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Role of CO₂, climate and land use in regulating the seasonal amplitude increase of carbon fluxes in terrestrial ecosystems: a multimodel analysis

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Abstract. We examined the net terrestrial carbon flux to the atmosphere ($F_{TA}$) simulated by nine models from the TRENDY dynamic global vegetation model project for its seasonal cycle and amplitude trend during 1961–2012. While some models exhibit similar phase and amplitude compared to atmospheric inversions, with spring drawdown and autumn rebound, others tend to rebound early in summer. The model ensemble mean underestimates the magnitude of the seasonal cycle by 40 % compared to atmospheric inversions. Global $F_{TA}$ amplitude increase ($19 \pm 8 \%$) and its decadal variability from the model ensemble are generally consistent with constraints from surface atmosphere observations. However, models disagree on attribution of this long-term amplitude increase, with factorial experiments attributing $83 \pm 56 \%$, $-3 \pm 74$ and $20 \pm 30 \%$ to rising CO₂, climate change and land use/cover change, respectively. Seven out of the nine models suggest that CO₂ fertilization is the strongest control – with the notable exception of VEGAS, which attributes approximately equally to the three factors. Generally, all models display an enhanced seasonality over the boreal region in response to high-latitude warming, but a negative climate contribution from part of the Northern Hemisphere temperate region, and the net result is a divergence over climate change effect. Six of the nine models show that land use/cover change amplifies the seasonal cycle of global $F_{TA}$: some are due to forest regrowth, while others are caused by...
crop expansion or agricultural intensification, as revealed by their divergent spatial patterns. We also discovered a moderate cross-model correlation between $F_{TA}$ amplitude increase and increase in land carbon sink ($R^2 = 0.61$). Our results suggest that models can show similar results in some benchmarks with different underlying mechanisms; therefore, the spatial traits of CO$_2$ fertilization, climate change and land use/cover changes are crucial in determining the right mechanisms in seasonal carbon cycle change as well as mean sink change.

1 Introduction

The amplitude of the atmospheric CO$_2$ seasonal cycle is largely controlled by vegetation growth and decay in the Northern Hemisphere (NH) (Bacastow et al., 1985; Graven et al., 2013; Hall et al., 1975; Heimann et al., 1998; Pearman and Hyson, 1980; Randerson et al., 1997). Since 1958, atmospheric CO$_2$ measurements at Mauna Loa, Hawai‘i, have tracked a 15% rise in the peak-to-trough amplitude of the detrended CO$_2$ seasonal cycle (Zeng et al., 2014), suggesting an enhanced ecosystem activity due to changes in the strength of the ecosystem’s production and respiration and to a shift in the timing of their phases (Randerson et al., 1997). In addition, some evidence suggests a latitudinal gradient in CO$_2$ amplitude increase in the NH, with a larger increase at Pt. Barrow, Alaska (0.6 % yr$^{-1}$) than at Mauna Loa (0.32 % yr$^{-1}$) (Graven et al., 2013; Randerson et al., 1999). Previous studies have attempted to attribute the long-term CO$_2$ amplitude increase to stimulated vegetation growth under rising CO$_2$ and increasing nitrogen deposition (Bacastow et al., 1985; Reich and Hobbie, 2013; Sillen and Dieleman, 2012). Another possible explanation offered is the effect of a warmer climate, especially in boreal and temperate regions, on the lengthening of growing season, enhanced plant growth (Keeling et al., 1996; Keenan et al., 2014), vegetation phenology (Thompson, 2011), ecosystem composition and structure (Graven et al., 2013). The agricultural green revolution, due to widespread irrigation, increasing management intensity and high-yield crop selection, could also contribute to the dynamics of the CO$_2$ seasonal amplitude (Zeng et al., 2014; Gray et al., 2014). Even though these studies are helpful in understanding the role of CO$_2$, climate and land use/cover changes, detailed knowledge of the relative contribution of these factors is still lacking.

Dynamic vegetation models are useful tools not only to disentangle effects of various mechanisms but also to offer insights on how terrestrial ecosystems respond to external changes. Attribution of the role of CO$_2$, climate and land use has been attempted with a single model (Zeng et al., 2014), but comprehensive multimodel assessment efforts are still missing. Two important questions must be addressed in such efforts, namely, whether the models can simulate observed CO$_2$ amplitude increase, and to what extent their factorial attributions agree. For the first question, the Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models seem to be able to simulate the amplitude increase measured at the Mauna Loa and Point Barrow surface stations (Zhao and Zeng, 2014); however, they underestimate the amplitude increase compared to upper air (3–6 km) observations significantly (Graven et al., 2013). It is possible that uncertainty in vertical mixing in atmospheric transport models (Yang et al., 2007), instead of biases in dynamic vegetation models themselves, causes the severe underestimation of upper air CO$_2$ amplitude increase. For the second question, in a unique modeling study conducted by McGuire et al. (2001), both CO$_2$ fertilization and land use/cover changes were found to contribute to CO$_2$ amplitude increase at Mauna Loa, but the four models disagreed on the role of climate and the relative importance of the factors they studied. Since then, no published study has explored the reliability of models’ simulation of seasonal carbon cycle and quantified the relative contribution of various factors affecting it.

An important trait of the three main factors (i.e., CO$_2$, climate and land use/cover change) we consider in this study is their different regional influence. Rising CO$_2$ would likely enhance productivity in all ecosystems. Climate warming may affect high-latitude ecosystems more than tropical and subtropical vegetation, and droughts would severely affect plant growth in water-limited regions. Similarly, the effect of land use/cover change may be largely confined to agricultural fields and places with land conversion, mostly in midlatitude regions. Because of their different spatial traits, it is possible to determine which factor is most important with strategically placed observations. Forkel et al. (2016) recently derived a latitudinal gradient of CO$_2$ amplitude increase based on CO$_2$ observational data, which would provide strong support that high-latitude warming is the most important factor. However, with only two sites north of 60° N, the robustness of the result is limited. In lieu of additional observational evidence, as a first step, it is necessary to investigate how the models represent the regional patterns of seasonal change of carbon flux.

