

Improved Global Weather Prediction with GFDL's FV3 Dynamical Core

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Problem

A new dynamical core (dycore) is needed due to rapidly increasing HPC resources which allow global models to be run at finer resolutions. Within the next decade, it is anticipated that current operation model runs will be increased from 13km to cloud-resolving resolutions. In order to explicitly solve for clouds, a **non-hydrostatic dycore** is required.

NGGPS

NOAA's Next Generation Global Prediction System (NGGPS) project is an inter-agency effort and part of the NWS Research to Operations (R20) initiative that will replace the current Global Spectral Model (GSM).

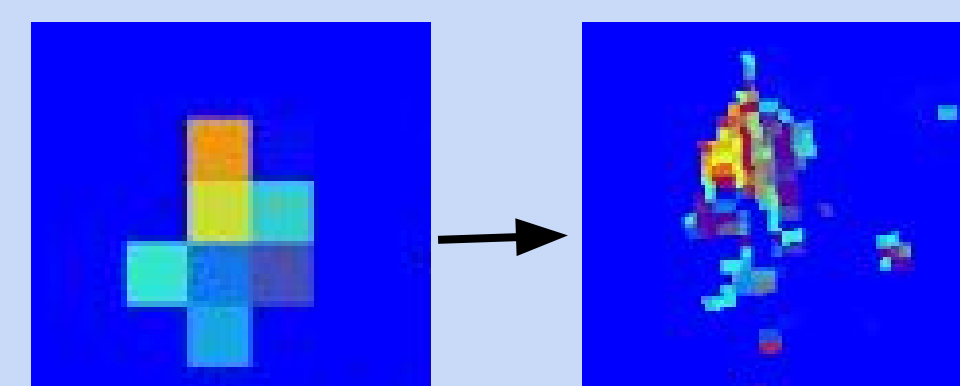
The new forecasting system will:

- increase global horizontal resolutions to 3 - 9 km, with nests of 0.5 - 2 km
- improve the 10 - 30 day operational forecasting skill
- incorporate fully coupled atmosphere, ocean, ice, land, waves, and aerosol models
- unify all components in the NOAA Environmental Modeling System (NEMS) architecture
- improve software architecture and systems engineering
- implement a community-based model to streamline the R20 implementation

The non-hydrostatic **finite volume dynamical core (FV3)** at the **Geophysical Fluid Dynamics Laboratory (GFDL)** has been chosen as the dycore for the NGGPS.

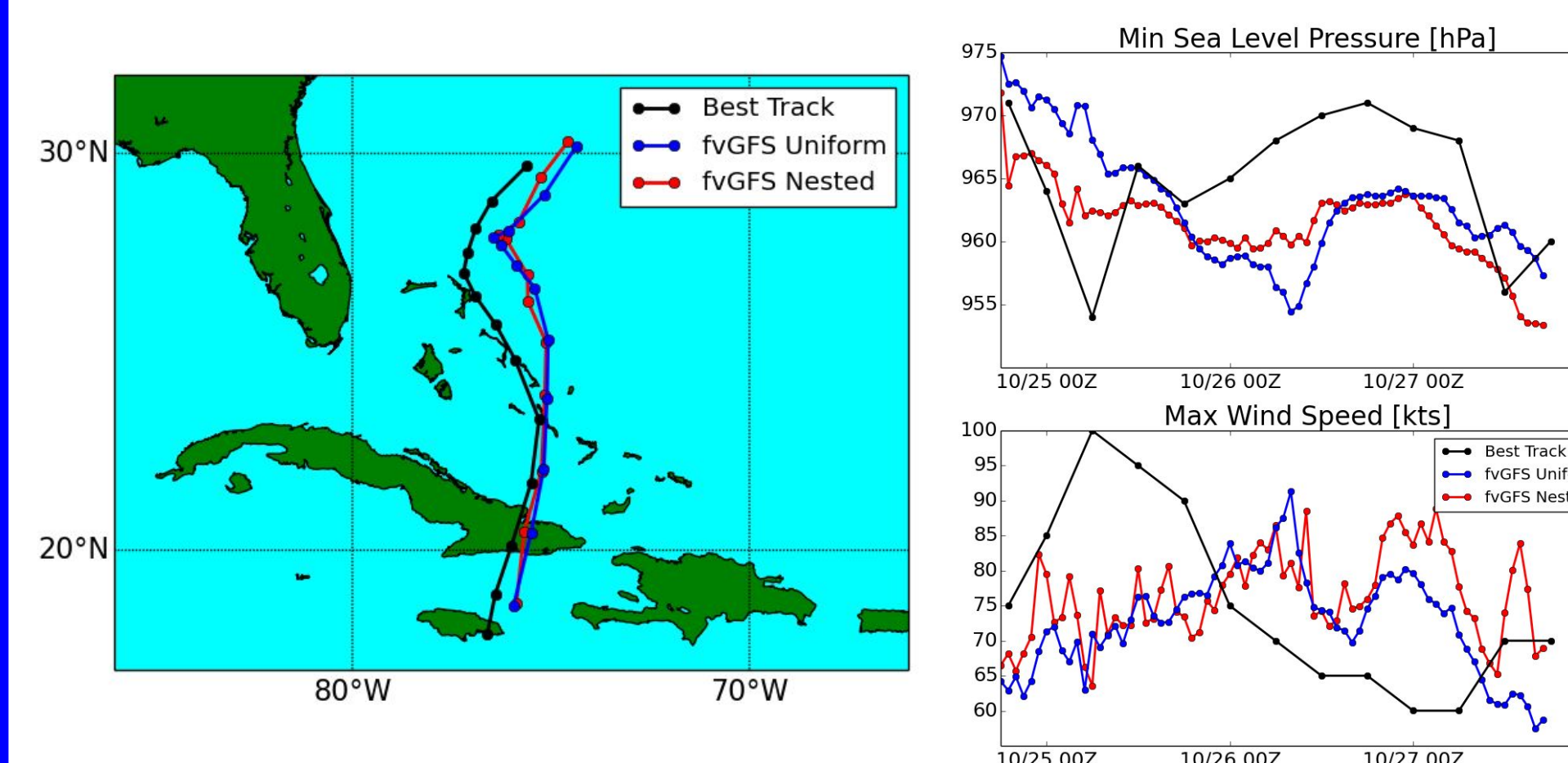
Hydrostatic vs. Non-Hydrostatic Simulation

