Dear Referee 1:

We greatly appreciate your time and effort to read, understand, and make comments on our manuscript. We have carefully studied your comments. Hope our responses (in blue) have adequately addressed your concerns.

Xingjie Lu and Yiqi Luo

On behalf of all co-authors

Anonymous Referee #1

Reviewer 1: It is well known that carbon turnover time as computed by carbon stock divided by carbon flux has a well defined meaning only for stationary states, while the meaning of transit time as mean age of carbon released from the system remains valid also for nonstationary states. On this background the submitted paper investigates how strongly transit and turnover times deviate in historical and RCP8.5 scenario simulations. The simulations are performed using the land surface model CABLE in offline simulations forced by CRU-NCEP (historical) and CLM (scenario) data. To separate the physical and biogeochemical effect of CO2 on transit and turnover times, separate simulations are performed where either the temperature forcing or the photosynthethically relevant CO2 level are kept fixed. To determine transit time using the approach by Rasmussen et al. (2016), the authors equipped CABLE with a diagnostic to follow changes in carbon stocks of all pools of their land carbon model and the fluxes between them. The authors show that the expression for changes in transit time based on this approach can be separated into two components, one arising from changes in the mean age of the carbon in the different pools (abbreviated in the following as MAC – Mean Age Change), the other arising from changes in the age composition of the carbon fluxes ’respired’ from the different carbon pools (abbreviated in the following as ACC – Age Composition Change). The authors show how the MAC and ACC contributions to transit time change in their scenario simulations.

Response: We greatly appreciate the reviewer for carefully reading our manuscript. The above paragraph is a good summary of what we did in our study.

Major Remarks

Reviewer 1: 1) **The study is not well motivated**

In the abstract the authors motivate their study by writing that considering transit and turnover times “neither of them has been carefully examined under transient C dynamics in response to climate change”. This is not a very convincing argument for their study since (i) the study should not be published if its contents would not be new,

Response: We thank the reviewer for the great point. First, we totally agree that “something hasn’t been done does not mean it is scientifically relevant”. The reviewer is a critical thinker. He or she may agree that any sentence out of a context may not make sense in a manuscript. A sentence, however, carries meanings in connection with other sentences. For our manuscript, the first sentence of the abstract is “Ecosystem carbon (C) transit time is a critical diagnostic parameter to characterize land C sequestration." Combining the first sentence with the third sentence in the abstract can form a sentence “Such a critical parameter 'has not been carefully examined under transient C dynamics in response to climate change.'" This new sentence by placing "not been carefully examined" in the context, we think, identifies an important knowledge gap and thus makes our study scientifically relevant.

Nevertheless, we take the criticism seriously from the reviewer and changes the sentence to be "However, we know little about whether transit time or turnover time better represents carbon cycling through multiple compartments under non steady state." (See Line 16-18)

Reviewer 1: and (ii) that something hasn't been done doesn't qualify it as scientifically relevant.

Response: We also agree with reviewer's statement "the study should not be published if its contents would not be new". Since the reviewer did not elaborate this point in reference to our manuscript, we consider her or his comment is a general statement.

Reviewer 1: And also the introduction is not clear about the motivation of the study, except that from the subtext the authors let arise the impression that results from other studies using turnover time for a non-steady state situation cannot be trusted. Here e.g. a study by He et al. (2016) is cited with the result that in CMIP5 simulations the "soil C sequestration potential can be overestimated due to under estimation of C turnover time". But in this study "turnover times" are decay parameters of a model and not a diagnostic turnover time computed by carbon stock divided by carbon flux so that this study is not suitable for motivating the study reviewed here.

Response: We greatly appreciate the reviewer's effort to identify the motivation of our study in the introduction section. The last sentence in the first paragraph of the introduction section states: "It is not clear how much estimates of C turnover time deviate from mean C transit time and what cause their deviation under climate change." If this is not clear to the reviewer, we were wondering if the reviewer has any more specific suggestion to revise our sentence so as to make our motivation of the study apparent to her/him.

The reviewer is very knowledgeable and knows the technical detail very well in the study by He et al. (2016). The reviewer is right that in He et al. (2016) study, "turnover times" were derived from decay parameters of a model and not by carbon stock divided by carbon flux. Our sentence "Up to 40% of soil C sequestration potential can be overestimated due to underestimation of C turnover time in current CMIP5 models (He et al., 2016)" reflects a main conclusion from that study. Besides, He et al. (2016) used the term "turnover time" in their paper. As Sierra et al. (2017) pointed out, there are many different ways to define "turnover time" in the literature. We used the study by He et al. (2016) as one example to highlight the need to understand turnover time better instead of to define the term of turnover time at this stage. We were puzzled why the reviewer thought the paper by He et al. (2016) "is not suitable for motivating" our study.

Reviewer 1: A similar remark concerns the study of Friend et al. (2013) cited in the introduction: Friend et al. indeed calculate turnover time as carbon stock divided by carbon flux but as a diagnostic to test the validity of their simple carbon model, but not for drawing any other conclusions from it that could be improved by using transit time. Hence, in my opinion the authors handle the cited literature inappropriately to motivate their study and thereby give a wrong impression of their relevance.

Response: The reviewer used another sentence in the manuscript to question the motivation of our study. The sentence "Recent model inter-comparison study indicated that a major cause of uncertainty in predicting future terrestrial C sequestration is the variation in C turnover time among the models (Friend et al., 2014)" was used to highlight the need to understand turnover time better as well. We were very confused by reviewer's point that because Friend et al. (2014) did not mention transit time in their paper, we could not use it to motive our study on turnover time in relation with transit time.

Overall, we are grateful to the reviewer for his/her critiques, which made us to carefully examine our manuscript again.

Reviewer 1: 2) **The relevance of the results of the study is unclear**

According to section 5 ('Conclusions') the study has two major results. The first (lines 357-361) concerns the development of transit and turnover time in their simulations, in particular that they increasingly deviate from one another during the 21st century, and that the deviations are stronger in some regions than in others. But what to conclude from this? Is this a useful knowledge?

Response: We were not sure if the reviewer asked those two questions philosophically or practically. In practice, knowledge about the deviation between C transit time and turnover time in different regions under different scenarios (warming and [CO2] rising) is useful for us to understand time characteristic of the ecosystem carbon dynamics. When we lump all pools and fluxes together to calculate turnover time by "stock over flux", the time characteristic is different from that of transit time when individual pools and fluxes are considered to be networked together to form compartmental dynamical system. Thus, our results provide information on how turnover time deviates from transit time in specific region and ecosystems. Because "stock over flux" is still the easiest way to measure how fast C cycle through ecosystem, it is not our purpose to persuade the community to completely give up the method. Instead, we only provide information about how carbon transit time deviates with the turnover time in the non-steady state. We estimated both C transit time and turnover time globally. We assume the deviation between them is due to the lost information by lumping pools and fluxes to calculate the turnover time. The temporal and spatial estimates on the deviation tell us whether we can still use turnover time at a specific place and time.

If those are philosophical questions, we may not be able to answer either of the questions correctly. In this case, it is only reviewer's perspective that matters.

Anyway, in the revision, we added how this knowledge is practically useful in the Conclusion. (See Line 419-424)

Reviewer 1: The second result (lines 363-368) is that transit time can be separated into contributions from MAC and ACC because the residual is small (see eq. (6) and Fig. 3). Therefore on first sight I indeed thought that this separation is an interesting idea that could help to understand better how transit time behaves under different forcings. The authors claim (lines 364/365) that MAC is determined by carbon input and ACC by "differential responses of various C pools to climate warming and rising atmospheric [CO2]". While this latter formulation is rather cryptic, I take from it that the authors think that one could pin down what affects MAC and ACC so that e.g. for scenarios of different CO2 and/or temperature rise one could understand why transit time would develop differently.

Response: We thank the reviewer for her/his carefully examining the separation of Mean Age Change (MAC) from Age Composition Change (ACC) in our study. We agree that the contributions by MAC and ACC are not independent with each other, similarly as pool and flux influence each other. But the separation of pool and flux is so fundamental for any research to understand carbon cycle. In this study MAC is related to the change caused by carbon age, which is equivalent to pool change in the pool-flux separation whereas ACC is more about the change caused by flux.

We understand that it may take time to fully comprehend new concepts about MAC and ACC. The separation was made according to derivative of an equation with two components. This method is very commonly used in many studies. For example, Koven et al. (2015) used this method to separate relative contributions of NPP vs. turnover time in influencing carbon sequestration. By separating the two terms, we can better understand mechanisms underlying the changes in transit time.

Reviewer 1: But I very much doubt that this separation helps understanding anything since there is no way to see how MAC and ACC are separately affected by the carbon inputs or the forcings: this is because MAC and ACC are not independent from one another since they are both derived from the same development of carbon stored in the compartments (xi(t) in eq. (2) and eq. line 166). Hence a change of the carbon input into the system changes both MAC and ACC, and also a change in pool turnover time parameters by a changing climate (temperature, moisture) changes both MAC and ACC.

Response: The reviewer "very much doubt that this separation helps understanding anything since there is no way to see how MAC and ACC are separately affected by the carbon inputs or the forcings". We do not agree that contributions from different reasons cannot be separated only because they are both partly affected by the same factor. There are many opposite examples in C cycle study. For examples, C pool and flux may both respond to change in C input. However, their responses have different ecological meanings.

Moreover, eq. (6) is the major equation to show the differences between MAC and ACC. MAC is mainly contributed by the change in age and ACC is mainly contributed by the change in composition.

Reviewer 1: Only if one could understand how climate and CO2 act differently on MAC and ACC this separation could contribute to a better understanding of transit time development in transient simulations.

Response: Reviewer was wondering "how climate and CO2 act differently on MAC and ACC". Our results have shown different responses of MAC and ACC to climate and CO2. Figure 3d shows that contribution from ACC (in blue) changes from negative to positive in response to C balance change, whereas MAC (in red) keep increasing. These features are very similar to C pool and flux that C flux response faster than C pool to input change. More evidence that contributions from MAC and ACC vary spatially (Figure 4) also indicates the separation is helpful for our understanding.

Reviewer 1: That MAC and ACC have no individual meaning can also be seen directly in the simulation results: In the simulation with both forcings combined (simulation S3) the contribution to transit time from ACC is not even approximately the sum of the ACC contributions from the simulations with forcings separated (S1, S2), and the same is true for MAC. Hence, the behaviour of simulation S3 cannot be understood as combination of results from S1 and S2.

Response: The reviewer also doubted that "MAC and ACC have no individual meaning" because the sum of individual effects (warming effect and [CO2] rising effect) does not equal to the combined effects. The non-additive MAC or ACC in response to warming and [CO2] rising is possibly due to the non-linear or interactive effects, which have commonly been found in other experimental and modelling studies. For examples, climate and rising atmospheric [CO_2] affect GPP together, but usually their co-effects are not equal to the sum of their individual effects (Norby and Luo, 2004; Luo et al., 2008; Leuzinger et al., 2011;

Campbell et al., 1997; Zhang et al., 2016). However, it does not necessarily mean climate effects and rising atmospheric [CO_2] effects on GPP should not be separated.

Meanwhile, MAC and ACC do have individual meaning. In theory, Eqn (6) has illustrated that MAC represents the contribution from change in age and ACC represents the contribution from change in composition. In practice, results from their responses (Figure 3d and Figure 4) have also confirmed they are completely different.

In the revision, we added clarification in the Results. (See Line 245-248)

Reviewer 1: – In conclusion, I think this separation is only technical and pretty useless. In order to convince me from the opposite, the authors had to show me a case where it leads to an improved unterstanding.