A number of recent studies have addressed different aspects of the seasonal amplitude topic. For example, the latitudinal gradient of CO$_2$ seasonal amplitude was used as benchmark in assessing the performance of JSBACH model (Dalmonech and Zaehle, 2013; Dalmonech et al., 2015). Based on a model intercomparison project – Multiscale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP; Huntzinger et al., 2013; Wei et al., 2014) – Ito et al. (2016) focused on examining the relative contribution of CO$_2$, climate and land use/cover changes, but little model evaluation was performed. In order to further explore and understand the seasonal fluctuation of carbon fluxes, a more comprehensive study including both the model evaluation and factorial analysis is needed. The TRENDY model intercomparison project provides a nice platform for such analysis (Sitch et al., 2015).
Site-level model–data comparison of seasonal carbon fluxes has been performed extensively in Peng et al. (2015) for the first synthesis of TRENDY models. Using both the second synthesis of TRENDY models simulations and observations, in this study we aim to achieve two main goals. (1) Assess how well the models simulate the climatological seasonal cycle and seasonal amplitude change of the carbon flux against a number of observational-based datasets (CO₂ observations and atmospheric inversions). (2) Analyze the relative contribution from the three main factors (CO₂ fertilization, climate and land use/cover change) to the seasonal amplitude increase, both at the global and regional level.

2 Method

2.1 Terrestrial ecosystem models and TRENDY experiment design

Monthly net biosphere production (NBP) simulations for 1961–2012 from nine TRENDY models participating in the Global Carbon Project (Le Quéré et al., 2014) were examined (Table 1). A set of three offline experiments driven by either constant or varying climate data and other input such as atmospheric CO₂ and land use/cover forcing were designed in the TRENDY project to differentiate the role of CO₂, climate and land use (Table 2). We primarily evaluated results from the S3 experiment, where the models are driven by time-varying forcing data (Appendix A). In addition, we also used results from the S1 and S2 experiments.

2.2 Observations and observational-based estimates

In light of the large difference in the Coupled Climate Carbon Cycle Model Intercomparison Project (C³MIP) models’ sensitivity to CO₂ change (Friedlingstein et al., 2013), it is essential to evaluate whether the terrestrial biosphere models are able to capture important features of CO₂ seasonal cycle. The scarcity of observational constraints, especially the lack of long-term continuous observational records, limits our capacity to fully evaluate the dynamic processes in terrestrial ecosystem models. Nevertheless, in this study we make a first-order approximation of the evolution of the global CO₂ seasonal cycle, using limited CO₂ observation data. Following Zeng et al. (2014), monthly Mauna Loa records from 1961 to 2012 and a global monthly CO₂ index for the period of 1981–2012 were retrieved from NOAA’s Earth System Research Laboratory (ESRL; www.esrl.noaa.gov/gmd/ccgg/trends/). Details on the data processing, choice of stations and quality control procedures in deriving the global CO₂ index (globally averaged CO₂ concentration) can be found in Thoning et al. (1989) and Masarie and Tans (1995).

Fluxes from process-based models can be directly compared with monthly gridded fluxes from atmospheric inversions, which combine measured atmospheric CO₂ concentration at multiple sites across the globe with atmospheric transport driven by meteorological data. Two representative inversions, Jena (Jena81 and Jena99, Rödenbeck et al., 2003) and the CarbonTracker (Peters et al., 2007), are included for comparison (Appendix B). For an exhaustive intercomparison of the atmospheric inversions, please refer to Peylin et al. (2013).

2.3 Calculating the seasonal cycle and its amplitude change

All monthly NBP- and inversion-derived fluxes are first resampled (box averaging, conserving mass) to a uniform 0.5° × 0.5° global grid in units of kg C m⁻² yr⁻¹. For the TRENDY model simulations, we further define net carbon flux from the land to the atmosphere (F_TA), which simply reverses the sign of NBP, so that positive F_TA indicates net carbon release to the atmosphere, and negative F_TA indicates net carbon uptake. F_TA represents the sum of residual land sink and land use emission, including fluxes from ecosystem production and respiration, fire, harvest, etc.; although some models may not simulate all the processes. Changes in global atmospheric CO₂ concentration are then equal to ΔF_TA plus ocean–atmosphere flux and fossil fuel emission. For inversion-derived fluxes, only terrestrial ecosystem fluxes are used (optimized global biosphere fluxes plus fire fluxes in CarbonTracker), which are conceptually similar to F_TA, except that atmospheric transport is included. Atmospheric transport can significantly affect local carbon fluxes (Randerson et al., 1997); however, the impact is limited on global and large zonal band totals.

The seasonal amplitudes of Mauna Loa Observatory CO₂ growth rate, global CO₂ growth rate and fluxes from model simulations and inversions are processed with a curve fitting package called CCGCRV from NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/mlb/crvfit/crvfit.html). This package first filtered out the high-frequency signals with a series of internal steps involving polynomial and harmonic fitting, detrending and band-pass filtering, and then the amplitude is defined as the difference between each year’s maximum and minimum. For the latitudinal plots only, we simply use maximum and minimum of each year to define the seasonal amplitude without first filtering the data. Previous studies (Graven et al., 2013; Randerson et al., 1997) have established that F_TA accounts for most of seasonal amplitude change from atmospheric CO₂, and the Mauna Loa CO₂ record is considered to represent the evolution of global mean CO₂ well (Kaminski et al., 1996). Therefore, similar to our earlier work (Zeng et al., 2014), we evaluated the amplitude change of modeled ΔF_TA with Mauna Loa CO₂, ESRL’s global CO₂ and the atmospheric inversions, to assess whether the models are able to capture both the global trend and latitudinal patterns. For relative amplitude changes, we compute the multimodel ensemble mean after deriving the time series (relative to their 1961–1970 mean) from individual model simulations, so that models with large amplitude change would not have a huge ef-
2.5 Spatial attribution

Vegetation models, such as those shown in previous sensitivity runs, are likely small in some of the current generation dynamic vegetation models (e.g., CHIDEE and VEGAS) simulate a mean global seasonal cycle of similar amplitude and phase compared with the Jena99 and CarbonTracker inversions (Fig. 1, Table 3). The model ensemble annual mean seasonal cycle simulation flux for 2001–2010, 30 % smaller than the inversions (Table 3). In some cases, notably different. As a result, the models’ ensemble global $F_{TA}$ maximum-minus-minimum seasonal amplitude trends would then approximately be equal to the trend of global $F_{TA}$ maximum-minus-minimum seasonal amplitude.

3 Results

3.1 Mean seasonal cycle of $F_{TA}$

Four of the nine models (CLM4.5BGC, LPX-Bern, ORCHIDEE and VEGAS) simulate a mean global $F_{TA}$ seasonal cycle of similar amplitude and phase compared with the Jena99 and CarbonTracker inversions (Fig. 1, Table 3). The other five models have much smaller seasonal amplitude than inversions, and the shape of the seasonal cycle is also notably different. As a result, the models’ ensemble global $F_{TA}$ has seasonal amplitude of 26.1 Pg C yr$^{-1}$ during 2001–2010, about 40 % smaller than the inversions (Fig. 4 inset, Table 3). The model ensemble annual mean $F_{TA}$ (residual land sink plus land use emission) is $-1.1$ Pg C yr$^{-1}$ for 2001–2010, 30 % smaller than the inversions (Table 3). In some cases, notably different. As a result, the models’ ensemble global $F_{TA}$ maximum-minus-minimum seasonal amplitude trends would then approximately be equal to the trend of global $F_{TA}$ maximum-minus-minimum seasonal amplitude.

