Dear Dr. Arndt,

We would like to thank the two reviewers for their careful and constructive comments for improving our manuscript. In the following, we address all comments and questions from the reviewers. The marked-up manuscript showing the changes made is attached at the end of the response.

Thanks,
Yilin Fang

Response to the Reviewer1's Comments

We thank the reviewer for the constructive comments on our initially submitted manuscript. In the following, we provided clarifications to each comment and question from the reviewer. The comments by the reviewer are given in blue, our responses are in black.

Review of "Accelerating the spin-up of the coupled carbon and nitrogen cycle model in CLM4" for Geoscientific Model Development (GMD).
General Comments
The manuscript reviews challenges for spinning up global biogeochemical models, such as those coupled into Earth System Models (ESMs), in particular the Community Land Model 4 with Carbon-Nitrogen (CLM4CN). These models are typically initialized arbitrarily and then run to equilibrium as a surrogate for pre-industrial conditions. Because the equilibrium is dynamic (with repeated cycles of some representation of historical atmospheric forcing) and because of the nonlinear nature of the governing equations (in particular, the coupling between the carbon and nitrogen cycles in CLM4CN), an analytical solution to the spinup is difficult to achieve, and spinup simulations can be expensive, comprising the majority of the time required for generating results for a climate scenario with a particular model configuration. CLM4CN spinup has been addressed in previous manuscripts, as noted by the authors, but current methods leave room for improvement.
The authors investigate a Gradient Projection method for accelerating the spinup by extrapolating the change in slowly changing state variables over the course of one or more cycles of atmospheric forcing. They find that this approach can be used successfully to enhance the computational efficiency of spinup compared to previous approaches, especially when a strict criterion for "equilibrium" is used. As found by previous authors cited in the manuscript (e.g., Koven et al. 2013), the method works well, as CLM4 involves the coupling of processes ranging in timescale by many orders of magnitude: i.e., 30-min biogeophysical processes vs. accumulation of soil carbon pools with turnover times of hundreds of years. The authors also identify the non-convergence of CLM4CN under some conditions due to both representation of oscillatory physical processes (such as fire) and spurious numerical oscillation (due to the discretization and solution of the equations for soil moisture diffusion and interaction with groundwater). The authors are able to eliminate these oscillations when turning off the fire model or replacing the subsurface hydrology with a variably-saturated flow model with apparently better numerical properties.
As the manuscript addresses a challenge to climate modelers and presents clear and useful methods and results, I recommend it for publication in GMD. I would only recommend minor

revisions in presentation to enhance readability and make the context clear to readers. The manuscript is currently well within the typical length of a GMD article, and some expanded explanation in some sections would improve the manuscript. Suggestions for doing so along with minor points of clarification are detailed below.

We thank the reviewer for the positive feedback.

Specific Comments

Introduction

1. Equations 1 & 2: as I understand it, I think these equations are missing factors for the fraction of carbon not respired to the atmosphere as they are transferred from faster to slower pools. Presumably this omission is only a problem for the presentation of these equations, as the actual numerical rate of change of carbon pools calculated from the model was apparently used later.

We thank the reviewer for the comment. Eqs (1) and (2) include the heterotrophic respiration fraction and the fraction of carbon that's not respired to the atmosphere. These two fractions add up to 1. When Figure 1 was presented, we added "Note that heterotrophic respiration fractions are not shown." We also added "The first term on the right hand side of Eqs. (1) and (2) includes heterotrophic respiration." after the equations in the revised manuscript.

2. The last paragraph of the introduction moves abruptly from the current problems with spinup to a brief mention of the new approach. I would here include some additional introduction about numerical methods for improving spinup, in particular the "Gradient Projection" approach used here: what problems is it applicable to, and are there similar applications in which it has been successfully applied previously?

We added the following in the revised manuscript:

In implicit time integration approaches, based on knowledge about the trajectory of the solution of the initial value problem, linear extrapolation from time integration was often used to find a good initial value for iterative multirate multidisciplinary processes [*Birken et al.*, 2014 and references therein]. A number of explicit Euler steps with small time steps followed by explicit Euler step with large time steps when the change in components due to fast processes become negligible has been shown to efficiently solve stiff ordinary differential equations [*Eriksson et al.*, 2003; *Gear and Kevrekidis*, 2003]. We made use of those concepts, referred to as the Gradient Projection approach in this study, to further improve the spinup.

Birken P., Gleim T., Kuhl D., and Meister A. (2014), Fast Solvers for Unsteady Thermal Fluid Structure Interaction, arXiv:1407.0893v1.

Eriksson, K., C. Johnson, and A. Logg (2003), Explicit time-stepping for stiff ODES, *Siam J Sci Comput*, *25*(4), 1142-1157, doi:Doi 10.1137/S1064827502409626.

Gear, C. W., and I. G. Kevrekidis (2003), Projective methods for stiff differential equations: Problems with gaps in their eigenvalue spectrum, *Siam J Sci Comput*, *24*(4), 1091-1106, doi:Pii S1064827501388157

Methods

3. p. 9113, l. 12: Expand "(carbon and nitrogen)" to include the bigeochemical processes, as provided for the list of biogeophysical processes. Some of this is included in the following text, but at least expand to "carbon and nitrogen cycling in vegetation and soils".

We replaced "(carbon and nitrogen)" with "(phenology, autotrophic respiration, heterotrophic respiration, carbon and nitrogen allocation, and nitrogen source/sink)".

4. p. 9114, l. 9-10: Please explain or cite the stability requirement noted. How was jp chosen?

We added the following in the revised manuscript:

Explicit or forward Euler method is used in CLM4-CN to solve the time-dependent ordinary differential equations with given arbitrary initial conditions. The explicit method can be numerically unstable (convergence of solution is not guaranteed) if the time step is too big [*LeVeque*, 2007]. For the first order kinetic type problem, i.e., $u'(t) = ku(t)$, the stability requirement is $|1 + kh| \leq 1$, in which k is the rate constant and h is the time step.

jp can be chosen as the time period needed to stabilize the components from fast processes after perturbation, or set as ~100 years.

LeVeque, R. J. (2007), *Finite Difference Methods for Ordinary and Partial Differential Equations: Steady-State and Time-Dependent Problems* Society for Industrial and Applied Mathematics, Philadelphia, PA.

5. p. 9116, l. 14-15: Please explain why mass conservation error occurs.

By moving water mass around after the Richards' equation is solved, Richards' equation at each node is no longer satisfied if its moisture deviates from its previous solution. We have confirmed the local mass conservation error of water in the original model of CLM4. We added the explanation in the revised manuscript.

6. Please add a sentence or two explaining and/or providing additional references for "using the integral finite difference approach and discretized temporally using first-order backward Euler differencing," for improved readability. ("Backward Euler differencing" is equivalent to an implicit-timestepping solution, right?) Please also mention or cite the theory for why this method is numerically stable and avoids the oscillations associated with the current CLM4 hydrology.

Yes, backward Euler differencing is equivalent to an implicit time stepping solution.

In STOMP, the water mass conservation equation equates the time rate of change of water mass within a control volume with the flux of water mass crossing the control volume surface. The mass conservation equation is discretized following the integrated finite difference approach of Patankar [1980], which is locally and globally mass conserving. Backward Euler differencing or implicit time stepping is suitable for the solution of the equation that is numerically unstable [*LeVeque*, 2007].

LeVeque, R. J. (2007), *Finite Difference Methods for Ordinary and Partial Differential Equations: Steady-State and Time-Dependent Problems* Society for Industrial and Applied Mathematics, Philadelphia, PA.

Patankar, S. V. (1980), *Numerical Heat Transfer and Fluid Flow* , Hemisphere Publishing Corporation, Washington, D.C.

The above sentences and reference have been added in the revised manuscript.

Results
7. p. 9117, l. 8: Do the authors have any explanation for why the results are wetter and cooler with the ostensibly improved numerical scheme?

We added the following explanation:
Using STOMP, mass conservation is improved, and the moisture content calculated is more accurate, resulting in a wetter and cooler soil.

8. p. 9117, l. 15: Please clarify that "the model" here means the Gradient Projection.

Yes, the model means the Gradient Projection. We made the clarification in the revised manuscript.

