Climate-Carbon Interactions in the Current Century

An Executive Summary of the Horizon 2020 Project 4C

Science Summary
January 2024

Over the past four years, the 4C project team has been working to tackle persistent knowledge gaps in carbon cycle science.

By using new observations and observational techniques, together with enhanced process understanding and new improvements in Earth system modelling, the 4C project has been working towards the following objectives:

- Improve our understanding of processes controlling the global carbon cycle
- Develop near-term prediction of the climate and carbon cycle
- Reduce uncertainties in climate projections over the 21st century
- Knowledge transfer

This document summarises the key advances in science achieved by 4C. The project results, outputs and publications can be found at: 4c-carbon.eu.

CURRENT CARBON CYCLE

The 4C project developed a consensus view of the role of the ocean as an important sink for carbon, supported by multiple lines of evidence from models, and several and independent types of observations (Figure 1).

The 4C research has produced, integrated and analysed new data-products of ocean carbon for the surface and interior, and new model simulations, which have helped narrow uncertainties in the ocean carbon dioxide (CO_2) sink. These 4C products were used for extensive regional analysis of the ocean CO_2 sink as part of the international RECCAP2 exercise.

Constraining the ocean CO_2 sink helps to constrain also the other components of the global carbon budget, and hence improve our understanding of the global carbon cycle. Having this understanding is an essential prerequisite for near-term predictions and long-term projections.

The trends in the ocean sink in the past decade still needs attention as different estimates diverge (Figure 1), an issue which has been linked to difficulties in constraining high-latitude CO_2 fluxes.

The 4C project team progressed towards understanding the land CO_2 sink. Observational constraints from remote-sensing (SiF) and flask network monitoring (CO_2, COS) have enabled an evaluation of model performance for both the net land biosphere exchange (NBP) and now in addition component flux gross primary productivity for the seasonal cycle.

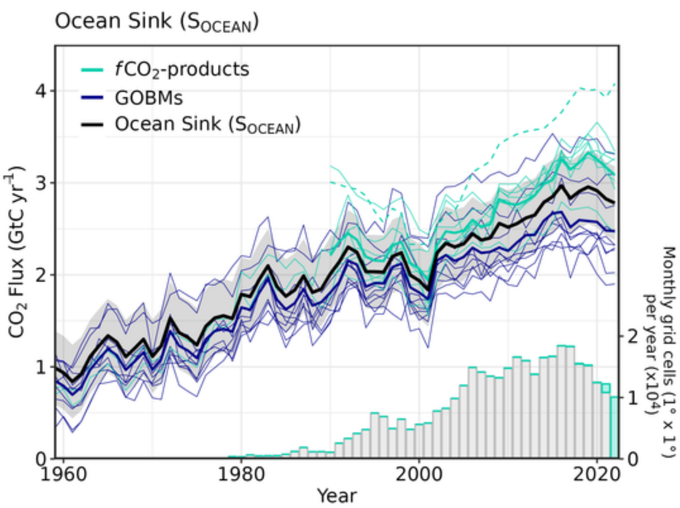

Figure 1. Ocean CO_2 sink from 1959 to 2022. Estimates are from data-products and their average (green), the ocean models and their average (purple), and the consensus estimate used by the Global Carbon Budget 2023 (black; Friedlingstein et al., 2023).

Using dual products enables the separation of the net flux NBP into its component gross fluxes, i.e. Gross Primary Production (GPP) and Respiration (RESP). Results demonstrate the systematic bias in both magnitude and a season shift in NBP and identify the cause (GPP) and towards early onset of the growing season in several land models.

Satellite column CO_2 (xCO_2) has been applied successfully as a benchmark test of both coupled Earth System Models (ESMs), and their offline land surface model component, the latter in combination with an atmospheric transport model. This is a useful new test of spatio-temporal NBP projections of land models covering seasonal, interannual scales and recent trends. These new benchmark tests have been incorporated into the

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ESMValTool and offer a great future resource to constrain and benchmark land models as the further develop for CMIP7.

Novel datasets using machine learning have enabled a revision of the land sink estimates based on the fluxnet network of eddy covariance towers (ECT) to derive a new forest CO_2 flux product. Account is now taken for an ECT bias towards young-age vegetation, and lack of account of disturbance and lateral fluxes. An exciting new remote-sensed product L-band Vegetation Optical Depth (L-VOD) gives a good proxy of biomass change through time since 2011.

4C has extensively used this product to monitor changes in above-ground biomass in global relevant biomes, across latitude regions (pan-tropical, boreal), and at global scales. These data also form an important land model benchmark alongside satellite-based high resolution biomass products.