2.4 Factorial analyses

Relative amplitudes for 1961–2012 (relative to 1961–1970 mean seasonal amplitude) from the experiments S1, S2 and S3, respectively, are calculated using the CCGCRV package for each model, and a linear trend (in % yr$^{-1}$) is determined for that period. We use relative amplitude for percentage change to minimize impacts of some differing implementation choices like climate data in S1 (CO$_2$) among the models. The effect of CO$_2$ on the relative amplitude change is represented by a trend of S1 (CO$_2$ only) results; the S2 (CO$_2$+climate) results show a trend that is the sum of CO$_2$ and climate effects, and the S3 (CO$_2$+climate+land use/cover) simulations include trends from time-varying CO$_2$, climate and land use/cover change (abbreviated as land use for text and figures). For simplicity, the effect of “climatic” as used in this paper includes the synergy of CO$_2$ and climate, and similarly the effect of “land use/cover” also includes the synergy terms. Therefore, the effects of CO$_2$, climate and land use/cover are then quantified as the trend for S1, the trend of S2 minus the S1 trend and the trend of S3 minus the S2 trend, respectively. Note that the synergy terms are likely small in some of the current generation dynamic vegetation models, such as those shown in previous sensitivity experiment results (Zeng et al., 2014).

Table 1. Basic information for the nine TRENDY models used in this study.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Abbreviation</th>
<th>Spatial resolution</th>
<th>Nitrogen cycle</th>
<th>Fire simulation</th>
<th>Harvest flux</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community Land Model 4.5</td>
<td>CLM4.5BGC</td>
<td>1.25° × 0.94°</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>Oleson et al. (2013)</td>
</tr>
<tr>
<td>ISAM</td>
<td>ISAM</td>
<td>0.5° × 0.5°</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>Jain et al. (2013)</td>
</tr>
<tr>
<td>Joint UK Land Environment Simulator</td>
<td>JULES</td>
<td>1.875° × 1.25°</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>Clark et al. (2011)</td>
</tr>
<tr>
<td>Lund-Potsdam-Jena</td>
<td>LPJ</td>
<td>0.5° × 0.5°</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Sitch et al. (2003)</td>
</tr>
<tr>
<td>LPX-Bern</td>
<td>LPX-Bern</td>
<td>0.5° × 0.5°</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Stocker et al. (2014)</td>
</tr>
<tr>
<td>O-CN</td>
<td>OCN</td>
<td>0.5° × 0.5°</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>Zaehle and Friend (2010)</td>
</tr>
<tr>
<td>ORCHIDEE</td>
<td>ORCHIDEE</td>
<td>2° × 2°</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>Krinner et al. (2005)</td>
</tr>
<tr>
<td>VEGAS</td>
<td>VEGAS</td>
<td>0.5° × 0.5°</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>Zeng et al. (2005b)</td>
</tr>
<tr>
<td>VISIT</td>
<td>VISIT</td>
<td>0.5° × 0.5°</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>Kato et al. (2013)</td>
</tr>
</tbody>
</table>
models (ISAM, JULES and LPJ for the northern tempera-
ture region in Fig. 2) $F_{TA}$ rebounds back quickly, resul-
ting in a late summer $F_{TA}$ maximum. The midsummer re-
bound is unlikely a model response to pronounced seasonal
drought after 2000, as it is persistent in the mean seasonal
cycle over every decade since 1961. A probable cause is the
strong exponential response of soil respiration to temperature
increase, which may lead to heterotopic respiration higher
than net primary production (NPP) in summer. For example,
HadGEM2-ES and HadCM3LC, which employ a forerunner
of JULES3.2 used in this study, are found to have a com-
paratively better simulation of the seasonal cycle (Collins et
al., 2011), due to a combination of a more sensitive temper-
ature rate modifier combined with a larger seasonal soil tem-
perature that is used in the later version of JULES. Alexan-
drov (2014) shows that both the amplitude underestimation
and phase shift of $F_{TA}$ seasonal cycle can be improved by
increasing water use efficiency, decreasing temperature depen-
dence of heterotrophic respiration and increasing the share
of quickly decaying litterfall. Another probable factor is the
simulation of plant phenology. With the help of remote sens-
ing data, better phenology in model simulation has been
shown to improve seasonal cycle simulation of carbon flux
(Forkel et al., 2014). Additionally, the effect of carbon re-
lease from crop harvest is considered. If harvested carbon is
the main cause for the midsummer rebound in some mod-
els, the rebound should be much less pronounced for the S2
(constant 1860 land use/cover) experiment, given that crop-
land area in 1860 is less than half of the 2000 level. However,
based on the comparison between the S2 and S3 experiments
over the global and northern temperate (major crop belts)
$F_{TA}$ seasonal cycle (Figs. S1 and S2 in the Supplement),
the impact of harvested carbon flux is unlikely to explain
the midsummer rebound. This is probably due to modeling
efforts to prevent the sudden release of harvested carbon. In-
stead, carbon release of harvested products and/or their resid-
uals is usually either spread over 12 months (i.e., LPJ, LPX-
Bern, OCN, ORCHIDEE), or it enters soil litter carbon pool
(i.e., ISAM) for subsequent decomposition over time.

TRENDY models and inversions agree best over the boreal
region (Fig. 2a). While underestimating the global seasonal
cycle, LPJ and VISIT both simulate similar boreal $F_{TA}$ am-
plitude as inversions. In addition to ORCHIDEE and

VEGAS, LPJ and LPX-Bern also simulate maximum $CO_2$
drawdown in July for the boreal region, same as the inver-
sions, while the other five models have the $F_{TA}$ minimum in
June. Large model spread is present for the northern tempera-
ture region, especially in summer. Both inversions and models
agree marginally over the phase of the $F_{TA}$ seasonal cycle in
the tropics. The northern and southern tropics seasonally cyclen
which are largely out of phase except for LPJ (Fig. 2c, d), due to the seasonal movement of the tropical rain belt in
the intertropical convergence zone (ITCZ). The southern ex-
tratropics exhibit even smaller $F_{TA}$ amplitude due to the rel-
atively small biomass of the southern extratropics, and most
tropics (0–23.5° N and southern tropics (0–23.5° S) from nine TRENDY models and two inversions, Jena99 and CarbonTracker, averaged over 2001–2010.

