Fast Spin Up of Components of an Earth System Model

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Statement of Spin-up Problem

- Generate tracer/pool distributions that are in balance with respect to (time-varying) forcing.
- Applications:
  - Initializing transient experiments
  - Analyze dynamics/properties of spun-up tracers
  - Compare tracers to observations
  - Optimize parameters to reduce model bias
    - Requires ability to spin up repeatedly
- Brute force is prohibitively expensive, particularly for OGCMs
  - wall-clock time and computing allocation
  - (2000 yrs) / (50 yrs/day) = 40 days

Mathematical Formulation of Problem

- Let c(t) denote tracer state, i.e., tracer concentrations.
  - for 1 tracer on POP gx1 grid, len(c) ≈ 4.2×10^6
  - for 1 tracer on MOM t061 grid, len(c) ≈ 10^7
  - Century-based soil model on ne30 SE grid, len(c) ≈ 1.5×10^7

- Model Map: $c(t) = \Phi(c(0),t)$
- Φ is the result of integrating $\partial c/\partial t$ forward in time.

- Find initial condition, c^*, such that $\Phi(c^*,T) = c^*$.
  - Tracer end-state is the same as the initial condition.
  - T is period of forcing.

- Rewrite as $G(c) \equiv \Phi(c,T) - c = 0$.

Newton's Method

- Iterative method for solving $G(c) \equiv \Phi(c,T) - c = 0$
- Generate sequence $c_1, c_2, \ldots, c_k, \ldots$ that converge to solution of system of equations
- $0 = G(c_{k+1}) = G(c_k) + (\partial G/\partial c) * (c_{k+1} - c_k) + \ldots$

$$c_{k+1} = c_k - (\partial G/\partial c)^{-1} * G(c_k)$$

- Equation for Newton Increment: $(\partial G/\partial c)(\delta c_k) = -G(c_k)$

Computing the Increment in Newton's Method

- Equation for Newton Increment: $(\partial G/\partial c)(\delta c_k) = -G(c_k)$
- It is not feasible to compute $(\partial G/\partial c)$, much less store it.

- Use a Krylov method, an iterative method for systems of linear systems well suited for this scenario.
- Key feature, each iteration evaluates the expression

$$(\partial G/\partial c)(\delta c) \approx (G(c+\sigma\delta c) - G(c)) / \sigma$$

- Evaluating this uses a forward model run of length T.

- To improve convergence of Krylov method, apply a preconditioner $P \approx (\partial G/\partial c)^{-1}$ to both sides of the linear system for the Newton increment.

Challenges/Issues that Arise

- Adding Newton increment can lead to non-physical values; the model might not be able to deal with this.
- Scale down increment to ensure physical values.
- Tracers with non-linear dynamics on timescales, O(days) or shorter, much shorter than integration length, O(years) are a challenge for the linearization of Newton's method.
- Apply Newton's method to 'shadow' copy of 'slow' tracers to allow prescribed 'fast' dynamics while spinning up long-time scale dynamics. Perform forward runs between Newton iterations to adjust 'fast' tracers to updated 'slow' tracers.

Applying Solver to Spinning Up CLM/CTSM joint with Sam Levis, Will Wieder

- Current spin-up approach use accelerated decomposition (AD) to spin up belowground pools.
- Q: Can Newton-Krylov (NK) work faster than AD?
  - relevant for hi-res and PPE

- AD is not compatible with soil microbial model (MIMICS).
- Q: Can Newton-Krylov (NK) fill the gap?

Plan:

- Get NK working for a single column, without MIMICS.
- Get NK working for global model, without MIMICS.
- Extend to MIMICS.

