# The GFDL FV3 dynamical core and the NGGPS

NCAR MPAS


GFDL FV3

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# The Next Generation Global Prediction System (NGGPS)

***An inter-agency effort in the US to develop a unified global model for 0-100 day predictions, to be used for the next 10-20 years***

## Dynamical core inter-comparisons:

- **GFDL FV3: Finite-Volume on the cubed-sphere**
- **NCAR MPAS: Finite-difference/finite-volume on icosahedral grid**
- ~~NCEP NMM-UJ~~: finite-difference NMMB on cubed-sphere grid
- ~~ESRL NIM~~: finite-difference/finite-volume on icosahedral grid (similar to FIM)
- ~~NAVY NEPTUNE~~: spectral-element on cubed-sphere (similar to NCAR CAM-SE)

**Phase-1 comparisons:**

- **idealized tests, 3 km global cloud-permitting simulations, and computational benchmarks**

**Phase-2 comparisons:**

- **Computational performance**
- **Idealized tests**
- **Effective resolution (based on Kinetic Energy spectra)**
- **Real-data forecasts at 13 km with the operational GFS physics and ICs**

# What's "Finite-Volume" about FV3? 20-yr of R/D in one slide

1. Vertically Lagrangian control-volume discretization based on 1st principles (Lin 2004)
   - Conservation laws solved for the control-volume bounded by two Lagrangian surfaces

2. Physically based forward-in-time "horizontal" transport (between two Lagrangian surfaces)
   - Conservative analog to the highly efficient trajectory based two-time-level semi-Lagrangian schemes in IFS; locally conservative and (optionally) monotonic via constraints on sub-grid distributions (Lin & Rood 1996; Putman & Lin 2007) – good for aerosols and cloud MP
   - Space-time discretization is non-separable -- hallmark of a physically based FV algorithm

3. Combined use of C & D staggering with optimal FV representation of <u>Potential Vorticity</u> and <u>Helicity</u>

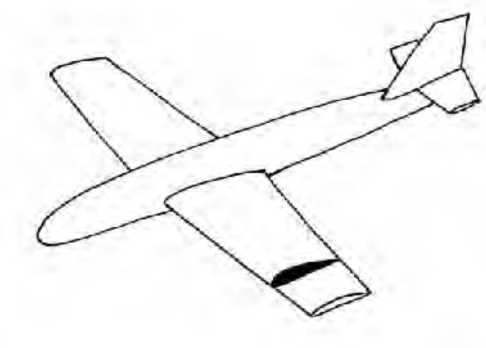
   → important from synoptic-scale down to storm-scale

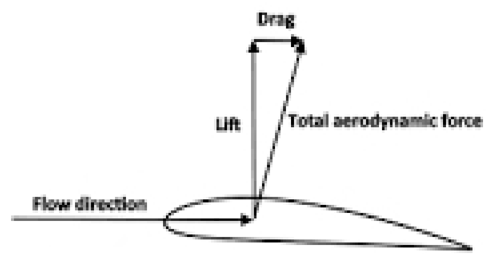
4. Finite-volume integration of pressure forces (Lin 1997)
   - Analogous to the forces acting upon an aircraft wing (lift & drag forces)
   - Horizontal and vertical influences are non-separable (Arakawa-type linear analyses are not applicable to FV's Lagrangian discretization)

5. For non-hydrostatic extension, the vertically Lagrangian discretization reduces the sound-wave solver into a 1-D problem (solved by either a Riemann solver or a semi-implicit solver with conservative cubic-spline)

# Inspired by the aerodynamics

## The forces acting on the wing of an aircraft






*Control-volume*

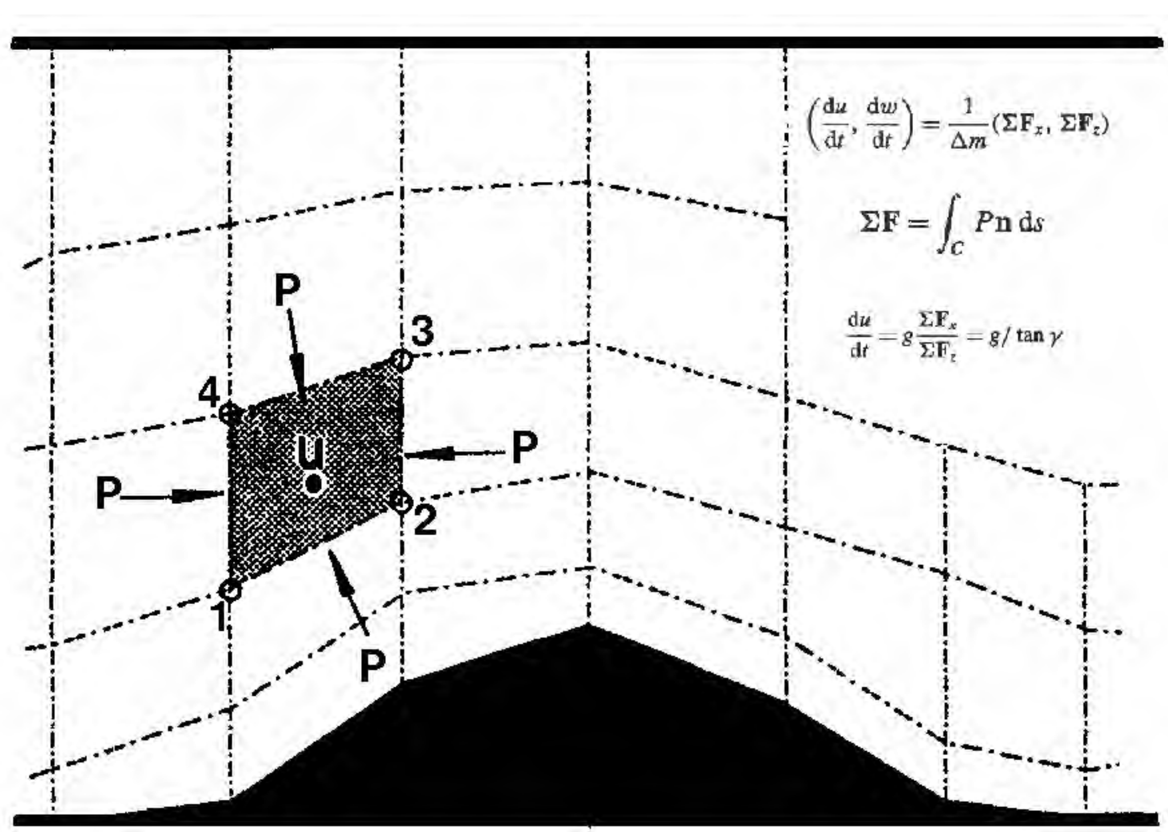
- The “**lift**” force is the net force in the vertical direction
  - **Hydrostatic (cruising)**: the lift supports the weight (dw/dt = 0)
  - **Non-hydrostatic (g-force)**: the lift produces the vertical acceleration (dw/dt = F_lift)

- The “**drag**” is the projection of the force in the horizontal direction (du/dt)

# Physically based Finite-Volume integration of Pressure Force

## Lin (1997, QJ)

- The model top and bottom are Lagrangian surfaces
- Physically based finite-volume integration using Newton's 2nd law and Green's integral theorem
- Vertical-horizontal discretization is therefore non-separable



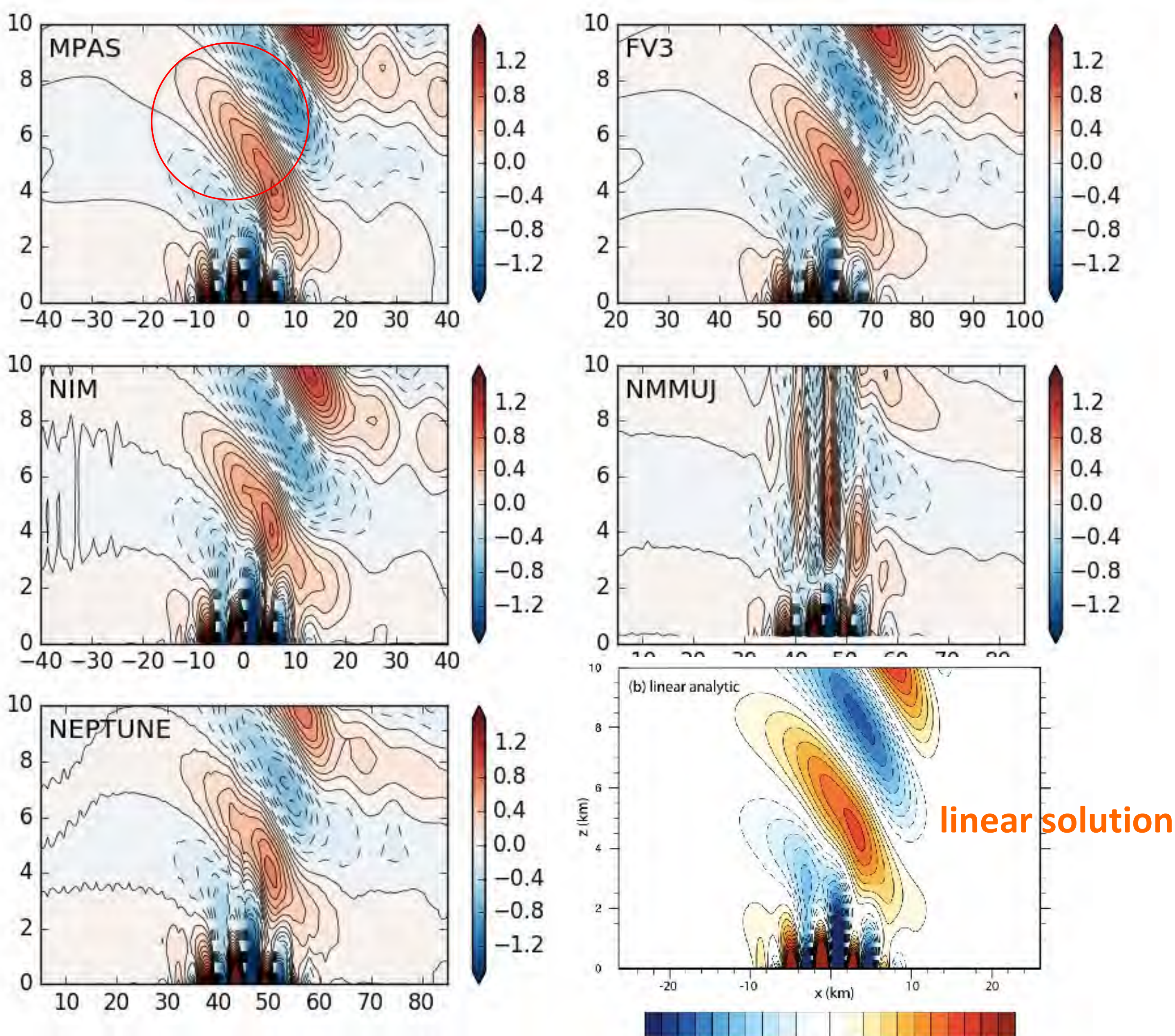

$$\left(\frac{du}{dt}, \frac{dw}{dt}\right) = \frac{1}{\Delta m}(\Sigma \mathbf{F}_x, \Sigma \mathbf{F}_z)$$

$$\Sigma \mathbf{F} = \int_C P\mathbf{n}\, ds$$

$$\frac{du}{dt} = g\frac{\Sigma \mathbf{F}_x}{\Sigma \mathbf{F}_z} = g/\tan\gamma$$

