Matrix Approach to Accelerate Spin-Up of CLM5

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"Spin-up"

Spin-up is a process to make a model to reach a steady state.

It is an essential procedure to define the initial conditions of biogeochemical models before the models are used to predict ecosystem response to climate change.
Spin-up methods:

1. Native dynamic (ND), \(1000-10,000\) years (Thornton and Rosebloom, 2005)

2. Accelerated decomposition (AD), \(\sim 4000\) years (Randerson et al., 2009)

Traditional Spin-up methods take lots of simulation time. An efficient spin-up method with high quality results is needed.

3. Semi-analytic spin-up (SASU), \(\sim 500\) years (Xia et al. 2012)
• SASU is applied to matrix models of the terrestrial carbon cycle, such as CLM5 matrix model

\[
\frac{dC_{\text{veg}}}{dt} = B I_{\text{cin}} + (A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic})C_{\text{veg}}(t)
\]

(1)

\[
\frac{dN_{\text{veg}}}{dt} = B I_{\text{cin}} + (A_{phc}(t)K_{phc} + A_{gmc}(t)K_{gmc} + A_{fic}(t)K_{fic})N_{\text{veg}}(t)
\]

(2)

\[
\frac{dC_{\text{soil}}}{dt} = I_{C_{\text{soil}}} + \left(A_{hc}(t)\xi(t)K_h + V(t) + K_f(t)\right)C_{\text{soil}}(t)
\]

(3)

\[
\frac{dN_{\text{soil}}}{dt} = I_{N_{\text{soil}}} + \left(A_{hc}(t)\xi(t)K_h + V(t) + K_f(t)\right)N_{\text{soil}}(t)
\]

(4)

(Xingjie Lu et al., 2020)
**Method**

- Calculation of analytic solution

The system converges to a steady state when Input = output.

\[
\frac{dC_{\text{veg}}}{dt} = B I_{\text{cin}} + (A_{\text{phc}}(t)K_{\text{phc}} + A_{\text{gmc}}(t)K_{\text{gmc}} + A_{\text{fic}}(t)K_{\text{fic}})C_{\text{veg}}(t) = 0
\]

\[
\frac{dN_{\text{veg}}}{dt} = B I_{\text{cin}} + (A_{\text{phc}}(t)K_{\text{phc}} + A_{\text{gmc}}(t)K_{\text{gmc}} + A_{\text{fic}}(t)K_{\text{fic}})N_{\text{veg}}(t) = 0
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\frac{dC_{\text{soil}}}{dt} = I_{C_{\text{soil}}} + \left( A_{hc} \xi(t)K_h + V(t) + K_f(t) \right)C_{\text{soil}}(t) = 0
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\frac{dN_{\text{soil}}}{dt} = I_{N_{\text{soil}}} + \left( A_{hc} \xi(t)K_h + V(t) + K_f(t) \right)N_{\text{soil}}(t) = 0
\]

**Theoretical steady state**

\[
C_{\text{soil}} = \left( A_{hc} \bar{\xi} K_h + \bar{V} + \bar{K}_f \right)^{-1} I_{C_{\text{soil}}}
\]
The workflow of SASU in CLM5

- The matrix module is used instead of the original update mode.
- SASU module is called at the end of each loop.
- Analytic solution is used as pool sizes of next loop.
➢ Brazil site Verification

- Native dynamics (ND) / Accelerated decomposition (AD)
- Semi-analytic Spin-up (SASU)

➢ Global Verification

- Accelerated decomposition (AD)
- Semi-analytic Spin-up (SASU)

- Derived by CLM5 spin-up using 20-year recursive from Global Soil Wetness Project Phase 3 (GSWP3)
- $4^\circ \times 5^\circ$ resolution grid
## Results

- **Brazil site Verification**

Mean steady state values (KgC/m²) of state variables with SASU and ND

<table>
<thead>
<tr>
<th>State Variable</th>
<th>SASU-ND (KgC/m²)</th>
<th>SASU Pool size (KgC/m²)</th>
<th>ND Pool size (KgC/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Wood Debris</td>
<td>-6.51E-5</td>
<td>2.34</td>
<td>2.34</td>
</tr>
<tr>
<td>Total Soil Carbon</td>
<td>1.45E-3</td>
<td>7.32</td>
<td>7.32</td>
</tr>
<tr>
<td>Total Vegetation Carbon</td>
<td>-3.57E-4</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Total Ecosystem Carbon</td>
<td>1.02E-3</td>
<td>25.2</td>
<td>25.2</td>
</tr>
</tbody>
</table>

( threshold = 0.05 g/m²)

The steady states in Brazil obtained by the two methods are highly consistent.
Results

• Brazil site Verification

- SASU take 480 years and ND/AD use 4720 years to reach the same steady state in Brazil.