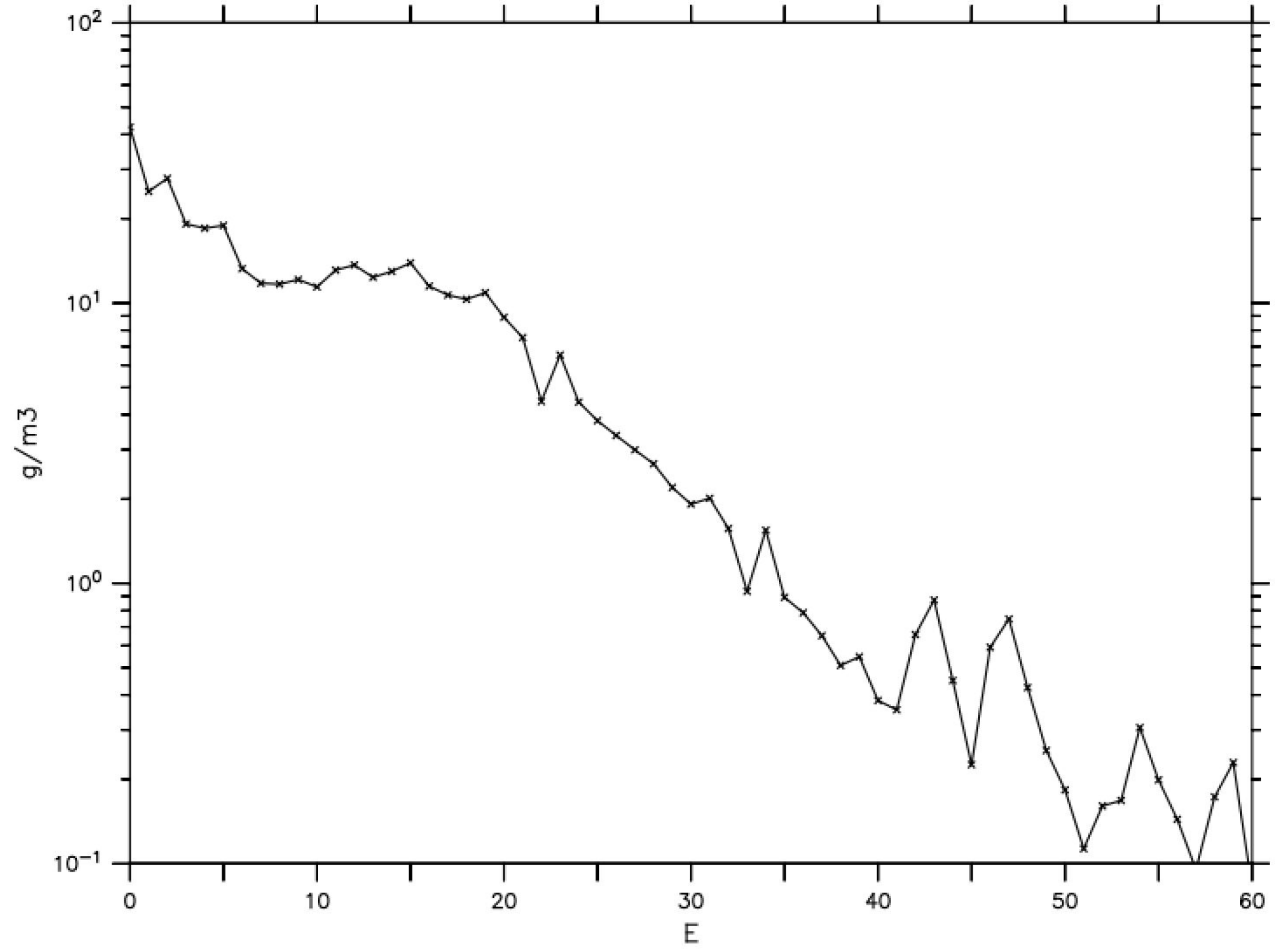
Easier Said Than Done…

1. Extend NK solver incrementally to support CLM/CTSM
2. Attempt to exercise new support
3. Run into problem
4. Investigate/analyze problem
5. Solve problem
6. Go back to 1

Sometimes this is easy, like adding history variables for a*b, because mean(a*b) does not equal mean(a)*mean(b).

