FV3 In a Nutshell

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for the GFDL FV3 Team
UFS S2S All-Hands Meeting
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FV3 Community Resources

FV3 Portal
Documentation, publications, tutorials, and demos
www.gfdl.noaa.gov/fv3

www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/
“Nobody can contribute to FV3”

Misconception #1
FV3 Community GitHub

• An open GitHub repository for FV3 was established in 2019 as a **community hub** and official repository for codes.

• FV3 GitHub accepts submissions (**merge requests**) from collaborators and **tracks issues** submitted when problems arise.

• GFDL personnel review and approve issues/MRs as they arrive, time permitting

• **Continuous Integration/ Deployment (“CI/CD”)** automatically tests MRs

```html
github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere
```
“There is too little information on FV3”
A Scientific Description of the GFDL
Finite-Volume Cubed-Sphere
Dynamical Core

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14 June 2021
Revision v1.0 16 June 2021
GFDL, Weather and Climate Dynamics Division
Technical Memorandum: GFDL.2021.001

Harris et al. (2021)
109-page FV3 Scientific Documentation
on GitHub and NOAA Institutional Repository

www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/
FV3 GitHub Resources

- Documentation (with LaTeX source) and example notebooks available on GitHub
- Issues, discussions, and versioned releases
  - GFDL has a heavy presence on GitHub. FMS, MOM6, AM5, SHiELD, Pace, containers, & GFDL tools all developed through GitHub.

[GitHub GFDL Atmosphere](https://github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere/tree/main/docs)
“FV3 has stability problems”

Misconception #3
Timestepping in FV3

• Innermost “acoustic”/Lagrangian loop and non-passive advection
  • Limited by $U + c_s$: in stratosphere $U$ can get to $200 \text{ m/s}$!!

• Lagrangian layers periodically remapped to reference “Eulerian” layers
  • Needed to run \textit{physics}, both intermediate (microphysics) and slow
  • Relieves strongly distorted layers and prevents $\delta p \rightarrow 0$

• Passive tracers are advected on the remapping step
  • \textit{Adaptive} substepping from global $U_{max}$: rarely more than 3 per remap

• Lagrangian Vertical Coordinate: \textbf{No} vertical courant number restriction
Examples of timesteps in GFDL global models

<table>
<thead>
<tr>
<th></th>
<th>C768 SHiELD</th>
<th>C3072 X-SHiELD (lower top)</th>
<th>C384 AM5/SPEAR-Hi (hydrostatic, AM5 phys.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x_{\min}$ ($\Delta x_{\text{mean}} \div 1.3$)</td>
<td>10.2 km</td>
<td>2.5 km</td>
<td>19.2 km</td>
</tr>
<tr>
<td>“Acoustic” timestep</td>
<td>18.75 s</td>
<td>4.5 s</td>
<td>28.5 s</td>
</tr>
<tr>
<td>Courant number</td>
<td>0.998</td>
<td>0.98</td>
<td>0.80</td>
</tr>
<tr>
<td>Remapping/MP timestep</td>
<td>150 s</td>
<td>36 s</td>
<td>200 s</td>
</tr>
<tr>
<td>Physics Timestep</td>
<td>150 s</td>
<td>180 s</td>
<td>600 s</td>
</tr>
</tbody>
</table>

Tracer timestep is *adaptively chosen* from domain-maximum windspeed

\[
\text{“Acoustic” timestep Courant Number: } \left( U_{\max} + c_s \right) \frac{\Delta t}{\Delta x_{\min}} \leq 1
\]

Using $c_s = 343$ m/s and $U_{\max} = 200$ m/s
“FV3 is a Hack”

Misconception #4
FV3 dynamics and consistency

• FV3 is fully finite-volume and nearly all processes can be represented as advection—and so consistently computed.

• Consistency means better conservation, realism, accuracy, and fewer computational modes.

• Fluid flows are strongly vortical at all scales. FV3 emphasizes vorticity dynamics and its conservation laws (PV, UH)

• FV3 uses the unique C-D grid to get accurate fluxes: the best of both rotational and divergent modes
“FV3 is too diffusive and uses too many filters”

Misconception #5
13-km FV3-based GFS and SHiELD simulate mesoscale spectrum with higher effective resolution than Legacy GFS or 9.5-km ECMWF IFS.

