FV3 In a Nutshell

Lucas Harris
for the GFDL FV3 Team

UFS S2S All-Hands Meeting

29 September 2023

FV3 Community Resources

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FV3: Finite-Volume Cubed-Sphere Dynamical Core

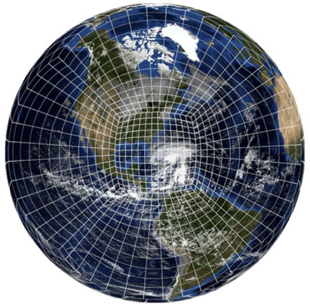
FV3 Home | Key Components | Grids | Performance | Applications | The FV3 Team

The GFDL Finite-Volume Cubed-Sphere Dynamical Core (FV3) is a scalable and flexible dynamical core capable of both hydrostatic and non-hydrostatic atmospheric simulations. The design of FV3 was guided by these tenets:

1. The discretization should be guided by physical principles as much as possible.
2. A fast model can be a good model, but a good model must be a fast model! Computational efficiency is crucial.

FV3 was "reverse engineered" to incorporate properties which have been used in engineering for decades, but only first adopted in atmospheric science by FV3.

FV3 is the dynamical core for all GFDL weather and climate models, including the world-leading AM4 and the powerful SHiELD unified weather-to-subseasonal prediction model and SPEAR seamless coupled prediction system. FV3 has been chosen as the dynamical core for the Unified Forecast System (UFS), formerly the Next Generation Global Prediction System project (NGGPS). The UFS is designed to unify the National Weather Service's suite of prediction models, including the operational Global Forecast System (GFS) and regional models to run as a unified, fully-coupled system in the NOAA Environmental Modeling System infrastructure. FV3 was successfully implemented within the GFS, and the FV3-based GFSv15 became operational on 12 June 2019. Since then, the GFS and GFS Ensemble have both received further updates to FV3 and other model components. An FV3-based limited area model was implemented operationally in 2019 in the High-Resolution Ensemble Forecast (HREF), and form a key role in the upcoming implementations of the Hurricane Analysis and Forecast System (HAFS) and Rapidly-Refreshing Forecast System (RRFS).



Quick Links

- Real-time GFDL SHiELD Forecasts
- SHiELD Model Description
- Documentation and References
- Recent Publications
- FV3 on GitHub

FV3 is also the dynamical core for NASA's GEOS global model, NASA's next-generation Mars Climate Model, and for other systems worldwide.

This website describes FV3, including the evolution of its development, basic algorithm, and its global variable resolution capabilities, in both nested and stretched grid configurations. The Performance page explains how efficient FV3 can be.

Dynamics isn't the whole story. Coupling to physics and the ocean is necessary! Please see the Applications page for the family of models using FV3 and examples of how FV3 has been successfully implemented.

FV3 Portal

Documentation, publications, tutorials, and demos

www.gfdl.noaa.gov/fv3

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FV3 Documentation and References

Disclaimer: We have made every effort to ensure that the information here is as accurate, complete, and as up-to-date as possible. However, due to the *very* rapid pace of FV3 dynamical core and FV3-powered model development these documents may not always reflect the current state of FV3 capabilities. Often, the code itself is the best description of the current capabilities and the available options, which due to limited space cannot all be described in full detail here. **We strongly recommend anyone who wishes to understand FV3 in more detail to read and study the articles linked below.** Contact GFDL FV3 Dycore support or GFDL SHiELD/fvGFS model support for assistance and more information.

FV3 Scientific Documentation:

- GFDL Technical Note GFDL2021001 (July 2021):
  - Official Release on the NOAA Institutional Repository
  - Source, updates, and examples on GitHub
- GFDL Technical Note GFDL2022002 (July 2022), on v2 of the GFDL Microphysics

Tutorial Presentations:

- Lecture for AOS 575, Princeton University, Fall 2022
- 2020 UFS Medium-Range Weather Application Users' Training: FV3 algorithms and configuration, physics-dynamics coupling, and applications (recording).
- ECMWF Annual Seminar 2020: Design and Prospects for Global and Unified Modeling (recording).

Key Journal Articles (many now open access):

- Lin, Chao, Sud, and Walker, 1994: Van Leer transport scheme
- Lin and Rood 1996: FV advection scheme
- Lin and Rood 1997: FV lat-lon shallow-water model
- Lin 1997: FV pressure-gradient force formulation
- Lin 2004: The latitude-longitude FV core
- Putman and Lin 2007: FV3 cubed-sphere advection
- Zhao, Held, and Lin, 2012: Divergence damping and tropical cyclones
- X. Chen, Lin, and coauthors, 2013: A nonhydrostatic finite-volume algorithm
- J.-H. Chen and Lin, 2013: Seasonal hurricane prediction with GFDL Microphysics
- Harris and Lin, 2013: FV3 global-to-regional nesting
- Harris, Lin, and Tu, 2016: FV3 stretched-grid regional refinement
- Lin, Harris, X. Chen, Yao, and Chai, 2017: Nonlinear colliding modons idealized test
- J.-H. Chen, X. Chen, Lin, Magnusson, Bender, Zhou, and Rees, 2018: Initialization from ECMWF analyses
- X. Chen, Lin, and Harris, 2018: 1D Riemann Solver and higher-order dispersion analysis
- Harris, Rees, Morin, Zhou, and Stern, 2019: Prediction of continental convection in a global-nest model
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Other relevant papers:

- Colella and Woodward, 1984: The Piecewise Parabolic Method
- The Van Leer cycle: Part I Part II Part III Part IV Part V

