c, 2019d)

[3] Boucher et al. (2018, 2019a, 2019b, 2019c)

[4] Volodin et al. (2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h)

[5] Hajima et al. (2019)

[6] Tachiiri et al. (2019a, 2019b, 2019c)

[7] Jungclaus et al. (2019)

[8] Schupfner et al. (2019a, 2019b, 2019c)

[9] Wieners et al. (2019a, 2019b, 2019c, 2019d)

[10] Tang et al. (2019)

[11] Good et al. (2019a, 2019b, 2019c)

[12] Swart et al. (2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h, 2019i)

[13] Krasting et al. (2018)

[14] John et al. (2018a, 2018b, 2018c)

Table S1- Models that have submitted at least one realization for all of the historical, ssp126, ssp245 and ssp245 experiments as well as the realization chosen for this study. The footnotes indicate references for the corresponding CMIP6 dataset used.

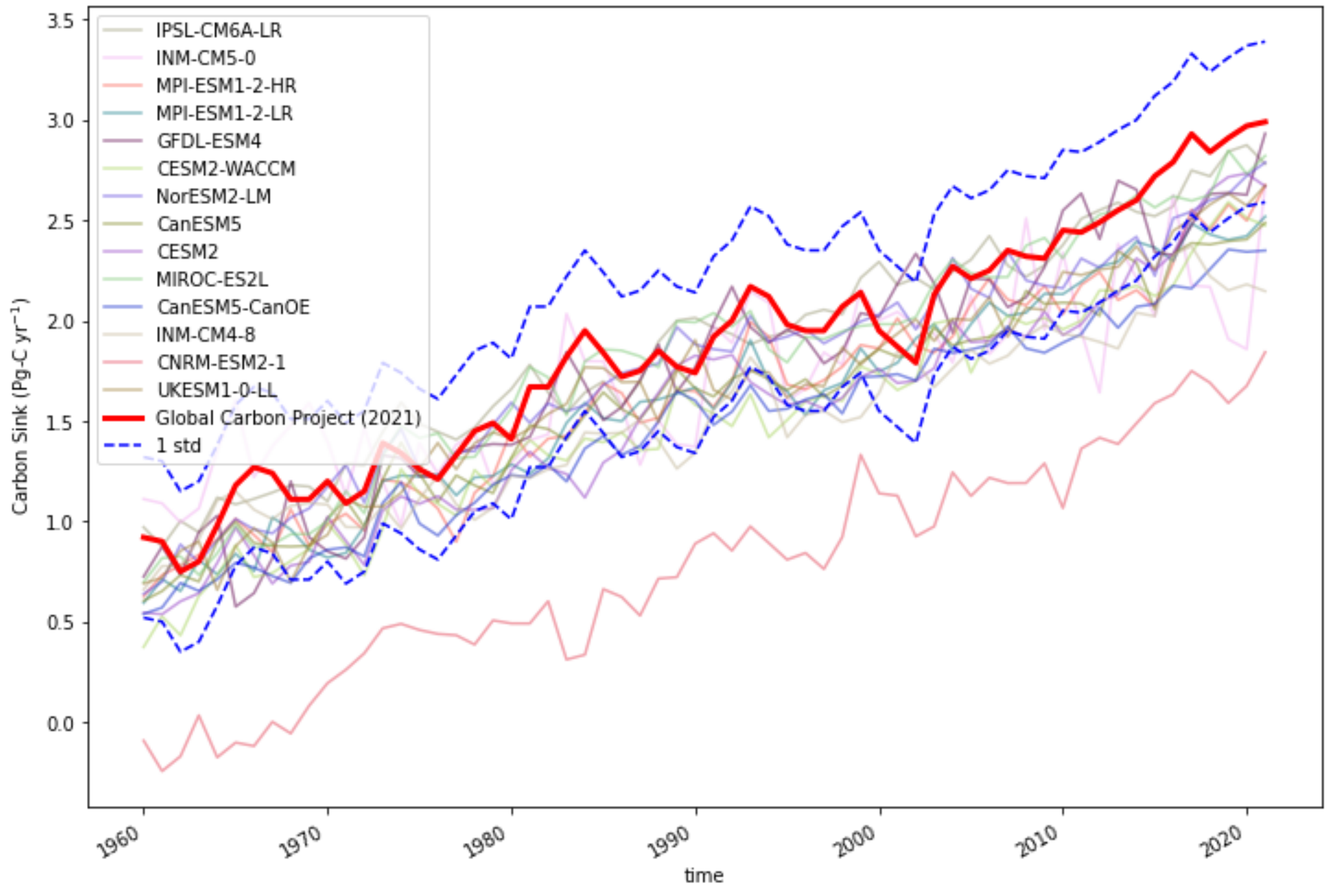

Figure S1- Ocean CO_2 sink from various estimates. The thick red line is the ocean CO_2 sink (SOCEAN) from the Global Carbon Project 2021 (Friedlingstein et al., 2021). The dashed blue lines represent the uncertainty bounds of the observations (±1 standard deviation). The other lines show the 13 models included in the analysis and CNRM-ESM2-1 in pink at the bottom.