Hydrostatic models, like the current operational GFS, assume that vertical acceleration is negligible compared to vertical pressure gradients and buoyancy forces. This is a good approximation down to ~10 km resolution. At smaller scales the model must resolve convective-scale features. Non-hydrostatic models include the vertical momentum equation so they are able to solve for clouds explicitly, instead of just using parameterizations.

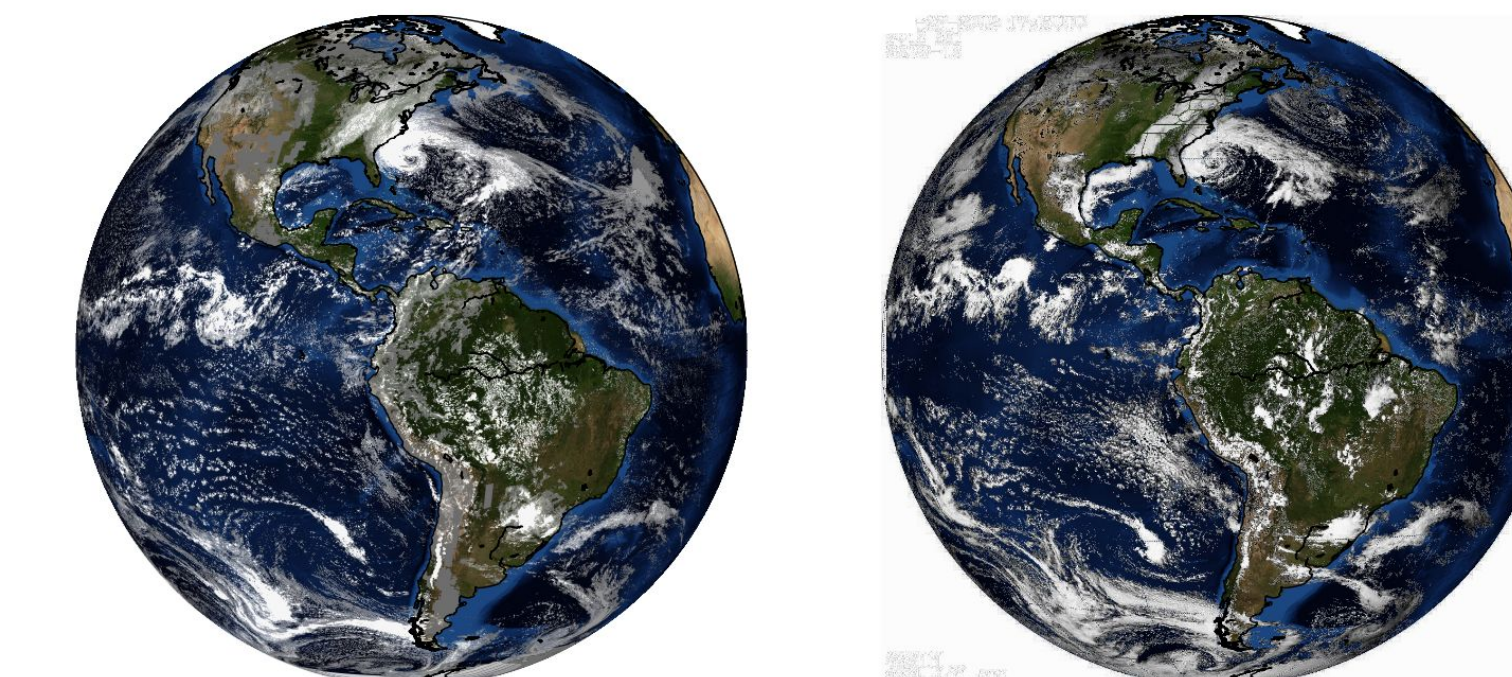


Hurricane Sandy (2012)

FV3 72-hour forecast at 18 UTC October 27



The large-scale is represented well in this nested grid case. Can you tell which one is the forecast and which is observations?

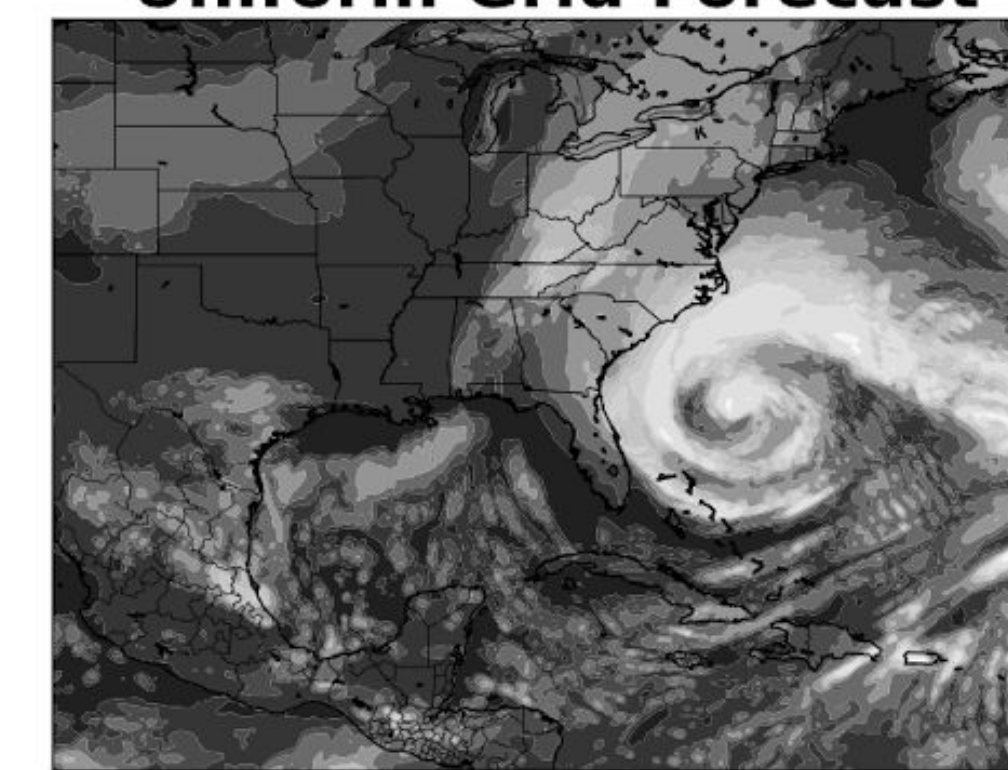


	Uniform	Nested
Grid Spacing	13 km	3 - 30 km
Processor Cores	1536	3072
Total Runtime	4926.9 s	12555.7 s
Minutes/Day	8.2	20.9

