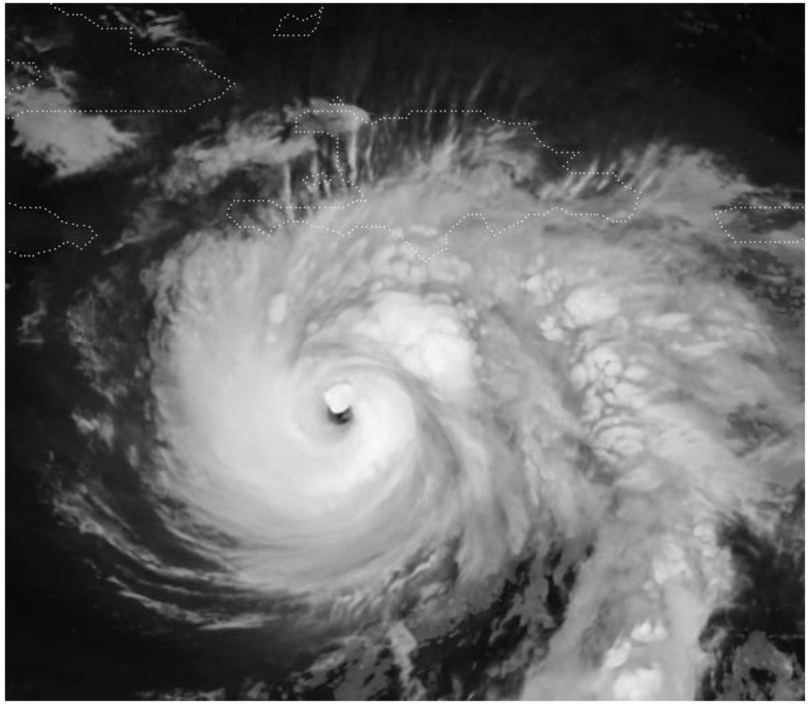
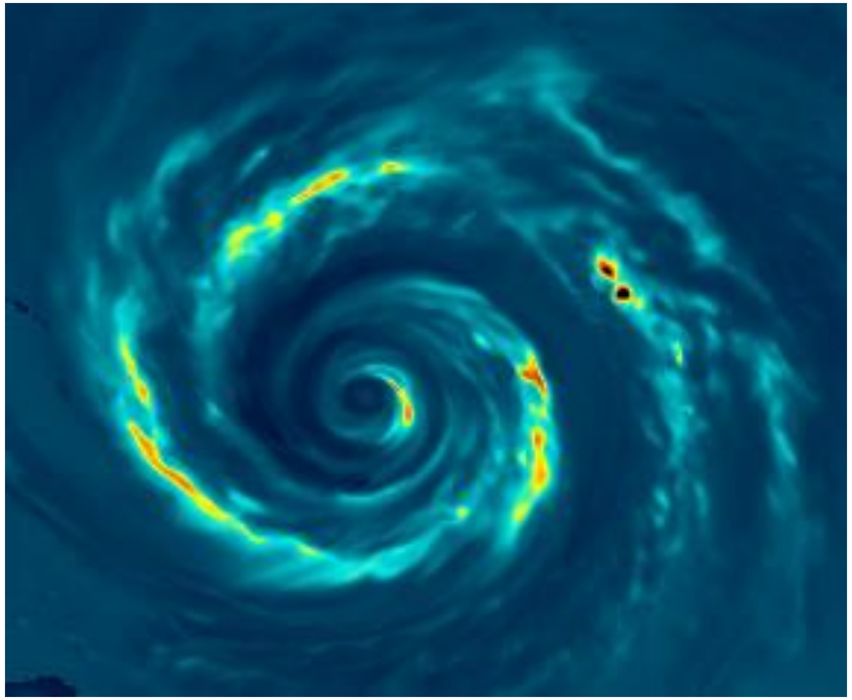
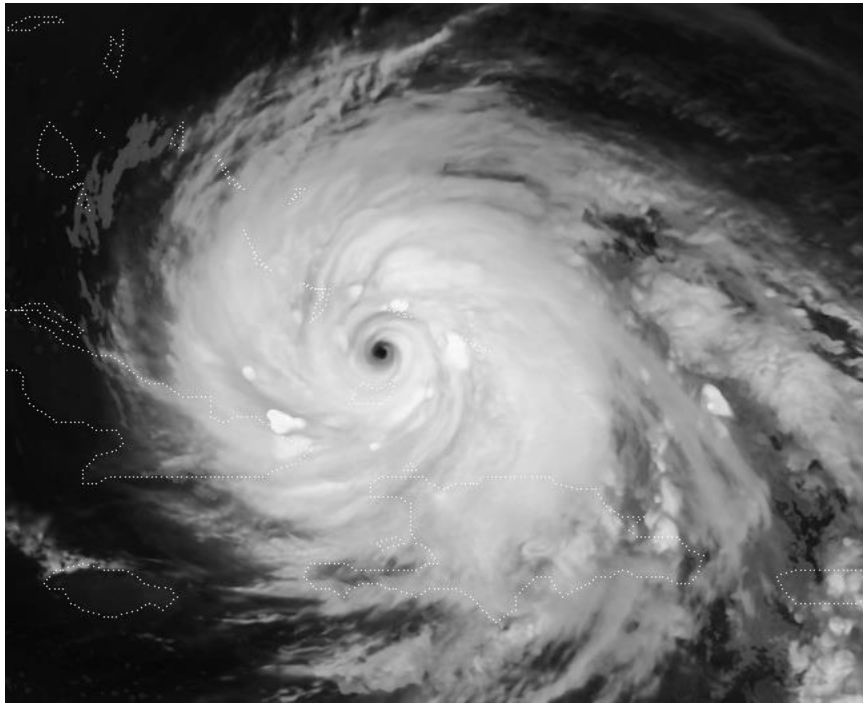
  

Variable-resolution weather and climate modeling with GFDL FV3

Lucas Harris for S-J Lin and the GFDL FV3 Team

18th Workshop on high-performance computing in Meteorology

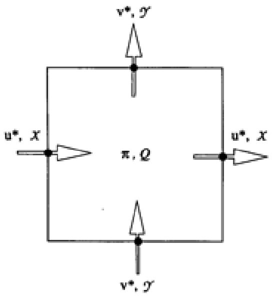
ECMWF, Reading, UK

26 September 2018

FV3: The GFDL Finite-Volume Cubed-Sphere Dynamical Core

Goal: Physical consistency, fully-FV numerics, component coupling, and computational efficiency

Lin & Rood 1996
Efficient 2D high-order conservative FV transport



Lin & Rood 1997
FV horizontal solver focusing on nonlinear vorticity dynamics

the two-grid system: the 'CD-grid'. The time-centered a
d as in the C-grid (as in Fig. 1) whereas the prognostic win
D-grid. The cell-averaged relative vorticity is computed

the diffusion is scale-dependent and nonline
ome evidence that the nonlinear diffusion assc
n be interpreted physically, at least for stratos
urrent implementation of the FFSL algorithm f
plicit diffusion will be needed.
nt difference between the FFSL algorithm and
y is transported in a general divergent flow. I
Ω fields are taken as cell-averaged values, not
ed for transporting h and Ω, regardless of the
etween h and Ω can therefore be better preser

$$\Sigma \mathbf{F}_z = \int_1^2 P\,dx + \int_3^4 P\,dx$$

, 3, and 4 are the four vertices of the finite volume.
on so far is for the general non-hydrostatic flow. For a
dition must hold

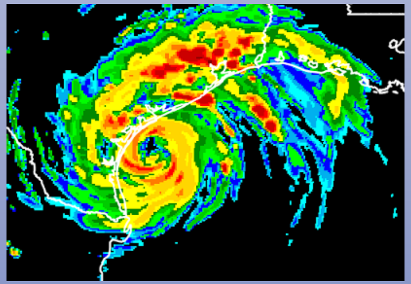
$$\Sigma \mathbf{F}_z = g\Delta m$$

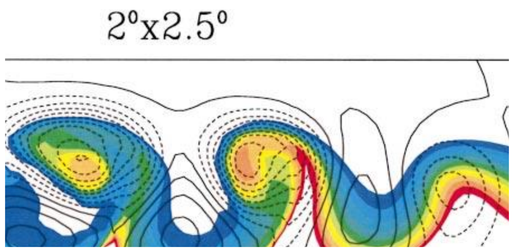
celeration due to gravity. Equation (5) states that the v
essure force acting on the finite volume exactly balanc
ne. The horizontal acceleration, after eliminating Δm

Lin 1997 Efficient, mimetic FV PGF

GFDL FV3

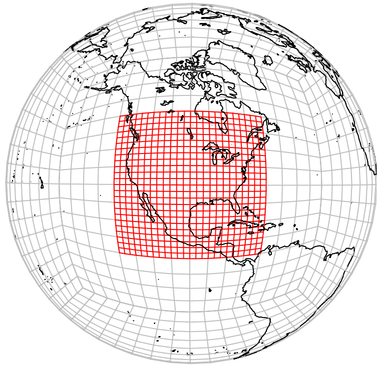
Next-generation FV3
Rigorous Thermodynamics
Flexible dynamics
Adaptable physics interface
Variable-resolution techniques
Regional & periodic domains

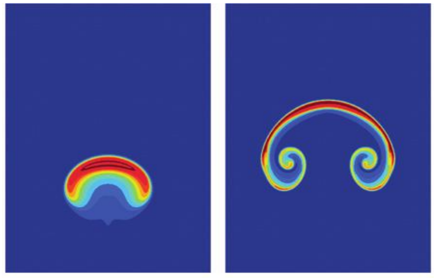




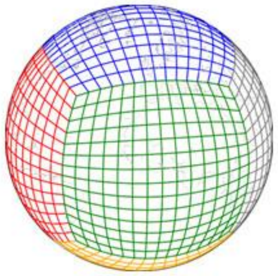
Lin 1998–2004 FV core with "floating" Lagrangian vertical coordinate

Harris & Lin 2013, 2016
Variable resolution with two-way nesting and Schmidt grid stretching





Lin 2006, Chen & Lin et al 2013
Consistent Lagrangian nonhydrostatic dynamics



Putman & Lin 2007
Scalable cubed-sphere grid, doubly-periodic domain

The FV3 community

Many Models
Many Applications
One flexible dynamical core

CESM Framework
CAM-FV
CAM-FV3

FMS Framework
AM/CM/ESM 2/3/4
HiRAM, FLOR, HiFLOR, SPEAR
fvGFS

NEMS Framework
FV3-powered GFS, GEFS, CFS, WAM
HAFS, UFS, RRFS
FV3-based regional model
for HREF, Warn-on-Forecast

GEOS Chem
GEOS-Chem High-Performance

GMAO Framework
GEOS, DAS, MMF, MERRA(2)
GISS Model E
Ames Mars model

LASG FAMIL

Chinese Academy of Sciences

TaiESM; CWB prediction model

GFDL Unified Modeling

Models for prediction, projection, and research at all scales

- FV3: GFDL Finite-Volume Cubed-Sphere Dynamical Core
  - Not a model, a dynamical core…for now
- FMS: GFDL Flexible Modeling System
  - Elegant and powerful framework and library for component coupling and model utilities
  - Fits nicely inside of NEMS, CESM, GEOS, etc.

- **AM4**: GFDL's CMIP6 Atmosphere Model
- **CM4/ESM4**: GFDL's CMIP6 Coupled-Climate Models
- **HiRAM**: High-Resolution Atmosphere Model for S2S prediction
- **FLOR/SPEAR**: Coupled models and ODA systems for S2S and S2D prediction

GFDL Physics Suite and LM4 Land Model

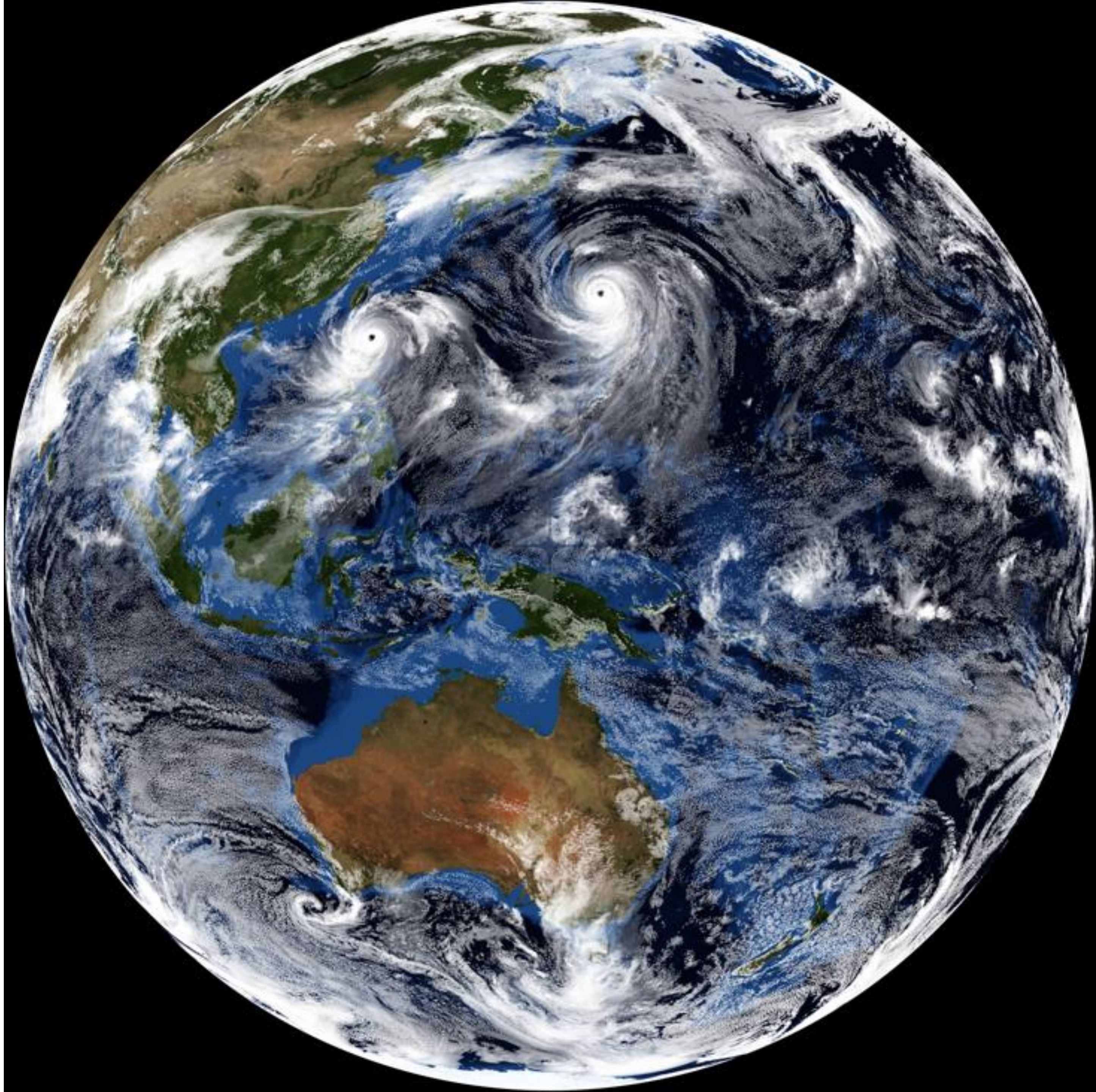
- **fvGFS**: GFDL's Experimental NGGPS implementation
  - **3-km nested cfvGFS**: CONUS nest for continental convection
  - **3-km nested hfvGFS**: North Atlantic nest for hurricanes

Modified GFS Physics Suite and NOAH Land Model

DYAMOND

Weather ❤ Climate

- International global cloud-resolving model inter-comparison
  Including NICAM, ICON, UKMO, GEOS, ARPEGE-NH
- 40-day fvGFS runs
  - 3-km c3072, 79 layers
    - Also 6.5-km c1536, 91 layers
  - GFDL MP, no convective parameterization, new SGO
- Evaluating climate (energy balance, circulation) as well as variability and weather events