S2. Use of SMILE to measure internal variability

The ensemble size of a SMILE must be large enough to accurately estimate internal variability from the variance across the ensemble members. The global average of the internal variability at each grid cell grows as the number of ensemble members included in the estimate increases and then becomes constant after a certain point (Fig. S2). Moreover, at regional scales even more members are required to converge than at the global scale. However, only 3 models have enough realizations (at least 20) to be considered well sampled over the historical period, and only CanESM5 has enough realizations for all three scenarios.

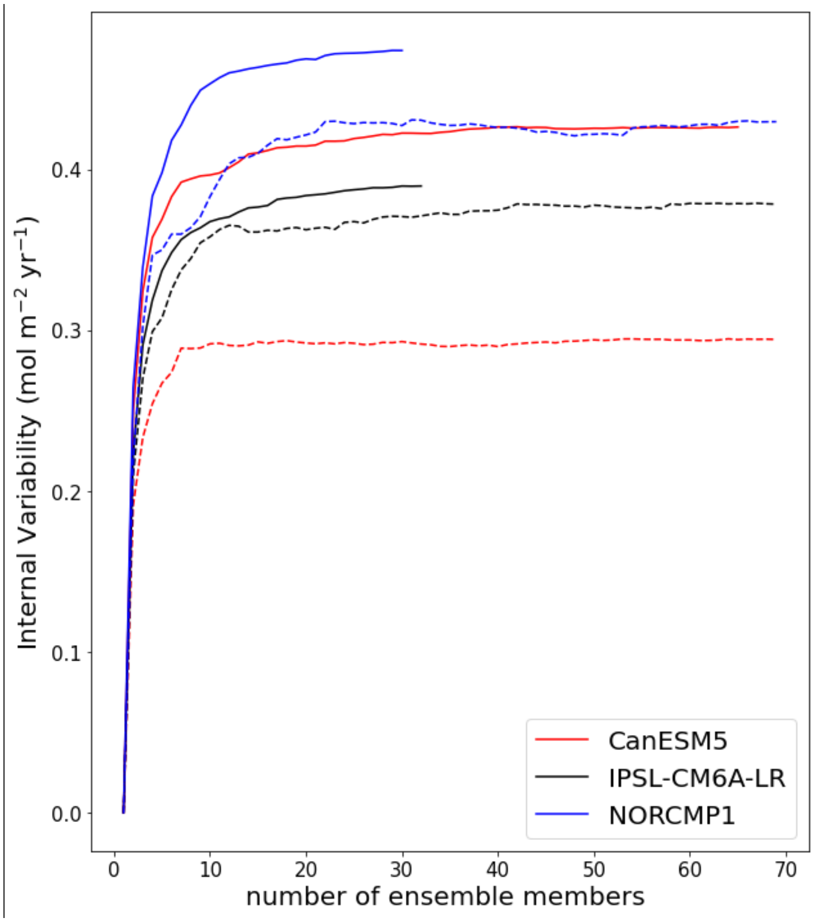

Figure S2- Global average of internal variability at each grid point (measured as two times the standard deviation). Solid lines show internal variability across different ensemble sizes of different models over 1995-2015. Dashed lines show internal variability for pi-Control runs where the ensembles were acquired by choosing 70 random years (at least 10 years apart) from the pi-Control run

This leaves only one SMILE that can be used to estimate internal variability as a function of time and scenario. Our analysis shows that for the three SMILEs that are well sampled over the historical period, the global average of the internal variability at each grid point is consistent between the models with an error of less than 10 percent (Fig. S3). Therefore, the CanESM5 large ensemble is a suitable choice to calculate internal variability. Additionally, the results show that internal variability has a clear trend in time for different scenarios that HS09 did not consider but which should not be ignored. This trend is likely even more important on regional scales. The dashed black line in Fig. S3 is the IPSL model over the entire time period using ssp585, but with only six available realizations. Note that the IPSL ssp585 estimate is lower than the others, confirming that internal variability would be under-estimated if the ensemble is not well-sampled.

