Large historical growth in global terrestrial gross primary production

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Growth in terrestrial gross primary production (GPP) may provide a negative feedback for climate change[1,2]. It remains uncertain, however, to what extent biogeochemical processes can suppress global GPP growth[3]. In consequence, model estimates of terrestrial carbon storage and carbon cycle –climate feedbacks remain poorly constrained[4]. Here we present a global, measurement-based estimate of GPP growth during the twentieth century based on long-term atmospheric carbonyl sulphide (COS) records derived from ice core, firn, and ambient air samples[5]. We interpret these records using a model that simulates changes in COS concentration due to changes in its sources and sinks, including a large sink that is related to GPP. We find that the COS record is most consistent with climate-carbon cycle model simulations that assume large GPP growth during the twentieth century (31% ± 5%; mean ± 95% confidence interval). While this COS analysis does not directly constrain estimates of future GPP growth it provides a global-scale benchmark for historical carbon cycle simulations.

Climate change can be accelerated or dampened by feedbacks with terrestrial ecosystems[6]. The largest and most uncertain of these ecosystem feedbacks is enhanced photosynthetic CO_2 uptake resulting from increasing atmospheric CO_2 levels[4]. Clear evidence has been obtained from archived leaf material for the expected effect of increasing CO_2 on photosynthetic metabolism and much has been learnt about this feedback and other influences on photosynthesis (e.g. nitrogen deposition) from short-term and small-scale studies[1,3,7]. However, we lack global-scale, measurement-based estimates of the historical growth in photosynthetic CO_2 uptake (gross primary production, GPP). This knowledge gap leads to a wide spread of GPP growth estimates in different carbon-climate models, ranging from increases of +5% to +34% over the last century and +10% to +52% over the next century[3].

Here we seek to address this knowledge gap using carbonyl sulfide (COS) measurements to estimate historical growth of global GPP. This approach is based on the knowledge that the dominant global sink of atmospheric COS is uptake by terrestrial plant leaves through a process that is related to photosynthesis[8-11]. While other terrestrial ecosystem fluxes can be significant at times[12-14], the COS plant sink appears to be dominant at annual and continental scales[15-17]. The plant uptake is primarily compensated by ocean, industrial, and biomass burning sources[18-21]. Absent compensating changes in other sources or sinks, a change in plant uptake, and by relation GPP, would result in a new balance point in COS concentration with a relaxation time of about 2 years. This is the basis for our present analysis.

Our analysis focuses on the long-term atmospheric COS concentration record from Antarctica (Figure 1a)[5,22] which is a good proxy for the total atmospheric burden of COS. The Antarctic record derived from measurements of air trapped in Antarctic ice and firn, and from ambient air samples are consistent with independent long-term data from ground-based infrared solar spectra and global flask sampling (Figure 1b)[23-25]. The Antarctic record shows stability of COS concentrations in the preindustrial era, indicating that the natural sources and sinks were relatively stable over this time. The industrial period has an increase in COS (Figure 1a) that is unprecedented in the 54,300 year COS record.

This increase in Antarctic COS in the industrial period is clear evidence of a global industrial source[5]. In a separate study, we used economic data to construct the history of COS industrial sources[18]. While the magnitude of the industrial source is uncertain (Figure 2a), the relative change of the industrial source in time is well constrained by economic data (Figure 2b)[18].

In addition to the industrial source, we also consider the potential for other global sources and sinks to explain the trends in the Antarctic COS record. We analyze a wide range of source and sink estimates, including COS plant uptake linked to GPP (Figure 2c,d) – with GPP growth obtained from 11 different global carbon-climate models[3]. With these data sets in hand, we seek to identify the most plausible combination of source and sink simulations that explain the Antarctic COS record.

These simulations are based on a Monte Carlo, two-box, global modeling approach. The model output are historical time-series of atmospheric COS mixing ratios ([COS]) for the years 1900 through 2013 which we compare to the Antarctic COS record. The model input are time series estimates of global sources and sinks which are a function of their magnitude scalars (F) and normalized time trend vectors (Φ) as follows,

$$\frac{d[COS]}{dt} = F_{AN}\Phi_{AN} + F_{BB}\Phi_{BB} + F_{OC}\Phi_{OC} + F_{SS}\Phi_{SS} - F_P\Phi_P[COS] - F_I\Phi_I[COS] - F_S\Phi_S[COS] + \frac{1}{\tau}\Delta[COS] \quad (1)$$

including sources from industry (AN), biomass burning (BB), oceans (OC), and soils (SS), and sinks from terrestrial plants (P), atmospheric oxidation (I), and soils (S), and a transport rate (τ) scaled by the inter-hemispheric gradient ($\Delta[COS]$). The sources include direct emissions as well as indirect sources from emissions of short-lived precursors that are rapidly oxidized to COS in the atmosphere. Other sources and sinks may be important locally but were not included in our analysis because of their small contributions to global budgets.