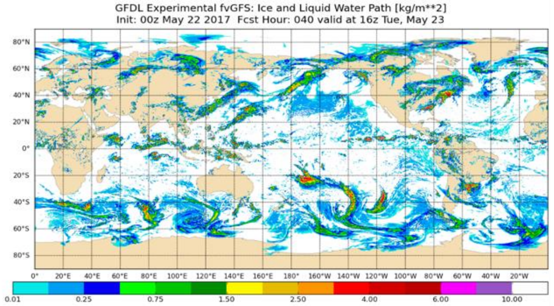
Courtesy S-J Lin, Xi Chen, and Linjiong Zhou

www.gfdl.noaa.gov/visualizations-mesoscale-dynamics/

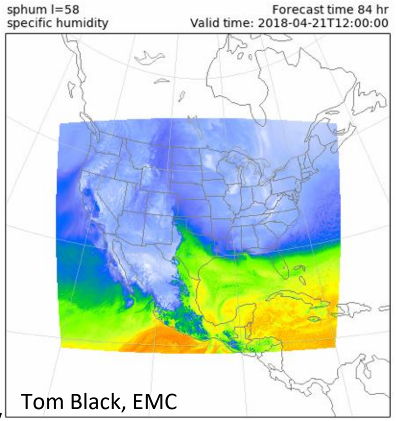
High-Resolution Modeling

Limited Area Model

- Simple, cheap, and easy for short-term forecasts
- Good for extremely high resolutions (urban scale, LES)
- Boundary errors creep in within a few days
- BCs may differ greatly from regional model
- No feedback to large scale—trouble for hurricanes

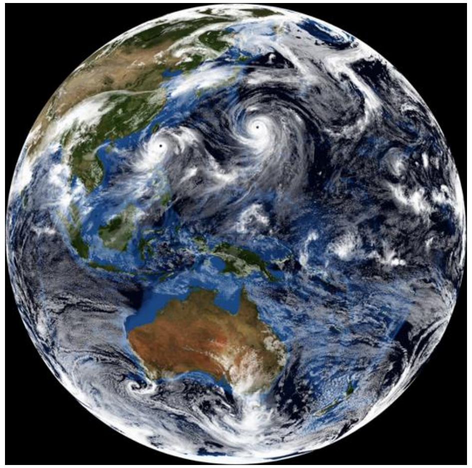


Three-hour
BC Update Frequency

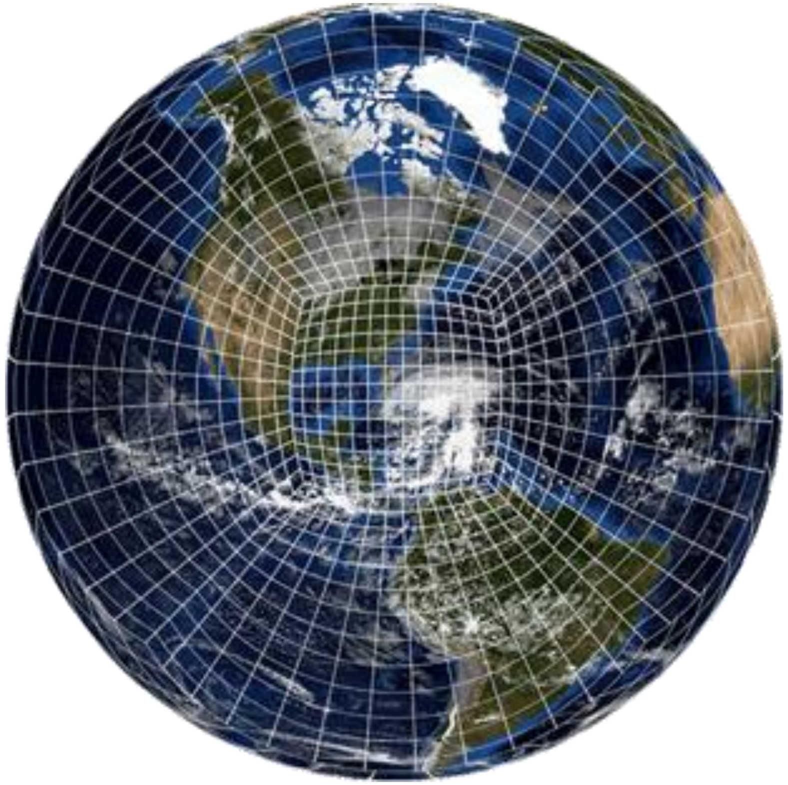


Uniform-resolution Global Model

- No boundaries!
- Globally consistent solution
- Too expensive to be practical without lowering the resolution
  - 3-km DYAMOND: 10K core-hours/day on Gaea c4



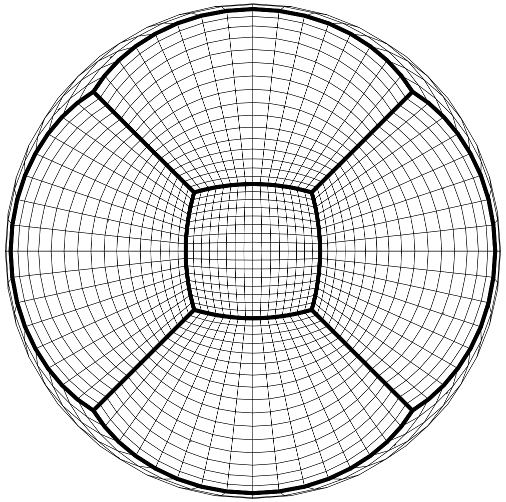
Solution: grid refinement of a global model!

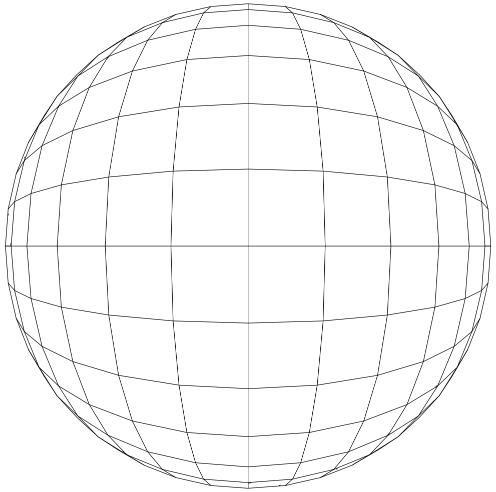


Stretched grid

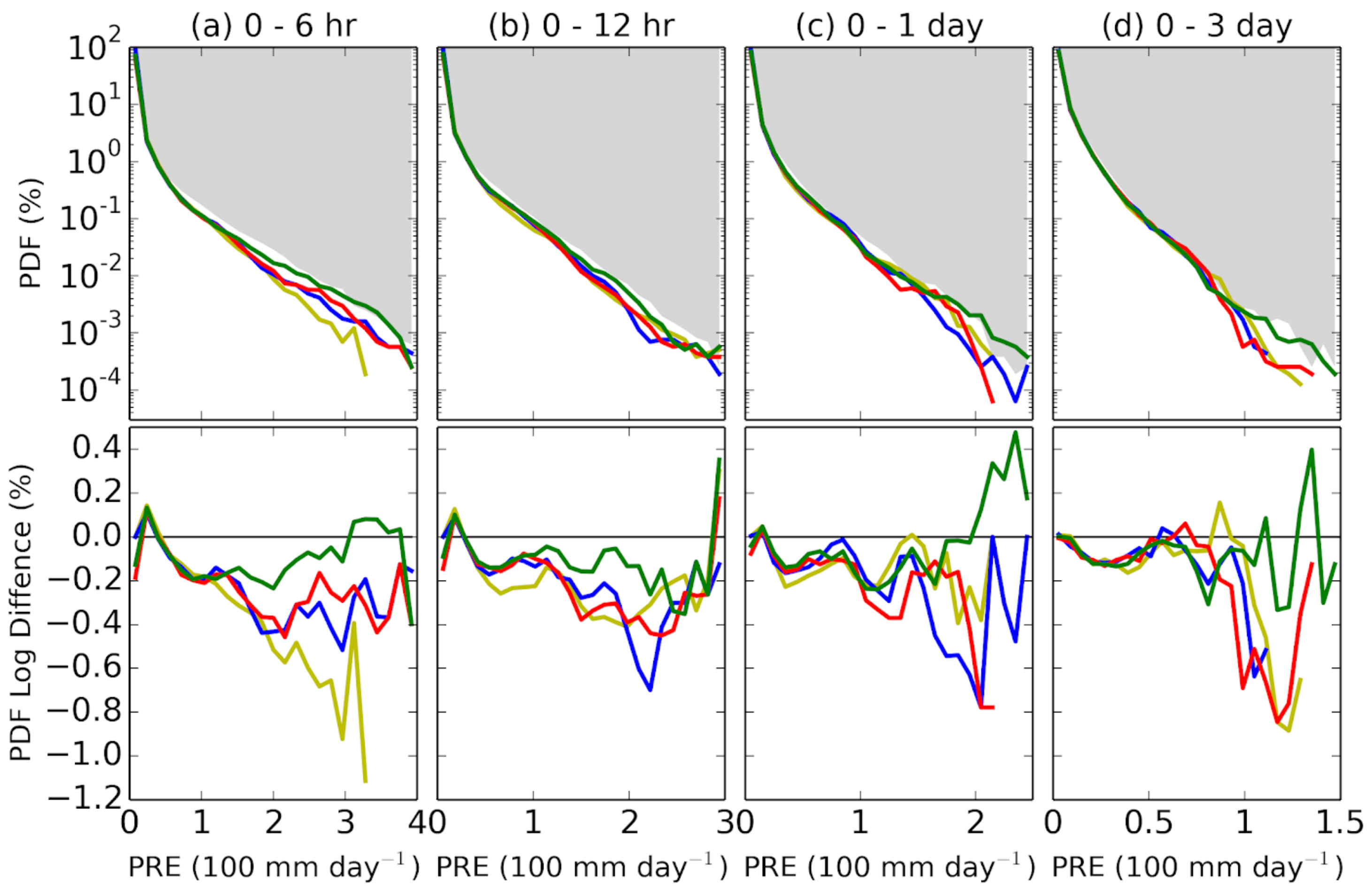
The simple, easy way to achieve grid refinement

- Analytic Schmidt deformation
  - Grids can be created in seconds
- Smooth: No abrupt refinement!
- Single domain: works in existing models
- Requires “compromise” tuning between coarse and fine regions
  - A good scale-aware scheme can help here
- Does coarsen opposing side, and more stretching reduces size of refined area





Stretched fvGFS: CONUS Precipitation PDFs



StageIV Observations (bottom of shaded)

Operational GFS

13-km fvGFS (old GFS MP)

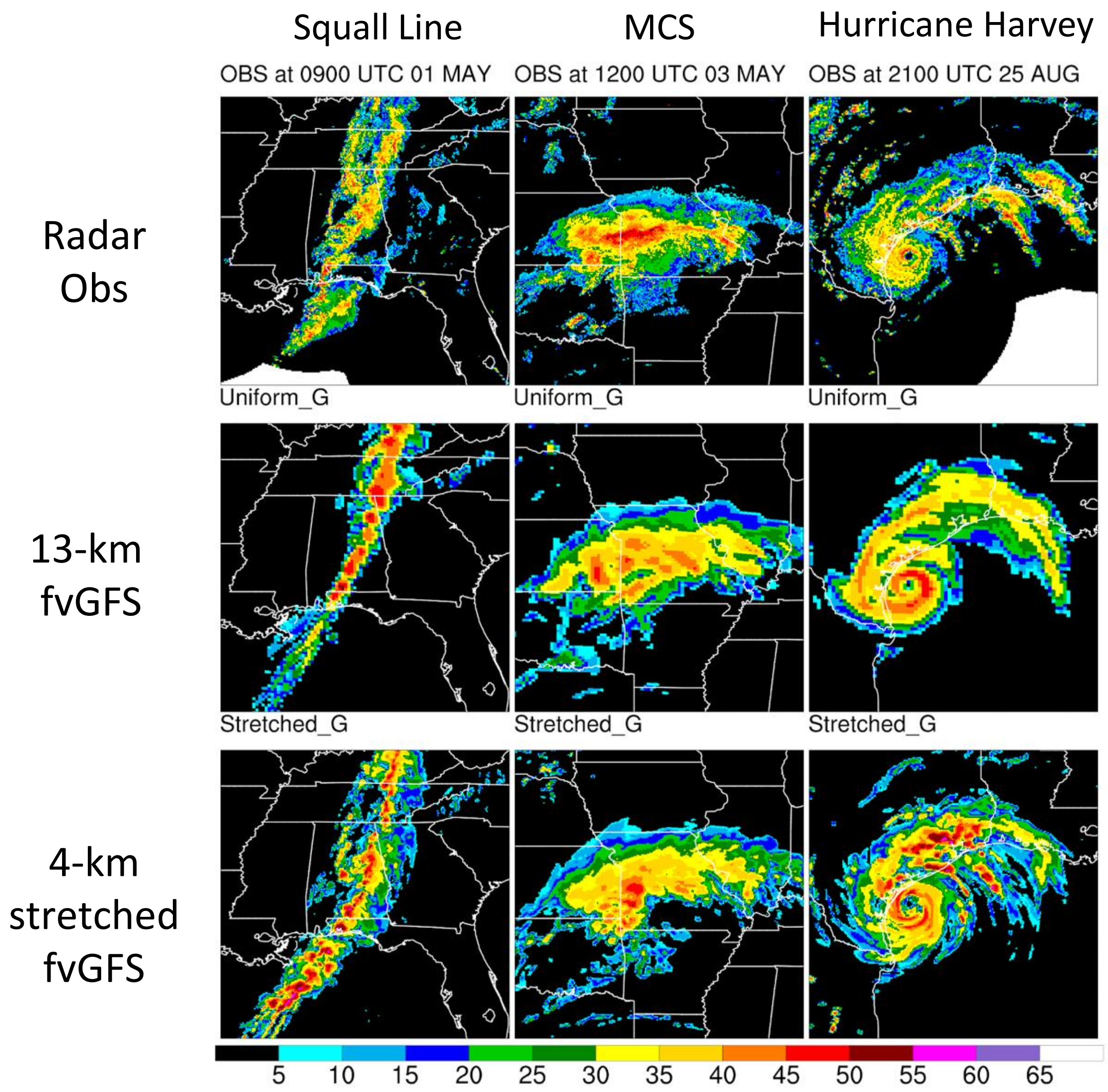
13-km fvGFS (GFDL MP)

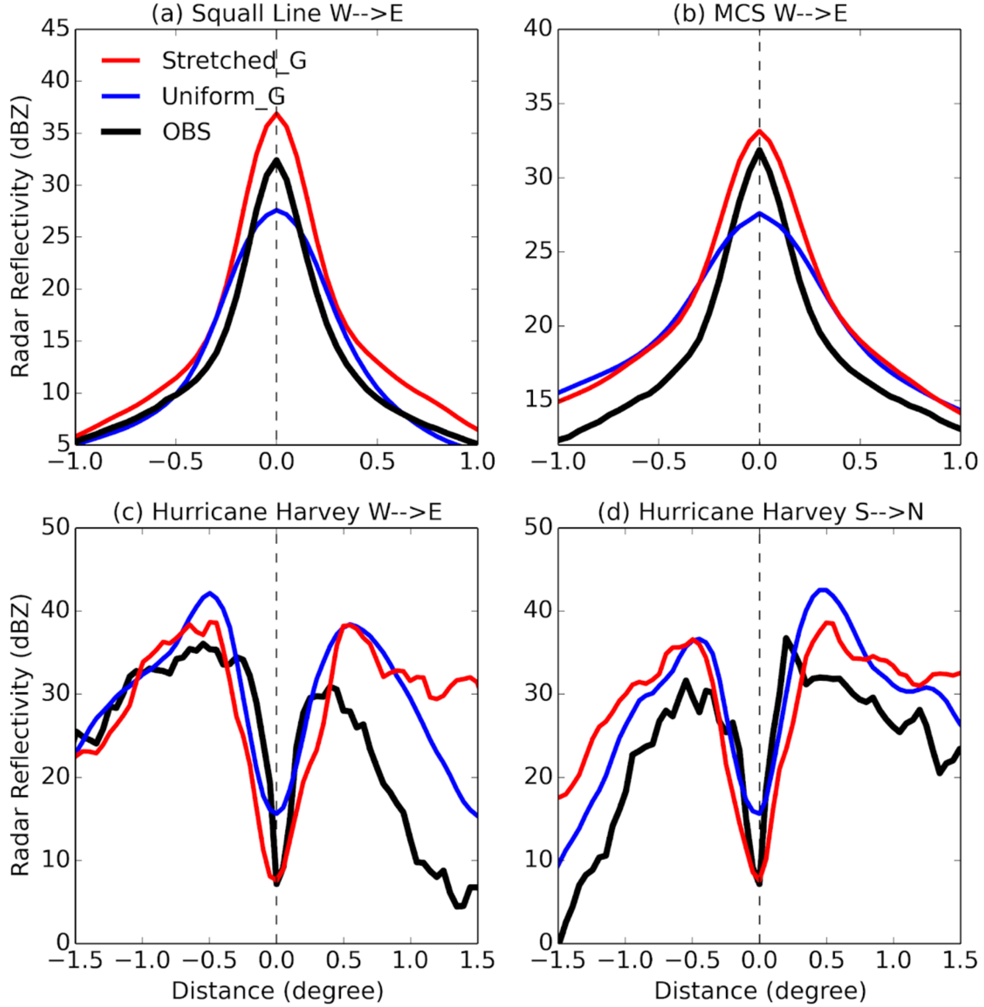
4-km stretched fvGFS

Value added by convective-scale simulation: much improved heavy and intense precipitation