“Effectively inviscid” numerics in 3.25 km X-SHiELD produce perfect mesoscale spectrum and 4Δx cutoff.
Explicit Diffusion in FV3

- All environmental models need some form of diffusion.
- FV3 has **two** forms of explicit diffusion:
  1. Linear higher-order diffusion, separate for divergent and rotational modes
  2. A very simplified nonlinear diffusion, currently only for divergence
- And a variety of *options* and upper-boundary diffusion.
- These are highly configurable due to the **vast** range of applications for FV3. What works at one resolution may not work for others.
- Divergence has **no** implicit diffusion in the numerics and needs to be controlled explicitly.
“FV3 is why the GFS has fallen behind”

Misconceptions #6a and #6b
SHiELD R2O: Improving Hurricane Forecasts

Better Model + Better Data ⇒ US #1 for Tropical Cyclone Track Forecast

Atlantic GFS track error leading for 2023 also
DIMOSIC

- International intercomparison of global prediction models, all initialized from EC (IFS) ICs
- FV3-based GFDL SHiELD on par with IFS, and better in some ways
- Careful implementation of EC ICs in SHiELD helps a lot

Magnusson et al., BAMS, 2022
J-H Chen et al., Earth Space Sci., 2023
The GFS is a Great Product

• A world class global model with many features and products not in other operational global models
  • Nonhydrostatic dynamics, -5/3 mesoscale spectrum, cold pools, comprehensive cloud microphysics, some realistic hurricane intensity
• GFSv15 and v16 implemented with **significant** skill improvements
• End-to-end **free** and **open** data, analyses, model, and output: an **incredible value** for scientists and stakeholders
• Used for purposes **far** beyond original hemispheric prediction
• “Falling behind” is meaningless
• Look at what people **use**—not what they **say**.

2018–2020 Retros NH H500:
GFSv15 = 0.891
GFSv16 = 0.896

2015–2018 Retros NH H500:
Legacy GFSv14 = 0.885
GFSv15 = 0.897

(Note interannual variation in skill)
“There is no community for FV3”

Misconception #7
The Global FV3 Community
Past, present, future earth and beyond

- NASA
- GEOS, DAS, MERRA(2)
  Ames Mars GCM
- GEOS Chem
  GEOS-Chem High-Performance
- CAM-FV
  CAM-FV3
- NCAR
- LASG FAMIL, F-GOALS
- Taiwan Central Weather Bureau
  CWBGFS
- National Weather Service
  AM4 CM4 ESM4
  SHIELD SPEAR
- GFSv15 v16 GEFSv12
  MRW SRW HAFS …
- The Global FV3 Community
- Past, present, future earth and beyond

Sponsors and Partners: NASA, GEOS, DAS, MERRA(2), GEOS Chem, GEOS-Chem High-Performance, CAM-FV, CAM-FV3, NCAR, LASG FAMIL, F-GOALS, Taiwan Central Weather Bureau, CWBGFS, National Weather Service, AM4 CM4 ESM4 SHIELD SPEAR, GFSv15 v16 GEFSv12, MRW SRW HAFS …
“FV3 was only selected because of its speed”
NGGPS Evaluation

• FV3 was selected due to better stability, efficiency, accuracy, and forecast skill at 50-km, 13-km, and 3-km scales. Three independent experts agreed.

• GFDL and EMC have enjoyed a close relationship since 2016 to transition FV3 into the UFS.

• Efficiency is crucial for practical applications.
Convective-scale Evaluation

200-mb KE spectrum (Skamarock 2004) in a global 3-km simulation. NGGPS Phase I Report

DCMIP (June 2016 @ NCAR): Zarzycki et al. 2019
Reduced-radius earth supercell test (4-2-1-0.5 km)
“FV3 cannot work on GPUs”

Misconception #9
AI2 Pace
Accelerating to k-scale

• Earlier GPU ports of FV3 at NASA and LASG got order-of-magnitude speedups—but were unsustainable

• Pace: GT4py implementation of FV3 + parameterizations

Performance + Python Flexibility
  • Compiled to optimized code for any processor

• Transitioned into NOAA + NASA with SENA funding

github.com/NOAA-GFDL/pace

Socket-for-socket comparison on Piz Daint
(CSCS Switzerland, 12x Intel Haswell + 1 NVIDIA P100)
“Nobody in NOAA knows this code”

Misconception #10
FV3 Ongoing Development

- Duo-Grid & LMARS
  - GFDL, LASG
- Advanced nesting: telescoping, moving, and vertical nests
  - GFDL, AOML
- Super-regular regional domain
  - EMC
- Whole and deep atmospheres
  - EMC, SWPC, GMAO
- FV3 Integrated/In-line physics
  - GFDL, AOML, EMC, LASG
- New advection and vertical remapping operators
  - GFDL, GMAO

- Semi-implicit solver revisions
  - GFDL + EMC
- Subgrid turbulence
  - GFDL, Clemson, FIU, AOML
- GitHub CI/CD
  - GFDL
- FV3 Adjoint
  - GMAO & JSCDA
- Revised 2D advection
  - U Sao Paulo
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“A key element that makes collaborations successful is having individuals who enjoy working together and are able to do so.”—Morris Bender, BAMS 2019
Thoughts on development

• “A good model must be a fast model” — S-J Lin
• Dynamics isn’t the whole story.
• Development is learned by doing development.
• Successful models are developed holistically.
  • “Mix ‘n’ match” or “plug ‘n’ play” development doesn’t work
• Common methods give common results.