Response: In practice, the contributions of MAC and ACC should be different among models. None of previous studies have diagnosed those two contributions separately. Although total change in C transit time has been compared recently (Sierra, 2017), a thorough assessment on their individual contributions would provide more useful information. Otherwise, models are very likely to get the right answer with wrong reasons. By combining compartment models with different types of measurements via data assimilation techniques, we may be able to better constrain MAC and ACC respectively. Therefore, modelled C cycle can be better calibrated by constraining MAC and ACC against measurements in the future.

In the revision, we have added a paragraph in the discussion to show how the separation can be useful. (See Line 403-411)

Reviewer 1: Concernig the other remarks related to the second result in lines 366-368, I think they are all wrong: (i) The calculation of turnover time by dividing stocks by fluxes is not assuming anything, it is simply a diagnostic that in the case of stationary states has a well defined meaning, but can, as a diagnostic, still be a useful concept (see my remark on the study by Friend et al. (2013) above).

Response: We appreciate that this reviewer clearly shows her/his view and perspective. He or she stand strongly for using turnover time. We agree that turnover time is a good and useful diagnostic, since both stock and fluxes are easy to measure. Our manuscript have admitted the advantages of C turnover time “C turnover time can be easily calculated from C stock over flux, both of which can be easily measured.” (Line 379-380) However, would his/her statement “the calculation of turnover time is not assuming anything” be contradictory to “it is simply a diagnostic that in the case of stationary states has a well-defined meaning”? Would “in the case of stationary states” be an assumption? But we hope the reviewer agrees that turnover time is calculated by lumping pools and fluxes together. As a scientist, he or she, we hope, will not be against research to explore other ideas related to time characteristics of carbon cycle.

Reviewer 1: (ii) Surely turnover time changes when MAC and ACC change, so that contrary to the authors claim it accounts for such changes.

Response: We mentioned “C turnover time does not account for changes in age structure and contribution fractions of different pools to ecosystem respiration.” (Line 366-367). This sentence did not say “turnover time does not change”. Obviously, C turnover changes when MAC and ACC changes. However, we care about whether the diagnostic really accounts for the certain critical information. The “change” in C turnover time with MAC and ACC is not really sufficient enough to accurately quantify the contributions from MAC and ACC to C cycle time characteristics.

Reviewer 1: Hence (iii) contrary to the claim by the authors one cannot conclude that transit time is a “better parameter”. – A similar claim is found in the last scentence of the abstract where the conclusion is even weirder by saying that the use of turnover time instead of transient time may “lead to biases in estimating land C sequestration” – how could the mere calculation of a time scale affect the estimation of C sequestration?

Response: The reviewer seems to believe that there is no better diagnostic than turnover time. We partly agree but it should depend on the specific case we are studying. Eg. Friend et al., (2014) identified that the source of the uncertainty in predicating land C sequestration C is mainly from turnover time. Qualitatively, turnover time and transit time behave similarly. Thus, the turnover time can be used in this case to point out a direction for model improvement. However, turnover time may not represent the time characteristic of carbon dynamics if we are interested in carbon sequestration in multiple pools, because turnover time uses lumped pools and fluxes for calculation.

Reviewer 1: 3) **Some suggestions for improving the paper**

There is one result of the paper – surprisingly not mentioned in the conclusions – that in my opinion makes an important contribution to land carbon research: This is the comparison of the CABLE results for transit time with the observational results by Carvalhais et al. (2014) in Fig. 2. When the Carvalhais et al. paper appeared, I thought it’s nice that they produced a map of stocks divided by fluxes so that this turnover time can be used as a diagnostic to easily compare with results from model simulations. But with the study under review here, we now know that despite the non-stationarity of todays carbon cycle, turnover times agree well with transit times (Fig. (5)) so that the observational turnover times of Carvalhais et al. (2014) can indeed be interpreted as proper carbon ages. And that the zonal distribution of CABLE results matches those of Carvalhais et al. quite well provides additional credit to this conclusion.

Response: Thanks for the great suggestion to improve our manuscript. We have included this point in the discussions to support Carvalhais et al. (2014). (See Line 323-330)

Reviewer 1: Hence, what I propose is that you focus your study on the question to what extend the observational estimates of turnover time by Carvalhais et al. (2014) (and if possible also those by Bloom et al. (2016) Fig. 3) can be interpreted as proper ages. In this respect it also interesting to see that shortly in the future this doesn’t work any more. For your paper this would mean that you drastically shorten it by dropping anything else (i.e. in particular the simulations S1, S2 and all stuff relating to the separation of transit time into contributions from ACC and MAC). With such changes I think a resubmission could make sense.

Response: This reviewer clearly has her/his own preference and tried to fit our study into his/her perspective. Hopefully this review is not Dr. Carvalhais or his associates. We do not believe Dr. Carvalhais or his associates would be such self-serving. Nonetheless, these are very constructive suggestions. We fully understand the reviewer’s point and do see some interesting conclusions being drawn in this way. It is very interesting that the reviewer states “In this respect it also interesting to see that shortly in the future this doesn’t work any more.” We thought we just did what the reviewer suggested us to do. Our analysis indicates that turnover time works quite well now and until the middle of this century before it significantly deviates from transit time. To do what the reviewer suggested us to do, we need the full length of the manuscript. In the revision, we have added a paragraph to discuss how the deviation could be used to address the question to what extend the turnover time by Carvalhais et al. (2014) is able to be interpreted as proper time characteristics in C cycle. (See Line 323-330)

Minor Remarks

Reviewer 1: • For a resubmission a better polished text would be appreciated. The current text is mostly understandable but the English shows quite some deficits (an annoyingly plentitude of missing articles; wrong grammar (lines 41, 47, 127, 154, 156, 175, 177, 178, 261, 357, 479; Supplement scattered with errors); incomplete formulations (lines 56, 139, 167, 210); wrong or missing preposition (lines 99, 333), ununderstandable formulations (line 168, 196, 274)). And results should be presented in present tense not in past tense as e.g. in the abstract.

Response: We have carefully checked grammar, formulations, etc. and used present tense.

Reviewer 1: • I do not see why in addition to the terms 'transit time' and 'turnover time' one needs the equivalent use of namings 'Olson method' and 'Rasmussen method', respectively, this is only confusing – by whatever method you compute turnover or transit time, they remain the same.

Response: Thanks for pointing out the confusion. In the revision, we will use only transit time and turnover time avoid the confusion.

Reviewer 1: • In the model description for CABLE you refer for the photosynthesis part to a paper by Farquhar that refers to the C3 pathway only. What does it mean for the realism of your simulations that CABLE is not accounting for C4 photosynthesis, happening at huge areas wordwide?

Response: Sorry for the misleading, but CABLE does account for C4 photosynthesis, which follows Kowalczyk et al. (2006). In the revision, we have added this information to clarify. (See Line 101-102)

Reviewer 1: • What about land use change? This seems to be not accounted for in CABLE, but replacement of forests with agricultural lands could in principle speed up the land carbon cycle by one magnitude (maybe forests: 30 years vs. agriculture 1 year).

Response: Land use change is not accounted for in CABLE and we have discussed the possible bias caused by this in the first paragraph in discussion section 4.3. (See Line 350-359)

Reviewer 1: • What about natural vegetation? How does it change in your CABLE simulations?

Response: CABLE is not a dynamics vegetation model, which means natural vegetation distribution is static. In the revision, we have added some discussions on how potential changes in natural vegetation distribution could influence the estimates of transit time and turnover time. (See Line 361-369)

Reviewer 1: • For the historical period CABLE was forced by CRU-NCEP data, while for 2006-2100 simulation data from CESM were used. How good do these simulated climate data fit at the transition period around 2005/2006 to the historical values, concerning e.g. the global and zonal levels of land temperature, precipitation, and radiation?

Response: To show the forcing in transition period, we have added the annual variation of 8 meteorological forcing variables and [CO_2] data from 1901 to 2100 in the Appendix B.

Reviewer 1: • When you introduce the Rasmussen method to calculate transit time it would be good to mention that this approach works only for linear box models. Is CABLE really of this type? You could demonstrate this by listing in the appendix the box-model equations for CABLE (like in section 8 of the Rasmussen et al. paper) – this would also help to make precise what at all your mathematical symbols mean. – I wonder about the applicability of the Rasmussen et al. approach because I would think that e.g. the phenology introduces some non-linearity in the dynamics of leaf carbon since leaf area cannot grow beyond a certain value depending on vegetation type – but maybe CABLE works differently. And what about structural allometries between different plant parts (stems, roots, leaves) that are also non-linear?

Response: These questions and suggestions are very helpful to improve the manuscript. We have given more details about CABLE in appendix C. Yes, C cycle in CABLE, even with phenology processes, can be considered as a linear model. In the deciduous plant functional type, CABLE's phenology only changes the leaf turnover rate and allocation fraction in spring and fall. When LAI grows over the upper limit, CABLE will set the leaf C allocation to "0" in order to prevent further leaf growth. The dynamics of both turnover rate and C input are determined by time-dependent environmental scalars. Because the environmental scalars are independent on C pool sizes in most cases, the model can be considered as a linear. In addition, CABLE does not include the structural allometries.

In the revision, we have clarified the required linear condition in Rasmussen method (See Line 152). Moreover, we have also listed equations for CABLE C cycle in the Appendix C.

Reviewer 1: • Fig. 1: (i) Title Fig. 1a: Transient→ Transit. (ii) Make the scale numbering for both plots of Fig. 1 better readable (e.g. in steps of 5 or 10 years, or, if logarithmic, use other round numbers, but definitely not something like 3623).

Response: We have revised as suggested. (See Line 575)

Reviewer 1: (iii) Are the colors at the edges of e.g. Antarctica and Greenland really a result of your simulations, or is it a plotting artefact e.g. from your grid cell interpolations?

Response: Those colors at the edges are the real results of the simulations. The red indicates that C transit time and mean age are really high in the high latitude region. In contrast, the edges of islands at lower latitudes, e.g., Hawaii, are relative low.

Reviewer 1: • Lines 147-150: I guess that this paragraph should say that the authors solve equation (2) by an Euler method starting from zero land carbon – this should be stated more clearly.

Response: We have followed the suggestion to describe more clearly. (See Line 160)

Reviewer 1: • Fig. 2: Why don't you also plot turnover time from CABLE? This would make it even more clear that transient and turnover time match well for this period of time.

Response: Thanks for the great suggestion. We have added turnover time in Figure 2. (See Line 216-217 and 582-586)

Reviewer 1: • Why do you talk of "permafrost areas" instead of e.g. "high latitudes"? I guess that CABLE is not accounting for permafrost.

Response: We agree that "high latitudes" is more accurate. We have revised the wording.

Reviewer 1: • Fig. 6g: You attribute the small difference in turnover and transit time for the stationary state to the presence of the seasonal cycle that makes the system non-stationary. Can this explain the increase of this difference beyond 60◦N?

Response: Yes, conceptually, the significant bias in high latitude should be due to the seasonal cycle. We have illustrated in the results. (See Line 269-270)

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Dear Referee 2:

We are very appreciated your comments on our manuscript. We have carefully read your comments. Hopefully, you will find our response (in blue) satisfactory.

Xingjie Lu

On Behalf of all co-authors

Anonymous Referee #2

Reviewer 2: Lu and colleagues use the CABLE model to show: a) how turnover time and transit time diverge under transient global change simulations, and b) decompose the contribution of turnover time between the age structure of ecosystem pools and their contribution to the output flux. This is an exciting and important paper. Previous studies have shown how turnover time contributes to our predictive uncertainty of the future response of the terrestrial biosphere to global change (e.g. Friend et al., 2013). However, this study nicely shows that turnover times themselves can also be an uncertain metric to assess model performance and quantify carbon storage potential in the terrestrial biosphere under non steady-state conditions. The manuscript expands on previous work by Rasmussen et al. (2016) who developed formulas for the mean transit time for non-steady-state conditions. It shows how global change drivers such as warming and CO2 can modify the time that carbon requires to transit through the terrestrial biosphere. The implications are not only for comparing two different modeling metrics, but it helps to understand how global change modifies the time scales of carbon storage in the terrestrial biosphere.