Zhou et al, in revision at BAMS

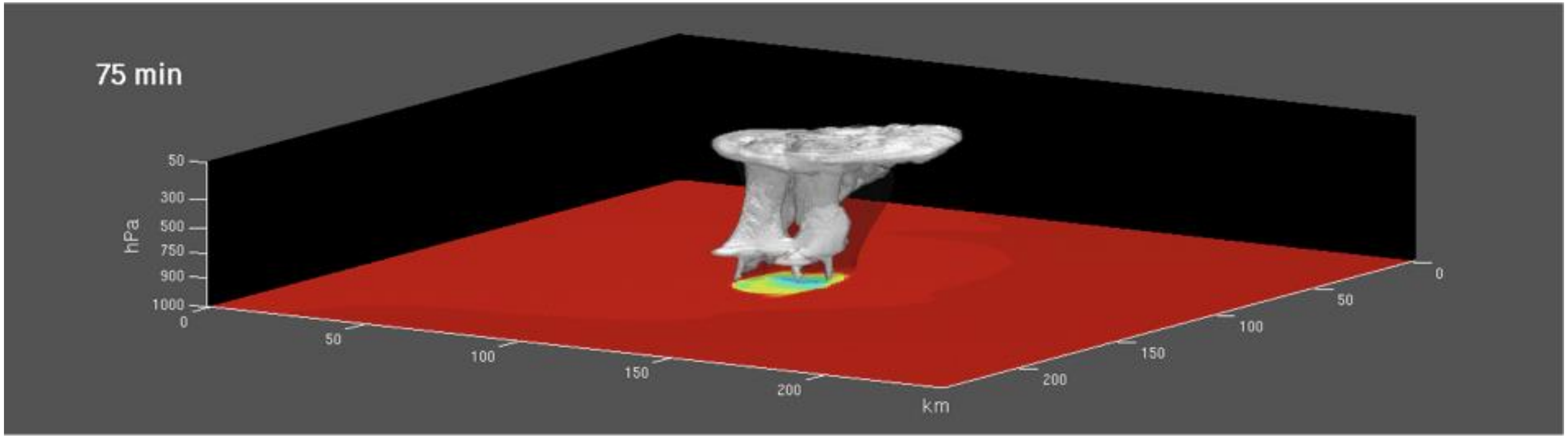
Stretched fvGFS: Storm structures



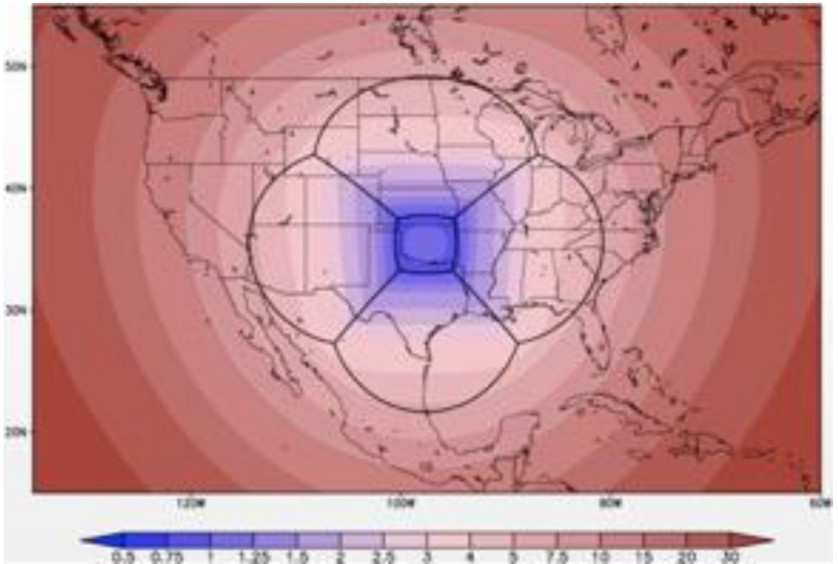


Zhou et al, in revision at BAMS

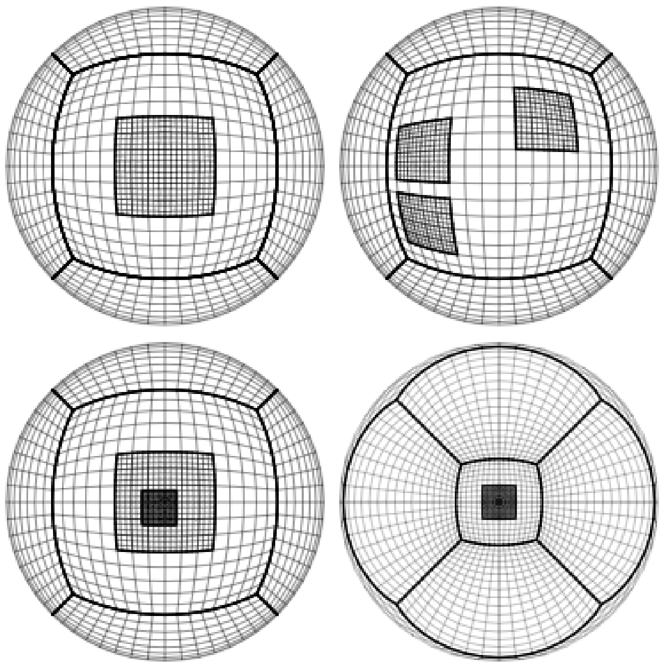
Super-stretched global model

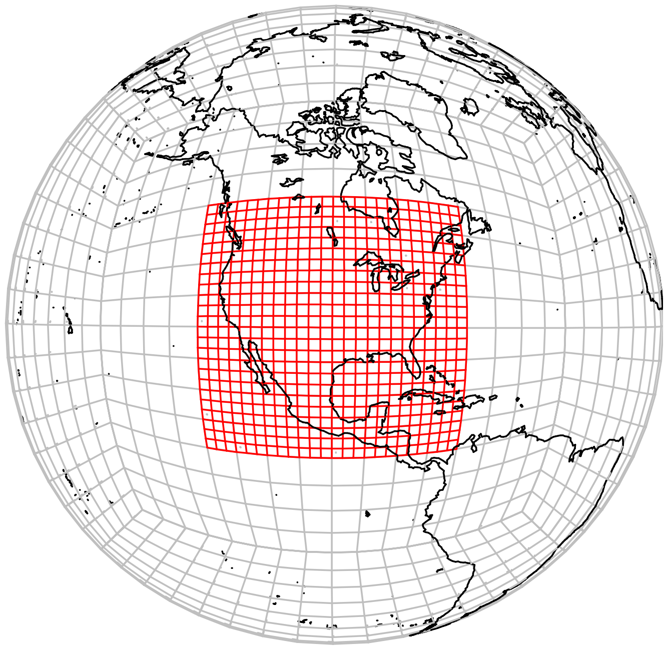


- c512r20: a **global model** refined to 1 km!!
- Solo FV3 coupled to warm-rain GFDL MP
- Idealized supercell test with Mike Toy's semicircle hodograph
  → "tornado-like vortices"?



http://www.gfdl.noaa.gov/visualizations-mesoscale-dynamics

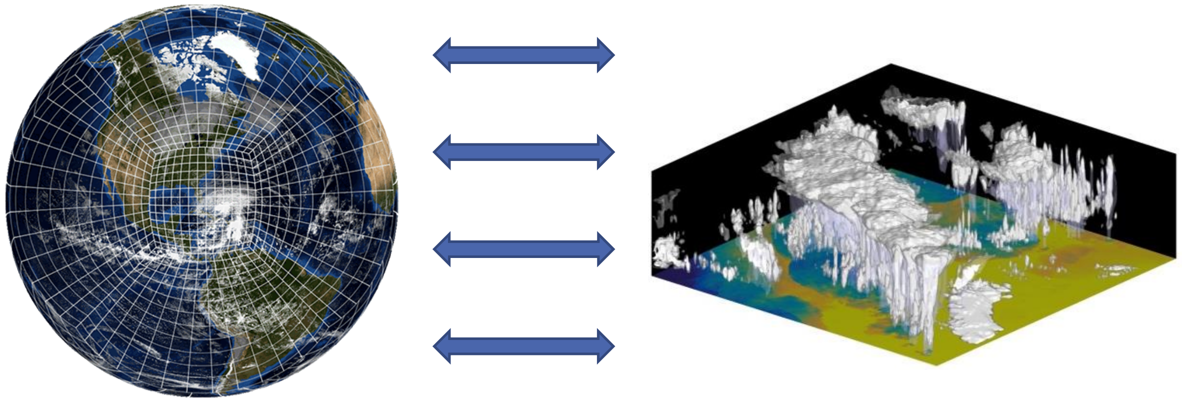




Two-Way grid nesting

- Simultaneous coupled, consistent global and regional solution
  - No waiting for a regional prediction!
- Different grids permit different parameterizations and timesteps
- Flexible! Great possibilities for combining nesting and stretching
  - Moving nests under development
- Does require extra infrastructure and code for nesting implementation.

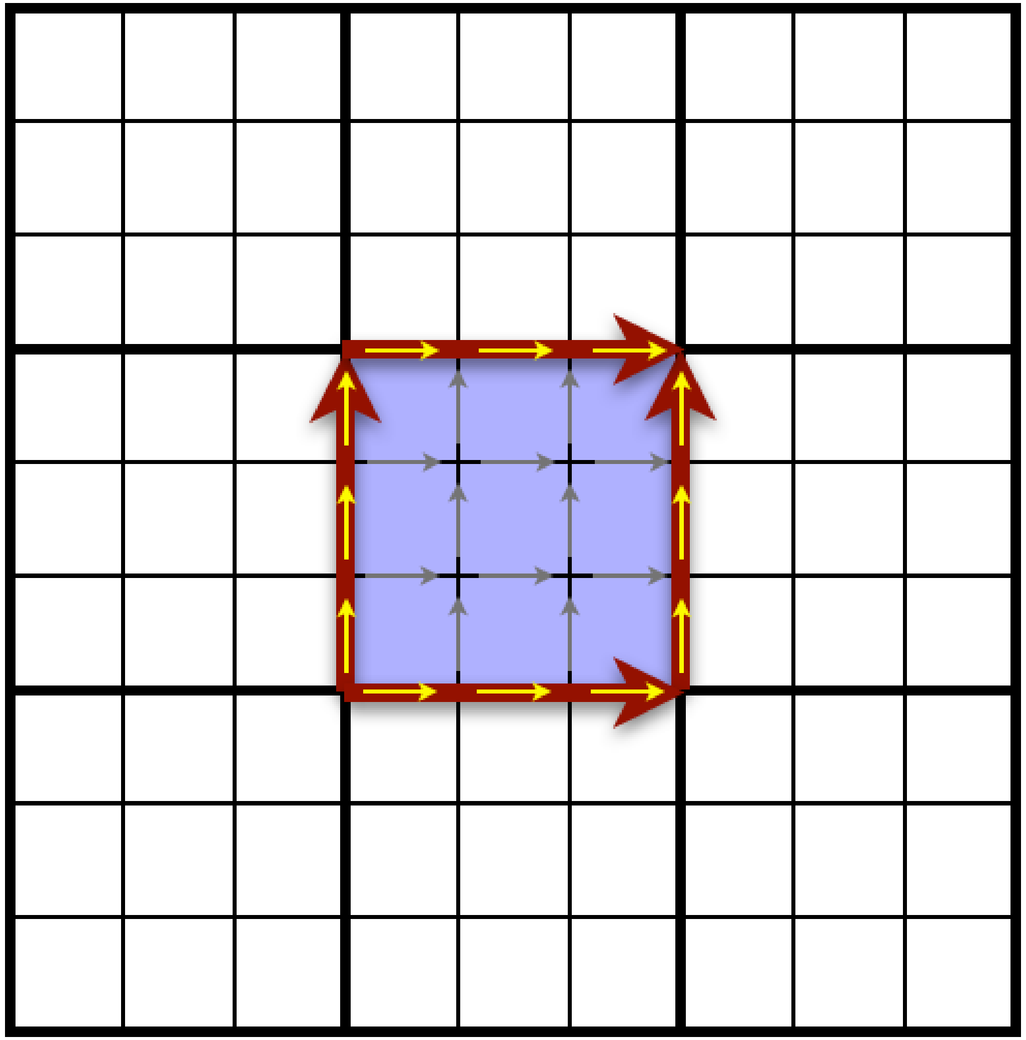
Nested-grid Boundary Conditions



- Boundary conditions for all variables (including tracers) are linearly interpolated into the boundary haloes of the nest.
  - Correct upwind BCs "baked in" by FV3's upwind-biased fluxes
- BC data refreshed usually every physics timestep
  - BCs stepped forward every small ("acoustic") timestep
- **Concurrent nesting:** nest and coarse grids integrated simultaneously on separate sets of processors. Great for many-core systems.
  - Requires *extrapolation* in time of two prior coarse-grid states

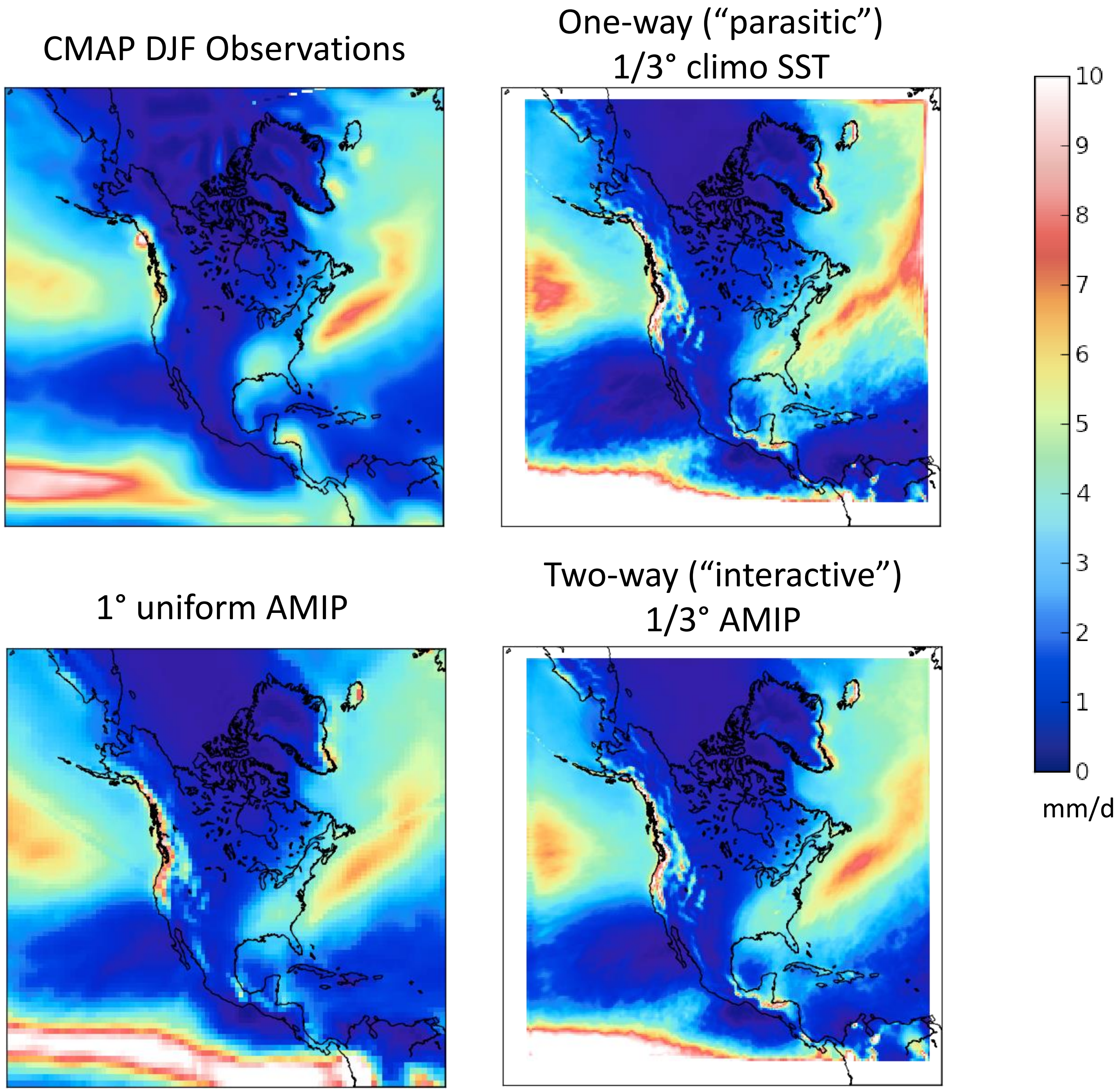
Two-way Interaction

- **Two-way nesting:** coarse grid periodically replaced ("updated") by nested-grid solution
- Cell average on temperature and w
  - Averaging consistent with FV numerics
- In-line average for winds, to conserve vorticity
- **Trivially mass-conserving**: air and tracer mass is *not* updated to coarse grid. Relies upon mass field to adjust to winds and temperature.