Results suggest that land models overestimate biomass sink in old forests, reflecting their parameterization of CO_2 fertilisation, yet underestimate biomass sink in young forests due to their lack of representation of forest disturbances and recovery. Furthermore, land models show widespread forest sinks with too high density in the boreal region.

Some important improvements include the land-use datasets used in GCB for key countries (e.g. Brazil), identification of missing processes in land modelling, long-term discrepancy on the northern extra tropics (demography/age) (Figure 2).

Moreover, based on satellite observation of terrestrial water storage and factorial model experiment, the importance of water on land carbon sink has been well-demonstrated and highlighted. Finally, mid-latitude surface ocean pCO_2 amplitude growth has been attributed to anthropogenic activities.

The 4C project research reduced uncertainty in the balance between the anthropogenic emissions of CO_2 from land and fossil fuel sources, and their partitioning among the atmosphere, land and ocean, called the "carbon budget imbalance (Bim)". The Bim did not decrease substantially over the 11 years of annual carbon budget updates after an initial decrease between 2009 and 2012, but a systematic selection of sub-model ensembles succeeded to reduce the Bim by a third. New global oxygen and ^{13}C isotope budgets provided additional constraints on the components of the global carbon budget.

Finally, the 4C project suggested ways to broaden IPCC assessments using IT, based on its experience with ScienceBrief.org (De-Gol et al. 2023).

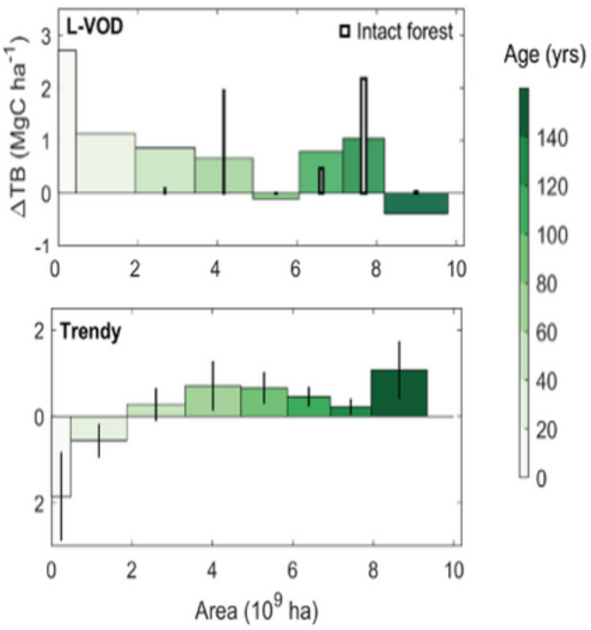

Figure 2. Relationship between total live biomass changes and forest age from L-VOD compared with land models (Trendy).

NEAR TERM PREDICTIONS

4C has built the capacity of three European ESMs to perform decadal predictions of climate and carbon cycle where CO_2 emissions (instead of concentrations) are prescribed. These predictions are expected to contribute to closing the gap between climate science and policy, since emissions are more directly linked to economic activities.

To achieve this final outcome, 4C has applied climate prediction practices and data assimilation schemes to expand the ESMs capabilities so as to represent the natural variability of the global carbon cycle (Ilyina et al., 2021). The work done under 4C allowed us to investigate different data assimilation schemes and assess drivers and limiters of predictability. Researchers managed to establish predictive skill for atmospheric CO_2 growth and carbon sinks into the land of 2 years, and for carbon sinks into the ocean up to 5 years (Figure 3).

Land CO_2 fluxes have been identified as the main limiter to atmospheric CO_2 predictability (up to 2 years in advance), while ocean CO_2 fluxes can be predicted up to 5-6 years in advance (Spring and Ilyina, 2020). One of the main reasons for this difference between land and ocean has been identified to be the uncertainty in the formulation of land vegetation models, likely due to unresolved processes that are still poorly understood (Dunkl et al., 2023; Martín-Gómez et al., 2023).

These newly developed ESMs capabilities have also been applied for the first time to reconstruct the global carbon budget and to predict next-year atmospheric CO_2 growth rate (Fig. 3), leveraging on their improved representation of natural variability (Fig. 4; Li et al., 2023; Bernardello et al., 2023).

The improvement in our ability to represent and validate land CO_2 fluxes has emerged as a priority to extend the predictive horizon of global carbon cycle dynamics.

Moreover, future research should focus on the maintenance and improvement of observation-based products of the physical climate that can be used in data assimilation (Spring et al., 2021) while, at the same time, extending the observational capability of carbon cycle dynamics in all realms, to strengthen the evaluation of the predictive systems biases.

Finally, a coordinated effort among the near-term prediction community, should focus on establishing agreed best practices in the quantification of predictive skill.