The latitudinal pattern of the multimodel median $F_{TA}$ am-
plitude is remarkably similar to the inversions (Fig. 3). A
notable feature is the large seasonality over the NH midl-
itude to high-latitude region driven by temperature contrast
between winter and summer. The model median also cap-
Table 2. Experimental design of TRENDY simulations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Time period</th>
<th>Atmospheric CO₂</th>
<th>Climate forcing</th>
<th>Land-use history**</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1901–2012</td>
<td>Time-varying</td>
<td>Constant*</td>
<td>Constant (1860)</td>
</tr>
<tr>
<td>S2</td>
<td>Time-varying</td>
<td></td>
<td>Time-varying</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Time-varying</td>
<td></td>
<td>Time-varying</td>
<td></td>
</tr>
</tbody>
</table>

* Constant climate state is achieved by repeated or randomized or fixed climate cycles depending on each model.
** Only the crop, pasture and wood harvest information is included, so land use in this study refers specifically to the related agricultural and forestry processes.

Table 3. Global mean net land carbon flux, seasonal amplitude, the maximum and minimum months of \( F_{TA} \) for the nine TRENDY models and their ensemble mean during 1961–1970 and 2001–2010 periods. For the later period, characteristics of the atmosphere inversions Jena99 and CarbonTracker are also listed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Net carbon flux ( (\text{Pg C yr}^{-1}) )</th>
<th>Seasonal amplitude ( (\text{Pg C yr}^{-1}) )</th>
<th>( F_{TA} ) minimum</th>
<th>( F_{TA} ) maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLM4.5BGC</td>
<td>0.1</td>
<td>-2.4</td>
<td>38.4</td>
<td>44.3</td>
</tr>
<tr>
<td>ISAM</td>
<td>0.7</td>
<td>0.0</td>
<td>17.6</td>
<td>19.1</td>
</tr>
<tr>
<td>JULES</td>
<td>-0.2</td>
<td>-1.7</td>
<td>15.1</td>
<td>19.0</td>
</tr>
<tr>
<td>LPJ</td>
<td>1.3</td>
<td>-0.6</td>
<td>18.6</td>
<td>23.4</td>
</tr>
<tr>
<td>LPX-Bern</td>
<td>0.6</td>
<td>0.0</td>
<td>33.0</td>
<td>37.9</td>
</tr>
<tr>
<td>OCN</td>
<td>0.9</td>
<td>-1.8</td>
<td>16.1</td>
<td>21.6</td>
</tr>
<tr>
<td>ORCHIDEE</td>
<td>0.1</td>
<td>-0.7</td>
<td>35.7</td>
<td>39.9</td>
</tr>
<tr>
<td>VEGAS</td>
<td>-0.4</td>
<td>-1.5</td>
<td>40.7</td>
<td>46.7</td>
</tr>
<tr>
<td>VISIT</td>
<td>0.2</td>
<td>-1.4</td>
<td>25.3</td>
<td>28.9</td>
</tr>
<tr>
<td>Ensemble</td>
<td>0.4</td>
<td>-1.1</td>
<td>22.4</td>
<td>26.1</td>
</tr>
<tr>
<td>Jena99</td>
<td>-1.7</td>
<td></td>
<td>46.8</td>
<td>49.1</td>
</tr>
<tr>
<td>CarbonTracker</td>
<td>-1.6</td>
<td></td>
<td>39.9</td>
<td>41.6</td>
</tr>
</tbody>
</table>

Figure 3. Latitudinal dependence of the seasonal amplitude of land–atmosphere carbon flux from the TRENDY multimodel median (red line, and the pink shading indicates the 10 to 90 percentile range of model spread), two atmospheric CO₂ inversions, Jena99 (black dashed line) and CarbonTracker (gray dashed line), and each individual model (thin line). Fluxes are first resampled to \( 2.5^\circ \times 2.5^\circ \), then summed over each \( 2.5^\circ \) latitude band \( (\text{Pg C yr}^{-1} \text{ per } 2.5^\circ \text{ latitude}) \) for the TRENDY ensemble and inversions.

Note that even at the same latitude band, factors like monsoons, droughts and spring snowmelt, etc. could lead to longitudinal difference in the phase of seasonal cycle (Figs. S3 and S4).
Figure 4. Trends for seasonal amplitude of TRENDY simulated multimodel ensemble mean land–atmosphere carbon flux $F_{TA}$ (black), of the Mauna Loa Observatory (MLO) CO$_2$ mixing ratio (CO$_2$MLO, green) and global CO$_2$ mixing ratio (CO$_2$GLOBAL, purple), and of $F_{TA}$ from atmospheric inversions of Jena81 (red), Jena99 (orange) and CarbonTracker (blue). The trends are relative to the 1961–1970 mean for the TRENDY ensemble and Mauna Loa CO$_2$ and the other time series are offset to have the same mean as the TRENDY ensemble for the last 10 years (2003–2012). A 9-year Gaussian smoothing (Harris, 1978) removes interannual variability for all time series, and its 1σ standard deviation is shown for CO$_2$MLO (green shading). Note that the gray shading here instead indicates 1σ models’ spread, which is generally larger than the standard deviation of the TRENDY ensemble’s decadal variability. Inset: average seasonal cycles of models’ ensemble mean $F_{TA}$ (Pg C yr$^{-1}$) for the two periods: 1961–1970 (dashed line; lighter gray shading indicates 1σ model spread) and 2001–2010 (solid; darker gray shading indicates 1σ model spread), revealing enhanced CO$_2$ uptake during spring/summer growing season. Mean seasonal cycles global $F_{TA}$ from the atmospheric inversions for 2001–2010 are also shown (same color as the main figure) for comparison.

3.2 Temporal evolution of $F_{TA}$ seasonal amplitude

The seasonal amplitude of global total $F_{TA}$ from the TRENDY model ensemble for 1961–2012 shows a long-term rise of 19 ± 8 %, with large decadal variability (Fig. 4). Similarly, the seasonal amplitude of CO$_2$ at Mauna Loa increases by 15 ± 3 % (0.85 ± 0.18 ppm) for the same period. This amplitude increase appears mostly as an earlier and deeper drawdown during the spring and summer growing season, mostly in June and July (Table 3, Fig. 4 inset). Changes in trend of yearly minima (indicating peak carbon uptake) and yearly maxima (dominated by respiration) contribute 91 ± 10 and 9 ± 10 % to the $F_{TA}$ amplitude increase, respectively. Gurney and Eckels (2011) suggest trend in respiration increase is more important, but they averaged all months instead of using maxima and minima in their amplitude definition. The multimodel ensemble mean tracks some characteristics of the decadal variability reflected by the Mauna Loa record: stable in the 1960s, rise in the 1970–1980s, rapid rise in the early 2000s and decrease in the most recent 10 years. Strictly speaking, Mauna Loa CO$_2$ data are not directly comparable with simulated global $F_{TA}$ because this single station is also influenced by atmospheric circulation as well as fossil fuel emissions and ocean–atmosphere fluxes. Nevertheless, the comparison of the long-term amplitude trend is still valuable because the Mauna Loa Observatory data constitute the only long-term record, and it is generally considered representative of global mean CO$_2$ (Heimann, 1986; Kaminski et al., 1996). The global total CO$_2$ index (CO$_2$GLOBAL) and $F_{TA}$ from three atmospheric inversions are also included in the comparison. All data (Jena81, CO$_2$MLO, CO$_2$GLOBAL) show a decrease in seasonal amplitude in the late 1990s, possibly related to drought in the Northern Hemisphere midlatitude regions (Buermann et al., 2007; Zeng et al., 2005a), and about half of the models (LPJ, OCN, ORCHIDEE, VEGAS) also exhibit similar change (Fig. 7). Details on models’ $F_{TA}$ global and regional changes in 2001–2010 compared to 1961–1970 are listed in Table 4.