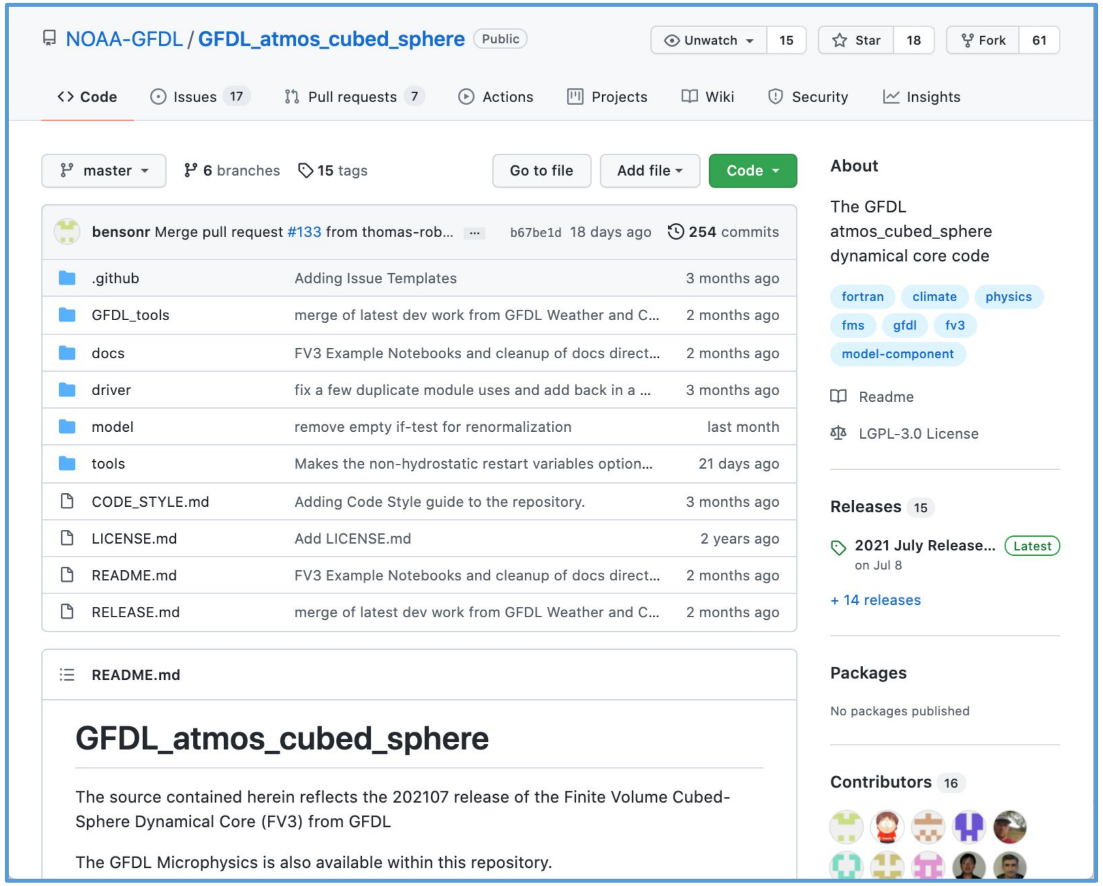
www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/

“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

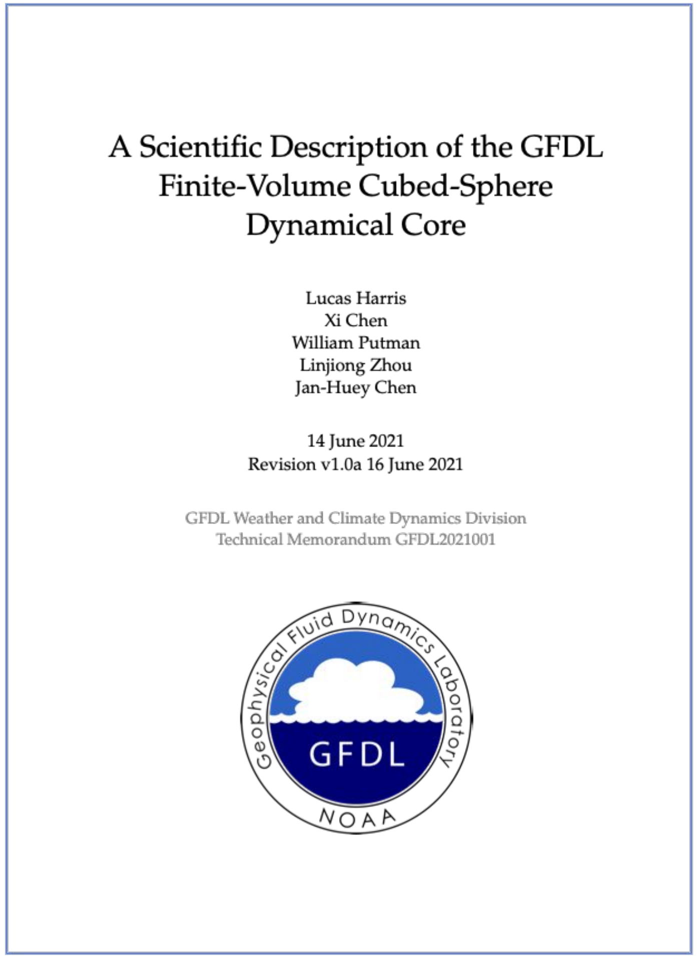


github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere

“There is too little information on FV3”