# NGGPS phase-1 *linear* mountain wave test (case: M2) at hour-2

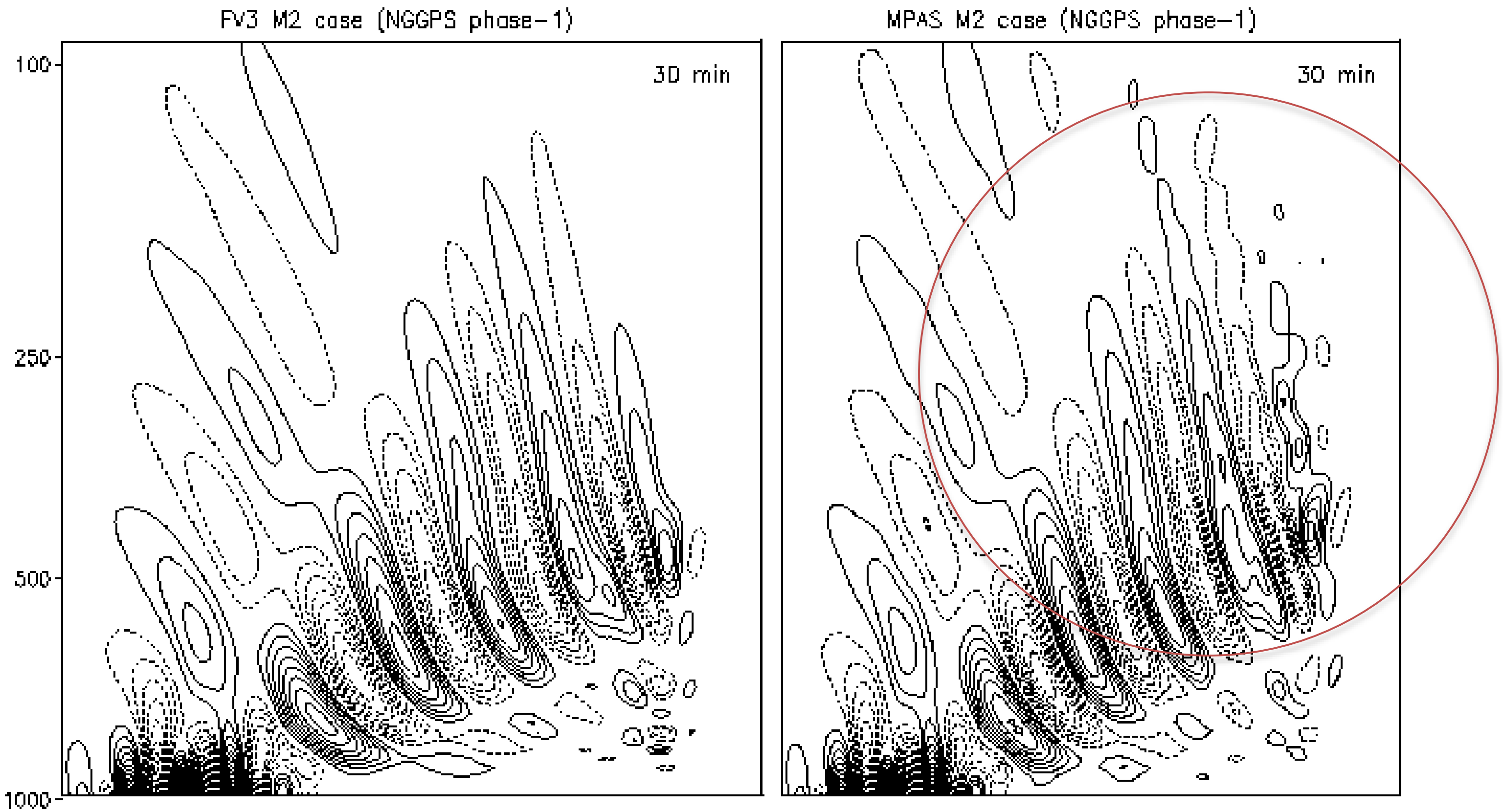
**(a constant u-wind blowing from west to east)**



# NGGPS phase-1 Mountain wave test at 30-min

MPAS numerical noises propagate out of mountain region

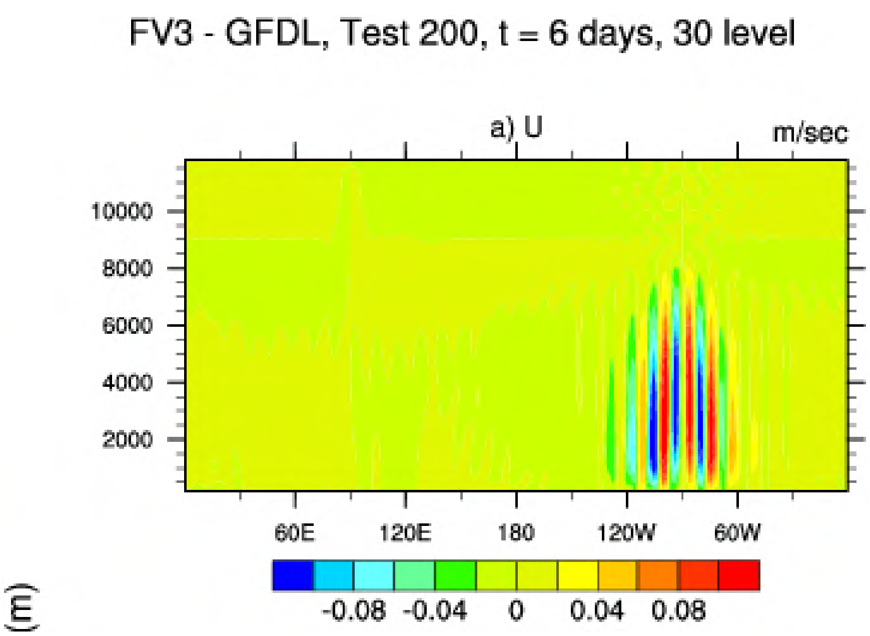
**FV3** **MPAS**



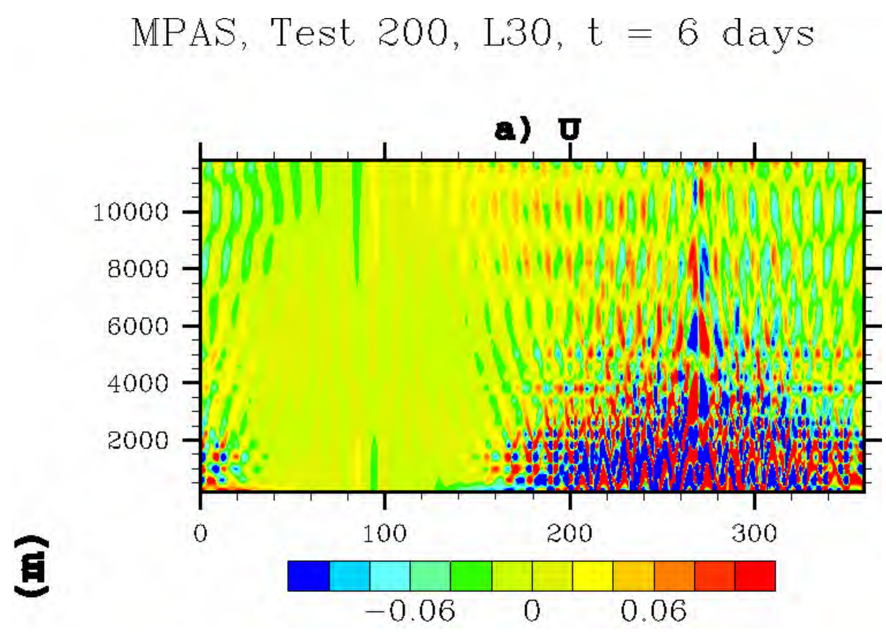
# DCMIP-2012 "hydrostatic equilibrium test"

For this "atmosphere-at-rest" test, noises can not propagate out of the source region (regional-only vs global design)

