CMIP6 simulations of GPP growth satisfy the constraint imposed by increasing CO$_2$ seasonal-cycle amplitude

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Abstract. The positive effect of rising atmospheric carbon dioxide concentration ([CO$_2$]) on gross primary production (GPP) is one of the factors that determine the strength of the carbon sink provided by terrestrial ecosystems. CMIP5 models tended to underestimate this effect. The study of CMIP6 simulations of GPP shows that GPP sensitivity to [CO$_2$] assumed by increasing CO$_2$ seasonal-cycle amplitude falls within the range of the values assumed by model runs. This make it possible to find the weights that force the weighted mean of GPP simulations to satisfy the constraint imposed by increasing CO$_2$ seasonal-cycle amplitude.

1. Background
Terrestrial ecosystems remove a large fraction of carbon dioxide released into the atmosphere from man-made sources [1]. The strength of the carbon sink provided by terrestrial ecosystems depends on several factors. One of them is the positive effect of rising mean annual atmospheric carbon dioxide concentration ([CO$_2$]) on gross primary production (GPP). The pause in the growth rate of [CO$_2$] has demonstrated again the importance of this effect [2].

Long-term atmospheric carbonyl sulfide (COS) records also show the large historical growth of GPP. The COS records, derived from ice-core and ambient air samples, imply a 31% increase in GPP during the twentieth century [3].

The further increase in GPP may essentially reduce the impact of anthropogenic CO$_2$ emissions. However, the previous generation of Earth System Models (ESMs) [4] tended to underestimate GPP sensitivity to [CO$_2$] growth [5,6]. Do the latest ESM versions [7], also underestimate it? This paper reports the results of the study undertaken to answer this question.

2. Methods
The observed growth of the atmospheric CO$_2$ seasonal-cycle amplitude ($A_{CO2}$) is thought to be a signal of increasing GPP [5,8,9]. Hence, $A_{CO2}$ sensitivity to [CO$_2$] provides an observational constraint to that of simulated GPP. The observational sensitivity of GPP ($S_0$) is calculated as $S_0 = 2.13 s_0$, where $s_0$ provides the best fit of $s_0([CO_2] - [CO_2])$ to $(A_{CO2} - A_{CO2})$, $A_{CO2}$ is the mean value of $A_{CO2}$, and $[CO_2]$ is the mean value of [CO$_2$] over the period from 1980 to 2014.
Similarly, the sensitivity of GPP simulated by the k-th model of CMIP6 ensemble ($S_k$) is calculated to provide the best fit of $S_k([CO_2] - \bar{[CO_2]})$ to $(A_{GPP,k} - \bar{A}_{GPP})$, where $A_{GPP,k}$ is the simulated GPP seasonal-cycle amplitude, and $\bar{A}_{GPP}$ is its mean value over the period from 1980 to 2014.

3. Results
The globally averaged monthly concentrations of atmospheric CO$_2$ (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html) suggest 15% increase in $A_{CO_2}$ during the 35-year period from 1980 to 2014. They also show (Fig. 1) a relatively high positive correlation ($R=0.8964$) between $A_{CO_2}$ and $[CO_2]$. The slope of the regression line, which is equal to 0.0106, gives $S_0=0.0225$ GtC ppm$^{-1}$, suggesting approximately 0.135 GtC month$^{-1}$ increase in the GPP seasonal-cycle amplitude during this period.

The monthly values of GPP simulated by IPSL-CM6A-LR model [10] imply even larger increase in the GPP seasonal-cycle amplitude and steeper slope of the regression line: $S_1=0.0249$ GtC ppm$^{-1}$ (Fig. 2). In contrast to IPSL-CM6A-LR simulations, CESM2 [11] simulations seemingly underestimate the increase in the GPP seasonal-cycle amplitude: $S_2=0.0170$ GtC ppm$^{-1}$ (Fig. 3).

The weights $w_1=0.6962$ and $w_2=0.3038$ force the weighted mean of GPP simulations, $w_1GPP_1 + w_2GPP_2$, to satisfy the observational constraint ($w_1S_1+w_2S_2=S_0$). Besides, they provide a relatively high correlation between observational and modelled $A_{GPP}$ anomalies (Fig. 4).

4. Discussion and conclusions
There is a tradition to present ESM projections as multimodel averages in IPCC reports [12]. The tradition is based on empirical evidence that, in general, a multimodel average is closer to observations than a single model projection. However, some studies show that giving equal weight to each model projections is not optimal compared to weighting based on model performance [13].

A weighted mean of GPP simulations could be considered as an emergent model of GPP, that is, the model emerged from CMIP6 simulations of GPP. Hence, it seems reasonable to weight the simulations in the way that makes the emergent model satisfy an observational constraint.

The statistical relationship between $A_{CO_2}$ and $[CO_2]$ is an observational constraint for

![Figure 1. The statistical relationship between the atmospheric CO2 seasonal-cycle amplitude ($A_{CO_2}$) and mean annual atmospheric carbon dioxide concentration ($[CO_2]$) during the 35-year period from 1980 to 2014 ($R=0.8964$). Data source: ESRL/NOAA (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html)](image1)

![Figure 2. The statistical relationship between the GPP seasonal-cycle amplitude simulated by IPSL-CM6A-LR and mean annual atmospheric carbon dioxide concentration ($[CO_2]$) during the 35-year period from 1980 to 2014 ($R=0.8799$).](image2)
GPP sensitivity to [CO2] that sufficiently informative in terms of the quality of model projections of GPP in the terrestrial ecosystems located north of 25°N. The terrestrial ecosystems located south of 25°N contribute a little to the seasonal cycle of CO2 exchange between the atmosphere and terrestrial ecosystems [9]. Therefore, this global-scale observational constraint does not constrain simulated GPP of the terrestrial ecosystems located south of 25°N.

Do CMIP6 simulations of GPP satisfy this global-scale observational constraint? If we all agree that not only multimodel average but also a weighted mean could be a valid ensemble-based projection of GPP, then the answer is positive.

CMIP6 simulations allows us to derive several emergent GPP models satisfying the observational constraint. The model, 0.6962GPP1 +0.3038GPP2, is one of them. Another model emerged from CMIP6 simulations is, 0.7241GPP1 +0.2759GPP3, where GPP3 is simulated with BCC-ESM1 model [14]. Moreover, these three simulations generate a spectrum of emergent models: 0.7108GPP1 +0.1446GPP2 +0.1446GPP3, 0.7064GPP1 +0.1929GPP2 +0.1007GPP3, and so on. Each of them satisfies the observational constraint, but some of them show higher correlation to observations than others. This makes it possible to select the best ensemble-based projection of GPP.

The variety of projections formed by the spectrum of emergent models characterizes the uncertainty of the ensemble-based projection of GPP. One may expect that projections produced by the constrained model ensemble vary in the less wide range than the projections of the un-constrained model ensemble. Testing this hypothesis is postponed to the time when the larger set of CMIP6 simulations of GPP becomes available.

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