Nested-grid boundary artifacts

- Does the abrupt nest refinement cause problems?
- HiRAM climate model cold-season precipitation
- Two-way nesting shows very little disruption
- One-way nesting shows substantial grid artifacts!
  - Overhead of two-way nesting (5–10% of runtime) is worth it



S2S Hurricane Structure and Rapid Intensification

Global 25-km grid
8-km Atlantic nest

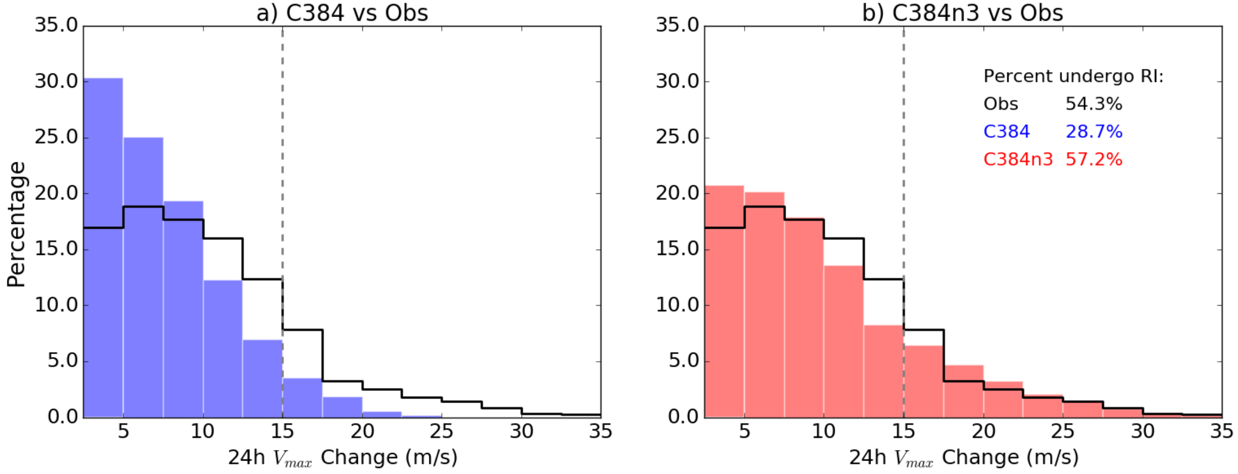
15 years of 30-day HiRAM runs, initialized the 1st of July—November

25-km simulates TCs which are too large and seldom undergo Rapid Intensification

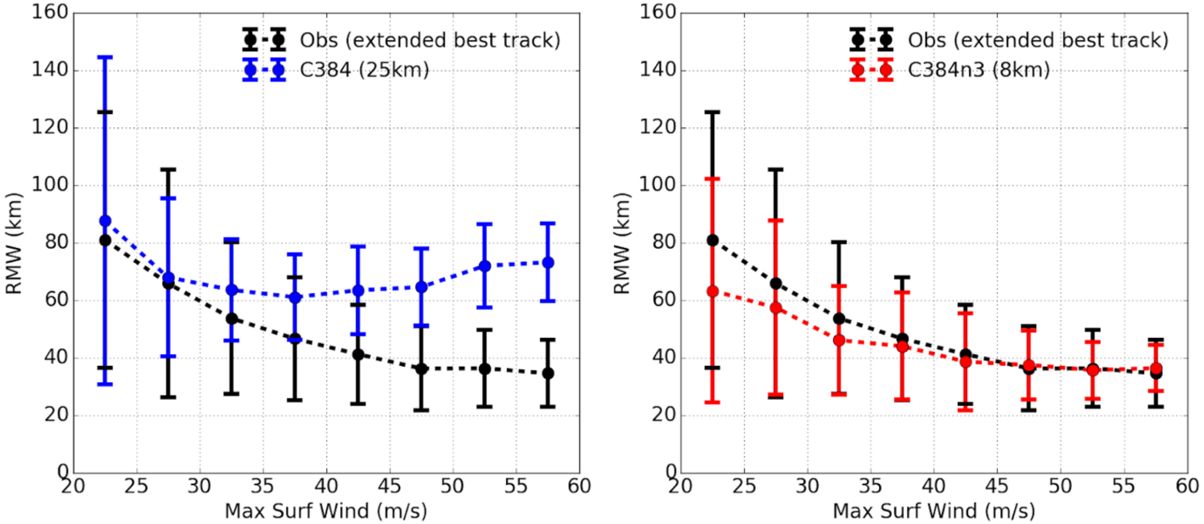
8-km matches observed RI rates; tied to better representation of small, intense cyclones?
➜ S2S Prediction of Rapid Intensification??

24 hour intensification rates

C384 (25km) vs Obs   C384n3 (8km nest) vs Obs

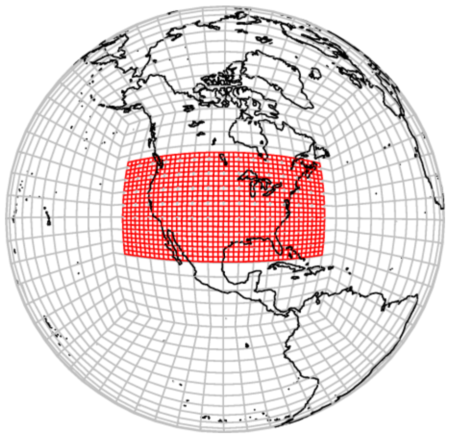


Radius of Mean Winds (RMW)



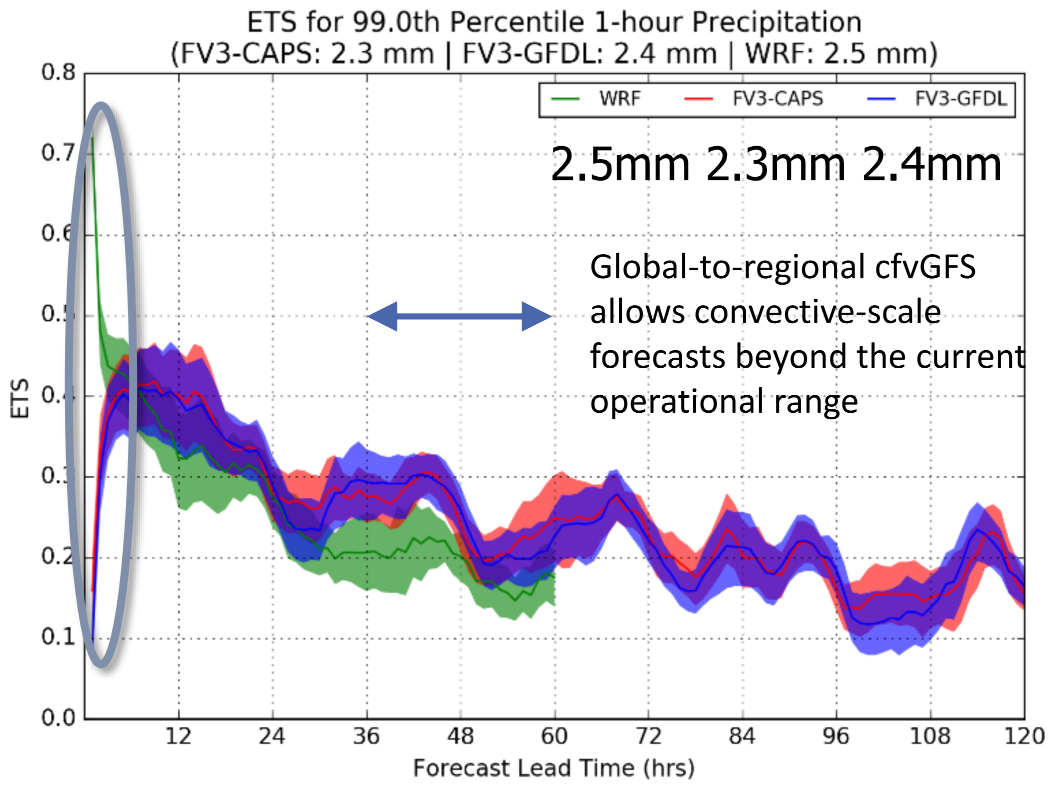
Gao et al, In revision at JAMES

3-km nested cfvGFS Spring Experiment Precipitation

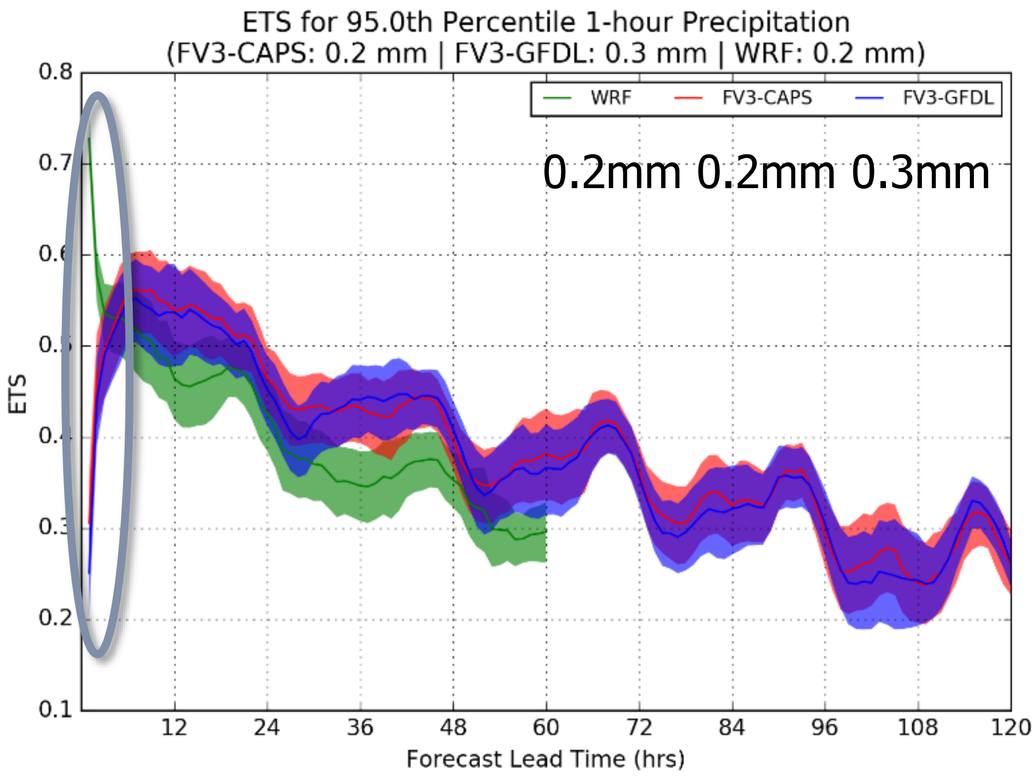


May 2017 Daily 00Z 3-km Forecasts

Heavy Precip



Light Precip



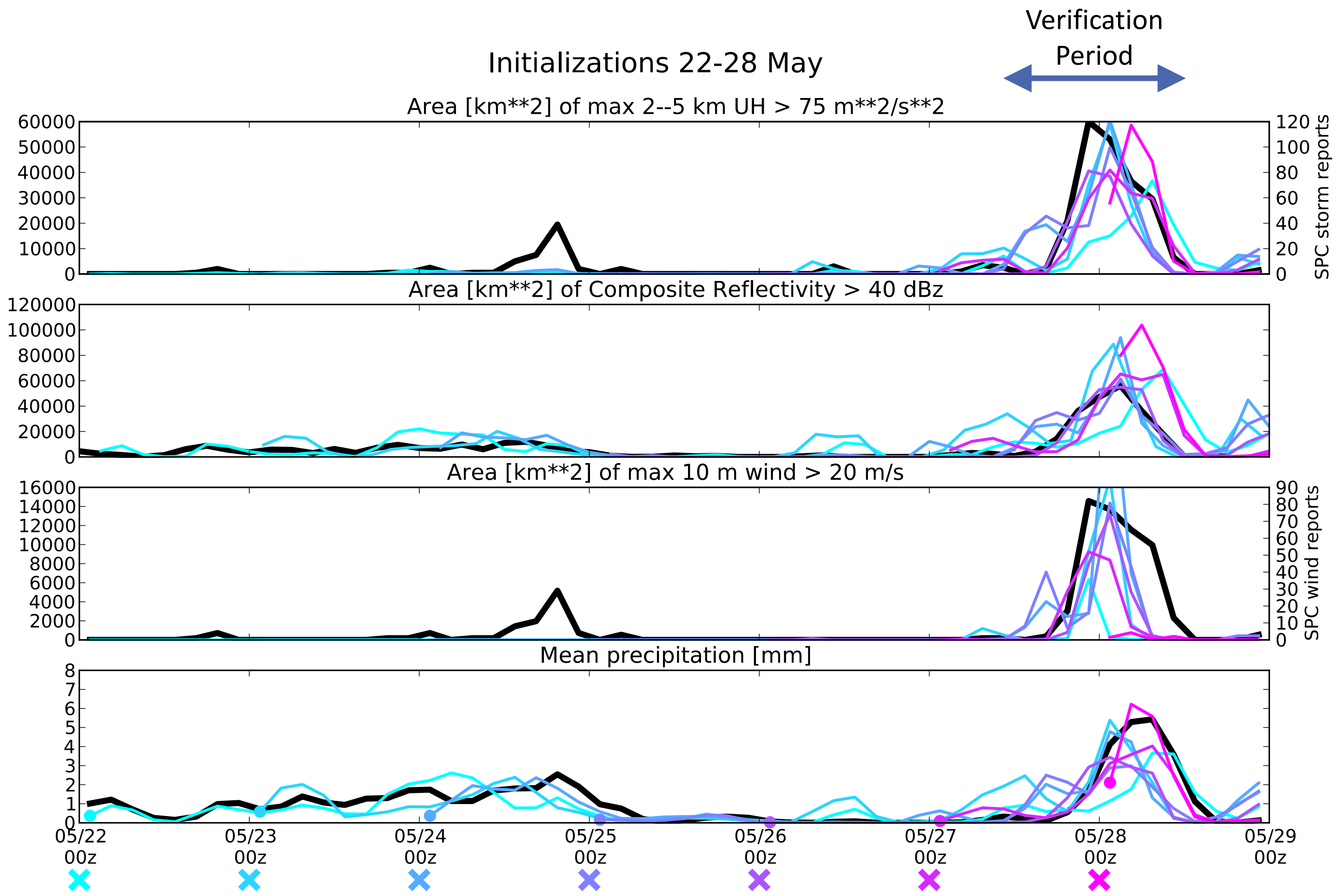
Very rapid spin-up from 13-km hydrostatic GFS ICs

FV3-GFDL: cfvGFS, GFDL Microphysics, **cold-started**
FV3-CAPS: cfvGFS, Thompson MP, **cold-started**
WRF: ARW, MYJ PBL, Thompson MP, CAPS cycled DA

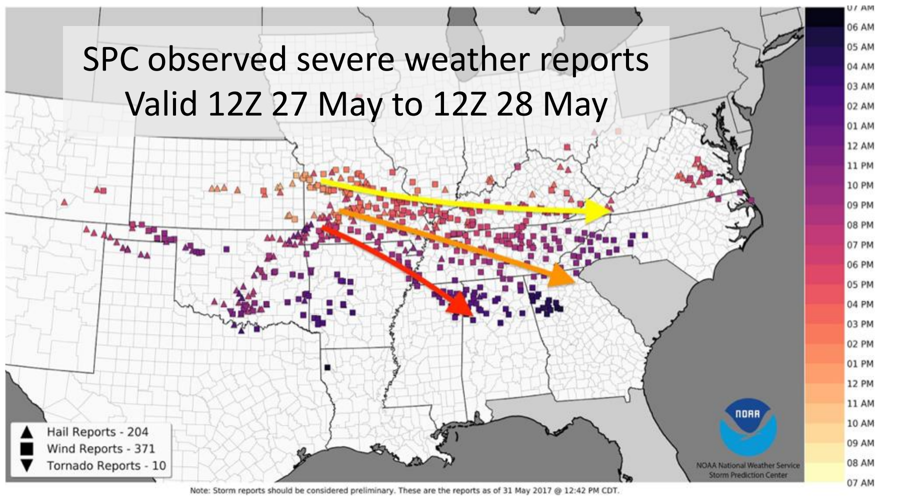
ETS for hourly precipitation
30-km neighborhood
90% confidence interval shaded