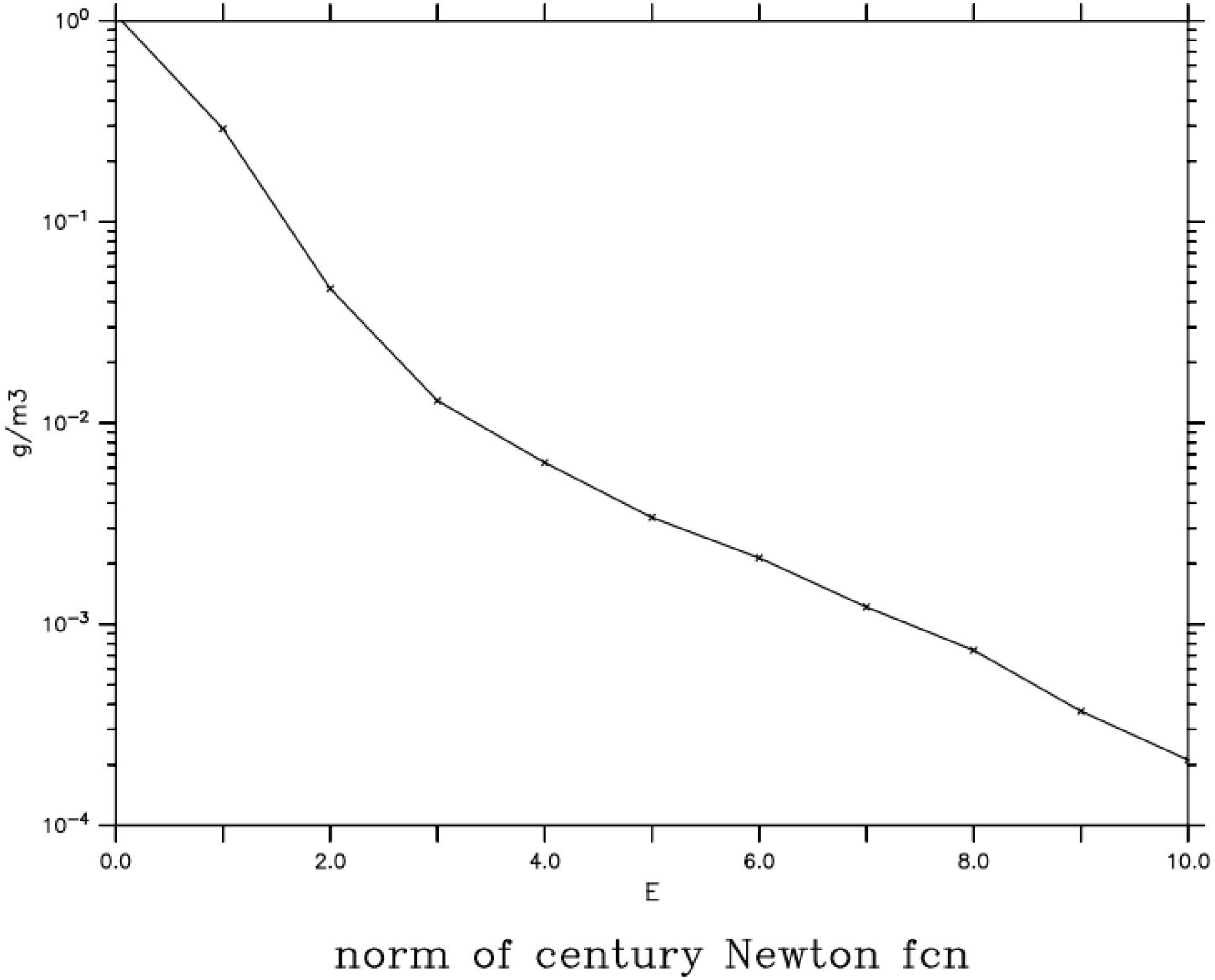
Sometimes this is more involved, like trying to understand changes in biophysics when belowground pools are updated.

