Self-consistency Testing in the MOM6 Ocean Model in Support of Open Development

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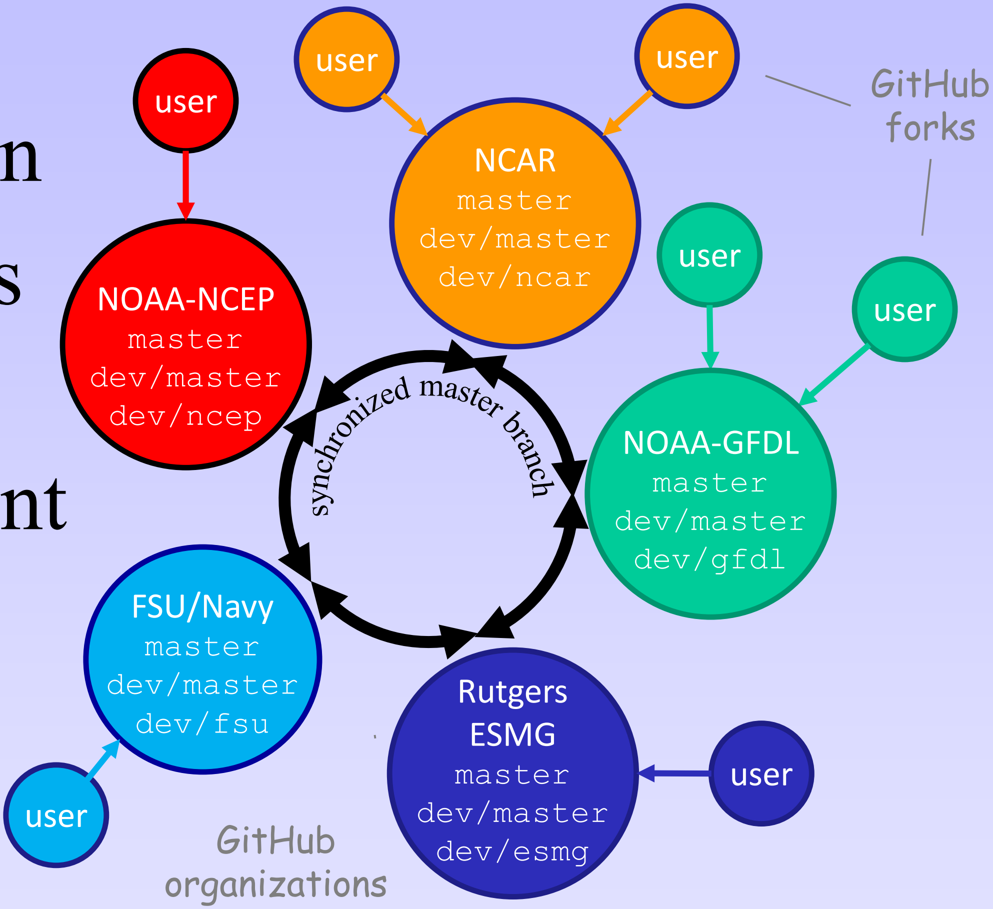
Testing Ocean Models

- How do you know an ocean model is "right"?
  - You can not prove a model is right.
  - There are always assumptions and approximations.
  - Reproducing observations to within some tolerance.
  - Expert judgement that a solution is informative for answering a particular question.
  - Reproducing known solutions in test cases.
  - Respecting physical properties (e.g., conservation).
- But you can prove that a model is wrong.
  - Failing self-consistency

MOM6 open development via GitHub

- Developing MOM6 on **GitHub** has removed barriers to collaboration
- Complete openness has attracted partners
- Continual + independent development
  - No "release delays"
- Numerous activities
  - 93 forks (as of Dec '19)
  - 5 major hubs/partners



Regression Tests

Every major center has a series of short "Regression tests" that give known answers that are reproduced whenever a test case is re-run

- The regression test answers are specific to a particular computer and compiler (and complier version)
- Code quality testing requires enough different tests to exercise most of the code (code coverage) in a wide range of parameter space to find unusual conditions
- Any solution that is important to maintain should be represented in a short test (e.g., GFDL does a 1-day run with ¼° global OM4)

Regression tests preserve solutions that are deemed right.