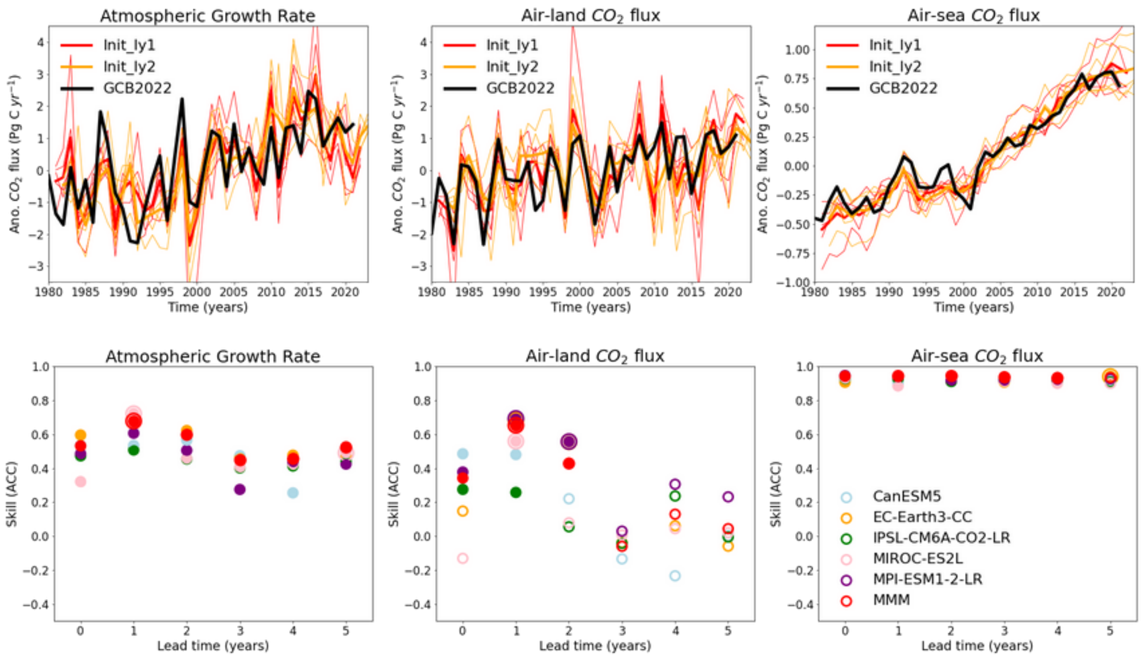

Figure 3. Upper row: Time series of anomalous atmospheric carbon growth rate (left), air-land CO_2 flux (middle), air-sea CO_2 flux (right) from multi-model initialised runs at lead times of 1 and 2 years together with NOAA-GML observation and GCB assessments (GCB2022, Friedlingstein et al. 2022). Lower 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. The filled circles show that the predictive skill is significant at a 95% confidence level, and the additional larger circles indicate an improved significant predictive skill due to initialization in comparison to the uninitialized simulations. We use a bootstrap method Goddard et al. (2013) to assess the significance of predictive skill. The predictive skill of correlation is based on annual mean data for 1985-2014.