Response: Thanks for the positive comments on our manuscript.

Reviewer 2: Unfortunately, the manuscript has problems with the English language (typos, grammar), but if these issues are addressed with the help of a native English speaker, the manuscript can be published with minor revisions. I only have a few minor comments to help improve the manuscript:

Response: Thanks for the suggestion. We have found an English native speaker to help edit the language.

Reviewer 2: • Line 22. Increase with respect to what? Do you mean increase in the transient simulations with respect to steady-state? Please clarify.

Response: Yes, increase with respect to steady state. We have revised the sentence to be clearer. See Line 24-26: “Warming increases C turnover time by 2.4 years and transit time by 11.8 years in 2100 relative to that at steady state in 1901”

Reviewer 2: • Line 29 plus 3 other occurrences. Change Olsen to Olson.

Response: We have deleted all “Olson method”, as suggested by reviewer 1. Sorry for the typos.

Reviewer 2: • Figure 2. I don’t understand why you plot together the turnover times from Carvalhais et al. (2014) versus the dynamic transit times. They are conceptually different and computed in very different ways. This figure gives the false impression that these metrics should be compared, and that they are roughly equal, which this very same manuscript clearly shows that they are not. I suggest removing this figure to avoid confusion.

Response: Thanks for pointing out the confusions we might have made without enough details. We agree that turnover time and transit time are calculated in different ways. However, theoretically, turnover time and transit time should be strictly equal under steady state condition (Sierra et al., 2017). Our assumption, which is also used by some other studies, is that ecosystem C cycle in most global areas may be close to the steady state in present-day (See Line 209-219), however, climate change may drive C cycle to a non-steady state in the future (See Line 327-330). Therefore, C transit time is comparable with C turnover time at present-day in Fig. 2. This figure serves as a validation of our model against the observations, which is very important for a modeling study. More importantly, reviewer 1 really likes it. As such, we would keep Figure 2, but have added more details, e.g., our assumption, in the figure caption (See Line 583-586) and will change “Rasmussen method” to “simulated C transit time” to avoid any confusions.

References:

Sierra, C. A., Muller, M., Metzler, H., Manzoni, S., and Trumbore, S. E.: The muddle of ages, turnover, transit, and residence times in the carbon cycle, Global Change Biol, 23, 1763-1773, 2017.

List of major relevant changes:

Line 16~18: “However, neither of them has been carefully examined under transient C dynamics in response to climate change” has been changed to “However, we know little about whether transit time or turnover time better represents carbon cycling through multiple compartments under non steady state”;

Line 419~424: added “Knowledge about the deviation between C transit time and turnover time in different regions under different scenarios (warming and [CO2] rising) is useful for us to understand time characteristic of the ecosystem carbon dynamics. When we lump all pools and fluxes together to calculate turnover time by “stock over flux”, the time characteristic is different from that of transit time when individual pools and fluxes are considered within a networked compartmental system. Thus, our results provide information on how turnover time in the future could deviates from transit time in specific regions and natural ecosystems under different climate change scenarios.”

Line 245~248: added “Note that the response under combined effects (S3) is not a sum of those from individual effects (S1 plus S2). The non-additive response to climate warming and rising atmospheric [CO2] is probably due to their interactions, which have been commonly found in many ecological studies (Norby and Luo, 2004; Luo et al., 2008; Leuzinger et al., 2011; Campbell et al., 1997; Zhang et al., 2016).”

Line 403~411: added “Estimating C transit times in the real world can help constrain projections in land C sequestration by C cycle models because C turnover time is a major source of model uncertainty (Friend et al., 2014; He et al., 2016). Our study has shown that the change in C transit time can be separated into two components, C composition change and C age change. Assessment on the two components would provide additional constraints on model projections. Has C transit time been further constrained through its two components with observation, modelled C cycle and land C sequestration can be significantly improved.”

Line 323~330: added “The deviation between C transit time and turnover time also indicates to what extend that turnover time can properly represent time characteristics in C cycle. In climate warming and rising atmospheric [CO2] scenario (S3), the deviation does not increase significantly until 2050. The modeled latitudinal pattern of present-day C transit time well matches the C turnover time estimated from observations (Carvalhais et al., 2014). It indicates that the stock-over-flux estimates are still useful at present day. However, the deviation between C transit time and turnover time remarkably increases after 2050 (Fig 5b). Then, it requires caution when we use the C turnover time for estimating C sequestration in multiple compartmental ecosystems.”.

Line 101~102: the sentence "Gross primary production (GPP) is calculated according to Farquhar photosynthesis model (Farquhar et al., 1980; Kowalczyk et al., 2006)" has been changed into "Gross primary production (GPP) is calculated for both C3 and C4 plants (Farquhar et al., 1980; Kowalczyk et al., 2006).".

Line 361~369: added "In contrast to the static vegetation distribution used in CABLE, natural vegetation distribution may change over time in the real world. C transit time and turnover time may further deviate under natural vegetation dynamics. However, whether forest will expand or dieback in a future warming world is still quite unknown. Previous studies variously conclude due to their focus on different areas with different methods (Masek, 2001; Soja et al., 2007; Cox et al., 2004; Cox et al., 2013). Nevertheless, most bioclimatic models consistently suggest temperate and boreal biomes rapidly increase in area under warming (Kirilenko and Solomon, 1998). If the forest species, which stores more C in slow-turnover tissue, takes over the grass species, which stores more C in fast-turnover tissue, the expansion of forest may increase C transit time significantly. However, C turnover time by lumping all different C compartments together may underestimate such changes."

Line 152: added "Note that this equation works only for linear models.".

Line 160: the sentence has been revised into "we obtain the steady state C ages in each compartment by solving Eqn (2) with an Euler method."

Line 216~217: added "Moreover, the simulated latitudinal pattern of C transit time almost overlaps with C turnover time, which also evident that C cycle is still near the steady state at present day."

Line 269~270: added "because seasonal soil frozen-thaw processes in this region lead to the strong seasonal cycle of the soil decomposition and violate the steady state assumption of the C turnover time."

Line 24~26: sentence has been revised: "Warming increases C turnover time by 2.4 years and transit time by 11.8 years in 2100 relative to that at steady state in 1901"

Line 583~586: added "Our assumption, which is also used by some other ecological studies (Trumbore, 2000), is that present-day ecosystem C cycle is closed to the steady state. Especially, in 1980s and 1990s, global land C uptake from Global Carbon Project (GCP) is about 0.8 GtC yr^{-1} with an uncertainty of 0.6 GtC yr^{-1}, which is not significant compared to current decade with global land C uptake is 2.7 GtC yr^{-1}."

Ecosystem carbon transit versus turnover times in response to climate warming and rising atmospheric CO_2 concentration

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Abstract. Ecosystem carbon (C) transit time is a critical diagnostic parameter to characterize land C sequestration. This parameter has different variants in the literature~~s~~, including a commonly used turnover time. However, we know little about ~~whether~~whether ~~-~~transit time or turnover time better ~~is a better diagnostic parameter to~~ represents carbon cycling through multiple compartment~~pool~~s under non steady state~~However, neither of them has been carefully examined under transient C dynamics in response to climate change~~. In this study, we estimate~~d~~ both C turnover time as defined by the conventional stock-over-flux ~~(i.e., Olson method)~~ and mean C transit time as defined by the mean age of C mass leaving the system~~(i.e., Rasmussen method)~~. We incorporate~~d~~ them into Community Atmosphere-Biosphere-Land Exchange model (CABLE) to estimate C turnover time and transit time, respectively, in response to climate warming and rising atmospheric [CO_2]. Modeling analysis shows~~ed~~ that both C turnover time and transit time increase~~d~~ with climate warming but decreases~~d~~ with rising atmospheric [CO_2]. Warming ~~The~~ increases ~~of~~ C turnover time ~~with respect to steady state~~ ~~with~~ under ~~warming was is estimated to be~~by 2.4 years ~~with Olson method~~ ~~whereas~~and ~~the~~ transit time ~~increased~~ by 11.8 years in 2100 relative to that at steady state in 1901~~with Rasmussen method~~. During the same period, ~~The decrease with~~ rising atmospheric [CO_2] decreases C turnover time by ~~was is estimated to be~~ 3.8 years ~~with Olson method~~~~in C turnover time~~ and ~~5.5 years with Rasmussen method~~~~in~~ transit time by 5.5 years. Our analysis ~~based on Rasmussen method~~ shows~~ed~~ that 65% of the increase in global mean C transit time with climate warming results from the depletion of fast-turnover C pool. The remaining 35% increase results from accompanied changes in compartment C age structures. Similarly, the decrease in mean C transit time with rising atmospheric [CO_2] results approximately equally from replenishment of C into fast-turnover C pool and subsequent decrease in compartment C age structure. Greatly different from the ~~Rasmussen method~~transit time, the ~~Olsen method~~turnover time, which does not account for changes in either C age structure or composition of respired C, underestimated impacts of either warming or rising atmospheric [CO_2] on C diagnostic time and potentially lead to biases in estimating land C sequestration in multi-compartmental ecosystems.

1 Introduction

Terrestrial ecosystem plays an important role in mitigation of climate change through sequestering carbon (C) from the atmosphere. Terrestrial C storage is co-determined by C input and C transit time, which is defined as the mean age of C mass leaving the system (Luo et al., 2001; Taylor and Lloyd, 1992; Nir and Lewis, 1975; Sierra et al., 2016; Manzoni et al., 2009; Eriksson, 1971; Bolin and Rodhe, 1973). As transit time cannot be easily estimated from observation, its variant, C turnover time, has been commonly used in the literature (Sierra et al., 2016). Recent model inter-comparison study indicated that a major cause of uncertainty in predicting future terrestrial C sequestration is the variation in C turnover time among the models (Friend et al., 2014). Up to 40% of soil C sequestration potential can be overestimated due to underestimation of C turnover time in current CMIP5 models (He et al., 2016). The C turnover time has been mostly estimated with a conventional stock-over-flux method (Carvalhais et al., 2014; Chen et al., 2013; Yan et al., 2017), which is probably first introduced by (Olson, 1963) and ~~. Hereafter in this paper, we call assume that “C turnover time” also indicates the use of “stock-over-flux” methodit Olson method. The Olson methodC turnover time is~~ based on a steady-state assumption. In response to climate change, terrestrial ecosystem C dynamics move away from steady states to be at dynamic disequilibrium (Luo and Weng, 2011). Estimation of C turnover time ~~with Olson method~~ likely deviates from C transit time in response to climate change (Sierra et al., 2016). It is not clear how much the ~~do~~ estimate~~s~~ of C turnover time deviates from mean C transit time and what causes their deviation~~s~~ under climate change.