MOM6 Self-Consistency Tests

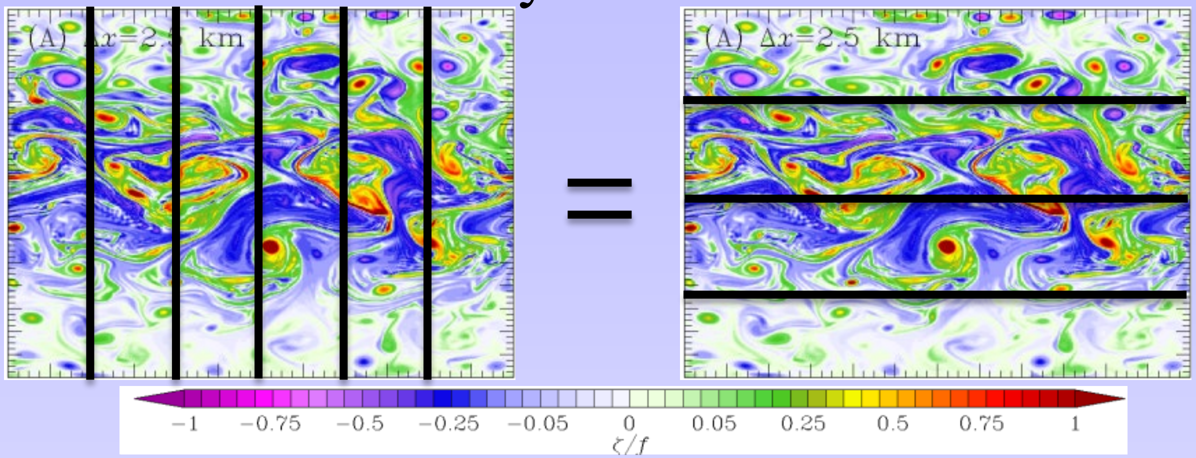
MOM6 has a series of self-consistency test which give bitwise identical answers:

- Processor count and layout
- Reproduction across restarts
- Rotational symmetry (by 180°, 90° or 270°)
- Static or dynamic memory allocation
- Symmetric or non-symmetric memory
- Input parameter validation
- Dimensional consistency rescaling by 2^n

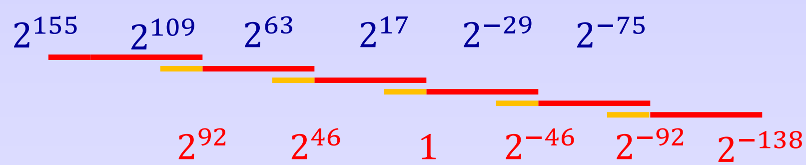
Failed self-consistency demonstrates the code is wrong.

Consistency across Processor Count

- All MOM6 and SIS2 solutions and diagnostics are identical for all processor counts and layouts



- Consistency proves that parallelization is correct
- Uses order-invariant global sums:



Represent real numbers with N integers

$$r = \sum_{i=0}^{N-1} a_i 2^{(i-N/2)M}$$

$$1 + 10^{-40} - 1 = 10^{-40}$$

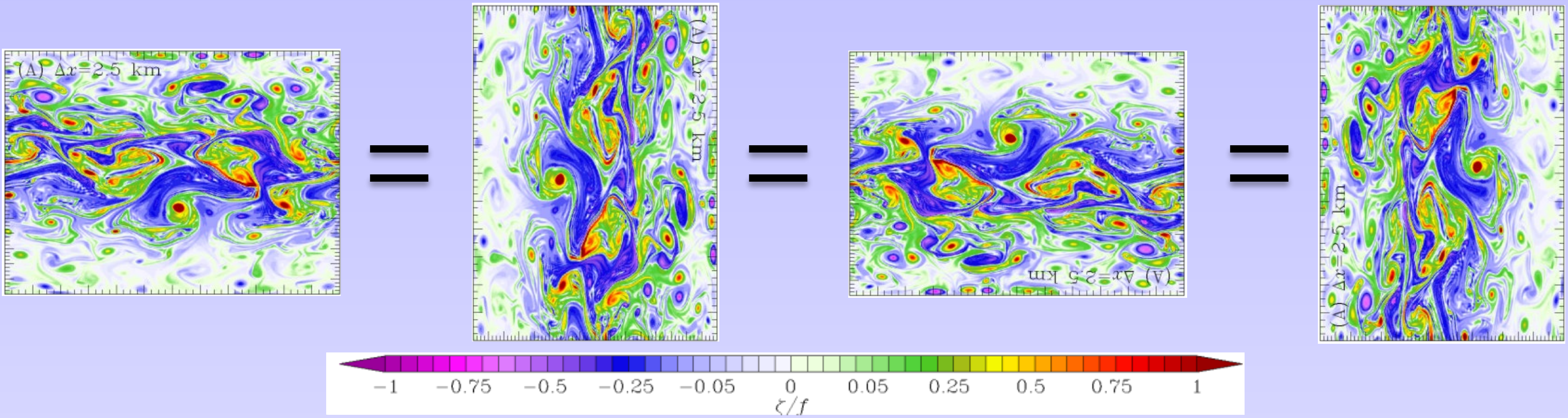
Sum the a_i to sum the real numbers, up to 2^{63-M}-1 times between carries

M=46, N=6 represents 5.605×10^{-45} to 2.923×10^{48}, up to 131071 sums/carry.