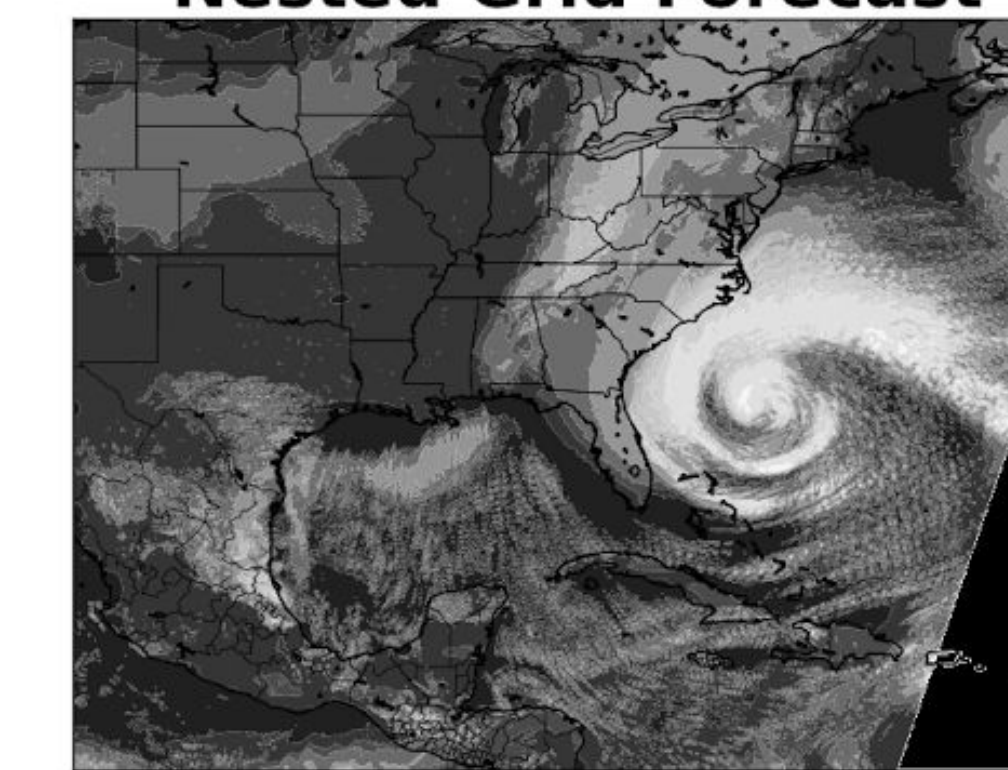
Operational threshold is 8.5 minutes per day.

Grid nesting allows us to more than triple the resolution of the Hurricane Sandy forecast without increasing the cost by 27x. Notice the enhanced fine-scale structure of the clouds.