Misconception #2

FV3 Documentation and References


A Scientific Description of the GFDL Finite-Volume Cubed-Sphere Dynamical Core

Lucas Harris
Xi Chen
William Putman
Linjiong Zhou
Jan-Huey Chen

14 June 2021
Revision v1.0a 16 June 2021

GFDL Weather and Climate Dynamics Division
Technical Memorandum GFDL2021001

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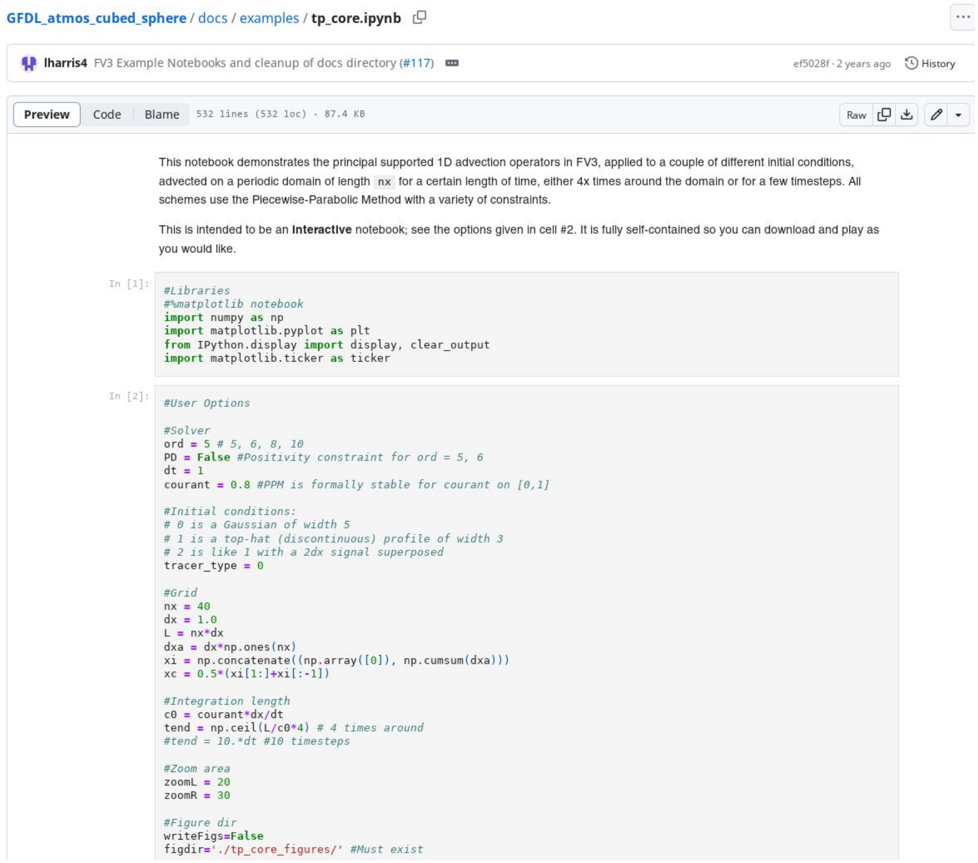
FV3 GitHub Resources

- 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.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 m/s**!!
- Lagrangian layers periodically remapped to reference “Eulerian” layers
  - Needed to run **physics**, both intermediate (microphysics) and slow
  - Relieves strongly distorted layers and prevents $\delta p \rightarrow 0$
- Passive tracers are advected on the remapping step
  - **Adaptive** substepping from global U_{max}: rarely more than 3 per remap
- Lagrangian Vertical Coordinate: **No** vertical courant number restriction

Examples of timesteps in GFDL global models

	C768 SHiELD	C3072 X-SHiELD (lower top)	C384 AM5/SPEAR-Hi (hydrostatic, AM5 phys.)
Δx_{min} (Δx_{mean} ÷ 1.3)	10.2 km	2.5 km	19.2 km
"Acoustic" timestep	18.75 s	4.5 s	28.5 s
Courant number	0.998	0.98	0.80
Remapping/MP timestep	150 s	36 s	200 s
Physics Timestep	150 s	180 s	600 s

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

"Acoustic" timestep Courant Number: $$(\mathrm{U}_{\mathrm{max}} + \mathrm{c}_s)\frac{\Delta t}{\Delta x_{\mathrm{min}}} \leq 1$$

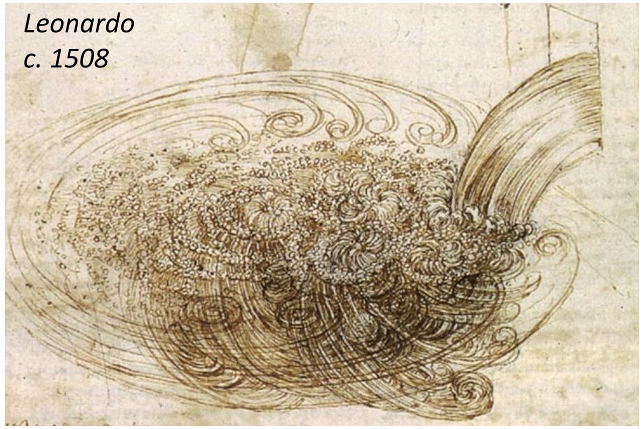
Using c_s = 343 m/s and U_{max} = 200 m/s

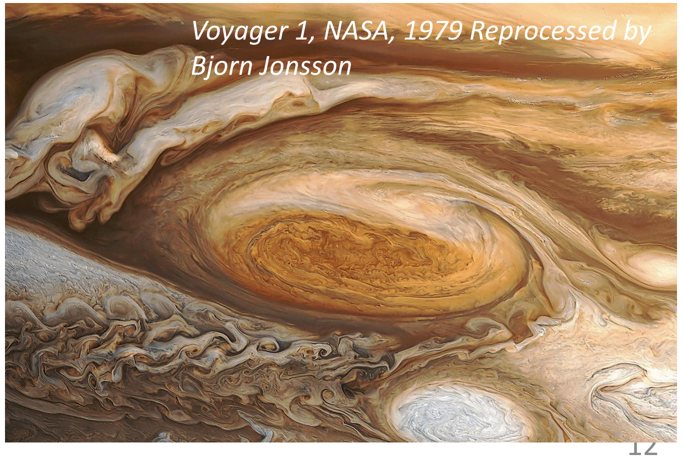
“FV3 is a Hack”