The plant uptake was further divided into parameters for GPP (F_{GPP}, Φ_{GPP}) and the normalized ratio of COS plant uptake to GPP (F_{LRU}, Φ_{LRU}). For the normalized ratio of COS plant uptake to GPP (LRU), we considered both empirical and mechanistic models (see Supporting Information 4.1). GPP histories were either based on linear relationships to atmospheric CO_2 or obtained from 11 global carbon-climate models. We also used recent data-driven estimates of current global GPP as input for the COS simulations[26,27].

We explored the range of possible simulations using a Monte Carlo approach. In each Monte Carlo simulation, a set of F and Φ values was selected at random from uniform distributions of *a priori* values based on a review of the recent literature. We evaluated the agreement between the Monte Carlo simulation output and the Antarctic record using the root mean squared (RMS) error.

We found that the RMS error of the Monte Carlo simulations (Figure S11) was most sensitive to three input variables: ocean magnitude (F_{OC}), anthropogenic magnitude (F_{AN}) and the GPP time trend (Φ_{GPP}). Given the high sensitivity of these three variables, we explored optimization scenarios that adjust these three input variables in order to minimize the RMS error of the model output. We also considered optimization scenarios in which all input variables were adjusted to minimize the RMS error (Supporting Information 7).

Our first Monte Carlo simulations minimized the RMS error by adjusting the ocean magnitude scalar (F_{OC}) to best match the Antarctic record while randomly drawing from the *a priori* distributions for all other input variables (Figure 3a). These Monte Carlo simulations were generally consistent with the Antarctic record, but had significant RMS error (Figure 3a).

Next we explored the influence of the other two highly sensitive variables (F_{AN} and Φ_{GPP}). We considered simulations in which the ocean magnitude was optimized while the anthropogenic magnitude and GPP time trend were specified. When the GPP time trend was specified for low GPP growth, the RMS error remained high (Figure 3b). However, when the GPP trend was specified for high GPP growth, the simulations were able to capture the trends relatively well when combined with a large industrial magnitude (Figure 3c blue).

To account for interactions between input variables, we performed another set of Monte Carlo simulations in which these three sensitive input variables were simultaneously optimized (Figure 3d). While this set of simulations underestimated the peak COS mixing ratios in the 1980's, it resulted in a 50% reduction in RMS error (46% reduction in mean bias) relative to the simulations that only optimized F_{OC}. The optimal value of GPP growth from these simulations was 31% ± 5% (mean ± 95% confidence interval) which is at the high end of the historical range of +5% to +34% used in global carbon-climate model, providing a new global estimate of this largely unconstrained process.

For these simulations we used the mean Antarctic record, but we also repeated the analysis with individual Antarctic records (H1, H2, H3, EV, SIG from Fig. 1). Optimization simulations based on each individual Antarctic record gave similarly high optimal GPP growth results (95% confidence intervals range from 22% to 34% GPP growth).

While the preceding simulations used an a priori range of GPP time trends (Φ_{GPP}) that were modeled as a linear function of atmospheric CO_2, we also tested GPP histories from carbon-climate models (Figure 4). All COS simulations using these GPP histories resulted in reductions in RMS error relative to COS simulations that had no historical growth in GPP. Some GPP growth scenarios performed much better than others. The lowest RMS error was achieved with COS simulations that used GPP from carbon-climate models with the highest historical GPP growth rates (25% to 35% growth).

The simulations described so for had a range of GPP magnitudes (F_{GPP}) of 107 to 152 Pg C yr^{-1} that we obtained from carbon-climate models. However, measurement-based estimates of GPP are as large as 175 Pg C yr^{-1} [26,27]. After expanding our GPP range to include these higher estimates, we found a negligible effect on our optimal estimate of GPP growth (<1% change in RMS error and optimal GPP growth).

In carbon-climate models, GPP growth over the twentieth century is correlated with GPP growth over the twenty-first century (Figure 4b). For example, the UMD carbon-climate model has the lowest GPP growth rate over the twentieth century and it also simulates the lowest GPP growth rate and the weakest CO_2 fertilization effect over the twenty-first century. While this close relationship suggests that historical GPP analysis is relevant to projections, the relationship may be weakened in next generation models that include more restrictive nutrient parameterizations.

Our analysis is based on a global-scale constraint. Previously published estimates of GPP trends are not directly comparable because they were generally conducted at smaller spatial and at shorter temporal scales. Furthermore, previous evidence is mixed with respect to whether GPP growth is small or large. Plot-scale measurements from free-air CO_2 enrichment (FACE) experiments have had equivocal results which is likely due to the very limited number of experiments relative to the large spatial heterogeneity and long period for global GPP growth[1,3]. Of the two decadal forest FACE experiments, one experiment found an initial 23% GPP growth that declined over time to 9% due to nutrient limitation while the other experiment found a range of 22% to 30% GPP growth that was sustained. Observation-based estimates of current global GPP vary widely and are not yet useful for estimating temporal trends[26,27]. Long-term trends in satellite vegetation indices from the year 1982 show positive trends in greenness, but are more directly related to plant structure than GPP growth[28,29]. Change in background atmospheric CO_2 mixing ratios relative to fossil fuel emissions have been attributed to GPP growth, but the combined influence of photosynthesis and respiration makes it difficult to constrain GPP with CO_2 data alone[30]. Analysis of the historical growth in the seasonal atmospheric CO_2 amplitude is supportive of substantial GPP growth[31,32], but again cannot be directly compared to our work because these amplitude observations are confined to Northern Hemisphere high latitudes.