The C transit time as the mean age of C mass leaving the system can be estimated only from age structure of C atoms in a multi-compartment ecosystem. In contrast, the C turnover time is estimated without any information of age structure of C atoms among compartments. Thus, C turnover time is equivalent to C mean transit time only in the autonomous (i.e., time-invariant) ~~linear~~ system at steady state~~s~~ (Sierra et al., 2016) with ~~three~~ two conditions to be satisfied. The first condition is that C fluxes and turnover rates of ~~each~~ individual pools do not change with time (i.e., time invariant or autonomous). ~~The second is that C turnover rate of each pool is not a function of pool size as in linear C transfer models.~~ The ~~third~~ second is that C influx to each pool equals to C efflux from the pool (i.e., at steady state). However, the autonomous, ~~linear~~ and steady state ~~system~~ conditions~~at steady state~~ ~~is~~ are ~~a very~~ usually too strict to completely meete ~~ondition~~ for real-world ecosystems. For examples, ~~Ecosystem~~ ecosystem C input via photosynthesis has diurnal variation, seasonal cycle, and inter-annual variability. C turnover time also exhibits strong seasonal variation (Luo et al., 2017). With seasonal cycles and inter-annual variability in both C input and turnover time, ecosystem C cycle is rarely at steady state rather than mostly at dynamic disequilibrium (Luo and Weng 2011). Therefore, C turnover time hardly equals C transit time in the real world, especially when land C cycle is under transient dynamics in response to climate change.

The estimates of C transit time requires information of C age structure in ecosystems so that the mean age of the C atoms at ~~the~~ a time when they leave the system can be calculated (Manzoni et al., 2009). In a multi-compartmental ecosystem, the C age within each compartment is represented by a single compartment C mean age and different compartments have different C mean ages (Rasmussen et al., 2016). Thus, the C transit time is the weighed mean of ages of C atoms leaving different compartments according to the contributing fraction of C loss from each pool to the total C loss. ~~Hereafter in this paper the term "C transit time" This will also indicate this calculation of transit time hereafter is calledfrom (Rasmussen et al., 2016) is being used.~~ ~~Rasmussen method.~~ In response to rising atmospheric $[CO_2]$, increased C input with young age into an ecosystem is usually allocated more to fast than slow turnover pools, leading to ~~the~~ changes in the C age structure of~~in~~ the ecosystem. The fast turnover pools usually contribute more to the respiratory loss than the slow pools~~ to the respiratory loss~~. Thus, it is expected that rising atmospheric $[CO_2]$ decreases C transit time due to both changes in the C age structure ~~in the ecosystem~~ and contributing fractions of different pools to total C loss from the ecosystem. Although it ~~C turnover time~~ may change in response to rising atmospheric $[CO_2]$ due to changes in both C fluxes and pools, C turnover time does not account for changes in the C age structure ~~are not accounted for in Olsen method~~~~C turnover time~~and contributing fractions to ecosystem respiration. Consequently, estimates of C turnover time are likely to deviate from transit time estimates under climate change.

In this study, we aim to answer following questions: 1) How do both C turnover time and C transit times change in response to climate warming and rising atmospheric $[CO_2]$? 2) How much does the C turnover time ~~estimated with Olson method~~ deviate from C transit time ~~estimated with Rasmussen method~~ under future climate change? 3) What mechanisms cause the deviation between the two methods? 4) Which regions show the greatest biases under different climate change scenarios? To answer those questions, we incorporated new algorithm ~~both Olsen and Rasmussen methods~~~~C turnover time and transit time~~ into Community Atmosphere-Biosphere-Land surface Exchange (CABLE) model (Wang et al., 2010; Wang et al., 2011) to calculate both C turnover time and transit time~~estimate changes in C turnover time and transit time~~. We ran the modified CABLE under three climate change scenarios, climate warming only, rising atmospheric [CO2] only, and both climate warming and rising atmospheric [CO2] to compare changes in C transit time with those in C turnover time.

2. Materials and Methods

2.1 The CABLE model

CABLE is a global land surface model as described by (Kowalczyk et al., 2006) and incorporates global carbon, nitrogen and phosphorus cycles (Wang et al., 2010; Wang et al., 2011). ~~For the sake of simplicity, t~~This study ~~did~~ does not activate phosphorus cycle in the model largely because phosphorus has minor impacts on C cycle (Zhang et al. 2011). Leaf photosynthesis, stomatal conductance, and heat and water transfer in CABLE are calculated using the two-leaf approach (Wang and Leuning, 1998).

Gross primary production (GPP) is calculated ~~according to a modified Farquhar photosynthesis model including~~for both C3 and C4 ~~pathway~~plants (Farquhar et al., 1980; Kowalczyk et al., 2006). Farquhar model is a biochemical model and ~~was~~ is modified in CABLE to calculate CO_2 assimilation rate at canopy level as a minimum of three potential limitation processes of photosynthesis: light, enzyme and C sink. Generally, all these three photosynthetic limitations are positively related to maximal carboxylation rate (V_{cmax}) or maximal potential electron transport rate (J_{max}) and intercellular CO_2 concentration (C_i). Both V_{cmax} and J_{max} are temperature dependent (Leuning, 2002), which are maximized at around 30°C. Thus in response to warming, model usually predicts a positive response in GPP in cold and temperate regions but a negative response in GPP in hot regions. C_i depends on the stomata conductance and atmospheric [CO_2]. GPP in CABLE positively responds to rising atmospheric [CO_2]. CABLE photosynthesis is also controlled by soil moisture.

Autotrophic respiration (R_a) in CABLE is also temperature dependent, which follows modified Arrhenius formula (Ryan, 1991; Sitch et al., 2003). ~~In~~ ~~On~~At the canopy scale, R_a is proportional to vegetation nitrogen content and a temperature related coefficient. R_a will positively respond to warming climate. Heterotrophic respiration (R_H) is proportional to litter and soil decomposition rate and C pool sizes. The decomposition rates in the model are controlled by soil temperature and water. The temperature response is based on a Q_{10} Eqn. Decomposition rates will positively respond to warming. The water response function is from the daily time step ecosystem model (DAYCENT) (Kelly et al., 2000) and the decomposition rate positively responds to wetter soil condition.

CABLE model has three vegetation compartments (leaf, wood and root), three litter compartments (metabolic litter, structure litter and coarse wood debris), and three soil compartments (fast soil pool, slow soil pool and passive soil pool) (Wang et al., 2010).

2.2 Simulation design

We use the meteorological data sets from National Centers for Environmental Prediction and Climatic Research Unit – (CRU-NCEP) to drive our model. The meteorological inputs from 1901 to 2100 include temperature, specific humidity, air pressure, downward solar radiation, downward long-wave radiation, rainfall, snowfall, and wind speed. The meteorological variables of CRU-NCEP data from 1901 to 2005 ~~were~~ are interpolated from the 6-hourly into hourly (Qian et al., 2006) and re-gridded from 0.5° by 0.5° to 1.875° by 2.5° spatial resolution. From 2006 to 2100, the hourly meteorological variables ~~were~~ are generated from Community Earth System Model version 1.0 (CESM) (Li et al., 2016; Hurrell et al., 2013) for Representative Concentration Pathway (RCP) 8.5.

C storage for all three scenarios (climate warming, rising atmospheric [CO_2] and both together) are initialized at pre-industrial steady states, which is achieved by a spin-up approach. The spin-up method cycles 10-year CRU-NCEP data (1901-1910) to drive CABLE model, with [CO_2] being constant at 1901 level. A semi-analytic solution ~~was~~ is used to accelerate spin up simulation (Xia et al., 2012).

The description of three scenarios in this study are summarized in Table 1. Simulation one (S1) fixes the atmospheric [CO_2] but uses changing climate forcing. Simulation two (S2) fixes climate forcing but increases atmospheric [CO_2]. Simulation three (S3) uses both changing climate forcing and increasing atmospheric [CO_2].

2.3 Calculation of ecosystem C mean age

C mean age is defined as the mean time elapsed since ~~the~~ C atoms (current in the system) entered the system, which is important for understanding C transit time described below. Following Rasmussen et al. (2016), C mean age ($\bar{a}$) can be formulated:

$$\bar{a}(t) = \frac{\sum_{i=1}^{d} a_i(t) x_i(t)}{\sum_{i=1}^{d} x_i(t)} \tag{1}$$

In Eqn (1), a_i represents the mean age of C in the i^{th} compartment; x_i represents C pool size of the i^{th} compartment, and d is total number of C compartments.

Mixing fresh C input into ecosystem old C may reduce the ecosystem C mean age. Meanwhile, C remaining in the system will age with the time. As shown by Rasmussen et al. (2016), dynamics of compartment C mean age can be described by the following differential equation:

$$\frac{da_i(t)}{dt} = 1 + \frac{\sum_{j=1}^{d}\left(a_j(t) - a_i(t)\right) b_{ij} k_j(t) x_j(t) - a_i(t) s_i(t)}{x_i(t)} \tag{2}$$

In Eqn (2), s_i(t) is direct C input rate from net primary production to the i^{th} compartment in g C m^{-2} $year^{-1}$, b_{ij} is the proportion of decomposed carbon from j^{th} compartment to be transferred to the i^{th} compartment. k_j is the decomposition rate of the j^{th} compartment, the unit is $year^{-1}$. Thus, change in compartment C age depends C aging, network C transfers among pools with different ages, and C input. ~~Be n~~Note~~d~~ that this equation works only for linear models.

With a time step Δt, the C transferred from the j^{th} compartment to the i^{th} compartment (F_{ij}) equals to $b_{ij} k_j(t) x_j(t) \Delta t$ and C input (S_i) equals to S_i(t)=s_i(t)Δt, Eqn (2) can be rewritten in a finite element form to represent C age dynamics:

$$\Delta a_i(t) = \Delta t + \frac{\sum_{j=1}^{d}\left(a_j(t) - a_i(t)\right) F_{ij} - a_i(t) S_i(t)}{x_i(t)} \tag{3}$$

In Eqn (3), the first term, Δt, indicates natural C aging. the second term, $\frac{\sum_{j=1}^{d}\left(a_j(t) - a_i(t)\right) F_{ij} - a_i(t) S_i(t)}{x_i(t)}$, represents the mean age change of the i^{th} compartment due to mixing with transferred C from other compartments or external C input (i.e., NPP).

After the C cycle spin up, we obtain the steady state C ages in each compartment by solving Eqn (2) with an Euler method. ~~ran age-structured CABLE to obtain initial steady state of each compartment C age by cycling 10-year (1901-1910) C fluxes and pool sizes from CABLE to force Eqn (3) until the~~ The changes of C compartment mean age are less than 0.1% between two successive cycles.

2.4 ~~Rasmussen e~~Ecosystem C transit time

C transit time is defined as the average time for a C atom spend in the ecosystem until its exit, or the time from entering the ecosystem to leaving the ecosystem (or residence time, (Luo et al., 2001)). For a multiple-compartment system, the mean C transit time, $\bar{\tau}_R$, ~~estimated by Rasmussen method~~ can be calculated ~~as~~ using the following equation (Rasmussen et al., 2016):

$$\bar{\tau}_R(t) = \frac{\sum_{i=1}^{d} a_i(t) x_i(t) (\sum_{j=1}^{d} b_{ji}) k_i(t)}{\sum_{i=1}^{d} x_i(t) (\sum_{j=1}^{d} b_{ji}) k_i(t)} \tag{4}$$

~~when~~ When $i = j$, b_{ji} ~~$= -1$,~~ equals -1, indicating one unit of C exited from the i^{th} compartment. When $i \neq j$, b_{ji} represents the proportion of exited C of the i^{th} compartment transferred to j^{th} compartment. $\sum_{j=1}^{d} b_{ji} = 0$ when the exited C from the i^{th} compartment is fully transferred to all the other compartments, such as litterfall from plant to litter compartments, without C loss. $\sum_{j=1}^{d} b_{ji} < 0$ when the exited C from the i^{th} compartment is partly transferred to the other compartments, such as litter or soil C decomposition, with the rest lost to the atmosphere via respiration. The denominator is the total amount of C loss from the ecosystem. The numerator is the sum of respired age-mass C.

