Responses to Reviewer 1

We thank the reviewer for her/his supportive review of our manuscript. Her/his suggestions will help us to strengthen the revised manuscript. In the response below, we address her/his concerns sequentially, with our responses indicated in "Arial" font, whereas her/his comments are indicated in "Times New Roman" font.

This study explores different contributors to the increase in the atmospheric CO_2 seasonal amplitude, as predicted by the CESM in simulations that span 1950—2300. I am generally supportive of this paper. Clearly an impressive effort went into it and it is well organized and written. However, I have some major concerns, listed in order of decreasing priority:

1) There are some steps in the methodology that need more detail and justification – some of them could/should really be stand-alone papers. These include a) The pulse-response method. b) The documentation of mid-latitude trends in observed CO_2 amplitude

We have added additional documentation, detailed below, to demonstrate the pulse-response approach we used to calculate atmospheric CO_2 mole fraction data. Because the focus of this paper is not on attributing drivers of the observed change in the amplitude, but rather exploring how seasonality changes in the future in a prognostic ESM, we prefer to minimize the discussion of observed mid-latitude trends.

2) The CESM does a poor job of reproducing the current CO_2 amplitude and the historical observed amplitude trends, which undermines confidence in the results presented here. Although I think the exercise is still worthwhile, some sort of well thought out rationale or statement is needed to explain why readers should believe or pay any heed to the future model results going out to 2300, e.g., are there certain results that are robust and insightful despite the model's poor present-day performance?

The exercise of predicting carbon-climate coupling in a fully prognostic model is still relatively new. Although CESM shows significant deficits in the simulated mean annual cycle and its trend, the model includes parameterizations for many of the processes that may be important in controlling its change with time, and we note that CESM qualitatively captures the northward increase in the NH atmospheric CO_2 seasonal amplitude as well as the increasing trend in the annual seasonal cycle amplitude. These suggest that the parameterizations included in CESM can be used to examine how the seasonal amplitude might evolve when subject to the radiative and fertilization effects of increased atmospheric CO_2 concentration, and also to identify deficiencies in current model parameterizations. While we do not expect that the simulation provides an accurate description of either carbon cycling or physical climate out to 2300, the results of the simulation do allow us to (1) understand the balance of major drivers, (2) identify deficiencies that may need to be addressed in future model development.

We will add the following statement to the discussion of the revised manuscript:

"Although CESM does not quantitatively reproduce the contemporary mean annual cycle amplitude or its trend over the last 50 years, parameterizations in the model qualitatively reproduce diagnostics such as the increase in both the mean annual cycle and its multi-decadal trend. Thus, we can use the model to understand partitioning of the long-term response to climate change or to fertilization, with an eye toward identifying areas for future model improvement."

Expanding on 1a) The pulse-response method. This could really be a stand- alone paper (see, e.g., Nevison, C.D., D.F. Baker, and K.R. Gurney, A methodology for estimating seasonal cycles of atmospheric CO_2 resulting from terrestrial net ecosystem exchange (NEE) fluxes using the Transcom T3L2 pulse-response functions, Geosci. Model Dev. Discuss., 5, 2789-2809, 2012, www.geosci-model-dev- discuss.net/5/2789/2012/ doi:10.5194/gmdd-5-2789-2012, 2012.)

While I support the method and realize that it would be prohibitively expensive computationally to break down the contributions to CO_2 amplitude change from different regions and mechanisms without some sort of shortcut approach like the Pulse Response method, I think it needs more than a 1 paragraph explanation. For example:

i) Is there any IAV in the meteorology used to create the pulse fields? Also, what is the consequence of assuming those met fields will still apply in 2300?

We appreciate that the reviewer recognizes that the pulse-response method is a necessary computational shortcut to examine the regional contributions to atmospheric CO_2, and will provide more details about the method in the revised manuscript. The pulse response approach does contain interannual variability in the met fields, but as the reviewer identifies, there are substantial consequences in assuming those met fields will still apply in 2300. We note that in our manuscript Fig. 2c, mismatches grow from 2 ppm to 3 ppm in the mid- and high latitudes when the land CO_2 tracer in CESM (4-d) is sampled at the sites we use in Fig. 1 vs when NEE (which embodies all the land processes that influence the land CO_2 tracer) is convolved with the pulse-response function. This deficiency should be identified in the paper, and we plan to add the following text to our description of the pulse-response method:

"Although the CESM simulated the three-dimensional structure of atmospheric CO_2, we used a pulse-response transport operator to separate the imprints of CO_2 fluxes from different regions on the hemispheric CO_2 patterns. The transport operator was developed using the GEOS-Chem transport model (version 9.1.2, Nassar et al. (2010)). GEOS-Chem was configured as in Keppel-Aleks et al. (2013) on a 4° × 5° horizontal grid with 47 vertical layers, and forced with meteorology fields from the 3–6-hourly Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis dataset (Rienecker et al., 2011). A tagged 1 Pg C month^{-1} pulse was released for each of the 20 terrestrial source regions in Fig. 1 for each calendar month. Each 1 Pg C month^{-1} pulse was distributed spatially according to monthly fluxes from the Carnegie-Ames-Stanford Approach (CASA) fluxes from Olsen and Randerson (2004). At a given location, the magnitude and phasing of the atmospheric CO_2 response of the pulse depends on the characteristics of atmospheric transport. For example, at Barrow (BRW) in Northern Alaska, a 1 Pg pulse released in Boreal North America has a large impact on atmospheric CO_2 (2 ppm, Fig. SA1a) during the first 1-3 months after a pulse is released. In contrast, when the pulse is released from temperate North America, there is a phase lag of 1 month (Fig. SA1b,c), and when the pulse is released from the Amazon, there is a delay in the peak response at BRW of 3 months (Fig. SA1d). The magnitude of the response is also smaller (e.g., 0.02 ppm for a 1 Pg pulse released in the Amazon vs 2 ppm for boreal North America; Fig. SA1), since the pulse has already diffused over much of the globe. We also note that seasonal patterns in atmospheric transport affect the imprint a pulse leaves on atmospheric CO_2 (Fig. SA2). For example, a 1 Pg pulse from the boreal region leaves a 2 ppm contribution on CO_2 at Barrow during the winter months, but more rigorous vertical mixing in the summer months reduces the imprint to 0.5 ppm. Following the twelve month period in which pulses were released, the signals were allowed to decay for 60 subsequent months, at which point CO_2 was well-mixed in the atmosphere (Fig. SA2a-d).

We then sampled GEOS-Chem at the locations of 41 NOAA cooperative CO_2 flask sample sites (Dlugokencky et al. (2013); Table 1, Fig. 1) for each month simulated. This resulted in a CO_2 transport operator matrix with dimensions $N_{reg.} \times N_{obs.} \times N_{mon.}$. We aggregated NEP fluxes from CLM4 to the spatial scale of the 20 source regions (Fig. 1), and used matrix multiplication to propagate these fluxes to atmospheric CO_2 space. We calculated the monthly mean CO_2 mole fraction at the observation sites by summing over the regional contributions to get a CO_2 response matrix with dimensions (N_{obs} x N_{mon}).

We analyzed both the CO_2 fields from global fluxes and CO_2 patterns influenced only by larger regions representing Arctic, boreal, temperate, subtropical, tropical, and Southern Hemisphere (SH) ecosystems. We calculated the CO_2 annual cycle amplitude values as the peak-to-trough differences in CO_2 summed over each component region (e.g., the CO_2 annual cycle amplitude at a given station from pulses emitted from the Arctic was calculated as the peak-to-trough difference in the sum of CO_2 from pulses emitted by the blue regions in Fig. 1). We note that our analysis focuses on surface observations of atmospheric CO_2, and does not include aircraft measurements.

The advantage of this method is that we can efficiently compute the regional contribution to changes in atmospheric CO_2; it would be prohibitively expensive to run a full atmospheric transport model for each of the regions separately for 350 years. To evaluate this method, we show a comparison in which we have generated CO_2 using NEE, since the land CO_2 tracer in the CAM4 is derived from NEE (despite that we use NEP for subsequent analyses). The magnitudes generally differed by less than 2 ppm due to different model boundary layer schemes and atmospheric transport (Fig. 2c). We note that the largest differences were during the last century of the simulation, which we hypothesize was due to shifts in atmospheric transport in response to the dramatic climate change in the CAM4. The fact that long-term trends in transport are not simulated by the pulse-response approach is one of the major sources of bias. By neglecting long-term trends in transport, we induce a bias into atmospheric CO_2 that increases with time (Fig. 2c). In a site-by-site comparison (Fig. SA3), the mismatch in time appears to be due to amplification of existing biases in the pulse-CO_2 compared to the full transport-CO_2. A second source of uncertainty is that the spatial distribution of fluxes within each region is different in CESM compared to CASA. We expect that this has a minimal impact based on results from Nevison et al. (2012), who showed that a similar pulse response code using different transport models did a reasonable job (r^2=0.8) of simulating the fossil fuel influence on CO_2 despite that CO_2 has a vastly different spatial configuration than do ecosystem fluxes.

We also assessed the validity of the assumption to model only the land contributions to trends in the mean annual cycle of CO_2 by calculating the CO_2 amplitudes in the CAM land and ocean tracers. We found that the contemporary peak-to-trough amplitude in the ocean tracer averaged across our high latitude stations was 2 ppm (in contrast to 10 ppm in the land tracer). Although both the land and ocean amplitudes grow with time, by 2300, the high latitude ocean tracer had an amplitude of 3 ppm, only 18% of the land amplitude for this time period. Ocean carbon uptake was found to change significantly in CESM through 2300 (Randerson et al., 2015), but based on these numbers, ocean CO_2 still had a smaller imprint on the atmospheric annual cycle."

ii) How are the 60-month decaying pulses combined to create a model atmospheric CO_2 cycle?

We have addressed the reviewer's question in the revised text, above, and created two additional figures (Fig. SA1 and Fig. SA2) to show this process graphically.

iii) In figure 2, the pulse-response amplitudes at midlatitudes are 3 ppm or more smaller than the fully prognostic tracer. This doesn't seem "broadly similar" and undermines confidence that this methodology can detect subtle trends, esp. in the midlatitudes.

To provide better validation for the reader to assess the bias induced by the pulse-response method, we have prepared Fig. SA3, which shows the mean seasonal cycle at a high-latitude (BRW), mid-latitude (SHM), subtropical (KEY), and tropical (MLO) NH site. These sites were selected since they have observational records dating to the 1980s (gray circles shown in Fig. 1). We plot both the CESM land CO_2 tracer and the pulse-response CO_2 for four periods for each site: 1990—1999, 2090—2099, 2190—2199, and 2290—2299.

The site-by-site comparison shows that (1) the biggest mismatches in 2300 between the full-transport and the pulse-response CO_2 owe to persistent biases that exist for the present, e.g., the high January bias at Barrow (BRW) and the one-month phase shift in the summer minimum at KEY. This would suggest that changes in transport patterns due to climate change induce a smaller mismatch than present-day biases in the method. (2) the method is able to capture fairly subtle variations in the mean annual cycle, such as the "W" shape that the mean annual cycle at SHM develops over time.

iv) The GMD Discussions paper above was never accepted for final publication, due to reviewers who thought adjoint methods were superior. While the current method is superior in that it divides land into a larger number of regions (20 v. 11), the GMDD paper on the other hand was applying the method to estimate mean seasonal cycles, which are easier to get right than the more subtle trends in amplitude over time examined here.

We agree with the reviewer that not only are the improved resolution of land areas an advantage of our pulse-response code over the Transcom regions, but also the fact that these land regions were determined based on similarity in annual mean NPP and its seasonality. We agree that comparison of mean annual CO_2 cycle, rather than its trend, places a lower burden on the code. For this application, however, the mean annual CO_2 amplitude changes by up to 10.6 ppm by 2300. Thus, the relative error, assuming a 3 ppm difference, is still only ~28% of the total trend.

Expanding on 1b) I'm not sure there is any evidence that CO_2 seasonal amplitude is increasing at midlatitude sites such as NWR or UUM, KZM/D. In fact, if anything, they may be decreasing – possibly due to drought effects. The most robust effects are seen at BRW, with the amplitude increase at MLO less than half that of BRW. I don't think Zeng et al. (2014) is an adequate reference to prove that midlatitude CO_2 amplitude is increasing, since they don't actually show this.

We thank the reviewer for this comment. One of the reasons we aggregate the sites depicted in Fig. 1 into high-, mid-, subtropical, and tropical latitude belts is to minimize local effects that may be present at the sites we have chosen and to instead focus on a more large-scale pattern of variation. A challenge to this approach is that there are relatively few ESRL sites with records dating to the 1980s or earlier. We will include this rationale in our methods discussion by including the text:

"In our analysis, we aggregate the sites into high-, mid-, subtropical, and tropical latitude belts to minimize local effects at individual sites and instead to focus on large-scale trends owing to broad patterns of climate change."

We will also thoroughly check our referencing in the revised paper and be sure to reference observationally based papers such as Randerson et al. (1997) and Graven et al. (2013) rather than modeling-derived studies.

Minor comments: p.1, L8, The term "changing atmospheric composition" to encompass CO_2 fertilization and N deposition is confusing. These two don't really belong in the same category, in my opinion, since the N deposition is relevant mainly after it deposits on the soil, i.e., the authors are not looking at some sort of physiological response of plants to increased atmosphere NOx or NH3 concentration.

We agree with the reviewer that CO_2 fertilization and N-deposition represent two distinct forcings on ecosystem carbon exchange. Unfortunately, the simulations which were conducted as part of the CESM Biogeochemistry Working Group did not separate these two changes, thus we cannot resolve the specific forcing from the model output available since there is no analogous CESM ECP simulation that excludes N-deposition and the CO_2 radiative effect. In each of the ECP simulations, reactive nitrogen deposition was kept constant at 2100 values (Randerson et al., 2015), so future trends in the mean annual cycle amplification were due to nitrogen deposition levels at 2100 interacting with trends in CO_2.

Devaraju et al. (2016) did perform experiments looking at the individual and combined effects of CO_2

fertilization, N-deposition, climate change, and LUC on historical NPP trends using the CESM1(BGC). They found that CO_2 fertilization and N-deposition contributed 2.3 and 2 PgC yr^{-1} to the 4 PgC yr^{-1} historical increase in global terrestrial NPP. Given the conditions of the experiments and the fact that CO_2 fertilization and N-deposition contribute similarly to global and historical NPP trends in the CESM, we present our results based on the combined effects of CO_2 fertilization and N-deposition.

We will reference this paper in the text, and include the following statement:

"Results from Devaraju et al. (2016) suggest that global NPP is influenced equably by CO_2 fertilization and nitrogen deposition over the historical period in CESM, so trends in the mean annual cycle amplitude were likely influenced by this enhanced NPP. In these simulations, nitrogen deposition was held fixed after 2100, so trends in the amplitude were influenced by anthropogenic nitrogen deposition but not forced by transient deposition."

We will also use clearer language to describe that these two effects are included in the simulations by replacing "changing atmospheric composition" with "CO_2 fertilization and N-deposition" throughout the revised manuscript.

p.1, L12 is confusing as written – in one case we have the end time (2300) and in the other we have the start time (after 2100). Please rewrite to clarify start and end times for both effects

We will revise the sentence to read "CO_2 fertilization and N-deposition in NH boreal and temperate ecosystems were the largest contributors to mean annual cycle amplification over the midlatitudes for the duration of the simulation (1950—2300) and for the Arctic from 2100—2300."

p.1, L15 "rather than the strength of the terrestrial carbon sink" please explain more clearly what is meant here.

We will clarify this sentence to read "Greater terrestrial productivity during the growing season was the largest contributor to the annual cycle amplification throughout the Northern Hemisphere."

p.1, L17, suggest replacing "is not predicated on" with "does not necessarily imply" p.1, L20 I think it's more accurate to say "at some NH sites" rather than "over the NH" (see my comments above about midlatitude trends).

We will change the sentence to read "Prior to 2100, CO_2 annual cycle amplification occurred in conjunction with an increase in the NH land carbon sink, but these trends decoupled after 2100, underscoring that an increasing atmospheric CO_2 annual cycle amplitude does not necessarily imply a strengthened terrestrial carbon sink."

p.2, L31 missing AND between citations.

We will add the "and" between McDonald et al. (2004), and Barichivich et al. (2013).

p.2, L35 suggest saying, "Model evidence suggests that the combined effects . . ." and delete "in simulations."

We will revise the sentence to read, "Model evidence suggests that the combined effects of climate change and shifts in vegetation cover can also enhance GPP."

P2., L20 and p.3, L17 again I find the catch-all term "changes in atmospheric composition" confusing.

We will refer to “changing atmospheric composition” as “CO_2 fertilization and N-deposition”.

p. 6, L30. It seems like a stretch to call 425 ppm and 391 ppm “roughly equivalent”

We agree with the reviewer and will modify the text in the revised manuscript to state "We note that the drivers of the amplitude increase during 1985—2013 were simulated to different levels of fidelity: the NH atmospheric temperature increase over land was roughly equivalent (1.02 K vs 0.95 K in the NCEP-NCAR reanalysis [Kalnay et al., 1996]), but the NH atmospheric CO_2 mole fraction in CESM was too high (425 ppm vs 391 ppm). Previous analysis of the CESM shows that the high CO_2 bias is attributable to persistent weak uptake in both land and ocean (Keppel-Aleks et al., 2013; Long et al., 2013)."

p.7, L5 Please provide a reference for the observed mid-latitude trend of 0.04 ppm yr^{-1}.

We thank the reviewer for calling this detail to our attention. We calculated the 0.04 ppm yr^{-1} midlatitude trend from the 1985—2013 monthly observations at Shemya Island, Alaska (SHM), which we selected to represent the midlatitudes (40°N—60°N; Table 1) based on its sufficiently long period of record.

We will revise the text to clarify "Both the modeled and observed trends in the CO_2 annual cycle amplitude were calculated from individual sites whose records date to 1985 (gray circles in Fig. 1). The modeled trend in the CO_2 annual cycle amplitude..."

P8, L19 Please explain further. Why is this consistent with effects being proportional to GPP?

Regional GPP is smaller in the Arctic than in the other regions we analyze in the paper, thus fertilization acts as a knob on a smaller gross flux term. We will revise the statement to read, "CO_2 fertilization and N-deposition effects were smallest in the Arctic, the region with the smallest GPP for the contemporary period. In the CESM, the impact of CO_2 fertilization on the amplitude trend roughly scales with to the magnitude of overall GPP, consistent with hypotheses from Tans et al., (1990) and Schimel et al (2015) that the fertilization effect on the land carbon sink is proportional to productivity."

P9, L12, to avoid confusion, would suggest splitting into 2 sentences: “..simulation. These latter influences added 4.7 ppm . . .”

We will split these two sentences in the revised manuscript.

P9, L27 The Zeng et al reference, in my reading, does not actually demonstrate that the spatial distribution of where atmospheric CO_2 amplitude increases are seen (mainly at high latitudes) are consistent with agriculture, which is large at mid-latitudes.

We agree with the reviewer that the Zeng et al. (2014) reference does not explicitly calculate the impact of midlatitude agricultural fluxes on the high latitude mean annual cycle amplitude, where the trend is largest. However, our results (Fig. 7) show that temperate ecosystems leave a large imprint on the mean annual cycle amplitude at high latitudes. Thus, if crops were included in the CESM, the model would show the imprint at high latitudes. We therefore prefer to leave the statement unchanged.

P10, L23, “perhaps indicating . . .” Please explain further.

Based on comments from both reviewers, we have decided to revise the text to remove this statement. Instead, we will include a statement that this finding demonstrates the importance of considering latitudinally resolved CO_2 in models for diagnosing compensating errors. As described in the response to Reviewer 2, one difference between our paper and other papers on the mean annual cycle is that we explicitly consider how fluxes propagate to atmospheric CO_2 rather than simply aggregating hemispheric fluxes.

We will revise the text to read: "This result underscores the importance of considering meridionally resolved atmospheric CO_2 data that explicitly considers the role of transport, since a Northern Hemisphere average masks incorrect spatial patterns in the CESM."

Additional References

Devaraju, N., Bala, G., Caldeira, K., and Nemani, R.: A Model Based Investigation of the Relative Importance of CO_2-Fertilization, Climate Warming, Nitrogen Deposition and Land Use Change on the Global Terrestrial Carbon Uptake in the Historical Period, Clim. Dynam., 47, 173—190, doi:10.1007/s00382-015-2830-8, 2016.

Nevison, C. D., Baker, D. F., and Gurney, K. R.: A methodology for estimating seasonal cycles of atmospheric CO2 resulting from terrestrial net ecosystem exchange (NEE) fluxes using the Transcom T3L2 pulse-response functions, Geosci. Model Dev. Discuss., 5, 2789–2809, doi:10.5194/gmdd-5-2789-2012, 2012.