Conclusions
9. p. 9118, l. 3: The authors claim the results are "more accurate" with the new hydrology submodel, but this phrasing implies some improved comparison to observations. It seems the authors wish to argue that the better theoretical grounding or numerical properties of this model make it superior, and that the oscillations noted in the existing hydrology are not a correct behavior given the governing equations. If this is the case, this argument should be made in the Results or a Discussion section and referenced in the Conclusions.

We agree with the reviewer that the accuracy was improved because of a superior numerical scheme. It has been clarified in the revised manuscript. The argument is made in the Results section as suggested by the reviewer.

10. p. 9118, l. 4: Likewise, in noting that "more C [is] predicted," the tone implies that this is an advantage, but they do not reference observations to show that it is more realistic. In fact, CLM4CN does have too low soil carbon, but other factors besides the hydrology may also contribute to this bias, such as nominal turnover times shorter than observed (i.e., Koven et al 2013). Please rephrase so that it is clear that the prediction of more carbon is not suggested to be an advantage but merely a result, as there may be compensating errors in the model formulation.

The reviewer is right that the conclusion was based on comparison between two models, with no comparison to observations to suggest which solution is more accurate. Some discussion has been added in the revised manuscript.

11. The authors may have an opportunity here to comment in a Discussion section on the context of their procedure and future work. Is an equilibrium spinup approach appropriate? What

properties should this model satisfy ideally for such a procedure to be used (e.g., convergence to a unique solution independent of starting conditions or acceleration procedure)? Are there other methods that could be applied to improve spinup further that might require more significant modification of the model structure?

We added the following in the Conclusion section:

No matter what modification is made to improve the speedup efficiency, a final spinup is always needed to reach a converged solution due to disequilibrium caused by the modification. This approach is especially useful when new model formulation is proposed and high quality solution (small convergence threshold) is needed for a fair comparison.

Response to Dr. Luo and Manoj's Comments

We thank Dr. Luo and Manoj for their detailed and constructive comments on our original manuscript. In the following, we provided clarifications to each of their comments and questions. In this response, Dr. Luo and Manoj's comments are given in blue, our responses are in black.

The manuscript describes a method to accelerate the spin-up of biogeochemical models based on gradient projection method, which was applied to the slow turnover soil carbon pools in CLM4 model. The authors claimed that their method "can reduce the computation time by 20–69% compared to the fastest approach in the literature". They also showed that their method did not work in three specific sites and the cyclic instability of carbon cycle in two of the three sites was resolved after replacing hydrology scheme in CLM4 with STOMP.

The manuscript is well-written, easy to read, and falls within the scope of the journal. The method is straightforward and should, in principle, work for this monotonic carbon accumulation system during spin-up.

However, there are some areas that need further explanation.

1. Their claim that their method "can reduce the computation time by 20–69% compared to the fastest approach in the literature" is not well grounded. They only compared their method to the AD method. The latter is not the fastest approach in the literature. The semi-analytic method is probably the fastest one published in the literature, which the authors did not at least compare with.

We agree that the reduction in computation time using our method was compared only to the modified AD method. We had previously restructured CLM4-CN and developed a steady-state solution directly using annually averaged rate parameters [*Fang et al.*, 2013; *Fang et al*. 2014]. Using our approach, we were able to implement the semi-analytical method in Xia et al. [2012]. As we mentioned in the manuscript, the semi-analytical method needs initial spin-up values of net primary productivity (NPP), which still requires long simulation time for stabilization because CN are tightly coupled in CLM4-CN. Besides, a final spinup is needed after the analytical solution. Our numerical experiment showed that the semi-analytical method is not necessarily the fastest. We added the above discussion in the revised manuscript and reworded the "fastest" to "one of the fastest" to include the possibility of other existing schemes that are faster.

Fang, Y., M. Huang, C. Liu, H. Li, and R. Leung (2013), A generic biogeochemical module for Earth system models: Next Generation BioGeoChemical Module (NGBGC), version 1.0, *Geoscientific Model Development*(6), 1977-1988.

Fang, Y., C. Liu, M. Huang, H. Li, and R. Leung (2014), Steady state estimation of soil organic carbon using satellite-derived canopy leaf area index, Journal of Advances in Modeling Earth Systems.
DOI: 10.1002/2014MS000331

2. The oscillation at US-IB1 and periodicity at US-SO2 are due to fast turnover (short residence time), with which total soil C dynamics are mainly determined by external forcing. The pool sizes (total amount of soil carbon content) is only at scales of 2-5 kgC m-2 at the two sites. NPP at those two sites is probably around 1 kgC m-2, leading to residence times of 2-5 years. When residence time is short, the soil C varies with environmental forcing (see the second paragraph on page 6 of Yiqi Luo, Trevor F. Keenan, Matthew Smith. 2014. Predictability of the terrestrial carbon cycle. Global Change Biology, doi: 10.1111/gcb.12766.) The oscillation and periodicity has nothing to do with the hydrological model of CLM but can be solved by having longer residence times (or reducing transfer coefficients). Thus the section from ling 21 of page 7 to line 18 of page 9 is unnecessary.

Thank you for the comment. We'd like to clarify that the issue of oscillation that we are trying to address refers to the oscillation of the annual average solution from one full length (multiple years) of forcing cycle to the next. For example, if the length of the forcing cycle is 3 years, the annual average solution of year one should be close to that at year four, which is driven by the same year one forcing. Within each forcing cycle, soil C varies with environmental forcing as shown in your reference. Note that Figures 2, 4 and 7 show the annual average total C, and the oscillations in Figure 4b and 4c correspond to fluctuations from one forcing cycle to the next rather than within the forcing cycle, which last 3 and 9 years for US-IB1 and US-SO2, respectively. The apparent fast turnover at US-SO2 was due to the long annual fire disturbance. Following your argument, soil C dynamics at US-SO2 should be determined mainly by the external forcing, which varies from year to year within the forcing cycle. However, this argument cannot be used to explain the oscillation of the annual average solution from one forcing cycle to the next. We don't rule out the possibility that the oscillation may be caused by factors other than the hydrological model.   However, we demonstrated the non-conservation problem with the hydrological model used in CLM4 and were able to resolve the oscillation problem with a better hydrological model.

We made the clarification and added your reference to differentiate the oscillation from the daily, seasonal and interannual variability in the revised manuscript.

3. In section 2.2, page #5, it is better to write the equation of spin-up time as years, otherwise reader may miscalculate the spin-up time.

Because the number of years in a cycle of atmospheric forcing is different at each site, we are not able to give a specific number to replace the equation.

4. Since the main basis of the study is based on the extrapolation of the carbon at a future time tn, it is important that the value of the gradient of the carbon cycle between times t0, t1 and tn does not change considerably. Hence the value of mc chosen becomes critical for the gradient projection method to work. For example in Fig. 2a, consider that a user choses mc =12. Based on

the ks4 value in Fig. 1, the turnover year, t_27 years. According to the author, tn -t1 = t mc _324 years, but we can see that the gradient changes slightly when time > 300 years in Fig. 2a. The extrapolation may produce more extreme result depending upon the change in gradient in different cases. Hence it becomes crucial that the user choses appropriate value of mc but the author does not provide any information or suggestions on how to pick the value of mc.

As mentioned in the original manuscript, mc is the number of years of known atmospheric forcing. It is a given number. The future time step Δt is chosen so that the solution of slow processes won't diverge or the solution is stable. In the case of soil4C, the future time step Δt is chosen such that $\Delta t/\tau < 2$, where τ is turn over years of soil4C. We picked $\Delta t = \tau$ in the manuscript. A stop point of ~300 years for the modified AD approach was selected based on the results in *Koven et al.* (2013), but it is not required. The best approach is to stop when NPP reaches dynamic steady-state. After each execution of the Gradient Projection (GP) approach, we gave it about 100 years in a sort of prediction/correction for the system to stabilize due to perturbation of the components from fast processes. The explicit integration approach using a number of small time steps followed by a large time step when the change in components due to fast processes become negligible has been successfully used to solve stiff ordinary differential equations [*Eriksson et al.*, 2003; *Gear and Kevrekidis*, 2003]. From our experiment, as long as there is no oscillation in the trajectory of time integration between forcing cycles, the GP approach works fine.

We added a brief discussion of how we pick the initial spinup and how long a simulation is needed after each projection in the revised manuscript.

Koven, C. D., Riley, W. J., Subin, Z. M., Tang, J. Y., Torn, M. S., Collins, W. D., Bonan, G. B., Lawrence, D. M., and Swenson, S. C.: The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4, Biogeosciences, 10, 7109–7131, doi:10.5194/bg-10-7109-2013, 2013.