2.5 Components of ~~Rasmussen~~ C transit time and their changes

Equation (4) can be re-organized as:

$$\bar{\tau}_R(t) = \sum_{i=1}^{d} a_i\,(t) f_{\mathrm{hr},i}(t) \tag{5}$$

when we define fraction of the total C loss from the i^{th} compartment ($f_{\mathrm{hr},i}$) as:

$$f_{hr,i}(t) = \frac{x_i(t) (\sum_{j=1}^{d} b_{ji}) k_i(t)}{\sum_{i=1}^{d} x_i(t) (\sum_{j=1}^{d} b_{ji}) k_i(t)}$$

Equation (5) indicates that ecosystem C transit time ~~has~~ consists of products of two components: compartment C age (a_i) and the fractional composition of respired C ($f_{\mathrm{hr},i}$). Compartment C age as represented by Eqn (2) changes due to C mixing ~~with those transferred~~ with C in other compartments or ~~from~~ external input.

According to Eqn (5), the change in ecosystem C transit time $\bar{\tau}_R$ can be attributed to the change in compartment C age (change in C age structure) and the change in respired C composition as (See Supplementary Information for details):

$$\Delta\bar{\tau}_R(t) = \sum_{i=1}^{d} a_i(t) \Delta\left(f_{\mathrm{hr},i}(t)\right) + \sum_{i=1}^{d} f_{\mathrm{hr},i}(t)\, \Delta\left(a_i(t)\right) + \mathrm{o}(a_i(t), f_{\mathrm{hr},i}(t)) \tag{6}$$

The first term in Eqn (6) refers to C transit time change due to change in respired C composition. If the fraction of respired C from fast-turnover pool decreases, the ecosystem mean C transit time may increase because more respired C comes from slow-turnover pools with older C ages. The second term refers to C transit time change due to change in compartment C age structure. Under elevated CO_2, for example, ~~If more~~ young-age C enters ~~influx into~~ a compartment ~~is~~ more than ~~the C efflux~~it leaves. ~~,~~ ~~aseg.~~ ~~under elevated CO_2,~~ C ~~age structure~~ in the compartment ~~will become~~ becomes younger (i.e., young-age C replenishment). Subsequently, ecosystem mean C transit time will reduce. The third term refers to residuals that cannot be explained by the previous two terms.

3. Results

3.1 Global steady-state patterns of ecosystem C transit time

The global ecosystem C transit time at steady state ~~estimated by Rasmussen method~~ generally shows a latitudinal variation pattern (Fig. 1). The high values (greater than 70 years) are simulated not only in high latitude regions, such as northern Russia, northern Europe, and northern Canada but also in high altitude regions such as Tibet plateau. Small values in C transit time (less than 30 years) are simulated in tropical rainforest, such as Amazon forest, Conga forest, and Indonesia forest. Ecosystem C transit times in some grass lands in middle-south Africa, south America, Southern Great Plains of US, and central north Australia (savanna) sometime are even smaller than that in tropical forest. The spatial patterns of the ecosystem C mean age are quite similar with the patterns of C transit time. However, the magnitude is significantly higher than ecosystem C transit time. The ecosystem C mean age ranges from 118 years to 7952 years, whereas ecosystem C transit time ranges only from 13 years to 341 years.

The global latitudinal pattern of C transit time ~~estimated from Rasmussen method~~ in 1982-2005 is consistent with the observation-based pattern of turnover time (Fig. 2). The latter is estimated at each grid cell globally by ~~Olson~~ "stock-over-flux" method to divide ecosystem C storage by gross primary productivity (GPP) (Carvalhais et al., 2014). The magnitude of the estimate is mostly within the uncertainty range of the observation-based pattern. We compare~~d~~ estimated C transit time in 1982-2005 with the turnover time, partly to match modelled values with contemporary observations, ~~which is based on~~and partly due to the fact that terrestrial C cycle is still approximately at a quasi-steady state between 1982 and 2005. Over the 1980s and 1990s, the annual average of global net land carbon sink estimated from Global Carbon Project (GCP) is about 0.8 GtC yr^{-1} with an uncertainty of 0.6 GtC yr^{-1}. As a reference, the annual average of net land carbon sink in recent decade (2007-2016) is 2.3 GtC yr^{-1} with an uncertainty of 0.7 GtC yr^{-1} (Le Quere et al., 2018). The net change of global land carbon in 1980s and 1990s is not that significant, which indicates land C cycle has not moved away too far from the steady state. Moreover, the simulated latitudinal pattern of C transit time almost overlaps with C turnover time, which also evident that C cycle is still near the steady state at present -day. Annual C turnover time ~~using Olson method~~ theoretically equals to C transit time ~~from Rasmussen method~~ when C cycle is close to the steady state (Sierra et al., 2016).

3.2 Responses of global C mean transit time to climate change

In 200-year simulation, global ecosystem C mean transit time increases~~d~~ by 11.8 years in response to climate warming (S1) and decrease by 5.6 years in response to rising atmospheric [CO_2] (S2) (Fig. 3a). When climate warming and rising atmospheric [CO_2] force~~d~~ together (S3), C transit time decreases~~d~~ by 1.6 years. The increase in C transit time in S1 is not significant in the 20th century but substantial in the 21st century. Oppositely, the decrease in C transit time in S2 is steady before 2060 but slow down afterward. Mean C transit time in S3 decreases but with a smaller magnitude than that for S2 in the 21st century.

Across all the three scenarios, the ~~most ~~majority (over 93.4%) ~~of the ~~changes in C transit time can be explained by ~~the ~~two combined changes in compartment C age structure and respired C composition. Changes in the compartment C age structure and the respired C composition both significantly contribute~~d~~ to the total change in global C transit time. However, the contribution fraction ~~varied ~~vary among the three scenarios at different time. In climate warming scenario (S1), respired C composition changes contribute about 70% of the increase in C transit time in the 21st century (Fig. 3b). In the rising atmospheric [CO_2] scenario (S2), respired C composition change and C age structure change contribute equally (Fig. 3c). When coupling climate warming and rising atmospheric [CO_2] together in S3, respired C composition change significantly contributes only in the middle of 200-year simulation (around year 2000), but little at the end of the 21st century. The contribution of C age structure change to the change in C transit time gradually increases.

The increase in C transit time in climate warming scenario (S1) is the most significant from low latitude regions in ~~south~~South America and Africa (Fig. 4a). Respired C composition change explains most of these regional changes (Fig. 4c). The decrease in C transit time in rising atmospheric [CO2] scenario (S2) is evenly simulated all over the world (Fig. 4d). Respired C composition change also plays an important role in most regions except for ~~north~~North Africa with little vegetation coverage. The C transit time in combined climate warming and rising atmospheric [CO_2] scenario (S3) mostly decrease in northern hemisphere, but increase in some tropical grassland regions in South America and Africa (Fig. 4g). In those regions where C transit time decrease, compartment C age structure change due to fresh C replenishment explain most of the change in C transit time.

~~It should be n~~Note~~d~~ that the response under combined effects (S3) is not a sum of those~~at~~ from individual effects (S1 plus S2). The non-additive response to climate warming and rising atmospheric [CO_2] is probably due to ~~non-linear interactive effects~~their interactions, which have been commonly found ~~and widely studied ~~in many ~~other ~~ecological ~~research~~studies (Norby and Luo, 2004; Luo et al., 2008; Leuzinger et al., 2011; Campbell et al., 1997; Zhang et al., 2016).

3.3 Global C turnover time and its bias

Similar to the changes in C transit time~~ estimated by Rasmussen method~~, the global C turnover time ~~estimated by Olson method~~ increases with climate warming and decreases with rising atmospheric [CO_2] (Fig. 5a). However, the magnitude substantially differs between these two methods (Fig. 3a, 5a). In response to climate warming (S1), global ecosystem C turnover time increases by only 2.4 year at end of the simulation, which is only one-fifth of the increase in C transit time (11.8 year). In response to rising atmospheric [CO_2] (S2), global C turnover time decreases by 3.7 year, whereas C transit time decreases by 5.6 year. In response to the coupled scenario (S3) where climate warming and rising atmospheric [CO_2] force together, global ecosystem C turnover time decreases by 4.5 year, while C transit time decreases by only 1.6 year.

In 1901, the global C turnover time is about 0.5 year longer than the C transit time (Fig. 3a, Fig. 5a). Theoretically, C turnover time equals transit time when land C cycle is at steady state. The offset at the initial state of simulations probably results from C seasonal cycles, which is not at steady state. The underestimates of the change in C turnover time relative to C transit time increases in climate warming scenario (S1) by up to 9.4 years in the end of the 21st century, which is 79.6% of the total increase in C transit time (Fig. 5b). In rising atmospheric [CO_2] scenario (S2), the bias constantly grows to about 1.9 years, a 27.7% of the underestimated decrease in C turnover time. In climate warming and rising atmospheric [CO_2] scenario (S3), the change in C turnover time is overestimated by 2.9 years or 181.1% in relative to the change in C transit time in 2100 (Fig. 5b, 5c).

3.4 Latitudinal variation in C turnover time and its bias

Latitudinal patterns in C transit time and C turnover time at the initial state in 1900 are nearly the same. Steady state estimates are both from 20 years in low latitude to 100 years in high latitude (Fig. 6a, 6d). However, significant bias still exists in high latitudes (north of 60ºN and south of 50ºS) (Fig. 6g), because seasonal soil frozen-thaw processes in this region lead~~s~~ to the strong seasonal cycle of the soil decomposition~~,~~ ~~which severely~~and violate~~s~~ the steady state assumption of the C turnover time. The underestimates of C turnover time can be up to 10 years in ~~permafrost~~ high latitude regions, which is about 8% of C transit time. In other area, bias of turnover time is less than 0.5 years.

Changes in C turnover time and C transit time deviate in different regions in response to climate warming (S1) (Fig. 6b, 6c, 6e, 6f). In temperate and tropical regions, C transit time significantly increases, while C turnover time also increases but in a much smaller magnitude. In tropics, C transit time increases by 13 years in 2100, up to 60% of the initial value in 1900, whereas C turnover time increase by only 2 years. In the ~~permafrost~~ high latitude region, C transit time slightly decreases (Fig. 6b and c) but C turnover time significantly decreases by several decades in the high latitude (Fig. 6f). In some regions between 40ºN and 60ºN, C transit time increases but turnover time decreases in response to climate warming. C turnover time overall changes less than C transit time in the S1 scenario. Warming-induced changes in C turnover time is underestimated by 5% at the high latitude of the southern hemisphere to 50% at the low latitude (Fig. 6h), which range from 2 to 29 years (Fig. 6i).

In response to rising atmospheric [CO_2] (S2), both C turnover time and transit time decrease. The magnitude of changes for both of them are generally greater at the mid latitudes than those at either low or high latitudes (Fig. 6b, 6e). At most latitudes, C turnover time decreases less than C transit time, leading to the positive bias (Fig. 6h and 6i). The deviation of the change is higher in the low than high latitude. In response to rising atmospheric [CO_2], the underestimate of the decrease in C turnover time is by at most 2 years in absolute bias or 10% in relative bias (Fig. 6h, 6i).

In climate warming and rising atmospheric [CO_2] scenario (S3), C turnover time and C transit time decrease at most of the latitudinal regions except for some tropic areas (Fig. 6b, 6c, 6e, 6f). The decrease in C turnover time is more than that in C transit time (Fig. 6h, 6i). Especially in high latitudes ~~where covered by permafrost soil~~, the difference in changes is much more significant. C turnover time is reduced by up to three decades (Fig. 6f) or 35% (Fig. 6e), whereas C transit time shows nearly no relative changes in those. Bias in these areas can be up to 27 years (Fig. 6i).

