Climate-Carbon Interactions in the Current Century

Draft: Emergent constraints for carbon processes and biogeochemical feedbacks

Deliverable 3.1

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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

The goal of Task 3.1 is the establishment of novel observational constraints on land and ocean carbon processes to reduce uncertainty on the transient climate response to cumulative carbon emissions and carbon cycle feedbacks. Substantial progress has been made to set us on the right path to achieve this goal. We provide spatially explicit information of dryness stress on land ecosystem production from observations and highlight the relevance of soil moisture for explaining inter-model variability of the future land carbon sink. An emergent constraint on the sensitivity of soil carbon to climate warming is established. Another constraint for the Arctic Ocean reduces the uncertainty of future ocean acidification, while increasing the best estimate for the anthropogenic carbon inventory and reducing the best estimate for the saturation states of aragonite and calcite. We underscore that the availability of column-integral CO_2 from satellite data opens the door to emergent constraints based on spatial variability. Lastly, we evaluate emergent constraints on Equilibrium Climate Sensitivity (ECS) determined for CMIP5 on CMIP6.

Keywords

Land carbon-cycle, Ocean carbon-cycle, soil moisture, soil carbon, ocean acidification

1 Introduction

This report on emergent constraints for carbon and biogeochemical feedbacks contributes to the work package “Projecting the required mitigation effort over the 21st century”, for which the objective is to deliver observationally constrained estimates of 21st century cumulative carbon emissions consistent with the Paris Agreement aim of limiting warming to 1.5°C. The work within this task consists of developing and applying emergent constraints on the carbon cycle using a wide range of observational products over land and over the ocean.

2 Emergent constraints on land carbon processes

2.1 Relevance of soil moisture for land carbon projections

There is growing evidence about the important role of soil moisture (SM) for the land carbon cycle from ETHZ. Liu et al. (2020) shows that SM dominates dryness stress on ecosystem production globally, by combining satellite observations of solar-induced fluorescence with estimates of SM and vapor pressure deficit. The global coverage of the data provides spatially explicit information of dryness stress on ecosystem production (Figure 1), which is useful to constrain how Earth system models (ESMs) represent dryness stress on plants and consequently reduce uncertainties in the projection of terrestrial carbon fluxes. An accurate representation of the response of the carbon cycle to dryness is crucial, especially under an ongoing intensification of the dry season across large regions (Padrón et al., 2020).

A study about the relevance of SM for projections of net biome production (NBP) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) is currently underway by ETHZ. Results show that for most models and across most regions SM dominates over temperature as a control of detrended interannual variability in NBP, and also that trends in SM are as relevant as trends in temperature to explain trends in NBP. Consequently, differences across models in SM conditions and in their sensitivity of NBP to SM, contribute to explain inter-model differences in land carbon projections.