Tans, P. P., Fung, I. Y., and Takahashi, T: Observation constraints on the global atmospheric CO_2 budget, Science, 247, 1431–1438, 1990.

Olsen, S. C., and J. T. Randerson: Differences between surface and column atmospheric CO_2 and implications for carbon cycle research, J. Geophys. Res., 109, D02301, doi:10.1029/2003JD003968, 2004.

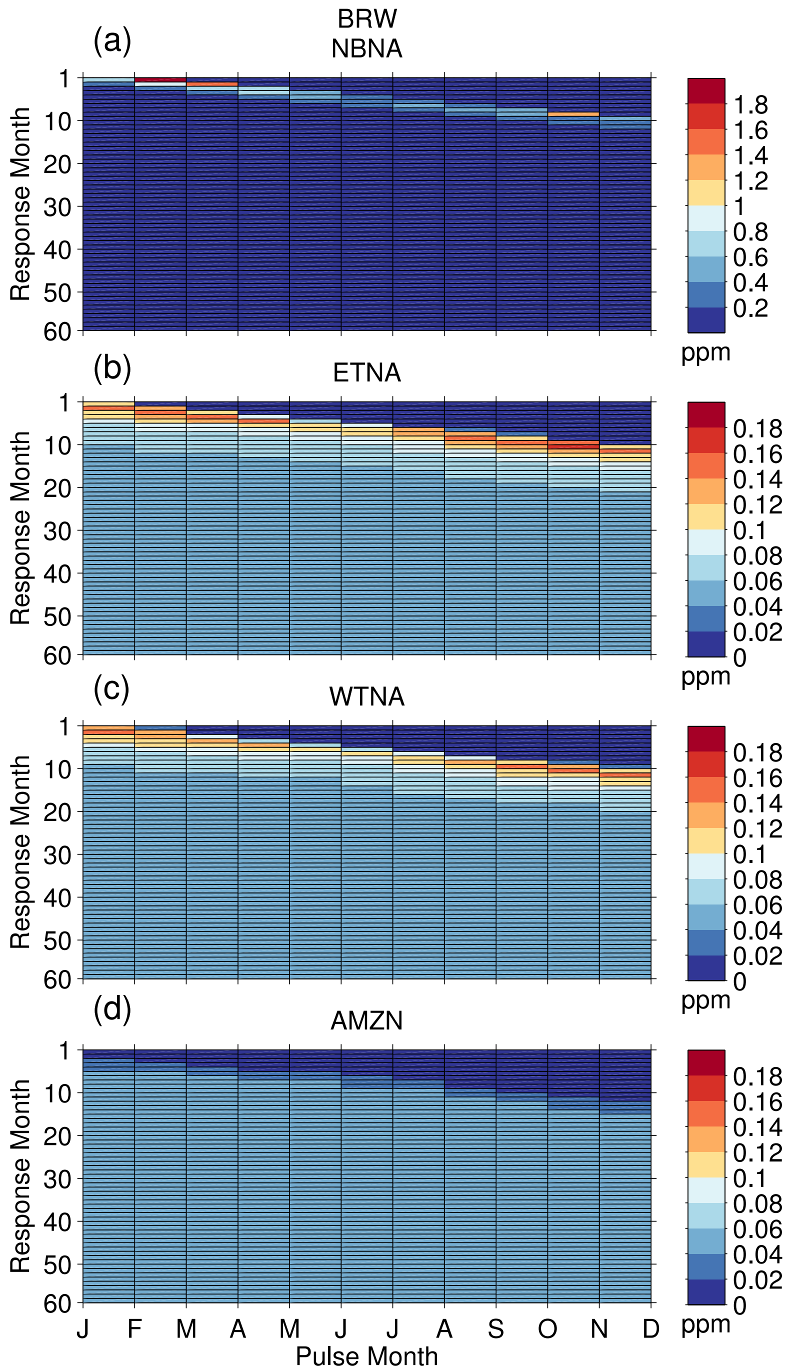

Fig. SA1: The imprints of 1 Pg pulses emitted in 12 successive months (x-axis) from (a) NBNA, (b) ETNA, (c) WTNA, and (d) AMZN on the atmosphere sampled at BRW over a 60-month period (y-axis).

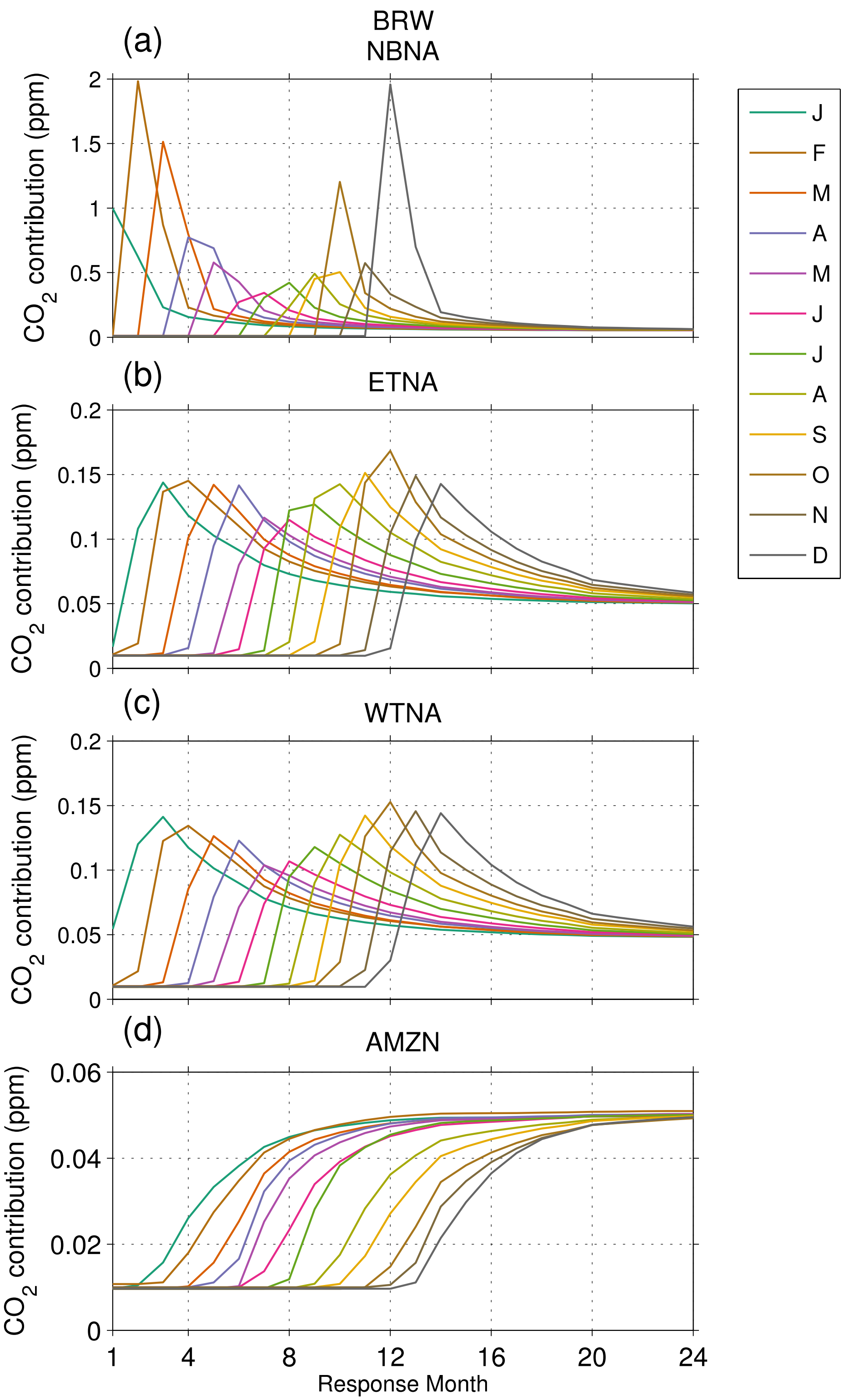

Fig. SA2: The imprints of 1 Pg pulses emitted from (a) NBNA, (b) ETNA, (c) WTNA, and (d) AMZN in each month (contours) on the atmosphere sampled at BRW.

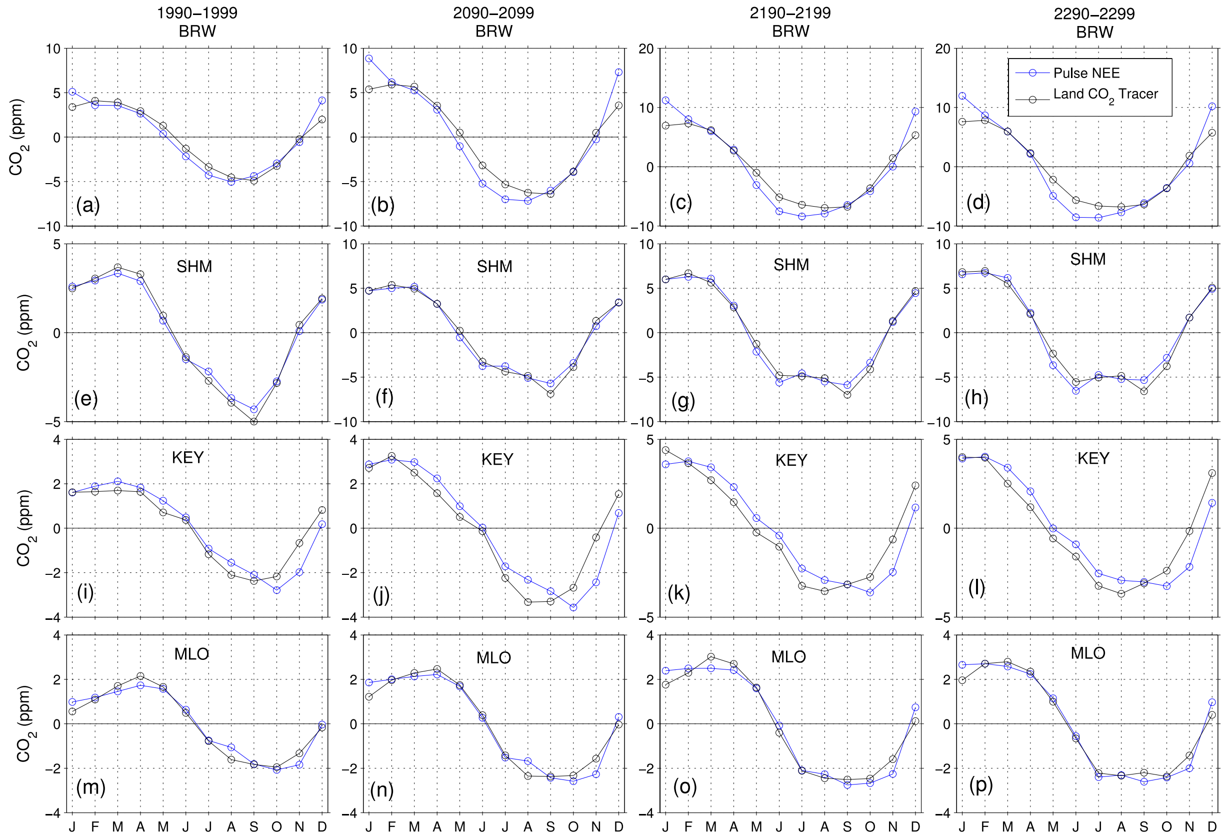

Fig. SA3*:* Mean annual cycles of atmospheric CO_2 derived from (blue curves) NEE run through the pulse response function and (black curves) the CESM land CO_2 tracer for (a—d) BRW, (e—h) THD, (i—l) KEY, and (m—p) MLO in 1990—1999, 2090—2099, 2190—2199, and 2290—2299.

Responses to Reviewer 2

We thank the reviewer for her/his constructive review of our manuscript. We found the comments very helpful, as they revealed that in the revised manuscript we must revise our language to show the insights gained in understanding how the mean annual cycle of CO_2 changes in response to climate and environmental drivers in a fully coupled ESM. The review underscored that the rationale for our study was not made clear, and we will remedy this in the revised manuscript. Here, we respond point-by-point to the reviewer's comments (Times New Roman font) with our rationale and proposed modifications to the revised text (Arial font).

The paper describes an analysis of potential drivers of multi-century trends in the seasonal cycle amplitude of the atmospheric CO_2 concentration with a Prognostic Earth System Model. The study follows from the paper of Graven et al. (2013) that analyzed in detail the large increase of atmospheric CO_2 seasonal cycle amplitude at high northern latitudes over the past 60 years; In a series of studies trying to disentangle the drivers of the observed increase in atmospheric CO_2 seasonal amplitude, this paper propose a first attempt with a prognostic coupled carbon-climate cycle model and an investigation of the amplitude changes up to the horizon 2300.

While our study follows from several papers [e.g., Randerson et al. (1997) and Graven et al. (2013)] that showed that the mean annual cycle of CO_2 at high northern latitudes has increased steadily since measurements began in 1958, the goal of our paper is less to attribute drivers of the observed increase and more to test the abilities of a prognostic ESM to simulate the increase and to explore whether the ESM predicts nonlinearities or tipping points in the long-term increasing trend as climate in the model continues to evolve past the present-day. The climate and biogeochemical communities have invested tremendous time into the development of fully-coupled, mechanistic models, and rarely has a multi-decadal phenomenon such as the long-term CO_2 amplitude increase been observed in nature and therefore provided an opportunity to test a multi-decadal model in a fully-coupled, prognostic model.

The paper is clearly written and relatively easy to follow. However, it seems to me that the simulations performed in this study with the chosen model does not completely allow to investigate some of the questions (for instance, what are the drivers of the increased atmospheric CO_2 seasonal amplitude). The coupled climate–carbon cycle model helps to understand the potential feedback between the land surface processes and the atmosphere and to investigate long term prediction; but the chosen model with its biases (i.e., the too low amplitude of the mean seasonal CO_2 cycle) requires more caution when discussing the relative contribution of all potential drivers of the observed amplitude change (CO_2, climate, agricultural changes, . . .).

We agree with the reviewer that more discussion of biases in the version of CESM run for this study requires additional attention in the reviewed manuscript. We also recognize that we need to reframe discussion away from "what drove the observed amplitude" and more toward "what nonlinearities are present in a prognostic ESM that influences its ability to simulate multi-decadal through multi-century trends in coupled climate-carbon cycling?".

It is not clear (at least to me) what the study brings in comparison to previous studies as I feel it does not focus enough on the “potential novelty” linked to i) the use of a coupled ESM...

i) We thank the reviewer for her/his helpful comments here that prompt us to recognize the need for us to provide better framing for our study's motivation and results. The use of a coupled ESM is crucial for our major goal, which is to explore whether there are changes in drivers of the mean annual cycle amplitude in a future climate change. We will add the following text to the introduction: "The use of a coupled model allows us to simulate the co-evolution of physical climate and biogeochemistry using a self-consistent framework. This is crucial since carbon fluxes are inherently linked to the physical climate; for example, a change in GPP will be associated with changes in evapotranspiration, which feeds back on metrics such as humidity, cloud cover, and precipitation. Moreover, in a fully prognostic model, both climate and carbon cycle diagnostics are free to evolve rather than being tied to input data sets that reflect the contemporary climate."

... as well as ii) the use of "regional atmospheric influence functions" to analyze the regional and temporal contribution of the potential drivers. Note that this last part is poorly valorized and not discussed in detail enough.

ii) In response to this comment, and some comments from Reviewer 1, we plan to add additional figures to demonstrate the pulse response methodology and validation against the full-transport land CO_2 field simulated by CESM. We will also add the text included in our response to Reviewer 1 to better explain and validate the method.

I also find that on average the results are exposed but not analysed enough in terms of processes (GPP versus the different respiration terms; contribution of different PFT; which are the key processes in the model that are responsible for the modeled trend and CO_2 amplitude (water versus temperature limitations, . . .)). The limits of the model are also not discussed enough in terms of which scientific results are "robust" versus those that are likely not very uncertain (especially when discussing the time frame 2100–2300).

We address these drivers in our responses to the reviewer's individual comments below.

I thus recommend major revisions prior to consider that such work brings new information for the understanding and the prediction of the atmospheric CO_2 seasonal amplitude changes.

Main comments

* Introduction:

- The authors provide a nice literature review of articles that have tried to explain the increase of atmospheric CO_2 amplitude. However, they lack the recent study by Hakihiko Ito et al., 2016 in Tellus " Decadal trends in the seasonal-cycle amplitude of terrestrial CO_2 exchange resulting from the ensemble of terrestrial biosphere models" Note that such study is using an ensemble of process-based land surface models, including two versions of CLM (CLM4 and CLM4VIC) which are probably close to CLM4CN used in this study? Although such study was just published, it would be now crucial to include it in the literature review, given how comprehensive it is.

We thank the reviewer for bringing this article to our attention, and will include discussion of this article in the revised manuscript. We note that this article was published after our manuscript was published in *Biogeosciences Discussions*, so we did not have the opportunity to include it in our initial submission. Likewise, another relevant paper was published in *Biogeosciences Discussions* a few days after our initial submission. These papers are valuable in that both us multi-model ensembles (MsTMIP and TRENDY, respectively) to consider changes in the mean annual cycle of land-atmosphere carbon fluxes.

An important difference between these papers and our manuscript is that these papers focus on the seasonal cycle of fluxes, rather than propagating those fluxes to atmospheric CO_2 concentration, which we focus on in our paper. The propagation of fluxes to atmospheric CO_2, even using a simple method such as the pulse response code that we use, is important since atmospheric transport plays a major role in the spatial gradient in atmospheric mean annual cycle trends. We also note that in terms of understanding future observations, we cannot directly observe GPP (although promising remote sensing tools such as chlorophyll fluorescence are being developed) or ecosystem respiration at large spatial scales. Thus, using a model such as CESM to develop hypotheses about how individual process might change the quantity that *is* directly observable (atmospheric CO_2) is a valuable exercise, in our opinion.

We will revise the introduction to include discussion of these manuscripts and to differentiate our approach from these papers. The following text will be inserted before the paragraph on p3, L10: "Several recent papers have considered how the amplitude of NH net carbon exchange has changed over the historical period. Ito et al. (2016) analyze MsTMIP terrestrial ecosystem models to determine how atmospheric CO_2, climate change, and land use affect the NH flux amplitude for the historical period, and Zhao et al. (2016) analyze the net terrestrial flux to the atmosphere in TRENDY models. Both of these studies find that CO_2 fertilization is the strongest driver of increasing ecosystem productivity and thus the amplitude of the net carbon exchange in the NH. The results from these ensemble-based analyses provide a useful basis for comparison for our analysis of a single, fully coupled ESM. A significant difference between the approach used by these papers and our study is that they consider the net flux amplitude, whereas we propagate fluxes using an atmospheric transport operator to determine the influence on latitudinally resolved atmospheric CO_2 fields. We hypothesize that fingerprints of climate change or CO_2 fertilization may be evident in different latitude bands in the CESM output."

This statement will be followed by the following text, to be included in the discussion section of the revised manuscript:

"CESM simulations show that the major drivers of the mean annual cycle amplification leave differential imprints on atmospheric CO_2 in different latitude bands. For example, CO_2 fertilization leaves the largest imprint in both absolute and relative terms on midlatitude CO_2, whereas climate change may amplify high latitude CO_2 while having a near-neutral impact on CO_2 annual cycle amplitudes south of 60°N (Fig. 10). These fingerprints may be useful for developing hypotheses regarding observed trends and determining future observational strategies to monitor carbon-climate feedbacks."

- Secondly and more importantly, we miss after such review what are the remaining critical uncertainties around the drivers of the seasonal CO_2 increase? For instance, Forkel et al. (2016) claimed that they could reproduce reasonably well the observed CO_2 amplitude increase. What is thus missing or what is uncertain from their study? A critical analysis of the past literature in order to define the "niche" for this paper is missing. It would be good to have a set of more precise questions that the paper will target.

We thank the reviewer for this constructive comment. An implicit premise of our study was that the drivers of changes in the mean annual cycle between 1958 and 2013 need not continue to drive changes in the mean annual cycle of CO_2 into the future. Fertilization impacts could saturate, while further increases in temperature or related changes in drought conditions may actually reverse trends in seasonal productivity. We recognize that we need to make this premise more explicit in the revised manuscript. The Forkel et al. (2016), Ito et al. (2016), and Zhao et al. (2016) studies all focus on explaining only the historical trend, not future projections. We choose to study this topic in a single climate model so that we can in more detail analyze the regional contributions by driver to future changes in the mean annual cycle amplitude.