Eriksson, K., C. Johnson, and A. Logg (2003), Explicit time-stepping for stiff ODES, *Siam J Sci Comput*, *25*(4), 1142-1157, doi:Doi 10.1137/S1064827502409626.

Gear, C. W., and I. G. Kevrekidis (2003), Projective methods for stiff differential equations: Problems with gaps in their eigenvalue spectrum, *Siam J Sci Comput*, *24*(4), 1091-1106, doi:Pii S1064827501388157

Specific Comments Minor comments that have been marked in the pdf manuscript.
Note that Manoj is a post-doc in Yiqi Luo's group.

The following are responses to the specific comments made in the manuscript.

We corrected most of the editorial errors pointed out by Manoj in the revised manuscript, such as lower case letter for turnover rates, definition of first abbreviations etc.

p.5, l.24: why 300 here?

~300 years as a stop point for the modified AD approach was selected based on the results in *Koven et al.* (2013), but it is not required. The best approach is to stop when NPP reaches dynamic steady-state.

p.6, l.5: Since the method is based on the gradient or slope of two consecutive cycles of carbon, it seems that the method may fail when the gradient between the cycles changes. Like in fig 2a it can be that the gradient changes at least 2 or 3 times. How does the author suggest to deal with those changes?

This approach is analogous to using a large time step that satisfies stability requirement to integrate the slowest processes once the contributions from fast processes become negligible (e.g. after 100 years of small time step integration). After each execution of the Gradient Projection approach, we gave it about 100 years for the system to stabilize or damp the components from fast processes to offset the error caused at the projection step.

p.6, l.11: why 100?

With small time steps, we use 100 year simulation that is long enough to correct perturbation caused by the projection. It doesn't have to be 100 years. It can be the time period needed to stabilize the components from fast processes. We added the statement in the revised manuscript.

p.7, l.13 and l.14: reduction compared to what?

The reduction was compared to the modified AD approach. We made it clear in the revised manuscript.

p.7, l.18: (regarding oscillation) why? may occur with strong interannual variability in forcing and short residence times in carbon pools.

The oscillation we referred to is the fluctuation of the annual average total carbon between each full length of forcing cycle rather than interannual variability within the forcing cycle. We made the clarification in the revised manuscript.

p.7, l. 19: (regarding longer periodicity than atmospheric forcing for US-SO2) why, only occurs for pools with very short residence times?

Site US-SO2 has long annual fire disturbance (> half year).

p.7, l.23: does the model have fire simulations?

CLM4-CN can simulate fire effects based on a statistical fire model.

p.7,l.24-27: forcing will be reflected in oscillation only if the pool residence time is very short.

This comment is related to what we mean by oscillation in the manuscript. The oscillation we referred to is the fluctuation of the annual average total carbon between each full length of forcing cycle. Hence it is not a reflection of the forcing variability within each forcing cycle, and it cannot be explained by the short residence time of the C pool.

p.8, l.3: you need to obtain steady-state water table depth in order to get the spin-up results for carbon

Agree. That's why we investigated STOMP when we found that the water table oscillates from one forcing cycle to the next cycle in the CLM4 formulation.

p.8, l.13: (mass conservation) for water or carbon? should be water only.

Yes, it is water only. We added "water" in the statement in the revised manuscript.

p.8, l.14-16: "The water content formulation itself has been previously shown to cause solution instability for soils near saturation (Hills et al., 1989)." may not relevant to carbon cycle spin-up

We intended to point out the inherent issue of the water content based formulation regarding oscillations.

p.8,l.17: (comment on the new flow model investigation) its root is in carbon cycle model

We believe this comment is again related to the clarification of oscillation used in the manuscript. We were able to use a better hydrological model to resolve the issue.

p.8, l.20: (STOMP description) this paragraph may not be necessary

We think a brief introduction is necessary for the readers.

p.9, l.13: it should be separated from carbon cycle

It's possible that when the residence time of soil carbon is long enough, it can damp out the role of water table oscillation. However, the true residence time at certain location could be long or short, as governed by the underlying processes. For locations with short residence time, we still need to resolve the issue that may arise from other aspects such as the hydrological model.

p.10,l.3-5: (regarding more carbon predicted and less uncertainty if correct numerical scheme is used) Is it always true? you changed ware scalars so that you predict more soil carbon.

There are other uncertainties too. Yes, the conclusion was based on model observation. We made it clear in the revised manuscript.

Accelerating the spin-up of the coupled carbon and nitrogen cycle model in CLM4

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Abstract

The commonly adopted biogeochemistry spin-up process in earth system model is to run the model for hundreds to thousands of years subject to periodic atmospheric forcing to reach dynamic steady state of the carbon-nitrogen (CN) models. A variety of approaches have been proposed to reduce the computation time of the spin-up process. Significant improvement in computational efficiency has been made recently. However, a long simulation time is still required to reach the common convergence criteria of the coupled carbon/nitrogen model. A gradient projection method was proposed and used to further reduce the computation time after examining the trend of the dominant carbon pools. The Community Land Model version 4 (CLM4) with carbon and nitrogen component was used in this study. From point scale simulations we found that the method can reduce the computation time by 20-69% compared to one of the fastest approaches in the literature. We also found that the cyclic stability of total carbon for some cases differs from that of the periodic atmospheric forcing, and some cases even showed instability. Close examination showed that one case has a carbon periodicity much longer than that of the atmospheric forcing due to the annual fire disturbance that is longer than half a year. The rest was caused by the instability of water table calculation in the hydrology model of CLM4. The instability issue is resolved after we replaced the hydrology scheme in CLM4 with a flow model for variably saturated porous media.

1. Introduction

The Initial starting values of carbon/nitrogen (CN) models are not commonly available, especially for large scale applications, but they have important influence on the subsequent C/N states simulated by the models. Typically, Earth system model (ESM) simulations are initialized in the pre-industrial period to allow sufficient time for the coupled system to respond to the various forcing. Initialization of the CN model is usually achieved by a spin-up run of the CN model given an arbitrary initial condition until an approximate C equilibrium is reached. This time marching of the model requires several hundreds to thousands of years of model simulations before a dynamic steady state is reached. The length of the transient state to reach a dynamic steady state is dependent on the initial conditions of the system. It has long been recognized that the spin-up process of CN models is time consuming due to the slow turnover rates of the soil carbon pools, which significantly affect the computational efficiency for global modeling. A number of approaches have been proposed in the past to improve upon the explicit forward time integration of ordinary differential equations in their native form and rate parameters for CN models. These approaches include the initialization of soil organic matter carbon pools with observations [*Zhang et al.*, 2002], accelerated decomposition method using a higher decomposition rate for litter and soil carbon pools [*Thornton and Rosenbloom*, 2005], decelerated bulk denitrification and leaching method [*Shi et al.*, 2013], and semi-analytical steady-state solution for soil organic C and N pools [*Xia et al.*, 2012]. Except for the semi-analytical approach, other approaches mentioned above have been summarized and compared in Shi et al. [2013]. The semi-analytical model needs initial spin-up values of net primary productivity (NPP), which still requires long simulation time for stabilization because C and N are coupled in CN models. We had previously restructured the CN model in Community Land Model version 4 (CLM4-CN) [*Lawrence et al*. 2011] and developed a steady-state solution directly using annually averaged rate parameters [*Fang et al.*, 2013; *Fang et al*. 2014]. Using our approach, we were able to implement the semi-analytical method in *Xia et al*. [2012]. Our numerical experiment showed that the semi-analytical method is not necessarily faster compared to the modified form of the "accelerated decomposition" approach in Koven et al. [2013].

Recently Koven et al. [2013] used a modified form of the "accelerated decomposition" (hereafter referred as AD approach) by numerically increasing the decomposition rates for the two slowest soil carbon pools (named as Soil3C and Soil4C) to a level so that their turnover rates are similar to the fast pools during the initialization. Numerical evaluation found that the approach significantly reduced the spin-up time [*Koven et al.*, 2013]. Figure 1 shows the structure of the soil C pool represented in ~~the~~ CLM4-CN. Note that heterotrophic respiration fractions are not shown. The reason that the AD approach can accelerate the spin-up is because these two slowest pools are essentially decoupled from the rest of the ordinary differential equations, in that all other pools do not need input from them. The approach, however, cannot be applied to the coarse woody debris (CWD) pool even though its turnover rate is on the same order of Soil3C, because it is an input to the litter pools. Changing the rate of CWD will give a different solution of other pools during each integration step using the same initial condition, which will lead to a state far from equilibrium if the state is used in a restart simulation.