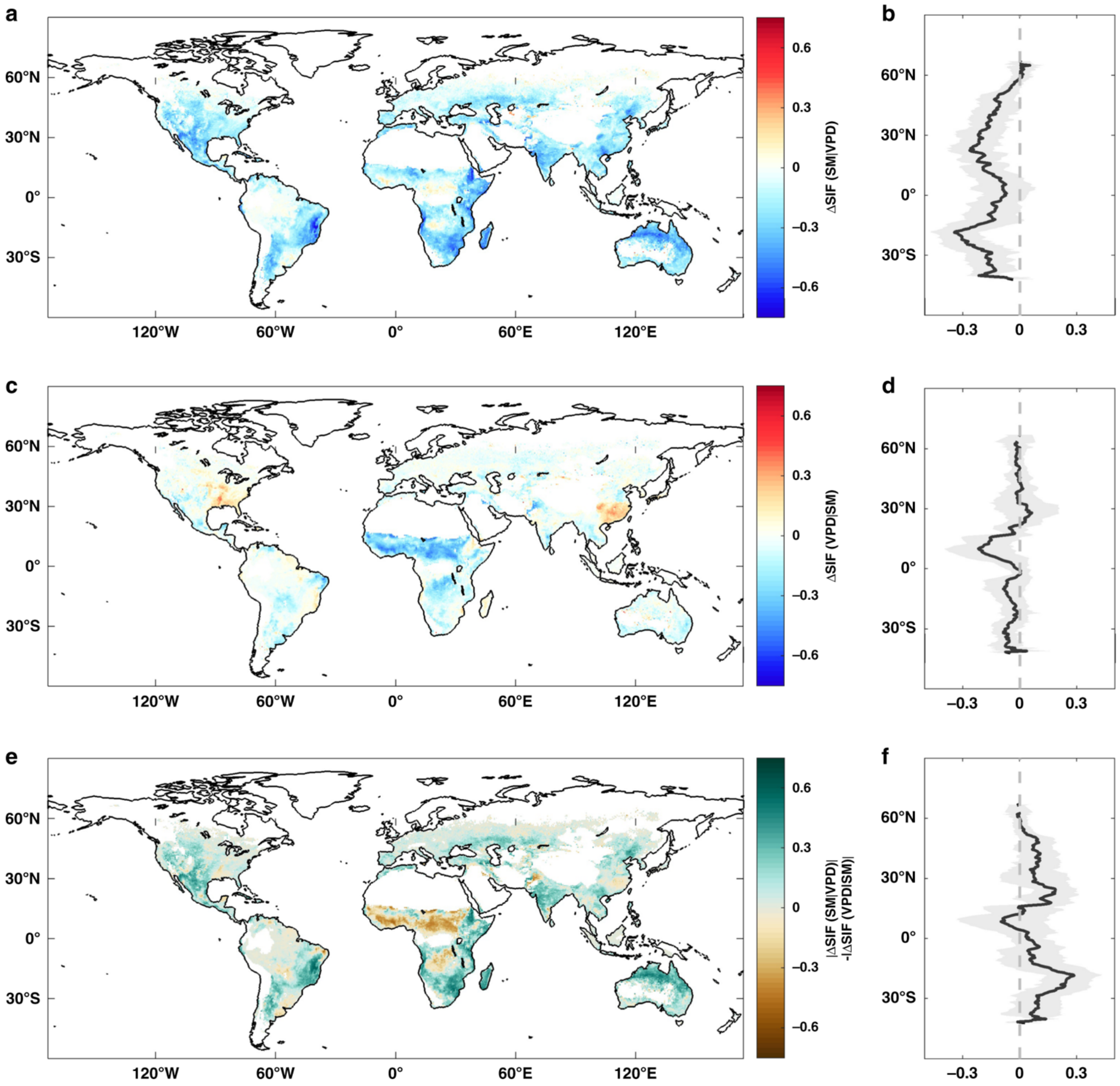

Figure 1. Effect of soil moisture and vapor pressure deficit on ecosystem production globally. **a, c, e** Spatial distribution of the changes in solar-induced chlorophyll fluorescence (SIF) caused by low soil moisture (SM) (ΔSIF(SM|VPD)) and high vapor pressure deficit (VPD) (ΔSIF(VPD|SM)), and their differences in absolute values (i.e., |ΔSIF(SM|VPD)|−|ΔSIF(VPD|SM)|). **b, d, f** Zonal means of SM and VPD effects on SIF and their differences in absolute values. The units refer to the fractions relative to average SIF exceeding the 90th percentile in each grid cell. Black lines indicate the mean values, and gray shaded bands show the standard deviation. Regions with sparse vegetation and regions without valid data are masked in white. From Liu et al. (2020).

2.2 Emergent constraint on the sensitivity of soil carbon to climate warming

A novel emergent constraint on the sensitivity of soil carbon to climate warming is established by UNEXE (Varney et al., 2020). This is an important step forward given the high contribution of the response of soil carbon to climate change to the overall uncertainty in land carbon projections. The developed constraint is on the projected changes in turnover time of soil carbon ($\Delta C_{s,\tau}$), by making use of current heterotrophic respiration and the spatial variability of the turnover time (τ_s) inferred from observations. Through this spatial emergent constraint, the new estimate of $\Delta C_{s,\tau}$ for the top one meter of soil at 2 °C of warming is −232 ± 52 PgC, as opposed to the unconstrained estimate of −196 ± 117 PgC (Figure 2).