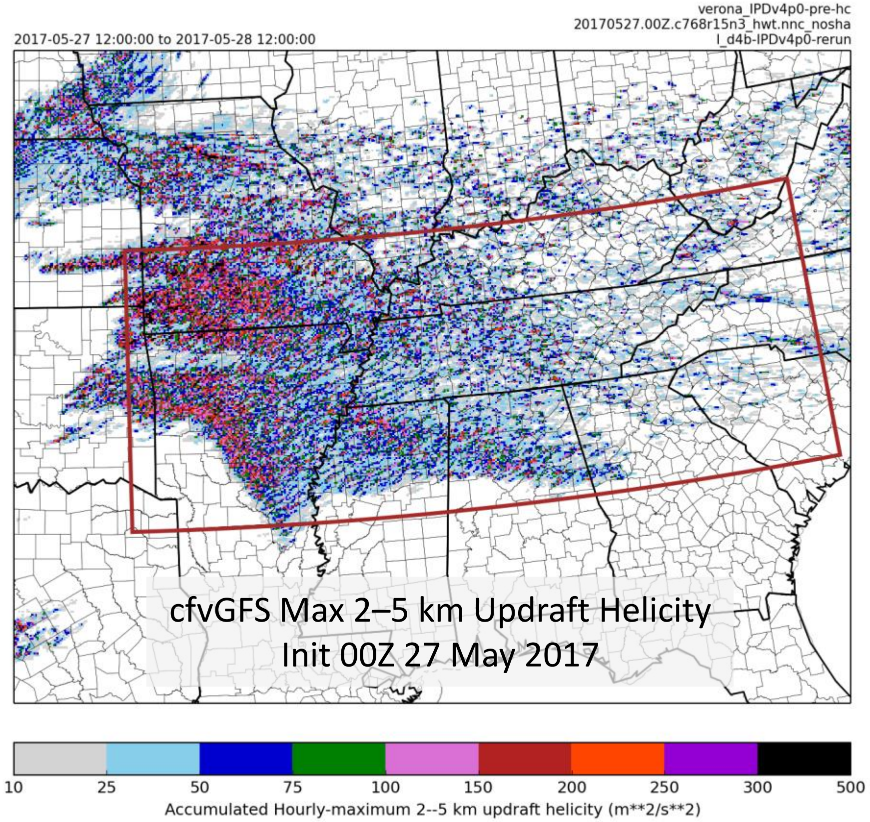
Courtesy Tim Supinie and Ming Xue (U. Oklahoma)

Medium-range derecho prediction
27–28 May 2017 “Triple Derecho”



x = Model initialization; all run to 00z 29th





2017 GFDL cfvGFS: EDMF PBL, GFDL MP

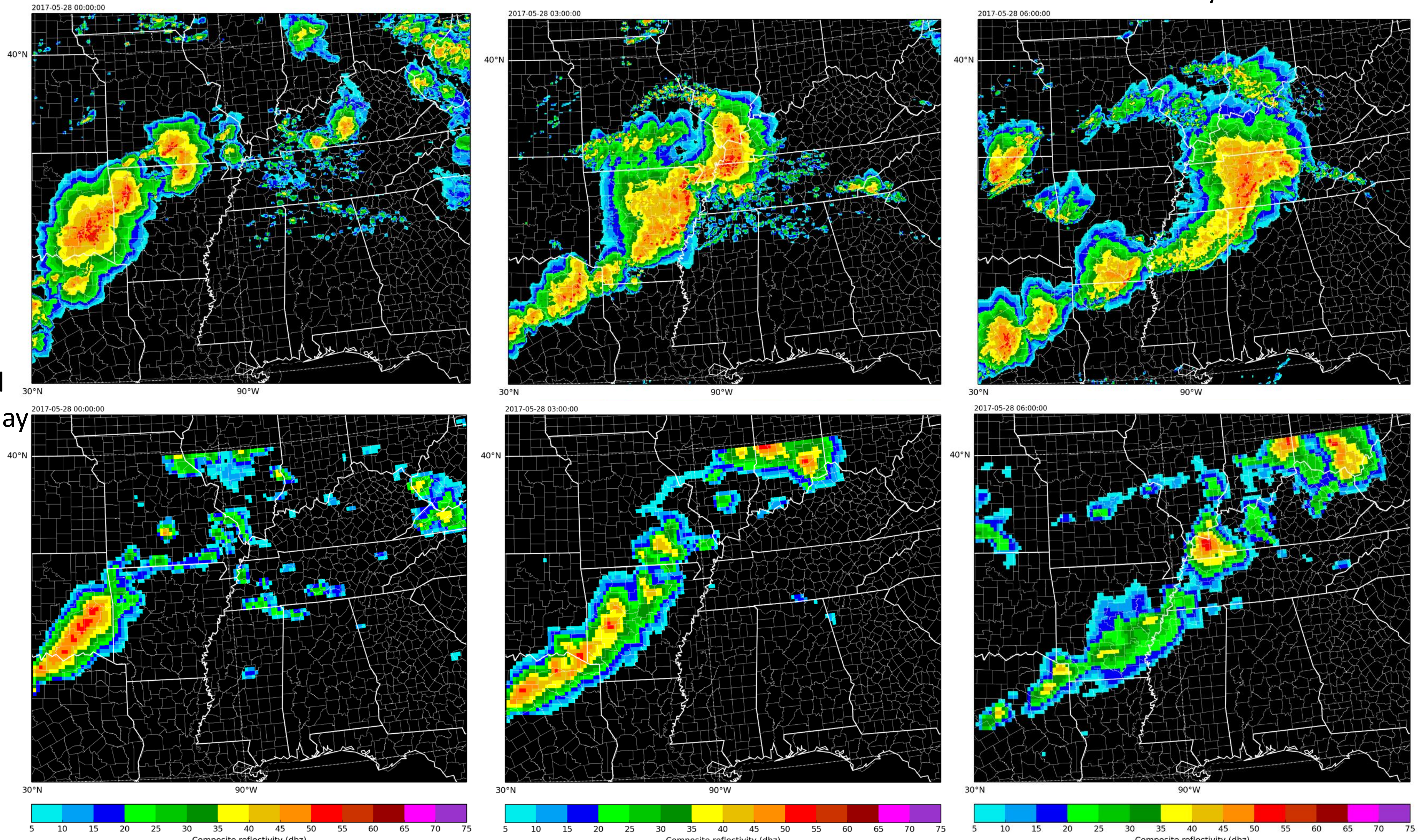
Updraft Helicity = w x ζ : severe storm proxy

00Z 28 May 2017 | 03Z 28 May 2017 | 06Z 28 May 2017

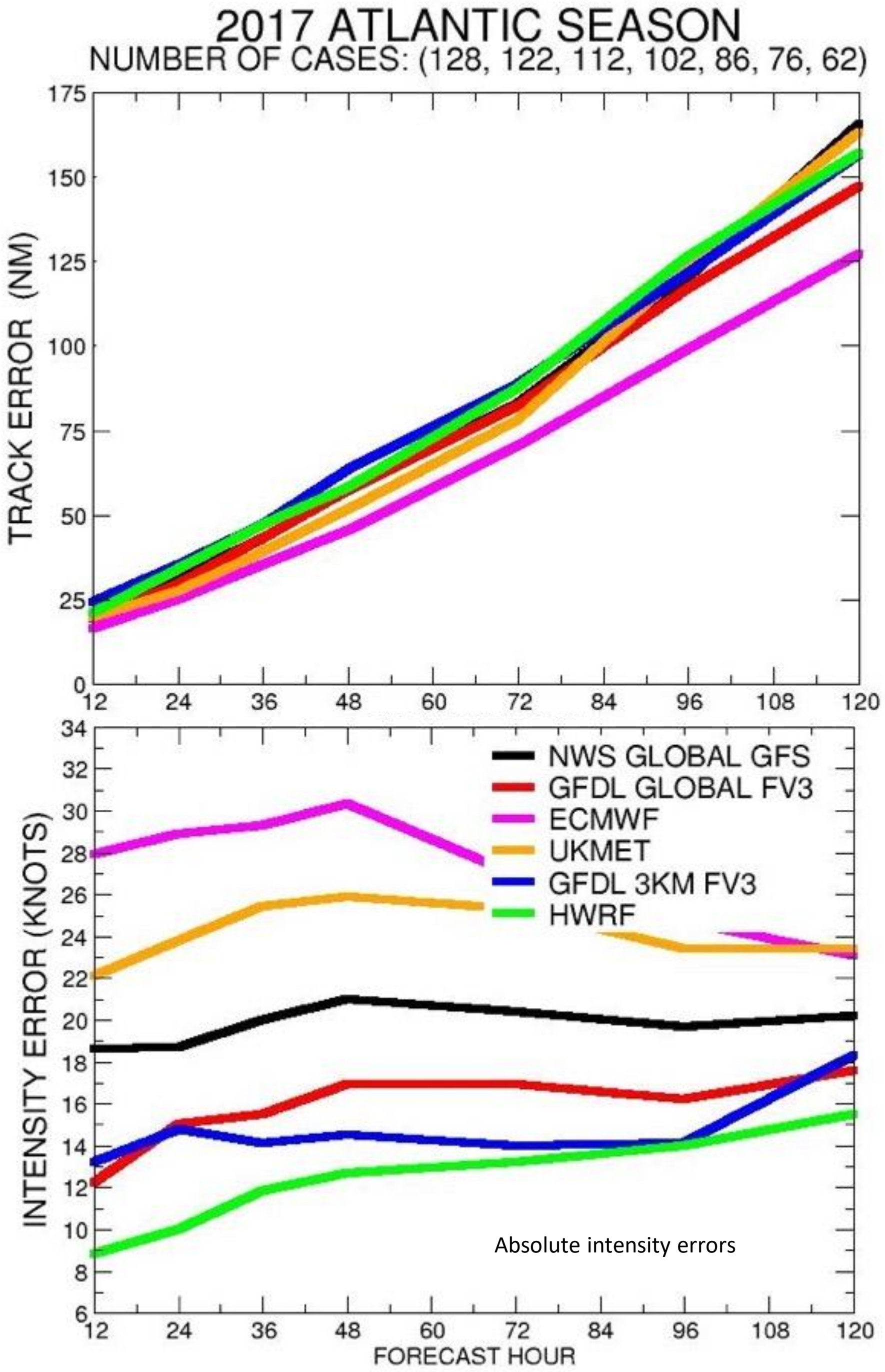
3-km cfvGFS

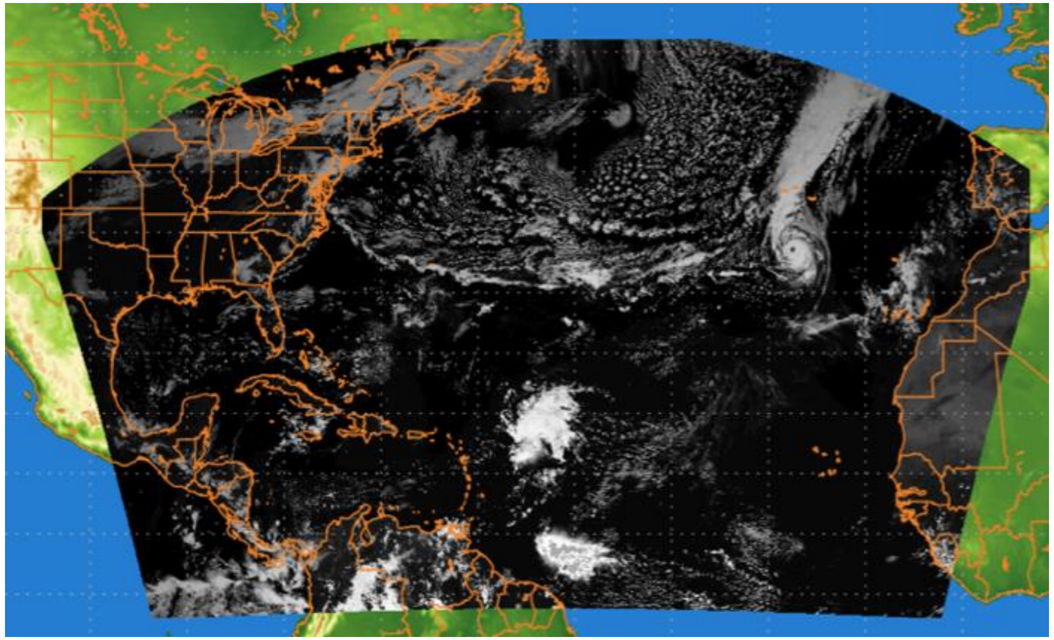
Initialized 00Z 25 May

13-km fvGFS



hfvGFS: Atlantic hurricane nest





hfvGFS 3-km Nested Domain

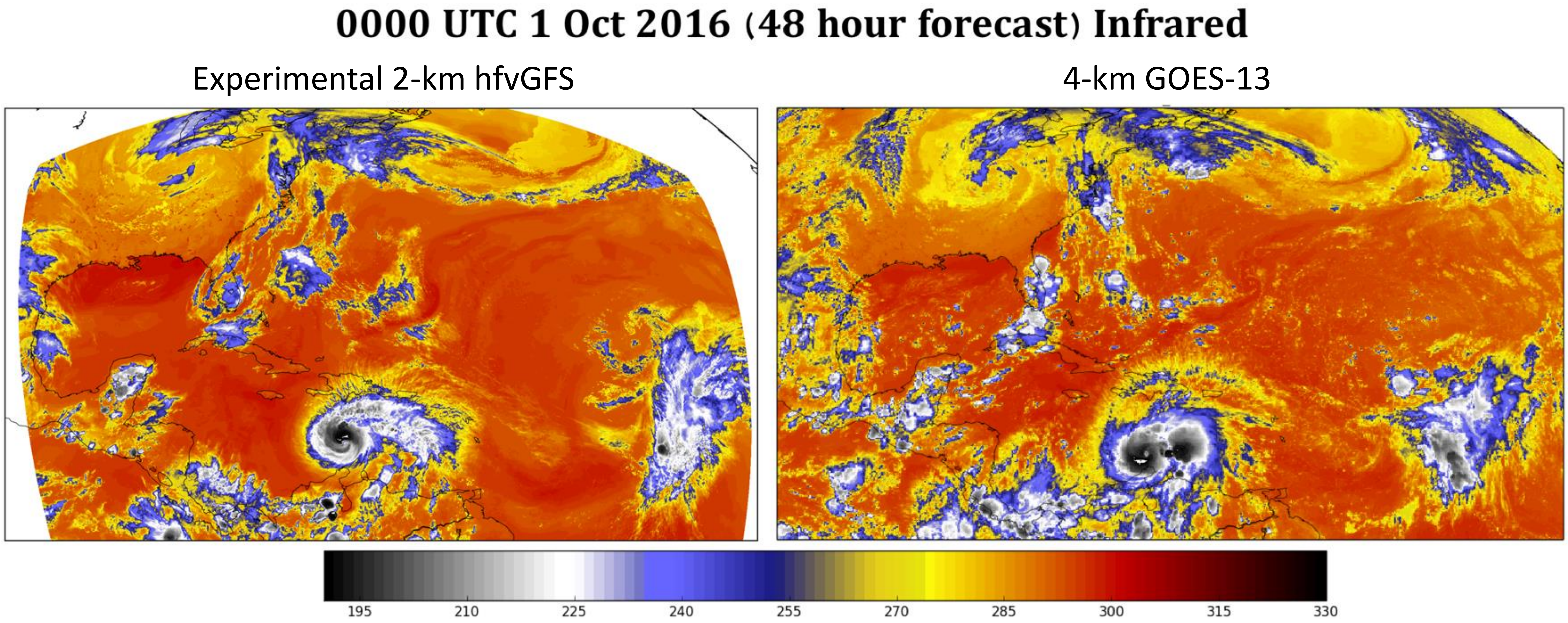
fvGFS intensity nearly the best, despite:

- Lower resolution (13 or 3 km vs. 2 km)
- Cold-started from 13-km hydro GFS
- No ocean coupling
- No TC-optimized PBL scheme

