Spinning Up Tracers in the Ocean

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Statement of Problem

- Generate tracer distributions that are in balance with respect to (non-stationary) ocean model circulation (advection and mixing).
  - More precise statement later
- Applications:
  - Initializing transient experiments
  - Compare modeled tracers to observations
  - Optimize parameters to reduce model bias
    - Requires ability to spinup repeatedly

Target Model Configurations

- x1 grid: 320x384x60 (~4.2×10^6 grid points)
- Tracer modules
  - Abiotic radiocarbon: 2 tracers
  - Dye tracers: arbitrary # of independent tracers
  - CESM 1.2 ecosystem: 27 tracers
  - Active tracers: temperature & salinity
- Daily surface forcing w/ interannual variability
  - CORE or coupled model forcing
- Parameterized diurnal cycle for shortwave
  - Precludes taking large time steps for ecosystem

Newton-Krylov Solvers

Li & Primeau (2008) , Khatiwala (2008)

- Let u(t) denote tracer state.
- Model Map: $u(t) = \Phi(u(0),t)$
- Φ incorporates advection, mixing, surface fluxes, interior BGC, etc.

- Solve $\Phi(u_0,T)=u_0$ for u_0.
  - T is period of forcing and circulation.

- Rewrite as $F(u) \equiv \Phi(u,T)-u=0$
- Newton's Method:

$$u_{k+1} = u_k - (\partial F/\partial u)^{-1} * F(u_k)$$

Newton-Krylov Solvers

Li & Primeau (2008) , Khatiwala (2008)

- Use Krylov iterative method (GMRES) to solve:

$$(\partial F/\partial u)(\delta u_k) = -F(u_k)$$

- Construct Krylov basis

$$y_0,\ (\partial F/\partial u)y_0,\ (\partial F/\partial u)^2 y_0,\ (\partial F/\partial u)^3 y_0,\ \ldots$$

- Find linear combination of basis that minimizes

$$|(\partial F/\partial u)\, x + F(u_k)|^2$$

- Each GMRES iteration evaluates $(\partial F/\partial u)(\delta u)$
- Finite Difference Approximation
  - $(\partial F/\partial u)(\delta u) \approx (F(u+\sigma\delta u)-F(u))/\sigma$
  - Note this is a forward model run of length T.

Newton-Krylov Solvers

Li & Primeau (2008) , Khatiwala (2008)

- Preconditioner is a MUST for GMRES

  $(P^{-1}(\partial F/\partial u))(\delta u_k)=(P^{-1})(-F(u_k))$, $P\approx(\partial F/\partial u)$

- We use P based on time mean advection and mixing operators, extracted from POP with impulse response function tracer module.