Misconception #4

FV3 dynamics and consistency

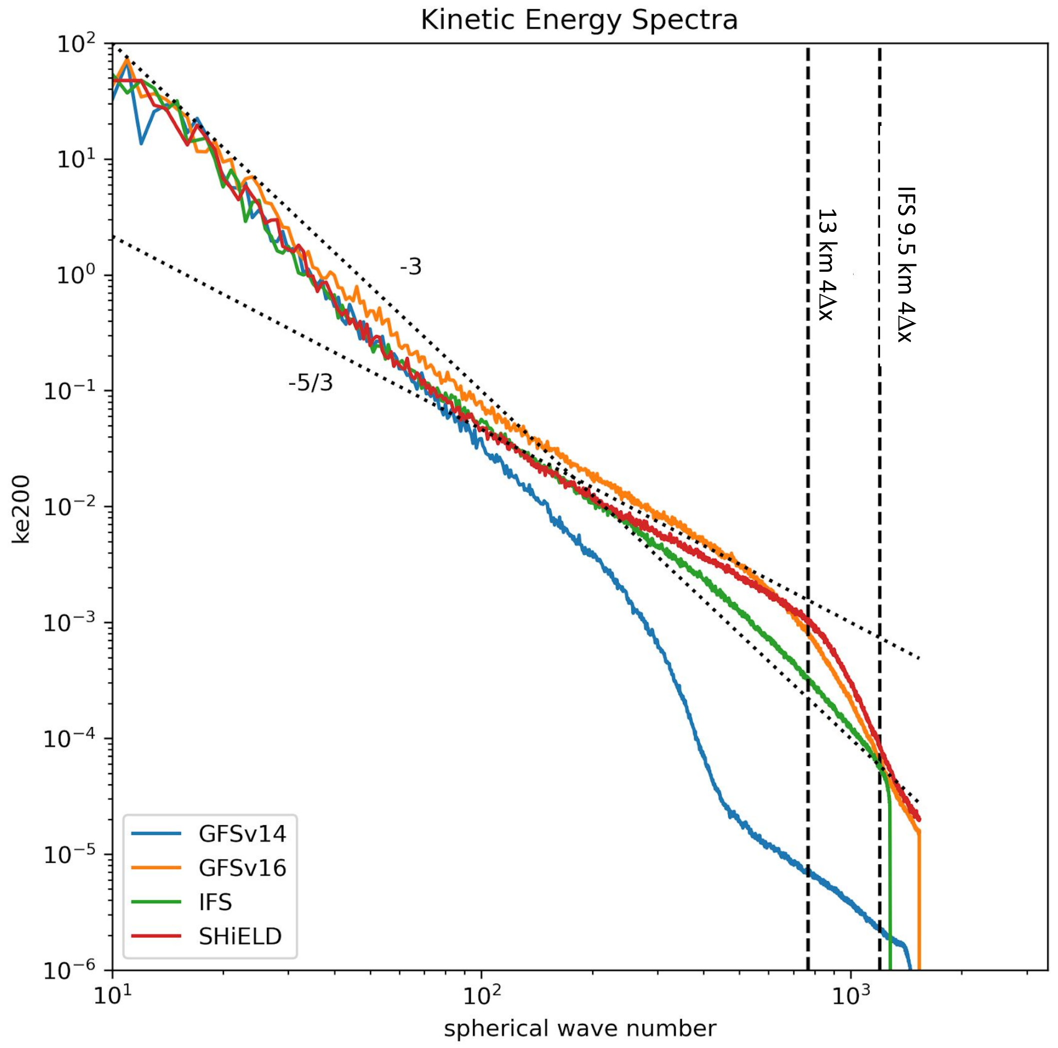
- FV3 is **fully finite-volume** and nearly all processes can be represented as advection—and so consistently computed.
- Consistency means better conservation, realism, accuracy, and fewer computational modes.
- **Fluid flows are strongly vortical at all scales.** FV3 emphasizes vorticity dynamics and its conservation laws (PV, UH)
- FV3 uses the unique C-D grid to get accurate fluxes: **the best of both rotational and divergent modes**