3.2.1 Attribution of global and regional $F_{TA}$ seasonal amplitude

Models agree on increase of global $F_{TA}$ seasonal amplitude during 1961–2012, but they disagree even in sign in the contribution of the different factors (Fig. 5). By computing the ratios between amplitude trends from rising CO$_2$, climate change and land use/cover change with the total trend for each model, we find that the effect of varying CO$_2$, climate change and land use/cover contribute 83 ± 56, −3 ± 74 and 20 ± 30 % to the simulated global $F_{TA}$ amplitude increase. All models simulate increasing amplitude for total $F_{TA}$ in the boreal (50°–90° N) and northern temperate (23.5°–50° N) regions, and most models also indicate amplitude increase in the northern (0°–23.5° N) and southern tropics (0°–23.5° S) (Fig. 6). There is less agreement on the sign of amplitude change among the models in the southern extratropics (23.5–
90° S). Individual models’ global and regional trends of $F_{\text{TA}}$ amplitude attributable to the three factors (CO$_2$, climate and land use/cover) are listed in Table S1. For most models, latitudinal contribution to global $F_{\text{TA}}$ amplitude (computed with $F_{\text{TA}}^{\text{lat}}$) shows that the pronounced midlatitude to high-latitude maxima in the NH dominate the simulated amplitude increase over 1961–2012 (Fig. S8, red dashed line for S3 results). All models also indicate a negative contribution from at least part of the northern temperate region. The four models (CLM4.5BGC, VEGAS, LPX-Bern and ORCHIDEE) that simulate a more realistic mean global $F_{\text{TA}}$ seasonal cycle (Fig. 1) are also relatively close in global $F_{\text{TA}}$ seasonal amplitude, clustering around an increase of 14 ± 3 % during 1961–2012. Furthermore, they all suggest that land use/cover change contributes positively to global $F_{\text{TA}}$ seasonal amplitude increase. On the other hand, four of the remaining five models (OCN, LPJ, JULES, VISIT) show a much larger rate of increase (26 ± 3 %), but given that these four models underestimate the mean amplitude by about 50 %, the absolute increase in global $F_{\text{TA}}$ seasonal amplitude is actually similar (about 5 Pg C yr$^{-1}$) between the two groups of models. ISAM is an exception; it both underestimates the mean global $F_{\text{TA}}$ seasonal amplitude and has the lowest rate of amplitude increase.

### 3.2.2 The rising CO$_2$ factor

Seven of the nine models suggest that the CO$_2$ fertilization effect is most responsible for the increase in the amplitude of global $F_{\text{TA}}$, while VEGAS attributes it to be approximately equal among the three factors (Fig. 5). The CO$_2$ fertilization effect alone seems to cause most of the amplitude increase in a majority of models, with notable contribution from climate change and land use/cover change in CLM4.5BGC and VEGAS (Fig. 7). The effect of rising CO$_2$ appears to be slightly negative for JULES, possibly reflecting an offsetting of the strong seasonal soil respiration response found in this model. For each model, rising CO$_2$ in the boreal, northern temperate and the southern extratropics leads to a similar trend (Fig. 6). The magnitude of this trend may indicate each model’s differing strength for CO$_2$ fertilization. This is possibly due to similar phases of $F_{\text{TA}}$ seasonal cycle within the three regions that are mainly driven by climatological temperature contrast. The positive amplitude trend in the carbon flux of the northern and southern tropics from CO$_2$ fertilization is similar, and they likely would cancel out each other because their seasonal cycles are largely out of phase. Latitudinal contribution analyses reveal that the trend in the northern midlatitudes to high-latitudes is the main contributor to global $F_{\text{TA}}$ amplitude increase when considering CO$_2$ fertilization effect alone (Fig. 8, blue line).

### 3.2.3 The climate change factor

The effect of climate change on $F_{\text{TA}}$ amplitude is mixed: five models (OCN, LPJ, LPX-Bern, ORCHIDEE and ISAM) suggest climate change acts to decrease the $F_{\text{TA}}$ amplitude, and four models (JULES, VISIT, CLM4.5BGC and VEGAS) suggest it is an increasing effect (Fig. 5). The high-latitude greening effect is evident in six out of nine models (Fig. 6), contributing, on average, 29 % of boreal amplitude increase. The latitudinal contribution analyses (Fig. 8) also suggest that warming-induced high-latitude “greening” effect is present in all models, but this positive contribution only exhibits a wide range of influence in about half of the models (CLM4.5BGC, JULES, VEGAS and VISIT).

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**Table 4.** The seasonal amplitude (maximum minus minimum, in Pg C yr$^{-1}$) of mean net carbon flux for 2001–2010 relative to the 1961–1970 period, according to the nine TRENDY models (values are listed as percentage change in brackets, for both regions and the entire globe). The four large latitudinal regions are the same as in Fig. 3: boreal (50–90° N), temperate (23.5–50° N), northern tropics (0–23.5° N), southern tropics (0–23.5° S) and southern extratropics (23.5–90° S). Values from the two inversions, Jena99 and CarbonTracker, are also listed for comparison.