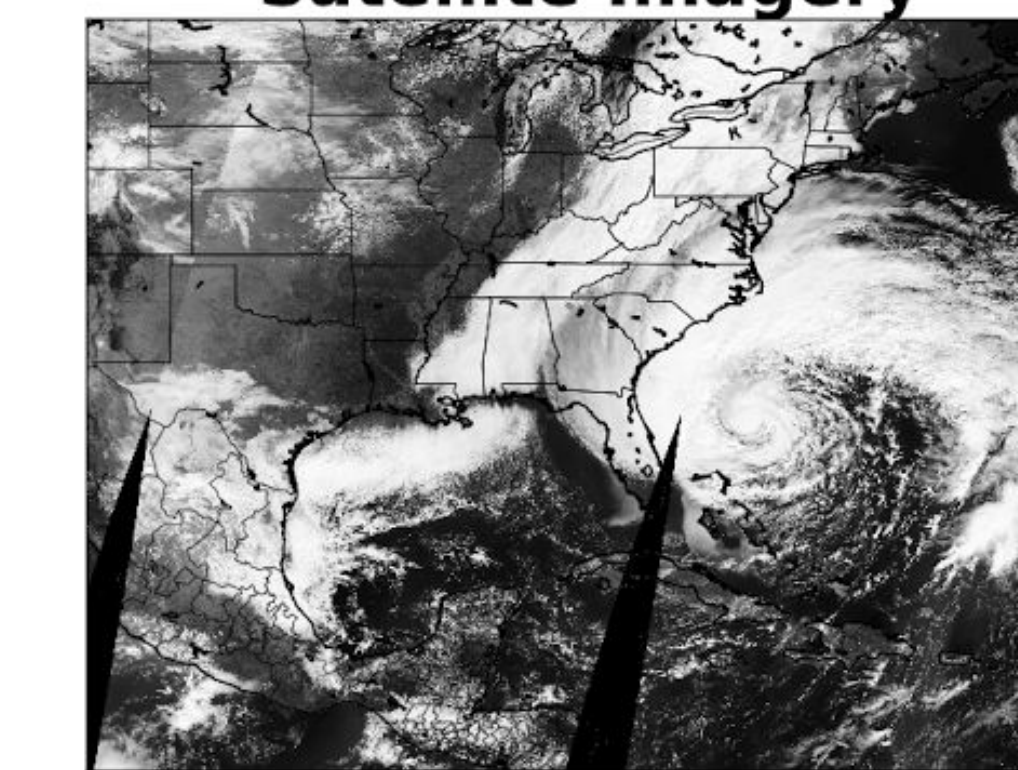
Uniform Grid Forecast



Nested Grid Forecast



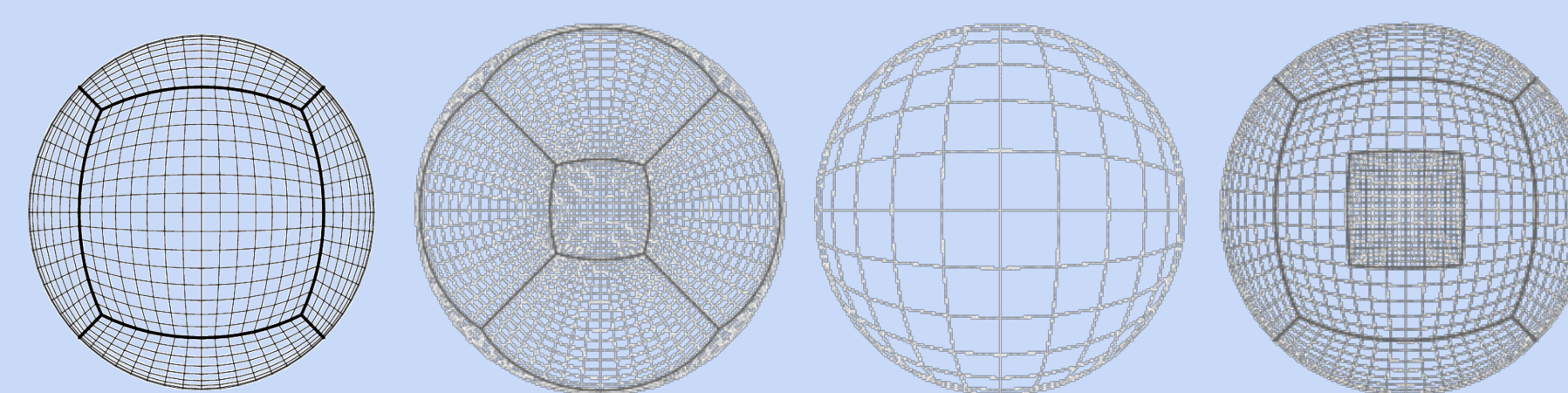
MODIS Visible Satellite Imagery



The FV3 Dynamical Core

Nested Grids

The GFDL FV3 dycore is a scalable and flexible core capable of both hydrostatic and non-hydrostatic simulation. It evolved from FV, a latitude-longitude finite volume core at NASA/Goddard in the mid-90s^{2,3}. FV3 was designed to have the discretization guided by physical principles as much as possible, while still maintaining computational efficiency.

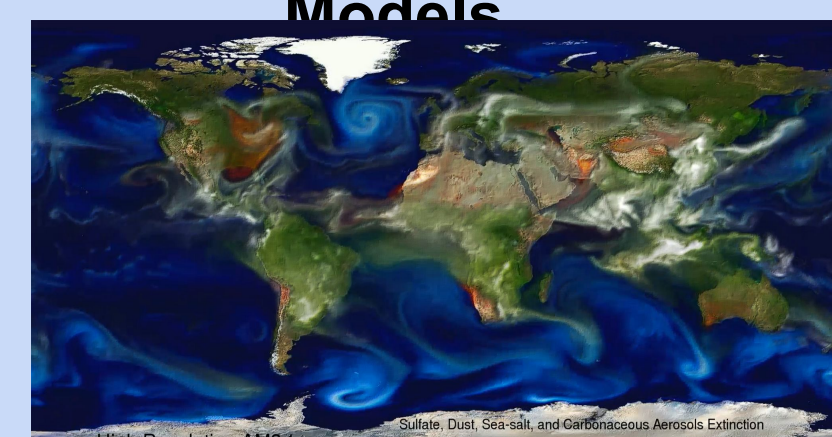


- Superior speed and efficiency
- Full finite-volume discretization
 - Finite-volume pressure gradient evaluation has errors an order of magnitude smaller than other schemes⁴
 - Finite-volume vertically-lagrangian discretization is the key to efficiency for cloud-resolving applications⁵
 - The transport algorithm conserves mass and has no false vorticity generation
- Prognostic winds on D-grid allow for consistent transport of Potential Vorticity, air mass, and all tracers³
- High-order monotonic advection is used consistently for momentum and all other prognostic variables²
- A gnomonic cubed-sphere grid is used with grid-stretching and two-way nesting capabilities^{6,7}
- No spatial or temporal scale restrictions