In the Ito et al. (2016) paper, a fair amount of attention is given to the idea that the mean annual cycle strength correlates with the net terrestrial sink strength. Because the simulations were run to 2300, we are able to determine the time period in CESM where this statement is no longer true. In the extended concentration pathway simulations, the mean Northern Hemisphere CO_2 amplitude is correlated with increased Northern Hemisphere carbon uptake (using NEP and neglecting land use change, disturbance, and harvest fluxes) through ~2150, at which point NEP shows significant declines in the Northern Hemisphere while there are only small changes to the amplitude (Fig. SB1).

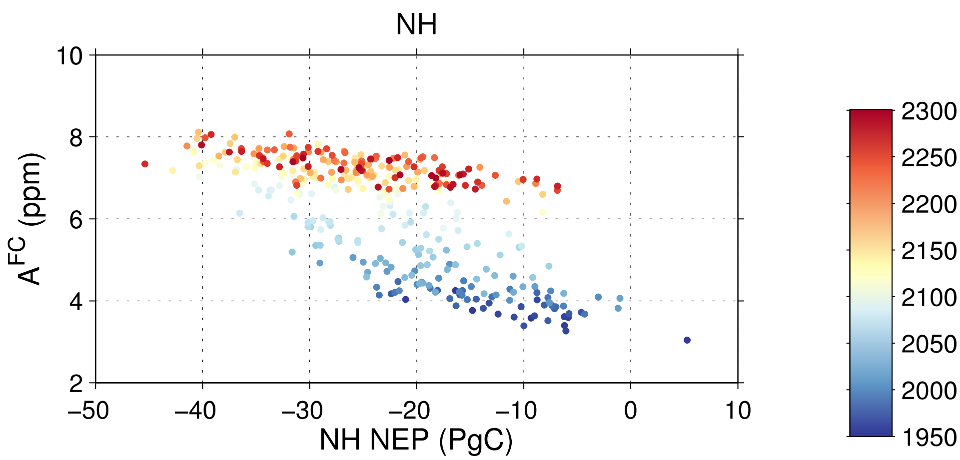

Fig. SB1: FullyCoupled atmospheric CO_2 annual cycle amplitudes (A^{FC}) versus NEP averaged over the NH and shaded according to simulation year. Negative NEP values indicates net carbon uptake by the land surface.

Based on the reviewer's comment, we plan to add a section on " Uncertainties and future model needs" to the discussion section to the paper, in which we explicitly discuss how lack of permafrost parameterizations, vegetation successional patterns, active human management, etc. affect the simulation results. It is exciting that CESM2, in preparation for the CMIP6 experiments, has much improved representation on frozen soil carbon and temperature interactions (Koven et al., submitted) as well as land management representation (P. Lawrence et al., BGCWG February Meeting presentation). Moreover, a version of CLM-ED will be released this fall. These new developments present opportunities for follow-on studies to explore the impact of these "missing" interactions. However, we feel that these comparisons are outside the scope of the current paper and are best reserved for a future study. Our paper, instead, provides a baseline analysis of the CESM1.

We also thank the reviewer for the suggestion of explicitly including questions that the paper will address. We will include the following questions at the close of the "Introduction" section of the revised manuscript:

"The questions guiding our analysis of CESM extended concentration pathway simulations are as follows:

1. Does the relative importance of drivers of the CO_2 amplitude trend change after 2100? For example, do we see evidence of saturation of the CO_2 fertilization effect or evidence of a climatic tipping point after which the CO_2 amplitude declines?

2. Do the regional contributions to CO_2 mean annual cycle trends change in response to large changes in climate?

3. Does the CO_2 annual cycle amplitude scale with the hemispheric carbon sink from NEP as climate and atmospheric conditions evolve in the future?"

- Page 3, l13: The justification for the need of a full land-atmosphere-ocean coupled model is not provided, at least given the scientific questions that underlines the study? You need to justify why using the full ESM is beneficial and what can it bring compared to others studies (for instance, Ito et al. (2016) have used an ensemble of land surface models and similar experimental set up to separate the effect of potential drivers)? You could have envisaged forcing the CLM4CN model with climate predictions with a bias correction. What do you gain from your coupled approach?

Since the goal of the paper is to explore future trends the use of a prognostic climate model is crucial since we do not have some bias-corrected estimate for climate change. Given the scientific questions we have added to the paper, and our response (above) for why CESM is a good tool for this analysis, we think that our approach has now justified in the manuscript text.

- It seems strange to me to emphasize the period 2100–2300 with a model that does not include Permafrost modeling and other critical processes linked to land management (no crop specific module, or no vegetation dynamic); while these may be more crucial in very long term simulations. You have at least to justify that the model is suitable to answer the question you pose.

We agree with the reviewer that there are limitations to the CESM configuration for the science questions we address in our paper, including the lack of permafrost modeling and land management. We note that ESM development is a slow and steady process, and that there is value to fully exploring processes in CESM1–the first fully coupled version of this model. Moreover, comparisons among different model versions are crucial, so careful analysis of CESM1 will provide better insights and science questions for subsequent analysis of CESM2.

We will add the following text to the introduction P3, paragraph ending on line 22: "The CESM provides a unique platform for exploring these questions in that it is one of the few prognostic ESMs to include coupled carbon-nitrogen biogeochemistry and diagnostic atmospheric CO_2 variability."

- In general the introduction should propose a set of questions that follow from points that have not been treated by previous studies or based on the uncertainties that are still prevailing? And your approach (i.e. the use of CESM1) should be justified or at least explained with respect to the objectives.

Per the reviewer's suggestion, in the revised paper we plan to introduce the following questions:

1. Does the relative importance of drivers of the CO_2 amplitude trend change after 2100? For example, do we see evidence of saturation of the CO_2 fertilization effect or evidence of a climatic tipping point after which the CO_2 amplitude declines?

2. Do the regional contributions to CO_2 mean annual cycle trends change in response to large changes in climate?

3. Does the CO_2 annual cycle amplitude scale with the hemispheric carbon sink from NEP as climate and atmospheric conditions evolve in the future?"

* Model section:

What does CLM4CN do for natural vegetation shift. This will be crucial in the boreal zone with possible tree migration northward especially with such long time frame investigated (2300). Few word on this aspect would be beneficial.

CLM4CN does not include dynamic vegetation. We will include the following text in the model description (Section 2.1): "These simulations were run without dynamic vegetation, which potentially also damps feedbacks that could contribute to changes in the CO_2 annual cycle through 2300."

We will also add text to the "Uncertainties and future model needs" section that will be added to the discussion: "The lack of dynamic vegetation in this version of CESM contributes some uncertainty to these results. Tree cover is expected to expand further northward with climate change (e.g., Lloyd et al., 2005), which may contribute to the long-term increase in NEP flux amplitude within high latitude ecosystems. In contrast, drying at lower latitudes may lead to replacement of trees with grasses and subsequent decreases in NEP amplitude. Thus, the balance of these processes on the overall flux amplitude and spatial variability in the atmospheric CO_2 trend is uncertain. An ecosystem demography version (CLM-ED) is currently being developed that would permit successional patterns in response to environmental change. We consider the documentation of trends in the static-vegetation configuration presented in this manuscript to be a crucial first step toward eventually determining the sensitivity of land-atmosphere biogeochemical couplings in more sophisticated, future configurations of the CESM model."

* Experiment:

- The authors mention using "impose CO_2" for the different experiment while in the result sections they say "The imposed emission scenario" (page 7, l10). The procedure became only clear to me when reading the note page 7, l15: "We note that the atmospheric CO_2 mole fraction values were diagnostic only. . ..". I thus think that the "experiment section" should describe more precisely what was done and differences between imposed CO_2 and diagnostic CO_2.

We will include this description in Section 2.2 "Experiments". The revised text will read: "The mole fraction of CO_2 in the atmosphere is prescribed according to the RCP8.5 and ECP8.5 scenario described by Meinshausen et al. (2011), and it is this value that controls radiative forcing as well as CO_2 fertilization. However, the CESM retains a separate, spatially-varying CO_2 tracer that is a diagnostic passive tracer of land, ocean, and fossil fuel carbon fluxes; the additional carbon exported from the surface to the atmosphere does not exert any forcing on the climate."

- Page 5, L 13: you should precise which patterns of the monthly CASA fluxes was used to prepare the pulse functions: GPP, NEP, NEE?

We will revise section 2.4 to state we used monthly mean NEP from the CESM to derive atmospheric CO_2 from the pulse response function.

- Page 5, L25—28: There are potentially large differences between the CASA NEP spatial patterns and the CLM4CN ones so that it is not at all obvious that the "mapping approach with GEOS-Chem" will not be biased through differences in these spatial patterns. Discussion of Figure 2c brings a first insight but the authors should discuss more the impact of "surface pattern differences" and "transport differences" for the trend in the atmospheric CO_2 amplitude rather than for the amplitude itself.

We have included revised text and figures in the response to Reviewer 1 to address these points. We anticipate that surface pattern differences are a minor source of disagreement since Nevison et al. (2012, GMDD) tested a similar pulse-response framework for fossil fuel emissions. The fossil emissions were distributed according to NEE, which represents a gross mismatch, but still had an r^2 value of 0.8 compared to a full transport simulation. Mismatches between CESM and CASA terrestrial fluxes are likely much smaller, although we have mentioned this factor as an additional source of error in the revised text.

* Results

- Page 6, 30: It is not clear when you compare the 425 ppm simulated by CESM to the observed 391 ppm in 2010, over which period the drift occurred (missing sink). This would need to be clarified so that we see more how much is he missing sink per year?

Previous results have shown that the missing sink for atmospheric CO_2 in CESM is attributable to weak uptake in both the land and the ocean, and that this sink is relatively smooth with time.

We will revise the first paragraph of section 3.1 to conclude with "We note that the drivers of the amplitude increase during 1985—2013 were simulated to different levels of fidelity: the NH atmospheric temperature increase over land was roughly equivalent (1.02 K vs 0.95 K in the NCEP-NCAR reanalysis (Kalnay et al., 1996)), but the NH atmospheric CO_2 mole fraction in CESM was too high (425 ppm vs 391 ppm derived from observations in 2010). Previous analysis of CESM shows that the high CO_2 bias is attributable to persistent weak uptake in both land and ocean (Keppel-Aleks et al., 2013; Long et al., 2013)."

- Page 7, L11: As I said above, you mention the "imposed emission scenario" but this is not detailed in the experiment section?

We will clarify in the experiment section the details of the imposed emission scenario as described in our previous response.

- The change in surface temperature of 6 K in 2100 and then 11 K by 2300 makes me wonder about the prediction of the CO_2 amplitude increase. With such large temperature change after 2100, neglecting permafrost melt and potentially large natural vegetation change in the artic may be severe limitation? At least this should be discuss to gain confidence that the other effect accounted for are the primary ones

We agree with the reviewer that more discussion of this limitation, beyond noting the absence of permafrost dynamics in Section 2.1, should be addressed in our paper, and will add the following discussion to the "Uncertainties and future model needs" section of the revised manuscript: "The lack of permafrost dynamics likely has a large impact on CO_2 annual cycle trends, especially later in the simulation when global mean temperature has increased by over 10 K in the fully coupled simulation. Ongoing model development in CESM includes improved representation of permafrost carbon (Koven et al., 2015), and thus future model configurations will provide an improved tool for investigating a process that may provide one of the tipping points we identify in our key science questions."

- More generally the fact that the model simulate only of the seasonal cycle atmospheric amplitude at high latitude is probably a strong limitation to study the "drivers of the amplitude increase". This should be discussed in more detail. Such a bias has probably large implications on the relative contribution of atmospheric CO_2 increase, versus climate and land use change?

Many CMIP5 models exhibit the same bias (e.g., Zhao et al., 2016) show that the mean TRENDY model shows a 40% deficit in the annual mean). Since we intend the study to be an examination of what a fully prognostic model can tell us about trends, tipping points, and our current ability to simulate these interactions, we feel there is still value in quantifying drivers of trends within CESM1.

We will add the following text to Section 3.1, Line 27: "Although the CESM simulates low mean annual cycle amplitude throughout the NH, we note that many land models have a low bias in their simulated fluxes. For example, TRENDY land models show a 40% deficit in the magnitude of the seasonal cycle (Zhao et al., 2016)".

- Page 8, L28: Why do you think that you still obtain a strong fertilization effect on the amplitude increase even given that CLM4CN has the lower fertilization effect of last CMIP5 models? Maybe you should explain a bit more which processes are contributing? Only the GPP increase? or other effects linked to autotrophic and heterotrophic respirations?

We will add the following text to clarify that GPP is the main driver of the trends:

"Enhanced GPP seasonality appears to drive to the amplification of the atmospheric CO_2 seasonal cycle over northern temperate and boreal regions during 1950—2300. In midlatitude temperate regions where CO_2 fertilization drives the CO_2 seasonal cycle amplification, the seasonal amplitudes of GPP, HR and AR increase from 1950 to 2250, but the magnitudes of and increases in GPP seasonal amplitude are larger than those of HR, AR, and NEP in the FullyCoupled, NoRad, and NoLUC simulations. For example, in eastern temperate North America (ETNA), FullyCoupled GPP seasonal amplitudes increase from 6.8 PgC in 1950 to 11 PgC in 2250, while HR amplitudes increase from 0.85 PgC to 1 PgC, and AR amplitudes increase from 4 PgC to 7.6 PgC. The absolute increases in the seasonal amplitudes of GPP and total respiration (AR+HR) are, respectively, 2.5 and 2.4 times larger than the increase in the NBNA NEP amplitude during this period. Moreover, we find that GPP in high latitude regions, where climate change is the dominant contributor to amplification of net fluxes, is highly correlated with temperature. In the pulse regions that comprise our broader Arctic and boreal zones, GPP continues to increase with temperature until surface air temperatures surpass ~300 K."

- Climate change effect (section 3.3.2): I feel that not enough insight on the processes that lead climate change to impact the changes in atmospheric CO_2 amplitude are given? What is the role of the different respiration terms versus photosynthesis? Do you see different contribution between grass and tree PFTs? What are the mechanisms in CLM4CN that explain the contribution (sensitivity of the maximum photosynthetic uptake to temperature)?

We address the reviewer's comment in the response/text above.

In addition, we will include an analysis of the changes in PFT cover that contribute to the reduction FullyCoupled atmospheric CO_2 seasonal amplitudes from land-use change (LUC). As stated in the Methods section 2.2, PFT fractions vary on an annual basis from 1850—2100, then are held at 2100 values through 2300 in the FullyCoupled simulation. In the NoLUC simulation, PFT fractions are held at 1850 values. Crops (treated as unmanaged grass), needleleaf evergreen trees, and grass PFTs cover most of the NH boreal and temperate vegetated land. Between 1850 and 2100, boreal, temperate, and subtropical crop cover increase, while grass and needleaf tree cover decrease. Therefore, the decrease in the NH atmospheric CO_2 seasonal amplitude in response to temperate and boreal LUC reflects the fact that needleleaf evergreen tree and grass cover in these regions is lower in FullyCoupled than in NoLUC, resulting in lower GPP and smaller NPP seasonal amplitudes.

- LUC effect (section 3.3.3): It seems strange to mention that "the model is providing contrary results to previous studies" with the explanation that it does not properly treat cropland! At least we need a discussion to show that the current LUC effects are not completely wrong given such "model shortcut". The authors should detail why they think the other component of the LUC effect may be important and why "their message about LUC effect" is still a valuable one?

We agree that prescribing LUC and treating crops as unmanaged grass may produce unrealistic responses in atmospheric CO_2 seasonality. The contrast between our results, which show that LUC reduces NH atmospheric CO_2 seasonality and other studies, such as Zhao et al. (2016), showing that LUC increases atmospheric CO_2 seasonality indicate that more sophisticated treatment of changes in vegetation cover and explicit representation of crop cover are likely necessary in the CESM.

- Page 9, l34: Precise over which period the growing season length increased by 1 month. Overall the section 3.3.4 on the growing season length is not bringing much information. You could explain what contributes in the model to the change in growing season length (earlier starts or later end of the season). As for the tropic and the argument on the water use efficiency, you could provide more support by discussing how the soil moisture has evolved in the simulation with climate change.

In section 3.3.4, we will add additional details to the text to state "The NH CO_2 annual cycle amplitude increase resulted not only from changes in the mean temperature affecting GPP, but also from lengthening of the growing season. We found that the growing season, defined as months with negative NEP (net terrestrial carbon uptake), increased for all NH terrestrial regions by about 1 month. The overall lengthened growing seasons accounted for 1—1.3% yr^{-1} of the high latitude net terrestrial carbon uptake after 2050, and up to 5% yr^{-1} of the midlatitude terrestrial carbon uptake after 2100. Thus, while this is an important contributor, it is secondary to increased mid-summer GPP."

We also expand our discussion to include analysis of soil water content in CESM, per the reviewer's helpful suggestion: "The driver of the increased growing season length was different for different ecoclimate regions. For regions north of 30°N, climate change was the driver of increased growing season length. In boreal and Arctic regions, climate change extended the growing season for an additional month in the fall. In contrast, midlatitude climate change facilitated an earlier start to the growing season in the spring (Fig. 11a). CO_2 fertilization was the major driver of changes in the growing season length in the subtropics, while climate change had the opposite effect. This result suggests that subtropical ecosystems in CESM are near a temperature optimum, but may be water-limited. In the FullyCoupled simulation, soil water content over the top three model layers, corresponding to 0.06 m depth, decreases in the Amazon and central America by 13% on average from 1950 to 2300. In the simulation without radiative forcing (but including CO_2 fertilization effects), soil water content increases by 1% on average in these regions, and suggests improved water use efficiency by vegetation. Thus, increases in water use efficiency associated with increased atmospheric CO_2 permit longer periods of carbon uptake."

* Discussion:

- Page 10, l22-23: You mention that the CESM has probably a too strong CO_2 fertilization effect. This is not intuitive as you previously mentioned that CLM4CN has the lowest fertilization effect from the CMIP5 suite of model and that it provides a too low mean amplitude and mean amplitude trend for high latitude. The reasoning and conclusion should be more detailed as it is not intuitive. You can have several compensating effects so that the fertilization in the model is not too strong. Also, what is potentially missing is a discussion of the fertilization effect in CLM4CN with respect for instance to "FACE" experiment to put in perspective the results and conclusion drawn for the 23 century.

Upon further analysis, we have decided to remove this discussion from the paper as it is speculative and relies on relative, rather than absolute, trends in the amplitude.

- Page 10, l28: You mention that LUC reduced the amplitude of atmospheric CO_2 seasonal cycle, contrary to previous studies. You should indicate why the simulation with CESM provides new plausible information, given that you have mentioned that "treating crop as grassland" is a severe limitation (see my comment above). You have to provide some explanation on why you think the results with CESM provide a new perspective with respect to LUC. Basically what was the typical LUC that is contributing to such decrease, through which processes, . . . ?

We will clarify the discussion to state that: "In contrast, land use change in CESM reduced the atmospheric CO_2 mean annual cycle amplitude throughout the NH, with the largest reductions over the mid- and high latitudes. Reductions in tree cover in the FullyCoupled simulation compared to the NoLUC simulation are associated with decreases in the net carbon flux amplitude and a negative trend in the CO_2 annual cycle amplitude. In the FullyCoupled simulation, croplands replace the lost tree cover. Several recent papers (e.g., Zeng et al., 2014; Gray et al., 2014) suggest that agricultural amplification, facilitated by irrigation and fertilization, may be an important driver of the observed mean annual cycle trend. In the CESM, however, crop cover is currently treated as unmanaged grass and thus these agricultural practices are not explicitly modeled, and thus do not mitigate the reduction in tree cover. These results underscore that explicit consideration of human modifications may be necessary for prognostic models both to match observations and to provide realistic predictions of future changes. We note that in CLM, development is under way to represent irrigation and fertilization in croplands in future versions of the model."

- Page 11, last paragraph: Further discussion on the fact that "the results indicate that there is no high-temperature tipping point at which terrestrial productivity declines" would be valuable. Does this mean that the temperature dependence of the maximum photosynthesis peaks at high enough temperature threshold? or is it linked to the nitrogen cycle?

We have removed this statement from the paper given that in individual pulse regions, there is a clear turnover in GPP with temperature. At high latitudes, this occurs above 300 K, and in the tropics, this occurs above 305 K. We note that temperature acclimation of GPP has recently been incorporated into CLM (Lombardozzi et al., 2015), but for CLM4, which we use, there is a clear decline. Instead, we close the paper with the "Uncertainties and future model needs" section prompted by the reviewer's comments.