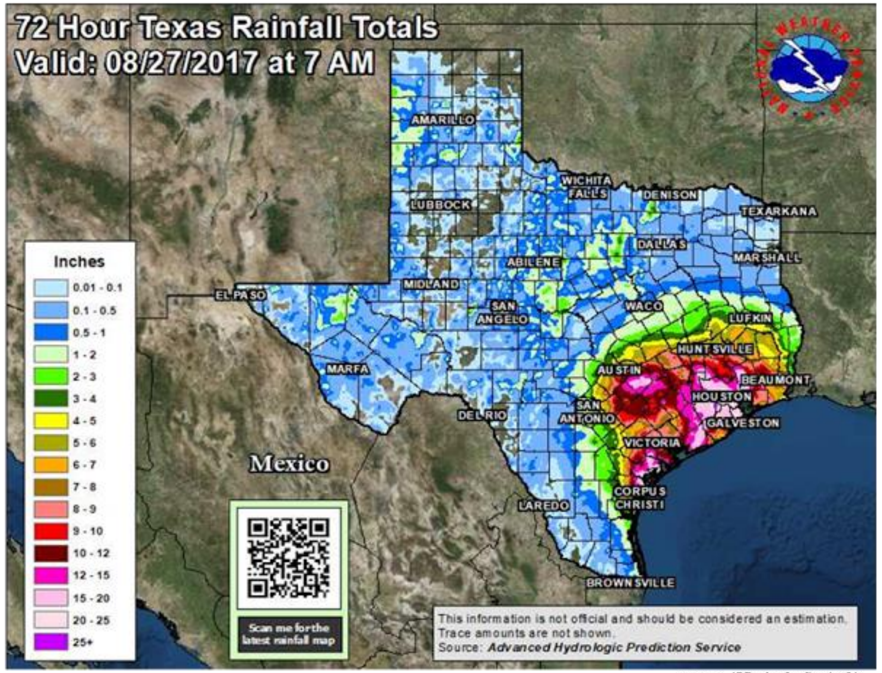
Better dynamics and better microphysics likely make the difference

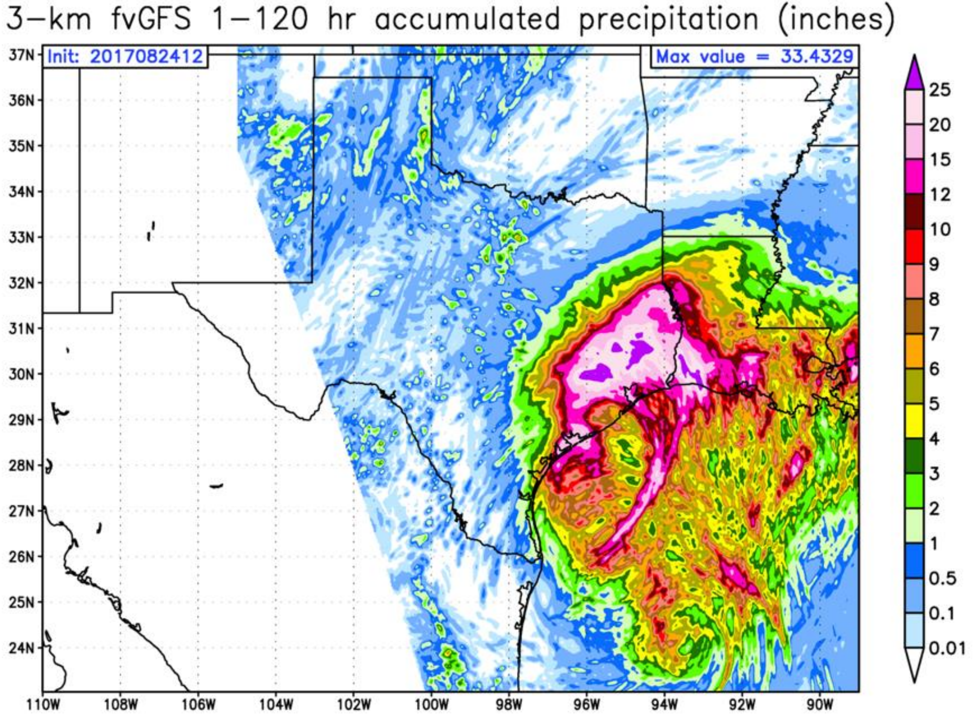
Hazelton et al, accepted by Wea. Forecasting

2-km hfvGFS: Hurricane Matthew

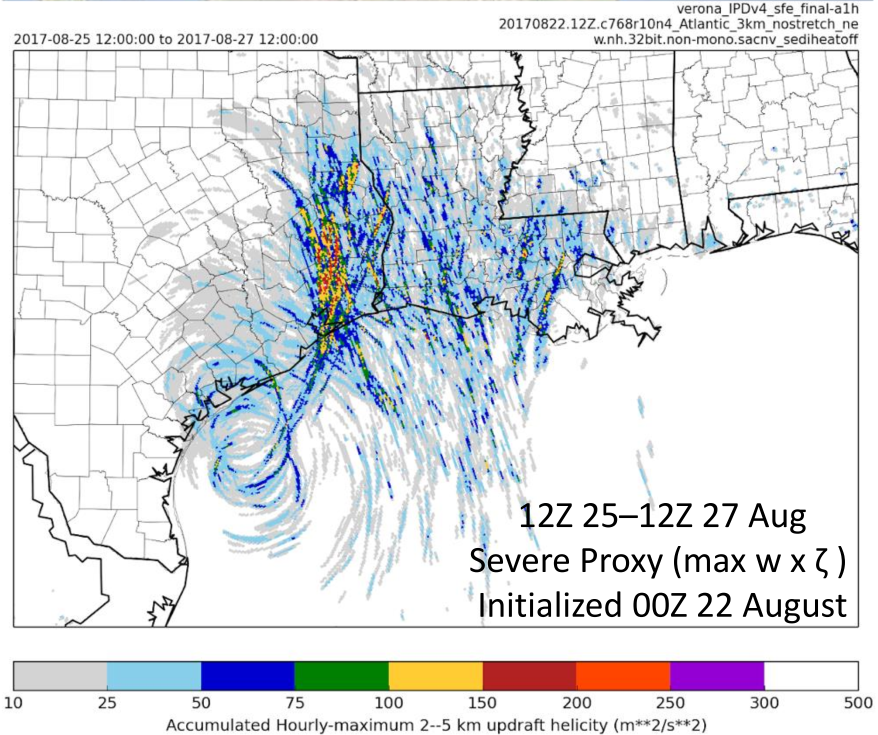


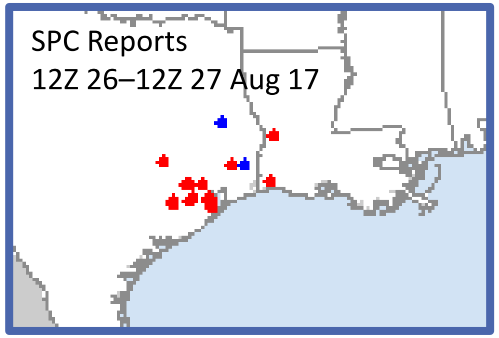
Courtesy Sharon Nebuda and Jason Otkin (SSEC/UWisc)

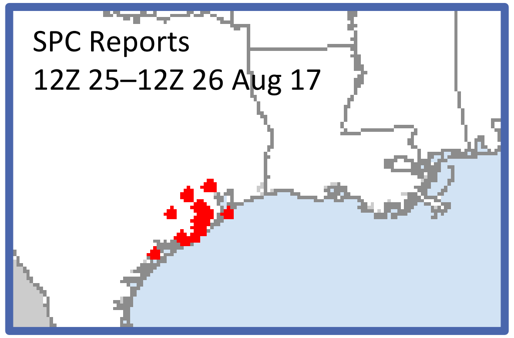




Init 12Z
24 August





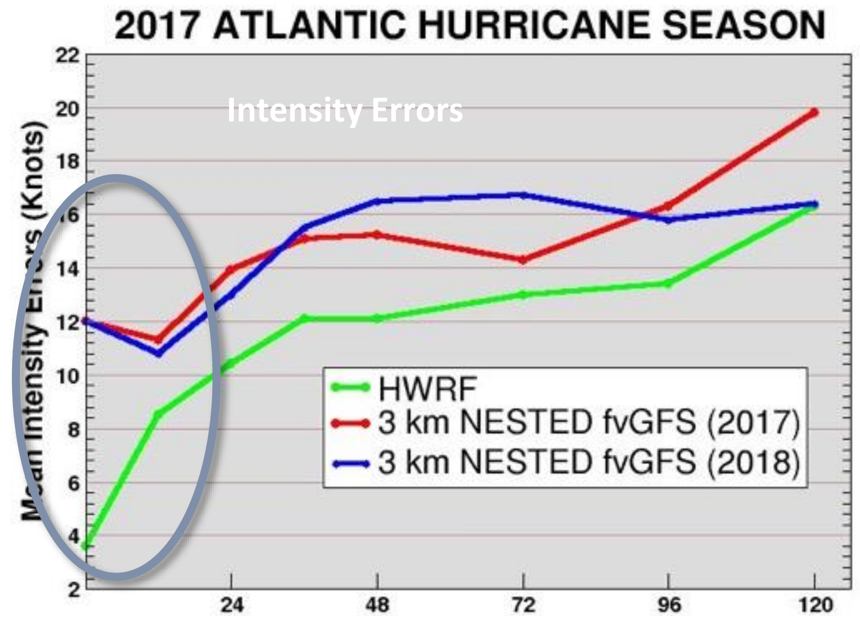


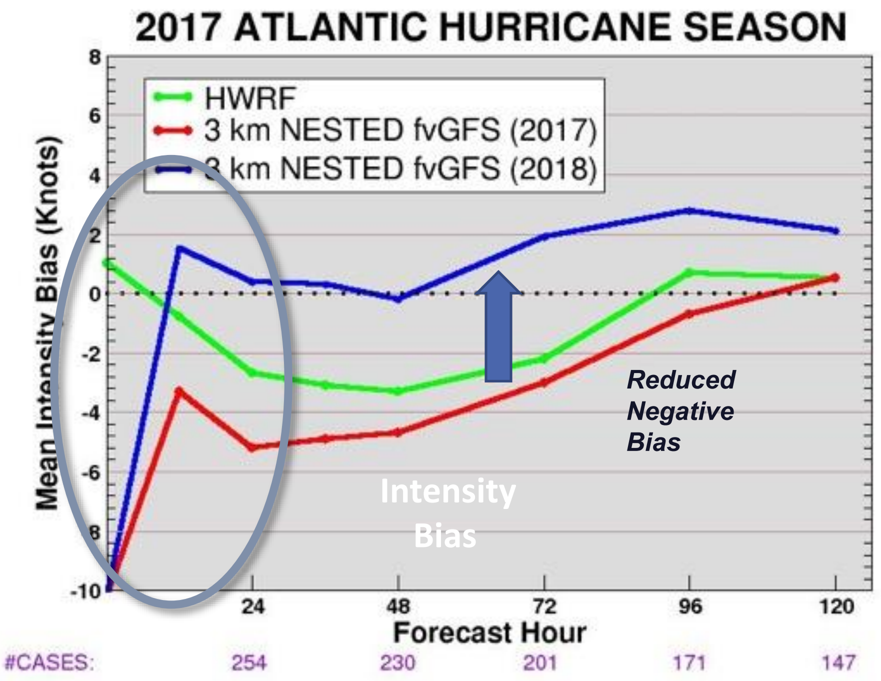
Hurricane Harvey:
3-km nested hfvGFS

Hazelton et al, Accepted by Wea. Forecasting

2018 3-km GFDL hfvGFS upgrades

- 2018 FV3 core and GFDL MP
- S-J's positive-definite tracer advection replaces monotonic
  → much improved TC structure
- Mixed-layer ocean and YSU PBL
  → improved intensity biases and RI
- Scale-aware SAS



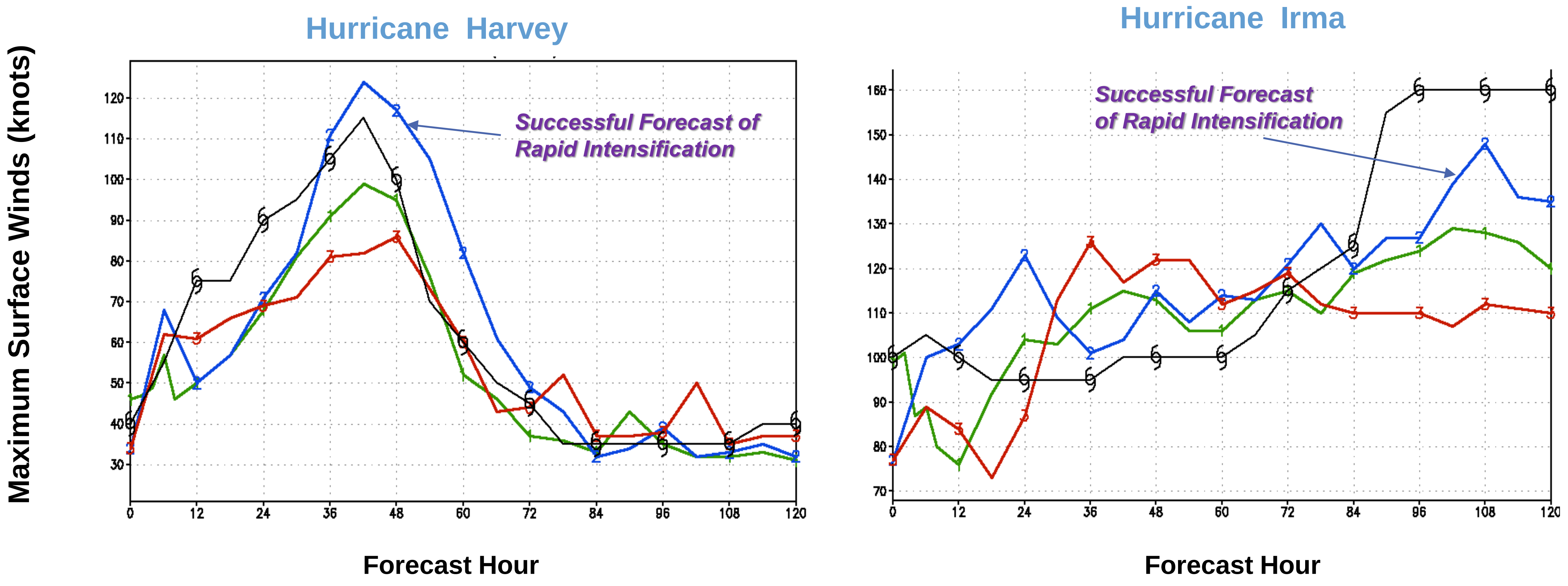


Linjiong Zhou, Andy Hazelton, and Morris Bender, Princeton/GFDL
Baoqiang Xiang and Hailey Shin, UCAR/GFDL

Very rapid spin-up from 13-km hydrostatic GFS ICs

2018 3-km GFDL hfvGFS upgrades:

Rapid Intensification Forecasts

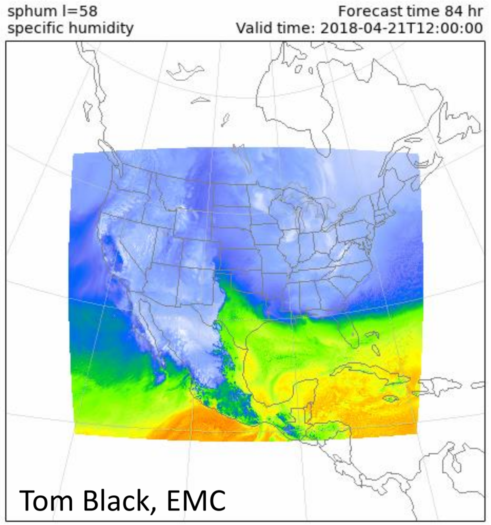


Observed
HWRF
2017 hfvGFS
2018 hfvGFS

Courtesey Morris Bender

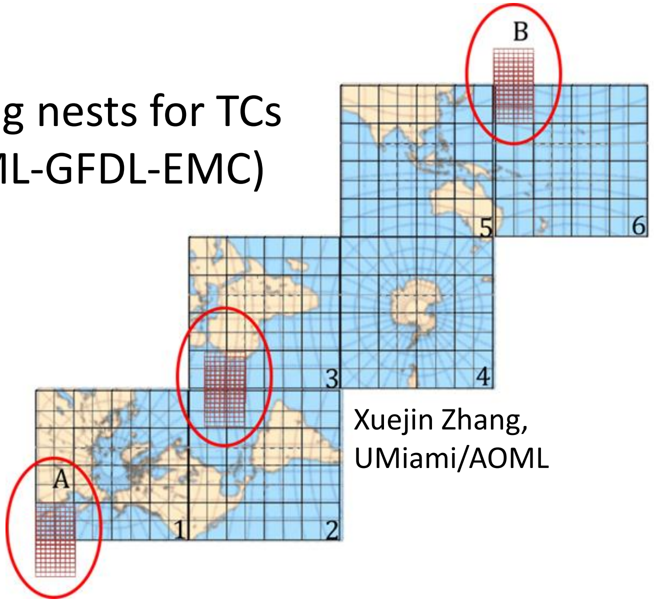
Additional Material

Under Construction



Stand-alone regional
(EMC-GFDL)