In the AD approach, once the solution is obtained from the accelerated run, the state of Soil3C and Soil4C can be analytically solved. From Fig. 1, the flux of Soil3C and Soil4C pools can be described by the following equations:

$$\frac{dC_{Soil3}}{dt} = -k_{S3}C_{Soil3} + k_{S2}C_{Soil2} + k_{L3}C_{Litr3} \tag{1}$$

$$\frac{dC_{Soil4}}{dt} = -k_{S4}C_{Soil4} + k_{S3}C_{Soil3} \tag{2}$$

where k_{L3}, k_{S2}, k_{S3}, and k_{S4} are the turnover rates of Litter 3, Soil 2, Soil 3, and Soil 4 C pool shown in Fig. 1, respectively. C_{Litr3}, C_{Soil2}, C_{Soil3} and C_{Soil4} are the amount of C in Litter 3, Soil 2, Soil 3 and Soil 4 C pools, respectively. The first term on the right hand side of Eqs. (1) and (2) includes heterotrophic respiration. At the steady state, the left hand side of Eqs. (1) and (2) becomes 0, the amount of ~~soil3C~~ Soil3C and Soil4C can then be solved:

$$C_{Soil3} = \frac{k\cancel{K}_{S2}}{k\cancel{K}_{S3}} C_{Soil2} + \frac{k\cancel{K}_{L3}}{k\cancel{K}_{S3}} C_{Litr3} \qquad (3)$$

$$C_{Soil4} = \frac{k\cancel{K}_{S3}}{k\cancel{K}_{S4}} C_{Soil3} \qquad (4)$$

Eqs. 3 and 4 are applicable regardless whether AD or native run was used (the native run was defined here as the simulations without changing the decomposition rates of Soil3 and Soil4 C pools). Therefore, multiplying Eqs. (3) and (4) by their corresponding accelerator, the results should be close to the native runs. That is

$$C_{Soil3,N} = \frac{k\cancel{K}_{S2}}{k\cancel{K}_{S3,N}} C_{Soil2} + \frac{k\cancel{K}_{L3}}{k\cancel{K}_{S3,N}} C_{Litr3} = A_{S3} C_{soil3} \qquad (5)$$

$$C_{Soil4,N} = \frac{k\cancel{K}_{S3}}{k\cancel{K}_{S4,N}} C_{Soil3} = A_{S4} C_{Soil4} \qquad (6)$$

where “$_{,N}$” denotes the native run, A is the accelerator.

Even with this modified accelerator approach, long simulation time cannot be avoided at dry and cold places because decomposition scaling factor is associated with soil water potential and temperature. Hence new methods are needed to address the spin-up problem. In implicit time integration approaches, based on knowledge about the trajectory of the solution of the initial value problem, linear extrapolation from time integration was often used to find a good initial value for iterative multirate multidisciplinary processes [*Birken et al*., 2014 and references therein]. A number of explicit Euler steps with small time steps followed by an explicit Euler step with large time step when the change in components due to fast processes become negligible has been shown to efficiently solve stiff ordinary differential equations [*Eriksson et al*., 2003; *Gear and Kevrekidis*, 2003]. We made use of these concepts, referred to as the Gradient

Projection (GP) approach in this study, to further improve the computational efficiency of the biogeochemistry spin-up processes.

2. Methods

2.1 *Model Description*

Community land model, CLM4, is the land component of the Community Earth System Model (CESM) [*Lawrence et al.*, 2011]. Processes simulated in CLM4 include biogeophysics (solar and longwave radiation, momentum, heat transfer in soil and snow, hydrology of canopy, soil, and snow, and stomatal physiology and photosynthesis) and biogeochemistry (phenology, autotrophic respiration, heterotrophic respiration, carbon and nitrogen allocation, and nitrogen source/sink). The vegetation structures (leaf area index, stem area index and height) in CLM4-CN are represented through the predictive state variables of leaf and stem carbon, which are coupled to simulate fluxes of carbon and nitrogen state variables in vegetation, litter, and soil organic matter [*Lawrence et al.*, 2011; *Thornton and Zimmermann*, 2007]. The tree, shrub and grass plant functional types (PFTs) are divided into tropical, temperate and boreal climate groupings using the PFT physiology and climate rules of Nemani and Running [1996] and C3/C4 photosynthetic pathways in the case of grasses [*Lawrence and Chase*, 2007]. For this study, we used CLM4-CN in offline mode, which is not coupled to an atmosphere model.

2.2 *Gradient Projection Method*

If m_c is the number of years (one cycle) of atmospheric forcing which will be used repeatedly in the spin-up run, we use a spin-up time of $[(n+1)\ m_c]$ years as a stop point for the accelerated decomposition (AD) run, where $n = 300/m_c$ is an integer. For example, if the number of years of forcing is $m_c = 7$, the stop time will be at year 301. A stop point of ~300 years for the modified AD approach was selected based on the model results in *Koven et al.* [2013], but it is not an absolute requirement. The best approach is to stop when NPP reaches a dynamic steady-state.

At the end of the accelerated run, a dynamic steady state water table should be reached in the soil column. Due to the slow turnover rates, the total soil carbon gradually approaches steady state from one cycle to the next (Fig. 2(a)). We can approximate C at a future time t_n (Fig. 2(b)) using the C gradient between two consecutive cycles expressed in the following equation:

$$C(t_n) = C(t_1) + \frac{C(t_1) - C(t_0)}{m_c}(t_n - t_1) \quad (7)$$

where t_0 is the beginning of the first cycle, t_1 is the beginning of the next cycle, and $t_1 - t_0 = m_c$; $t_n - t_1 = \tau\, m_c$, τ is an integer close to the turnover years (reciprocal of turnover rate) of Soil4 C pool to satisfy the stability requirement of forward or explicit time integration that is used in CLM4-CN to solve the time-dependent ordinary differential equations. The explicit method can be numerically unstable (convergence of solution is not guaranteed) if the time step is too big [*LeVeque*, 2007]. For the first order kinetic type problem, i.e., $u'(t) = ku(t)$, the stability requirement is $|1 + kh| \leq 1$, in which k is the rate constant and h is the time step.

We call the method shown in Eq. (7) the gradient projection (GP) method. This method is analogous to that described in Eriksson et al. [2003], which uses a large time step that satisfies stability requirement to integrate the slowest processes once the contributions from fast processes become negligible. We allow j_p to be chosen based on the time period needed to stabilize the components from fast processes between cycles after perturbation, or set as an integer equals to $m_c \times (100/m_c + 1))$ years of simulation after restart from the accelerated run before using this approach, and also perform j_p years of simulation followed by each projection until the solution meets the common convergence criteria of 0.5 g m^{-2} for total soil C during two consecutive cycles [*Shi et al.*, 2013; *Thornton and Rosenbloom*, 2005]. During each projection, balance check for C and N is turned off. The GP method is only applied to the dominant C and N pools, i.e., coarse wood debris, dead stem, dead coarse root and Soil4 pool.

3. Results

A total of 38 single point tower sites from the FLUXNET [*Baldocchi et al.*, 2001] were selected to assess the gradient projection method. These sites include temperate, boreal, tropical, and subtropical climatic environments and four ecosystem types (tropical forests, temperate forests, boreal forest, grasslands, and Mediterranean-type ecosystems) (Table 1).

The meteorological forcing, site information such as soil texture, vegetation cover, and satellite-derived phenology at each site are provided by the North American Carbon Program (NACP) site synthesis team for the sites located in North America and by the Large Scale Biosphere-Atmosphere Experiment in Amazônia Model Intercomparison Project (LBA-MIP) for the sites located in South America. The NACP site synthesis and LBA-MIP datasets are detailed in Schwalm et al. [2010] and at http://www.climatemodeling.org/lba-mip. Each site has two runs, one using the AD method and the other using the GP method. The available forcing (Table 1) is applied repeatedly during the simulation for each site.