## FV3

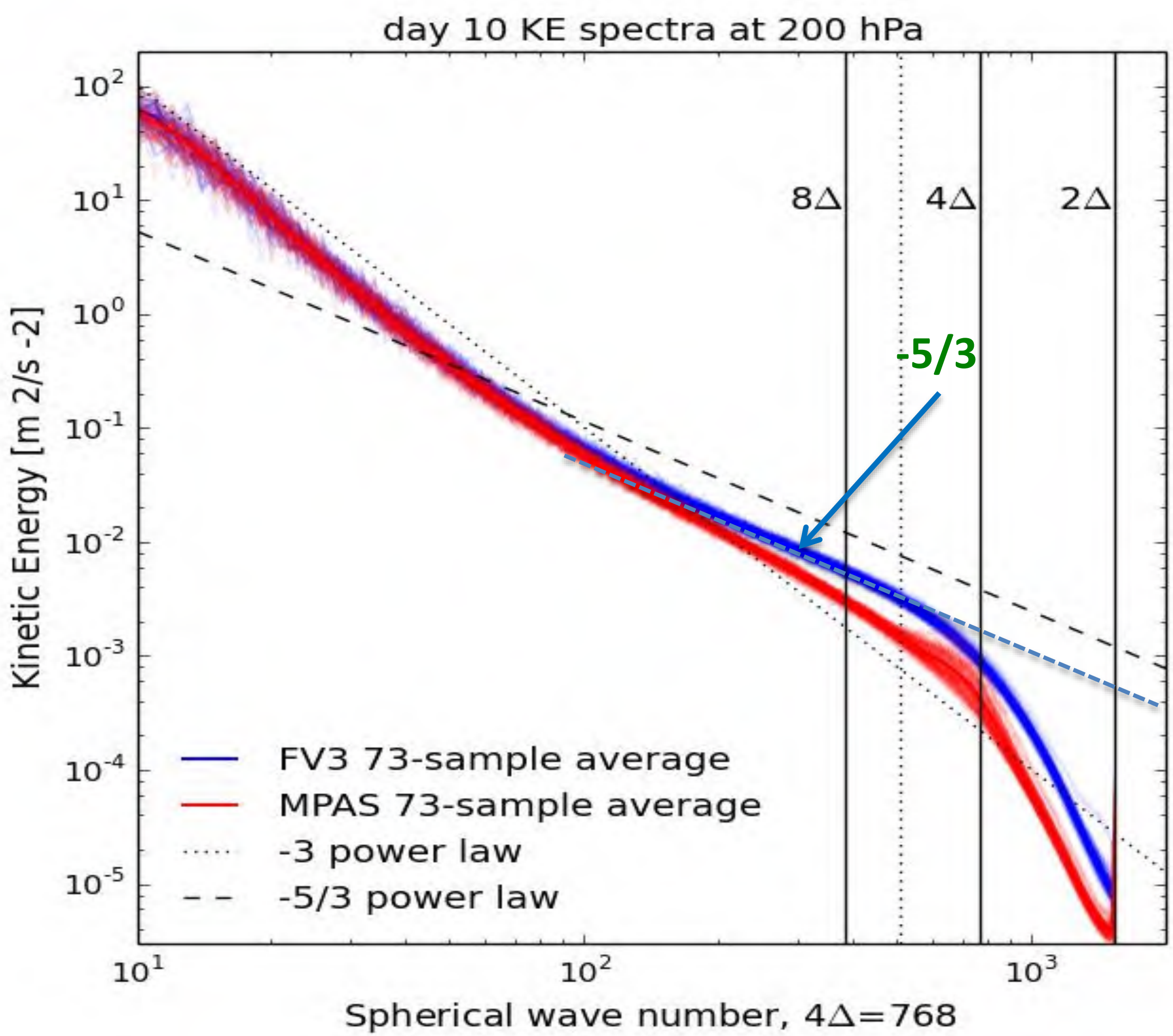



## MPAS



# Algorithm design and diffusion tuning: FV3 vs MPAS

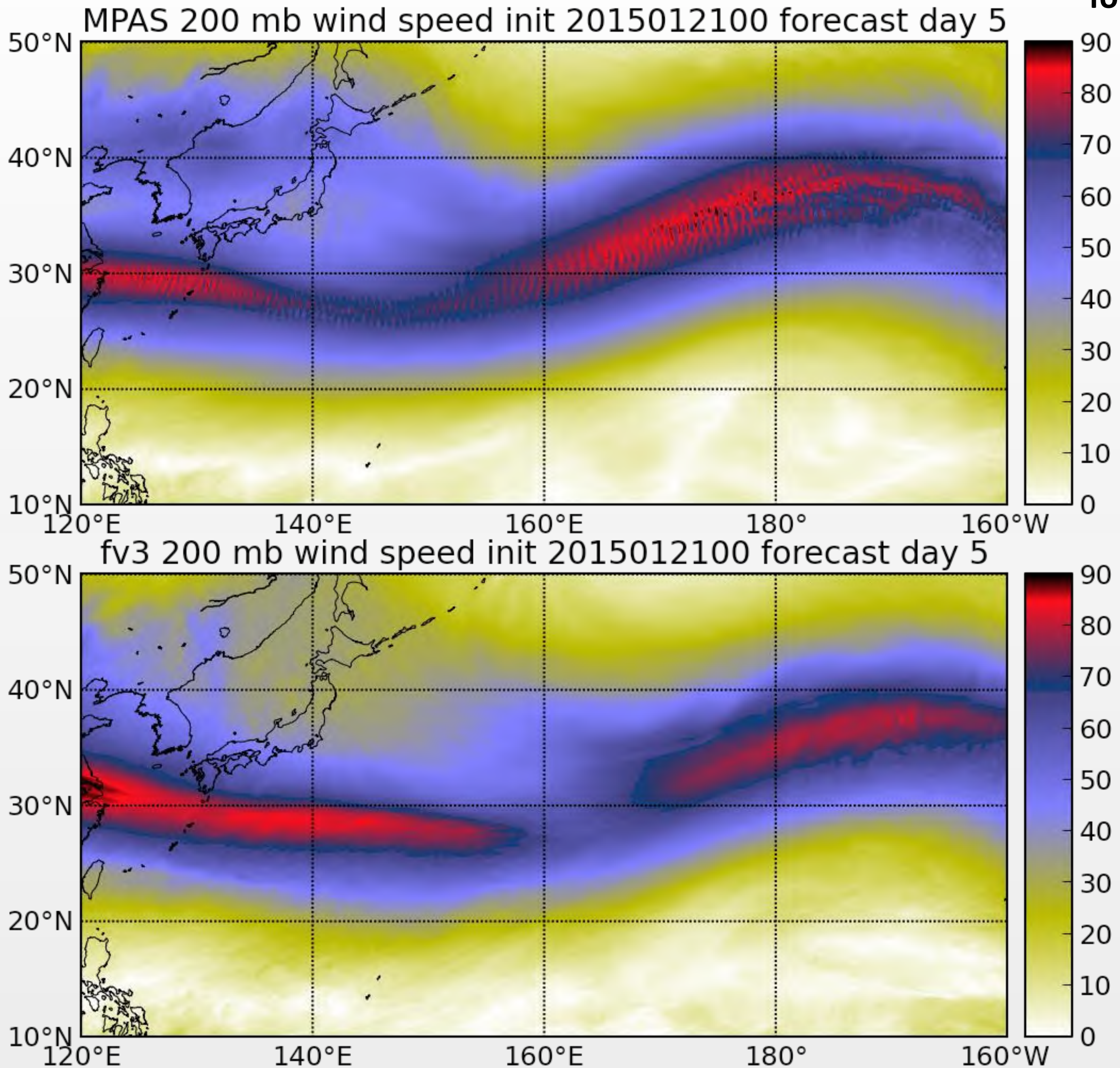
## The story told by the KE spectra (composite 73 cases, 13-km NGGPS phase-2)




- FV3 simulated the -5/3 "meso-scale" spectrum
- MPAS has an energy deficit of ~50% in the meso-scale and failed to simulate the -5/3 spectrum

# The ~4-delta-x noises in MPAS 10-day forecasts (the false -5/3 spectra in MPAS)

(noises appear in MPAS forecasts whenever the jet stream is strong)

