Assessment of predictability of atmospheric CO_2 and C sinks in E-driven simulations

Deliverable 2.4

Authors: Bernardello R., Bopp L., Ilyina T., Li H., Mignot J., and Tourigny E.

This project received funding from the Horizon 2020 programme under the grant agreement No. 821003.

Document Information

GRANT AGREEMENT	821003
PROJECT TITLE	Climate Carbon Interactions in the Current Century
PROJECT ACRONYM	4C
PROJECT START DATE	1/6/2019
RELATED WORK PACKAGE	WP2
RELATED TASK(S)	T2.3.3
LEAD ORGANIZATION	BSC
AUTHORS	Bernardello R., Bopp L., Ilyina T., Li H., Mignot J., and Tourigny E.
SUBMISSION DATE	31-10-2022
DISSEMINATION LEVEL	PU

History

DATE	SUBMITTED BY	REVIEWED BY	VISION (NOTES)
31-10-2022	R. Bernadello		
01-11-2022		K. Hope	

Please cite this report as: Bernardello R., Bopp L., Ilyina T., Li H., Mignot J. and Tourigny E. (2022), Assessment of predictability of atmospheric CO_2 and C sinks in E-driven simulations, D2.4 of the 4C project

Table of Contents

List of tables

List of figures

About 4C

Climate-Carbon Interactions in the Coming Century (4C) is an EU-funded H2020 project that addresses the crucial knowledge gap in the climate sensitivity to carbon dioxide emissions, by reducing the uncertainty in our quantitative understanding of carbon-climate interactions and feedbacks. This will be achieved through innovative integration of models and observations, providing new constraints on modelled carbon-climate interactions and climate projections, and supporting Intergovernmental Panel on Climate Change (IPCC) assessments and policy objectives.

Executive Summary

For the first time ever, we have performed retrospective predictions of atmospheric CO_2 growth rate using three European Earth System Models driven by emissions of CO_2 rather than by prescribed atmospheric CO_2 concentrations. A multi-model inter-comparison that includes also two external models is showing a consistent picture with atmospheric CO_2 growth rate predictable up to 2-3 years in advance. In agreement with previous work done within 4C, the land CO_2 flux is the main limiter to atmospheric CO_2 prediction, while air-sea fluxes are predictable for longer (up to 5-6 years in advance). Moreover, we have used one of these predictive systems to reconstruct the global carbon budget while taking advantage of the assimilation of physical variables routinely done to produce initial conditions for retrospective predictions. This procedure allows to better represent climate variability while, at the same time, representing the carbon sinks in an internally consistent system and therefore provides an additional line of evidence for the ongoing assessments of the anthropogenic GCB.

Keywords

CO_2 emission-driven simulations, reconstruction, carbon cycle predictions

1 Introduction of E-driven prediction systems

In this deliverable, we present results from the three 4C ESM-based emission-driven prediction systems EC-Earth3-CC, IPSL-CM6A-LR and MPI-ESM-LR. With respect to D2.3, where the ESMs were driven by prescribed

atmospheric CO_2 concentrations, here the retrospective predictions are driven by emissions of CO_2, allowing for the representation of interactive atmospheric CO_2 and its prediction, besides the predictions of the land and ocean carbon sinks. The characteristics of these systems were described in detail in D2.5 while here we report only the main components of each model, along with the references to the relevant literature (Table 1).

Table 1. Summary of CO_2 emission-driven prediction systems based on 4C Earth system models (ESMs), i.e., EC-Earth3-CC, IPSL-CM6A-LR, MPI-ESM-LR.

ESMs	EC-Earth3-CC	IPSL-CM6A-LR	MPI-ESM-LR
Resolution Atmosphere	T255, 91 levels	2.5° x1.3°, 79 levels	T63, 47 levels
Resolution Ocean	1°, 75 levels	1°, 75 levels	1.5°, 40 levels
Initialization Atmosphere	ERA5 Full field	Indirect	ERA-40 before 1979 and ERA5 from 1980: full field vorticity, divergence,log(p), T
Initialization Ocean	Offline NEMO-PISCES-LIM reconstruction, nudging full field EN4 subsurface T-S, and full field ORAS5 SST and SSS.	EN4 SST and Atlantic SSS	EN4 3D full field T and S with ensemble Kalman filter
Initialization Land	Indirect	Offline land reconstruction with ERA5 atmospheric forcings	Indirect
Ensemble size	15 (10 used in analysis)	5	10
Period of reconstruction	1980-2021	1961-2021	1958-2021
Retrospective predictions	Yearly from 1st Nov. for 7 years	Yearly from 1st Jan. for 10 years	Yearly from 1st Nov. for 5 years
External forcings	CMIP6	CMIP6	CMIP6
References	Döscher et al., (2021)	Boucher et al. (2020)	Mauritsen et al. (2019)