4. Discussion

4.1 C transit time and its two components

Changes in C transit time can be explained by its two components: the respired C composition and compartment C age structure. The first component is to account for different contributions of respired C from different pools to total ecosystem C loss. Previous studies have demonstrated that pathways of ~~ecosystem~~ respiring C from multiple compartments are ~~vary~~variably ~~with~~ controlled by global change factor (Luo et al., 2001). Results from this study provide more spatial details about where C transit time change due to respired C composition change. For example, over 80% of the increase in C transit time under warming is explained by respired C composition change in the South America grassland region (Fig. 4a). In contrast, change in respired C composition only accounts for approximately 10% of the increase in C transit time under warming in the boreal and ~~permafrost~~ high latitude region of North America.

The second component is the C age structure, primarily from change in C mean age of individual pool modified by relative fraction of each pool. In coupled climate warming with rising atmospheric [CO_2] scenario (S3), C age structure change primarily contributes to the C transit time response in most global regions in 2100 (Fig. 4h). In this scenario, ecosystem mean C transit time decreases by 1.6 years. The decrease in C transit time results from increased young-age C uptake with rising atmospheric [CO_2], which is more than the increased young-age C loss with warming. A previous study has also shown that models with multiple pools usually have a more heterogeneous C age structure and thus can store extremely older C than a single pool model (Manzoni et al., 2009).

4.2 Bias arising from estimated C turnover time

C turnover time ~~estimated by stock-over-flux (i.e., Olson method)~~ has been widely used to quantify ecosystem C cycle partly because both ecosystem C storage and C flux can be easily measured (Sanderman et al., 2003; Chen et al., 2013; Carvalhais et al., 2014; McCulley et al., 2004; Raich and Schlesinger, 1992; Yan et al., 2017). The C turnover time ~~estimated by Olson method~~ has been theoretically shown to equal C transit time ~~estimated by Rasmussen method~~ at steady state but they deviate under non-steady states (Sierra et al., 2016). This study illustrates how much deviation occurs between C transit time and C turnover time in response to three scenarios of climate change. Our results show that even at initial steady state, global ecosystem C turnover time is slightly greater than C transit time by 3%. This is because the steady state reached by spin-up does not mean the terrestrial C cycle system is completely at equilibrium. Seasonal variations of ecosystem C uptake and turnover still lead to periodical oscillation of the terrestrial C cycle.

The deviation between C transit time and turnover time also indicates to what extend that turnover time can properly represent~~s~~ time characteristics in C cycle. In climate warming and rising atmospheric [CO_2] scenario (S3), the deviation ~~of global average~~ does not increase significantly until 2050. The modeled latitudinal pattern of present-day C transit time~~-~~ well matches the C turnover time ~~by both~~estimated from~~ model and~~ observations (Carvalhais et al., 2014)~~ very well~~. ~~These results provide credit to~~ It indicates that the ~~present-day~~ stock-over-flux estimates are still useful at present day. However, ~~more importantly,~~ the ~~increasing~~ deviation between C transit time and turnover time remarkably increases after 2050 ~~in~~ (Fig 5b). Then, it requires caution when we ~~also warns us that~~use the C turnover time for estimating C sequestration in multiple compartmental ecosystems~~will be remarkably overestimated in the very near future~~.

In transient state, the changes in C transit time and C turnover time differ the most in climate warming scenario (S1). Tropical and ~~permafrost~~ high latitude regions contribute the most of the deviation (Fig. 6h, 6i). In tropical and subtropical regions, C transit time increases by about 60% (Fig. 6b) while C turnover time increases by 20% or less (Fig. 6e). The great difference between changes in C transit time and turnover time is due to their different assumptions. In response to climate warming, composition change in respired C contributes most to the change in C transit time in tropical regions. However, ~~Olson method~~C turnover time assumes the whole ecosystem C as one homogenous pool, even if both plant and soil C can be extremely heterogeneous. This homogeneity assumption ignores the composition changes in respired C, which causes up to 80% of change in C transit time.

In ~~permafrost~~ high latitude regions, C transit time slightly decreases by up to 10%, whereas C turnover time considerably decreases by over 30% in response to climate warming. Warming significantly increases soil respiration due to permafrost thaw, whereas the change in permafrost ecosystem C pool size is relatively small. Thus, C turnover time ~~estimated by Olson method~~ significantly decreases. C transit time slowly responds to climate warming because the young-age C input added to permafrost ecosystem is relatively small compared to large C storage in this area and C age structure does not change much. These big deviations between C turnover time and C transit time in tropical and permafrost regions suggest that future C cycle analysis based on turnover time likely leads to strong biases as it does not represent transient C dynamics in multi-pool ecosystems.

4.3 C transit time versus turnover time under other global change scenarios

This study has illustrated how C transit time and turnover time deviate under climate warming and rising atmospheric [CO_2] scenarios. Those deviations may become even bigger under other global change scenarios. For example, land use change and fire can drive ecosystems out of steady state to be at disequilibrium (Luo and Weng, 2011). Clearcut of forest or forest fire removes at least the aboveground wood C pools and thus greatly changes both the total C stock and NPP, leading to a large change in C turnover time (Wang et al., 1999; Zhou and Luo, 2008). Clearcut of forest or forest fire also changes age structure and composition of respired C from different pools within the ecosystem, resulting in change in C transit time. Such a disturbance usually drives ecosystem to a stronger degree of disequilibrium than climate change does~~,~~ . ~~the~~ The deviation between turnover time and transit time should be bigger under a severe disturbance than climate change~~.~~ , ~~It is consistent with~~ since our results have indicated that C transit time and turnover time deviates more significantly when an ecosystem is further away from equilibrium (Fig. 5).

~~Meanwhile, i~~In contrast to the static vegetation distribution used in CABLE, natural vegetation distribution may change ~~substantially~~over time in the real ~~-~~world. C transit time and turnover time may further deviate under natural vegetation ~~distribution change~~dynamics. However, whether forest will expand or dieback in a future warming world is still quite unknown. Previous studies variously conclude due to their focus~~ing~~ on different areas with different methods ~~conclude variously~~ (Masek, 2001; Soja et al., 2007; Cox et al., 2004; Cox et al., 2013). Nevertheless, most bioclimatic models consistently suggest temperate and boreal biomes rapidly ~~could~~ increase ~~rapidly~~ in area under warming (Kirilenko and Solomon, 1998). If the forest species, which stores more C in slow-turnover tissue, takes over the grass species, which stores more C in fast-turnover tissue, the expansion of forest may increase C transit time significantly. However, C turnover time by lumping all different C compartments together may underestimate such changes.

In the real world, land C cycle is always at dynamic disequilibrium due to cyclic environmental conditions (e.g., diurnal, seasonal, and interannual variability), directional global change (e.g., climate warming, rising atmospheric CO2 concentration, altered precipitation, and nitrogen deposition), recursive disturbance-recovery cycles, shifted climatic and disturbance regimes, and vegetation changes (Luo and Weng, 2011). Thus, the estimated C turnover time ~~by Olson method~~ is expected to differ from the C transit time ~~by Rasmussen method~~ at any time point and at any spatial location. The degree of deviation between C turnover time and transit time may vary.

In addition to various agents to cause ecosystem to be at disequilibrium, deviation between estimated C transit time and turnover time ~~is~~ also depends on~~ent~~ model structure. Vertically resolved soil C models, for example, includes vertical C mixing and depth-dependent C decomposition rates (Koven et al., 2013; Huang et al., 2018). Representation of vertically resolved processes likely increase soil heterogeneity. When warming induces deep soil thaw and increases deep soil decomposition, the fraction of respired C from deep layer with old-age C increases. The C transit time ~~estimated by Rasmussen method~~ together with a vertically resolved model may substantially increase whereas C turnover time, which implicitly assumes ecosystem as one homogeneous pool, may not respond much.

4.4 Estimation of C transit time in the real world

Previous studies have argued that C transit time is conceptually sounder than C turnover time (Rasmussen et al., 2016; Sierra et al., 2016). In this study, we have shown that the C turnover time can substantially deviate from the transit time in response to climate change and other environmental change. However, C turnover time can be easily calculated from C stock over flux, both of which can be easily measured. In contrast, C transit time cannot be easily estimated from field measurements. Equation (5) indicates that we need data from measurement of C mean ages (a_i) and fractional composition of respired C ($f_{hr,i}$) in individual C pools in order to calculate ecosystem mean C transit time ($\bar{\tau}_R$). Neither a_i nor $f_{hr,i}$ can be easily measured in field. Thus, our research community faces a tremendous challenge to estimate a conceptually sound and scientifically important parameter.

In the past, radiocarbon ^{14}C has been used to quantify C mean ages of various litter and soil pools (Gaudinski et al., 2000). Measured soil respiration in response to elevated CO_2 treatment in Duke Forest has been decomposed to various fractional composition using a deconvolution method or inverse analysis (Luo et al., 2001). It appears that estimation of C transit time in the real-world ecosystems requires measurement of isotope signatures in different litter and soil fractions together with measurement of respiration from soil surface and soil components. Those measurements, together with many other data sets, may need to be analyzed to estimate C mean ages, fractional composition of respired C in individual C pools, and then ecosystem mean C transit time ($\bar{\tau}_R$) using some innovative ways, such as data assimilation.

~~By e~~Estimating C transit times in the real world can help constrain projections in land C sequestration by ~~, different terrestrial land~~ C cycle models because C turnover time is a major source of ~~are able to be constrained by these diagnostics~~model uncertainty ~~. Especially, uncertainties in C cycle time characteristics are the major reason to hinder precise future prediction in land C sequestration~~ (Friend et al., 2014; He et al., 2016)~~. In the transient state, the response in C cycle time characteristics are usually extraordinarily complicated. Since this~~Our study has ~~provided insights~~shown that ~~to separate~~ the change in C transit time can be separated into two components, C composition change and C age change. ~~, a more thorough model a~~Assessment on the two~~individual~~ components would provide additional ~~critical model~~ constraints on model projections. To further constrain C transit time ~~in~~through its two components with observation, modelled C cycle and land C sequestration can be significantly improved~~ based on this separation method~~.

5. Conclusions

This study explores how global ecosystem C transit time deviates ~~with~~ from the turnover time under climate warming and rising atmospheric [CO_2]. Although both global ecosystem C transit time and turnover time increase in response to climate warming and decrease in response to rising atmospheric [CO_2], their deviations increase with time in all the three climate change scenarios. In 2100, the deviations are high in tropical regions under climate warming scenario (S1) and rising atmospheric [CO_2] scenario (S2), and in ~~permafrost~~ high latitude regions under S1 and combined change scenario (S3). Knowledge about the deviation between C transit time and turnover time in different regions under different scenarios (warming and [CO_2] rising) is useful for us to understand time characteristic of the ecosystem carbon dynamics. When we lump all pools and fluxes together to calculate turnover time by "stock over flux", the time characteristic is different from that of transit time when individual pools and fluxes are considered ~~to be~~within a networked ~~together to form~~ compartmental ~~dynamical~~ system. Thus, ~~in practice,~~ our results ~~from S3~~ provide information on how ~~future~~ turnover time in the future could deviates from transit time in specific regions and natural ecosystems under different climate change scenarios. ~~In addition, our results from S1 and S2 are special cases that help us identify what climate change factors are critically contributed to the biases in specific regions, so that we gain further insights on the cause of the biases.~~

The changes in C transit time results from both the C age structure changes and composition changes in respired C in multi-pool ecosystems. The C age structure changes mainly depend on young-age C replenishment from external C input. The composition change is due to differential responses of various C pools to climate warming and rising atmospheric [CO_2]. However, C turnover time assumes ecosystem as one homogeneous pool, and it does not account for changes in age structure and contribution fractions of different pools to ecosystem respiration. Thus, C transit time is a better parameter than C turnover time to characterize C cycle in multi-pool ecosystems, especially when they are at transient states.