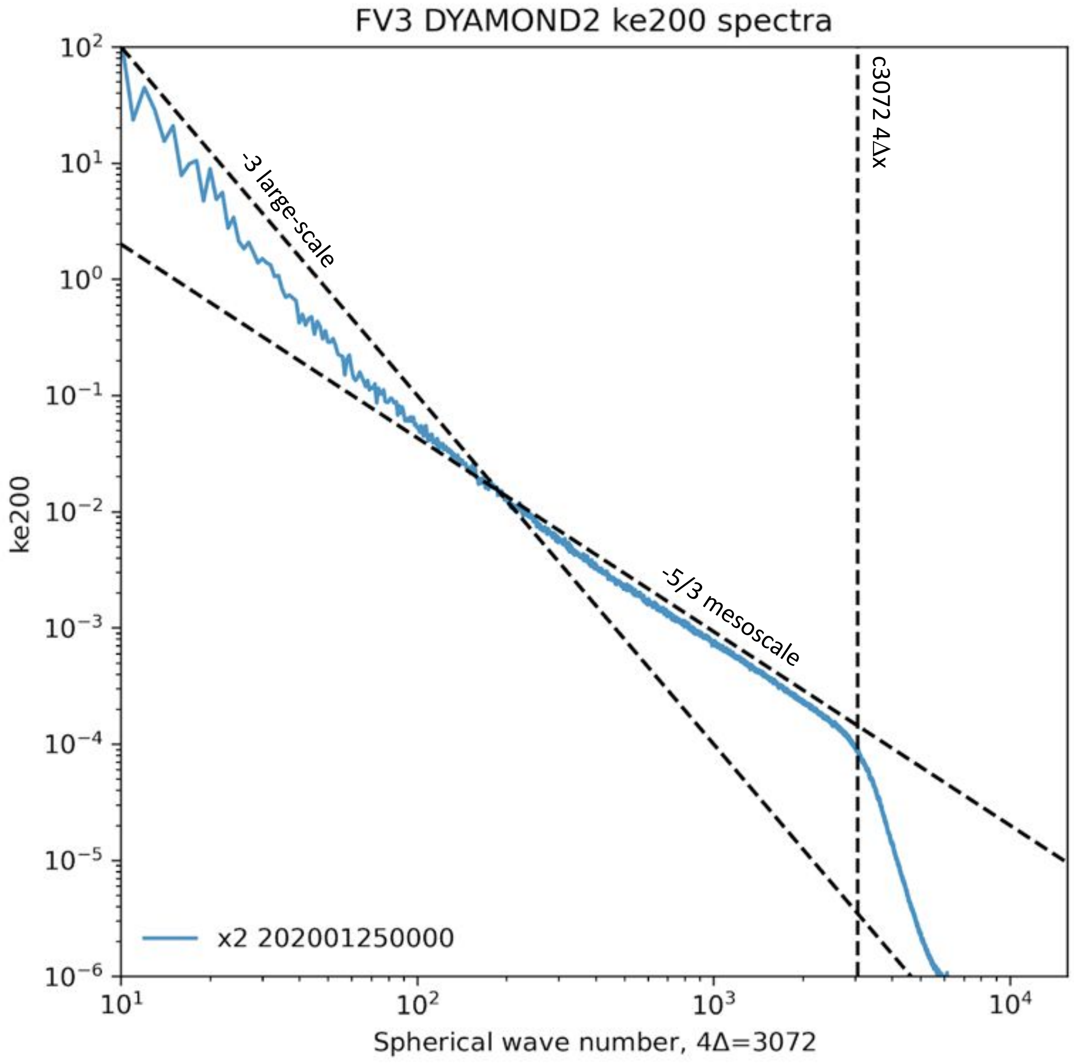


“FV3 is too diffusive and uses too many filters”

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

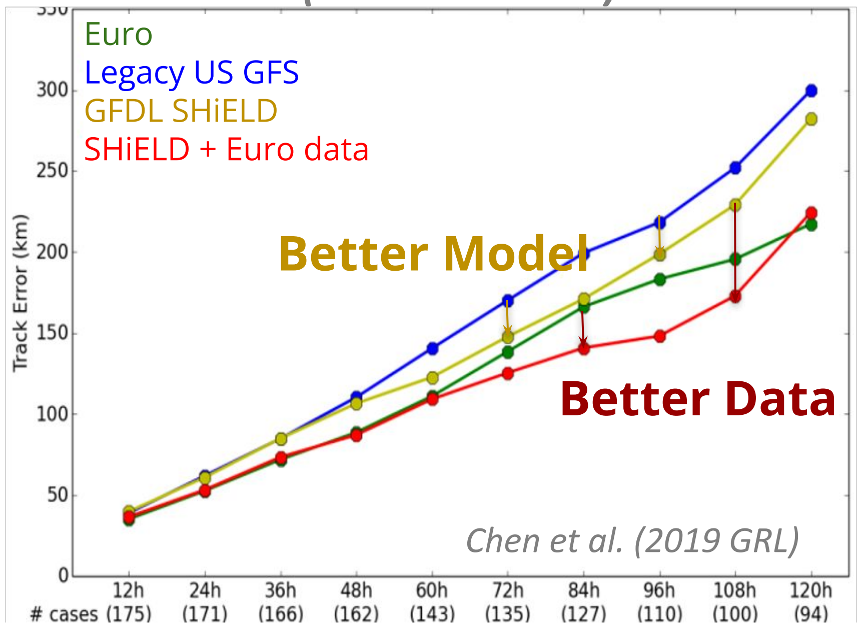
- **All environmental models need some form of diffusion.**
- FV3 has **two** forms of explicit diffusion:
  1. Linear higher-order diffusion, separate for divergent and rotational modes
  2. A very simplified nonlinear diffusion, currently only for divergence
- And a variety of *options* and upper-boundary 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

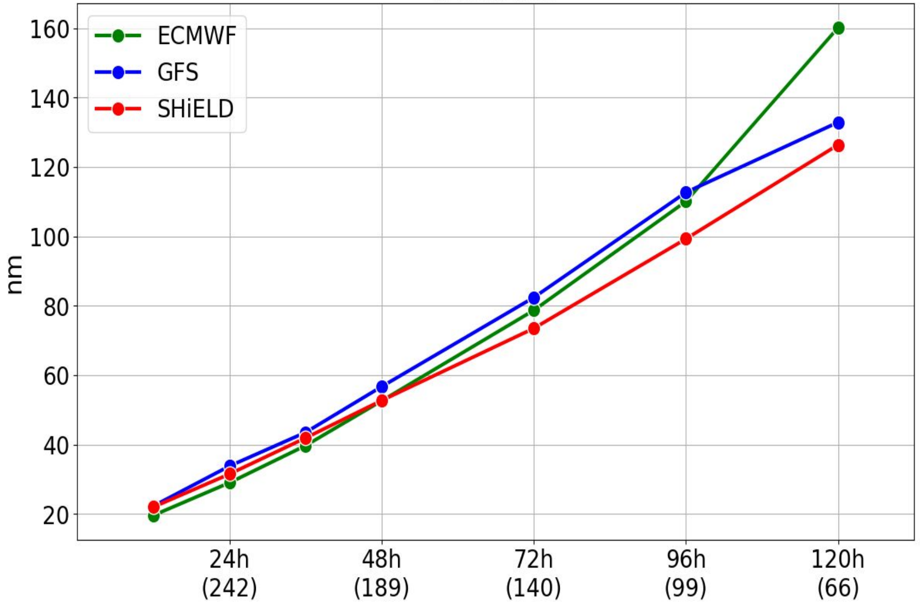
SHiELD R2O: Improving Hurricane Forecasts