This COS analysis provides evidence of increases in historical GPP by 31% ± 5% (mean ± 95% confidence interval) over the twentieth century at the global scale. The range of growth rates indicated in this study provides a significant new constraint for evaluating historical simulations of earth system models, such as in fusion frameworks that combine multiple observations[33].

Figure Captions

Figure 1. Measurement-based histories of atmospheric carbonyl sulfide at South Pole and global sites. (a) Alternative histories that are consistent to varying degrees with measurements of COS at South Pole from air trapped in Antarctic ice and firn, and ambient air[5]. The flasks line (orange), is the annual mixing ratio for ambient-air collected at the South Pole[9]. **(b)** Comparison of normalized mixing ratios of COS for South Pole atmospheric firn histories, global surface flasks, and infrared FTIR solar observations[23-25]. The mean (black solid line) and standard deviation (grey shading) are plotted for the five firn histories. Global surface flask observations (thin pink lines; one line for each site) were obtained from the NOAA monitoring network (Barrow, Mauna Loa, Niwot Ridge, Alert, Cape Kumukahi, Mace Head, Cape Grim, Tutuila).

Figure 2. *A priori* distribution of the current magnitudes (a) and alternative time trends (b-d) for the dominant components of the global COS budget. Width of the bars in (a) are the uncertainties. Budget distributions for the year 2013 (a) are used to estimate the magnitude scalar parameters (*F's,* equation 1). The ranges are taken from the literature as the best estimates for the ocean and the minimum and maximum values for the other budget component (see supporting information Sections 3 and 4). Alternative scenarios representing the range of plausible time trends are plotted for industry (b), oceans (c), and plant uptake (d). Time trends for the smaller budget components (biomass burning, soils, and atmospheric oxidation) are also included in the model and are presented in the supporting information. Monte Carlo simulations randomly draw from *a priori* distributions to simulate the COS mixing ratio history. Alternative industrial time trends shown here represent extreme cases for maximizing the contributions from either the rayon, aluminum, or coal sectors. Additional details on the industrial source and other budget components are provided in the supporting information.

Figure 3. Long-term trends in global atmospheric COS concentrations. The Antarctic record (grey) is the mean of five firn histories[5]. Modeled concentrations are plotted for Monte Carlo optimization simulations. Optimization minimizes the model root mean squared (RMS) mixing ratio error with respect to the difference between the modeled and observed time series from 1900 to 2013. The RMS error is provided in the legend as the mean ± 95% confidence interval. In the "Optimize F_{OC}" simulations (a), the ocean magnitude scalar (F_{OC}) is optimized while all other variables are drawn at random from *a priori* distributions. In the "Min GPP Growth" simulations (b), F_{OC} is optimized, the GPP time trend (Φ_{GPP}) is set to the minimum *a priori* history (5% growth), the industrial magnitude (F_{AN}) is specified (see legend), and all other parameters were randomly drawn from *a priori* distributions. The "Max GPP Growth" simulations (c) are equivalent except Φ_{GPP} is set to the maximum *a priori* growth history (34% growth). Additional simulations optimizes F_{OC}, F_{AN}, and Φ_{GPP}, while making random draws from *a priori* distributions for all other parameters (d). Model uncertainty (green/blue shaded areas) accounts for uncertainty in the non-optimized source and sink parameters (standard deviation, n = 100). Observation uncertainty (grey shaded area) accounts for the standard deviation between the five firn histories and measurement uncertainty.

Figure 4. a) Atmospheric COS model error using a range of GPP histories. GPP growth over the twentieth century were obtained from published carbon-climate models (UMD, FRCGC, etc.) and three hypothetical scenarios with more extreme GPP growth (G40 - 40% growth, G45 - 45% growth, G50 - 50% growth). Each GPP history was used as input for a different set of Monte Carlo atmospheric COS simulations. The root mean squared (RMS) error for each set of COS simulations was calculated using the difference between the simulated COS mixing ratios and the atmospheric COS mixing ratio histories derived from Antarctic ice core, firn air, and ambient flask samples (years 1900 through 2013)[5]. The simulations optimized two variables (magnitude scalar for the ocean and anthropogenic sources) and obtained estimates of all other parameters through random draws from their *a priori* distributions. Error bars are standard deviations for each set of Monte Carlo simulations (n = 100). (b) The GPP growth in each carbon-climate model is compared for simulations over the twentieth century and simulations in the twenty-first century.

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Contributions

J.E.C. and J.A.B. designed the research. J.E.C. conducted all simulations and analysis except ocean simulations which run by L.B and T.L and MCMC scenarios run by M.L. J.E.C. wrote the paper with input from all co-authors.

Competing financial interests

The authors declare no competing financial interests.

Data Availability

Data are available from the authors upon request.

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