Hallberg and Adcroft, 2014: An Order-invariant Real-to-Integer Conversion Sum. *Parallel Computing*, 40(5-6), DOI:10.1016/j.parco.2014.04.007

Rotational Symmetry

- MOM6 solutions give identical solutions when rotated by 90°, 180°, or 270°



- Precludes horizontal indexing errors
- Ensures consistent discretizations of u- and v- velocity equations, 4 orientations of open boundary conditions
- Requires appropriate combinations of parentheses

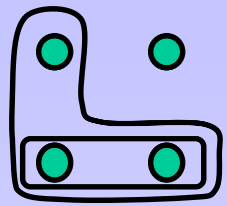
Averaging for Rotational Symmetry

Indeterminate symmetry – order up to complier:

$$\overline{h}^{i,j} = \frac{1}{4}(h_{i,j}+h_{i+1,j}+h_{i,j+1}+h_{i+1,j+1})$$

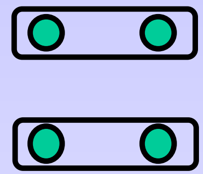
No rotational symmetry:

$$\overline{h}^{i,j} = \frac{1}{4}(((h_{i,j}+h_{i+1,j})+h_{i,j+1})+h_{i+1,j+1})$$



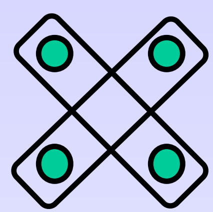
180° rotationally symmetric, not 90° :

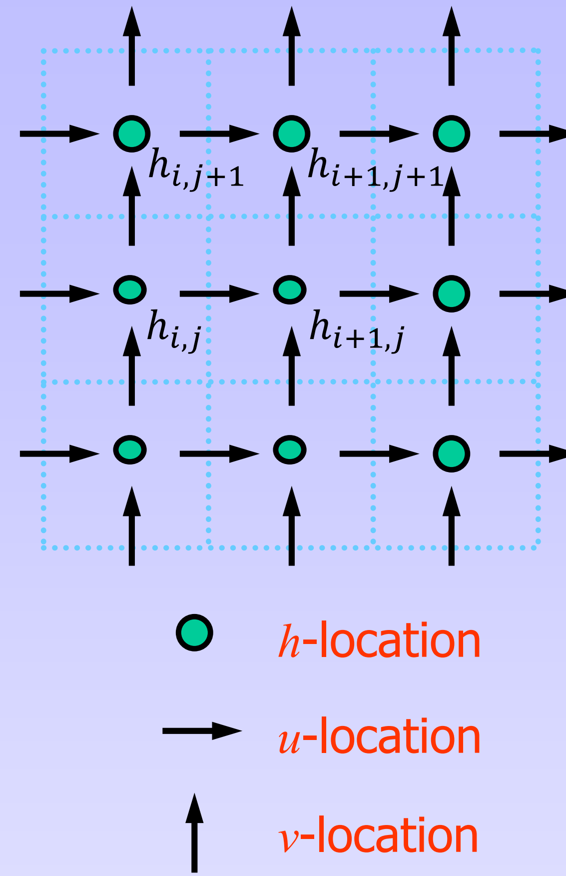
$$\overline{h}^{i,j} = \frac{1}{4}((h_{i,j}+h_{i+1,j})+(h_{i,j+1}+h_{i+1,j+1}))$$



Rotationally symmetric:

$$\overline{h}^{i,j} = \frac{1}{4}\left((h_{i,j}+h_{i+1,j+1})+(h_{i+1,j}+h_{i,j+1})\right)$$





Dimensional Consistency Testing

For any choice of integers T, L, and Z all of the following give identical solutions:

$\Delta t = 60 \ [s]$
$g = 9.8 \ [m/s^2]$
$\eta^0 = 1\cos(2\pi x/L) \ [\mathrm{m}]$

$$\underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^{n+1}} = \underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^n} - \underset{[s]}{\Delta t} \ \underset{\left[\frac{m}{s^2}\right]}{g} \ \underset{\left[\frac{1}{m}\right]}{\frac{1}{\Delta x}} \ \underset{[m]}{\left(\eta_{i+\frac{1}{2}}^n - \eta_{i-\frac{1}{2}}^n\right)}$$