"Although the results presented in this paper provide a useful look at the co-evolution of climate and the carbon cycle beyond 2100, several components of the model configuration induce substantial uncertainty into the results presented here. The lack of dynamic vegetation in this version of CESM contributes some uncertainty to these results. Tree cover is expected to expand further northward with climate change (e.g., Lloyd et al., 2005), which may contribute to the long-term increase in NEP flux amplitude within high latitude ecosystems. In contrast, drying at lower latitudes may lead to replacement of trees with grasses and subsequent decreases in NEP amplitude. Thus, the balance of these processes on the overall flux amplitude and spatial variability in the atmospheric CO_2 trend is uncertain. An ecosystem demography version (CLM-ED) is currently being developed that would permit successional patterns in response to environmental change. We consider the documentation of trends in the static-vegetation configuration presented in this manuscript to be a crucial first step toward eventually determining the sensitivity of land-atmosphere biogeochemical coupling in more sophisticated, future configurations of the CESM model.

The lack of permafrost dynamics likely has a large impact on CO_2 annual cycle trends, especially later in the simulation when global mean temperature has increased by over 10 K in the fully coupled simulation. Ongoing model development in CESM includes improved representation of permafrost carbon (Koven et al., 2015), and thus future model configurations will provide an improved tool for investigating a process that may provide one of the tipping points we identify in our key science questions."

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Manuscript changes for *Drivers of Multicentury Trends in the Atmospheric CO2 Mean Annual Cycle in a Prognostic ESM* (J.Liptak, G. Keppel-Aleks, K. Lindsay)

The marked-up document shows changes between the original and revised manuscript, with addition indicated by blue underlined text, and deletion indicated by red strikethrough text.

Major changes are listed below:

1. Reworded abstract
2. Expanded discussion of pulse response methodology in Section 2.3
3. Addition of Figures 2, 5, 8, 15
4. Revised values in text, Figures 4, 6, 7, 9, 13, and Tables 3 and 4 reflect corrections from a computation error in calculating amplitude changes in original manuscript
5. Revised NEP values in Fig. 1c and text now indicate annual mean net terrestrial carbon uptake rather than the annual total values reported in the original manuscript
6. Clarified Results section
7. Addition of section 4.1 *Uncertainties and future model needs* to the Discussion and Conclusions
8. Addition of references recommended by Reviewer 2 (e.g., Ito et al. 2016) to Discussion and Conclusions, rather than Introduction as stated in the initial reviewer responses.

Drivers of Multicentury Trends in the Atmospheric CO_2 Mean Annual Cycle in a Prognostic ESM

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Abstract. The amplitude of the mean annual cycle of atmospheric CO_2 has increased by at least 0.5% yr^{-1} is a diagnostic of seasonal surface-atmosphere carbon exchange. Atmospheric observations show that this quantity has increased over most of the Northern Hemisphere (NH) extratropics during the last three decades, likely from a combination of enhanced atmospheric CO_2, climate change, and anthropogenic land use change. Accurate climate prediction requires accounting for long-term interactions between the environment and carbon cycling, so analysis of the evolution of the mean annual cycle in a fully prognostic Earth system model may provide insight into the model sensitivity to the multi-decadal influence of environmental change on the carbon cycle.

We investigated how each of these factors affected the increase in We analyzed the evolution of the mean annual cycle amplitude in atmospheric CO_2 simulated by the Community Earth System Model (CESM) , a prognostic coupled climate-carbon cycle model. The simulated amplitude of the NH mean from 1950 to 2300 under three scenarios designed to separate the effects of climate change, atmospheric CO_2 fertilization and land use change.The simulated amplitude of the NH mean CO_2 annual cycle showed a weaker trend than observed, increasing by only 15% over the period spanning 1950–2010. By 2100, the amplitude rose to 57% above the present-day baseline (1950–1959), and reached a maximum of 76% above the baseline around 2250.The NH CO_2 seasonal amplitude increase in the CESM was mainly driven by reflected enhanced primary productivity during the growing season due to climate change and the combined effects of CO_2 fertilization and nitrogen deposition over climate change and changing atmospheric composition, with the largest amplitude gains occurring in the mid- and high latitudes. In additionHowever, the long-term simulations revealed shifts in key climate drivers of the atmospheric CO_2 seasonality that were not apparent before 2100. Climate change from NHboreal and temperateecosystems was the largest main driver of Arctic CO_2 annual cycle amplification between 1950 and 2100, but CO_2 fertilization had a stronger effect on the Arctic CO_2 annual cycle amplitude during 2100–2300.CO_2 fertilization and nitrogen deposition in the NH boreal and temperate ecosystems contributed the most to the amplitude increase over the midlatitudes through 2300 and over the Arctic after 2100. Greater terrestrial productivity during the growing season contributed the most to the annual cycle amplification over the high latitudes, midlatitudes, and the NH tropics, reflecting lengthening of the growing season rather than the strength of the terrestrial carbon sink.Prior to 2100, the NH CO_2 annual cycle amplification occurred amplitude increased in conjunction with an increase in the NH land carbon sink, but. However, these trends decoupled after 2100, underscoring that an increasing atmospheric CO_2 annual cycle amplitude is not predicated on does not necessarily imply a strengthened terrestrial carbon sink.

1 Introduction

The amplitude of the mean annual cycle of atmospheric CO_2, an indicator of the seasonal cycle of terrestrial and ocean carbon exchange, has increased over the Northern Hemisphere (NH) since observational records began in the late 1950s (Pearman and Hyson, 1981; Cleveland et al., 1983; Bacastow et al., 1985; Conway et al., 1994; Keeling et al., 1996; Randerson et al., 1997; Graven et al., 2013; Liu et al., 2015). The largest increases of 40–50% ~~were inferred~~ have been observed over the northern high latitudes ~~from surface observations~~ via surface monitoring (Keeling et al., 1996) and from aircraft observations of the free troposphere (Graven et al., 2013). The ~~isotopic composition of CO_2 indicates that the~~ amplification of the atmospheric CO_2 annual cycle primarily reflects enhanced net exchange of CO_2 ~~between the atmosphere and the land rather than~~ with land surfaces rather than with the ocean (Manning, 1993). Land-atmosphere CO_2 exchange is highly seasonal, especially in the NH mid- and high latitudes where photosynthesis draws down CO_2 in the spring and summer, and net ecosystem respiration returns CO_2 to the atmosphere (e.g., Komhyr et al., 1985; Enting and Mansbridge, 1989; Nemry et al., 1996; Dettinger and Ghil, 1998).

~~Recent work has identified several plausible drivers of the increasing mean annual cycle amplitude, although a full accounting of the trend remains elusive. Direct anthropogenic impacts on the mean annual cycleamplitude include changing patterns of fossil fuel emissions and land use. NH fossil fuel CO_2 emissions generally peak during winter when heating is required, enhancing the mean annual cycle from biospheric fluxes. Increasing fossil fuel emissions from 6 major industrial regions across the globe (Rotty, 1987), however, were shown to contribute less than 1% yr^{-1} to the trend in the NH CO_2 annual cycle amplitude (Randerson et al., 1997).~~

~~Responses to changing environmental conditions likely represent another important driver for increases to the CO_2~~ Because atmospheric observations are characterized by high precision and accuracy, the gradual, multi-decadal increase in the seasonal amplitude provides a unique observational target for Earth system models (ESMs) intended to predict the long term carbon cycle-climate evolution. ESMs enable the study of long-term effects of natural and anthropogenic forcing on the terrestrial carbon cycle. Unlike empirical models, ESMs provide mechanistic representations of the carbon cycle by coupling land surface models that explicitly resolve biogeochemical processes with models of the atmosphere, ocean, and other components of the climate system (Claussen et al., 2002). An advantage of using a coupled model is that feedbacks between the physical climate and biogeochemistry are represented in a self-consistent framework. This is crucial since carbon fluxes are inherently linked to the physical climate; for example, a change in gross primary productivity (GPP) will be associated with changes in evapotranspiration, which feeds back on metrics such as humidity, cloud cover, and precipitation. Moreover, in a fully-prognostic model, both climate and carbon cycle diagnostics are free to evolve rather than being tied to input data sets that reflect the contemporary climate. The mechanisms embedded in ESMs to predict future carbon-climate interactions have been identified as the likely drivers of the observed mean annual cycle ~~(Graven et al., 2013; Zeng et al., 2014).~~ amplitude increase as described below.

The magnitude of the amplitude increase ~~indicates~~ suggests a dominant role for enhanced ~~GPP~~ primary productivity during the growing season in addition to increased CO_2 release during the dormant season (Graven et al., 2013). ~~More recently,~~

~~agricultural intensification, including irrigation and fertilization of agricultural land, has been suggested to cause significant increases in the CO_2 amplitude by increasing carbon uptake during the summer growing season (Gray et al., 2014; Zeng et al., 2014). For example, Gray et al. (2014) found that enhanced summer growing season carbon uptake by midlatitude cropland contributed 17–25% (1.4 Pg C yr^{-1}) to the 1961–2008 NH extratropical CO_2 annual cycle amplitude trend. Zeng et al. (2014) likewise identified high-latitude natural vegetation and midlatitude crops as the largest contributors to the 1961–2010 NH annual cycle amplitude trend.~~

~~Changing atmospheric composition from increased CO_2 and anthropogenic nitrogen is another potential driver of enhanced terrestrial productivity.~~ Greater atmospheric CO_2 may facilitate plant carbon uptake through increased water use efficiency (Keenan et al., 2013), and results from Kohlmaier et al. (1989) and McGuire et al. (2001) suggest that CO_2 fertilization adds at least 10% to the CO_2 mean annual cycle amplitude trend. ~~The availability of nitrogen in the soil limits terrestrial productivity (Vitousek and Howarth, 1991) and, therefore, constrains the effects~~ Human activity has not only increased the atmospheric concentration of atmospheric CO_2~~fertilization on GPP as the demand for nitrogen increases (Luo et al., 2004). However, emission~~ , but also modified reactive nitrogen deposition (N-deposition) in ecosystems. Likewise, deposition of nitrogen oxides (NO_x) and ammonia from combustion, livestock, agriculture, and industrial sources may augment the supply of soil nitrogen available for fixation by plants (Prentice et al., 2001), alleviating a limitation on terrestrial GPP (Lloyd, 1999; Norby et al., 2010).

Climate change-induced warming ~~during the growing season~~ and lengthening of the growing season ~~present another pathway through which GPP may be stimulated~~may also stimulate GPP and increase the seasonality of net exchange. Keeling et al. (1996) proposed that increased terrestrial CO_2 uptake from a longer high latitude growing season has driven the amplification of the CO_2 annual cycle, since the trends in the CO_2 annual cycle amplitude strengthen moving northward, and the greatest warming has occurred during the winter and spring over the northern high latitudes. Findings by Randerson et al. (1999), McDonald et al. (2004) ~~,~~ and Barichivich et al. (2013) support the hypothesis that longer growing seasons enhance spring CO_2 uptake and annual cycle amplitudes over the Arctic. This effect may be counteracted by the fact that ~~growth during the spring over northern mid- and high latitudes may cause~~ early growing season onset may lead to growing season moisture deficits that reduce terrestrial productivity later in the growing season (Angert et al., 2005; Buermann et al., 2013; Parida and Buermann, 2014). ~~The combined effects of climate change and~~ Model evidence suggests that climate-driven shifts in vegetation cover ~~in simulations~~ can also enhance GPP. Forkel et al. (2016) showed that the interaction of vegetation dynamics and climate change lead to ~~greater~~ GPP over NH boreal and Arctic regions that, in turn, drove the observed increases in NH high latitude seasonal CO_2 amplitudes.

~~Disturbance may also contribute to the amplification of the NH CO_2 annual cycle. Fire contributes less than 10% to the NH mid- and high latitude CO_2 annual cycle amplitudes, and hence only a small percentage to the NH annual cycle amplification (Randerson et al., 1997; Wittenberg et al., 1998), but can have a large local impact on productivity. Zimov et al. (1999) showed that seasonal amplitudes of net ecosystem exchange (NEE) were 2–3.5 times greater at Siberian sites disturbed by grazing and fire than at undisturbed sites. Similarly, Welp et al. (2006) found that the CO_2 annual cycle amplitude was larger, despite the growing season starting 3 weeks later and lasting 7 fewer weeks, over a 15-year old previously-burned tree stand than an 80-year old stand.~~

In short, there are several potential drivers of the CO_2 annual cycle amplification that feed back onto the climate system~~and create large uncertainty surrounding the future behavior of the terrestrial carbon cycle. Earth System models (ESMs) make it possible to study long-term effects natural and anthropogenic forcing on the terrestrial carbon cycle. Unlike empirical models, ESMs provide mechanistic representations of the carbon cycle by coupling land surface models that explicitly solve for biogeochemical processes with models of the atmosphere, ocean, and other components of the climate system (Claussen et al., 2002). We~~ . Despite the representation of these mechanisms by ESMs, Graven et al. (2013) showed that none of the CMIP5 carbon cycle models was able to simulate the magnitude of the observed increase in atmospheric CO_2 seasonality. Since understanding the drivers of the CO_2 seasonality is crucial for model development, we used the Community Earth System Model (CESM) to study the contribution of natural drivers of variability in CO_2 fluxes to the increasing amplitude by separating the effects of CO_2 radiative forcing (climate change), CO_2 fertilization and ~~nitrogen deposition from changes in the atmospheric chemical composition~~N-deposition, and land use change on the atmospheric CO_2 annual cycle amplitude over the NH subtropics, NH midlatitudes, and the Arctic before and after 2100 in an extension of the high-emissions RCP8.5 scenario (Meinshausen et al., 2011).

In addition to revealing potential effects of continued increases in CO_2 emissions, anthropogenic nitrogen, and land use change up to 2100, extending the RCP8.5 scenario to 2300 allowed us to assess the behavior of the mean annual CO_2 cycle in warmer climate following stabilization of atmospheric CO_2 mole fraction, and a shift in the terrestrial biosphere from a CO_2 sink to a source as shown by Randerson et al. (2015).

The questions guiding our analysis of CESM extended concentration pathway simulations are as follows:

1. Does the relative importance of drivers of the CO_2 amplitude trend change after 2100? For example, do we see evidence of saturation of the CO_2 fertilization effect or evidence of a climatic tipping point after which the CO_2 amplitude declines?

2. Do the regional contributions to CO_2 mean annual cycle trends change in response to large changes in climate?

3. Does the CO_2 annual cycle amplitude scale with the hemispheric carbon sink from NEP as climate and atmospheric conditions evolve in the future?

The CESM provides a unique platform for exploring these questions in that it is one of the few prognostic ESMs to include coupled carbon-nitrogen biogeochemistry and diagnostic atmospheric CO_2 variability. This paper is organized as follows: First, we discuss the ability of the CESM to capture present-day observed changes in the mean CO_2 annual cycle amplitude throughout the NH. Second, we describe how climate change, ~~changing atmospheric composition~~CO_2 fertilization and N-deposition, and land use change impact the NH CO_2 annual cycle amplitude in the CESM before and after 2100. Third, we examine how forcing from different regions contributes to the amplitude changes attributed to each driver. Finally, we discuss our results and provide recommendations for future analysis.

2 Methods

2.1 Model

We analyzed simulations from the Community Earth System model with coupled biogeochemistry (CESM1(BGC); Hurrell et al. (2013)) to explore the role of environmental change on land-atmosphere carbon exchange. The Community Atmosphere Model (CAM, version 4; Neale et al. (2013)) and the Community Land Model (CLM, version 4; Lawrence et al. (2012)) were the most important components for our research, but all components of the model, including physical and biogeochemical ocean processes and sea ice processes were interactive in the model configuration. The CAM4 was run on a $0.94° \times 1.25°$ finite volume grid with 26 vertical levels. The model simulated climate conditions, including temperature, precipitation, and humidity that provide important boundary conditions for land biogeochemistry. Moreover, the CAM4 directly simulates three-dimensional transport of atmospheric CO_2, as well as separate CO_2 tracers derived from fossil fuel emissions, land exchange, and ocean exchange.

The CLM4 exchanged fluxes of sensible and latent heat, momentum, moisture, radiation, and terrestrial carbon with the CAM4, and was run at the same horizontal resolution. Biogeochemistry is represented in CLM4 by a prognostic carbon-nitrogen model (CLM4CN, Thornton et al. (2007)) and fire model adapted from the Thonicke et al. (2001) model. We note that important high latitude processes, such as permafrost carbon dynamics, were not simulated in the CLM4, meaning that the model may have underestimated both the seasonal dynamics of soil carbon fluxes and the long-term dynamics of permafrost melt and the subsequent radiative feedback onto the climate system (Koven et al., 2015).

In our analysis, we used the CLM4 net ecosystem productivity (NEP), defined as the difference between gross primary productivity (GPP) GPP and total respiration (autotrophic + heterotrophic) to calculate the atmospheric CO_2 annual cycle amplitudes described in Section 2.3.

2.2 Experiments

Three CESM simulations were run from 1850 to 2300 to separate the effects of climate change, changing atmospheric compositionCO_2 fertilization and N-deposition, and land use change. The simulations had identical boundary conditions for mole fraction of CO_2 , which was prescribed based on the historical, in the atmosphere is prescribed according to the RCP8.5 , and extended (and ECP8.5) scenario described by (Meinshausen et al., 2011), and it is this value that controls radiative forcing as well as CO_2 concentrations outlined by Meinshausen et al. (2011). fertilization. However, the CESM retains a separate, spatially-varying CO_2 tracer that is a diagnostic passive tracer of land, ocean, and fossil fuel carbon fluxes; the additional carbon exported from the land and ocean to the atmosphere does not exert any radiative forcing on the climate (e.g., Fig. 1). The degree of coupling between CO_2 biogeochemistry and radiative forcing differed across the three runs. In the first simulation, denoted FullyCoupled, the imposed CO_2 was radiatively active, and additional anthropogenic radiative forcing resulted from prescribed CH_4, chlorofluorocarbons, ozone, and aerosols. In this simulation, the increasing CO_2 was also biogeochemically active, meaning it contributed to CO_2 fertilization. Transient land use change (LUC) from agriculture and wood harvest, and land and ocean nitrogen deposition (N-deposition; Lamarque et al. (2010)) were applied through 2100, then held at 2100 values thru 2300. Keppel-Aleks et al. (2013) and Lindsay et al. (2014) provide additional descriptions of the model configuration and analyses of the FullyCoupled simulation during the 20th century. In the second simulation (NoRad), radiative and non-forcing from CO_2 atmospheric anthropogenic forcings were and other species was fixed at 1850 values, while but the changing CO_2 mole fraction , LUC , interacted with biogeochemistry via CO_2 fertilization. LUC and N-deposition were likewise prescribed as in FullyCoupled. Randerson et al. (2015) also details the design of the FullyCoupled and NoRad (referred to as "$\mathrm{NoCO_2Forcing}$") simulations through 2300. We isolated the impact of climate change on the mean annual CO_2 cycle by taking the difference between the FullyCoupled and NoRad simulations. The third simulation (NoLUC), was configured identically to FullyCoupled with the exception that LUC was held constant at 1850 values; therefore, LUC effects on terrestrial carbon exchange were determined from the difference between FullyCoupled and NoLUC.

Variations in fractional coverage, albedo, nutrient limitations, and surface energy fluxes among trees, grasses, and crops may enhance or oppose the effects of climate change and CO_2 fertilization on the atmospheric CO_2 mean annual cycle amplitude. These plant functional type (PFT)-based changes were approximated by prescribing transient land cover change through 2100 in FullyCoupled and NoRad based on annual fractional transition among primary vegetation, secondary vegetation, pasture (grazing land), and crops described by Hurtt et al. (2006) with CESM PFTs detailed in Lawrence et al. (2011). The crop model was inactive in the CESM simulations, and the crop PFT in Hurtt et al. (2006) data was specified as unmanaged grass (Lindsay et al., 2014). Therefore, our CESM results do not include anthropogenic influences such as fossil fuel emissions seasonality or agricultural intensification. Lawrence et al. (2011) details the assignment of the 15 CLM4 PFTs using the Hurtt et al. (2006) data types during 1850–2005. These simulations were run without dynamic vegetation, which potentially damps feedbacks that could contribute to changes in the CO_2 annual cycle through 2300.

2.3 Mapping atmospheric CO_2 from surface fluxes

Although the CESM simulated the three-dimensional structure of atmospheric CO_2, we used a pulse-response transport operator to separate the imprints of CO_2 fluxes from different regions on the hemispheric atmospheric CO_2 patternsvariations. The transport operator was developed using the GEOS-Chem transport model (version 9.1.2, Nassar et al. (2010)). GEOS-Chem was configured as in Keppel-Aleks et al. (2013) on a $4° \times 5°$ horizontal grid with 47 vertical layers, and forced with meteorology fields from the 3–6-hourly Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis dataset (Rienecker et al., 2011). A tagged 1 Pg C month^{-1} pulse was released for each of the 20 terrestrial source regions in Fig. 1 Fig. 2 for each calendar month, and allowed to decay for 60 subsequent months. Each 1 Pg C month^{-1} pulse was distributed spatially according to monthly fluxes from the Carnegie-Ames-Stanford Approach (CASA) fluxes from Olsen and Randerson (2004).