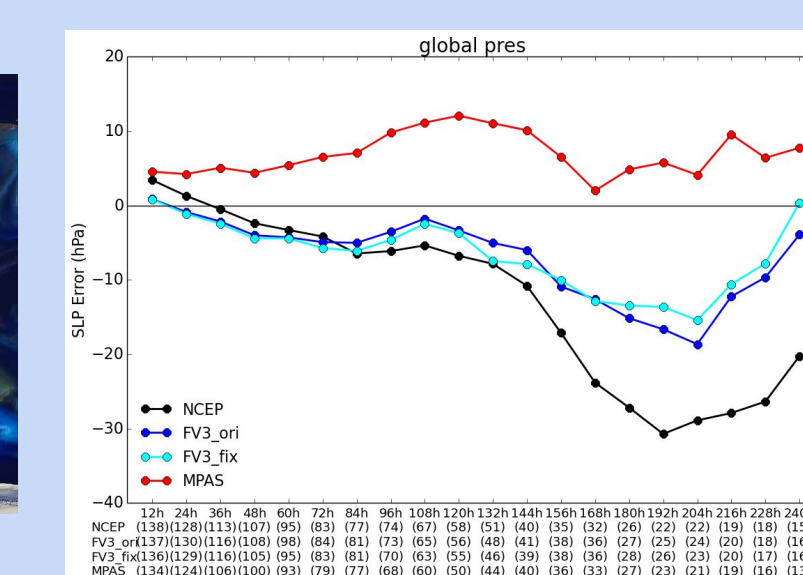
A nest is a domain of higher resolution embedded within the global model, that allows for simultaneous, coupled regional and global solutions. FV3's nested grid may use different time steps and physics parameterizations than the coarser grid. There is two-way interaction with wind and temperature fields⁷.

FV3's nesting efficiency is **96.9%** running with 3072 processor cores, while the other non-uniform domain competition is at 64%¹. Nesting efficiency is defined as the percent of expected gain in computational speed by running high-resolution over a subset of the globe instead of uniformly high-resolution on the same computational resources.

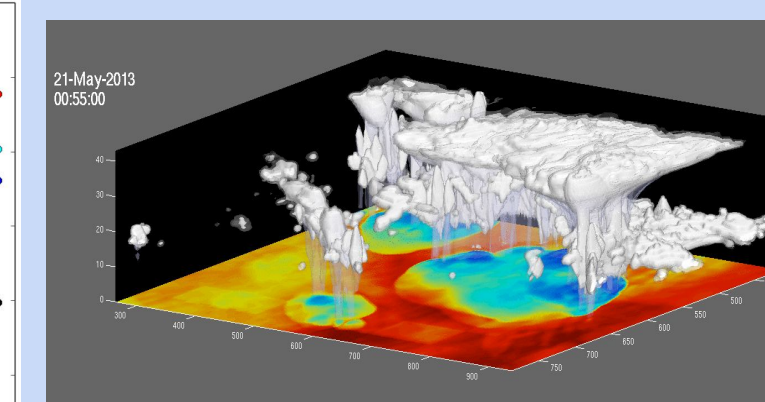
Chemistry Transport Models



Hurricanes



Supercells



FV and FV3 are used in many advanced weather, climate, and chemistry models:

- | | |
|----------------|-----------------------------|
| At GFDL | Outside of GFDL |
| • CM2.1/AM2.1 | • NASA's GEOS-5 |
| • ESM2 | • GEOS-CHEM (Harvard U) |
| • HIRAM | • GCM ModelE |
| • CM2.5/FLOR | • NCAR/DOE CESM |
| • CM3/AM3 | • Academia Sinica, Taiwan |
| • CM4/AM4 | • LASG/IAP, China |
| • ESM4 | • Seoul National University |

