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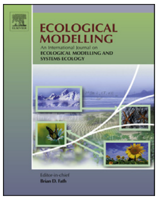

Spin-up processes in the Community Land Model version 4 with explicit carbon and nitrogen components

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ABSTRACT

Given arbitrary initial conditions, terrestrial biogeochemistry models typically require hundreds to thousands of years for carbon and nitrogen in various pools to reach steady-state solutions. Such long spin-up processes not only pose a significant burden to computational resources, but also are against observational evidence. The objectives of this study are to: (1) compare four spin-up methods and their steady-state solutions using the Community Land Model version 4 with explicit carbon and nitrogen processes (CLM4CN[2]); (2) elucidate the potential weaknesses of the model that are responsible for long spin-ups. The four methods can be classified into two groups: (1) the model spins up from arbitrary initial conditions (e.g., the traditional native dynamics or ND method); (2) the model is initialized with observed soil organic matter (SOM) pools. Our results show that: (1) compared to ND, accelerating SOM decomposition rates during spin-up reduces the spin-up timescales in tropical forests, grasslands, temperate forests, and boreal forests; (2) in some temperate forests, decelerating the denitrification and leaching rates and accelerating the decomposition rates during spin-up saves more computational time than the method only with decomposition rates accelerated; (3) a reasonable SOM initialization helps the model reach its steady state quickly. We also find that in some ecosystems the vegetation seasonality described by methods with decomposition or denitrification and leaching rates changed is inconsistent with that from the ND method. CLM4CN has the potential of improving the simulations and reducing the long spin-up timescales if the model structure and ways in representing decomposition and immobilization are improved.

1. Introduction

Model spin-up refers to the adjustment process through which the model reaches its steady-state solution in response to an arbitrary initial condition (Yang et al., 1995; Johns et al., 1997; Dickinson et al., 1998). Global gridded-models that need to spin-up from arbitrary conditions to steady-states may have high computational costs (with the problem only getting worse as model resolutions increase), an issue commonly referred to as the "spin-up problem" (Thornton and Rosenbloom, 2005). Land surface model (LSM) spin-up is an adjustment process as the model state variables (e.g., soil moisture, latent heat, and sensible heat) approach their equilibrium (Yang et al., 1995; Rodell et al., 2005), and a biogeophysical LSM spin-up is usually not computationally expensive. The carbon and nitrogen cycles are processes limiting spin-up for models with biogeochemical cycles. Therefore, up to thousands of years are required for terrestrial biogeochemical models to reach steady-state solutions, which are usually judged by carbon and nitrogen state variables (Thornton and Rosenbloom, 2005; Randerson et al., 2009). In addition, the steady-states of ocean general circulation models and ocean biogeochemical models are usually evaluated by biogeochemical tracers (e.g., inorganic and organic forms of carbon,

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[2] SOM, soil organic matter; ND, native dynamics; CLM4CN, the Community Land Model version 4 with explicit carbon and nitrogen; PFT, plant functional types; LPJ, Lund–Potsdam–Jena Dynamic Global Vegetation Model; AD, accelerated decomposition; DDL, decelerated bulk denitrification and leaching; SI, initialization of soil carbon and nitrogen pools; CESM, the Community Earth System Model; LBA-DMIP, Large Scale Biosphere–Atmosphere Data Model Intercomparison Project; GSDT, Global Soil Data Task; ORCHIDEE, ORganizing Carbon and Hydrology in Dynamic EcosystEms.

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nitrogen, phosphorus), and it usually takes several thousand years for these two types of models to reach steady-states (Merlis and Khatiwala, 2008; Khatiwala, 2008).

A typical spin-up for a terrestrial biogeochemical model starts from arbitrary initial conditions and is run to an equilibrium vegetation state, establishing steady-state values for its various pools, such as carbon and nitrogen in vegetation or in soil organic matter (SOM), depending on the model being used (Thornton and Rosenbloom, 2005). This type of spin-up is called the native dynamics (ND) method. Theoretically, for a terrestrial biogeochemical model running with observed meteorological data, a single unconditional steady-state solution exists for any combination of plant functional type (PFT) physiology and climate (Luo et al., 2001; Thornton and Rosenbloom, 2005; Xia et al., 2012). To obtain such a steady-state solution for all state variables, climate forcing needs to be applied repeatedly over a period, especially in experiments where the state variable residence time is longer than the post-steady-state simulation period (Thornton et al., 2002; Thornton and Rosenbloom, 2005).

In order to obtain the steady-state solutions, some studies have used a substantial amount of computational resources. For example, it took 900 years for the Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ) to spin-up from arbitrary initial conditions to equilibrium carbon pools and fluxes (Bondeau et al., 2007). In order to reach a global equilibrium in various carbon and nitrogen pools, Randerson et al. (2009) spun up the Community Land Model with explicit consideration of carbon and nitrogen processes (CLM4CN) 4000 years.