At a given location, the magnitude and phasing of the atmospheric CO_2 response of the pulse depends on the characteristics of atmospheric transport (Fig. 3). For example, at Barrow (BRW) in Northern Alaska, a 1 Pg pulse released in Boreal North America (NBNA) in the winter months (December–January) has a large impact on atmospheric CO_2 during the first 1–2 months after a pulse is released (2 ppm, Fig. 3a), but more vigorous vertical mixing in the summer months reduces the imprint to 0.5 ppm. In contrast, when the pulse is released from temperate North America (ETNA, WTNA), there is a phase lag of 2–3 months (Fig. 3b,c), and when the pulse is released from the Amazon (AMZN), there is a delay in the peak response at BRW of at least 4 months (Fig. 3d). Following the 12-month period in which pulses were released, the signals were allowed to decay for 60 subsequent months until , at which point CO_2 was well-mixed in the atmosphere (Fig. 3a–d).We then sampled GEOS-Chem at the locations of 41 NOAA cooperative CO_2 flask sample sites (Dlugokencky et al. (2013); Table 1, Fig. 1Fig. 2) for each month of 72 total months simulated. This resulted in a CO_2 transport operator matrix with dimensions $\mathrm{N_{reg.}} \times \mathrm{N_{obs.}} \times \mathrm{N_{mon.}}$.

We used monthly mean NEP from the CESM to derive atmospheric CO_2 from the pulse response function. We aggregated NEP fluxes from CLM4 to the spatial scale of the 20 source regions (Fig. 1)(Fig. 2), and used matrix multiplication to calculate propagate these fluxes to atmospheric CO_2. We calculated the monthly mean CO_2 mole fraction at the observation sites . Global by summing over the contributions, and the background contribution from fluxes released during the 60 previous months, to get a CO_2 was calculated from the sum of the atmospheric CO_2 responses to pulses emitted from the shaded regions in Fig. 2.response matrix with dimensions ($\mathrm{N_{obs.}} \times \mathrm{N_{mon.}}$).

We analyzed both the CO_2 fields from global fluxes (e.g., seasonal cycles in Fig. 5) and CO_2 patterns influenced only by larger regions representing Arctic, boreal, temperate, subtropical, tropical, and Southern Hemisphere (SH) ecosystems. We calculated the CO_2 annual cycle amplitude values as the peak-to-trough differences in CO_2 summed over each component region (e.g., the CO_2 annual cycle amplitude at a given station from pulses emitted from the Arctic was calculated as the peak-to-trough difference in the sum of CO_2 from pulses emitted by the blue regions in Fig. 2). We note that our analysis focuses on surface observations of atmospheric CO_2, and does not include aircraft measurements.

The spatial and temporal patterns in the annual cycle amplitudes using the pulse-response transport operator and the fully coupled CESM configuration were broadly similar.The advantage of the pulse-response method is that we can efficiently compute the regional contribution to changes in atmospheric CO_2; it would be prohibitively expensive to run a full atmospheric transport model for each of the regions separately for 350 years. However, using this simplified transport operator introduces errors.Since the land tracer in the CAM4 is derived from NEE, we presentTo evaluate the pulse-response method, we show a comparison in which we have generated CO_2 using NEE (net ecosystem exchange (NEE), which includes fire, harvest, and land use fluxes (Fig. 4), since the land CO_2 tracer in the CAM4 is derived from NEE (despite that we use NEP for subsequent analyses). The magnitudes generally differed by errors are generally less than 2 ppm between the full transport and pulse response calculations due to different model boundary layer schemes and atmospheric transport (Fig. 2c) (Fig. 4c). We note that the largest differences were during the last century of the simulation, which we hypothesize likely was due to shifts in atmospheric transport in response to the dramatic climate change in the CAM4. The fact that long-term trends in transport are not simulated by the pulse-response approach is one of the major sources of bias. In a site-by-site comparison (Fig. 5), the increasing bias through 2300 appears to be due to amplification of existing biases in the pulse-CO_2 compared to the full transport-CO_2. A second source of uncertainty is that the spatial distribution of fluxes within each region is different in CESM compared to CASA. We expect that this has a minimal impact based on results from Nevison et al. (2012), who showed that a similar pulse response code using different transport models did a reasonable job ($r^2 = 0.8$) of simulating the fossil fuel influence on CO_2 despite that fossil fuel emissions show a vastly different spatial configuration than do ecosystem fluxes.In our analysis, we aggregate the sites into high-, mid-, subtropical, and tropical latitude belts to minimize local effects at individual sites and instead to focus on large-scale trends owing to broad patterns of changing fluxes.

We ~~also~~ assessed the validity of the assumption to model only the land contributions to trends in the mean annual cycle of CO_2 by calculating the CO_2 amplitudes in the CAM land and ocean tracers. We found that the contemporary peak-to-trough amplitude in the ocean tracer averaged across our high latitude stations was 2 ppm (in contrast to 10 ppm in the land tracer). Although both the land and ocean amplitudes grow with time, by 2300, the high latitude ocean tracer had an amplitude of 3 ppm, only 18% of the land amplitude for this time period. ~~Ocean carbon uptake was found to change significantly in CESM through 2300 (Randerson et al., 2015), but based on these numbers, ocean CO_2 still had a smaller imprint on the atmospheric annual cycle.~~

2.4 Atmospheric CO_2 timeseries analysis

To place the CO_2 annual cycle amplitudes simulated by the CESM in the context of present-day observations, we quantified observed and simulated CO_2 annual cycle amplitude at NOAA observatories before aggregating amplitudes across four latitude bands spanning 60°–90°N (NH high latitudes), 40°–60°N (NH midlatitudes), 20°–40°N (NH subtropics), and 0°–20°N (NH tropics). We identified a subset of stations in the NOAA Global Monitoring Division (Conway et al., 1994) and Scripps Institute of Oceanography (Keeling et al., 2005) networks with better than 95% temporal coverage of monthly mean values from 1985–2013 (gray circles in ~~Fig. 1~~ Fig. 2). The trends at these stations were calculated iteratively as a second-order polynomial, as described by Keppel-Aleks et al. (2013). After subtracting the trend from the raw observations, we calculated the peak-to-trough amplitude (A^{Obs}) for each calendar year in which observations existed. We then aggregated A^{obs} from all stations within the specified latitude bands to determine a regionally averaged amplitude.

We calculated the regional CO_2 amplitudes for the fully coupled simulations (A^{FC}) using a nearly identical methodology. However, due to the length of the simulated timeseries, we detrended the data in ten-year increments. For CESM output, we used only the sampling locations with greater than 95% temporal coverage for comparison with the observations (~~Fig. 1~~ Fig. 2, gray circles), but aggregated amplitudes at a larger set of marine boundary layer observatories when assessing future trends (~~Fig. 1~~ Fig. 2, black circles). Due to the flexible transport operator, we separately calculated amplitudes from NoRad (A^{NoRad}), and NoLUC (A^{NoLUC}) simulations, and were further able to simulate only the contribution from specified ecosystem types. The contribution of climate change to the CO_2 mean annual cycle amplitude (A^{Clim}) was calculated from the difference between A^{FC} and A^{NoRad}. Likewise, the LUC contribution to the annual cycle amplitude was calculated from the difference between A^{FC} and ~~A^{NoLuc}~~ A^{NoLUC}.

3 Results

3.1 Trends in present-day observed and modeled CO_2 annual cycle amplitudes

Throughout the NH, the CESM simulated both smaller mean annual cycle amplitudes and a smaller trends in amplitude relative to observations. The CESM underestimated the magnitudes of A^{Obs} by roughly 50% (Fig. 3b, c) (Fig. 6b, c), and the 16% relative increase in the hemispheric-average amplitude between 1985 and 2013 estimated by the CESM was somewhat lower than the observed increase of 24%. The 1985–2013 mean A^{Obs} averaged over the whole NH was 9.510.5 ppm, while A^{FC} was 5.95.8 ppm. At high latitudes, the observed value was 16.01985–2013 value was 15.9 ppm, but only 10.110.8 ppm in the CESM, broadly consistent with Keppel-Aleks et al. (2013) who showed that the CESM1(BGC) underestimated NH seasonality by 25–40%. The CESM simulated a 17% relative increase the NH mean amplitude between 1985 and 2013 that was close to the observed 20% increase during this period. We note that the environmental drivers of amplitude increase during 1985–2013 were also simulated reasonably well by CESM: the annual mean NH atmospheric CO_2 mole fraction in CESM was 425 ppm compared to observations of 391 ppm in 2010, and the NH atmospheric temperature increase over land was also roughly equivalent (1.02 K vs 0.95 K in the NCEP-NCAR Reanalysis (Kalnay et al., 1996)).Although the CESM simulates low mean annual cycle amplitude throughout the NH, we note that many land models have a low bias in their simulated fluxes. For example, TRENDY land models show a 40% deficit in the magnitude of the seasonal cycle (Zhao et al., 2016).

Consistent with the observations, the CESM simulated an increasing amplitude trend with latitude over the NH. However, the meridional gradient in the CESM trend was too weak, resulting in much smaller trends over the high latitudes. leading to small absolute increases over the Arctic. Both the modeled and observed trends in the CO_2 annual cycle amplitude were calculated from individual sites whose records date to 1985 (gray circles in Fig. 2). The modeled trend in the CO_2 annual cycle amplitude over the high latitudes was 0.05 ppm yr^{-1} (0.460.43% yr^{-1}) for the 1985–2013 period, while the observed trend was 0.09 ppm yr^{-1} (0.57% yr^{-1}). Midlatitude and subtropical trends simulated by the CESM were around 0.03 ppm yr^{-1} (0.400.43% yr^{-1} and 0.470.46% yr^{-1}, respectively), and the trends in the magnitudes were closer to the observed midlatitude trend of 0.04 ppm yr^{-1} (0.22% yr^{-1}) and subtropical trend of 0.05 ppm yr^{-1} (0.61% yr^{-1}).

We note that the potential drivers of the amplitude increase during 1985–2013 were simulated to different levels of fidelity by the CESM: The 1985–2013 NH atmospheric temperature increase over land (1.02 K) was near the NCEP-NCAR Reanalysis (Kalnay et al., 1996) value (0.95 K), but the 2010 annual mean NH atmospheric CO_2 mole fraction in the CESM was too high (425 ppm vs 391 ppm). Previous analysis of CESM shows that this high bias in simulated CO_2 is attributable to persistent weak uptake in both land and ocean (Keppel-Aleks et al., 2013; Long et al., 2013).

3.2 Future CO_2 annual cycle amplitude changes

3.2.1 Total amplitude changes

Given the weak atmospheric CO_2 seasonal amplitude response in the CESM for the contemporary period, we examined the response of flux seasonality to stronger forcing in the FullyCoupled simulation run to 2300. Both near-surface atmospheric temperature and the mean atmospheric CO_2 mole fraction ~~in the FullyCoupled simulation increased by over 800 ppm by 2100 and by over 2000 ppm by 2300~~ increased markedly in the CESM (Fig. 1a~~).~~, b). The accumulated mean NH atmospheric CO_2 mole fraction (~~Fig. 4a~~ Fig. 1a, solid line) increased from approximately 320 ppm to 2350 ppm between 1950 and 2300. ~~The rate of atmospheric CO_2 mole fraction increase rose from about 1.7 ppm yr^{-1} during 1950–2000 to 11.0 ppm yr^{-1} between 2050 and 2150, then declined to approximately 0.5 ppm yr^{-1} during the final 50 years of the simulation.~~ In the NoRad simulation, where ~~CO_2 did not exert a radiative forcing~~ radiative forcing was held fixed at 1850 levels, the atmospheric mole fraction followed a similar pattern of increase, but ~~equilibrated~~ plateaued at a lower mean value by 2200. We note that the atmospheric CO_2 mole fraction values were diagnostic only, and the biogeochemical and radiative processes in the CESM responded to the lower mole fraction values prescribed according to the ECP8.5 forcing scenario indicated by the dashed black line in ~~Fig. 4a~~ Fig. 1a.

In the FullyCoupled simulation, the increases in CO_2 and other radiative forcing agents resulted in a 6 K ~~T~~ temperature increase by 2100 and an 11 K ~~T~~ temperature increase by 2300 relative to the 1950–1959 mean (Fig. 1b). ~~T~~ Temperature in the NoRad simulation only increased by $\sim$~~2~~1.5 K through 2300, which can be traced to changes in albedo and surface energy balance. For small temperature changes and high levels of CO_2 fertilization, the NoRad experiment was able to maintain a steady carbon sink ~~between 50–60~~of 4–5 Pg C yr^{-1} between 2100 and 2300 (Fig. 1c). In contrast, the sink in the FullyCoupled simulation reached a maximum of ~~56~~4.8 Pg C yr^{-1} by 2120, then declined to ~~35–50~~3–4 Pg C yr^{-1} in the last 100 years of the simulation, suggesting that the ~~large~~ extreme climate change in this simulation reduced the efficiency of the global terrestrial sink with time. LUC partly offset the weakening of the land carbon sink due to climate change ~~, increasing~~ (likely as a result of increased crop cover prescribed in the FullyCoupled simulation), enhancing net terrestrial carbon uptake by up to ~~30~~2.8 Pg C yr^{-1} after 2100.

The NH mean CO_2 annual cycle ~~amplified by 3.1~~amplitude increased by 3.4 ppm (~~57~~65%) by 2100, and ~~4.1~~5.0 ppm (~~76~~96%) by 2300 from the 1950–1959 baseline in the FullyCoupled simulation (~~Table 4~~ Table 3). Consistent with the observed present-day ~~CO_2~~ annual cycle amplification, the magnitudes of the A^{FC} increases strengthened ~~moving poleward~~ with increasing latitude (Fig. 7). A^{FC} increases between 1950 and 2300 ranged from 1.4 ppm (~~52~~56%) over the NH tropics to ~~9.2~~10.6 ppm (~~110~~122%) over the high latitudes (Table 3). Peak A^{FC} magnitudes occurred between ~~2180~~ 2230 and 2250 ~~(Table 3)~~, and ranged from ~~4.4~~4.2 ppm over the NH tropics to ~~17.7~~19.5 ppm over the high latitudes (Table 4).

Given ~~weak~~ the weak baseline seasonal exchange in the CESM, simulated CO_2 annual cycle amplitudes did not approach the contemporary mean observed mean A^{Obs} (2009–2013) until about 2240 in the NH high latitudes ~~, 2110 in the midlatitudes, and 2100 in the subtropics~~ (~~Fig. 5a~~ Fig. 7a, black filled ~~squares~~square, Table 4). Over the NH midlatitudes, subtropics, and tropics, peak A^{FC} occurred by 2240, but ~~was still 0.6~~values were still 0.4–2.5 ppm below current A^{Obs}. ~~The discrepancy between tropical~~ In the tropics, the discrepancy between CO_2 seasonality inferred only from simulated NEP and from observations reflects the non-trivial contributions of ocean and fossil fuel fluxes to the CO_2 annual cycle (Randerson et al., 1997, Table 4) and (Lindsay et al., 2014, Fig. 15). When high latitude CO_2 amplitudes reached peak values, climate change and non-radiative forcing from CO_2 fertilization and N-deposition each contributed about half of the ~~9.4~~9.6 ppm increase (relative to the 1950–1959 baseline). At this point, Arctic temperatures were ~~13~~16 K higher than the present-day baseline, midlatitude temperatures were 911 K higher (Fig. 5b, c Fig. 7b, c), and the mean NH atmospheric CO_2 mole fraction was approximately 2330 ppm (Fig. 4a Fig. 1a).

The relationship between the atmospheric CO_2 annual cycle amplitude and the NH annual net land carbon sink changed over the course of the FullyCoupled simulation. Several recent papers have hypothesized that the mean atmospheric CO_2 annual cycle may be a diagnostic of net terrestrial carbon uptake, since these variables tend to correlate positively in model simulations (e.g., Ito et al., 2016). While we found that the NH net land carbon sink and annual atmospheric CO_2 annual cycle amplitude were positively correlated through 2100 (Fig. 8), the net land carbon sink began to decrease before the CO_2 annual cycle amplitude decreased. In the FullyCoupled simulation, the NH decadal mean CO_2 annual cycle amplitude peaked near 10 ppm by 2240 (Table 4 Table 3) as a result of increased productivity due to longer growing seasons. After 2100, the magnitude of the NH land sink decreased (Fig. 1c), likely reflecting enhanced subtropical respiration. This underscores that, while amplification of the CO_2 annual cycle may reflect enhanced seasonality of land carbon uptake, it does not necessitate enhanced annually-integrated land carbon uptake. Moreover, in the 23rd century, both the CO_2 annual cycle amplitude and the NH net land carbon sink declined, but there was evidence of hysteresis between the two quantities. As both quantities declined, the slope of their linear relationship became shallower than when both quantities were increasing before 2100. We hypothesize that the change in the relationship between the CO_2 annual cycle amplitude and the NH net land carbon sink resulted from respiration exerting more control on both diagnostics after atmospheric CO_2 concentration, and thus the fertilization effect, leveled off in the last 100 years of the FullyCoupled simulation.

3.3 Contributions of changing atmospheric composition, climate change, and LUC to amplitude trends

3.3 Contributions of non-radiative forcing, climate change, and LUC to amplitude trends

3.3.1 Changing atmospheric composition effects

3.3.1 Effects of non-radiative forcing from CO_2 fertilization and N-deposition

CO_2 fertilization was the largest driver of CO_2 annual cycle amplification through 2300 over much of the NH (Fig. 6a) (Fig. 9a) with fertilization from increasing CO_2 and N-deposition adding 4, contributing 4.1 ppm to the 4.15.0 ppm increase in NH A^{FC} (ΔA^{FC}) between 1950 and the end of the 23rd century (Table 4)(Table 3). In contrast, LUC tended to reduce atmospheric CO_2 seasonalityResults from Devaraju et al. (2016) suggest that global NPP is influenced equably by CO_2 fertilization and N-deposition over the historical period in the CESM. Therefore, trends in the CO_2 mean annual cycle amplitude likely responded to both drivers prior to 2100. While we cannot fully separate the influence of CO_2 fertilization and N-deposition given the experimental design, N-deposition was held fixed at 2100 values for the last 200 years of the simulations, so we expect that amplitude trends after 2100 mainly reflect enhanced CO_2 fertilization.

The non-radiative component of the amplitude increase originated mainly from NH temperate regions (Fig. 7a)(Fig. 10a), which accounted for 2.3 ppm 2.2 ppm (53%) of ΔA^{NoRad} at the end of the 23rd century (Table 3). NH boreal regions (Fig. 8a)(Fig. 11a) made the second greatest contribution (32%, 1.3 ppm) to NH (35%, 1.4 ppm; Table 3) ΔA^{NoRad} . The remaining 7.5% (0.415% (0.6 ppm) of the NH ΔA^{NoRad} increase came from the Arctic (Fig. 9a)(Fig. 12a) or subtropical/tropical ecosystems.

Temperate ecosystems had the largest response to CO_2 fertilization and N-deposition. Consistent with this large temperate response, the increase in A^{FC} from non-radiative forcing was largest over the NH midlatitudes (Table 3). The effects of changing atmospheric composition CO_2 fertilization and N-deposition in boreal ecosystems contributed another 2625% to the high latitude CO_2 amplitude, 2822% to the midlatitude, and 4360% to the subtropical A^{FC}. Arctic CO_2 fertilization and N-deposition effects were small In the CESM, the impact of CO_2 fertilization on the amplitude trend roughly scales with to the magnitude of overall GPP, consistent with CO_2 fertilization effects being proportional to gross primary production (Schimel et al., 2015). hypotheses from Tans et al. (1990) and Schimel et al. (2015) that the fertilization effect on the land carbon sink is proportional to productivity. Thus, CO_2 fertilization and N-deposition effects on A^{FC} were smallest in the Arctic, the region with the smallest GPP for the contemporary period. Fig. 10 Fig. 13 shows that non-radiative forcing from boreal and temperate regions together constituted at least 4035% of the increase in high latitude, midlatitude, and subtropical A^{FC} from the beginning of the 21st century through the end of the 23rd century. Furthermore, temperate CO_2 fertilization and N-deposition were the primary drivers of midlatitude CO_2 annual cycle amplification in all periods, and subtropical amplification from 2050 onward. Our results are consistent with Randerson et al. (2015), who found that enhanced terrestrial productivity fromCO_2 fertilization, as well as warming-driven increases in heterotrophic respiration (HR), over boreal and temperate regions were responsible for most of the amplification of the NH CO_2 annual cycle after 2100 In temperate and boreal regions, where CO_2 fertilization was the dominant driver of increases in the mean CO_2 annual cycle amplitude, increases in GPP seasonality outpaced increase in respiration. For example, in eastern temperate North America (ETNA), FullyCoupled GPP seasonal amplitudes increased from 6.8 Pg C in 1950 to 11 Pg C in 2250, while HR amplitudes increased from 0.85 Pg C to 1 Pg C, and AR amplitudes increase from 4 Pg C to 7.6 Pg C. The strong fertilization effect on the amplification of the NH CO_2 annual cycle is surprising given that nitrogen limitation in the CLM4 produced weaker fertilization in the CESM compared to other CMIP5 models (Thornton and Zimmermann, 2007; Piao et al., 2013; Peng and Dan, 2015).