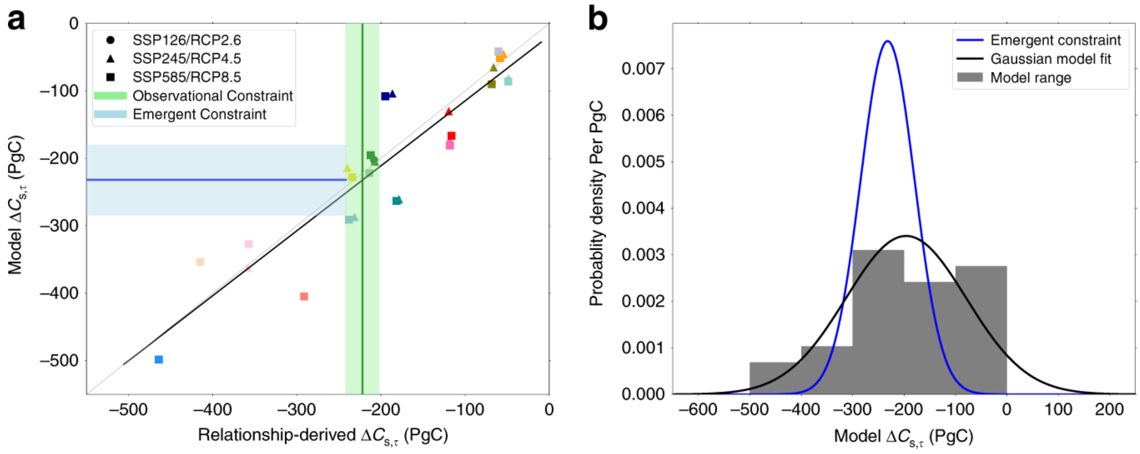

Figure 2. Emergent constraint on changes in turnover time of soil carbon ($\Delta C_{s,\tau}$) as a function of global warming. a Actual vs. estimated scatter plot for $\Delta C_{s,\tau}$ for 2 °C of global warming. The vertical green line defines the observational constraint which is derived using observational data and the future spatial temperature field of each model (decadal average), and the shaded region represents the corresponding uncertainty (±1 standard deviation). The horizontal blue line represents our emergent constraint, with the shaded region showing the corresponding uncertainty (±1 standard deviation) which results from the differing future spatial warming patterns seen in the future spatial temperature fields across the ESMs, and the emergent relationship between the model data points (black line). **b** Probability density function showing the Gaussian distribution of $\Delta C_{s,\tau}$ values from the unweighted prior model ensemble (black line) and the emergent constraint (blue line). Adapted from Varney et al. (2020).

3 Emergent constraints on ocean carbon processes

UBERN identified an emergent relationship between present-day maximum sea surface density in the Arctic Ocean and the Arctic Ocean anthropogenic carbon inventory as well as the associated ocean acidification at the end of the 21st century (Terhaar et al., 2020). Results indicate that CMIP5 models mainly underestimate Arctic Ocean sea surface density and hence carbon uptake and ocean acidification. Constrained estimates reduce the uncertainty of future ocean acidification, while increasing the best estimate for the anthropogenic carbon inventory and reducing the best estimate for the saturation states of aragonite and calcite (Figure 3).