2 Multi-model assessment of E-driven retrospective predictions of atmospheric CO2 concentration.

MPI is leading a multi-model inter-comparison of the emission-driven retrospective predictions performed by three 4C ESMs and two external models. The details of the ensemble sizes for each model are given in Table 2. In Figure 1, we show the time series of anomalous atmospheric carbon growth rate together with fluxes from land and ocean. In the lower panels the predictive skill is calculated as anomaly correlation coefficients relative to global carbon budget data. All models show skill for atmospheric CO_2 growth rate between 2-3 years. As a confirmation, from perfect model studies (D2.1) and concentration-driven retrospective predictions (D2.3), air-land CO_2 fluxes are the main limiter to atmospheric CO_2 growth rate predictability.

Table 2. Ensemble size for each model for uninitialized, assimilation and initialized simulations.

ESMs/Simulation	Can-ESM5	EC-Earth3-CC	IPSL-CM6A-CO2-LR	MIROC-ES2L	MPI-ESM1.2-LR
Uninitialized	10	10	1	10	10
Assimilation	10	5/1 Ocean/Land	1	10	10
Initialized	10	10	5	10	10

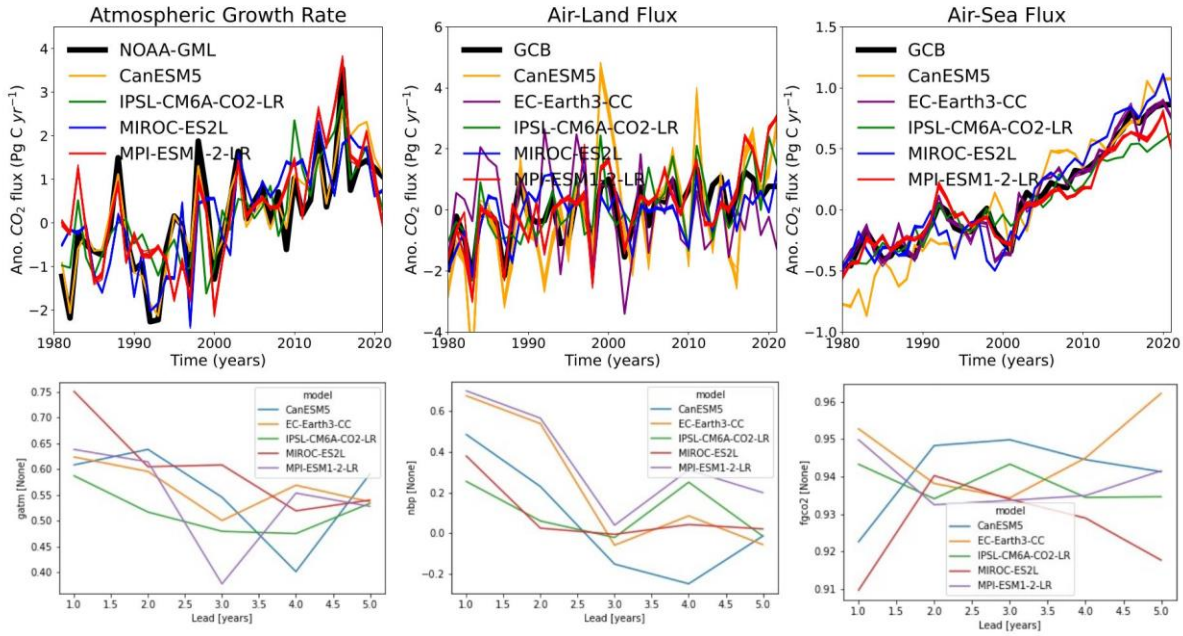

Figure 1. Upper row: Time series of anomalous atmospheric carbon growth rate (left), air-land CO2 flux (middle), air-sea CO_2 flux (right) from multi-model assimilation runs together with NOAA-GML observation and GCB assessments. Lower row: Predictive skill as anomaly correlation coefficients relative to the GCB data. The anomalies are calculated relative to the respective climatology for the period from 1985-2014.