- SASU use 480 years that is nearly 89.83% simulation time less than ND to reach the same state.

Carbon state trajectories (a, d, g) and the change of carbon between loops for SASU (b, e, h) and ND (c, f, i) on Brazil site.
Steady state defined as more than 97% areas achieved equilibrium.
Global threshold for total ecosystem carbon equilibrium is 0.02 PgC / yr.
Results

Global Verification

<table>
<thead>
<tr>
<th></th>
<th>SASU-AD Pool size (PgC)</th>
<th>AD Pool size (PgC)</th>
<th>SASU Pool size (PgC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWD</td>
<td>-0.42</td>
<td>144.6</td>
<td>144.2</td>
</tr>
<tr>
<td>SOIL 1</td>
<td>-0.59</td>
<td>17.15</td>
<td>16.56</td>
</tr>
<tr>
<td>SOIL 2</td>
<td>-8.50</td>
<td>547.5</td>
<td>539.0</td>
</tr>
<tr>
<td>SOIL 3</td>
<td>-0.29</td>
<td>1015</td>
<td>1015</td>
</tr>
<tr>
<td>TOTSOMC</td>
<td>-9.39</td>
<td>1580</td>
<td>1570</td>
</tr>
<tr>
<td>TOTECOSYSC</td>
<td>-10.9</td>
<td>2361</td>
<td>2350</td>
</tr>
<tr>
<td>TOTVEGC</td>
<td>-0.53</td>
<td>595.3</td>
<td>594.8</td>
</tr>
</tbody>
</table>

The top 2.72m soil layers reach a similar steady state.
## Results

### Global Verification

<table>
<thead>
<tr>
<th></th>
<th>Ecosystem C (Pg C)</th>
<th>Vegetation C (Pg C)</th>
<th>Soil C (Pg C)</th>
<th>Unequilibrium Percentage (%)</th>
<th>Total Simulate year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AD Spin-up</strong></td>
<td>3131.3</td>
<td>594.7</td>
<td>2352.4</td>
<td>2.99</td>
<td>2140</td>
</tr>
<tr>
<td><strong>SASU 40+360+40</strong></td>
<td>2410.9</td>
<td>595.9</td>
<td>1629.8</td>
<td>3.99</td>
<td>440</td>
</tr>
<tr>
<td><strong>SASU 80+280+40</strong></td>
<td>2408.8</td>
<td>595.6</td>
<td>1628.0</td>
<td>2.90</td>
<td>400</td>
</tr>
<tr>
<td><strong>SASU 120+280+40</strong></td>
<td>2416.5</td>
<td>595.7</td>
<td>1635.5</td>
<td>2.52</td>
<td>440</td>
</tr>
<tr>
<td><strong>SASU 160+200+40</strong></td>
<td>2410.0</td>
<td>595.3</td>
<td>1629.1</td>
<td>2.75</td>
<td>400</td>
</tr>
<tr>
<td><strong>SASU 200+200+40</strong></td>
<td>2417.9</td>
<td>595.6</td>
<td>1636.9</td>
<td>2.59</td>
<td>440</td>
</tr>
</tbody>
</table>

In general, AD-Spinup takes about 2,140 years to reach steady state, while SASU just take 400~440 years. SASU will save about 80% simulate time than AD-spinup.
Results

Global Verification

- AD-spinup results will be larger than SASU in high-latitude regions.
- Typically, these areas are in the permafrost.
- There will never be an input or output of carbon in the deeper soil, especially for passive soil carbon pools.
• Most of pool sizes along depth from two methods are consistent.
• Passive soil carbon in deep layers shows high difference. SASU keep it in a low values.
Global Verification

AD-Spinup

- Even after 2000 years model running, passive soil carbon in deep layers does not change much.
- The steady state of deep soil carbon pool (passive carbon pool) from AD largely depends on the initial state and expansion multiple.

\[
C_{soil} = (A_{hc} \bar{\xi} K_h + \bar{V} + \bar{K}_f)^{-1} I_{C_{soil}}
\]

• When there is no input and output, the analytic solution will be 0.
The steady states obtained by SASU and other methods are highly consistent.

SASU is an efficient method to accelerate coupled carbon and nitrogen cycle to equilibrium.

SASU is expected to improve the estimation accuracy of steady-state pool sizes, especially for the permafrost regions.
Thank you!

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