A Test Suite for GCMs: An Intercomparison of 11 Dynamical Cores

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Motivation

• Test cases for 3D dynamical cores on the sphere
  – are hard to find in the literature
  – are often not fully documented
  – have (often) not been systematically applied by a large number of modeling groups
  – lack standardized & easy-to-use analysis techniques

• Idea: Establish a collection of test cases that finds broad acceptance in the community

• Test suite that clearly describes the initial setups and suggests evaluation methods like the
  – Test suite for the SW equations (Williamson et al. 1992)
  – Proposed test suite for 2D non-hydrostatic dynamical cores (Bill Skamarock, NCAR, see Bill’s web page: http://www.mmm.ucar.edu/projects/srnwp_tests/#proposal)
Goals of the Test Suite

Test cases should

• be designed for hydrostatic and non-hydrostatic dynamical cores on the sphere, for both shallow and deep atmosphere models

• be easy to apply: analytic initial data (if possible) suitable for all grids formulated for different vertical coordinates

• be easy to evaluate: standard diagnostics

• be relevant to atmospheric phenomena

• reveal important characteristics of the numerical scheme

• have an analytic solution or converged reference solutions
Deterministic Test Cases for Dry Dycores

• Hydrostatic & shallow-atmosphere non-hydrostatic
  – Baroclinic waves:
    • Jablonowski and Williamson, QJ (2006)
    • Polvani et al., MWR (2004)
  – Test suite (Jablonowski et al., to be submitted to GMD)
    http://www-personal.umich.edu/~cjablono/dycore_test_suite.html

• Non-hydrostatic (deep and/or shallow atmosphere)
  – Exact solutions:
    • Steady-state: Staniforth and White, QJ (2007)
    • Unsteady: Staniforth and White, QJ (2008)
  – Reduced planet: Wedi and Smolarkiewicz, QJ (2009)
Test cases on the sphere:
NCAR 2008 ASP Colloquium (June ‘08)
Peter Lauritzen, Christiane Jablonowski, Mark Taylor, Ram Nair

A community effort towards standard evaluations of dynamical cores with over 11 modeling groups, 36 students and 17 lecturers
Participating Dynamical Cores

1) GISS-BQ (NASA GISS)
2) CAM Eulerian (NCAR)
3) CAM FV-isen with isentropic vertical coordinate (NCAR)
4) CSU Model (Colorado State University)
5) GEOS FV (NASA GSFC, GFDL, same as CAM-FV (NCAR))
6) GEOS FV-CUBE (NASA GSFC, GFDL)
7) GME (German Weather Service DWD)
8) HOMME (NCAR)
9) ICON (MPI, DWD)
10) MIT GCM (MIT)
11) OLAM (Duke University)
Models with Latitude-Longitude Grids

1) GISS-BQ (NASA GISS)
2) CAM Eulerian (NCAR)
3) CAM FV-isen with isentropic vertical coordinate (NCAR)
4) CSU Model (Colorado State University)
5) GEOS FV (NASA GSFC, GFDL, same as CAM-FV (NCAR))
6) GEOS FV-CUBE (NASA GSFC, GFDL)
7) GME (German Weather Service DWD)
8) HOMME (NCAR)
9) ICON (MPI, DWD)
10) MIT GCM (MIT)
11) OLAM (Duke University)
Models with Triangular/Icosahedral Grids

1) GISS-BQ (NASA GISS)
2) CAM Eulerian (NCAR)
3) CAM FV-isen with isentropic vertical coordinate (NCAR)
4) CSU Model (Colorado State University)
5) GEOS FV (NASA GSFC, GFDL, same as CAM-FV (NCAR))
6) GEOS FV-CUBE (NASA GSFC, GFDL)
7) GME (German Weather Service DWD)
8) HOMME (NCAR)
9) ICON (MPI, DWD)
10) MIT GCM (MIT)
11) OLAM (Duke University)
Models with Cubed-Sphere Grids