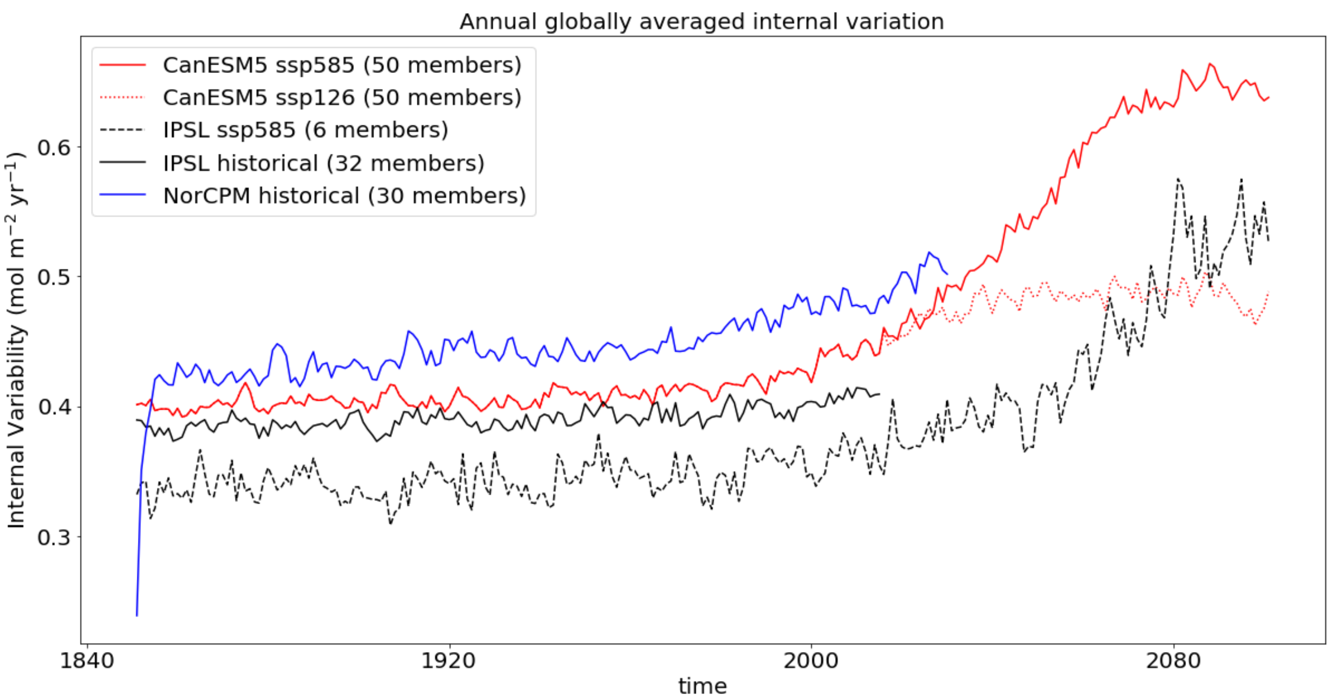

Figure S3- Timeseries of the globally averaged internal variability measured as two times the standard deviation within a SMILE. The historical period for the three SMILES, ssp585 for CanESM5 and IPSL, and ssp126 for CanESM5 are shown on this plot. For IPSL and NorCPM models, the full time period for ssp585 does not include enough realizations to be well sampled.

S3. Correcting for internal variability included in the model spread

Mathematically, the spread measured as the standard deviation across the first realization of each model can be related to model uncertainty as follows:

$$U_M(t,l) = 2\sqrt{\frac{1}{N_s}\sum_{s=1}^{N_s} \mathrm{Var}_m\big(F(m,s,t,l)\big)} \tag{S1}$$

where Var_m refers to the variance across the models. We can relate the variance of the total signal (*T*) to that of the forced signal (*F*) and the residual (*R*) as:

$$\begin{aligned}\mathrm{Var}_m\big(T(m,s,t,l)\big) = \mathrm{Var}_m(F(m,s,t,l) + R(m,s,t,l)) = \\ \mathrm{Var}_m\big(F(m,s,t,l)\big) + \mathrm{Var}_m\big(R(m,s,t,l)\big) + 2\mathrm{COV}_m(F, R)\end{aligned} \tag{S2}$$

where COV_m is the covariance between the forced signal and the residuals. Assuming that the residual from the forced signal for every realization (internal variability) is independent of the forced signal, the covariance is zero and the equation above can be re-ordered as:

$$\mathrm{Var}_m\big(F(m,s,t,l)\big) = \mathrm{Var}_m T(m,s,t,l)) - \mathrm{Var}_m\big(R(m,s,t,l)\big) \tag{S3}$$

The term $\mathrm{Var}_m\big(R(m,s,t,l)\big)$ refers to the variance of the residual from the forced signal across many models' first realization. If the number of models is large enough and given that internal variability is stochastic noise, based on the central limit theorem, $\mathrm{Var}_m\big(R(m,s,t,l)\big)$ equals the internal variability. Thus:

$$\mathrm{Var}_m\big(F(m,s,t,l)\big) \sim \mathrm{Var}_m(T(m,s,t,l)) - I(s,t,l) \tag{S4}$$

where $I(s,t,l)$ refers to internal variability at time *t*, scenario *s*, and location *l*. In Appendix B we showed that if the number of ensemble members included when estimating internal variability is not large enough, the variation is not well sampled and is biased low. Concretely, if we have 13 first realizations of 13 models and 50 members of one model to estimate internal variability, the internal variability measured using the 50 members would be larger than the term $\mathrm{Var}_m\big(R(m,s,t,l)\big)$, since $\mathrm{Var}_m\big(R(m,s,t,l)\big)$ does not represent internal variability in a well-sampled ensemble. Thus, the model uncertainty acquired by subtracting the "50-member internal variability" from the variance across first realizations of the models would be smaller than it should be. Instead, the best approximation is to sample our large ensemble (CanESM5) with the same number of realizations as the number of models we have. For this correction, 1000 randomly selected sets of 13 ensemble members of CanESM5 were chosen, the variance determined within each set, then averaged over the 1000 sets, and finally that average internal variance was deducted from the total variance across the 13 models.

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