3.3.2 Climate change effects

Climate change caused the CO_2 annual cycle amplitude to increase during the early part of the simulation, but the effect reversed in the 23rd century when the mean bottom-level atmospheric temperature had risen by 6–13 K across NH land regions. During the early part of the simulation, boreal (Fig. 8b) and Arctic (Fig. 9b)(Fig. 11b) and Arctic (Fig. 12b) climate change drove the increase in NH high-latitude atmospheric CO_2 annual cycle amplification, increasing A^{Clim} by 5 ppm by 2200 (Fig. 13a)., outpacing boreal and temperate N-deposition effectsAfter 2200, CO_2 fertilization and climate change contributed nearly equally to high-latitude CO_2 annual cycle amplification. The increase in NH high latitude A^{Clim} largely reflected high latitude climate change effects that increased growing season temperature, leading warmer growing season temperatures that led to larger peak GPP values and a longer growing season. In the pulse regions that comprised our broader Arctic boreal zones, annual mean GPP continued to increase with temperature ($r = 0.7$ PgC K^{-1}, $r^2 = 0.99$) until annual mean near-surface air temperatures surpassed 284 K.

By 2100, Arctic and boreal climate change increased high latitude A^{FC} by about 1 and 21.3 and 2.5 ppm (3739%) from the 1950–1959 mean, respectively, outweighing the combined contributions of boreal and temperate non-radiative forcing (2.32.2 ppm, 2623%) (Fig. 10a) (Fig. 13a). After 2100, Arctic climate change had a greater effect on extratropical A^{FC} than boreal or temperate climate change, adding 1.9 ppm (23%) to high latitude, 0.7 ppm (8%) to midlatitude, and 0.45 ppm (7.6%) to the subtropical base period A^{FC} by the end of the 23rd century (Fig. 13) when temperatures surpassed 278, 288, and 298 K, respectively. Overall, the However, the effects of temperate and boreal CO_2 fertilization and N-deposition outweighed climate change effects on CO_2 annual cycle amplification at the end of the simulation, adding 4.7. CO_2 fertilization and N-deposition added 5.3 ppm (5762%) to high latitude, 6.8 ppm (7881%) to midlatitude, and 3.83.5 ppm (6469%) to the subtropical base period A^{FC}.

It is worth noting that temperate climate change exerted its greatest impact on NH high latitude CO_2 before 2000 (T around 265 K), and on midlatitude and subtropical A^{FC} after 2200 (T > 289 K and 299 K, respectively). After 2100, climate change reduced the seasonality of CO_2 exchange in temperate ecosystem CO_2. Climate change climate change effects from lower latitudes made up most of the midlatitude residual high latitude and subtropical residuals after 2000, and were largest between 2100 and 2150. Low latitude climate change also made up most of the high latitude residual after 2000. midlatitude residual after 2200 (gray sections of bars in Fig. 13).

3.3.3 LUC effects

Land use change in the CESM decreased the seasonality of terrestrial CO_2 exchange and led to negative trends in the mean annual cycle amplitude . LUC reduced (Figs. 9c–12c). Between 1850 (the year used for PFT fraction boundary conditions in the NoLUC simulation) and 2100, crop cover increased at the expense of grass and tree cover in the NH, reducing the seasonal amplitude of NH mean GPP for the duration of the simulation. As a result, LUC decreased the hemisphere-average atmospheric CO_2 annual cycle amplitude by 0.9 ppm (17%) from the 1950–1959 baseline in 2300 (Fig. 9c, Table 4 Table 3)., opposing the non-radiative forcing and climate change effects on the mean CO_2 annual cycle amplitude. The largest reductions in ΔA^{FC} due to LUC (ΔA^{LUC}) occurred over the mid- (1.3 ppm) and high latitudes (1.6 ppm), with nearly all of the negative ΔA^{LUC} effects originating from boreal (Fig. 11c) and temperate (Fig. 10c) regions. While the magnitudes of boreal and temperate LUC forcing increased from the 21st through the 23rd century over the NH extratropics (Fig. 13), the percent contribution of LUC to ΔA^{LUC} declined over time since LUC fluxes were held constant after 2100.

This finding contrasts recent results suggesting that agriculture intensification contributes significantly to positive trends in the mean annual cycle amplitude (Gray et al., 2014; Zeng et al., 2014), and likely reflects the fact that croplands were treated as unmanaged grasslands in the CESM. Zeng et al. (2014) suggests that up to 45% of the observed trend may be due to land use practices, with the remainder partitioned roughly equally between climate and fertilization effects. We note that future LUC and its effect on the seasonality of the terrestrial carbon flux depends on the integration of climate and societal impacts across several climate scenarios.

3.3.4 Changes in growing season length

The NH CO_2 annual cycle amplitude increase resulted not only from changes in the mean temperature, but also from lengthening of the growing season. We found that the growing seasonThe growing season, defined as months with negative NEP (net terrestrial carbon uptake), increased for all NH terrestrial regions by about 1 month. The overall lengthened growing seasons accounted for 1–1.3% yr^{-1} of the high latitude net terrestrial carbon uptake after 2050, and up to 5% yr^{-1} of the midlatitude terrestrial carbon uptake after 2100. Thus, while this is an important contributor, it is secondary to increased mid-summer GPP. In boreal and temperate ecosystems, this change was not evident until 2100 (Fig. 11a).

The driver of the increased growing season length was different for different regions. For regions north of 30°N, climate change was the driver of increased growing season length, with boreal and temperate growing seasons increasing by one month after 2100 (Fig. 14a). Climate change was the primary contributor in boreal and Arctic regions extended the growing season for an additional month in the fall in the Arctic, and facilitated and earlier start to the midlatitude growing season in the spring (Fig. 14c). In the subtropics, however, CO_2 fertilization and N-deposition lengthened the growing season was the major driver of changes in the growing season length in the subtropics (Fig. 11b) (Fig. 14b), while climate change had the opposite effect . (Fig. 14c). This result suggests that subtropical ecosystems in CESM are near a temperature optimum, but are may be water-limited. Therefore, increases in In the FullyCoupled simulation, soil water content over the top three model layers, corresponding to 6 cm depth, decreased in the Amazon (Fig. 15a, b) and Central America (Fig. 15d, e) by 13% on average from 1950 to 2300. In contrast, soil water content increases by 1% on average in these regions (Fig. 15d, f) in the simulation with CO_2 fertilization effects, suggesting improved water use efficiency by vegetation. Thus, increases in water use efficiency associated with increased atmospheric CO_2 permit longer periods of carbon uptake.

4 Discussion and Conclusions

Extended Concentration Pathway simulations run in the CESM with coupled biogeochemistry show that the NH mean annual cycle of atmospheric CO_2 increased by 1716% from 1985 to 2013. The relative increase was in line with the observed 2024% increase over the NH during the same time period. However, the spatial pattern of the percent amplitude change was more uniform throughout the NH (around 0.40–0.50% yr^{-1} across latitude bands), whereas observedrelative increases ranged from 0.22% yr^{-1} in the midlatitudes to 0.57% yr^{-1} in the high latitudesthan observed. Furthermore, the trend in the magnitude of the amplitude at high latitudes was about half of the observed trend (0.05 ppm yr^{-1} vs 0.09 ppm yr^{-1}). The largest driver of the midlatitude CO_2 annual cycle amplitude trend in the CESM was temperate non-radiative forcing from CO_2 fertilization and nitrogen deposition, perhaps indicating that the model CO_2 fertilization effect was too strong. This result highlights the importance of considering meridionally-resolved atmospheric CO_2 data that explicitly considers the role of transport, since analysis of only hemispheric spatial patterns obscures incorrect spatial patterns simulated by the CESM.

By running the CESM to 2300 with the ECP boundary conditions, we were able to simulate notable carbon cycle interactions that were not apparent before 2100, the nominal end date for CMIP5 runs. We found that the mean NH atmospheric CO_2 annual cycle amplitude increased by 57% 65% from 1950 to 2100, and by an additional 20% 30% by 2300 in the CESM1(BGC). Even after 2100, these rates of increase resulted primarily from CO_2 fertilization and nitrogen deposition in temperate and boreal ecosystems. Climate change in boreal and Arctic ecosystems also contributed to NH amplitude increases through 2300 (over half the amplification prior to 2100). CESM simulations show that the major drivers of the mean annual cycle amplification impact differential imprints on atmospheric CO_2 in different latitude bands. For example, CO_2 fertilization eaves the largest imprint in both absolute and relative terms on midlatitude CO_2, whereas climate change may amplify high latitude CO_2 while having a near-neutral impact on CO_2 annual cycle amplitudes south of 60°N (Fig. 13). These fingerprints may be useful for developing hypotheses regarding observed trends and determining future observational strategies to monitor carbon-climate feedbacks.

Our analysis focused on natural drivers of the mean annual cycle, including climate change, CO_2 fertilization, and nitrogen deposition, since CESM1(BGC) did not include agricultural intensification, and land management that has been suggested as one driver of the amplitude increase over the last 50 years (Gray et al., 2014; Zeng et al., 2014). Zeng et al. (2014) suggests that up to 45% of the observed trend may be due to land use practices, with the remainder partitioned roughly equally between climate and fertilization effects. In contrast, land use change in the CESM reduced the atmospheric CO_2 annual cycle amplitude throughout the NH, with the largest reductions over the mid- and high latitudes. Decreased amplitudes possibly result from the exclusion of the effects of cropland intensification in the CESM simulations. After accounting for land management contributions to the amplitude increase, the sensitivity of the CO_2 amplitude to natural factors may be reasonable. Our results suggest that model development focused on human modification of carbon fluxes (e.g., by agriculture (Levis et al., 2014) or by disturbance (Kloster et al., 2012)) may facilitate improved comparison both of mean behavior and trends.

Despite the changes in the climate and atmospheric CO_2 mole fractions in the extended simulation, the sensitivity of the CO_2 annual cycle amplitude to drivers was remarkably similar for the duration of the simulation. We likewise found that regional contributions to the NH CO_2 seasonal amplitude trend were generally consistent throughout the simulation. CO_2 fertilization was the dominant driver of CO_2 annual cycle amplification for most of the NH, with the notable exception of Arctic ecosystems where temperature increases drove amplification prior to 2100. GPP leveled off in boreal high latitudes when annual mean temperatures exceeded 284 K, which contributed to small amplitude declines in the 23rd century. CO_2 fertilization increased the CO_2 annual cycle amplitude globally for the duration of the simulation even after the growth rate of CO_2 slowed during the 23rd century, suggesting that the CO_2 fertilization effect had not saturated in the CESM when CO_2 mole fractions were around 2000 ppm.

We saw evidence of hysteresis in the relationship between carbon cycle diagnostics that was only apparent after 2100. For example, we found that the relationship between the NH mean CO_2 annual cycle amplitude and the NH net land carbon sink changed after 2100. A strong positive relationship between the CO_2 annual cycle amplitude and terrestrial carbon sink that has been noted previously by Ito et al. (2016) became decoupled in the mid-22nd century when sink strength began to decrease after 2100, while the CO_2 annual cycle amplitude continued to increase. When the NH CO_2 annual cycle amplitude began to decrease in the 23rd century, the correlation between the amplitude and land carbon sink weakened considerably compared to the relationship between the two quantities during the 20th and 21st century correlations.

Several recent papers have considered how the amplitude of NH net carbon exchange has changed over the historical period in different categories of prognostic models. Ito et al. (2016) analyze MsTMIP terrestrial ecosystem models to determine how atmospheric CO_2, climate change, and land use affect the NH flux amplitude for the historical period, and Zhao et al. (2016) analyze the net terrestrial flux to the atmosphere in TRENDY models. Both of these studies find that CO_2 fertilization is the strongest driver of increasing ecosystem productivity and thus the amplitude of the net carbon exchange in the NH, consistent with our results. A significant difference between the approach used by these papers and our study is that they consider the net flux amplitude, whereas we propagate fluxes using an atmospheric transport operator to determine the influence on latitudinally-resolved atmospheric CO_2 fields. Given the importance of atmospheric transport on the mean annual cycle of atmospheric CO_2 (e.g., Barnes et al., 2016), and the small biases induced by the simplified pulse-response transport operator, we recommend that future studies explicitly simulate the full atmospheric CO_2 field.

4.1 Uncertainties and future model needs

The mean annual cycle of atmospheric CO_2 is a first-order diagnostic of terrestrial carbon exchange and its trend with time integrates a range of environmental and human factors(Randerson et al., 1997). An active area of carbon cycle research is determining the extent to which coupled ESMs provide predictive skill for future carbon-climate feedbacks. We note that many of the methods used to evaluate the carbon cycle in ESMs rely on benchmarking short-term responses to either seasonal or interannual climate variability (Keppel-Aleks et al., 2013), or on extrapolating future behavior based on some mechanistic link between short-term and long-term variability (Cox et al., 2013; Hoffman et al., 2014). The changing CO_2 annual cycle provides a unique opportunity to gauge a model's sensitivity to slow-varying climate and environmental changes, since we have observed large trends in this quantity over the instrumental record (Graven et al., 2013) .

~~We note, however, that~~ However, biases in seasonality in the CESM1(BGC) ~~does have overall biases in seasonality. Low seasonality, together with low absolute rates of increase, meant~~ that lead to smaller increases in NH atmospheric CO_2 seasonal amplitudes in the CESM compared to observations during 1950–2010 prompt further model development. Moreover, the relatively smooth response to extreme changes in temperature and CO_2 suggests that the CESM ~~mean annual cycle did not approach present values over the NH extratropics until the 22nd century~~may not parameterize processes that could cause nonlinear carbon cycle feedbacks. CESM1(BGC) did not include paramaterizations for permafrost carbon dynamics, which have since been improved in CESM (Koven et al., 2015). The lack of permafrost dynamics likely has a large impact on CO_2 annual cycle trends, especially later in the simulation when global mean temperature has increased by over 10 K in the FullyCoupled simulation. Thus, short soil carbon turnover time in CLM4 may have contributed to the amplitude underestimation by damping ecosystem respiration outside of the growing season (Keppel-Aleks et al., 2013; Koven et al., 2013) and would affect both baseline values and trends. Ongoing model development in the CESM includes improved representation of permafrost carbon (Koven et al., 2015), and thus future model configurations will provide an improved tool for investigating a process that may provide one of the tipping points we identified in our key science questions. In addition, Forkel et al. (2016) found that interaction between climate change and changes in vegetation cover over northern high latitudes was the primary driver of the north-south gradient in observed NH atmospheric CO_2 seasonal amplitude trends, indicating that the lack of dynamic vegetation in the CLM4 likely contributes to underestimation of the seasonal amplitudes by the CESM. ~~Additionally, we found that the net land sink began to decrease prior to amplitude decreasing. Until 2100, NEP became more negative (sink strength increased) while the mean annual cycle amplitude also increased. After 2100, the magnitude of NEP decreased (sink strength decreased), likely reflecting enhanced subtropical respiration, while the amplitude continued to increase until after 2250 as a result of increased productivity due to longer growing seasons. This underscores that while increasing amplitude may reflect enhanced seasonality of uptake, it does not necessitate enhanced annually integrated uptake~~Tree cover is expected to expand further northward with climate change (e.g., Lloyd, 2005), which may contribute to the long-term increase in NEP flux amplitude within high latitude ecosystems. In contrast, drying at lower latitudes may lead to replacement of trees with grasses and subsequent decreases in NEP amplitude. An ecosystem demography version (CLM-ED) that will permit successional patterns in response to environmental change is presently under development. We consider the documentation of trends in the static-vegetation configuration presented in this manuscript to be a crucial first step toward eventually determining the sensitivity of land-atmosphere biogeochemical couplings in more sophisticated future configurations of the CESM model.

Development is also under way to represent irrigation and fertilization in croplands in future versions of the CLM. Gray et al. (2014) and Zeng et al. (2014) suggest that agricultural amplification, facilitated by irrigation and fertilization, may be an important driver of the observed mean annual cycle trend. In the CESM, however, crop cover is currently treated as unmanaged grass. Thus, these agricultural practices are not explicitly modeled, and do not mitigate the reduction in tree cover in the FullyCoupled simulation. Our results indicate that explicit consideration of human modifications may be necessary for prognostic models both to match observations and to provide realistic predictions of future changes. After accounting for land management contributions to the amplitude increase, the sensitivity of the CO_2 amplitude to natural factors may be reasonable. Our results suggest that model development focused on human modification of carbon fluxes (e.g., by agriculture (Levis et al., 2014) or by disturbance (Kloster et al., 2012) may facilitate improved comparison both of mean behavior and trends.

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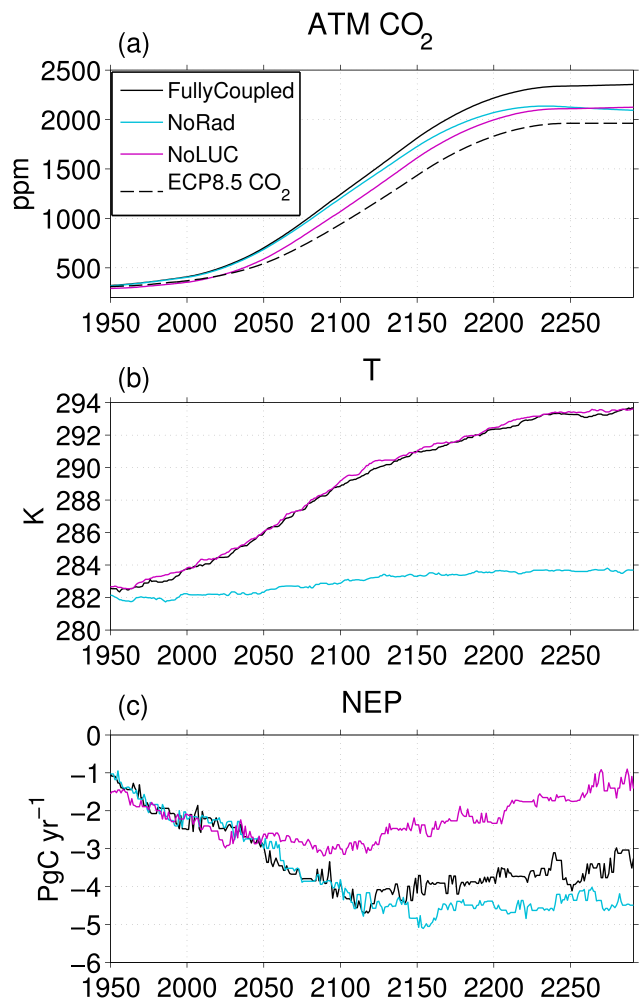

Figure 1. (a) Annual mean atmospheric CO_2, (b) annual mean bottom-level atmospheric T over land, and (c) annual ~~total~~ mean NEP averaged over the NH (0°–90°N) in the CESM FullyCoupled (solid black curves), NoRad (blue curves), and NoLUC (magenta curves) simulations. Negative NEP indicates net annual CO_2 uptake by the land surface. Values are filtered using a 10-year running median. The CO_2 mole fraction values in (a) result from the net contributions of land, ocean, and fossil fuel tracers calculated from NEE as described in Section 2.3, and differ from the atmospheric CO_2 mixing ratio that is prescribed according to the ECP8.5 scenario (dashed black curve).