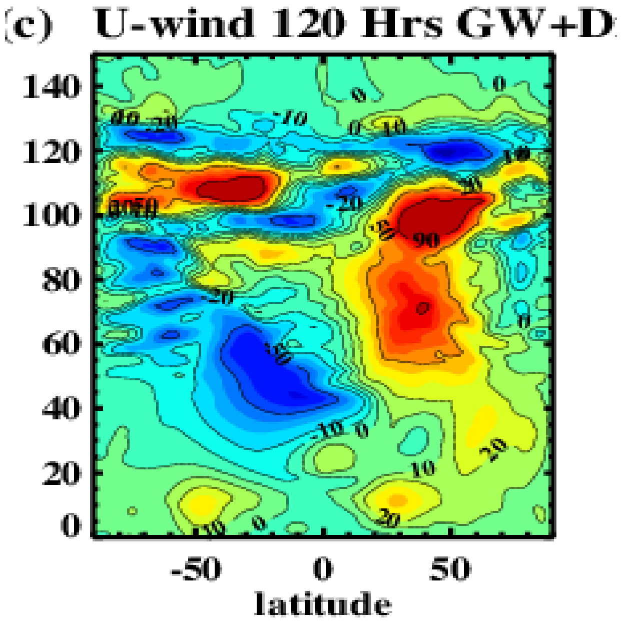
Moving nests for TCs
(AOML-GFDL-EMC)

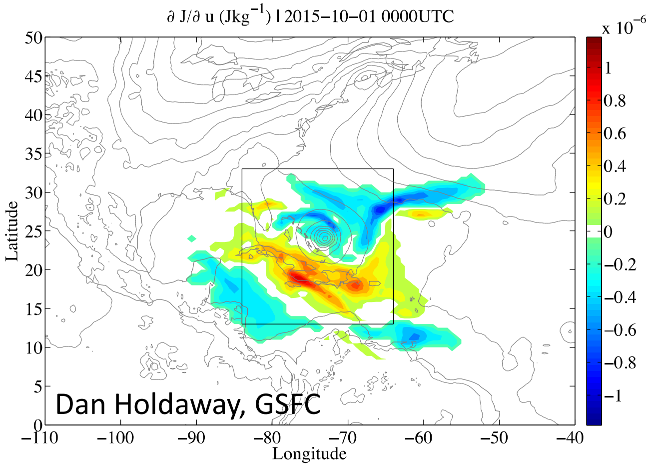


Xuejin Zhang,
UMiami/AOML

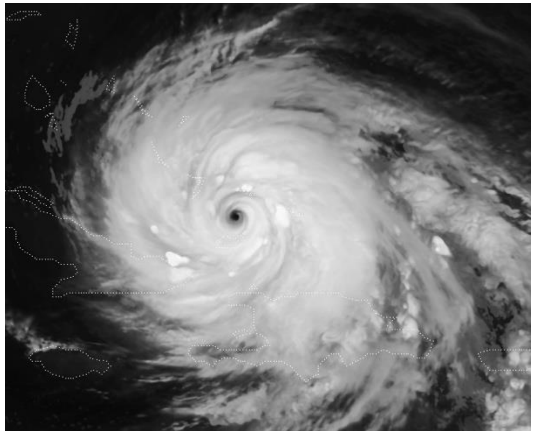
Deep atmosphere
and variable
composition for
WAM/ Geospace
(EMC-GFDL-SWPC)

Valery Yudin, CU/SWPC

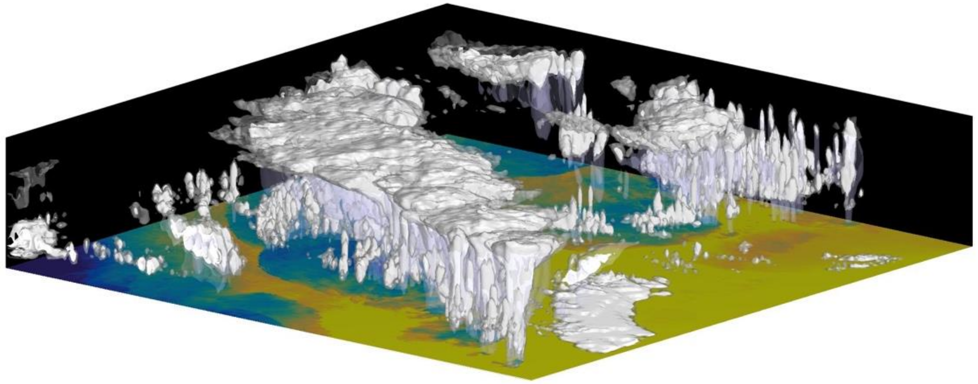




FV3 Adjoint (NASA Goddard)



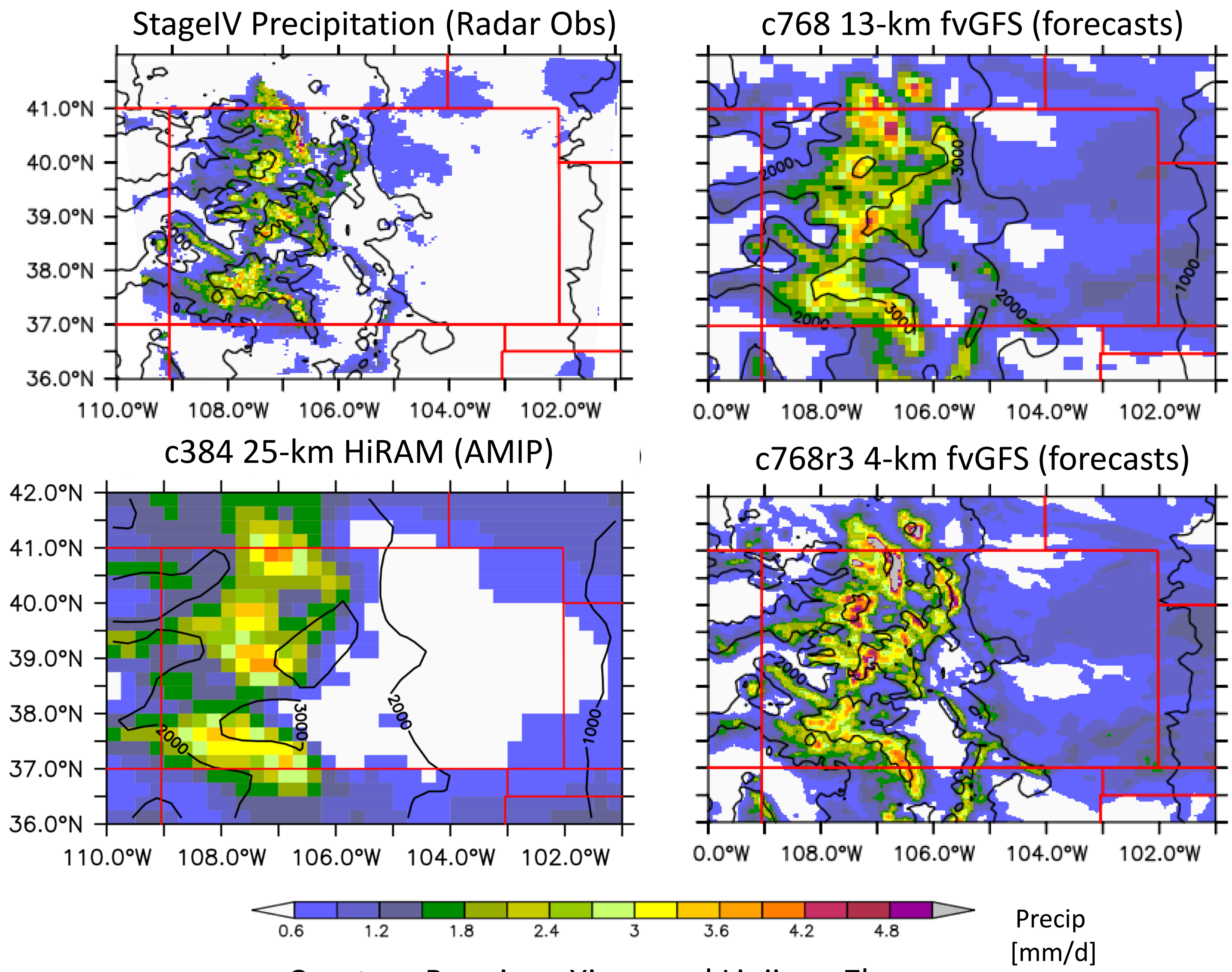
UWisc/SSEC Satellite
Simulator and Verification



Convective-scale prediction and DA
(GFDL, OU/CAPS, EMC, AOML, NSSL, PSU, ESRL, etc.)

GFDL "FV3-2020": Integrating Physics with Dynamics

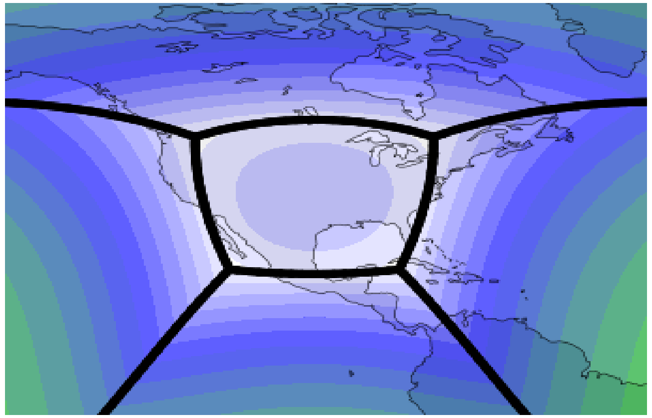
Orographic Precipitation: Uniform vs. Stretched



Courtesy Baoqiang Xiang and Linjiong Zhou

HiRAM Climate/S2S Model:
Simplified AM4 physics w/
6-category GFDL Microphysics and
specified SSTs

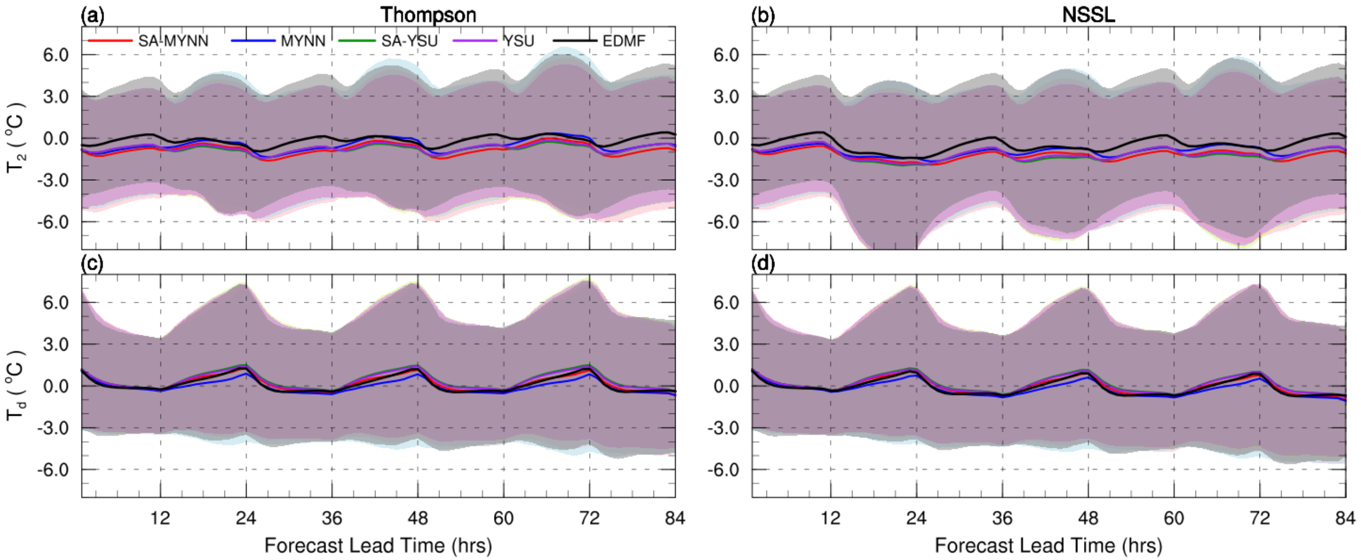
fvGFS Weather Prediction Model:
FV3 coupled to GFS Physics +
6-category GFDL Microphysics

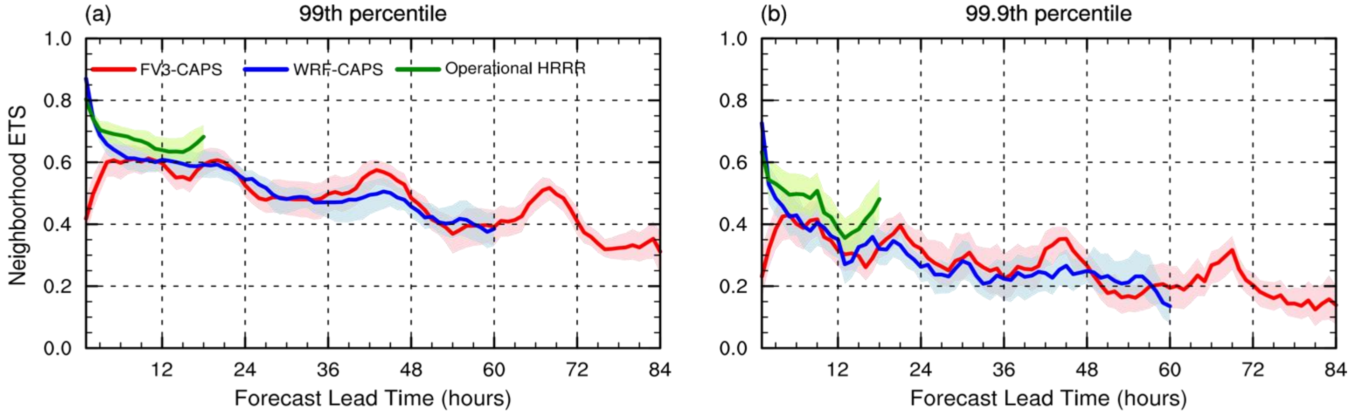


3-km nested cfvGFS 2018 Spring Experiment

C. Zhang et al, submitted to GRL

- CAPS (U. Oklahoma) contributed a 12-member mixed-physics fvGFS ensemble in 2018
- 2-m temperature biases lowest in afternoon; at night all but EDMF show cool bias
- Precipitation skill again rapidly spins-up from cold start; within reach of operational 3-km HRRR
    - Thompson MP more skillful than NSSL; little dependence on PBL scheme