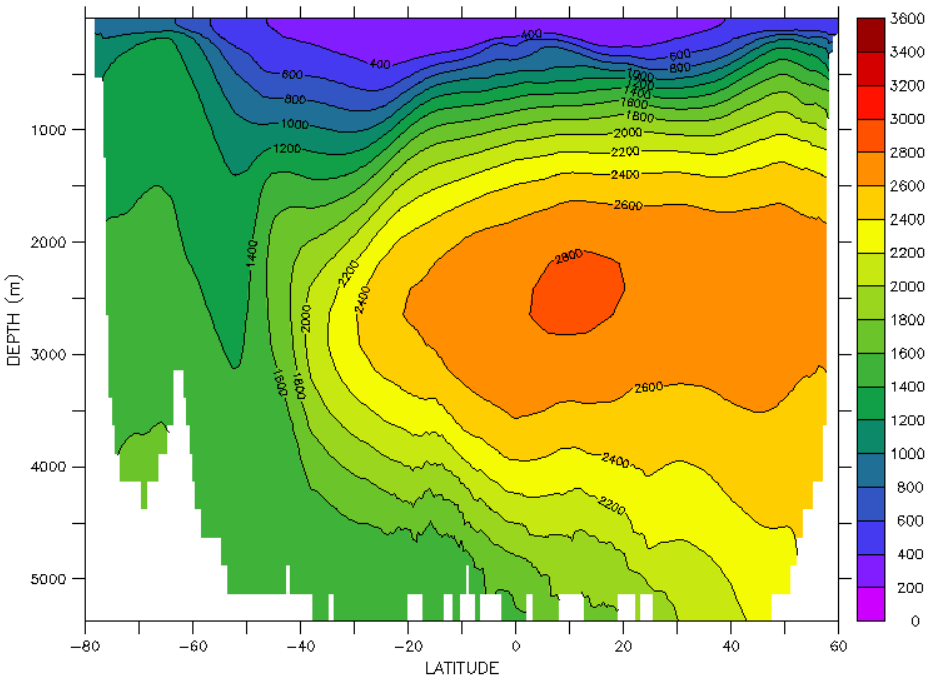
Results for Abiotic Radiocarbon

- Normal Year Forcing, x1 grid
- Active Ice Model
- Physics spun up for 150 years
- OCMIP2 protocols (implementation from A. Jahn)
- Spin up C and ^{14}C wrt model year 0151
  - Natural ^{14}C, no bomb signal
- 4 Krylov Iterations per Newton Iteration

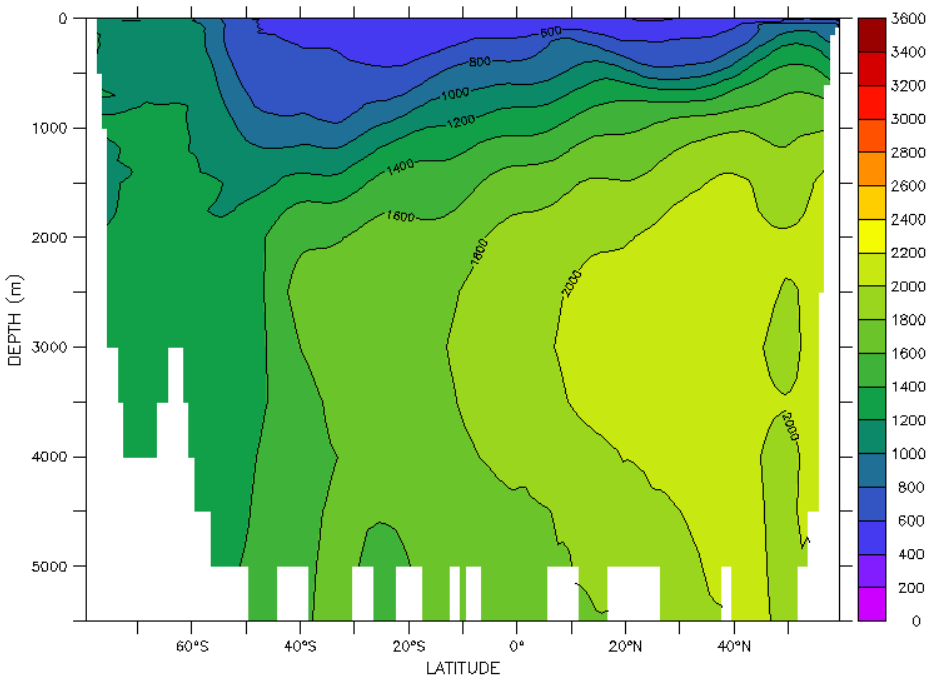
Newton Iteration	Residual RMS change	CO_2 Gas Flux (PgC/yr)	% ocean where drift in $\Delta^{14}C > 10^{-3}$ ‰/yr
0	1.5370	-3.471	100% (IC for $\Delta^{14}C = 0$)
1	0.2058	-0.228	79.2%
2	0.0247	-0.006	12.1%
3	0.0058	-0.001	2.2%

Comparing Results to GLODAP (physics spun up for 150 years)