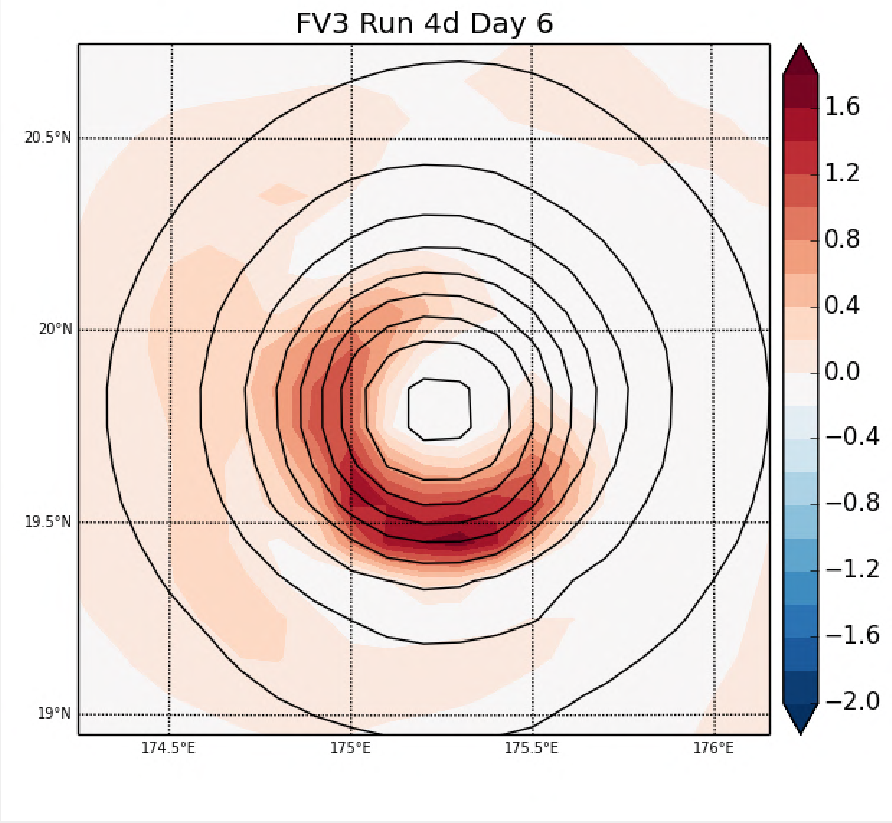



MPAS

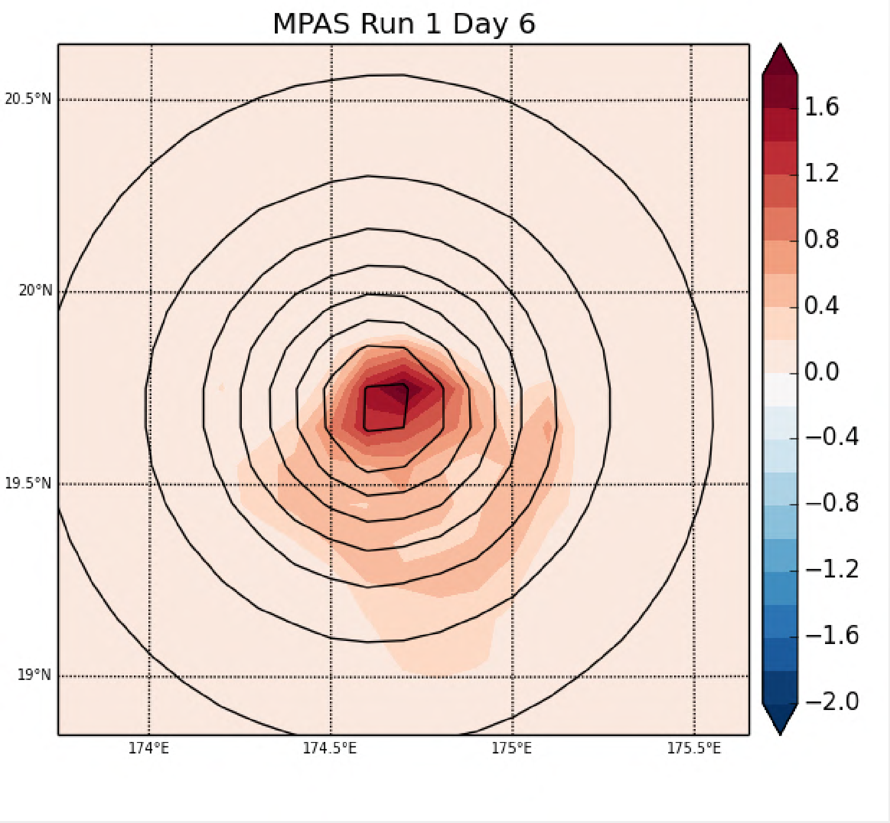
FV3

# NGGPS idealized TC test:
# Vertical velocity at 700-mb (shading) & SLP (contours)

**FV3 without vertical filter, shows a TC structure**



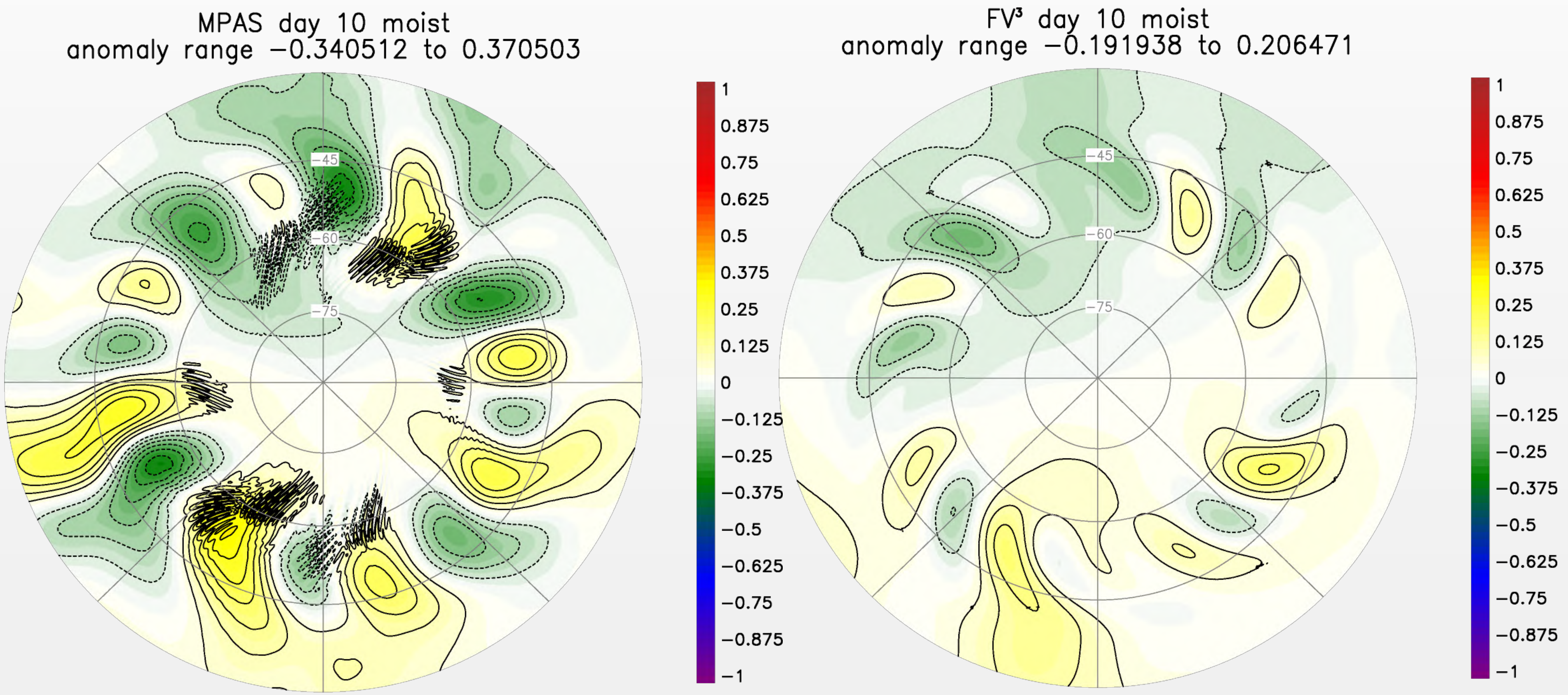

**MPAS shows a max updraft at the center of the "storm"**



# Grid imprinting

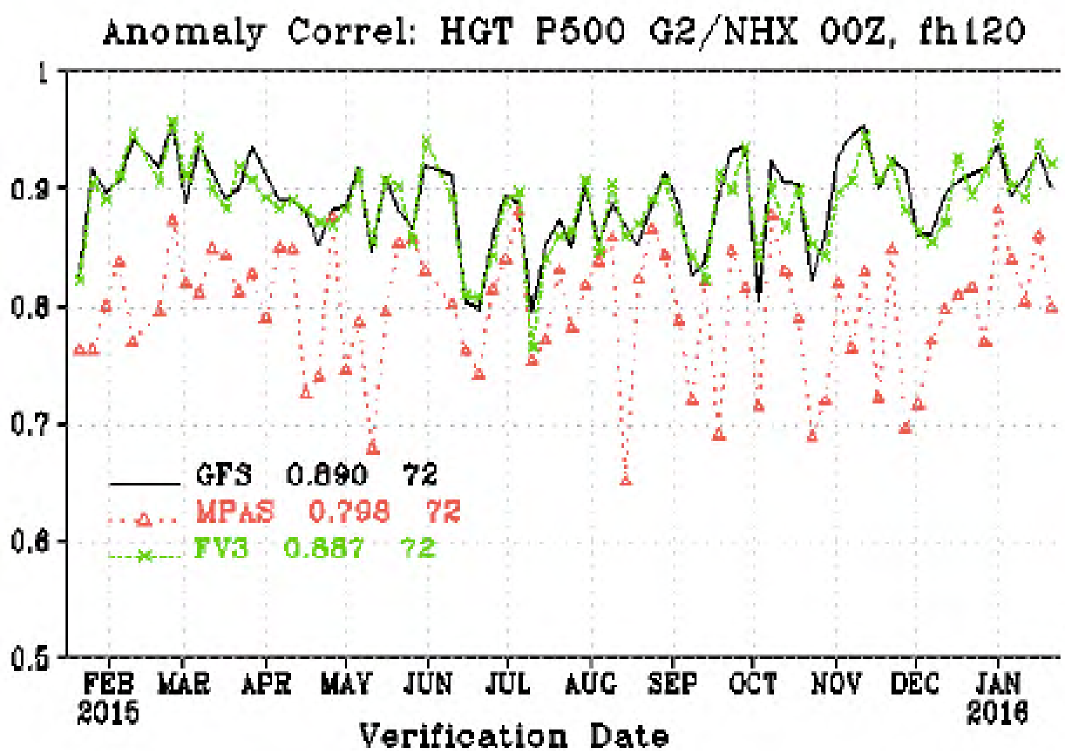
## Moist "conservation test": Day-10

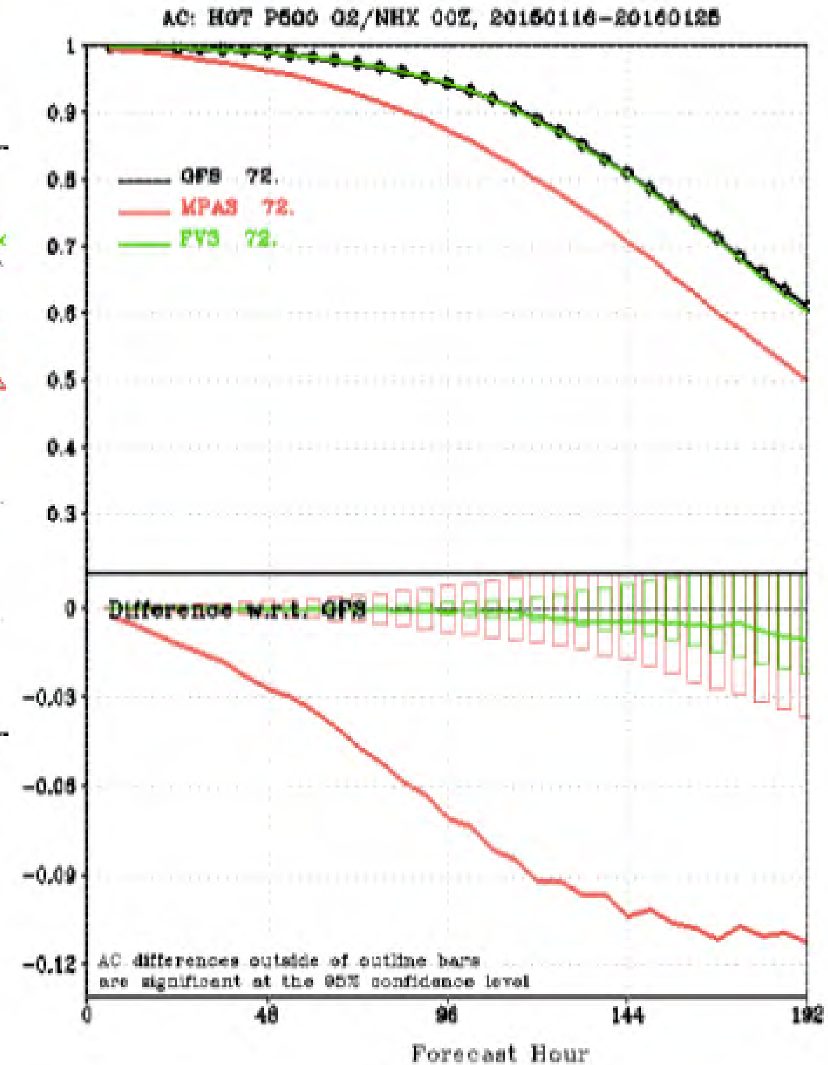
**MPAS** **FV3**




SH lowest-layer pressure (mb), zonal mean removed; contour interval 0.05 mb, (shading interval 0.025 mb)