||G|| from a Single Boreal Forest Column, 1 yr forcing

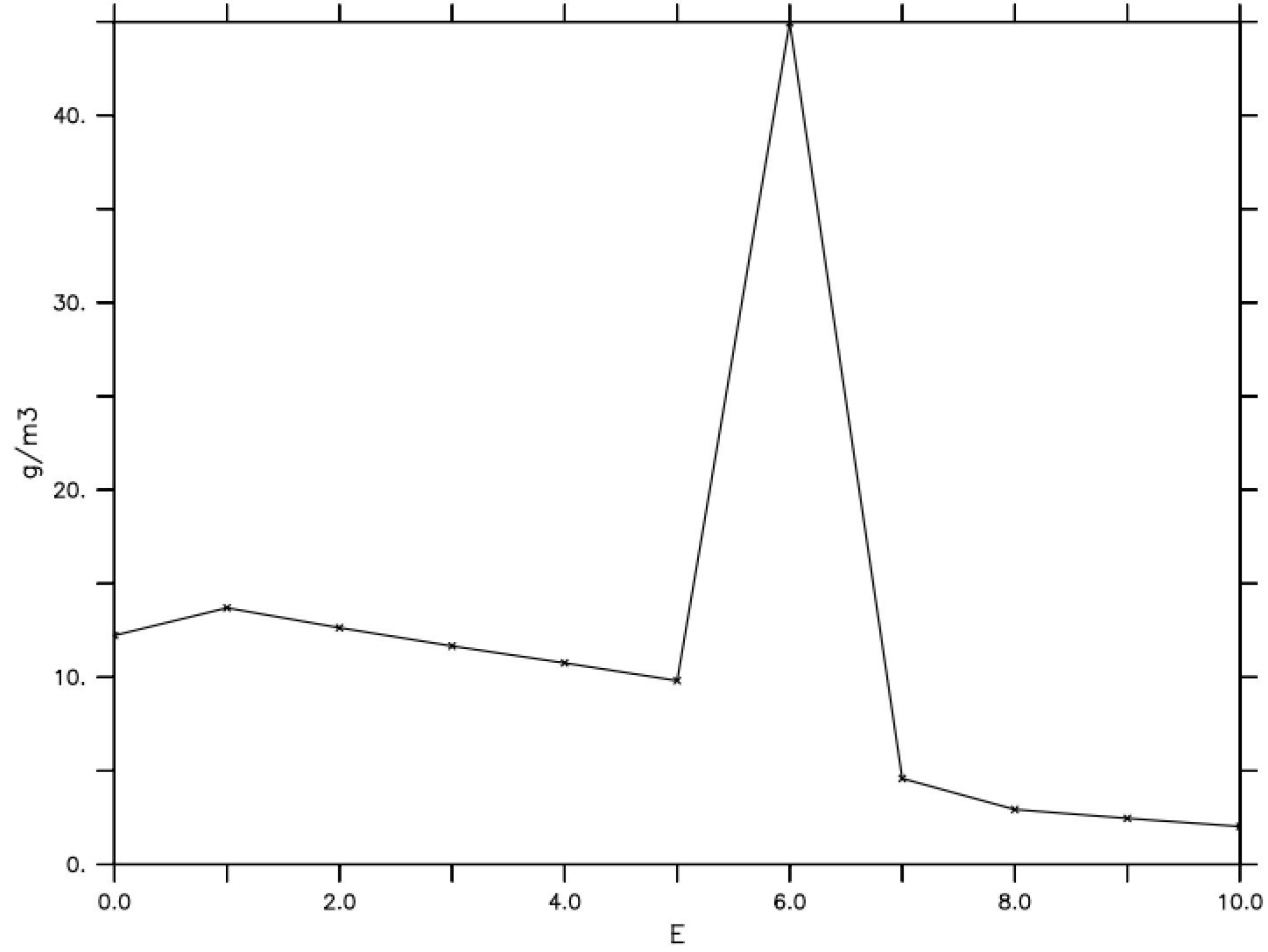


norm of century Newton fcn

||G|| from Column 108 in Global Model, 5 yrs forcing

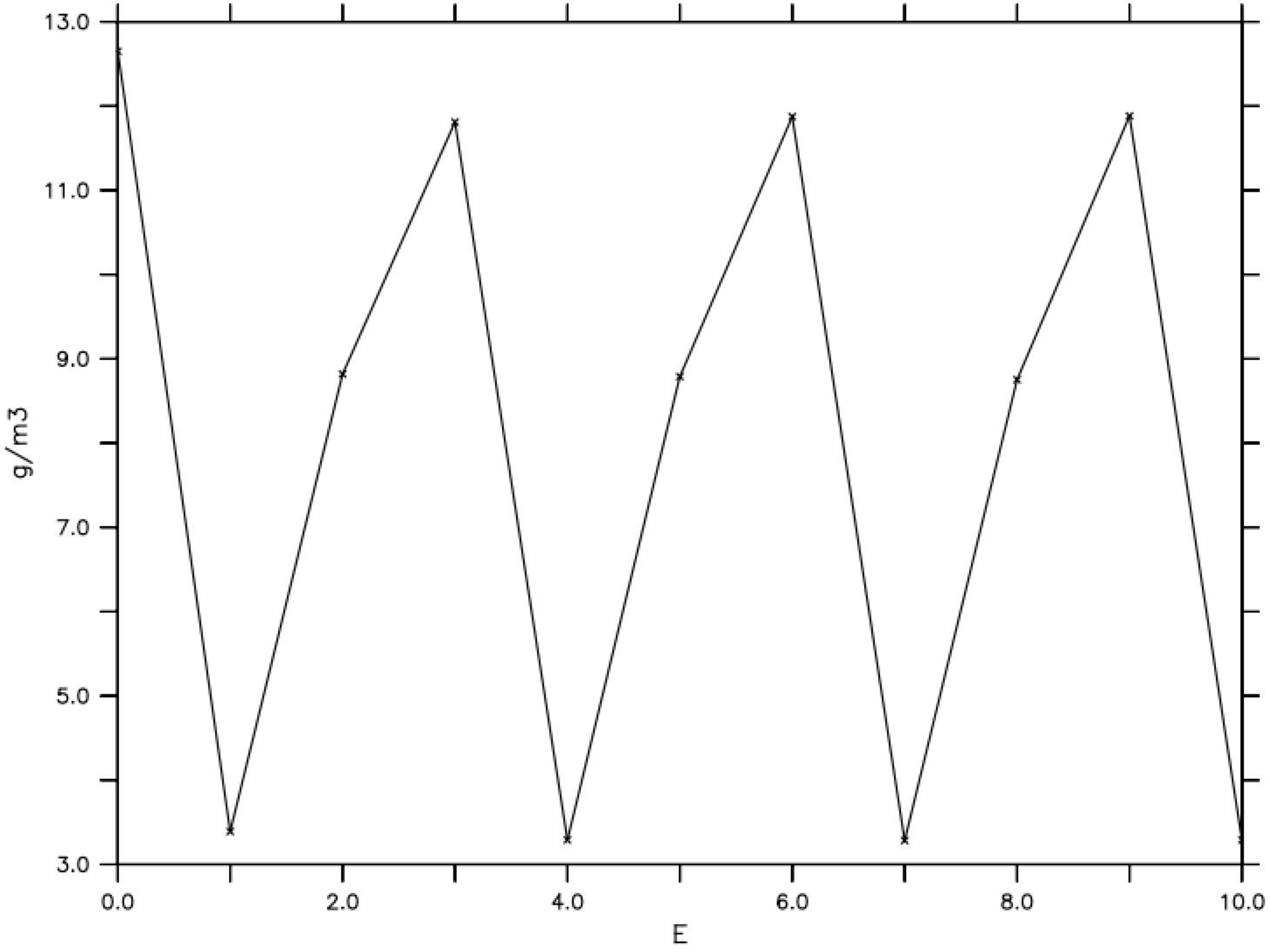


||G|| from Column 109 in Global Model, 5 yrs forcing



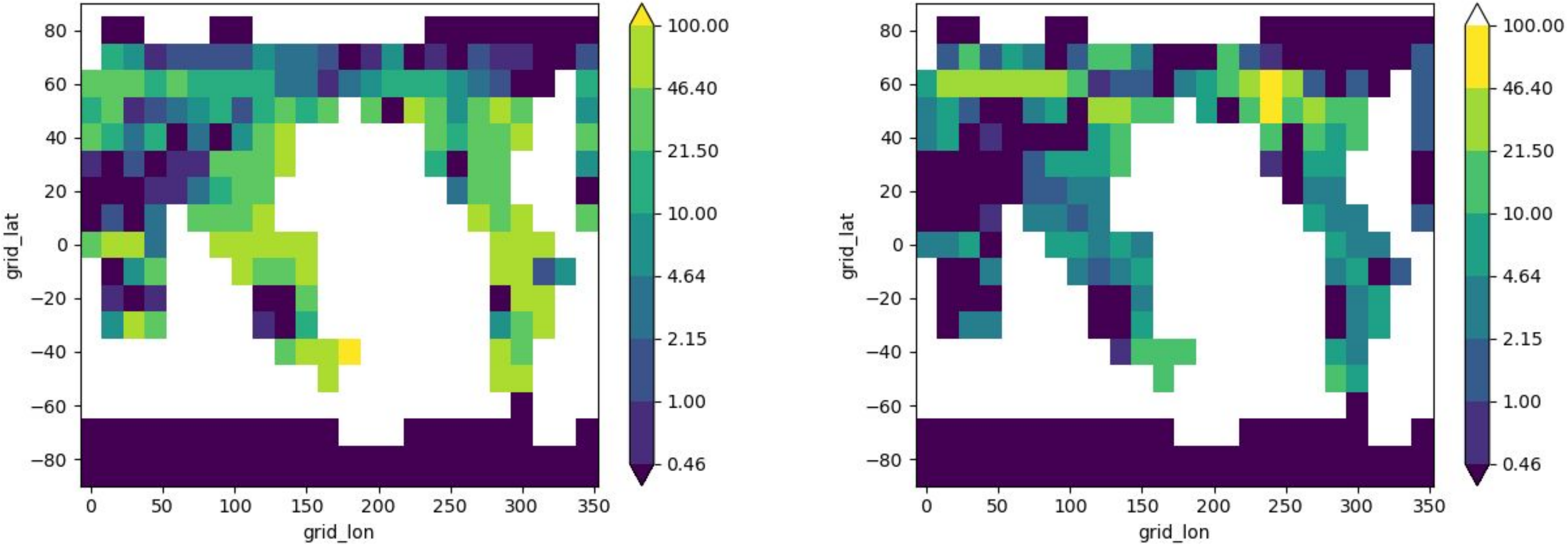