However, C transit time cannot be easily measured because it requires information of the C age structure and composition of respired C. Both of them are usually not measurable in field studies. Radiocarbon ^{14}C measurement in the field has the potential to offer information on mean C ages in various pools. It is not easy, either, to estimate contribution fractions of different pools from measured ecosystem or soil respiration to respired C. We may have to combine compartment models with different types of measurements via data assimilation techniques to estimate both age structure and composition of respired C before we can estimate ecosystem C transit time.

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Table 1 Summary of scenarios and forcing data.

Scenario name	Simulation abbreviation	Climate forcing	CO_2 data
Climate warming scenario	S1	Climate warming[#]	Pre-industrial[**]
CO_2 direct effect scenario	S2	Pre-industrial[##]	CO_2 increase[*]
Full effect scenario	S3	Climate warming[#]	CO_2 increase[*]

[#] Climate warming forcing data from 1901 to 2005 uses CRU-NCEP dataset. The forcing data from 2006 to 2100 uses CESM output under Representative Concentration Pathways with radiative forcing increased by 8.5 W m^{-2} (RCP8.5).

[##] Pre-industrial climate forcing repeatedly uses one-year climatology data averaged over 1901 to 1910 from CRU-NCEP dataset.

[*] CO_2 concentration data are from 200-year CMIP5 dataset under historical and future scenario (RCP8.5).

[**] Pre-industrial CO_2 concentration is from CMIP5 dataset for the year 1901.

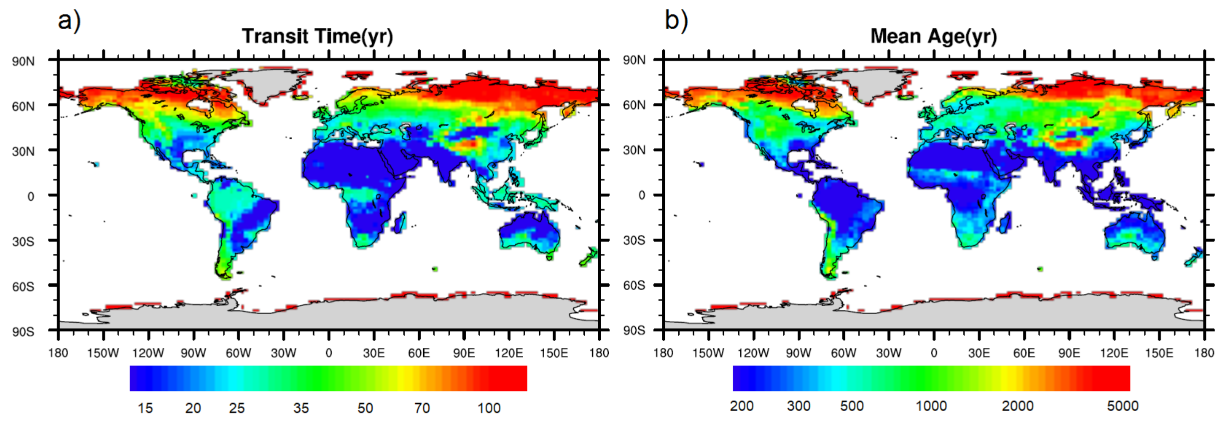

Figure 1 Global maps of a) carbon transit time and b) carbon mean age are the average over 1901 to 1910 at each grid cell ~~estimated by Rasmussen method~~.

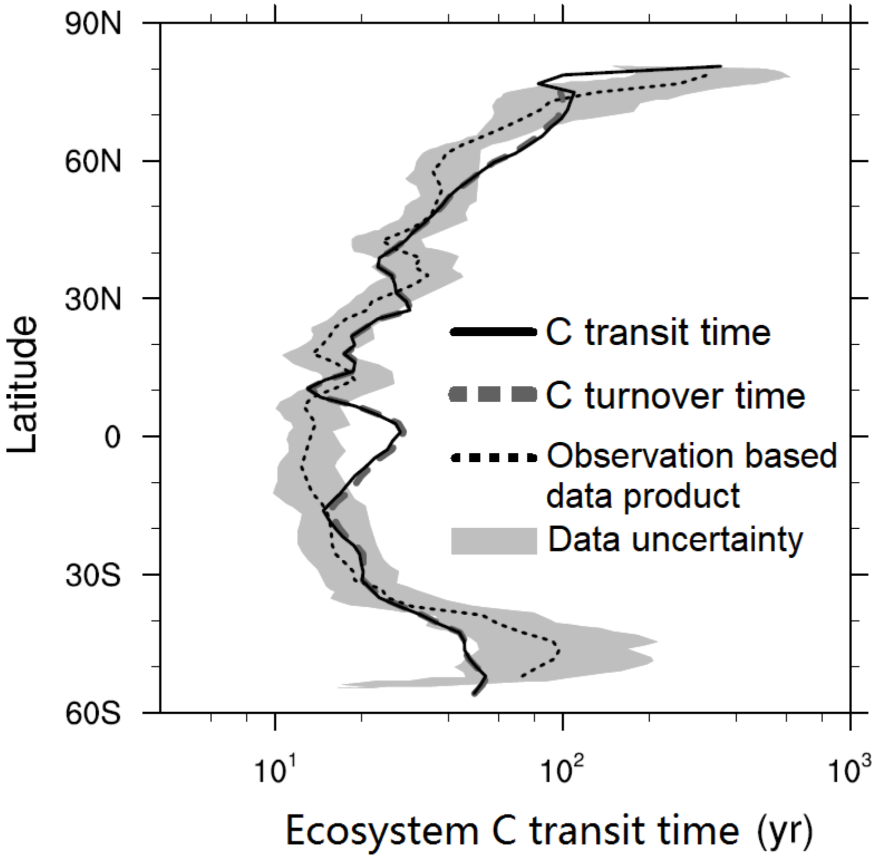

Figure 2 Validation of simulated latitudinal variation pattern in ecosystem C transit time. Comparison of the ecosystem C mean transit time from 1982 to 2005 as estimated in this study with the estimates from observation (Carvalhais et al., 2014) and simulated C turnover time from CABLE. Grey area indicates the uncertainty range of observation-based data. Our assumption, which is also used by some other ecological studies (Trumbore, 2000), is that present-day ecosystem C cycle is closed to the steady state.~~(Trumbore, 2000)~~ Especially, in 1980s and 1990s, global land C uptake from Global Carbon Project (GCP) is about 0.8 GtC yr^{-1} with an uncertainty of 0.6 GtC yr^{-1}, which is not significant compared to current decade with global land C uptake is 2.7 GtC yr^{-1}. (Le Quere et al., 2018)

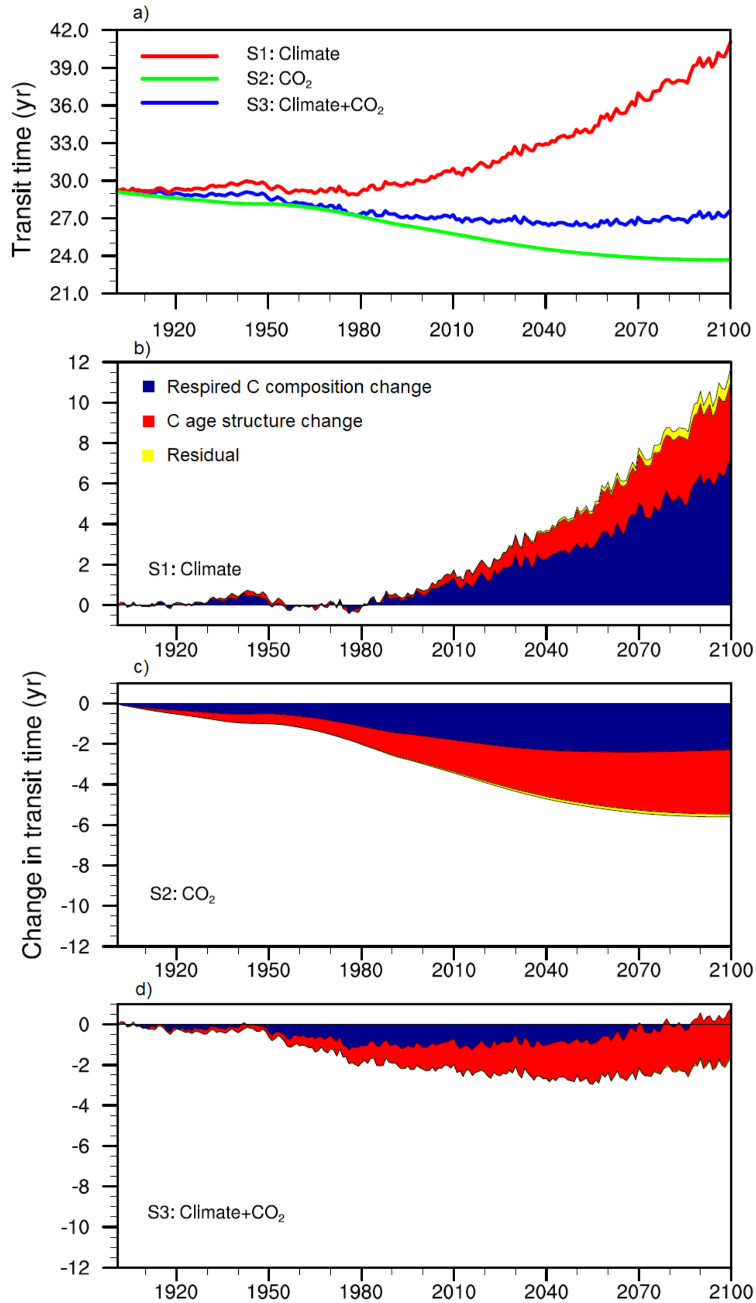

Figure 3 CABLE ~~simulated~~ simulates changes of global C transit time ~~using Rasmussen method~~ for each of the three scenarios in a): S1: climate warming scenario (red line); S2: rising atmospheric [CO_2] scenario (green line), and S3: Combining climate warming and rising atmospheric [CO_2] scenario (blue line). The changes in global ecosystem C transit time ~~were~~ are separated into three contributions based on Equation (6): contribution from respired C composition change, contribution from C age structure change and residual (b-d).