Table 2 shows the comparison of total simulation years till a certain convergence criterion is met. Three convergence threshold values in ΔC_{TOC} (3.0, 1.0, and 0.5 g m^{-2} yr^{-1}) were compared. The quality of total soil C is better when the threshold value is smaller [*Thornton and Rosenbloom*, 2005]. Compared to the modified AD approach, the reduction of computation cost is shown in Fig. 3. Fig. 3 shows that when high quality solution ($\Delta C_{TOC} \leq 0.5$ g m^{-2} yr^{-1}) is required, the average total reduction in computation cost is 40%. Average 23% of computation time is reduced for achieving the low quality solution ($\Delta C_{TOC} \leq 3$ g m^{-2} yr^{-1}).

Note that the computation cost reduction for sites US-Me2, RJA, US-IB1 and US-SO2 is not shown in Fig. 3. Site US-Me2 met the convergence criteria before the GP method is applied. Sites RJA and US-IB1 show oscillation of the annual average total C from one full length (multiple years) of forcing cycle to the next, and site US-SO2 shows a carbon periodicity much longer (81 years) than that of the atmospheric forcing (9 years) (Fig. 4). The oscillation noted in the simulations at RJA and US-IB1 differs from the variability within the forcing cycle, which happens when soil C has a fast turnover rate such that soil C dynamics are primarily controlled by variability of the forcing [*Luo et al.* 2014]. Due to the aforementioned reasons, the GP method failed at those three sites.

We first checked whether the oscillation and longer periodicity were caused by fire disturbance. However this can only explain the oscillation at site US-SO2. The annual fire disturbance at site US-SO2 is longer than half a year, while it is less than a month at the other two sites. In the original CLM4, soil water is calculated first for the top ten soil layers (3.8 m below the ground surface) and one aquifer layer using water content based formulation for water mass conservation and groundwater table as bottom boundary condition [*Oleson et al.*, 2010]; the Niu et al. [*Niu et al.*, 2005; *Niu et al.*, 2007] parameterizations are then used to simulate groundwater-soil water interaction and update the water table depth. If the water table is below 3.8 m, groundwater does not contribute to the soil moisture in the overlaying soil layers. We found that after a hundred years, the water table calculation scheme in CLM4 has resulted in significantly different evolution of water table depth from one cycle to the next when repeatedly forcing the model with atmospheric data at sites RJA and US-IB1. The issue has also been found previously and effort has been made to eliminate the oscillations [*Oleson et al.*, 2010], but such oscillations can still occur under specific conditions such as at RJA and US-IB1. When we turned off the groundwater component, i.e., applying zero flux boundary condition at the bottom of the soil column, we didn't see oscillations in SOC at RJA and US-IB1. In Niu et al. [2007] groundwater model, after solving the mass conservation equations (Richards' equation) in the top ten layers, water is then moved around to account for recharge and subsurface runoff and in the meantime satisfy two conditions for water content in each layer, i.e., the water content has to be greater than the minimum content and smaller than the effective porosity of the layer. By moving water mass around after the Richards' equation is solved, Richards' equation at each node is no longer satisfied if its moisture deviates from its previous solution. We have confirmed the local mass conservation error of water in the original model of CLM4. ~~This approach will cause local mass conservation error, and t~~The error is large when recharge or subsurface runoff is high. The water content formulation itself has been previously shown to cause solution instability for soils near saturation [*Hills et al.*, 1989]. Instead of solving the soil water and groundwater separately, we use a flow model for variably saturated porous media, STOMP (Subsurface Transport Over Multiple Phases) [*White and Oostrom*, 2000], to see if it can resolve the oscillation in the total soil C.

The STOMP simulator was developed to predict non-isothermal hydrological flow and reactive transport in variably saturated subsurface environments. In STOMP, the water mass conservation equation balances the time rate of change of water mass within a control volume with the flux of water mass crossing the control volume surface. ~~In STOMP, t~~The nonlinear equations describing mass conservation are discretized spatially on structured orthogonal grids using the integral finite difference approach of Patankar [1980], which is locally and globally mass conserving. ~~and~~ The equations are discretized temporally using first-order backward Euler differencing or implicit time stepping that is suitable for the solution of the equations that are numerically unstable [*LeVeque*, 2007]. Newton–Raphson iteration is used to resolve the nonlinearities from the constitutive equations that relate the primary and secondary variables.

Detailed information regarding STOMP, such as user's guide, theory guide and code availability can be found at http://stomp.pnnl.gov. For each soil column, the number of vertical grids used for STOMP is 15 and it is the same as that in CLM4. In CLM4, the top ten grids (3.8 m below ground) are used in the soil water scheme. The same initial saturation condition as that in CLM4 is prescribed. For the grid at the top, the Neumann boundary condition is used. For the bottom (42 m below ground), a zero flux boundary condition is used. Because the aquifer is unconfined, we use the bottom node pressure to calculate water table depth. Figs. 5 and 6 shows the model comparison at the beginning of the first 3 years between the simulations using the original soil hydrology scheme in CLM4 and the simulation after replacing the soil water and groundwater-soil water interaction scheme with STOMP at sites RJA and US-IB1. Using STOMP, mass conservation is improved, and the moisture content calculated is more accurate, ~~STOMP~~ resultings in wetter and cooler soil (Figs. 5 (b), (c) and Figs. 6 (b), (c)).

Fig. 7 (a) and (b) shows the oscillations of water table depth resolved at both RJA and US-IB1, i.e., the oscillations between forcing cycles noted in the original hydrology scheme in CLM4 are caused by the local water mass balance error. Each cycle of atmospheric forcing at both sites has 3 years. The GP method is successful at those two sites. The little jumps in Fig. 7 (c) and (d) are where the GP method is applied. Both sites show higher total soil C predicted compared to Figs. 4 (a) and (b) because of the new flow model. The issue of the original groundwater model in CLM4 might explain why it took so long (> 4000 years) for some of the grids in the global simulation to converge as shown in Shi et al. [2013]. In addition, the gradient projection model is not recommended for sites where the length of fire season is too long. For those sites, the overall time that takes for the spin-up run to steady-state is much shorter compared to others, therefore no improvement on the spin-up time is necessary.

4. Conclusions

We described a gradient projection method to further speedup the spin-up process based on the slow nature of soil organic C decomposition. Comparison between our approach and the modified accelerator approach showed that 20-69% of simulation years can be reduced with our approach. While the approach was specifically evaluated using CLM4CN, it can also be readily applied to other CN models in earth system models. No matter what modification is made to improve the spin-up efficiency, a final spin-up is always needed to reach a converged solution due to disequilibrium caused by the modification. Our approach is especially useful when new model formulation is proposed and high quality solution (small convergence threshold) is needed for a fair comparison.

In addition, we also found that the original numerical hydrology scheme, especially the water table calculation in CLM4 creates numerical oscillations in simulated water table, leading to a challenge to achieve the common convergence criteria for soil C. To resolve the issue, we replaced the hydrological model using a flow model for variably saturated porous media. The new flow model caused about 10% increase in computation time, but gives more accurate results that corrected the oscillation behavior of the original hydrological model. Comparing the total C predicted by the old and new flow models, we also see more C being predicted ~~U~~using the new flow model.~~,~~ ~~we also see more C being~~ Whether the prediction of more C is realistic depends on other factors besides the hydrology so we have not attempted to evaluate the simulated C using observations. Nevertheless, a correct implementation of numerical schemes is always desirable for reducing ~~will cause less~~ uncertainty in model prediction ~~due to numerical schemes~~.

5. Code availability

The source code of CLM4.0 and STOMP can be requested through http://www.cesm.ucar.edu/models/cesm1.0/ and http://stomp.pnnl.gov/licensing.stm, respectively. The method implemented in this study can be obtained upon request. Contact: yilin.fang@pnnl.gov.