# #3: Retrospective 13 km Forecast Skill




FV3 forecast skill matches the GFS using GFS ICs and GFS Physics

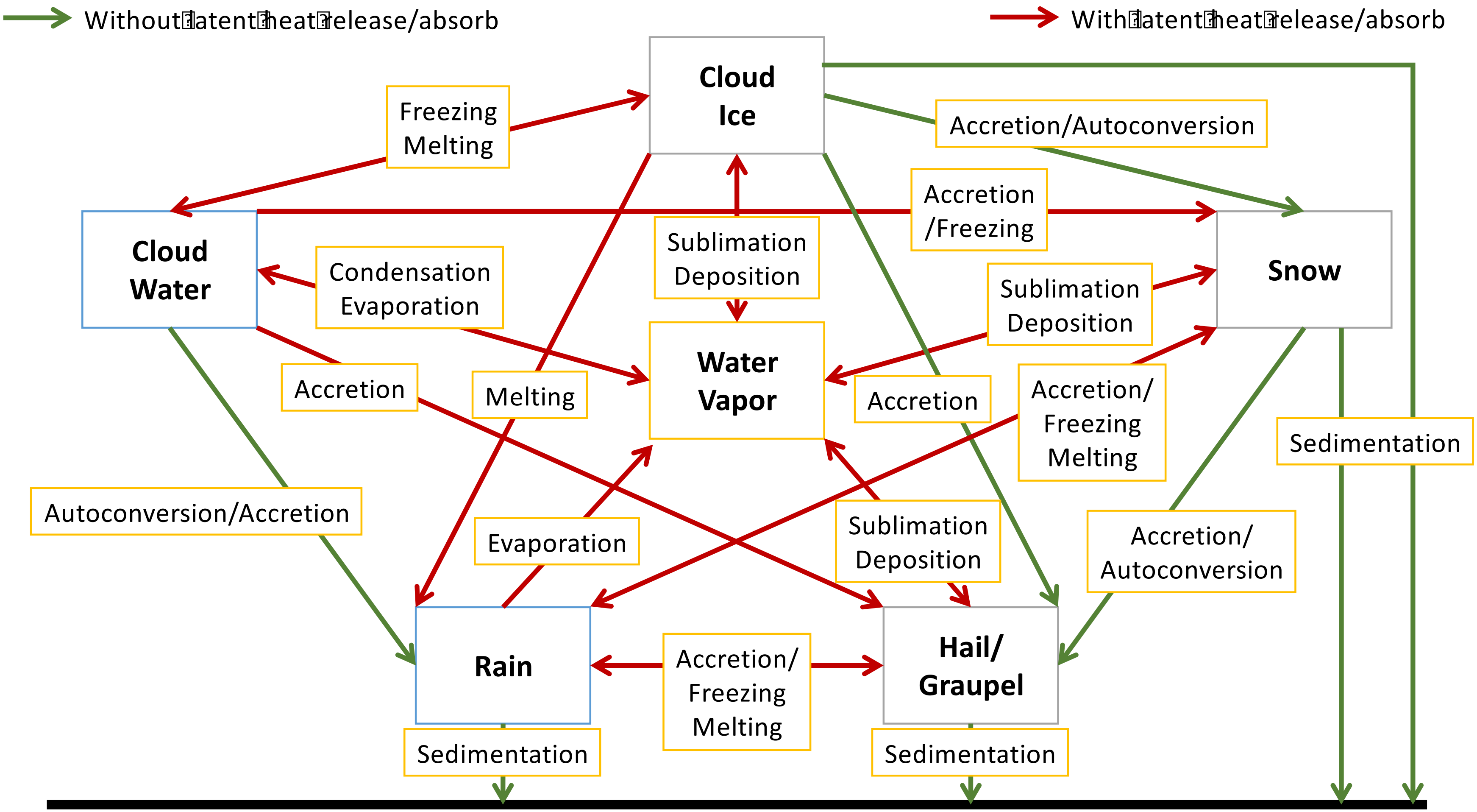
# Making fvGFS suitable for all-scale predictions:

**The 1st step: replacing the GFS's cloud Micro-Physics (MP) with GFDL_MP**

**GFDL_MP:**

- Designed for seasonal predictions (Chen & Lin 2011) and climate simulations, with "scale-aware" vertical & horizontal sub-grid distribution
- Tune for radiative balance at TOA
- Based on 1st principles: "*Ooyama-complian*t" and consistent with FV3 (heat & momentum transported by falling condensates)
- Time-implicit fall of precipitating condensates (rain, snow, graupel, and cloud ice)
- Compatible with cloud fields from latest IFS

# GFDL MP

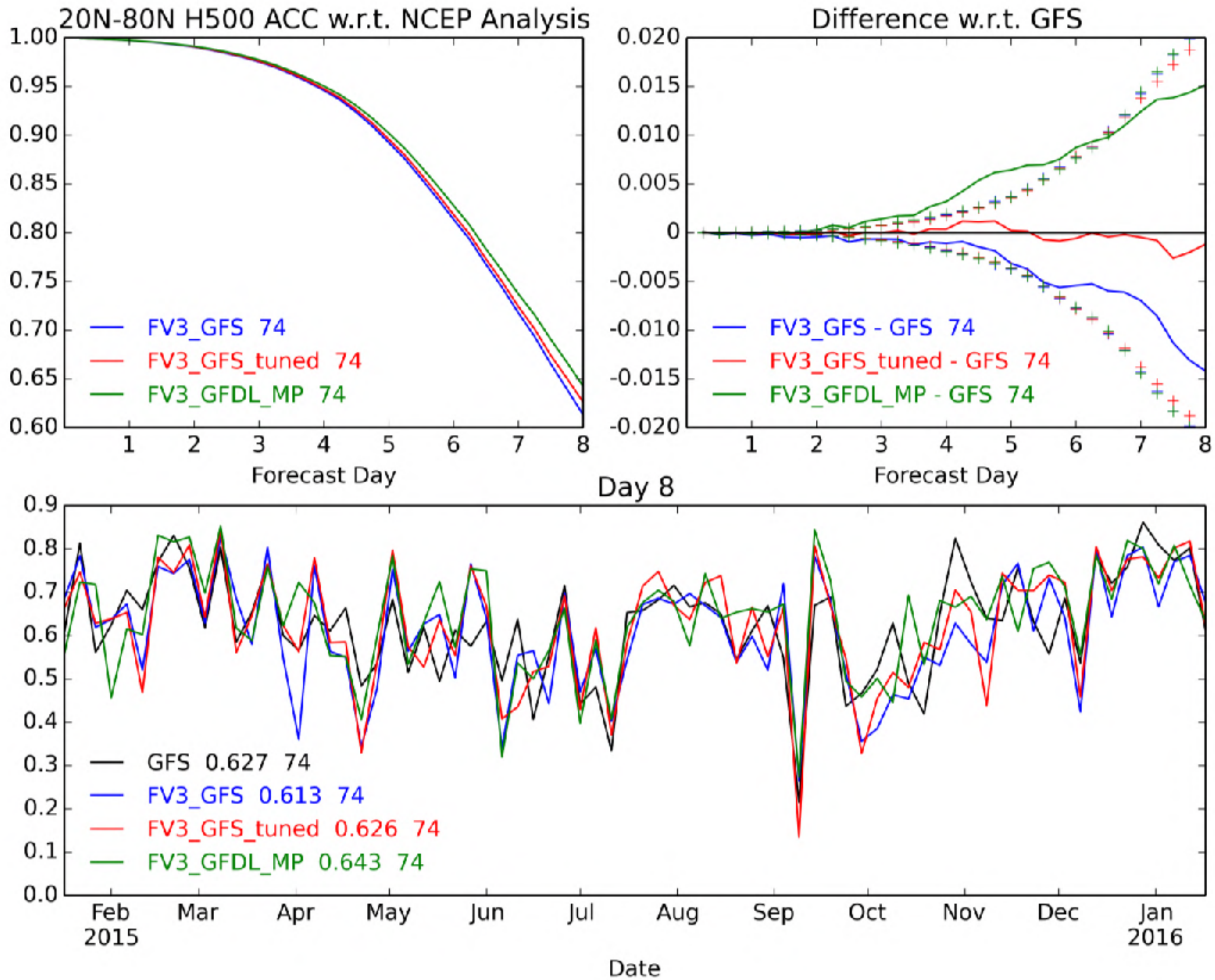


Without latent heat release/absorb
With latent heat release/absorb
Cloud Ice
Freezing
Melting
Accretion/Autoconversion
Cloud Water
Accretion
/Freezing
Snow
Sublimation
Deposition
Condensation
Evaporation
Sublimation
Deposition
Water Vapor
Accretion
Melting
Accretion
Accretion/
Freezing
Melting
Sedimentation
Autoconversion/Accretion
Evaporation
Sublimation
Deposition
Accretion/
Autoconversion
Rain
Accretion/
Freezing
Melting
Hail/
Graupel
Sedimentation
Sedimentation

# The 1st step towards regional-global unification:

Do no harm to global skill while enabling convection-scale with an advanced cloud microphysics

## Relative Skill to Operational GFS




13-km fvGFS with GFDL_MP

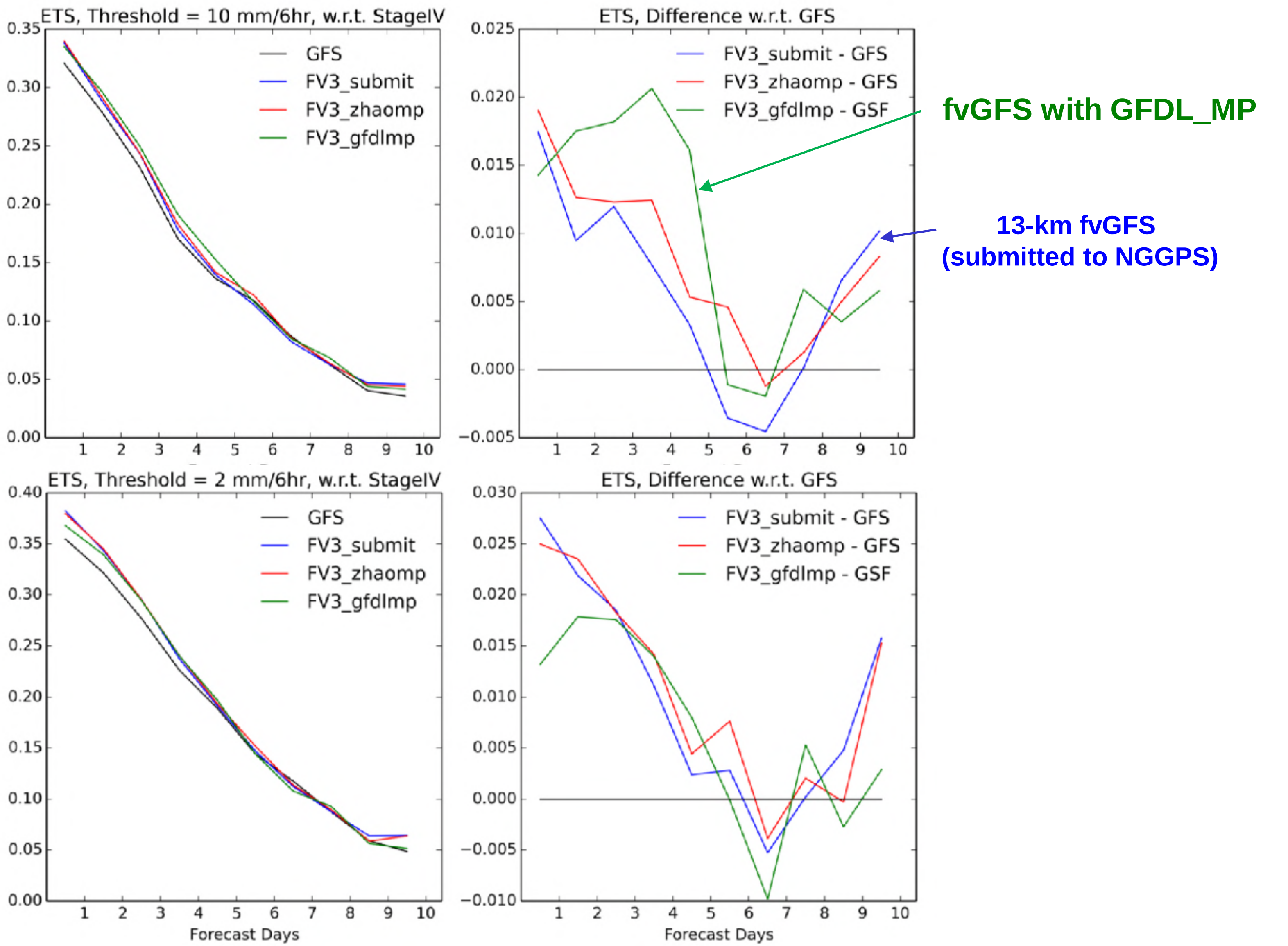
13-km fvGFS with tuned GFS

13-km fvGFS (no tuning) (as submitted to NGGPS)