$\Delta t = 60 \ [s]$
$g = 9.8 \ [m/s^2]$
$\eta^0 = 1 \times 2^{-Z}\cos(2\pi x/L) \ [2^Z\mathrm{m}]$

$$\underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^{n+1}} = \underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^n} - \underset{[s]}{\Delta t} \ \underset{[2^{-Z}]}{2^Z} \ \underset{\left[\frac{m}{s^2}\right]}{g} \ \underset{\left[\frac{1}{m}\right]}{\frac{1}{\Delta x}} \ \underset{[2^Z m]}{\left(\eta_{i+\frac{1}{2}}^n - \eta_{i-\frac{1}{2}}^n\right)}$$

$\Delta t = 60 \ [s]$
$g = 9.8 \times 2^Z \ \left[2^{-Z}\frac{m}{s^2}\right]$
$\eta^0 = 1 \times 2^{-Z}\cos(2\pi x/L) \ [2^Z\mathrm{m}]$

$$\underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^{n+1}} = \underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^n} - \underset{[s]}{\Delta t} \ \underset{\left[2^{-Z}\frac{m}{s^2}\right]}{g} \ \underset{\left[\frac{1}{m}\right]}{\frac{1}{\Delta x}} \ \underset{[2^Z m]}{\left(\eta_{i+\frac{1}{2}}^n - \eta_{i-\frac{1}{2}}^n\right)}$$

$\Delta t = 60 \times 2^{-T} \ [2^T s]$
$g = 9.8 \times 2^Z \ \left[2^{-Z}\frac{m}{s^2}\right]$
$\eta^0 = 1 \times 2^{-Z}\cos(2\pi x/L) \ [2^Z\mathrm{m}]$

$$\underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^{n+1}} = \underset{\left[\frac{\mathrm{m}}{s}\right]}{u_i^n} - \underset{[2^T s]}{\Delta t} \ \underset{[2^{-T}]}{2^T} \ \underset{\left[2^{-Z}\frac{m}{s^2}\right]}{g} \ \underset{\left[\frac{1}{m}\right]}{\frac{1}{\Delta x}} \ \underset{[2^Z m]}{\left(\eta_{i+\frac{1}{2}}^n - \eta_{i-\frac{1}{2}}^n\right)}$$

$\Delta t = 60 \times 2^{-T} \ [2^T s]$
$g = 9.8 \times 2^{Z+2T-2L} \ \left[2^{2L-Z-2T}\frac{m}{s^2}\right]$
$\eta^0 = 1 \times 2^{-Z}\cos(2\pi x/L) \ [2^Z\mathrm{m}]$

$$\underset{\left[2^{L-T}\frac{\mathrm{m}}{s}\right]}{u_i^{n+1}} = \underset{\left[2^{L-T}\frac{\mathrm{m}}{s}\right]}{u_i^n} - \underset{[2^T s]}{\Delta t} \ \underset{\left[2^{2L-Z-2T}\frac{m}{s^2}\right]}{g} \ \underset{\left[2^{-L}\frac{1}{m}\right]}{\frac{1}{\Delta x}} \ \underset{[2^Z m]}{\left(\eta_{i+\frac{1}{2}}^n - \eta_{i-\frac{1}{2}}^n\right)}$$

Dimensional Consistency Testing

MOM6 has complete dimensional consistency testing by rescaling 5 units:

1. Time [T ~> s]
2. Density [R ~> kg m^{-3}]
3. Horizontal distance [L ~> m]
4. Vertical height [Z ~> m]
5. Vertical thicknesses [H ~> m] (Boussinesq) or [H ~> kg m^{-2}]

- Rescaling each unit by powers of 2 ranging from 2^{-140} to 2^{140} ($\approx 1.4\times10^{42}$) gives bitwise identical answers.
- Could also implement rescaling for heat, salt, and tracer content.
- External packages (CVMix, equation of state) are excluded from testing.
- A "unit scaling type" with conversion factors is passed around the code for conversion to or from mks units for debugging, rescaling constants, etc.