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Table 1. Location, PFT, soil type and number of years of atmospheric forcing for each site

ID	Site	Longitude (°E)	Latitude (°N)	Elev (m)	Height[a] (m)	CLM4 PFT[b]	CLAY (%)	SAND (%)	SILT (%)	m_c[d] Years
1	US-Ha1 [*Goulden et al.*, 1996]	-72.1715	42.5378	343	30	BDTmp	6	66	29	1991-2006
2	US-WCr [*Yi et al.*, 2004]	-90.0799	45.8059	520	30	BDTmp	20.17	42.52	37.32	1998-2006
3	US-Syv [*Desai et al.*, 2005]	-89.3477	46.242	450	37	BDTmp	16.43	46.56	37.01	2001-2006
4	US-PFa [*Davis et al.*, 2003]	-90.2723	45.9459	470	122	BDTmp	20.17	42.52	37.32	1995-2005
5	US-UMB [*Curtis et al.*, 2005]	-84.7138	45.5598	234	50	BDTmp	0.6	92.6	6.8	1998-2006
6	US-MOz [*Gu et al.*, 2007]	-92.2	38.7441	219	30	BDTmp	24.68	46.38	28.94	2004-2007
7	US-Dk2 [*Katul et al.*, 2003]	-79.1004	35.9736	163	42	BDTmp	21.62	54.43	23.95	2003-2005
8	US-MMS [*Sims et al.*, 2005]	-86.4131	39.3231	275	48	BDTmp	63	34	3	1999-2006
9	US-Ton [*D D Baldocchi et al.*, 2010]	-120.966	38.4316	169	23	BDTmp and C3NAGrs	15	41	44	2001-2007
10	BAN[c]	-50.1591	-9.82442	120	40	BDTrop	37	24	39	2004-2006
11	CA-Oas [*Griffis et al.*, 2003]	-106.198	53.6289	530	30	BDBorl	18.8	50.32	30.87	1997-2006
12	CA-Gro [*McCaughey et al.*, 2006]	-82.1556	48.2167	300	30	BDBorl	20	65	25	2004-2006
13	US-Ho1 [*Hollinger et al.*, 1999]	-68.7403	45.2041	79	29	NETmp	15.9	50.35	33.75	1996-2004
14	CA-Ca1	-125.334	49.8672	300	45	NETmp	2.63	84.42	12.94	1998-2006

	[*Humphreys et al.*, 2006]									
15	CA-TP4 [*Arain and Restrepo-Coupe*, 2005]	-80.3574	42.7098	219	30	NETmp	0	98	2	2002-2007
16	US-NR1 [*Turnipseed et al.*, 2002]	-105.546	40.0329	3050	26	NETmp	21.43	43.13	35.45	1998-2007
17	US-Dk3 [*Katul et al.*, 2003]	-79.0942	35.9782	163	21	NETmp	13.66	51.59	34.81	1998-2005
18	US-Me2 [*Hudiburg et al.*, 2013]	-121.557	44.4524	1310	30	NETmp	7	67	26	2002-2007
19	CA-Obs [*Griffis et al.*, 2003]	-105.118	53.9872	629	30	NEBorl	4.12	80.89	14.97	2000-2006
20	CA-Qfo [*Chen et al.*, 2006]	-74.3421	49.6925	382	25	NEBorl	4	51.5	29	2004-2006
21	CA-Ojp [*Griffis et al.*, 2003]	-104.692	53.9163	579	30	NEBorl	2.5	94.47	3.02	2000-2006
22	K67[c]	-54.9589	-2.85667	130	63	BETrop	90	2	8	2002-2004
23	K83[c]	-54.9714	-3.01803	130	64	BETrop	80	18	2	2001-2003
24	RJA[c]	-61.9309	-10.0832	191	60	BETrop	10	80	10	2000-2002
25	K77[c]	-54.8944	-3.01983	130	18	Crop	80	18	2	2001-2005
26	FNS[c]	-62.3572	-10.7618	306	8.5	Crop	10	80	10	1999-2001
27	US-Ne2 [*Suyker and Verma*, 2012]	-96.4701	41.1649	362	6	Crop	31.68	30.7	37.62	2001-2006
28	US-Ne1 [*Suyker and Verma*, 2012]	-96.4766	41.1651	361	6	Crop	31.68	30.7	37.62	2001-2006
29	US-IB1 [*Matamala et al.*, 2008]	-88.2227	41.8593	225	4	Crop	37.2	7.8	55.4	2005-2007
30	US-Ne3 [*Suyker and Verma*, 2012]	-96.4397	41.1649	363	6	Crop	31.68	30.7	37.62	2001-2006
31	US-ARM [*Fischer et al.*, 2007]	-97.4884	36.605	311	65	Crop	43.1	27.98	28.92	2000-2007
32	PDG[c]	-47.6499	-21.6195	690	21	C3NAGrs and C4Grs	3	85	12	2001-2003
33	US-IB2 [*Matamala et al.*, 2008]	-88.241	41.8406	226	4	C3NAGrs and C4Grs	34.8	12.18	53	2004-2007

34	CA-Let [*Flanagan et al.*, 2002]	-112.94	49.7093	960	4	C3NAGrs	35.6	28.1	34.8	1997-2006
35	US-Var [*D D Baldocchi et al.*, 2004]	-120.951	38.4133	129	2	C3NAGrs	12.5	29.5	58	2001-2007
36	US-Shd [*Suyker et al.*, 2003]	-96.6833	36.9333	350	5	C3NAGrs	38.4	5.1	56	1997-2000
37	US-Los [*Yi et al.*, 2004]	-89.9792	46.0827	480	10	BEShr	16.43	46.56	37.01	2000-2006
38	US-SO2 [*Lipson et al.*, 2005]	-116.623	33.3739	1406	5	BEShr	21.31	43.94	34.75	1998-2006

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[a] Approximate height of the wind/temperature and flux measurements above the surface.

[b] Abbreviated plant functional types (PFTs) are : BDBorl – broadleaf deciduous boreal tree; BDTmp – broadleaf deciduous temperate tree; BDTrop – broadleaf deciduous tropical tree; BEShr – broadleaf evergreen shrub; BETrop – broadleaf evergreen tropical tree; crop – C3 crop; C3NAGrs – C3 non-arctic grass; C4Grs- C4 grass; NEBorl – needleleaf evergreen boreal tree; NETmp – needleleaf evergreen temperate tree.

[c] The site information and meteorological forcing is from the LBA-MIP dataset.

[d] m_c is the number of years of atmospheric forcing.

Table 2. Comparison between the gradient projection method (in bold) and the accelerated spin-up method.

ID	Site	Number of simulation years to reach		
		$\Delta C_{TOC} \leq 3$ (g m^{-2} yr^{-1})	$\Delta C_{TOC} \leq 1$ (g m^{-2} yr^{-1})	$\Delta C_{TOC} \leq 0.5$ (g m^{-2} yr^{-1})
1	US-Ha1	416/**416**	816/**480**	1024/**624**
2	US-WCr	828/**558**	1395/**729**	1809/**828**
3	US-Syv	930/**600**	1314/**744**	1680/**924**
4	US-PFa	1375/**617**	2057/**891**	2255/**946**
5	US-UMB	387/**387**	855/**567**	1116/**567**
6	US-MOz	772/**596**	1400/**924**	1776/**1096**
7	US-Dk2	453/**408**	888/**696**	1215/**849**
8	US-MMS	872/**552**	1136/**704**	1400/**744**
9	US-Ton	413/**402**	749/**574**	959/**672**
10	BAN	1281/**1050**	1677/**1284**	1959/**1452**
11	CA-Oas	1870/**860**	2170/**1090**	2470/**1240**
12	CA-Gro	351/**351**	966/**774**	1455/**1023**
13	US-Ho1	972/**585**	1503/**756**	1845/**864**
14	CA-Ca1	597/**468**	972/**549**	1215/**558**
15	CA-TP4	798/**528**	1170/**636**	1224/**828**
16	US-NR1	1310/**740**	1910/**870**	2470/**1000**
17	US-Dk3	640/**432**	848/**472**	992/**488**
18	US-Me2	312/**312**	318/**318**	354/**354**
19	CA-Obs	509/**441**	1029/**700**	1351/**770**
20	CA-Qfo	384/**384**	819/**612**	1143/**816**
21	CA-Ojp	520/**441**	812/**539**	1143/**651**
22	K67	543/**447**	720/**510**	831/**612**
23	K83	354/**354**	477/**411**	633/**510**
24	RJA	NA[a]/**348**	NA/**510**	NA/**606**
25	K77	310/**310**	440/**425**	585/**445**
26	FNS	468/**432**	1008/**750**	1350/**954**
27	US-Ne2	954/**726**	1368/**942**	1620/**1098**
28	US-Ne1	732/**534**	1200/**714**	1506/**858**
29	US-IB1	NA/**309**	NA/**333**	NA/**459**
30	US-Ne3	312/**312**	648/**474**	948/**612**
31	US-ARM	864/**552**	1192/**616**	1400/**672**
32	PDG	309/**309**	663/**540**	1077/**807**
33	US-IB2	536/**440**	804/**588**	900/**628**
34	CA-Let	630/**450**	960/**490**	1160/**560**
35	US-Var	608/**427**	881/**651**	1568/**679**

36	US-Shd	1784/**1168**	2128/**1368**	2320/**1472**
37	US-Los	490/**427**	903/**539**	1169/**651**
38	US-SO2	NA/NA		

[a] NA – not evaluated

FIGURE CAPTIONS

Figure 1. Soil Carbon pool structure of CLM4-CN. The arrows represent the decomposition pathways, and *k* is the turnover rate of each pool.