# Equitable Threat Score over CONUS

## (based on NGGPS 74 cases)

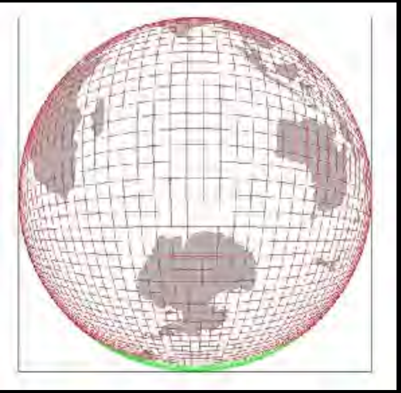
**GFDL_MP made a big improvement for strong events**



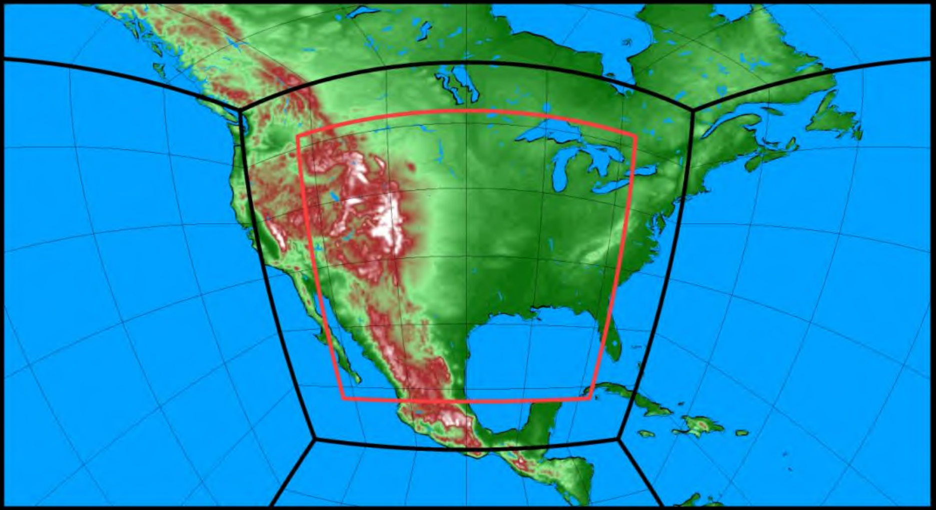
# Achieving thunderstorm-resolving resolution “TODAY” in a unified meso-global prediction system


1) **Grid stretching (smooth variation of grid spacing)**

1) **2-way nesting (Harris and Lin 2014)**
   **FV3 is uniquely suitable for 2-way nesting, due to the application of two-time-level Finite-Volume transport scheme**



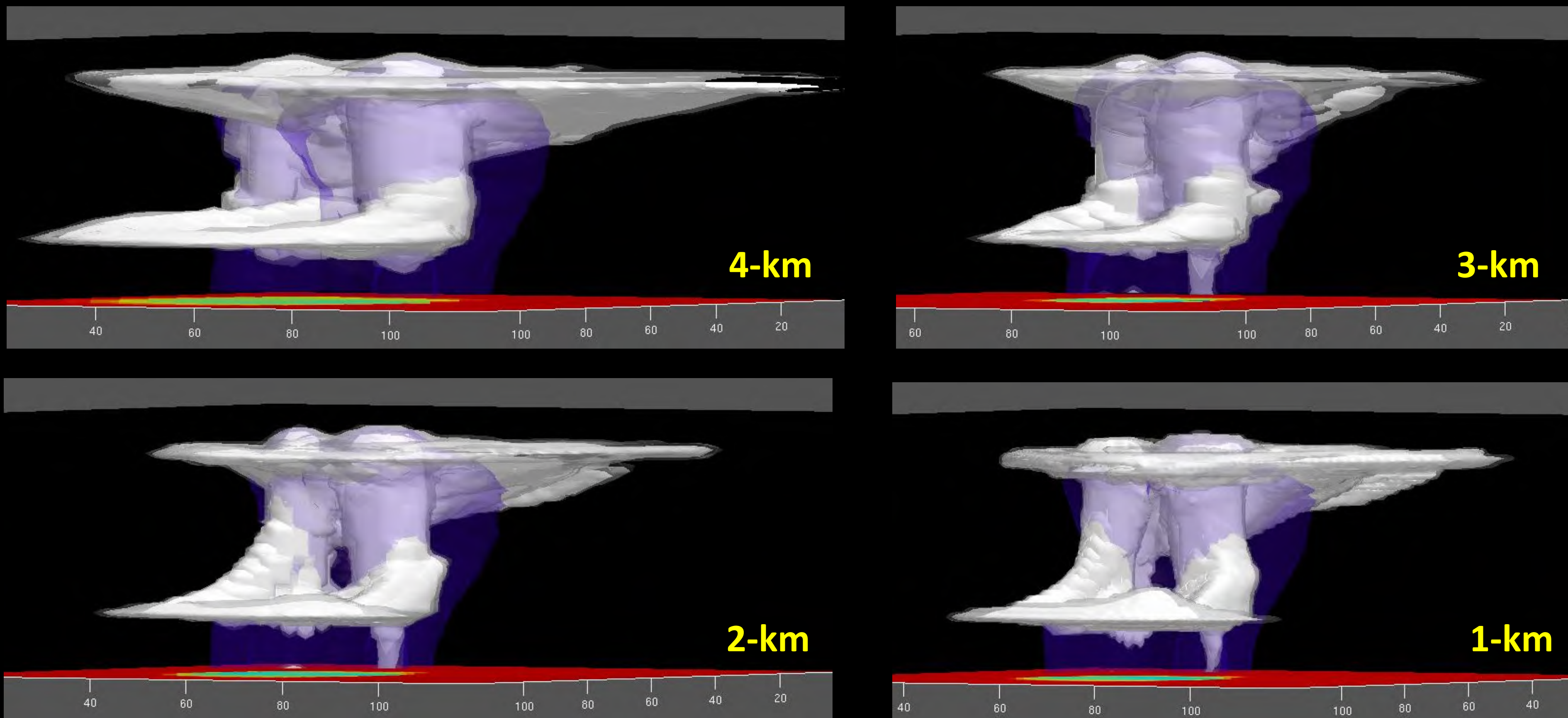
2) **Optimal combination of the “stretching” and “nesting”**



**Example**:

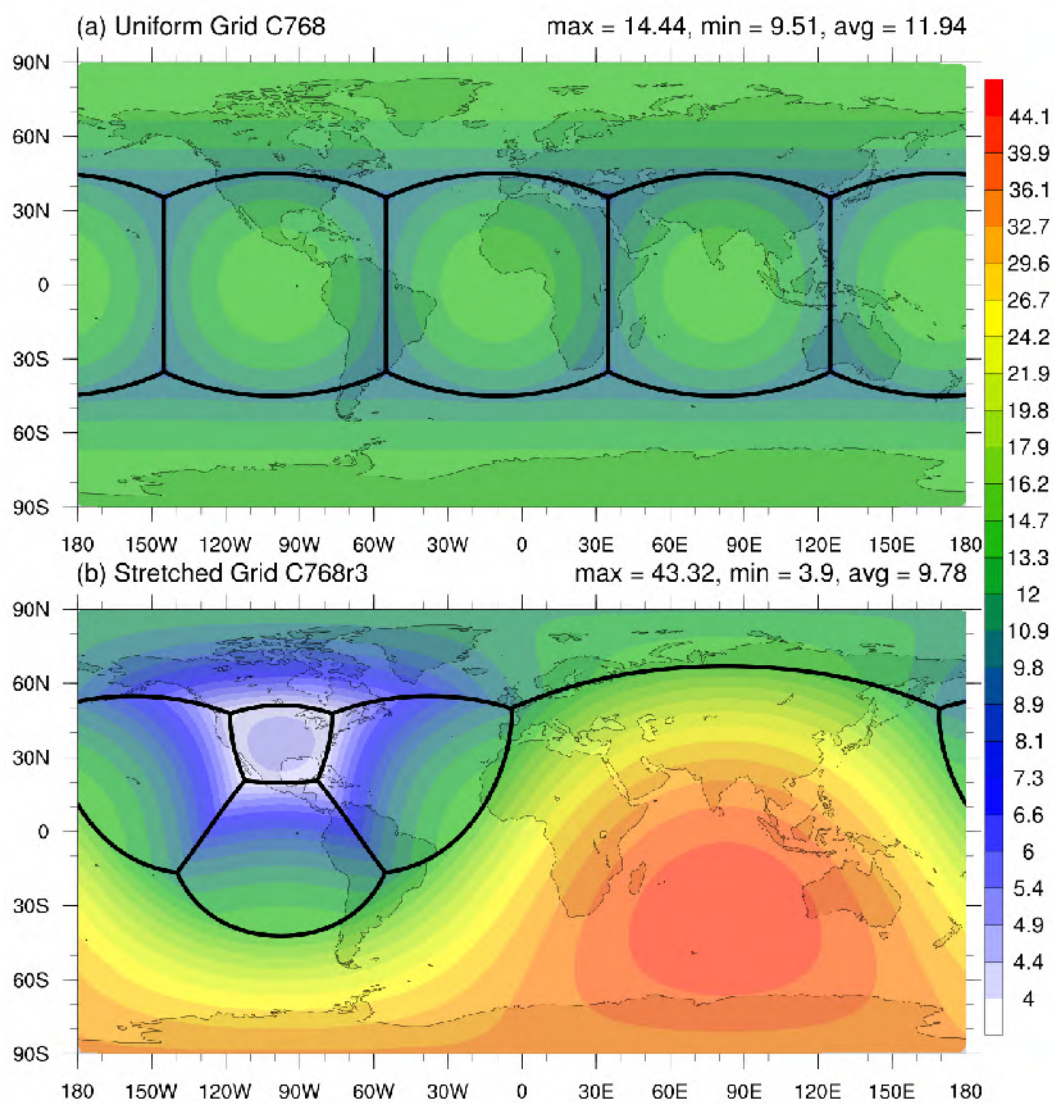
~ 3 km without the nest (black)
~ 1 km with a 2-way nest (red)