<table>
<thead>
<tr>
<th>Name</th>
<th>Global</th>
<th>Boreal</th>
<th>Northern temperate</th>
<th>Northern tropics</th>
<th>Southern temperate</th>
<th>Southern tropics</th>
<th>Southern extratropics</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLM4.5BGC</td>
<td>44.3 (15 %)</td>
<td>31.9 (17 %)</td>
<td>19.2 (15 %)</td>
<td>7.2 (22 %)</td>
<td>6.5 (–2 %)</td>
<td>4.9 (4 %)</td>
<td></td>
</tr>
<tr>
<td>ISAM</td>
<td>19.1 (9 %)</td>
<td>12.1 (11 %)</td>
<td>7.4 (13 %)</td>
<td>6.0 (1 %)</td>
<td>6.9 (–8 %)</td>
<td>0.4 (4 %)</td>
<td></td>
</tr>
<tr>
<td>JULES</td>
<td>19.0 (26 %)</td>
<td>12.2 (24 %)</td>
<td>14.3 (9 %)</td>
<td>11.6 (0 %)</td>
<td>11.3 (11 %)</td>
<td>2.2 (–24 %)</td>
<td></td>
</tr>
<tr>
<td>LPJ</td>
<td>23.4 (26 %)</td>
<td>23.0 (18 %)</td>
<td>14.7 (11 %)</td>
<td>10.5 (9 %)</td>
<td>11.8 (16 %)</td>
<td>2.0 (–12 %)</td>
<td></td>
</tr>
<tr>
<td>LPX-Bern</td>
<td>37.9 (15 %)</td>
<td>26.9 (10 %)</td>
<td>19.3 (6 %)</td>
<td>8.3 (9 %)</td>
<td>4.6 (–6 %)</td>
<td>4.2 (15 %)</td>
<td></td>
</tr>
<tr>
<td>ORCHIDEE</td>
<td>21.6 (34 %)</td>
<td>12.3 (33 %)</td>
<td>11.1 (23 %)</td>
<td>9.7 (17 %)</td>
<td>8.3 (3 %)</td>
<td>2.0 (14 %)</td>
<td></td>
</tr>
<tr>
<td>VEGAS</td>
<td>39.9 (12 %)</td>
<td>23.4 (14 %)</td>
<td>19.1 (5 %)</td>
<td>22.7 (9 %)</td>
<td>18.7 (2 %)</td>
<td>1.4 (37 %)</td>
<td></td>
</tr>
<tr>
<td>VISIT</td>
<td>46.7 (15 %)</td>
<td>22.3 (17 %)</td>
<td>24.7 (10 %)</td>
<td>4.0 (11 %)</td>
<td>3.4 (12 %)</td>
<td>2.1 (6 %)</td>
<td></td>
</tr>
<tr>
<td>Ensemble</td>
<td>28.9 (14 %)</td>
<td>22.9 (12 %)</td>
<td>15.6 (8 %)</td>
<td>3.4 (9 %)</td>
<td>3.2 (1 %)</td>
<td>3.1 (18 %)</td>
<td></td>
</tr>
<tr>
<td>Jena99</td>
<td>26.1 (17 %)</td>
<td>18.0 (19 %)</td>
<td>12.4 (15 %)</td>
<td>8.0 (8 %)</td>
<td>4.9 (–3 %)</td>
<td>2.1 (13 %)</td>
<td></td>
</tr>
<tr>
<td>CarbonTracker</td>
<td>46.8</td>
<td>23.3</td>
<td>21</td>
<td>8.2</td>
<td>8.5</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>
The latitudinal patterns also reveal that, once climate change is considered, the contribution from the northern temperate region around 40° N shifts to negative in all models. In the northern temperate (23.5–50° N) region, climate change alone would decrease the $F_{TA}$ amplitude – this is consistent among the four models with realistic mean global and northern temperate (Fig. 2) $F_{TA}$ seasonal cycle simulation, but is not the case for JULES and LPJ (Fig. 6). Such decrease is possibly related to midlatitude drought (Buermann et al., 2007), which is consistent with findings by Schneising et al. (2014), who observed a negative relationship between temperature and seasonal amplitude of $xCO_2$ from both satellite measurements and CarbonTracker during 2003–2011 for the Northern temperate zone. The negative contribution from the temperate zone counteracts the positive boreal contribution, suggesting that the net impact from climate change on $F_{TA}$ amplitude may not be as significant as previously suggested. With changing climate introduced, some models exhibit similar characteristics of decadal variability in global $F_{TA}$ amplitude (Fig. 7). OCN and ORCHIDEE appear to be especially sensitive to the climate variations after the 1990s, resulting in a decrease in $F_{TA}$ amplitude. It is also apparent from the time series figure that the strong increasing trend of $F_{TA}$ amplitude from climate change in JULES is mostly due to the sharp rise from early 1990s to early 2000s, suggesting some possible model artifacts (Fig. 7). The effect of climate change is more mixed in both tropics and the southern extratropics.

3.2.4 The land use/cover change factor

Six of the nine models show that land use/cover change leads to increasing global $F_{TA}$ amplitude (Fig. 5). Land use/cover change appears to amplify $F_{TA}$ seasonal cycle in boreal and northern temperate regions for most models. For some models (VEGAS, CLM4.5BGC and OCN), this effect is especially pronounced in the northern temperate region where most of the global crop production takes place (Fig. 6). Note that the effect of land use/cover change includes two parts: one is the change of land use practice without changing the land cover type; the other is the change of land cover, including crop abandonment etc. VEGAS simulates the time-varying management intensity and the crop harvest index, which is an example of significant contribution from land use change (Zeng et al., 2014). For many other models, crops are treated as generic managed grasslands (i.e., CLM4.5BGC, LPJ), and land cover change is possibly the more important factor. During 1961–2012, large cropland areas were abandoned in the eastern United States and central Europe, and forest regrowth often followed. New cropland expanded in the tropics and South America, midwestern United States, eastern and central North Asia and the Middle East. How such changes affect the global $F_{TA}$ amplitude is determined by the productivity and seasonal phase of the old and new vegetation covers. For CLM4.5BGC, JULES, LPJ and OR-
CHIDEE, enhanced vegetation activity from growing forest in these regions contributes positively to global $F_{TA}$ amplitude increase (Fig. 9). In contrast, for LPX-Bern, VISIT and VEGAS in the eastern United States, a loss of cropland leads to a decrease in the amplitude. Additional cropland in the midwestern United States and eastern and central North Asia contributes negatively to the $F_{TA}$ amplitude trend for JULES, LPJ and ORCHIDEE. These regions, however, are major zones contributing to the amplification of global $F_{TA}$ for LPX-Bern, OCN, VEGAS and VISIT. One mechanism mentioned previously is agricultural intensification in VEGAS: in fact, CO$_2$ flux measurements over corn fields in the US Midwest show much larger seasonal amplitude than over nearby natural vegetation (Miles et al., 2012). Similarly, although croplands are treated as generic grassland, they still receive time-varying and spatially explicit fertilizer input in OCN (Zaehle et al., 2011). Another plausible mechanism is irrigation, which can alleviate adverse climate impact from droughts, and crops may have a stronger seasonal cycle than the natural vegetation they replace in these regions. The overall effect of land use/cover change for each model, therefore, is often the aggregated result over many regions that can only be revealed by spatially explicit patterns. When examining the latitudinal contribution only (Fig. 8), CLM4.5BG, LPX-Bern, OCN and VEGAS are quite similar, even though the spatial patterns reveal that CLM4.5BG is very different from the other three models (Fig. 9). For JULES, LPJ and ORCHIDEE a significant part of land use/cover change contribution comes from the tropical zone (Fig. 8). While most models indicate that land use/cover change in the southern tropics (Amazon is probably the most notable region) decreases global $F_{TA}$ amplitude during 1961–2012, LPJ suggests that it would cause a large increase in the amplitude instead, possibly related to its different behavior in simulating the mean seasonal cycle of carbon flux for that region (Fig. 2d).