Figure 2. Annual average ~~T~~total soil carbon change with respect to time (a) and the gradient projection over a shorter time interval (b).

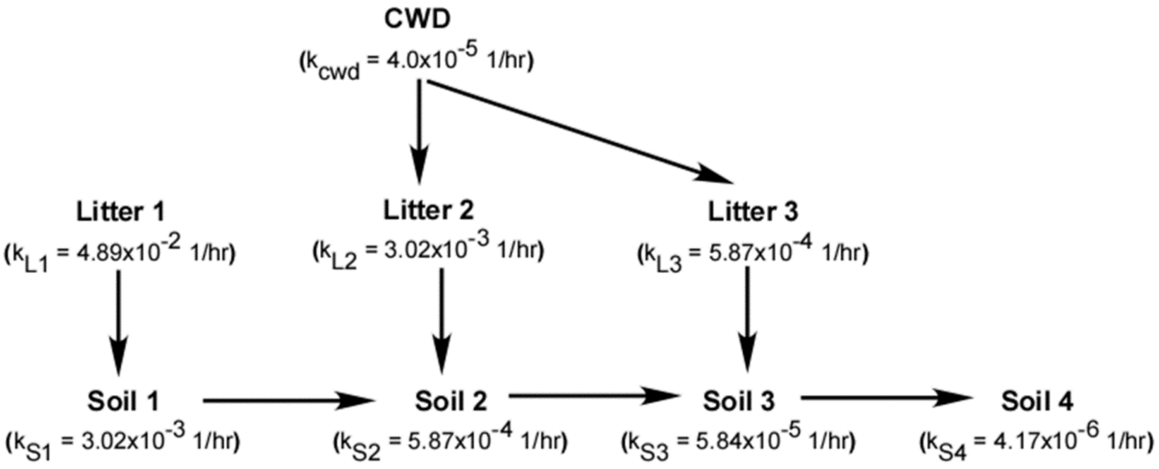
Figure 3. Stacked bar chart of percent reduction in computation cost for three convergence threshold values.

Figure 4. Annual average ~~T~~total soil C with respect to time at site RJA, US-IB1 and US-SO2.

Figure 5. Comparison of water table depth (a), average soil moisture content (b), and average soil temperature (c) using original soil hydrology model and STOMP in CLM4 at site RJA.

Figure 6. Comparison of water table depth (a), average soil moisture content (b), and average soil temperature (c) using original soil hydrology model and STOMP in CLM4 at site US-IB1.

Figure 7. Comparison of water table depth simulated by original soil hydrology scheme in CLM4 (solid line) and STOMP (dashed line) at site RJA (a) and site US-IB1(b) at the last 42 years of the simulation; (c) and (d) are annual average total soil carbon at site RJA and US-IB1 using STOMP in CLM4 and the GP method.



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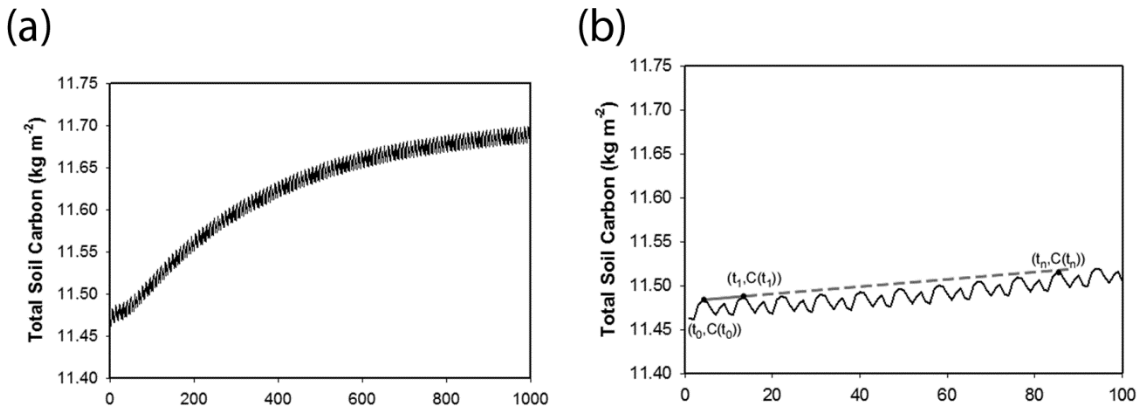

Figure 2. Annual average ~~T~~total soil carbon change with respect to time (a) and the gradient projection over a shorter time interval (b).

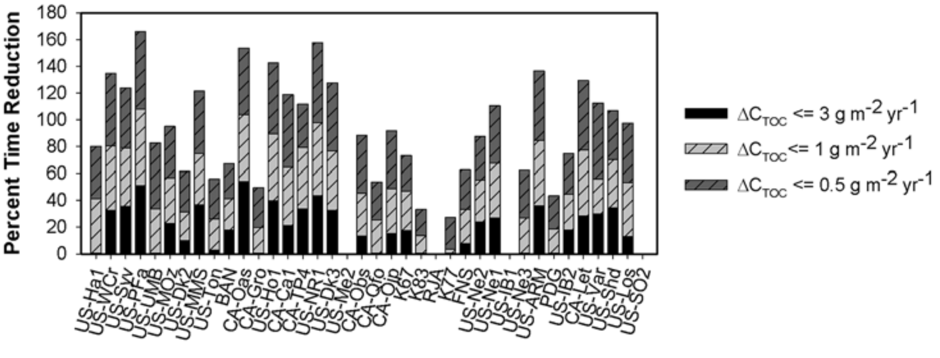

Figure 3. Stacked bar chart of percent reduction in computation cost for three convergence threshold values.

