GFDL’s finite-volume Cubed-Sphere Dycore: Basic formulation, performance, and its applications in weather & climate modeling

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- Model genealogy
- Improved FV algorithms on the cubed-sphere and the scaling performance
- New capability: Global “regional climate models”
  1. Stretch-grid
  2. 2-way nested regional-global
- Ultra-high resolution climate simulations and seasonal hurricane predictions

CESM Atmosphere Model Working Group Meeting, 1-3 Feb 2012
Recent GFDL publications using the cubed-sphere dycore


The Finite-Volume model family tree

- **NASA fvGCM**
  - NASA GEOS-5
  - NCAR CCSM/CESM
  - GFDL ESM
  - GFDL CM2.1
  - ECHAM 5 (transport)
  - NASA GMI
  - NASA GOCART
  - Harvard GEOS-Chem
  - Seoul Univ GCM

- **GFDL**
  - GFDL HiRam
  - GFDL CM2.5
  - GFDL CM3

- **Cloud-Resolving stretched-Cube**
  - GFDL

- **NASA**
  - GEOS-6
  - GMI

- **China**
  - IAP GCM

- **Seoul Univ**
  - GCM

**Color Code:**
- **RED:** IPCC AR4
- **BLUE:** IPCC AR5
- **Green:** research/weather
The GFDL Cubed-Sphere dynamical Core

Based on the Lin-Rood FV algorithms with the following mods:

- Cubed-Sphere geometry (Putman and Lin 2007) with two variable-resolution options (stretched and 2-way regional global nesting)
- Improved accuracy in vertical remapping with 2-delta-z constraint
- 4\textsuperscript{th} order remapping/interpolation between D and C grids
- 4\textsuperscript{th} order pressure gradient
- A new “alpha” parameter to control time weighting (fully backward with alpha = 0) → improved representation of gravity waves
- Optional del-n damping on divergence (n=2, 4, 6, 8)

\textit{Warning:} use of del-2 divergence damping may suppress QBO in low resolution simulations
Two alternatives to achieve ultra-high resolution within the GFDL cubed-sphere model

I. Multi-grid:

• 3X grid-size reduction with minimal impact to throughput using non-overlapping CPUs for the 7th tile

• Regional component can be run independently (for down-scaling) or coupled with global grid to allow feedback

II. Stretched grid

Single-grid model with smooth transition in resolution with 3X grid-size reduction in target region; 3X enlargement on the back side
C360 (~ 25 km) L47; Held-Suarez with 4 tracers on CRAY XE6

Notes:
- New NOAA “climate super-computer” not yet optimized for OpenMP
- Tracer transport scales better than the rest of the model components
Climate Model inter-comparisons: GFDL finite-volume models vs. 10 other IPCC AR4 models (Zhao et al 2009)
Annual mean Temperature

C720 (12.5 km) vs. ECMWF analysis

NCEP analysis vs. ERA40

NCEP Reanalysis vs. ECMWF analysis

RMSE=1.60 (deg.) vs. RMSE=0.88
DJF precipitation in Western US: GFDL models vs. PRISM

GFDL AM2 (220 km)

12.5-km GFDL HiRAM

50-km GFDL HiRAM

PRISM (obs)
Seasonal (July-November) hurricane predictions
1990-2010

(five months, five members)

North Atlantic Basin (Hurricanes)

- obs
- mean*1.154 (bias removed)
- mean

Corr. = 0.88 0.78 0.94
RMSE = 1.91 1.92 1.90
Bias = -0.94 -0.52 -1.33

21 yrs 90-99 00-10
Predicted PDF of the Tropical Cyclones intensity
(all basins 1990-2010)

10-m wind

Central pressure

(Chen & Lin, submitted)
Final notes

• The FV core on the cubed-sphere grid is an evolution/refinement of an existing product, not a brand new development.
  – There are some grid imprint at edges of the cubed sphere
  – Overall numerical accuracy is much improved as compared to the “lat-lon” core

• Scaling performance is excellent on platforms that can take advantage of non-blocking message passing (such as the new NOAA climate machine C2)

• Tracer transport is more efficient (and less numerical diffusion) than the old (frozen) FV lat-lon core

• Two variable resolution options (via stretched or regional-global 2-way nesting; or both); can also be run in doubly periodic domain

• Grid generation, terrain filters, vertical remapping and horizontal interpolation of ICs are built into the cubed-sphere core (therefore, parallelized) → no offline tools needed

• CESM implementation:
  – GFDL will support the effort
  – NCAR?
Testing the (non) impact of 2-way nesting on large-scale:

Rossby wave-4 at day 14

Fig. 5. Height at 14 d in the shallow-water Rossby-Haurwitz wave test (Willianson test case 6, contour interval = 2 m) for (a) c48 nested grid simulation and (b) a c180 nested grid simulation.

(Harris and Lin, manuscript submitted)
Enhancing regional resolution in a global modeling framework

Simulations of lee vortices west of Island of Hawaii

C360 uniform resolution  C120 2-way nested grid  C120 uniform resolution

Fig. 15. Surface vorticity (contour interval $10^{-5}$ s$^{-1}$, negative values in gray, values above $5 \times 10^{-5}$ s$^{-1}$ not plotted) at $t = 72$ h in simulations initialized at 0000 UTC on 1 August 2010. Hawaii is at center-right in each panel. Dotted line in left-most panel shows where the nest would be in the nested-grid c120 simulation.