Rather than running the model from arbitrary initial conditions, some scientists have applied a variety of methods to solve the "spin-up problem". Studies at specific sites have shown that by initializing with observed SOM (Zhang et al., 2002) or litter (D'Odorico et al., 2004) a model can reach equilibrium relatively quickly, but these studies did not explicitly evaluate the importance of pool initialization on spin-up timescales. Some terrestrial models that include carbon cycles (Luo et al., 2001; Baisden and Amundson, 2003; Zhan et al., 2003) have used analytical steady-state solutions under special cases of simple forcing. Xia et al. (2012) found that for some models an analytical solution may dramatically reduce spin-up timescales, but it is less clear in their study how the analytical solution can be applied to carbon and nitrogen cycle models where the interactions complicate the situation.

Using the Biome-BGC model, Thornton and Rosenbloom (2005) compared several spin-up methods, including the ND method and the accelerated decomposition (AD) method. As AD uses a higher SOM decomposition rate, the litter and SOM pool sizes are reduced and turned over more rapidly. As a result, more mineral nitrogen is maintained in the soil to support new growth of plants. Thornton and Rosenbloom (2005) showed that AD requires about 70% less computation than ND.

As one of the most widely used LSMs, CLM4CN is comprehensive in that it represents both biogeophysical and biogeochemical processes, with the latter processes derived from Biome-BGC. This study will provide a detailed study of ND and AD, globally and locally, along with two alternative spin-up methods, which are decelerated bulk denitrification and leaching (DDL) and initialization of soil carbon and nitrogen pools (SI). Next, this study will examine the steady-state solutions of the four methods in different ecosystems (e.g., tropical forests, grasslands, temperate forests, and boreal forests) and document the efficiencies of different methods. Finally, this paper will investigate the possible reasons for the long spin-ups and reveal the deficiencies in the fundamental processes represented in the model.

The structure of this paper is as follows. Section 2 describes the model, data, and spin-up methods used in this study. Section 3 analyzes the spin-up results globally and locally. Section 4 compares the CLM4CN with the CENTURY model, and discusses the possible reasons for the long spin-up processes of CLM4CN. Conclusions of this study are given in Section 5.

2. Methods

2.1. Model description

CLM4 (Oleson et al., 2010; Lawrence et al., 2011) is the land model of the Community Earth System Model (CESM) (Gent et al., 2011). It has been substantially modified and improved since CLM3 (Dickinson et al., 2006), and these improvements are documented in Lawrence et al. (2011). In CLM4CN, all carbon and nitrogen state variables in vegetation, litter, and SOM are prognostic (Thornton et al., 2007; Randerson et al., 2009). The CLM4CN vegetation pools include leaf, respiring and nonrespiring woody components of stems and coarse roots, and fine roots. Carbon and nitrogen obtained in one growing season are retained and distributed as new growth by plant storage pools in following years. Prognostic leaf phenology depends on the classified PFTs, and prognostic LAI depends on the prognostic leaf carbon pool and an assumed vertical gradient of specific leaf area (Thornton and Zimmermann, 2007). A coarse woody debris pool, three litter pools, and four SOM pools, representing carbon and nitrogen storage and fluxes, are included in the heterotrophic model, and arranged as a converging trophic cascade (Randerson et al., 2009). The three-litter-pool classification are based on the measured chemical fractionation of fresh litter into labile (Lit1 = hot water and alcohol soluble fraction), cellulose/hemicellulose (Lit2 = acid soluble fraction), and remaining mass (Lit3 = acid insoluble fraction). The fractions of these components are defined as constants, which are plant tissue and PFT dependent. The decomposition rates of the four SOM pools, which are also constants and derived from a variety of experiments, decrease exponentially by following the SOM cascade (Thornton and Rosenbloom, 2005; Fig. 1). A prognostic treatment of fire based on the model of Thonicke et al. (2001) is also included. This paper uses CLM4CN to discuss both the global and site spin-up timescale patterns. The model resolution for the global tests is 1.9° latitude × 2.5° longitude.

2.2. Atmospheric forcing data

In this study, CLM4CN was driven both globally and at 11 individual sites. The global simulation used the global atmospheric forcing data (1985–2004) discussed in Qian et al. (2006), consisting of temperature, precipitation, solar radiation, wind, pressure, and specific humidity. The atmospheric forcing data for the 11 individual sites are from five Large Scale Biosphere–Atmosphere Data Model Intercomparison Project (LBA-DMIP) sites in Amazonia, five AmeriFlux sites in mid-and-high latitudes, and one FLUXNET site in Europe (Dunn et al., 2007; Schmid et al., 2000; Sulman et al., 2009; Suni et al., 2003; Appendix A). All LBA sites provide hourly atmospheric forcing; some of the AmeriFlux sites provide hourly forcing, while others provide half-hour forcing; the chosen FLUXNET site in Europe provides half-hour forcing.

2.3. Spin-up methods

The three litter pools and four SOM pools of CLM4CN each have different nominal rates ($k_{\mathrm{Lit},i}$ and $k_{\mathrm{SOM},j}$, 1/h) (Table 1 and Fig. 1). Each rate constant is corrected by a combined decomposition rate scaling factor r_{total} (dimensionless) (Eqs. (1 and 2)):

$$kc_{\mathrm{Lit},i} = k_{\mathrm{Lit},i} r_{\mathrm{total}} \tag{1}$$

$$kc_{\mathrm{SOM},j} = k_{\mathrm{SOM},j} r_{\mathrm{total}} \tag{2}$$