2017 TC Track Error
(lower is better)



Operational Transition + Improved US Data

2021-2022
Mean Atlantic TC Track Error



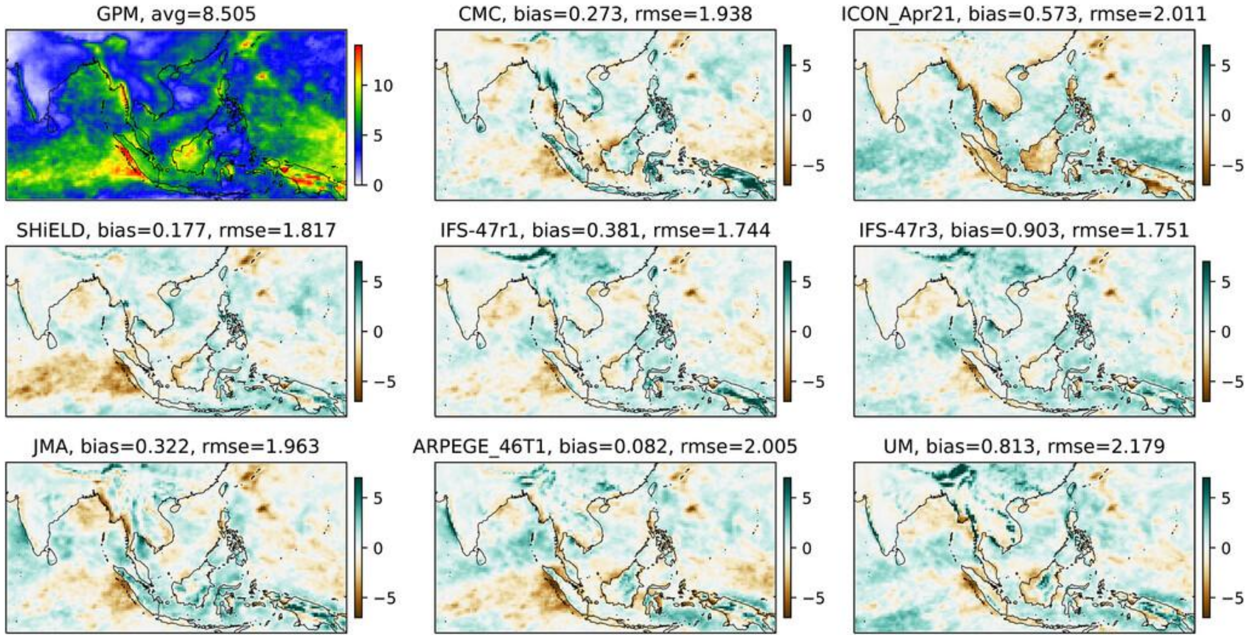
Courtesy Kun Gao and Jan-Huey Chen

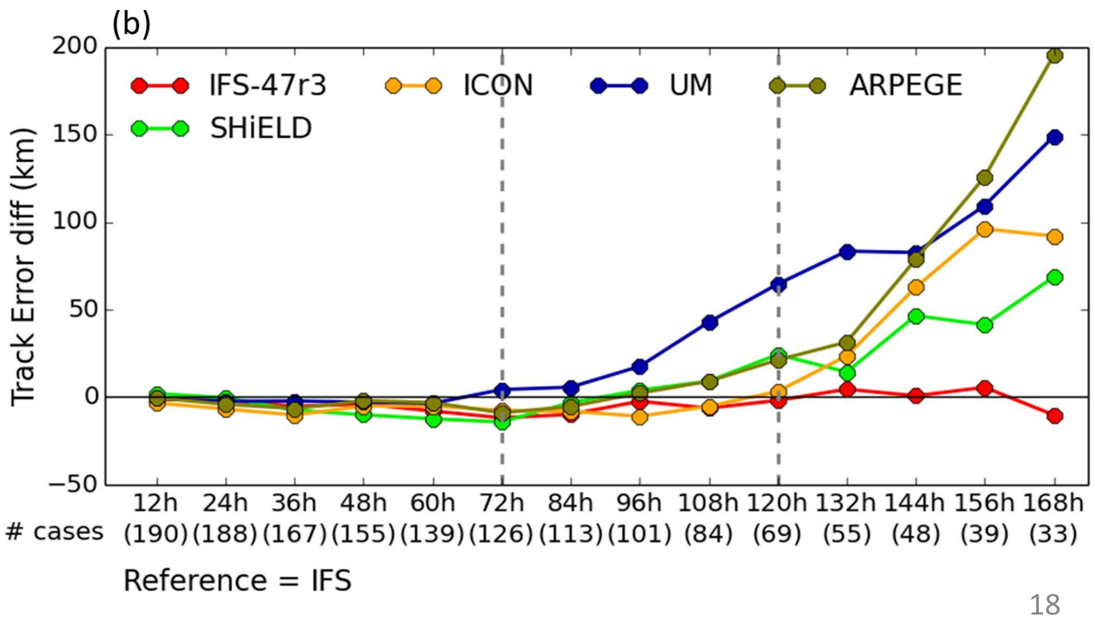
Better Model + Better Data ⇒ US #1 for Tropical Cyclone Track Forecast

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

UFS
UNIFIED FORECAST SYSTEM

GFDL
AM4 CM4 ESM4
SHiELD SPEAR

NATIONAL WEATHER SERVICE
GFSv15 v16 GEFSv12
MRW SRW HAFS …

NOAA 50 YEARS RESEARCH
NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION

GFDL FV3

NASA
GEOS, DAS, MERRA(2)
Ames Mars GCM

VE RI TAS HARVARD
GEOS Chem
GEOS-Chem High-Performance

NCAR
CAM-FV
CAM-FV3

IAP CAS
Chinese Academy of Sciences
LASG FAMIL, F-GOALS

Taiwan Central Weather Bureau
CWBGFS

“FV3 was only selected because of its speed”