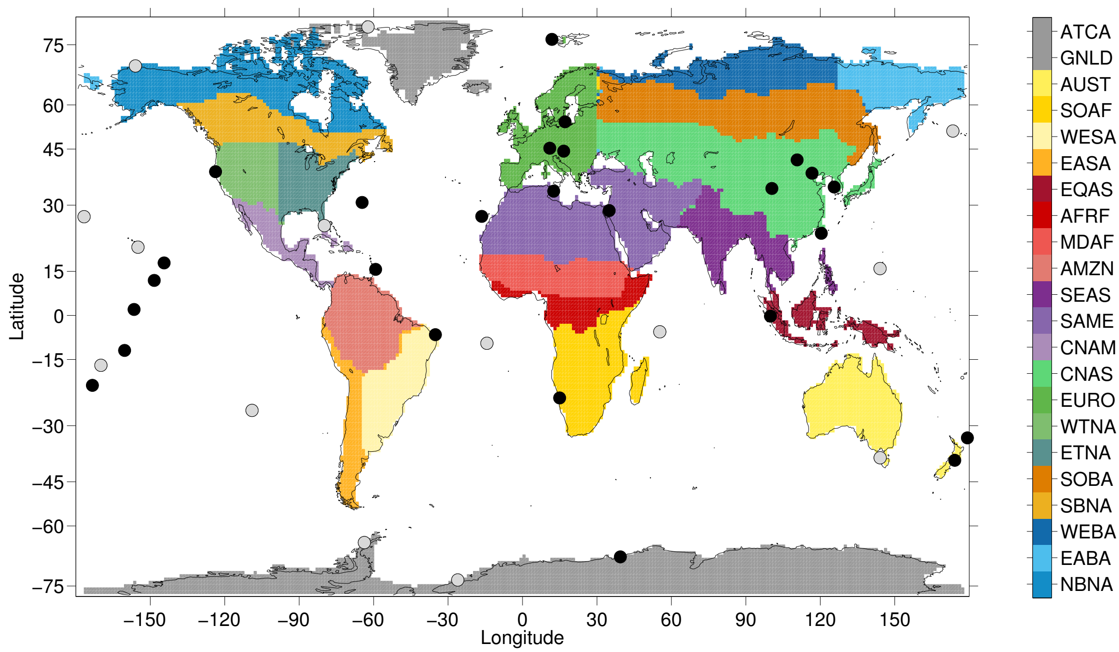

Figure 2. Map of stations where CO_2 from the pulse response code is computed. Table 1 lists the station identifiers and locations. Regions defined in the pulse response code (see Table 2) are shaded and grouped according the Arctic, NH boreal, NH temperate, NH subtropics, tropics, and SH land regions defined by Graven et al. (2013). Greenland and Antarctica were excluded from the analysis. Gray circles indicate a subset of stations from which the atmospheric annual CO_2 amplitudes were computed from 1985–2013 monthly mean observations (bold stations in Table 1).

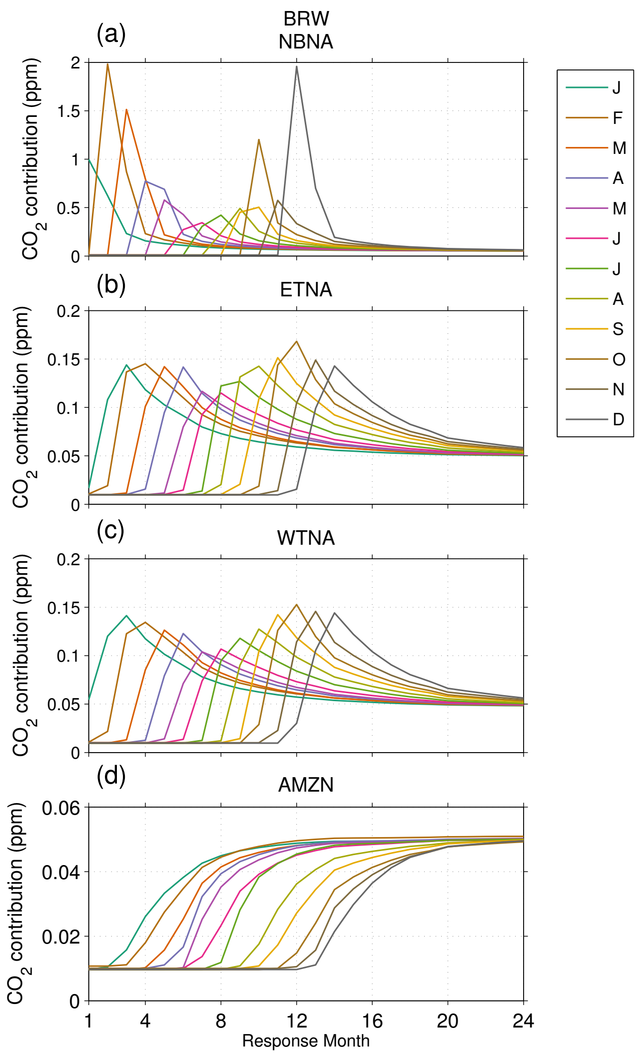

Figure 3. The imprints of 1 Pg pulses emitted in individual months (curves) from (a) Northern Boreal North America (NBNA, (b) Eastern Temperate North America (ETNA), (c) Western Temperate North America (WTNA), and (d) Amazon (AMZN) on the atmosphere sampled at Barrow (BRW). For clarity, we plot onlyl the first calendar year (months 13–24) after the pulses were released.

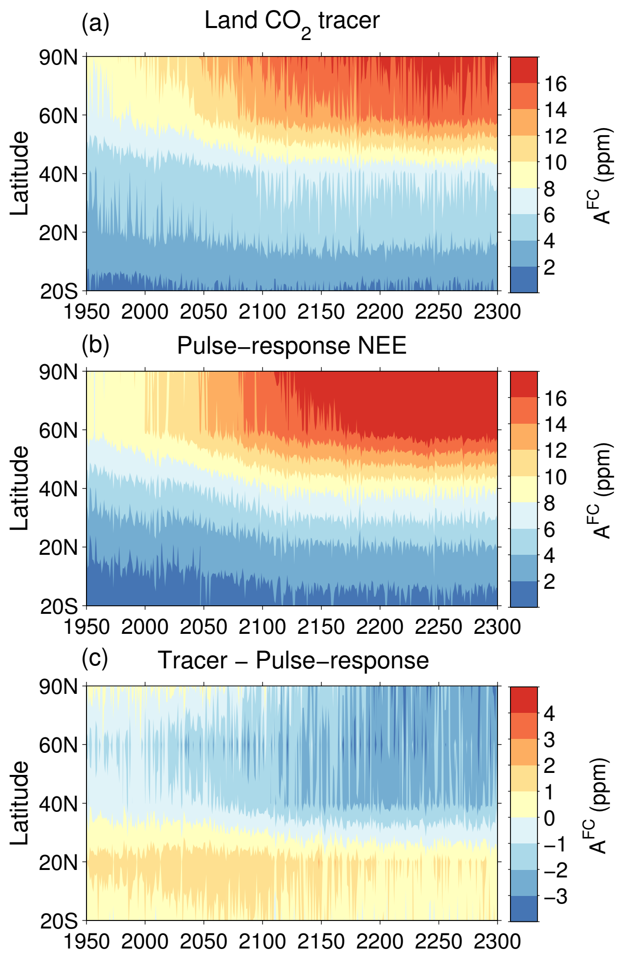

Figure 4. 10-year moving average of CO_2 annual cycle amplitudes in the FullyCoupled simulation derived from (a) the CESM land CO_2 tracer, and (b) running NEE from the CLM4 through the pulse-response code. (c) The difference between the land tracer and NEE-derived CO_2 annual cycle amplitudes.

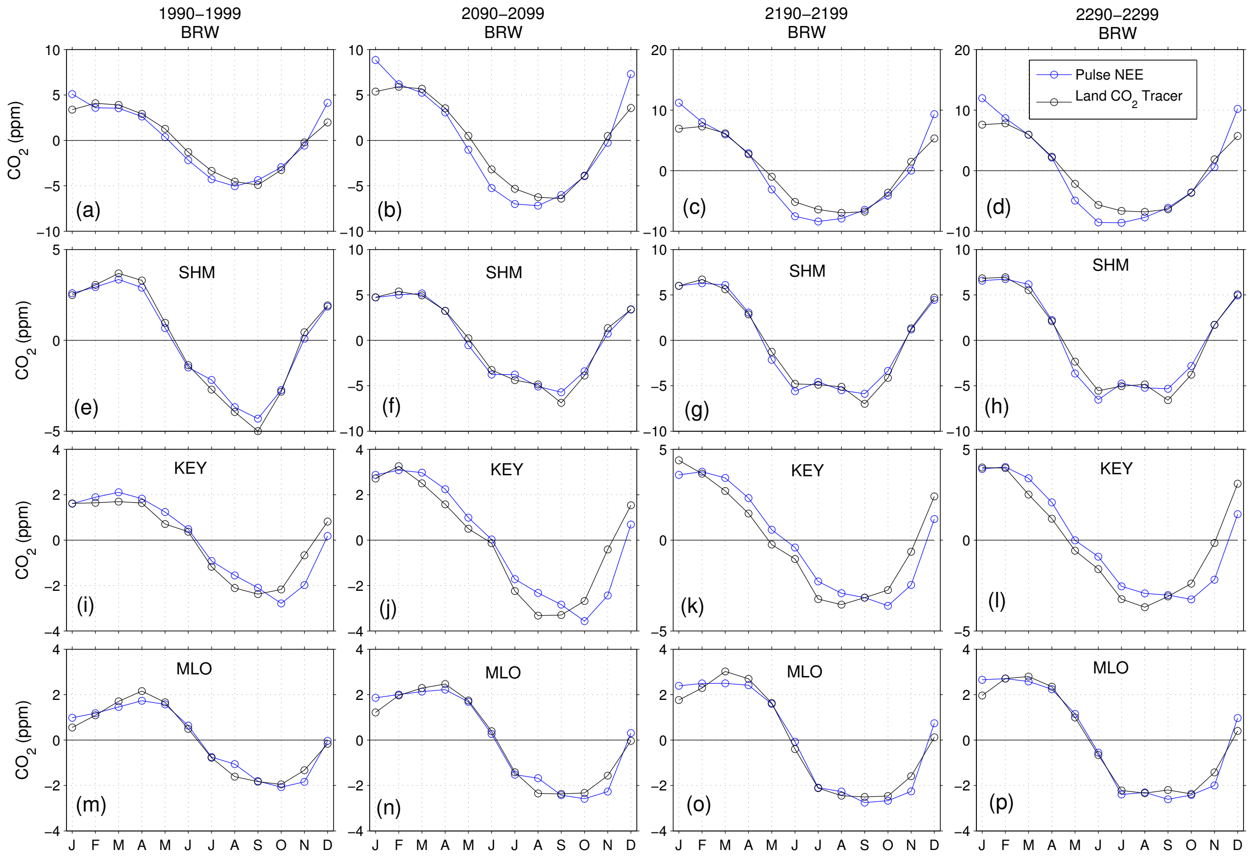

Figure 5. Mean annual cycles of atmospheric CO_2 derived from (blue curves) NEE run through the pulse-response function and (black curves) the CESM land CO_2 tracer for (a–d) Barrow (BRW), (e–h) Shemya Island (SHM), (i–l) Key Biscayne (KEY), and (m–p) Mauna Loa (MLO) in 1990–1999, 2090–2099, 2190–2199, and 2290–2299.

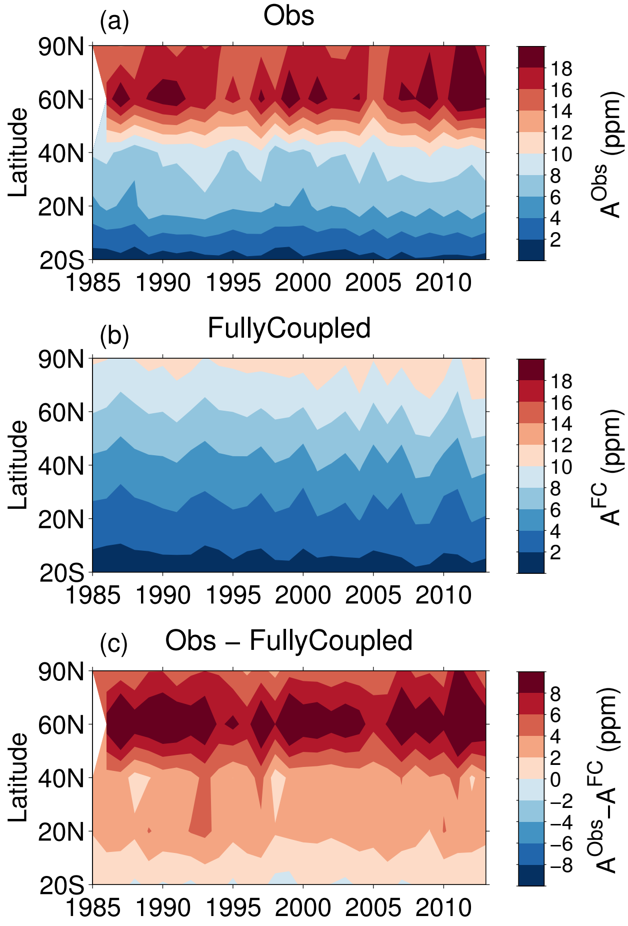

Figure 6. (a) Observed atmospheric CO_2 annual cycle amplitudes (A^{Obs}), (b) FullyCoupled atmospheric CO_2 annual cycle amplitudes (A^{FC}), and (c) the difference between A^{Obs} and A^{FC} during 1985–2013.

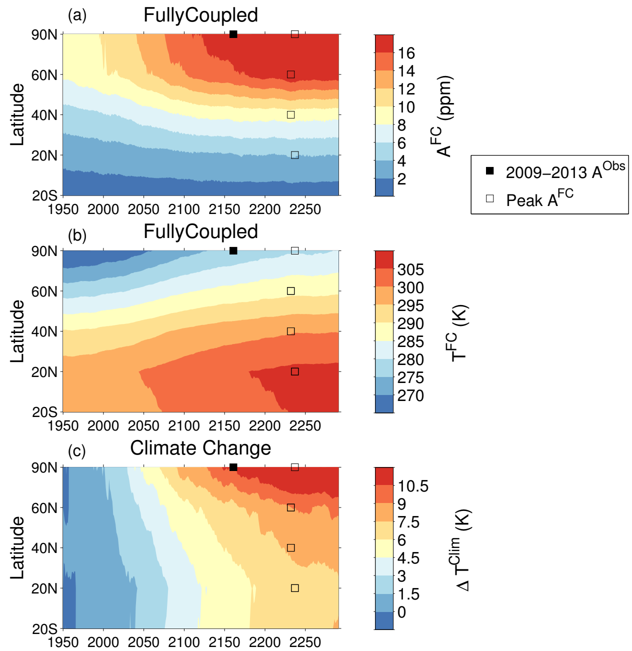

Figure 7. (a) 10-year moving averages of FullyCoupled atmospheric CO_2 annual cycle amplitude (A^{FC}) from 1950–1959 to ~~2280–2289~~2291–2300. ~~Black squares denote~~ The black square indicates the ~~decades~~ decade in which the CESM reached observed CO_2 annual cycle amplitudes averaged over ~~2008–2013~~ 2009–2013 in the NH high latitudes ~~, NH subtropics, and SH tropics~~ (Table 4). Open squares indicate the decades when peak amplitudes occurred~~in~~. In the NH midlatitudes, subtropics, and ~~NH~~ tropics, ~~but~~ peak amplitudes did not reach present observed values. (b) Atmospheric temperatures over land in the FullyCoupled simulation (T^{FC}). (c) The change in atmospheric temperature with respect to the 1950–1959 mean caused by climate change (ΔT^{Clim}).

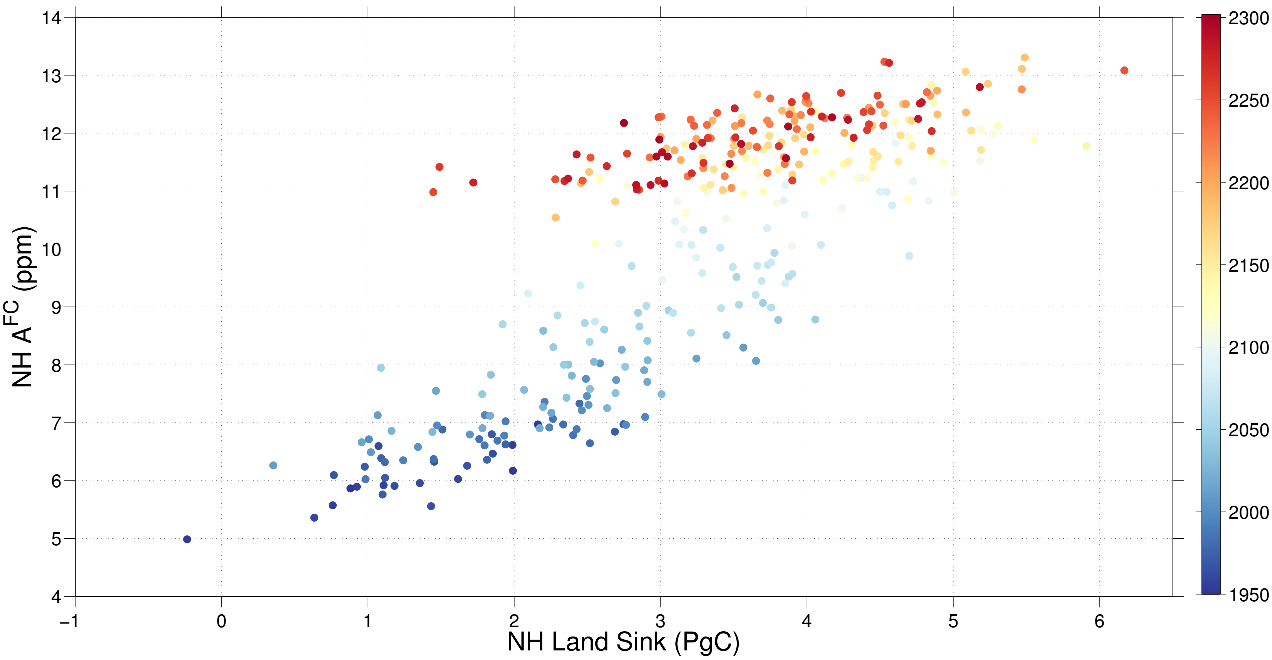

Figure 8. NH mean CO_2 annual cycle amplitude (ppm) versus annual mean NH land carbon uptake (PgC).

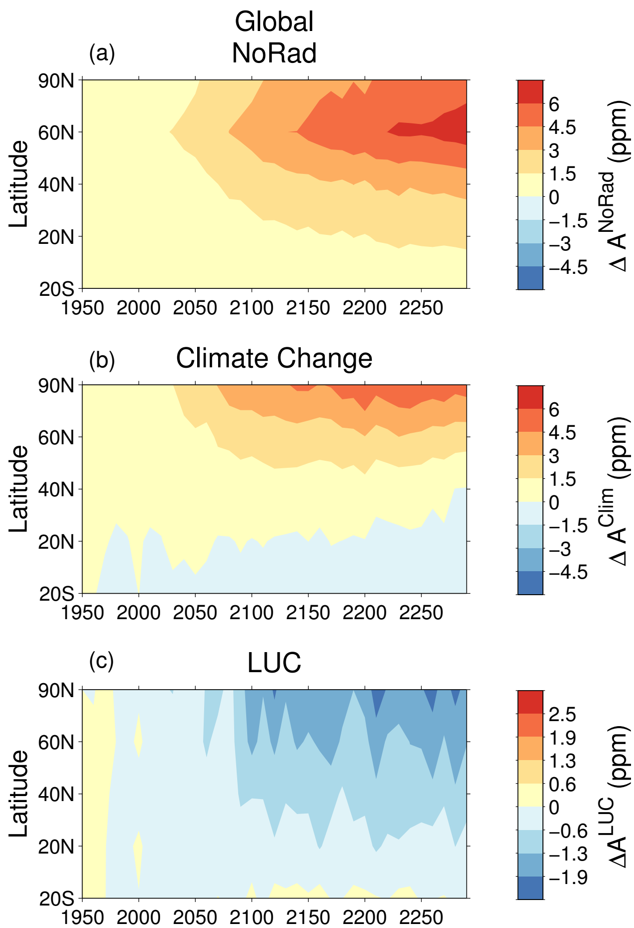

Figure 9. Changes in the decadal mean atmospheric CO_2 annual cycle amplitudes from present-day (1950–1959) values from (a) CO_2 fertilization and N-deposition (ΔA^{NoRad}), (b) climate change (ΔA^{Clim}), and (c) land use change (ΔA^{LUC}) from all land regions in each latitude bin.