Spatial Scales: 10,000-1,000 km → 1000-10 km → 10-1 km

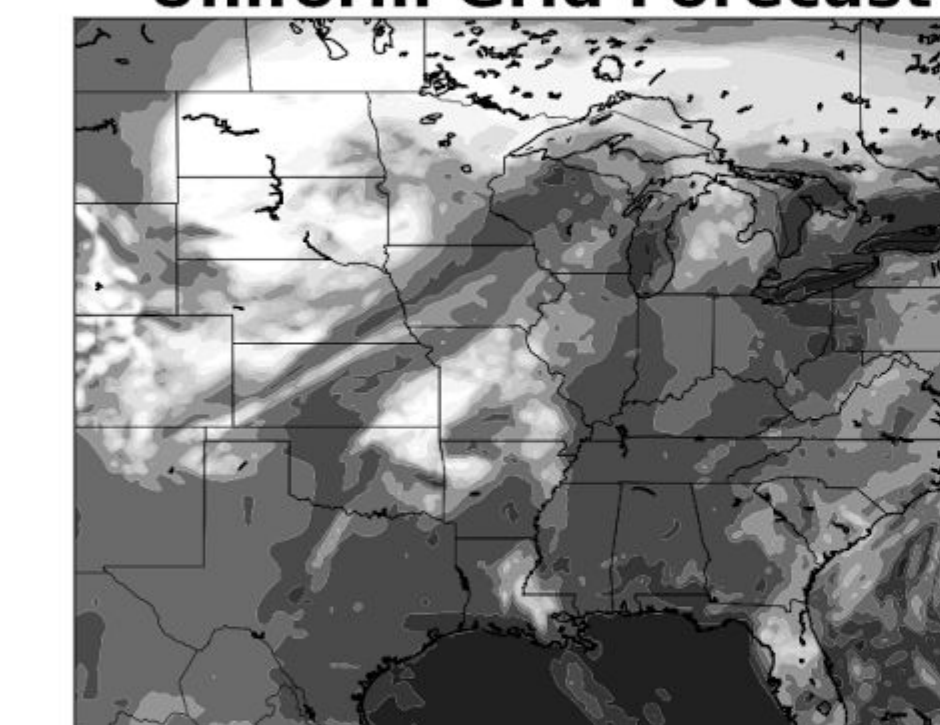
Moore, OK Tornado Outbreak (2013)

FV3 72-hour forecast at 00 UTC May 21

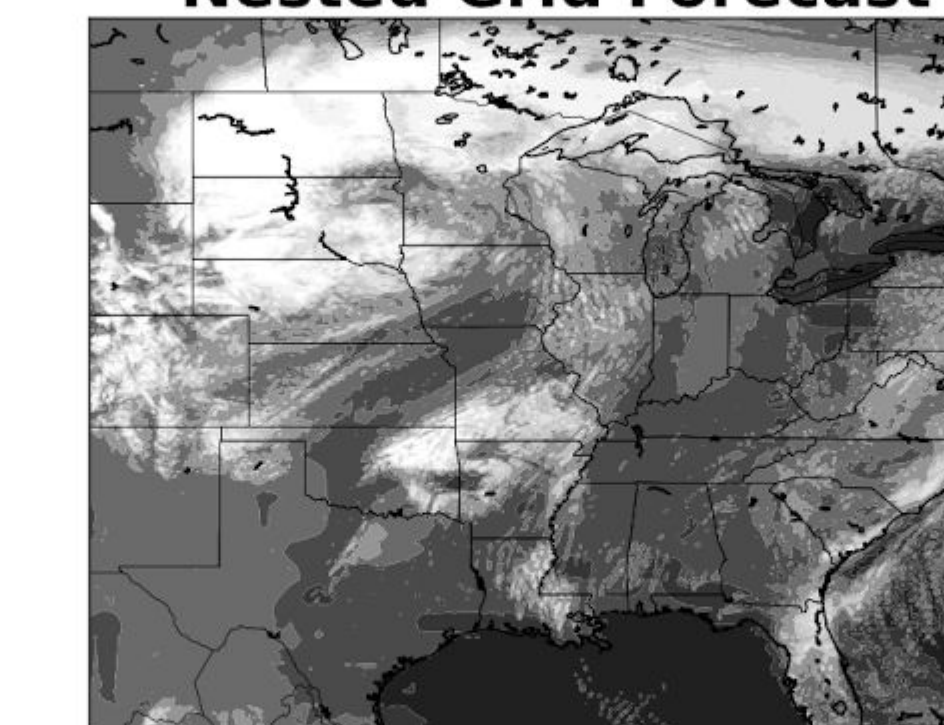
	Uniform	Nested
Grid Spacing	13 km	3 - 30 km
Processor Cores	1536	3072
Total Runtime	5006.1 s	12662.4 s
Minutes/Day	8.3	21.1

Forecasting at cloud-resolving resolutions is even more important for thunderstorm forecasting. This outbreak produced the deadly Moore, OK tornado and this global forecast got the storm timing within a few hours and the location within a few hundred km, 3 days in advance.