Misconception #8

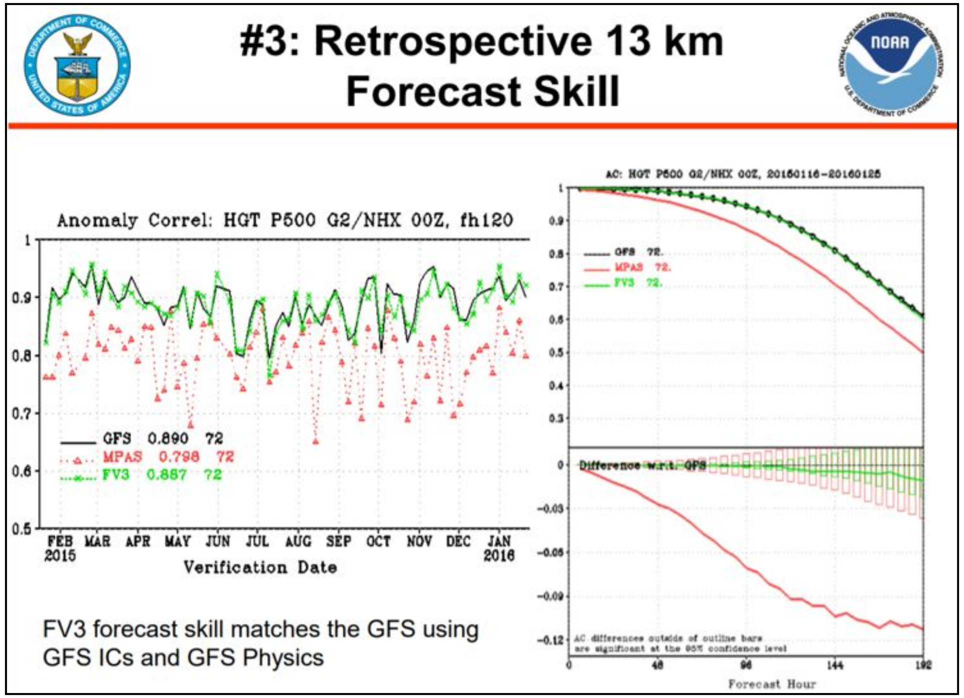
NGGPS Evaluation

- 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

Selecting a single dynamical core upon which to build a unified global coupled system, will be achieved through assessing 10 additional criteria described in the table below. As results from Phase 2 testing are generated, they will be made available here.

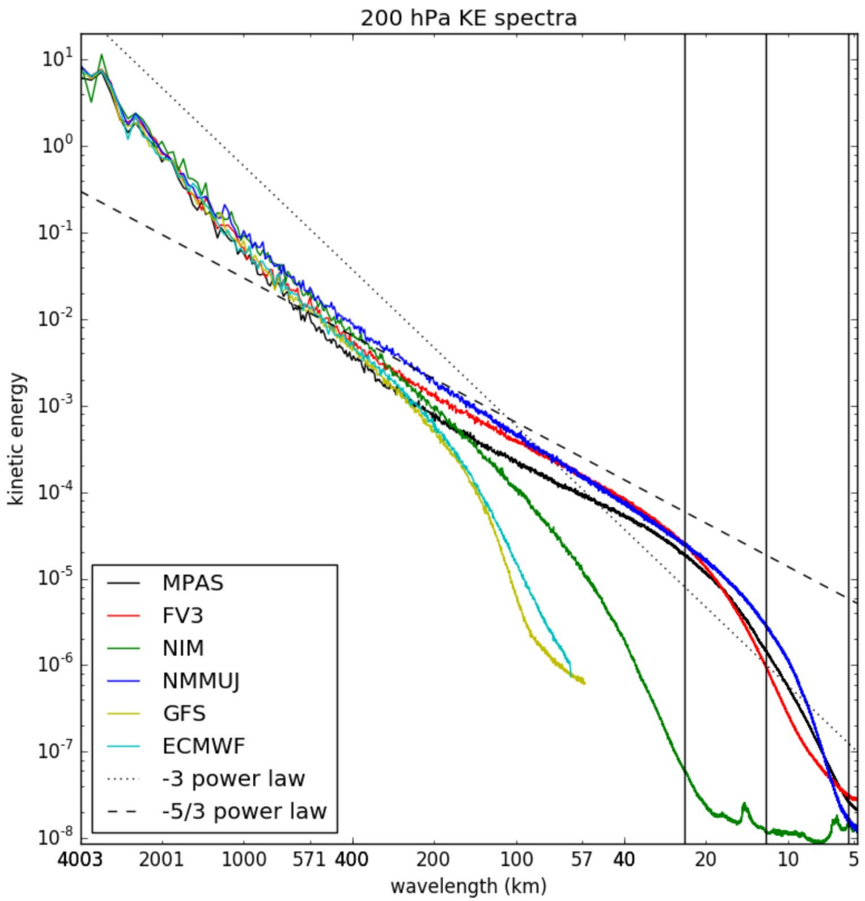
#	Evaluation Criteria	Results[1]
1	Relaxing shallow atmosphere approximation (deep atmosphere dynamics)	Results
2	Accurate conservation of mass, tracers, entropy, and energy	Results
3	Robust model solutions under a wide range of realistic atmospheric initial conditions using a common (GFS) physics package	Results Results (web)
4	Computational performance with GFS physics	Results
5	Demonstration of variable resolution and/or nesting capabilities, including physically realistic simulations of convection in the high-resolution region	Results
6	Stable, conservative long integrations with realistic climate statistics	Results
7	Code adaptable to NEMS/ESMF	Requirements
8	Detailed dynamical core documentation, including documentation of vertical grid, numerical filters, time-integration scheme and variable resolution and/or nesting capabilities	Documentation
9	Evaluation of performance in cycled data assimilation	Results
10	Implementation Plan (including costs)	Results