# Simulations of tornado-producing super-cell storms with GFDL's variable-resolution FV$^3$




Lin and Harris (manuscript)

# Does the variable-resolution grid degrade the ACC?



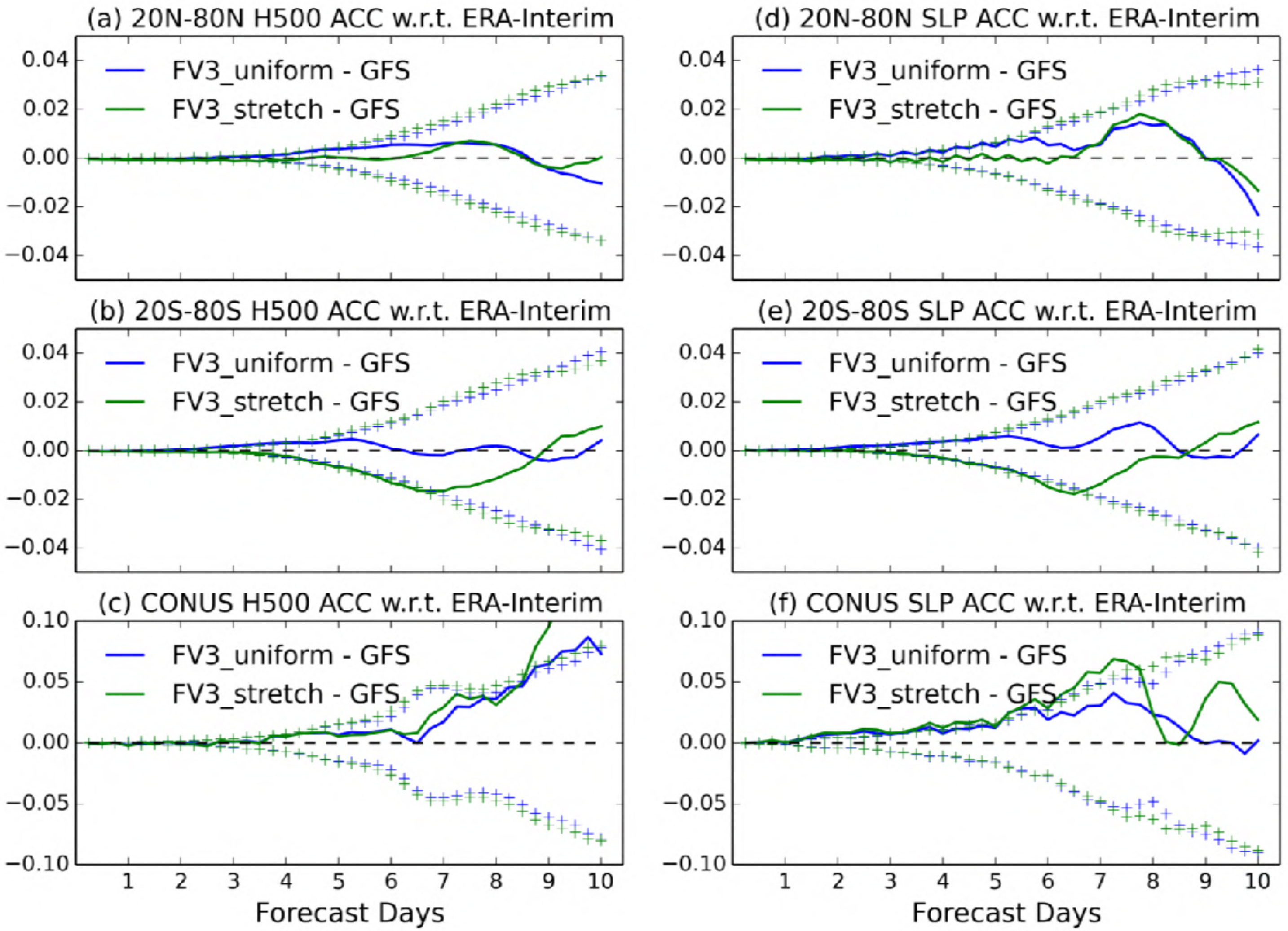

Uniform C768 (~13-km)

Stretched C768_r3 (4-30 km)

# Impact of variable-resolution (4-km over CONUS) on H500 ACC

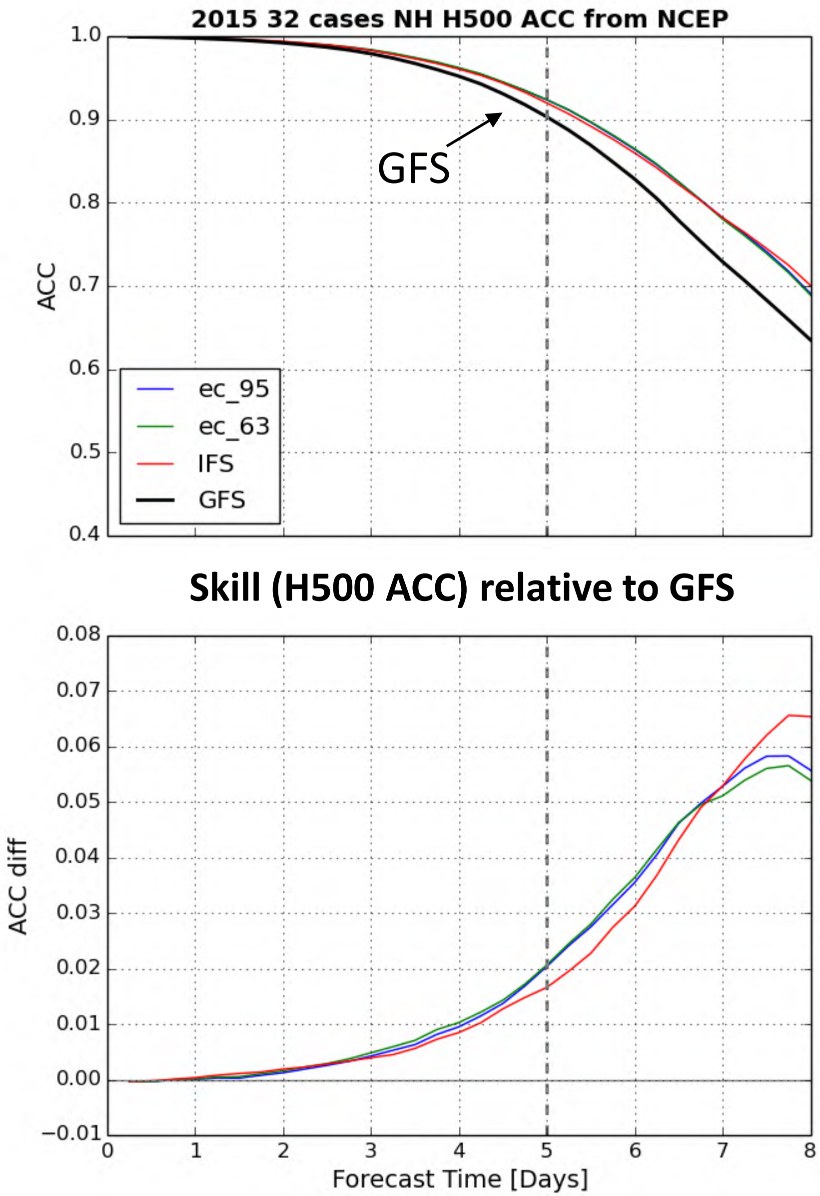
- **NH, particular CONUS, skill equal or better**
- **SH skill degraded**
- **10X faster than global uniform grid**

- C768L63_r3 with GFDL_MP
- Non scale-aware SAS (is that a problem?)
- All 74 NGGPS cases



# Transplant Experiments: 13-km fvGFS using IFS initial conditions (9-km, L137)

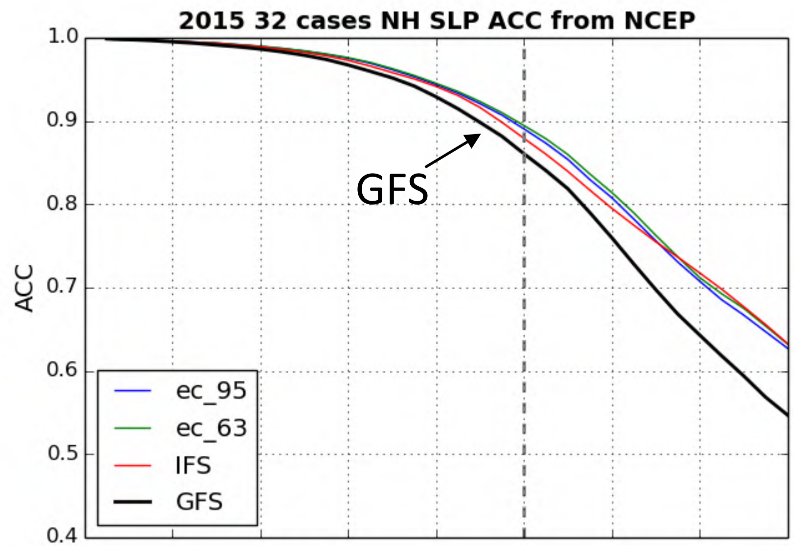
**Period: 20150814–20160116 (32 cases)**