4 Discussion and conclusion

Our results show a robust increase of global and regional (especially over the boreal and northern temperate regions) $F_{TA}$ amplitude simulated by all TRENDY models. During 1961–2012, TRENDY models’ ensemble mean global $F_{TA}$ relative amplitude increases (19 ± 8%). Similarly, the CO$_2$ amplitude also increases (15 ± 3%) at Mauna Loa for 1961–2012. This amplitude increase mostly reflects the earlier and deeper drawdown of CO$_2$ in the NH growing season. The models in general, especially the multimodel median, simulate latitudinal patterns of $F_{TA}$ mean amplitude that are similar to the atmospheric inversions results. Their latitudinal patterns capture the temperature-driven seasonality from the NH mid-latitude to high-latitude region and the two monsoon-driven subtropical maxima, although the magnitude or extent vary. Despite the general agreements between the models’ ensemble amplitude increases and the limited observation-based estimates, considerable model spread is noticeable. Five of the nine models considerably underestimate the global mean $F_{TA}$ seasonal cycle compared to atmospheric inversions, and peak carbon uptake takes place 1 or 2 months too early in seven of the nine models. The seasonal amplitude of model ensem-
ble global mean $F_{TA}$ is 40% smaller than the amplitude of the atmosphere inversions. In contrast to the divergence in simulated seasonal carbon cycle, atmospheric inversions in Northern temperate and boreal regions are well constrained: 11 different inversions agree on July $F_{TA}$ minimum in the Northern Hemisphere (25–90° N), with no more than 20% difference in amplitude (Peylin et al., 2013).

The simulated amplitude increase is found to be mostly due to a larger $F_{TA}$ minimum associated with a stronger ecosystem growth. Over the historical period, global mean carbon sink also increases over time, suggesting a possible relationship between seasonal amplitude and the mean sink (Ito et al., 2016; Randerson et al., 1997; Zhao and Zeng, 2014). The increasing trend of CO$_2$ amplitude, dominated by increasing trend of $F_{TA}$ amplitude, has been interpreted as evidence for steadily increasing net land carbon sink (Keeling et al., 1995; Prentice et al., 2000). However, the increasing amplitude could also arise from (climatically induced) increased phase separation of photosynthesis and respiration, e.g., due to warming-induced earlier greening (Myneni et al., 1997). For the nine models, we found a moderate relationship between enhanced mean land carbon sink and the seasonal amplitude increase similar to reported results by in Zhao and Zeng (2014), with an R-squared value of 0.61 (Fig. 10). There might be some possibility in constraining change in land carbon sink with changes in observed CO$_2$ seasonal amplitude; however, extra caution should be given when interpreting this global-scale cross-model correlation, as there could be important regional differences that cancel out in aggregated global values. A factorial analysis of the long-term carbon uptake could help to determine which factor contributes to what extent to this correlation. Further research is also needed to explore the mechanisms behind such a relationship at continental scale, where more data from well-calibrated CO$_2$ monitoring sites and data on air–sea fluxes and atmospheric vertical transport could better constrain carbon balance (Prentice et al., 2001). Changes in residual land carbon sink estimates are also shown (Fig. 10), with the caveat that it is not directly comparable with simulated net carbon sink increase if there is a trend in simulated carbon flux changes associated with land cover conversion (deforestation, crop abandonment, etc.). Additionally, the decadal changes in residual and net land carbon sink are far from linear; instead, a sudden increase in mean land uptake occurred in 1988 (Beaulieu et al., 2012; Rafique et al., 2016; Sarmiento et al., 2010). With the aid of atmospheric transport, CO$_2$ amplitude trends at remote sites have benchmarking potential to constrain the models, especially with more observations and improved understanding of vegetation dynamics at regional level in the near future.

Models with a strong mean carbon sink (for example JULES and OCN) can have relatively weak seasonal amplitude, and the LPX-Bern model shows no carbon sink despite having a strong $F_{TA}$ seasonality. Based on data from Table 8 of the Global Carbon Budget report (Le Quéré et al., 2014), the net land carbon sink for 2000–2009 is estimated to be 1.5 ± 0.7 Pg C yr$^{-1}$ (assuming Gaussian errors). Four models (JULES, OCN, VEGAS and VISIT) examined in this study are within the uncertainty range of this budget-based analysis. In spite of their similar mean land carbon sink, the shape of their $F_{TA}$ seasonal cycle differs. While VEGAS also shows a similar seasonal carbon cycle compared to inversions, the other three models exhibit an unrealistically long carbon uptake period with half the amplitude as the inversions. July and August are the only 2 months with net carbon release for JULES, whereas OCN and VISIT both have a long major carbon uptake period from May to September. Given that the mean global and regional $F_{TA}$ seasonal cycles are relatively well constrained in the northern extratropics, they can serve as a benchmark for terrestrial models (Heimann et al., 1998; Prentice et al., 2001). Insights gained from analyzing modeled seasonal amplitude of carbon flux may help to understand the considerable model spread found in the mean global carbon sink for the historical period (Le Quéré et al., 2015), which is possibly due to varied model sensitivity to different mechanisms (Arora et al., 2013). Examining details of different representations of important processes in models.

![Figure 10](image-url)

**Figure 10.** Relationship between the increase in net biosphere production (NBP, equal to $-F_{TA}$) and increase in NBP seasonal amplitude (as in Fig. 4’s red dots), for the 1961–2012 period for nine TRENDY models. Error bars indicate the standard errors of the trend estimates. Increase in residual land sink is estimated by taking the difference between two residual land sinks, over 2004–2013 and 1960–1969 (an interval of 44 years), as reported in Le Quéré et al. (2015). This difference is then scaled by 52/44 (to make it comparable with models’ NBP change for this figure), which is displayed by a black vertical line and shading (error added in quadrature, assuming Gaussian error for the two decadal residual land sinks, then also scaled). The cross-model correlation ($R^2 = 0.61, p < 0.05$) suggests that a model with a larger net carbon sink increase is likely to simulate a higher increase in NBP seasonal amplitude.
could also help to better assess the different future projections on both the magnitude and direction of global carbon flux (Friedlingstein et al., 2006, 2013).