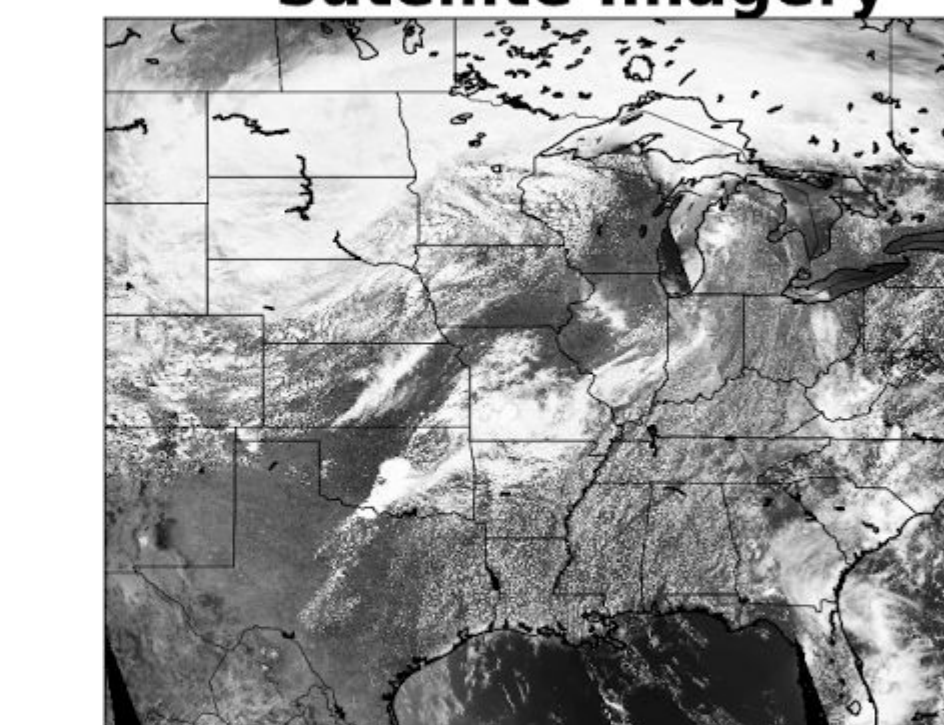
Uniform Grid Forecast



Nested Grid Forecast



MODIS Visible Satellite Imagery



Summary

In the coming decades global weather models will almost certainly be running at 1-5 km resolution! We need to plan ahead for a non-hydrostatic hybrid weather-climate modeling system which will be able to efficiently use HPC resources and take advantage of the research and experience of the academic, government, and private sector communities. FV3, which has no temporal or spatial limitations, performs well on all scales and has been chosen to become part of the NGGPS and run operationally by the Spring of 2019.

Main References

1. Advanced Computing Evaluation Committee. *AVEC Report: NGGPS Phase-2 Benchmarks and Software Evaluation*. Rep.: July 1, 2016.
2. Lin, S.-J., and R. B. Rood. "Multidimensional flux-form semi-Lagrangian transport schemes." *Monthly Weather Review* 124.9 (1996): 2046-2070.
3. Lin, S.-J., and R. B. Rood. "An explicit flux-form semi-lagrangian shallow-water model on the sphere." *Quarterly Journal of the Royal Meteorological Society* 123.544 (1997): 2477-2498.
4. Lin, S.-J. "A finite-volume integration method for computing pressure gradient force in general vertical coordinates." *Quarterly Journal of the Royal Meteorological Society* 123.542 (1997): 1749-1762.
5. Lin, S.-J. 2004: A vertically Lagrangian Finite-Volume Dynamical Core for Global Models. *Mon. Wea. Rev.*, 132, 2293-2307.
6. Putman, W. M., and S.-J. Lin. "Finite-volume transport on various cubed-sphere grids." *Journal of Computational Physics* 227.1 (2007): 55-78.
7. Harris, L. M., and S.-J. Lin. "A two-way nested global-regional dynamical core on the cubed-sphere grid." *Monthly Weather Review* 141.1 (2013): 283-306.