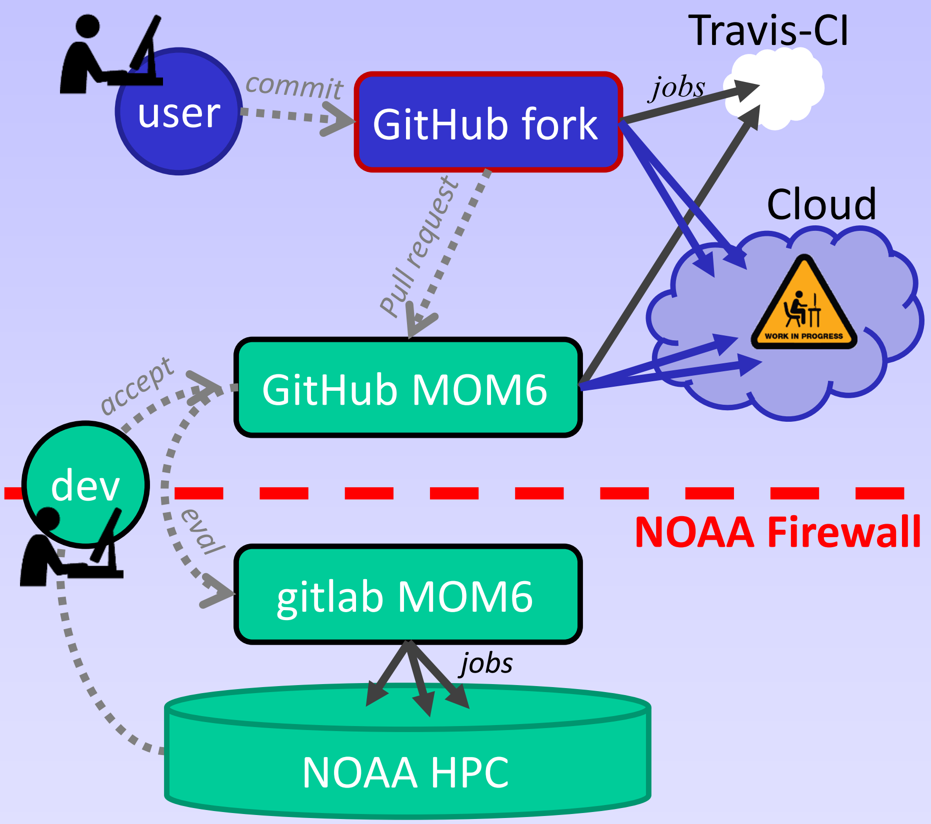
If underflow happens, it has to happen at the same rescaled value.

Rescaling is undone for diagnostics before output.
Reproducing sums via the extended fixed-point have to be unscaled before sums.

Additive adjustment (e.g. changing from °C to °K) leads to changes at roundoff.

MOM6, testing, and the cloud

- Cloud computing offers opportunity to stream-line open development
- Most testing currently uses HPC resources AFTER code evaluation
- We want to move more testing to the **cloud** to become part of code evaluation process



Where automated MOM6 testing happens

	NOAA HPC	Travis-CI	Other HPC
Compiles	Yes	Yes	Yes
Regressions	Yes		(NCAR, EMC)
Parallel Layout	Yes	Limited	
Restarts	Yes	Yes	
Static/dynamic Memory	Yes	Yes	
Symmetric Arrays		Yes	
Unit Tests (e.g. remapping)		Yes	
Valgrind			Yes
Performance Optimization	Yes	Limited	Yes
Rotational Symmetry	Partial	Yes	
Dimensional Units	Yes	Yes	
Code Style		Yes	
Code testing coverage		Yes	
Documentation coverage		Partial	

NOAA/GFDL perspective on "Community Models"

- Discussion should consider both community **codes** (e.g., MOM6 codebase) and publicly available **configurations** (e.g., GFDL-CM4 coupled climate model)
- Community codes offer opportunities for both access and input; MOM6 is using an **Open Development** approach via GitHub.
- Successful community codes require **institutional commitment**
  - MOM line of GFDL-supported community ocean models dates back to the 1980s.
  - All GFDL ocean & sea-ice development united around MOM6 & SIS2.
- Robust **testing** is required; available to all users and contributors.
  - MOM6 is routinely tested on ~40 standard test cases, with 3 different compilers..
  - Answer invariance to orientation, processor count, restarts, and unit changes by factors of 2^n.
  - Conservation of heat, salt and mass to 1 part in $\sim 10^{15}$ are routinely monitored.
- **Documentation**
  - Simple (short) introductory documentation & peer-reviewed detailed papers (no 1000 p. tome).
  - Clear standards for coding & style, consistently followed (always in progress).
  - Internal code documentation of all routines, arguments and variables (with units).
  - Self-documenting configurations (e.g., parameters).
- Community **engagement** is required…
  - MOM5 had 1000s of users, 10s of contributors; MOM6 community is still growing.
  - Diagnostics, physical process parameterizations & biogeochemical cycles provide particularly good opportunities for community contributions.