Unlike many previous studies that focused on comparing the season cycle at individual CO$_2$ monitoring stations (Peng et al., 2015; Randerson et al., 1997), we studied the global and large latitudinal bands. Such quantities often demonstrate well-constrained seasonality that is relatively robust against uncertainty from atmospheric transport, fossil fuel emission and biomass burning etc. We found greater uncertainty for the tropics and southern extratropics regions where atmospheric CO$_2$ observations are relatively sparse. Tropical ecosystems are also heavily affected by biomass burning; however, some models used in this study do not include fire dynamics. For models that simulate fire ignition/suppression, they are also varied by structure and complexity of fire-related processes, and many of them are prognostic (Poulter et al., 2015). It is not clear how fire would affect the $F_{TA}$ seasonal cycle at global scale, and recent sensitivity study shows only minor differences among fire and “no fire” scenarios in CO$_2$ seasonal cycle at several observation stations (Poulter et al., 2015). These uncertainties, however, are unlikely to affect our main conclusions because of the limited contribution of tropics to global $F_{TA}$ amplitude increase. Another possibly important factor is the impact from increased nitrogen deposition, which may have been included in the “CO$_2$ fertilization” effect for some models with full nitrogen cycle (Table 1); however, this can only be explored in future studies, as the TRENDY experiment design does not separate out the nitrogen contribution.

Our factorial analyses highlight fundamentally differential control from rising CO$_2$, climate change and land use/cover change among the models, with seven out of nine models indicating major contribution (83 ± 56 %) to global $F_{TA}$ amplitude increase from the CO$_2$ fertilization effect. The strength of CO$_2$ fertilization varies among models, but for each model, its magnitude in the boreal, northern temperate and southern extratropics regions is similar. Models are split regarding the role of climate change, as compared with the models’ ensemble mean (−3 ± 74 %). Regional analyses show that climate change amplifies the boreal $F_{TA}$ seasonal cycle but weakens the seasonal cycle for other regions according to most models. By examining latitudinal trends from $F'_{TA,i}$, we found all models indicate a negative climate contribution over the midlatitudes, where droughts might have reduced ecosystem productivity. This negative effect offsets the high-latitude greening, which in some models results in a net negative climate change impact on global $F_{TA}$ amplitude. Such a mechanism casts doubt on whether climate change is the main driver of the global $F_{TA}$ amplitude increase. Land use/cover change, according to majority of the models, appears to amplify the global $F_{TA}$ seasonal cycle (20 ± 30 %); however, the mechanisms seem to differ among models. Conversion to/from cropland could either increase or decrease the seasonal amplitude, depending on how models simulate the seasonal cycle of cropland compared to the natural vegetation it replaces/preccedes. For the same pattern of increasing amplitude, the underlying causes could include irrigation mitigating negative climate effect, agricultural management practices and other mechanisms.

Overall, this study is largely helpful to enhance our understanding of the role of CO$_2$, climate change and land use/cover change in regulating the seasonal amplitude of carbon fluxes. In particular, models’ disagreement in spatial pattern of carbon flux amplitude helps to identify optimal locations for additional CO$_2$ observations in the north. However, this work can be further improved through utilizing the CO$_2$ seasonal cycle and its amplitude at different locations as indicators to diagnose model behaviors. To achieve this, it is necessary to apply atmosphere transport on the simulated net carbon flux, along with ocean and fossil fuel fluxes, which would allow direct comparison with observed CO$_2$ amplitude change. In doing so, it is possible that models may overestimate CO$_2$ amplitude increase at most CO$_2$ observation stations if the simulated CO$_2$ fertilization effect is too strong.

5 Data availability

Results of TRENDY models analyzed in this study will be available on request by the end of 2016 (please contact S. Sitch at s.a.sitch@exeter.ac.uk for further updates and details).
Appendix A: Environmental drivers for TRENDY

For observed rising atmospheric CO₂ concentration, the models use a single global annual (1860–2012) time series from ice cores (before 1958: Joos and Spahni, 2008) and the National Oceanic and Atmospheric Administration (NOAA)’s Earth System Research Laboratory (after 1958: monthly average from Mauna Loa and South Pole CO₂; South Pole data are constructed from the 1976–2014 average if not available). For climate forcing, the models employ 1901–2012 global climate data from the Climate Research Unit (CRU, version TS3.21, http://www.cru.uea.ac.uk; or CRU-National Centers for Environmental Prediction (NCEP) dataset, version 4, from N. Viovy (2011), unpublished data) at monthly (or interpolated to finer temporal resolution for individual models) temporal resolution and 0.5° × 0.5° spatial resolution. For land use/cover change history data, the models adopt either gridded yearly cropland and pasture fractional cover from the History Database of the Global Environment (HYDE) version 3.1 (http://themasites.pbl.nl/tridion/en/themasites/hyde/, Klein Goldewijk et al., 2011), or the dataset including land use history transitions from L. Chini based on the HYDE data.

Appendix B: Atmospheric inversions

The Jena inversion is from the Max Planck Institute of Biogeochemistry, v3.7, at 5° × 5° spatial resolution (http://www.bgc-jena.mpg.de/christian.roedenbeck/download-CO2/, Rödenbeck et al., 2003), including two datasets abbreviated as Jena81 for the period of 1981–2010 using CO₂ data from 15 stations, and Jena99 using 61 stations for 1999–2010. Another inversion-based dataset used is the CarbonTracker, version CT2013B, from NOAA/ESRL at 1° × 1° spatial resolution (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/, Peters et al., 2007) for the period of 2000–2010, which integrates flask samples from 81 stations, 13 continuous measurement stations and 9 flux towers, and the surface fluxes from land and ocean carbon models as prior fluxes. These two inversion-based datasets are vastly different in their approach in inversion algorithm, choice of atmospheric data, transport model and prior information (Peylin et al., 2013). For example, to minimize the spurious variability introduced by changes in availability of observations, the Jena inversion provides multiple versions with different record length, each only using records covering its full period (for example, Jena99 includes more stations than Jena81, but with a shorter period). The CarbonTracker, however, opts for assimilating all quality-controlled data (with outliers removed), favoring a higher spatial resolution in estimated carbon fluxes. Therefore, we chose these two inversions to capture the uncertainty in atmospheric inversions to some extent.
The Supplement related to this article is available online at doi:10.5194/bg-13-5121-2016-supplement.

Author contributions. Fang Zhao and Ning Zeng designed the study and Fang Zhao carried it out. Shijie Sitch and Pierre Friedlingstein designed and coordinated TRENDY experiments. TRENDY modelers conducted the simulations. Fang Zhao wrote the paper with input from all authors.

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References