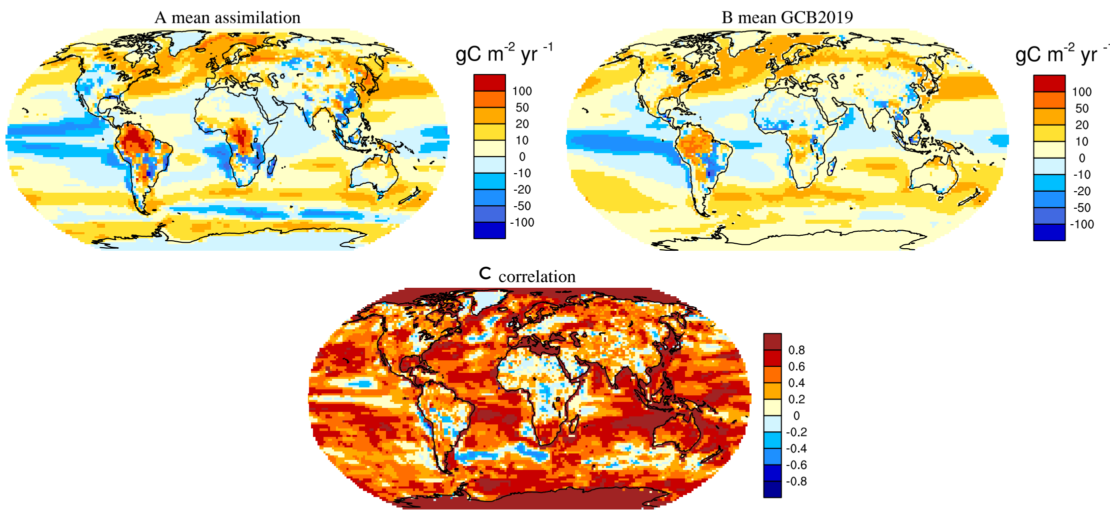

Figure 4. Spatial distribution of the CO_2 fluxes from model assimilations compared to GCB2019. Climatological mean CO_2 fluxes into the land and ocean from the atmosphere in assimilation (a) and Global Carbon Budget (GCB 2019, Friedlingstein et al., 2019) estimates (b). Correlation and between assimilation and GCB 2019 are shown in (c). The results are based on annual mean data for the time period 1970–2018. Positive values in (a) and (b) refer to CO_2 fluxes into the ocean or land.

CLIMATE PROJECTIONS

The 4C project team has been working to reduce the uncertainties in climate projections over the 21st century. 4C has identified several key processes of carbon-climate interactions and established novel observational constraints both on land and ocean carbon processes, and has applied the cumulative emissions concept (TCRE) to non-CO_2 emissions using CO_2-forcing equivalent emissions.

In addition, 4C has developed the Adaptive Emission Reduction Approach (AERA) that allows developing emissions trajectories for CO_2, CH_4, N_2O and other agents that iteratively adapt to meet a chosen temperature target (Terhaar et al., 2022). Its adaptive nature makes the approach robust against a wide range of uncertainties. AERA has been applied to the most comprehensive fully coupled Earth system models to provide an estimate of emission pathways that are compatible with the 1.5˚C and 2.0˚C global warming targets (Silvy et al., in prep).

In the 1.5°C simulations (Figure 5), all models exhibit a strong and almost immediate decrease in CO_2-fe emissions after 2026. The multi-model mean CO_2-fe emissions are projected to decline to 8.1 Pg C yr-1 (range: 3.1 to 11.9) by 2030, an approximately 40% reduction from 2025 levels. CO_2-fe emissions reach zero (range: -3.6 to 5.0 Pg C yr-1) in 2050, increase slightly to 1.0 (range: -1.7 to 2.9 Pg C yr-1) afterwards. Policymakers may employ the information from AERA to regularly update near- and long-term emission reduction goals.

A simplified visualisation of the Adaptive scenarios can be found in the 4C Explorable Explanation's final section on "The Long Term".

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4C RESOURCES

A number of communication, dissemination and policy-relevant resources have been developed in 4C. These can be found on the project website (4c-carbon.eu):

- Policy publications (Science summaries, Factsheets, Policy Brief)
- Carbon Outlooks
- Explorable Explanation
- Outreach material (e.g. Climate Classrooms, videos)
- Science Brief

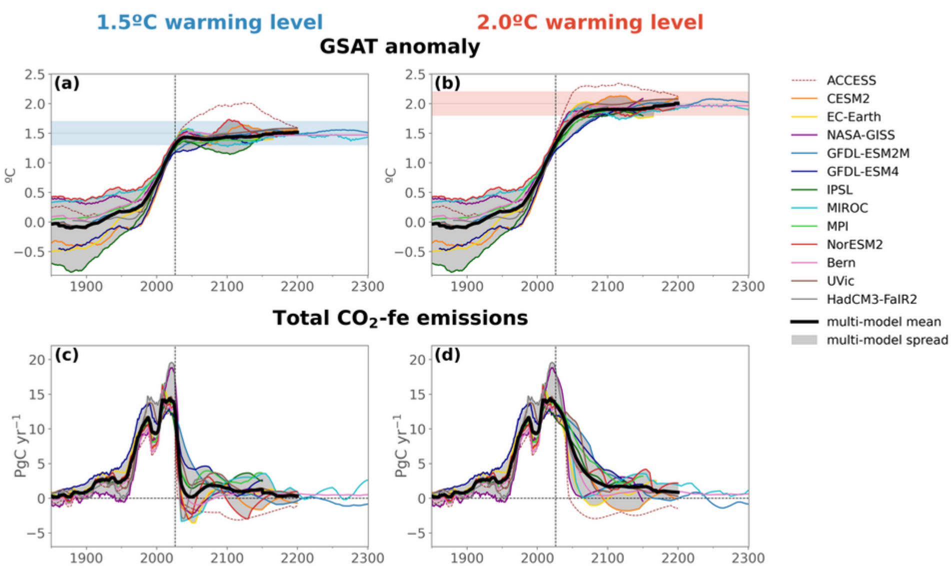

Figure 5. Simulated temperature, CO_2-fe emission and atmospheric CO_2 concentration pathways in the AERA-MIP Earth system model simulations for the global warming target of 1.5°C (upper panels) and 2.0°C (lower panels).

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