[1]See Dynamical Core Test Plan for description of testing methodology

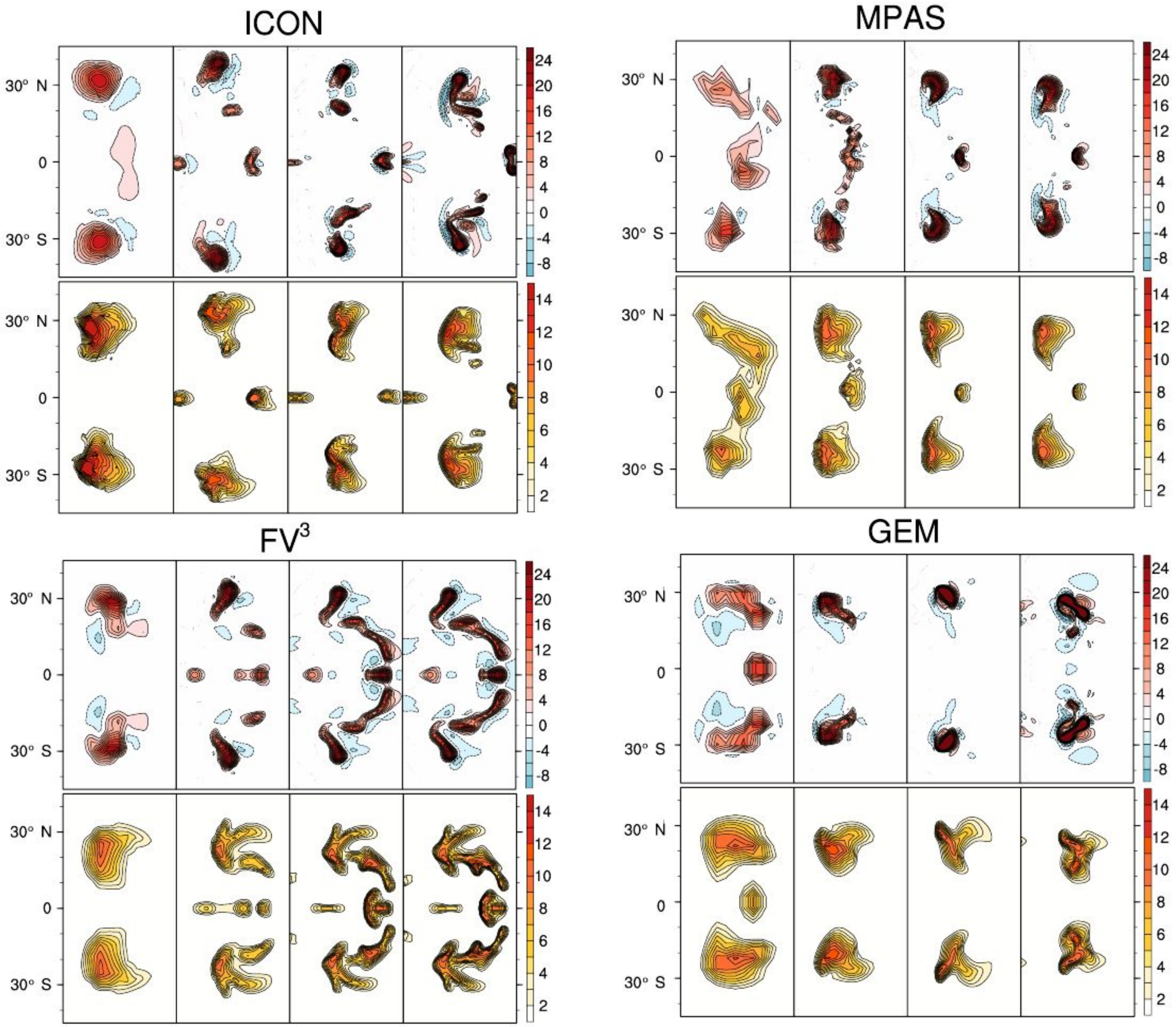


Evaluation with **same** physics.

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)

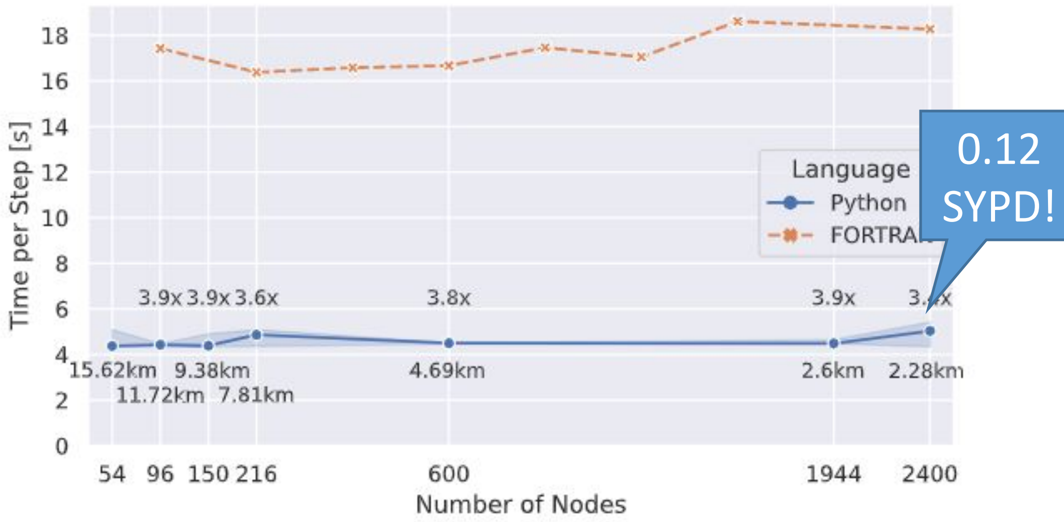
“FV3 cannot work on GPUs”

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
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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.

Thanks for comments from the GFDL FV3 Team and previous conversations
with GFDL Modeling Systems, AOML, EMC, Princeton CIMES, and AI2