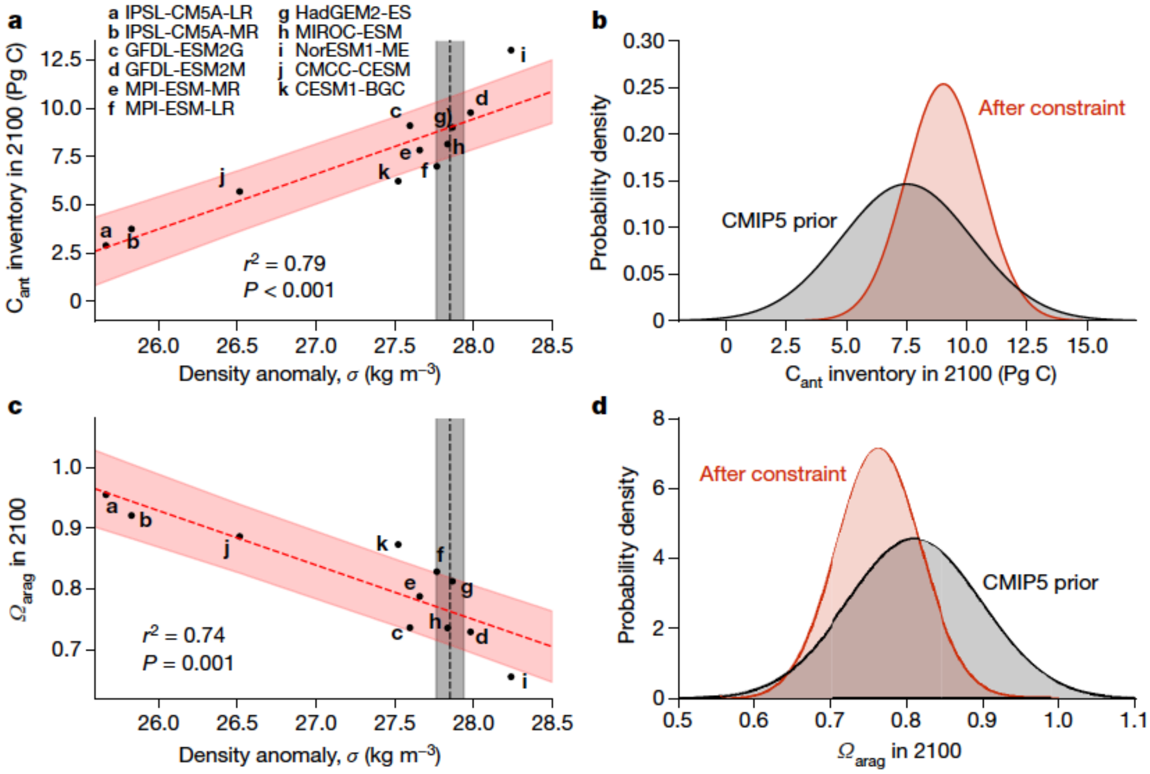

Figure 3. Emergent constraints on the projected anthropogenic carbon inventory and future acidification. a, c The projected Arctic Ocean anthropogenic carbon inventory **(a)** and basin-averaged Ω_{arag} **(c)** in 2100 against present-day maximum sea surface density (95th percentile waters) for the ESM ensemble (black dots). Linear regression fits (red dashed lines) and the associated 68% prediction intervals are shown, as are data-based estimates of present-day maximum sea surface density (black dashed lines) with the associated standard deviation (black-shaded area). **b, d** Probability density functions for the end-of-century Arctic Ocean anthropogenic carbon inventory **(b)** and basin-averaged Ω_{arag} **(d)** before (black) and after (red) the emergent constraint is applied. From Terhaar et al. (2020).

4 Spatially resolved evaluation of Earth system models with satellite column averaged CO_2

A study led by UBREMEN in collaboration with DLR and UNEXE (Gier et al., 2020) shows that a satellite observational time period of 2003-2014 is not sufficiently long to reproduce the emergent constraint from Cox et al. (2013) with CMIP6 data, but it might be feasible once more future simulations are available for a longer time overlap with the observations. Updating to a longer time period, with the recently produced time series up to 2019 (Deliverable 1.5), shows promise and will be reanalyzed with model projections (Figure 4). Furthermore, a previously believed discrepancy of a negative trend in seasonal cycle amplitude with increasing CO_2 from satellite measurements, which has not been seen in model or in-situ data has been resolved and attributed to the different spatial sampling of the satellites contributing to the dataset (Figure 5). This is important, as the positive trend present in models and in-situ data was the basis for the emergent constraint on carbon-concentration feedback in Wenzel et al. (2016). Gier et al. (2020) also show that availability of column-integral CO_2 from satellite data provides a promising new way to evaluate performance of ESMs on a global scale and opens the door to emergent constraints based on spatial variability.