1) GISS-BQ (NASA GISS)
2) CAM Eulerian (NCAR)
3) CAM FV-isen with isentropic vertical coordinate (NCAR)
4) CSU Model (Colorado State University)
5) GEOS FV (NASA GSFC, GFDL, same as CAM-FV (NCAR))
6) GEOS FV-CUBE (NASA GSFC, GFDL)
7) GME (German Weather Service DWD)
8) HOMME (NCAR)
9) ICON (MPI, DWD)
10) MIT GCM (MIT)
11) OLAM (Duke University)
Models with Hexagonal Grids

1) GISS-BQ (NASA GISS)
2) CAM Eulerian (NCAR)
3) CAM FV-isen with isentropic vertical coordinate (NCAR)
4) CSU Model (Colorado State University)
5) GEOS FV (NASA GSFC, GFDL, same as CAM-FV (NCAR))
6) GEOS FV-CUBE (NASA GSFC, GFDL)
7) GME (German Weather Service DWD)
8) HOMME (NCAR)
9) ICON (MPI, DWD)
10) MIT GCM (MIT)
11) OLAM (Duke University)
Proposed Dynamical Core Test Suite used during the 2008 NCAR ASP Colloquium

• All tests are formulated on the sphere
• Some have multiple test variants, e.g. rotation angle $\alpha$

1. Steady-state test case (various rotations $\alpha$)
2. Evolution of a baroclinic wave (various rotations $\alpha$)
3. 3D advection experiments (various rotations $\alpha$)
4. 3D Rossby-Haurwitz wave with wavenumber 4
5. Mountain-induced Rossby wave train
6. Pure gravity waves and inertial gravity waves
Test 1: Steady-State Initial Conditions

- Analytical solution to the Primitive Equations with pressure-based vertical coordinates (like $\sigma$ or $\eta$)
- Initial state is the analytic solution
- Prescribe $v = 0$ m/s, $p_s = 1000$ hPa
- Prescribe $u \rightarrow$ derive $\Phi_s$ and $T$

Test 1: Grid imprinting

- Grid imprinting decreases with increasing resolution
- Emphasized by idealized test setup
- Important for real runs?

Model GME: Surface pressure at day 11
Test 1: $p_s$ at day 1 with different $\alpha$

(2°x2°)

CAM-EUL

$\alpha = 0°$

CAM-FV

$\alpha = 45°$ new ‘poles’ $\alpha = 90°$

FV-CUBE

HOMME
Test 1: $p_s$ at day 1 with different $\alpha$

- Rotation angles increase the difficulty of the test and remove the grid alignment of the flow in lat-lon grids
- Test reveals problematic spots and grid imprinting
- Lauritzen et al., to be submitted to JAMES
Test 1: $p_s$ at day 9, rotated back

$\alpha = 0°$  $\alpha = 45°$  $\alpha = 90°$

Overlaid wave 2 and 4

‘Perfect’ balance

wave 4

Overlaid wave 2 and 4

wave 4

(2° x 2°)

CAM-EUL

CAM-FV

FV-CUBE

HOMME
Test 1: $p_s$ at day 9, rotated back

(2°x2°)

ICON

CSU (hybrid)

CSU (sigma)

- Initial (grid-induced) perturbation has grown
- Vertical coordinate matters (CSU)
Test 2: Baroclinic Waves

- 850 hPa temperature field (in K) of an idealized baroclinic wave at model day 9
- Initially smooth temperature field develops strong gradients associated with warm and cold fronts
- Explosive cyclogenesis after day 7
- Baroclinic wave breaks after day 9
- Models start converging at 1°
Test 2: Model Intercomparison, $p_s$ at Day 9

with $\alpha=0^\circ$, resolution $\approx 1^\circ \times 1^\circ L26$
Test 2: 850 hPa Vorticity at Day 9