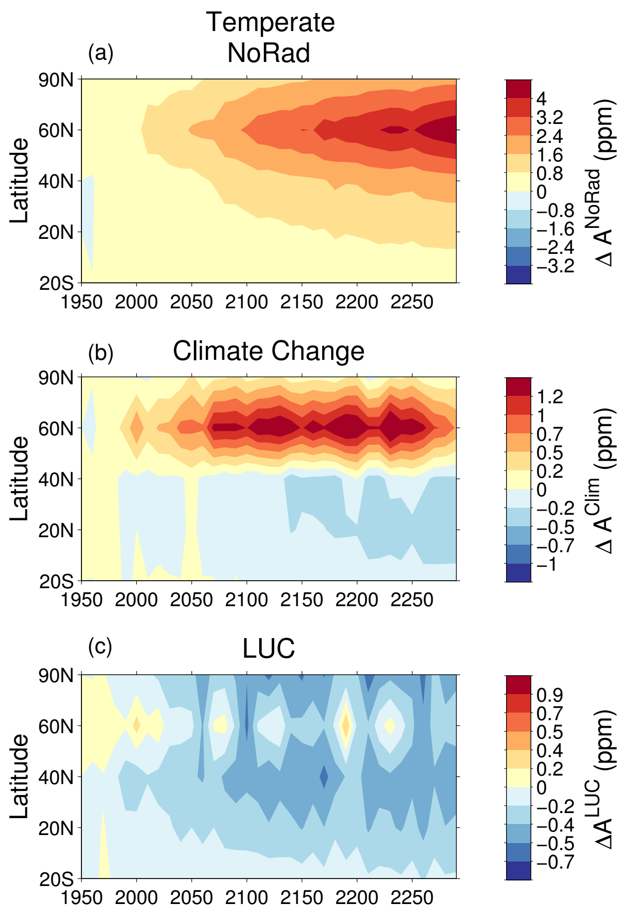

Figure 10. As in Fig. 9 but for CO_2 fertilization ~~,~~ + N-deposition, climate change, and LUC from ~~the~~ NH temperate ~~region~~regions.

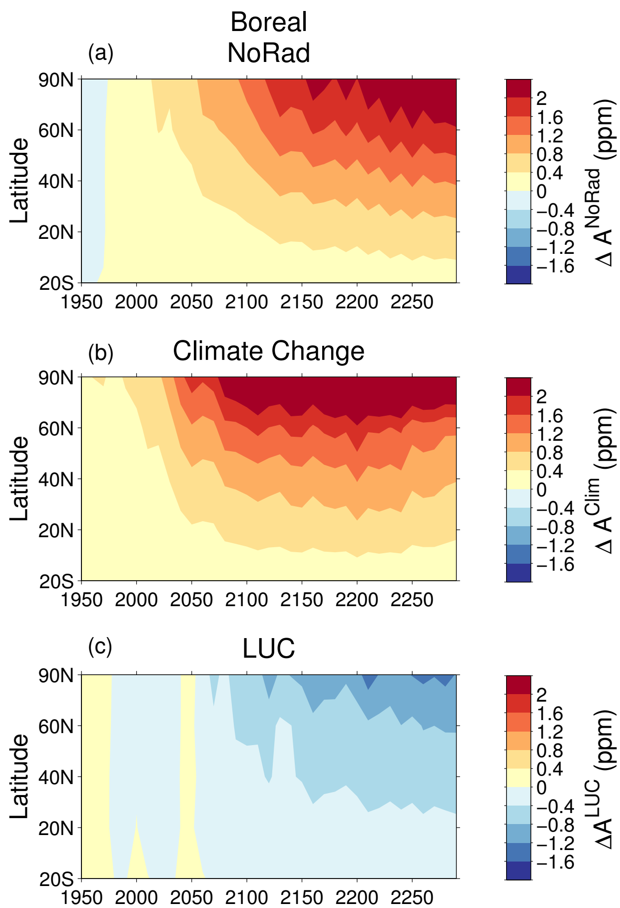

Figure 11. As in Fig. 9 but for CO_2 fertilization ~~,~~ + N-deposition, climate change, and LUC from ~~the NH~~ boreal ~~region~~regions.

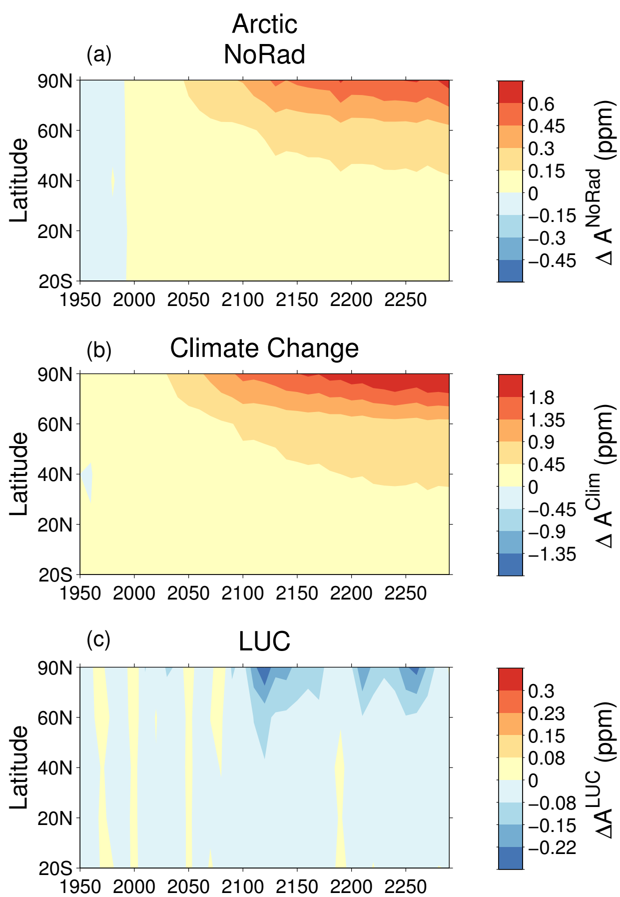

Figure 12. As in Fig. 9 but for CO_2 fertilization ~~,~~ + N-deposition, climate change, and LUC from the Arctic.

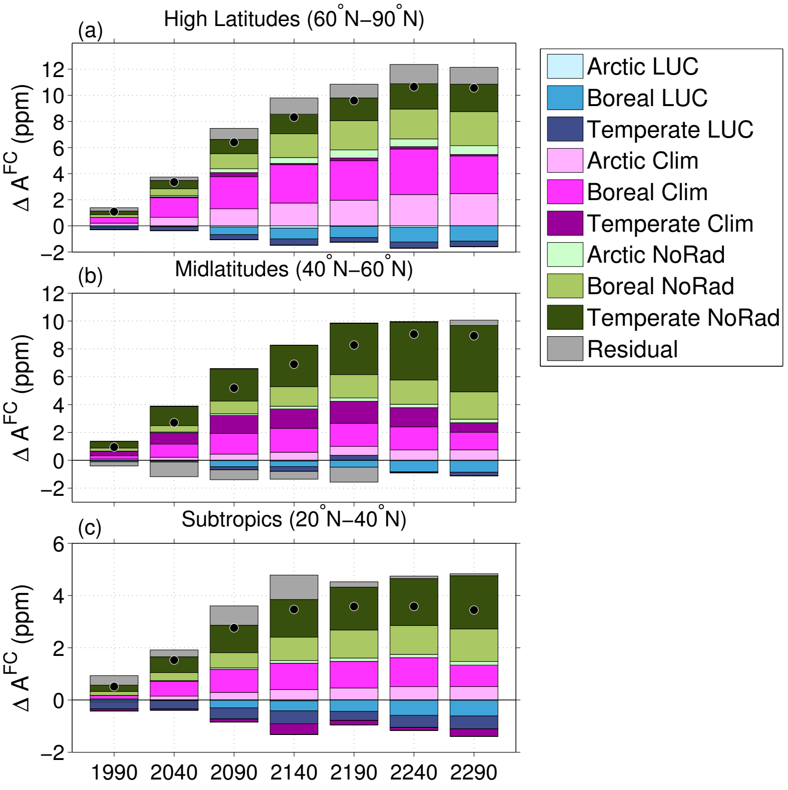

Figure 13. Contributions of Arctic, boreal, and temperate land use change (LUC), climate change (Clim), and combined CO_2 fertilization and N-deposition (NoRad) to the change in the FullyCoupled mean atmospheric CO_2 annual cycle amplitude from present-day (1950–1959) values (ΔA^{FC}) in the middle and final decades of the 21st, 22nd, and 23rd centuries over (a) the NH high latitudes, (b) the NH midlatitudes, and (c) the NH subtropics. Residual values are the sums of the contributions of LUC, climate change, CO_2 fertilization, and N-deposition in the subtropical, tropical, and SH GEOSChem land regions. Negative values indicate that the forcing decreased the atmospheric CO_2 annual cycle amplitude. Units are ppm.

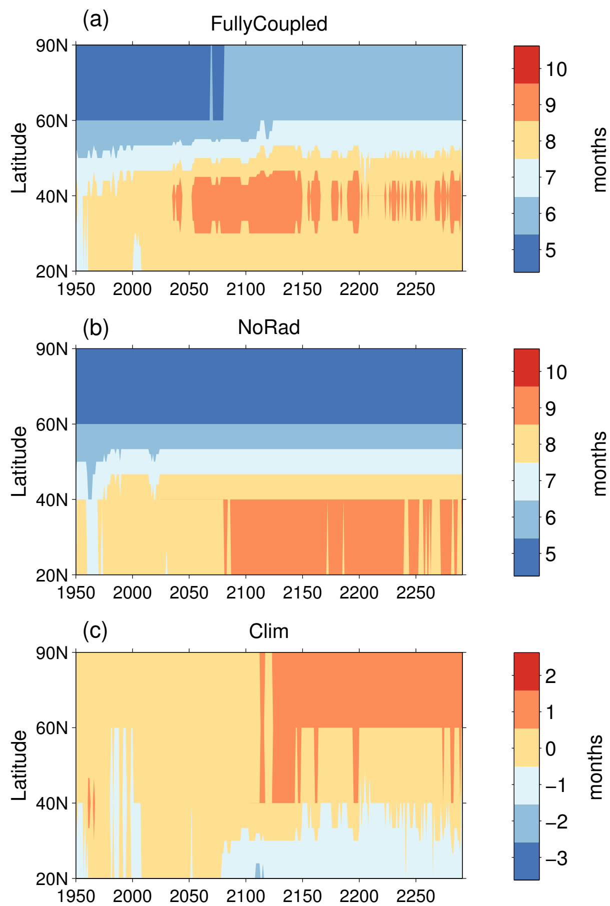

Figure 14. Growing season length (10-year running median of months with NEP < 0) in each latitude band in the (a) FullyCoupled, and (b) NoRad simulations. (c) The contribution of climate change to growing season length.

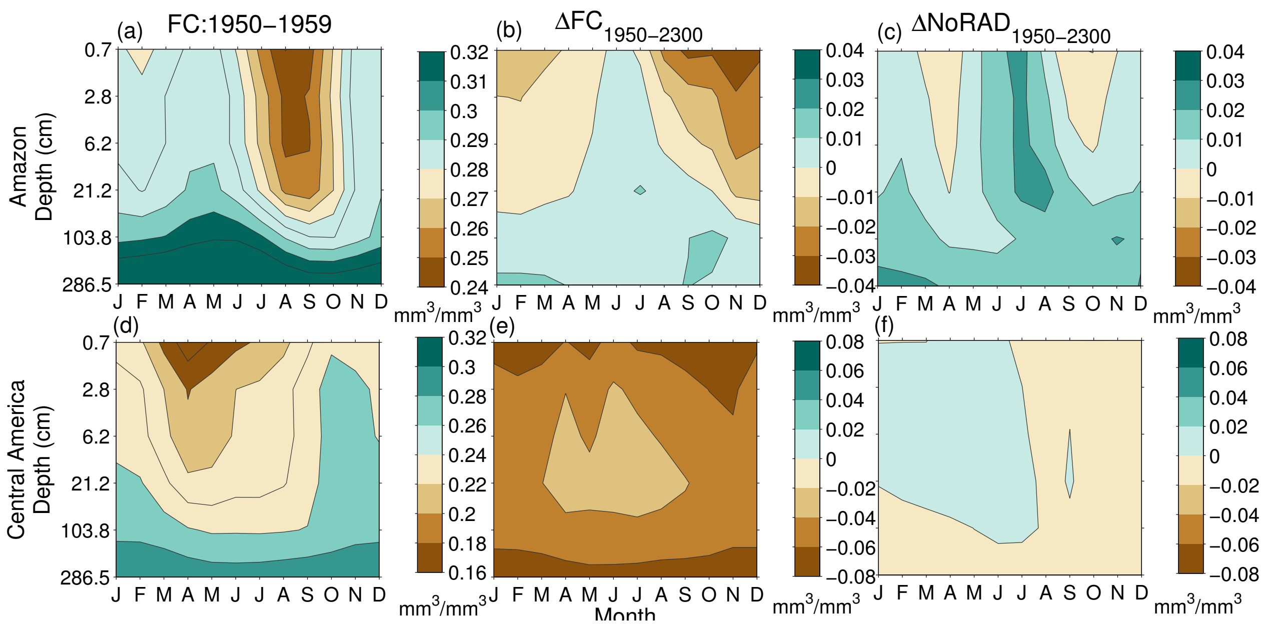

Figure 15. Volumetric soil water (mm^3/mm^3) in (top panels) the Amazon (AMZN) and (bottom panels) Central America (CNAM) in the top 2 m of soil during each month. (a,d) 1950–1959 seasonal averages in the FullyCoupled (FC) simulation, (b,e) differences in the 2091–2300 and 1950–1959 FullyCoupled (ΔFC) averages, and (b,e) differences in the 2091–2300 and 1950–1959 NoLUC (ΔNoLUC) averages.

Table 1. Region, station location, station ID, latitude, and longitude of CO_2 sample locations. Observations from bold stations were analyzed over the 1985–2013 period.

Region	Station Location	Station ID	Latitude	Longitude
Arctic	**Alert, Nunavut**	**ALT**	**82.45**	**297.49**
	Ny-Alesund, Svalbard	ZEP	78.90	11.90
	Barrow, Alaska	**BRW**	**71.30**	**203.40**
NH Midlatitudes	Baltic Sea	BAL	55.35	17.22
	Shemya Island, Alaska	**SHM**	**52.70**	**174.10**
	Hohenpeissenberg, Germany	HPB	47.80	11.02
	Hegyhatsal, Hungary	HUN	46.95	16.65
	Ulaan Uul, Mongolia	UUM	44.45	111.10
	Trinidad Head, California	THD	41.10	235.80
	Shangdianzi, China	SDZ	40.65	117.12
NH Subtropics	Tae-ahn Peninsula, Rep. Korea	TAP	36.70	126.10
	Mt. Waliguan, China	WLG	36.29	100.90
	Lampedusa, Italy	LMP	35.52	12.62
	Tudor Hill, Bermuda	BMW	32.30	295.10
	WIS Station, Negev Desert, Israel	WIS	29.97	35.06
	Izana, Tenerife, Canary Islands	IZO	28.31	343.50
	Sand Island, Midway, USA	**MID**	**28.21**	**182.62**
	Key Biscayne, Florida	**KEY**	**25.67**	**279.84**
	Lulin, Taiwan	LLN	23.47	120.87
NH Tropics	**Mauna Loa, Hawaii**	**MLO**	**19.50**	**204.42**
	Pacific Ocean (15°N)	POCN15	15.00	215.00
	Mariana Islands, Guam	**GMI**	**13.39**	**144.66**
	Ragged Point, Barabados	RPB	13.17	300.57
	Pacific Ocean (10°N)	POCN10	10.00	211.00
	Christmas Island, Rep. Kiribati	**CHR**	**1.700**	**202.85**
SH Tropics	Bukit Kototabang, Indonesia	BKT	-0.20	100.32
	Mahe Island, Seychelles	**SEY**	**-4.68**	**55.53**
	Maxaranguape, Brazil	NAT	-5.52	324.74
	Ascension Island, UK	**ASC**	**-7.97**	**345.60**
	Pacific Ocean (10°S)	POCS10	-10.00	199.00
	Tutuila, American Samoa	SMO	-14.25	189.44
	Pacific Ocean (20°S)	POCS20	-20.00	186.00
SH	Gobabeb, Namibia	NMB	-23.58	15.03
	Easter Island, Chile	**EIC**	**-27.16**	**250.57**
	Pacific Ocean (35°S)	POCS35	-35.00	180.00
	Cape Grim, Tasmania, Australia	**CGO**	**-40.68**	**144.69**
	Baring Head Station, NZ	BHD	-41.41	174.87
	Palmer Station, Antarctica	**PSA**	**-64.92**	**296.00**
	Syowa Station, Antarctica	SYO	-69.01	39.59
	Halley Station, Antarctica	**HBA**	**-75.61**	**333.79**
	South Pole, Antarctica	SPO	-89.90	335.20

Table 2. GEOS-Chem regions shown in Fig. 2

Number	ID	Long Name
1	NBNA	Northern Boreal North America
2	SBNA	Southern Boreal North America
3	ETNA	Eastern Temperate North America
4	WTNA	Western Temperate North America
5	CNAM	Central America
6	AMZN	Amazon
7	EASA	Eastern South America
8	WESA	Western South America
9	EURO	Europe
10	SAME	Sahara and Middle East
11	MDAF	Mid Africa
12	AFRF	African Rainforest
13	SOAF	South Africa
14	EABA	Eastern Boreal Asia
15	WEBA	Western Boreal Asia
16	SOBA	Southern Boreal Asia
17	CNAS	Central Asia
18	SEAS	Southeast Asia
19	EQAS	Equatorial Asia
20	AUST	Australia
21	GNLD	Greenland
22	ATCA	Antarctica

Table 3. Cumulative changes in mean CO_2 annual cycle amplitudes (ppm) from the 1950–1959 baseline in the FullyCoupled simulation, and the contributions of non-radiative forcing (CO_2 fertilization and N-deposition), climate change, and LUC to the FullyCoupled amplitude changes averaged over the NH high latitudes, midlatitudes, subtropics, tropics, and the NH.

	FullyCoupled			NoRad			Climate Change			LUC		
High Latitudes	~~5.7~~ 6.4	~~8.3~~ 9.6	~~9.2~~ 10.6	2.4	~~4.6~~ 4.5	~~5.2~~ 5.3	~~3.2~~ 4.0	~~3.7~~ 5.1	~~4.0~~ 5.2	~~-0.9~~ -1.1	~~-1.1~~ -1.3	~~-1.6~~ -1.7
Midlatitudes	~~5.5~~ 5.2	~~7.5~~ 8.3	~~7.4~~ 8.9	~~3.5~~ 3.3	~~6.3~~ 5.7	~~7.4~~ 6.8	1.9	~~1.2~~ 2.6	~~-0.1~~ 2.1	~~-0.6~~ -0.9	-0.7	-1.3
Subtropics	~~3.1~~ 2.8	~~3.9~~ 3.6	~~3.6~~ 3.4	~~2.0~~ 1.8	~~3.6~~ 3.0	~~4.1~~ 3.5	1.0	~~0.3~~ 0.6	~~-0.5~~ -0.1	~~-0.8~~ -0.7	-0.9	-0.9
NH Tropics	~~1.3~~ 1.0	~~1.6~~ 1.5	1.4	0.9	~~1.6~~ 1.5	1.8	~~0.1~~ -0.1	~~0~~ -0.1	~~-0.4~~ -0.3	~~-0.5~~ -0.4	~~-0.3~~ -0.4	-0.4
NH	~~3.1~~ 3.4	~~4.1~~ 4.7	~~4.1~~ 5.0	2.0	~~3.5~~ 3.4	~~4.0~~ 4.1	~~1.1~~ 1.4	~~0.6~~ 1.3	~~0.1~~ 1.0	-0.6	-0.7	-0.9
Year	2100	2200	2300	2100	2200	2300	2100	2200	2300	2100	2200	2300

Table 4. Observed and FullyCoupled 2009–2013 mean CO_2 annual cycle amplitudes, and corresponding decades when peak FullyCoupled amplitudes occurred in each latitude band shown in Fig. 6a.

Latitude	A^{Obs} (ppm) ~~1985–2013~~ 2009–2013	A^{FC} (ppm) ~~1985–2013~~ 2009–2013	Peak decadal mean A^{FC} (ppm)	Center year of Decade of Peak A^{FC}
High Latitude	~~17.5~~ 17.3	~~10.5~~ 11.3	~~17.7~~ 19.5	2241
Midlatitude	~~15.2~~ 19.5	~~8.1~~ 8.7	~~17.2~~ 17.8	2236
Subtropics	9.3	~~6.7~~ 5.9	~~10.0~~ 9.0	~~2188~~2236
NH Tropics	6.7	~~3.8~~ 3.7	~~4.4~~ 4.2	2241
NH mean	~~10.1~~ 11.3	~~6.3~~ 6.2	~~9.9~~ 10.4	~~2241~~2236