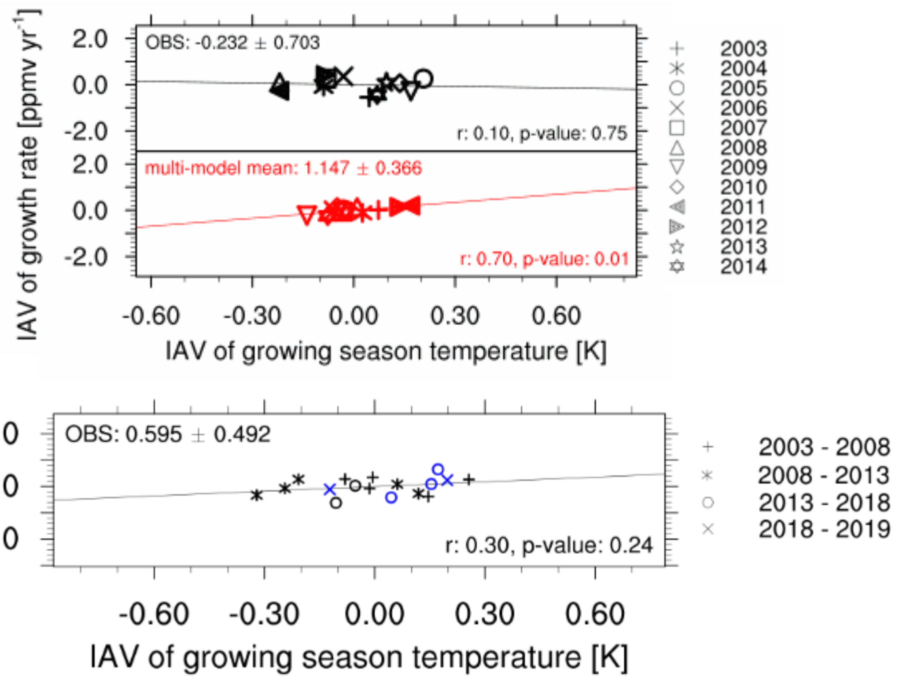

Figure 4. Trend of interannual variability of CO_2 growth rate with interannual variability of growing season temperature. Top: Shortened figure from Gier et al. (2020). **Bottom:** Updated figure for observations with new dataset from Deliverable 1.5. Blue denotes the additional years added compared to the dataset used in the publication.

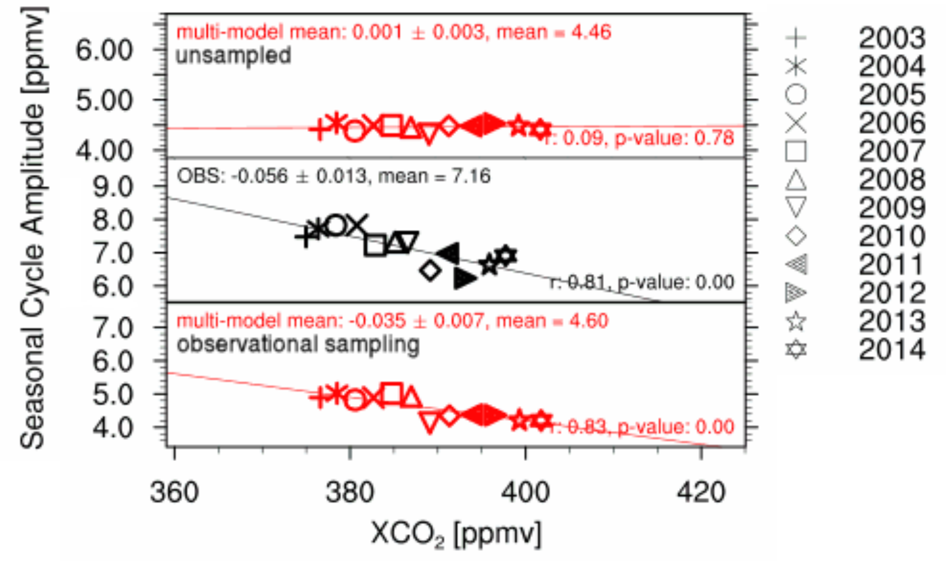

Figure 5. Seasonal cycle amplitude of column-averaged CO_2 (XCO_2) with respect to atmospheric XCO_2 content. Top: unsampled models. **Middle:** Observations. **Bottom:** models sampled as observations. Adapted from Gier et al. (2020).

5 Evaluation of emergent constraints on Equilibrium Climate Sensitivity

DLR systematically evaluated 11 published emergent constraints on Equilibrium Climate Sensitivity (ECS) that had mostly been derived from CMIP5 models on the Earth system models participating in the new CMIP6 phase (Schlund et al., 2020). The emergent-constrained best estimate of ECS increased from CMIP5 to CMIP6, with a best estimate range of 2.97–3.88 K for CMIP5 and 3.41–4.36 K for CMIP6. The findings support previous studies concluding that emergent constraints should be based on an independently verifiable physical mechanism, and that emergent constraints focusing on specific processes contributing to ECS are more promising than emergent constraints based on statistical model analysis.

6 Conclusions and Outlook

We are making progress and are on track to complete Task 3.1. We identified several key processes of carbon-climate interactions and established novel observational constraints both on land and ocean carbon processes. These results contribute to reduce uncertainty on carbon cycle feedbacks and on the transient climate response to cumulative carbon emissions. In this context, UNEXE is writing a subsection on Emergent Constraints for the carbon cycle chapter of the IPCC AR6. In addition, an online meeting – co-sponsored by 4C – on "Emergent Constraints and Tipping Points" is taking place on 23–26 November 2020 with over 150 participants. This is launching point from which we will build on our improved understanding and novel observational data to establish further emergent constraints for carbon and biogeochemical feedbacks.

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