- Differences in the vorticity fields grow faster than $p_s$ diff.
- Small-scale differences easily influenced by diffusion
- Spectral noise in EUL and SLD (L26)
Test 2: Model Convergence

- Single-model uncertainty stays well below the uncertainty across models
- Models converge within the uncertainty for the resolutions T85 (EUL & SLD), around 1° (FV), GME (55km / ni=128)
Test 2: Standard Diagnostics KE Spectra

Variation with resolution

Multi-Scale Kinetic Energy Spectrum (700 mb)

700 hPa, Day 15

GME, day 15
test 2

Variation with time

NASA
FVCUBE,
0.5°, test 2
Test 3: 3D Advection Tests

• Prescribe the 3D wind field: Solid body rotation in 2D (Williamson et al. 1992) plus vertical velocity
• Use different rotation angles $\alpha$

• Prescribe two 3D tracer distributions: $z-\varphi$ cross section

Smooth: Cosine bell
Non-smooth: Slotted ellipse
Test 3: Vertical advection

Tracers undergo 3 wave cycles in the vertical

Tracers return to initial position after 12 days:
Allows assessment of the diffusion
Test 3: Slotted Ellipse after 12 Days

with $\alpha=0^\circ$, ($\approx 1^\circ \times 1^\circ L60$, $dz=250$ m)
Test 3: Slotted Ellipse after 12 Days

Rotation angles can matter
Most insensitive: models GISS-BQ, FVCUBE, HOMME

≈1°×1°L60, dz=250 m
Test 4: 3D Rossby-Haurwitz Wave

BQ (GISS)  CAM-EUL  CAM-FV-isen
GEOS-FV  GEOS-FVCUBE  GME
HOMME  ICON  MIT

Zonal wind at day 15 (≈1°×1°L26)
Test 4: Assess diffusion and symmetry

- Diffusion is needed for stability in EUL
- OLAM shows reduced amplitudes

Zonal wind at day 15 ($\approx 1^\circ \times 1^\circ$ L26)
Test 5) Mountain-induced Rossby waves

- Initial $u$, $p_s$, $z_s$ fields, isothermal, $v=0$ m/s, balanced
- Mountain triggers the evolution of Rossby waves
- Hydrostatic, nonlinear regime
Days 15 & 25: Mountain-induced waves

CAM-FV 180x360L26
Test 5: Noise or Physical Nonlinear Effects?

700 hPa zonal wind at day 15 (≈1°×1°L26)
Test 5: Noise or Physical Nonlinear Effects?

CAM-EUL

Noise, underdiffused

700 hPa zonal wind at day 25 (∼1° × 1° L26)
Test 6: Pure Gravity Waves (time series)

CAM-EUL T106 L20 with standard diffusion, $\Theta'$ cross section along equator
Test 6: Θ’ cross section along the equator

Day 4, (≈1°×1°L20)

Check sharpness amplitude, speed
Observations

- Test suite used during the ASP colloquium got very positive feedback from the modeling community
- We suggested specific diagnostics and the evaluation of specific time snapshots
- Tests had increasing complexities:
  - Pure advection
  - Irrotational
  - Steady state
  - Idealized topography
  - From large to small scales, nonlinear barclinic waves
- Next version of the test suite needs
  - more nonlinear, small-scale tests
  - non-hydrostatic tests on the sphere
  - more diagnostics
  - Extensions/provisions for deep-atmosphere models
  - Simplified physics?
Future candidates

- 3D Mountain Waves (irrotational) on the sphere: hydrostatic & non-hydrostatic, linear & non-linear
- Acoustic Waves (non-hydrostatic)
- Dycore tests with real orography
- Moist dycore tests with intermediate complexity:
  - Moist baroclinic waves
  - Idealized tropical cyclones:
    - Prescribed tropical vortex
    - Balanced initial data, ocean-covered surface with specified (e.g. constant) SST