norm of century Newton fcn

||G|| from Column 113 in Global Model, 5 yrs forcing



norm of century Newton fcn

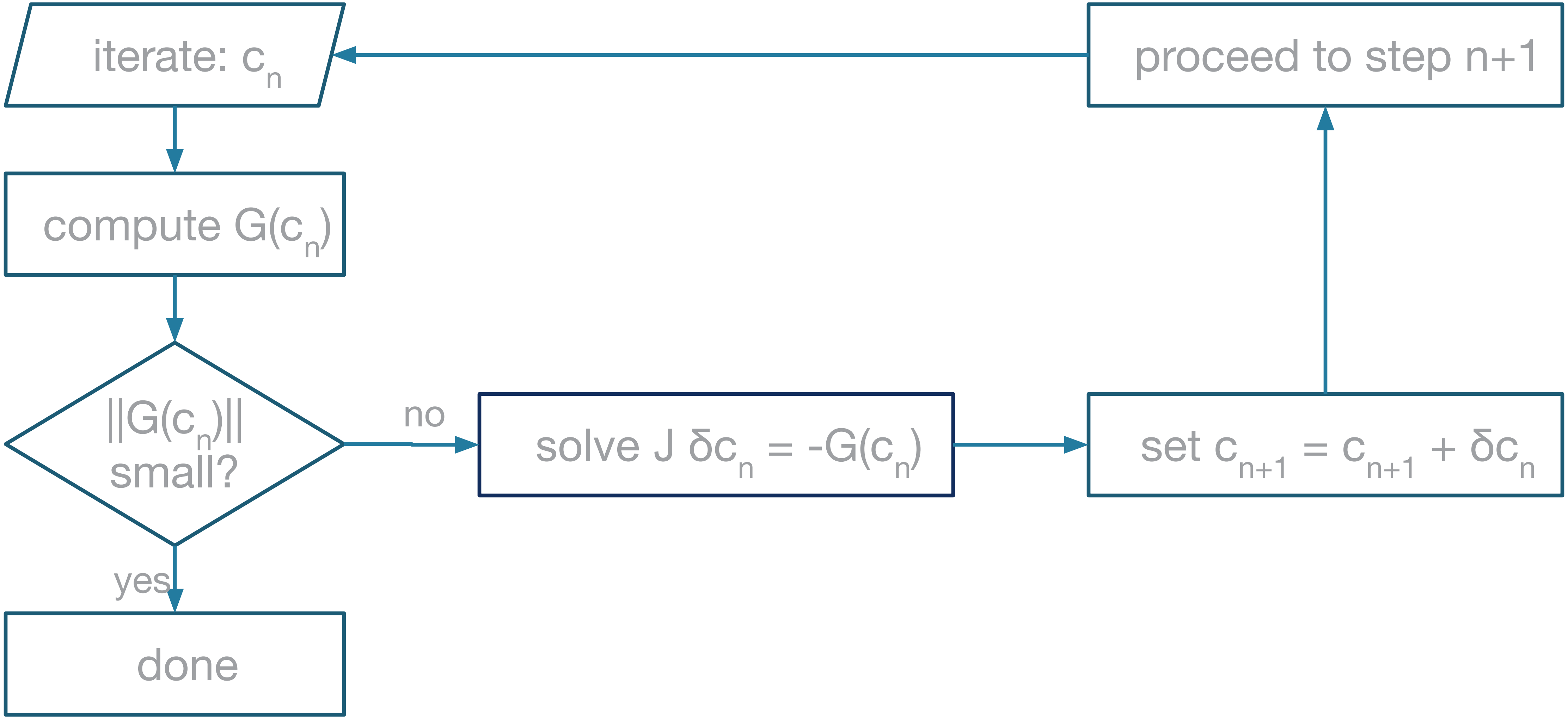
||NEE|| in Global Model, 5 yrs forcing
Newton Iterates 0 and 10



Ongoing/Future Work

- What is going wrong with problematic columns in global run?
- Why does single column require so many Newton iterations?
- Does number of Newton iterations depend on number of years of forcing?
- Can adjustment to belowground pools be accelerated?
- Can this be extended to FATES?

Simplified Newton's Method Flowchart, v1



Simplified Newton's Method Flowchart, v2