3 Assessment of the global carbon budget with an E-driven predictive system

By assimilating physical atmospheric and oceanic data products into the Max Planck Institute Earth system model (MPI-ESM1.2-LR), we can well reproduce the annual mean historical global carbon budget (GCB) variations in the last decades (Fig. 2 left and middle columns). The correlations of atmospheric CO_2 growth, air-land CO_2 fluxes and air-sea CO_2 fluxes in assimilation relative to the assessments from the Global Carbon Project are 0.75, 0.75 and 0.97, respectively. Such a fully coupled decadal prediction system, with an interactive carbon cycle enables representation of the GCB within a closed Earth system, and therefore provides an additional line of evidence for the ongoing assessments of the anthropogenic GCB. Retrospective predictions initialized from the assimilation simulation show high confidence in predicting the following year's GCB. The predictive skill is up to 5 years for the air-sea CO_2 fluxes, and 2 years for the air-land CO_2 fluxes and atmospheric carbon growth rate (Fig. 2 right column). This paper is under review by Earth System Dynamics.

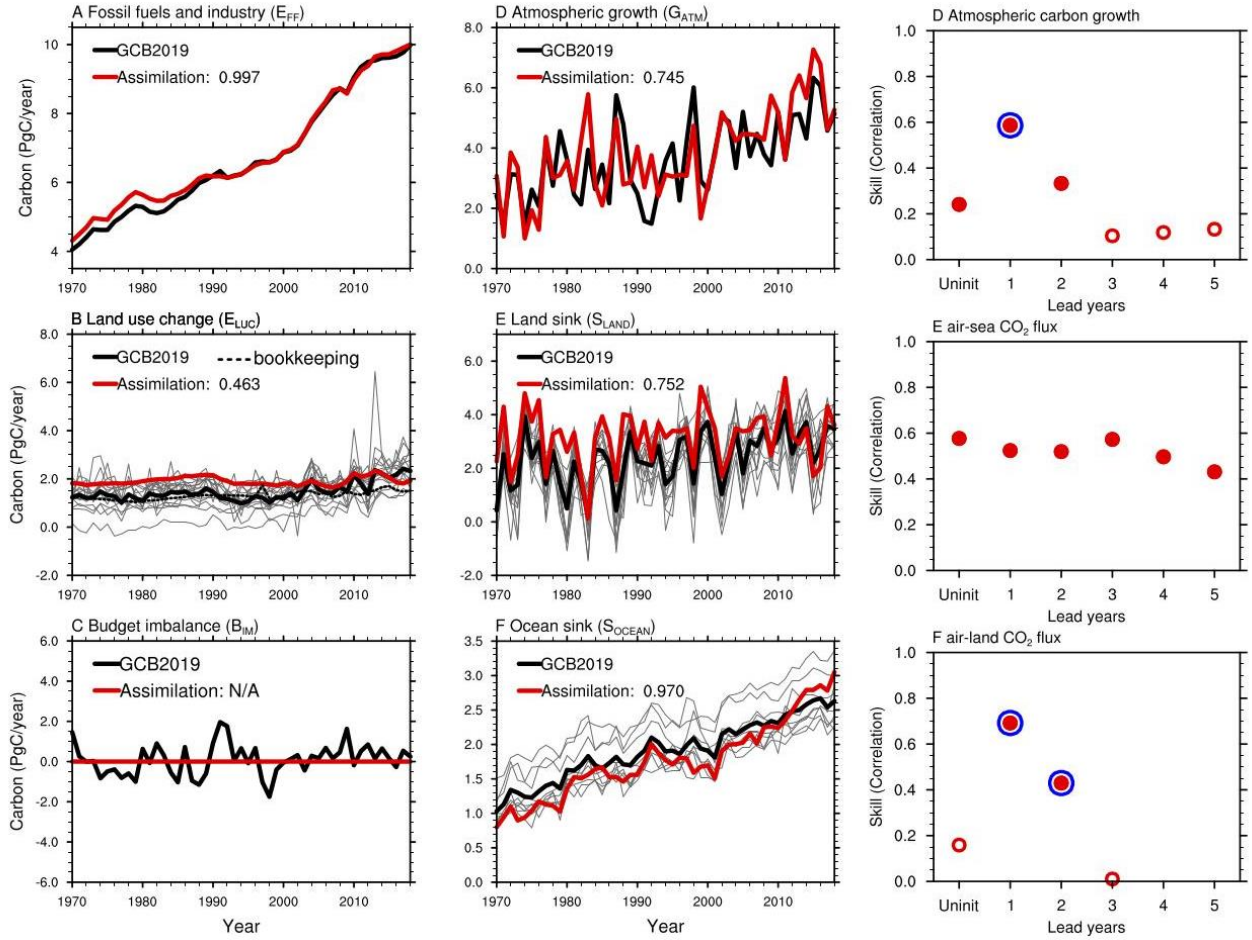

Figure 2. Left and middle columns: Time series of (A) fossil fuel and industry CO_2 emissions, (B) emissions from land-use change, (C) the budget imbalance that is not accounted for by the other terms, (D) atmospheric carbon growth rate, (E) the natural terrestrial carbon fluxes, and (F) air-sea CO_2 fluxes from MPI-ESM1.2-LR assimilation in comparison with Global Carbon Budget (GCB 2021, Friedlingstein et al., 2022). Emissions (A & B) are positive when they are fluxes into the atmosphere, while sinks (D, E & F) are positive as fluxes into the respective compartment. A positive BIM means a higher sum of emissions than sinks. The thin grey curves in B, E, and F show individual GCB stand-alone model results. The numbers in the legend show the correlation coefficients between assimilation and GCB2021. Right column:Predictive skill of atmospheric carbon growth rate (top), air-sea CO_2 fluxes (middle), and net air-land CO_2 fluxes (bottom) reference to GCB 2021. The filled red circles on top of the open red circles show that the predictive skill is significant at 95% confidence level and the additional larger blue circles indicate improved significant predictive skill due to initialization in comparison to the uninitialized simulations. We use a nonparametric bootstrap approach (Goddard et al., 2013) to assess the significance of predictive skill. The results are

based on annual mean data for the time period from 1970-2018. (Figures are from Li et al. 2022).