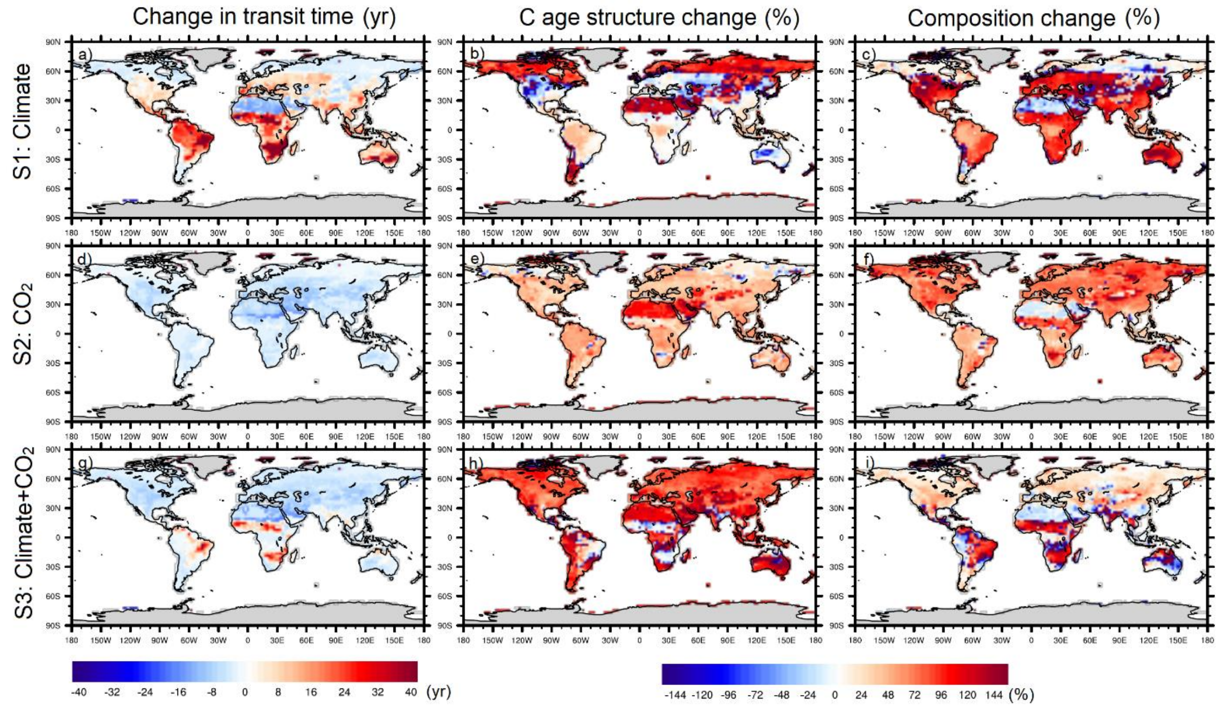

Figure 4 Global map of the change in C transit time in three scenarios, a) S1: climate warming scenario; d) S2: rising atmospheric [CO_2] scenario, and g) S3: Combination of climate warming and rising atmospheric [CO_2] scenario. In these three scenarios, contribution from C age structure change and contribution from respired C composition change are also estimated in relative to the change in C transit time (S1: b) and c); S2: e) and f); S3: h) and i)). The calculation of contribution from C age structure change and contribution from respired C contribution change are based on Equation (6). The positive contribution indicates the C age structure change or composition change leads to C transit time change towards the same direction.

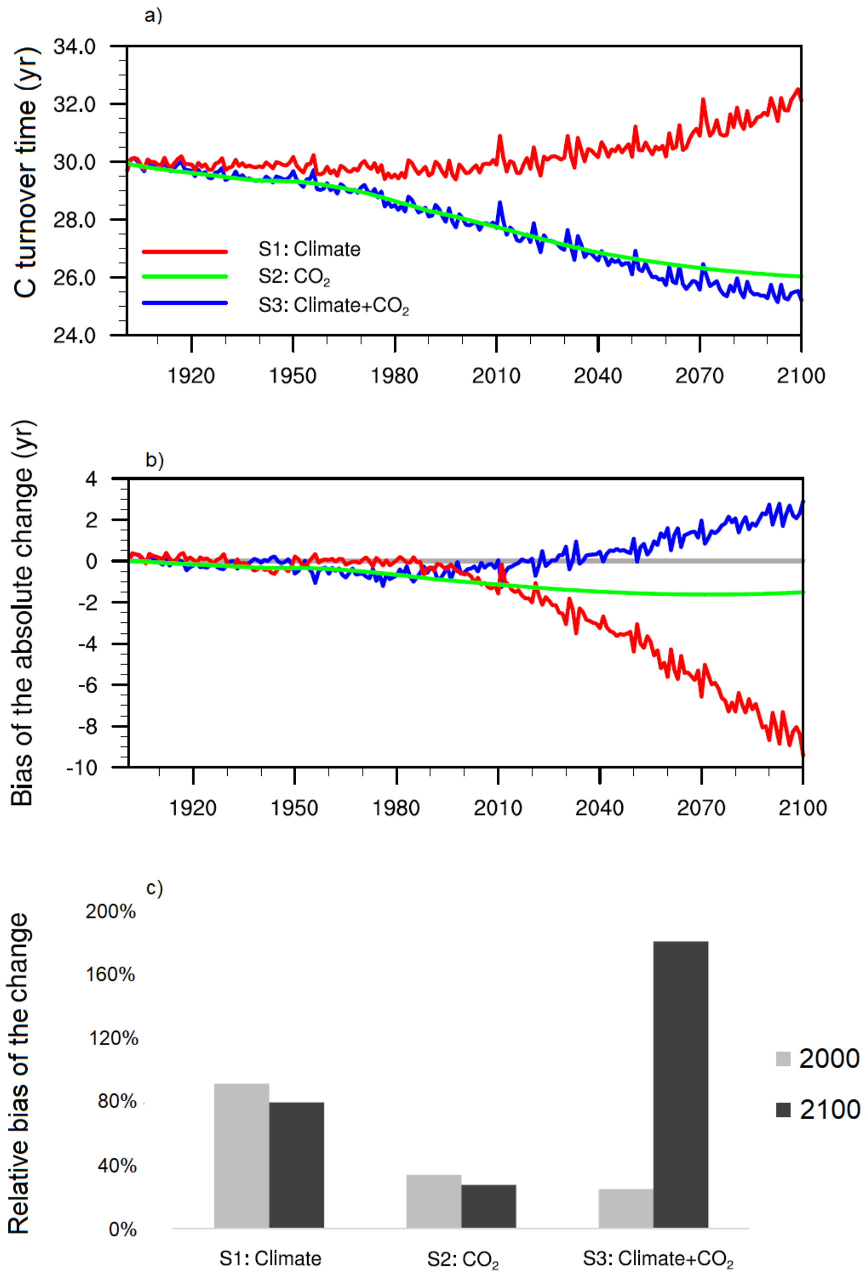

Figure 5 a) Changes of global ~~Olson~~ C turnover time (stock-over-flux) in three scenarios, S1: climate warming scenario (red line); S2: rising atmospheric [CO_2] scenario (green line), and S3: Combination of climate warming and rising atmospheric [CO_2] scenario (blue line). b) The bias of the change in C turnover time ($\Delta\tau_o$) ~~was~~ is estimated relative to the change in ~~Rasmussen~~ C transit time ($\Delta\tau_R$): ($|\Delta\tau_o| - |\Delta\tau_R|$). Positive indicates more change in C turnover time than C transit time. Grey line represents the reference of no bias. c) The relative bias of the change in C turnover time in year 2000 and 2100 ~~was~~ is also estimated relative to the change in C transit time: $\frac{(|\Delta\tau_o|-|\Delta\tau_R|)}{|\Delta\tau_R|} \times 100\%$.

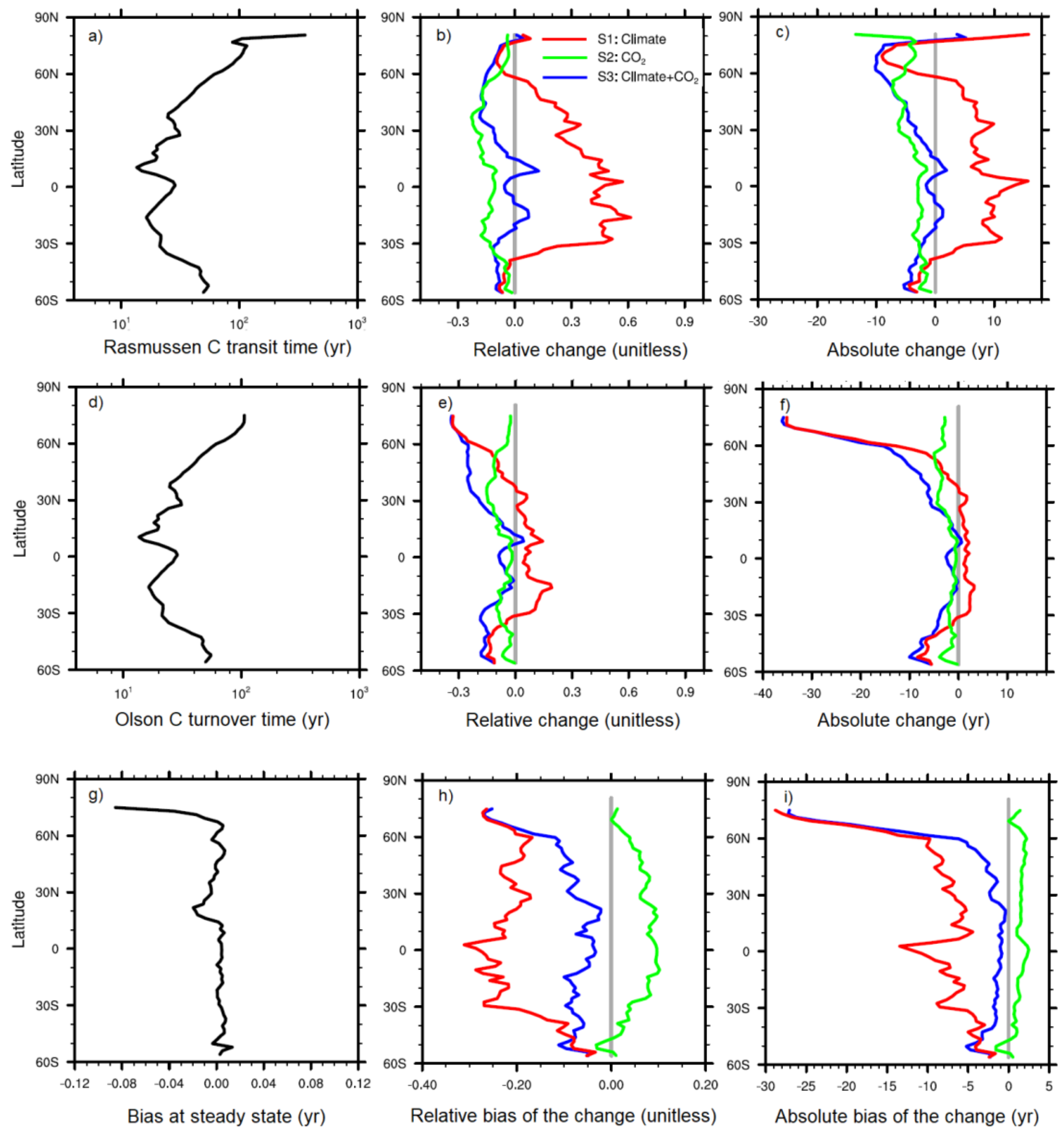

Figure 6 a) Latitudinal variation in ~~Rasmussen~~ C transit time (τ_R) at steady state and b)-c) its change are compared to d)-f) ~~Olson~~ C turnover time (τ_o). The changes between 2090s and 1900s are estimated by c), f) absolute value: $\Delta\tau = (\tau_{2090s} - \tau_{1900s})$ and by b), e) relative value: $\Delta\tau_r = \frac{\Delta\tau}{\tau_{1900s}}$. g) The bias of C turnover time in relative to C transit time is estimated by $(\tau_o - \tau_R)$ at steady state. In relative to C transit time, the bias of the change in C turnover time are estimated by h) absolute bias $(|\Delta\tau_o| - |\Delta\tau_R|)$ and i) relative bias in $\frac{(|\Delta\tau_o| - |\Delta\tau_R|)}{|\Delta\tau_R|}$. All variables are compared in three scenarios: S1: only climate warming scenario (red line); S2: rising atmospheric [CO_2] scenario (green line), and S3: Combination of climate warming and rising atmospheric [CO_2] scenario (blue line). Grey lines in b), c), e) and f) represent the reference lines of no change and those in h) and i) represent reference line of no bias.