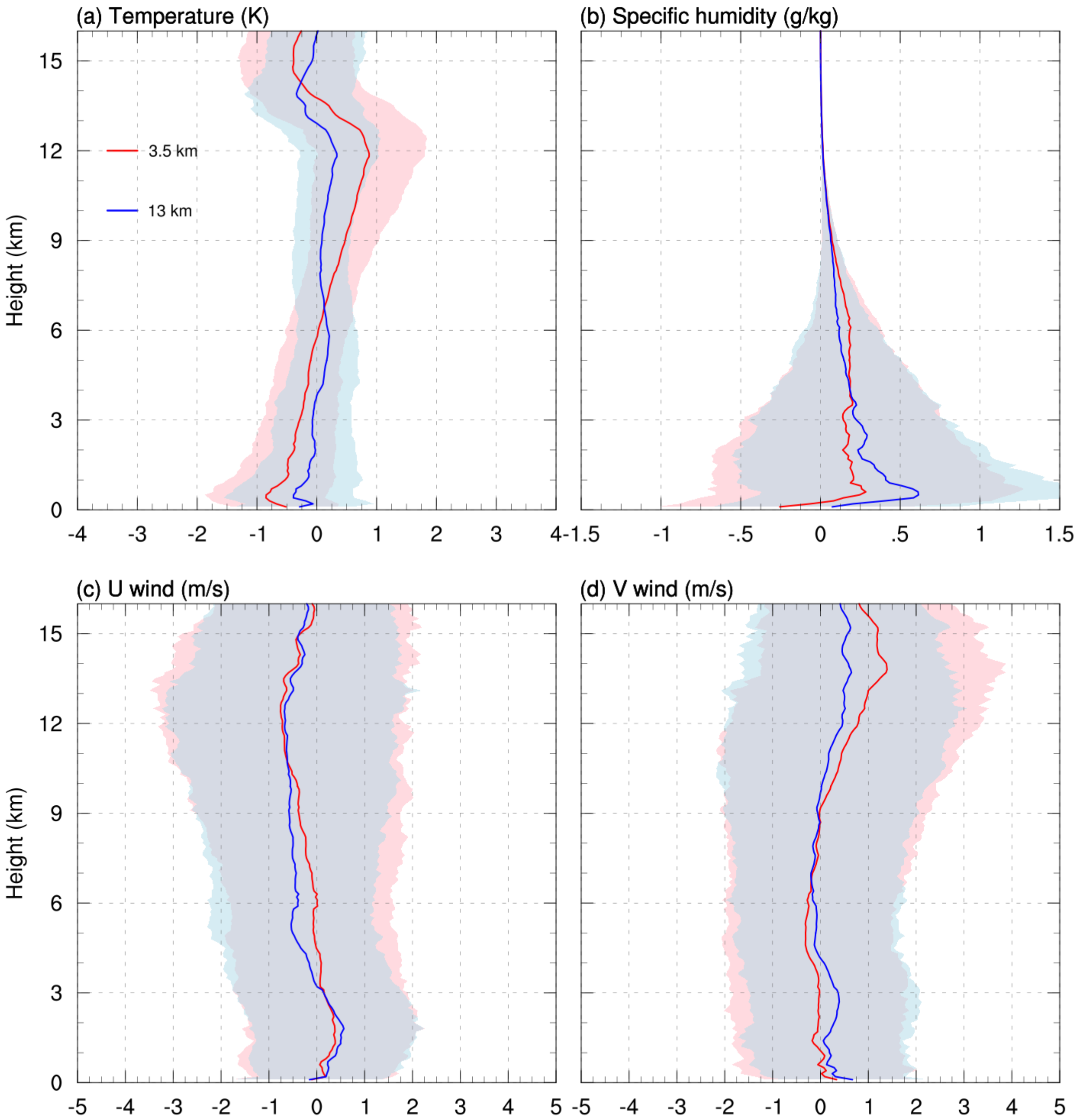


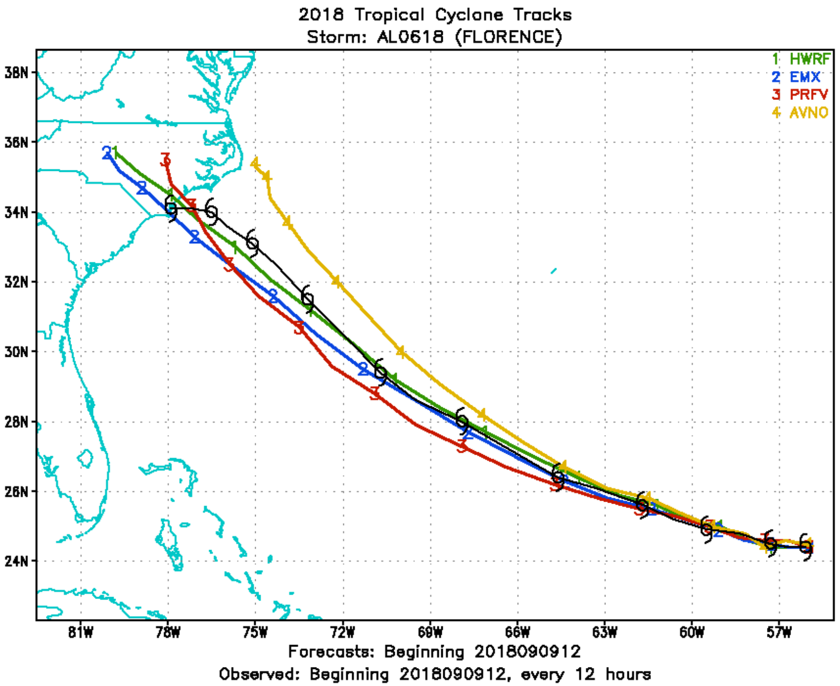
Thompson and SA-MYNN

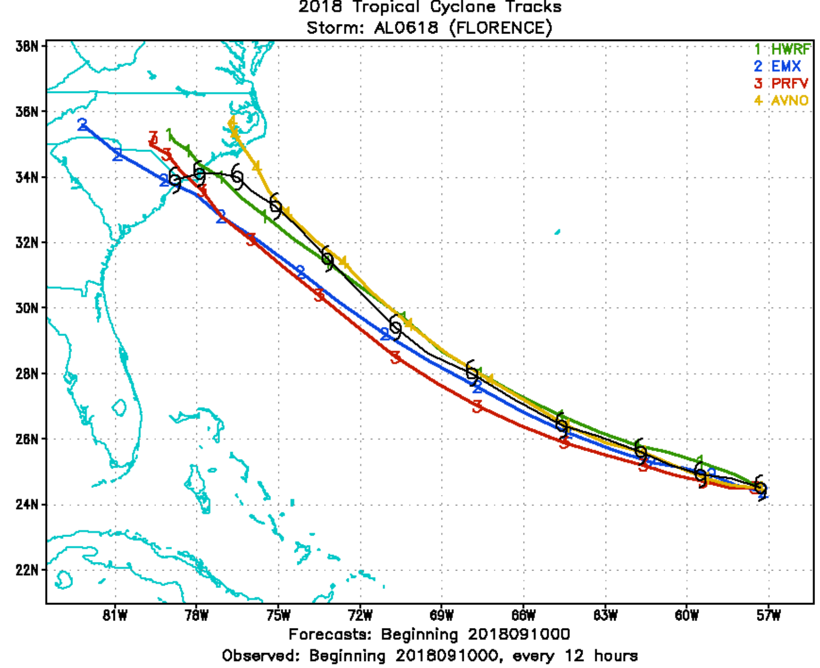
3-km nested cfvGFS 2018 Spring Experiment

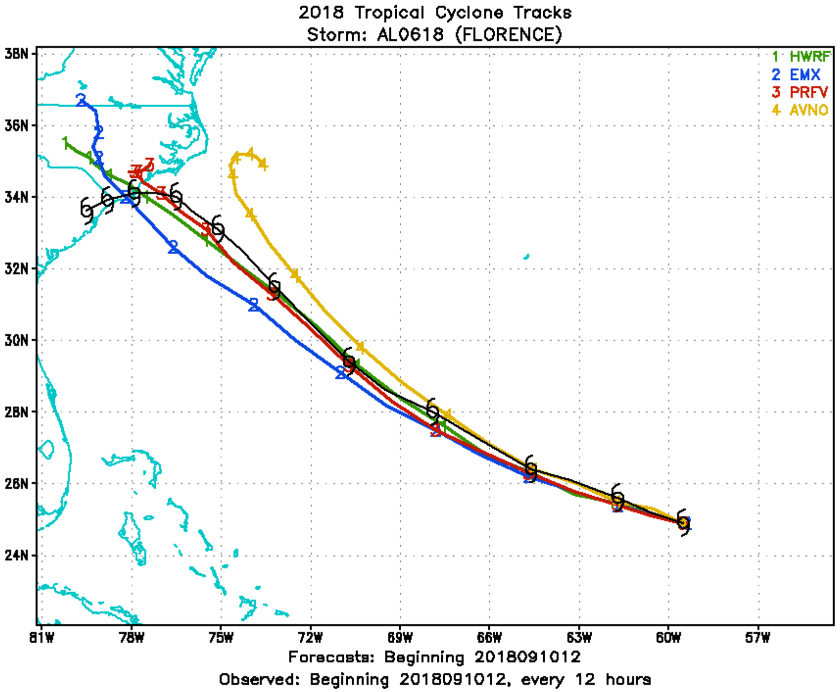
- CAPS (U. Oklahoma) contributed a 12-member mixed-physics fvGFS ensemble in 2018
-

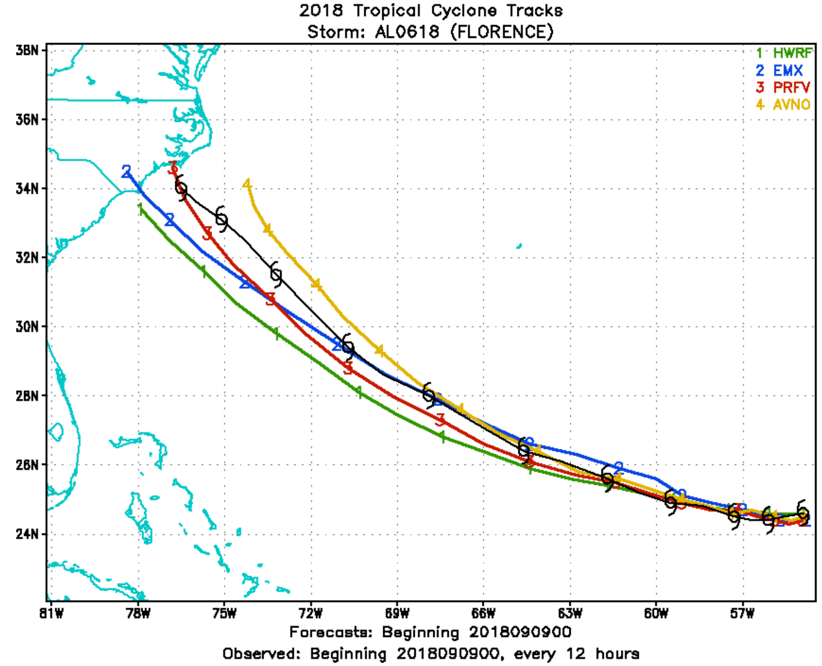
24-hour biases vs. radiosondes
SA-MYNN PBL + Thompson MP + Tiedtke (Global)

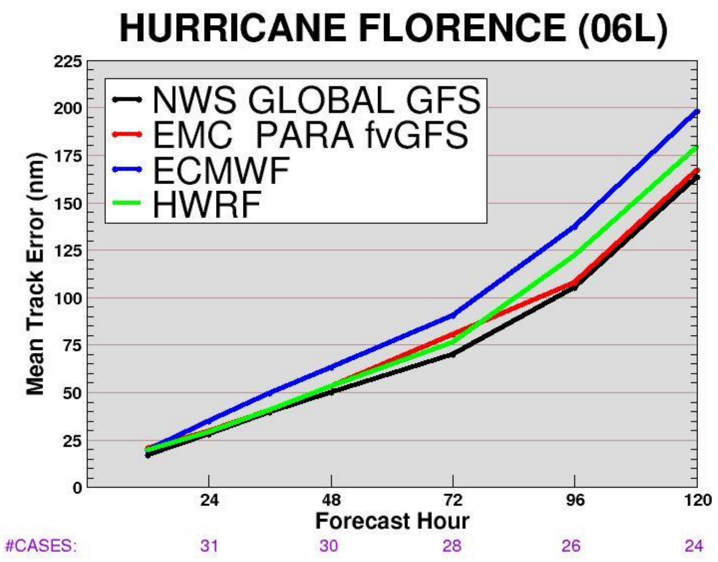


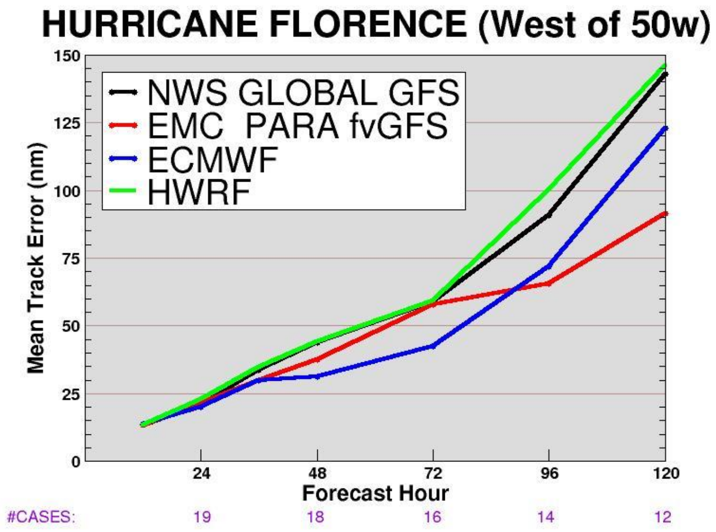

2018 Tropical Cyclone Tracks
Storm: AL0618 (FLORENCE)
1 HWRF
2 EMX
3 PRFV
4 AVNO
38N
36N
34N
32N
30N
28N
26N
24N
81W 78W 75W 72W 69W 66W 63W 60W 57W
Forecasts: Beginning 2018090912
Observed: Beginning 2018090912, every 12 hours

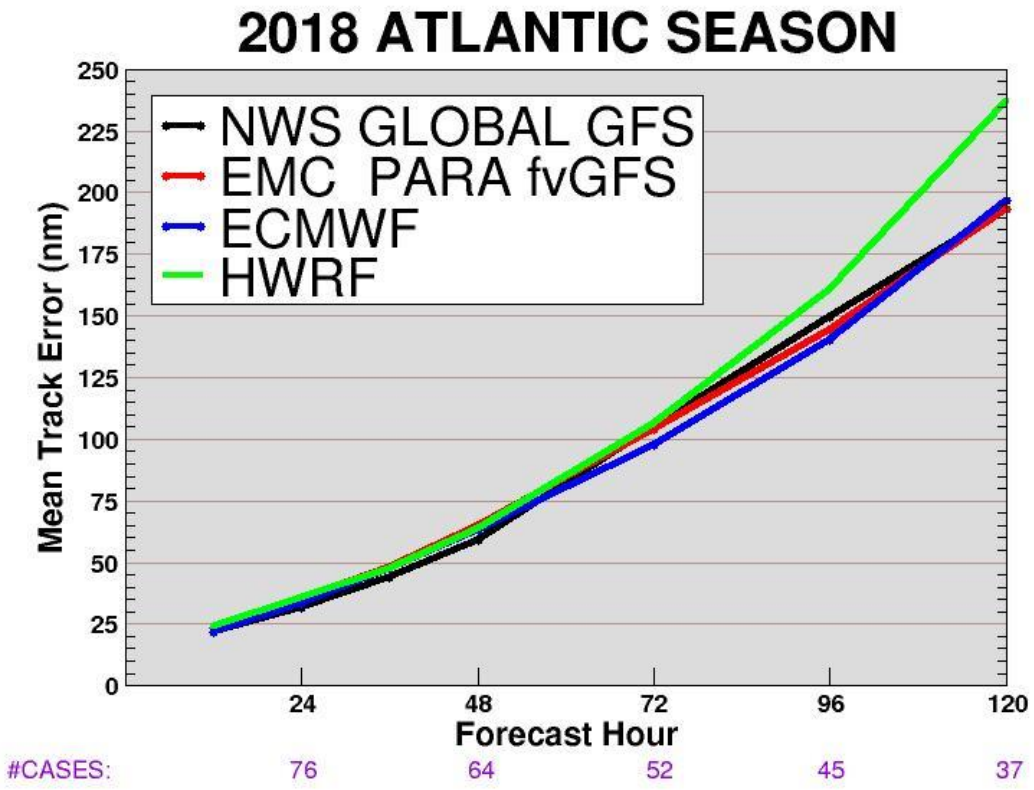

2018 Tropical Cyclone Tracks
Storm: AL0618 (FLORENCE)
1 HWRF
2 EMX
3 PRFV
4 AVNO
38N
36N
34N
32N
30N
28N
26N
24N
22N
81W 78W 75W 72W 69W 66W 63W 60W 57W
Forecasts: Beginning 2018091000
Observed: Beginning 2018091000, every 12 hours


2018 Tropical Cyclone Tracks
Storm: AL0618 (FLORENCE)
1 HWRF
2 EMX
3 PRFV
4 AVNO
38N
36N
34N
32N
30N
28N
26N
24N
81W 78W 75W 72W 69W 66W 63W 60W 57W
Forecasts: Beginning 2018091012
Observed: Beginning 2018091012, every 12 hours


2018 Tropical Cyclone Tracks
Storm: AL0618 (FLORENCE)
1 HWRF
2 EMX
3 PRFV
4 AVNO
38N
36N
34N
32N
30N
28N
26N
24N
81W 78W 75W 72W 69W 66W 63W 60W 57W
Forecasts: Beginning 2018090900
Observed: Beginning 2018090900, every 12 hours


HURRICANE FLORENCE (06L)
NWS GLOBAL GFS
EMC PARA fvGFS
ECMWF
HWRF
Mean Track Error (nm)
Forecast Hour
#CASES:
31
30
28
26
24


HURRICANE FLORENCE (West of 50w)
NWS GLOBAL GFS
EMC PARA fvGFS
ECMWF
HWRF
Mean Track Error (nm)
Forecast Hour
#CASES:
19
18
16
14
12


2018 ATLANTIC SEASON
NWS GLOBAL GFS
EMC PARA fvGFS
ECMWF
HWRF
Mean Track Error (nm)
Forecast Hour
#CASES:
76
64
52
45
37

Hurricane Florence

hfvGFS precip forecast