4 Conclusions

For the first time ever, we have performed emission-driven retrospective predictions with three 4C ESM-based predictive systems. These predictions allowed us to evaluate the skill of these systems in predicting atmospheric CO_2 growth rate as well as land and ocean carbon sinks. An inter-model comparison, including 2 external models shows a rather consistent picture across models, with these showing some skill in predicting atmospheric CO_2 growth rate up to 2-3 years in advance. In agreement with previous work done in 4C, land fluxes appear to be the main limiting factor to atmospheric CO_2 predictability. Moreover, we have used one of these systems to reconstruct the global carbon budget, taking advantage of an internally consistent representation of the three carbon sinks in the model and of the data assimilation performed to produce initial conditions for the retrospective predictions.

5 Publication

Li, H., Ilyina, T., Loughran, T., Spring, A., and Pongratz, J.: Reconstructions and predictions of the global carbon budget with an emission-driven Earth System Model, Earth Syst. Dynam. Discuss. [preprint], https://doi.org/10.5194/esd-2022-37, in review, 2022.

6 References

Acosta Navarro J. C., Bernardello R., Bopp L., Ilyina T., Li H., Mignot J. and Tourigny E. (2022), Assessment of predictability of the C cycle in C-driven simulations, D2.3 of the 4C project

Bernardello R., Bopp L., Ilyina T., Li H., Mignot J., and Tourigny E. (2021), Draft report on predictions of next year atmospheric CO2, D2.5 of the 4C project

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., . . . others (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. Journal of Advances in Modeling Earth Systems, 12 (7).

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégoz, M., Miller, P. A., Moreno-

Chamarro, E., Nieradzik, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., and Zhang, Q.: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, https://doi.org/10.5194/gmd-15-2973-2022, 2022.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S, et al.: Global Carbon Budget 2021, Earth Syst. Sci. Data, 14, 1917–2005, https://doi.org/10.5194/essd-14-1917-2022, 2022.

Goddard, L., Kumar, A., Solomon, A., Smith, D., Boer, G., Gonzalez, P., Kharin, V., Merryfield, W., Deser, C., Mason, S. J., et al.: A verification framework for interannual-to-decadal predictions experiments, Climate Dynamics, 40, 245–272, 2013.

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., . . . others (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1. 2) and its response to increasing co2. Journal of Advances in Modeling Earth Systems, 11 (4), 998-1038.