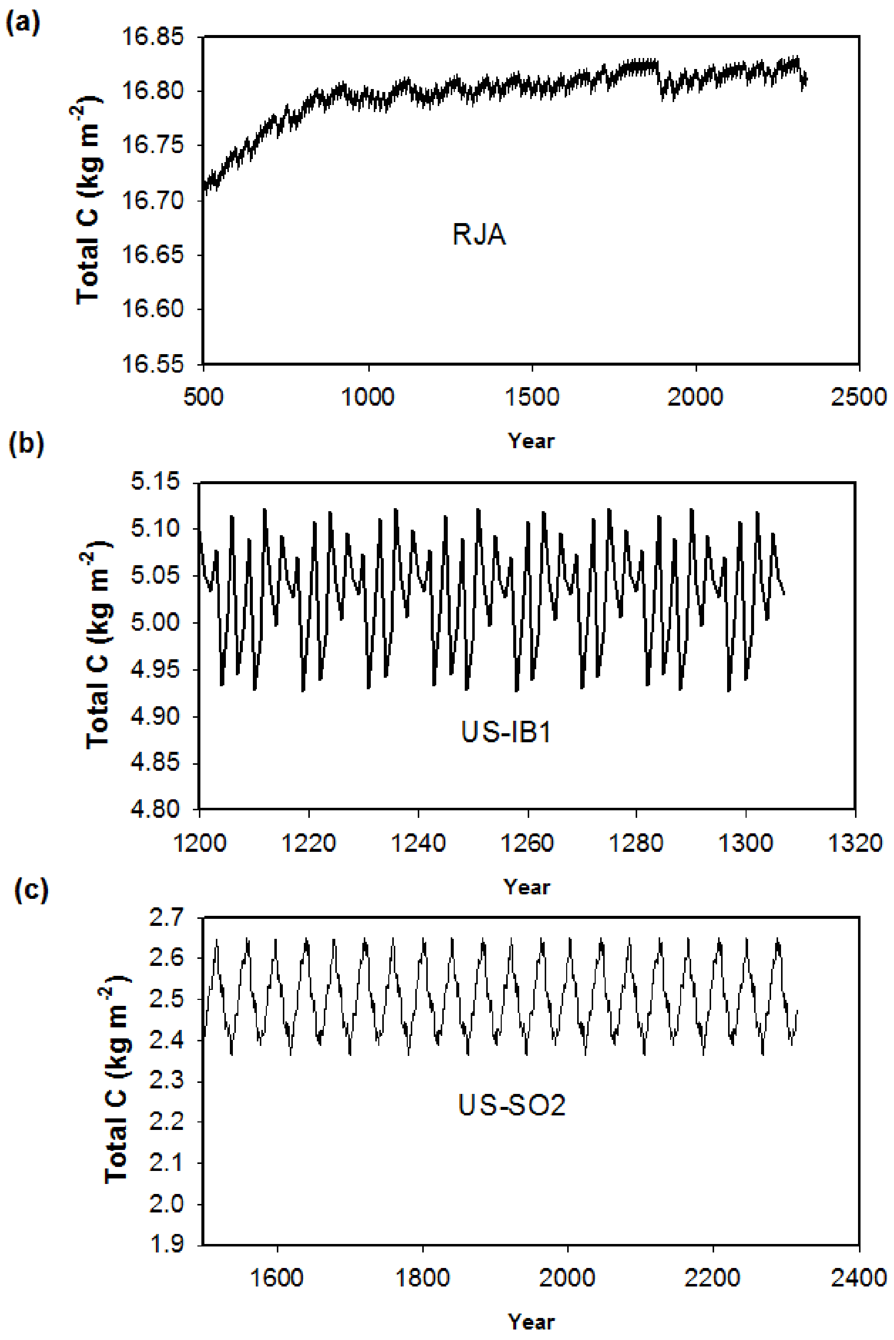

Figure 4. Annual average ~~T~~total soil C with respect to time at site RJA, US-IB1 and US-SO2.

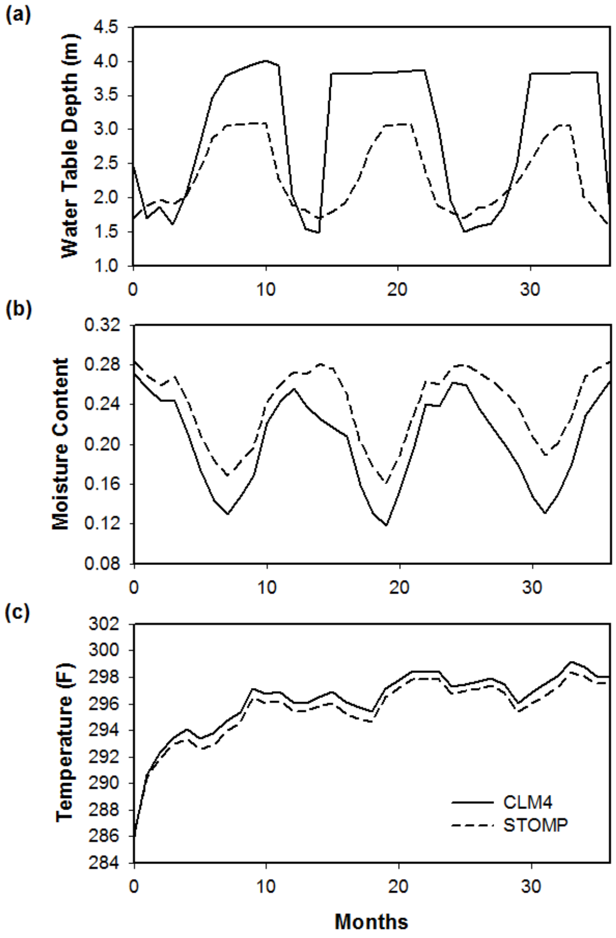

Figure 5. Comparison of water table depth (a), average soil moisture content (b), and average soil temperature (c) using original soil hydrology model and STOMP in CLM4 at site RJA.

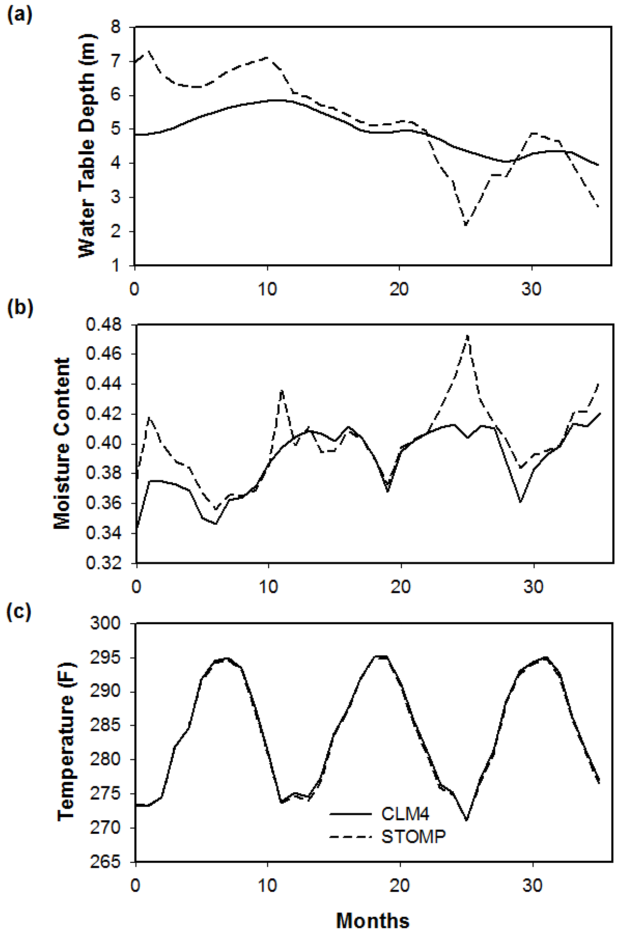

Figure 6. Comparison of water table depth (a), average soil moisture content (b), and average soil temperature (c) using original soil hydrology model and STOMP in CLM4 at site US-IB1.

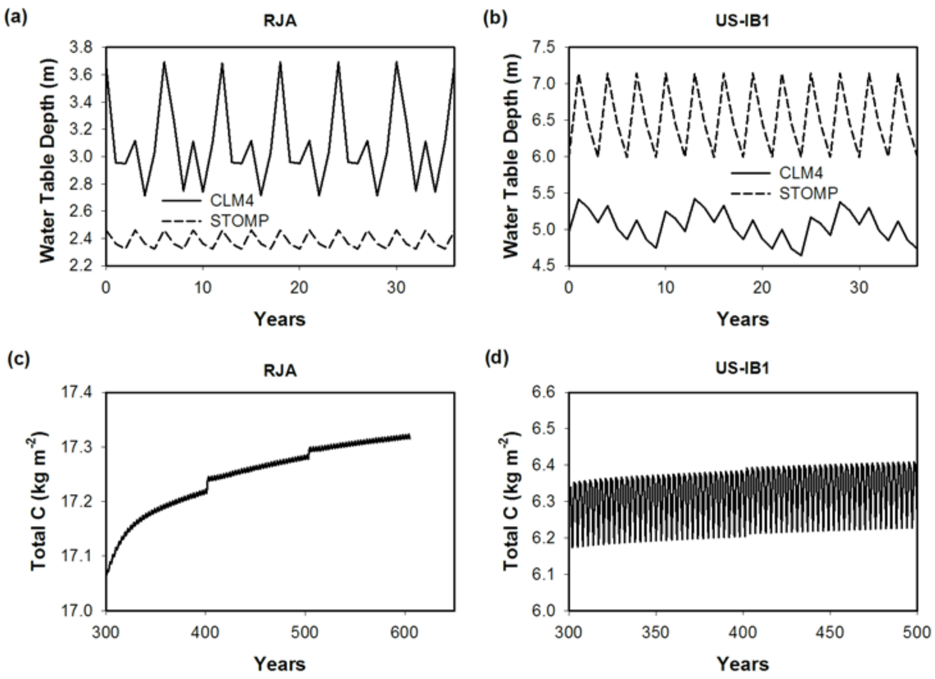

Figure 7. Comparison of water table depth simulated by original soil hydrology scheme in CLM4 (solid line) and STOMP (dashed line) at site RJA (a) and site US-IB1(b) at the last 42 years of the simulation; (c) and (d) are annual average total soil carbon at site RJA and US-IB1 using STOMP in CLM4 and the GP method.