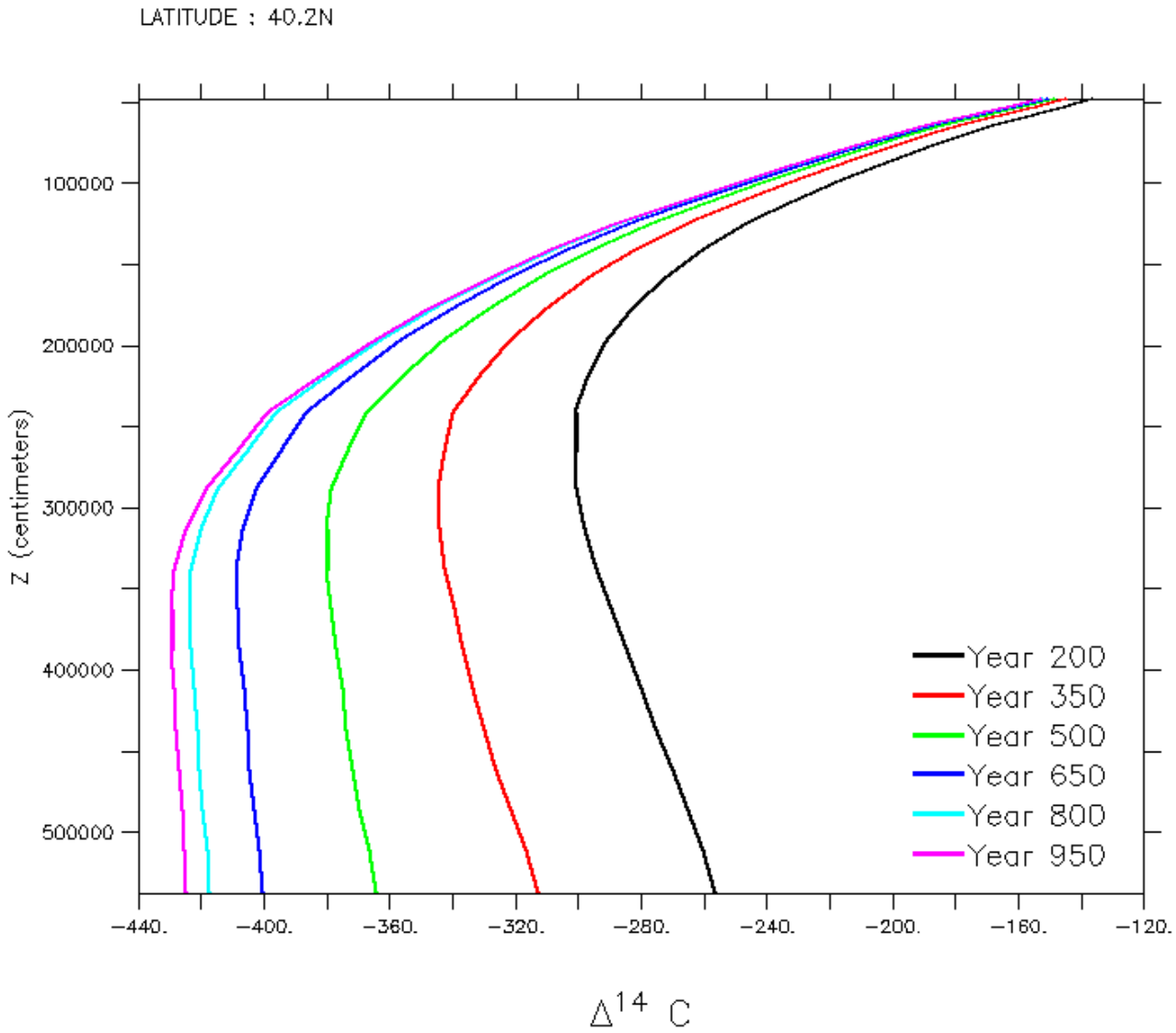
Model $\Delta^{14}C$ Age



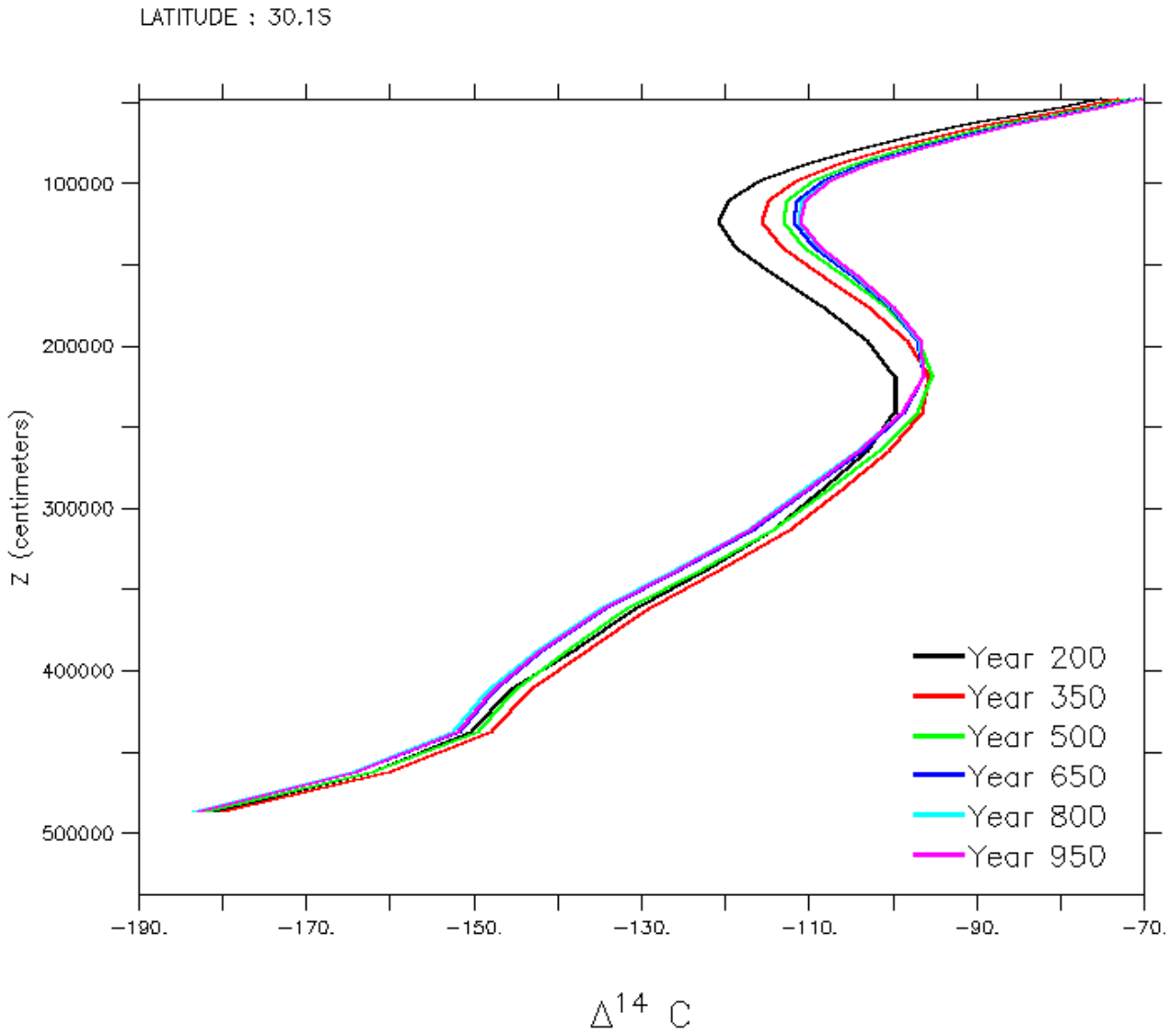
GLODAP $\Delta^{14}C$ Age



How long does the physics spinup need to be? N. Pac. O(1000 years)



How long does the physics spinup need to be? S. Atl. O(300 years)



Interannual Variability

- Spinup tracers with respect to an N-year segment of a run with interannual variability
- Each evaluation of $F(u) \equiv \Phi(u,T)-u$ now requires a forward model run of N years
  - More years is useful to avoid anomalous segments, but increases spinup cost
  - Q: How many years should you use? TBD

Interannual Variability

- Model physics (circulation and mixing operators, temperature, salinity) are no longer cyclostationary
- Results using 5 year segment of CORE hindcast indicate that this is not a problem, solver still finds cyclostationary tracer solution

Newton Iteration	Residual RMS change	CO_2 Gas+Virtual Flux (PgC/yr)	% ocean where drift in $\Delta^{14}C > 10^{-3}$ ‰/yr
0	2.6958	-0.2538	99.2%
1	0.0155	-0.0036	24.2%
2	0.0006	0.0003	0.1%

Summary & Ongoing Work

- NK spinup for ^{14}C and dye tracers (not shown) works on x1 grid
  - Useful diagnostic of deep ocean ventilation
  - Time need for physics spinup varies regionally, can be very long
- Technique works with interannual variability
  - Work is underway to study how spunup solution depends on segment of forcing
- Application to CESM 1.2 ecosystem is ongoing
  - Technique that worked in CCSM 3.5 not working
  - Alternatives are being explored
- Q: Can technique be extended to T & S?