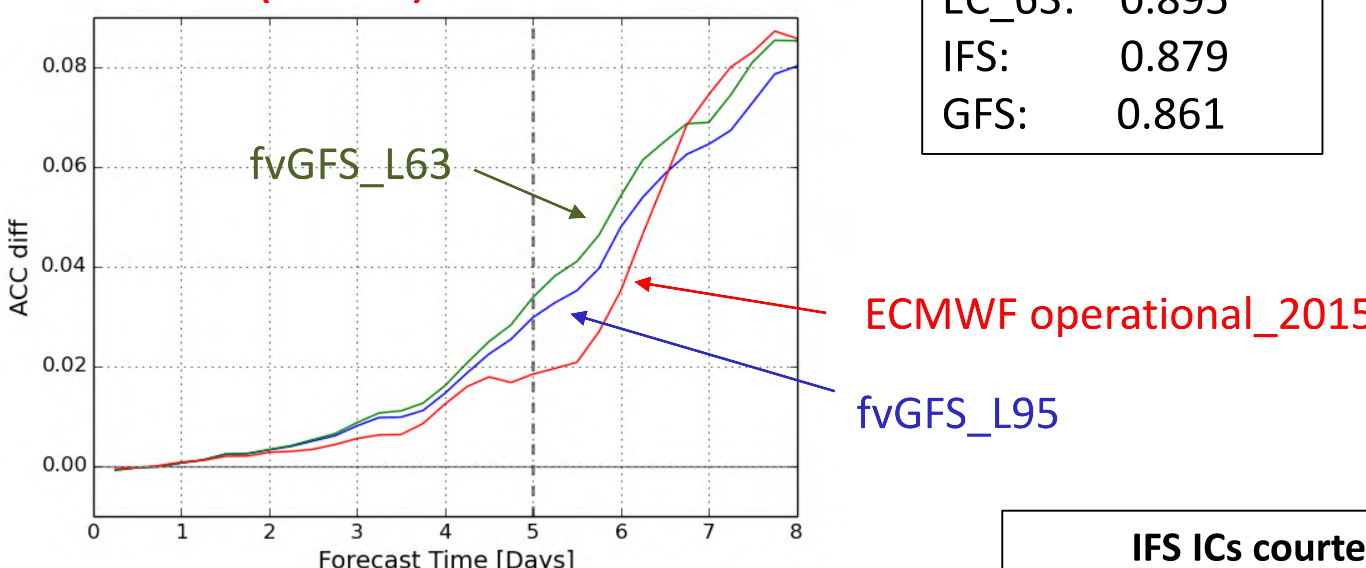

- **Using ICs from ECMWF IFS, fvGFS with GFDL_MP outperforms the <u>2015-operational</u> IFS (Red) and the GFS (black)**
- **Using ICs from GFS, it is extremely difficult to beat IFS**
- **Of course, H500 ACC is not the only metric**

**IFS ICs courtesy of Linus Magnusson, ECMWF**

# Transplant Experiments (32 cases): Sea-Level Pressure (SLP)




**Skill (SLP ACC) relative to GFS**

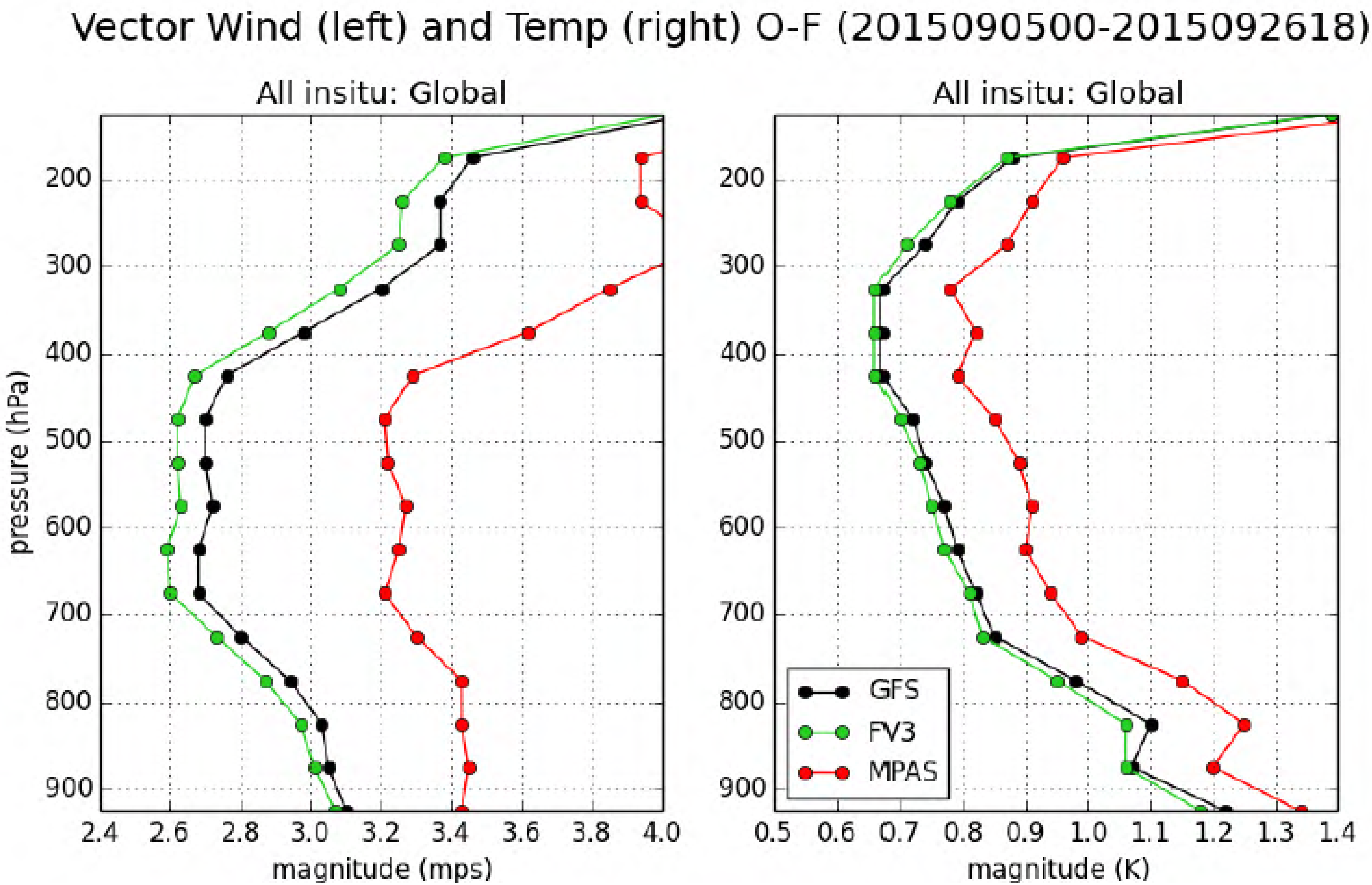



- **Spectral models (IFS and GFS) typically perform relatively worse in SLP than H500**
- **For the 32 cases, fvGFS outperforms ECMWF-IFS with same IC from IFS**

| **SLP ACC at Day-5** | |
|---|---|
| EC_95: | 0.891 |
| EC_63: | 0.895 |
| IFS: | 0.879 |
| GFS: | 0.861 |

**IFS ICs courtesy of**
**Linus Magnusson, ECMWF**

# DA cycle with FV3 and MPAS: NGGPS phase-2 (J. Whitaker)



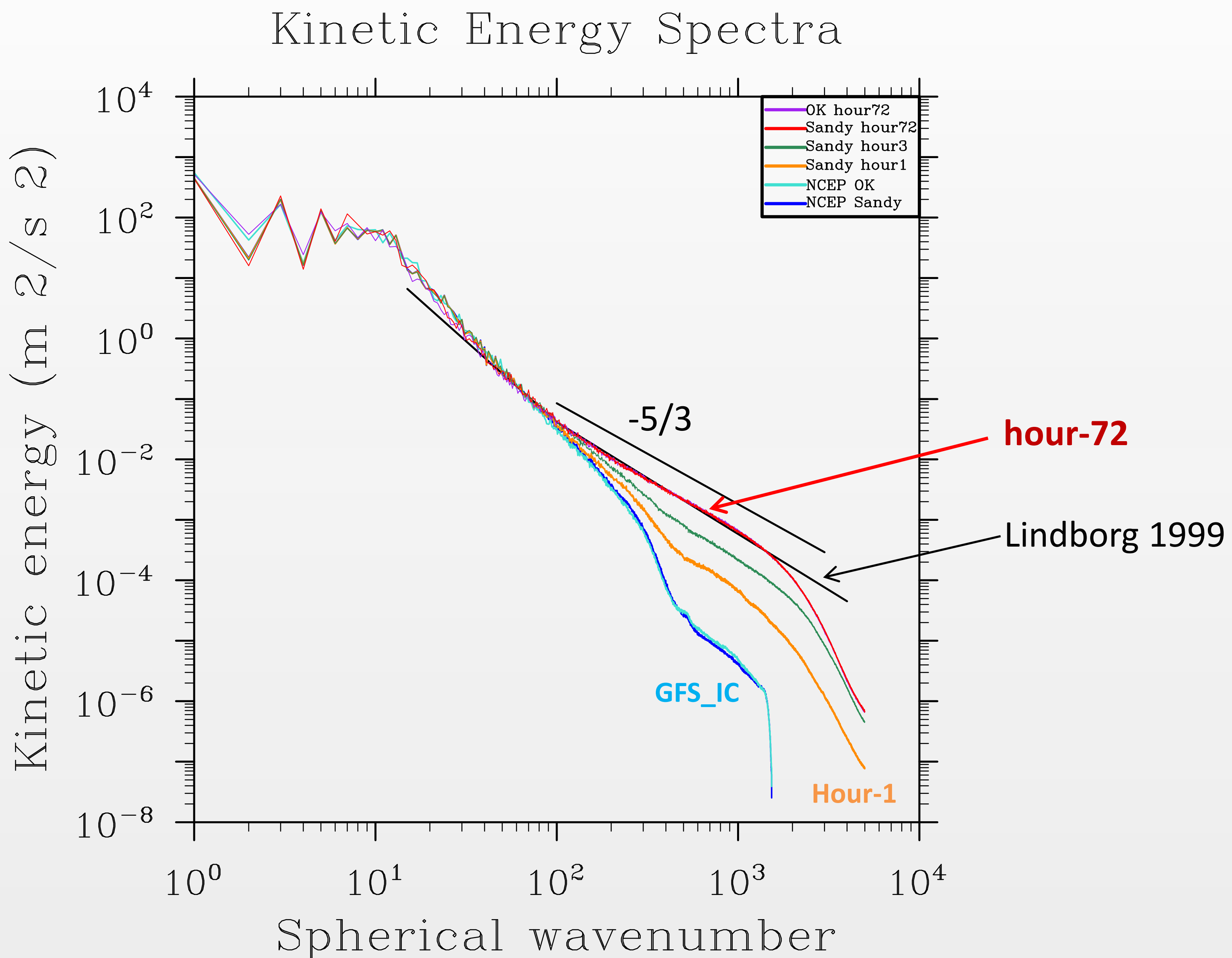
# Final notes:

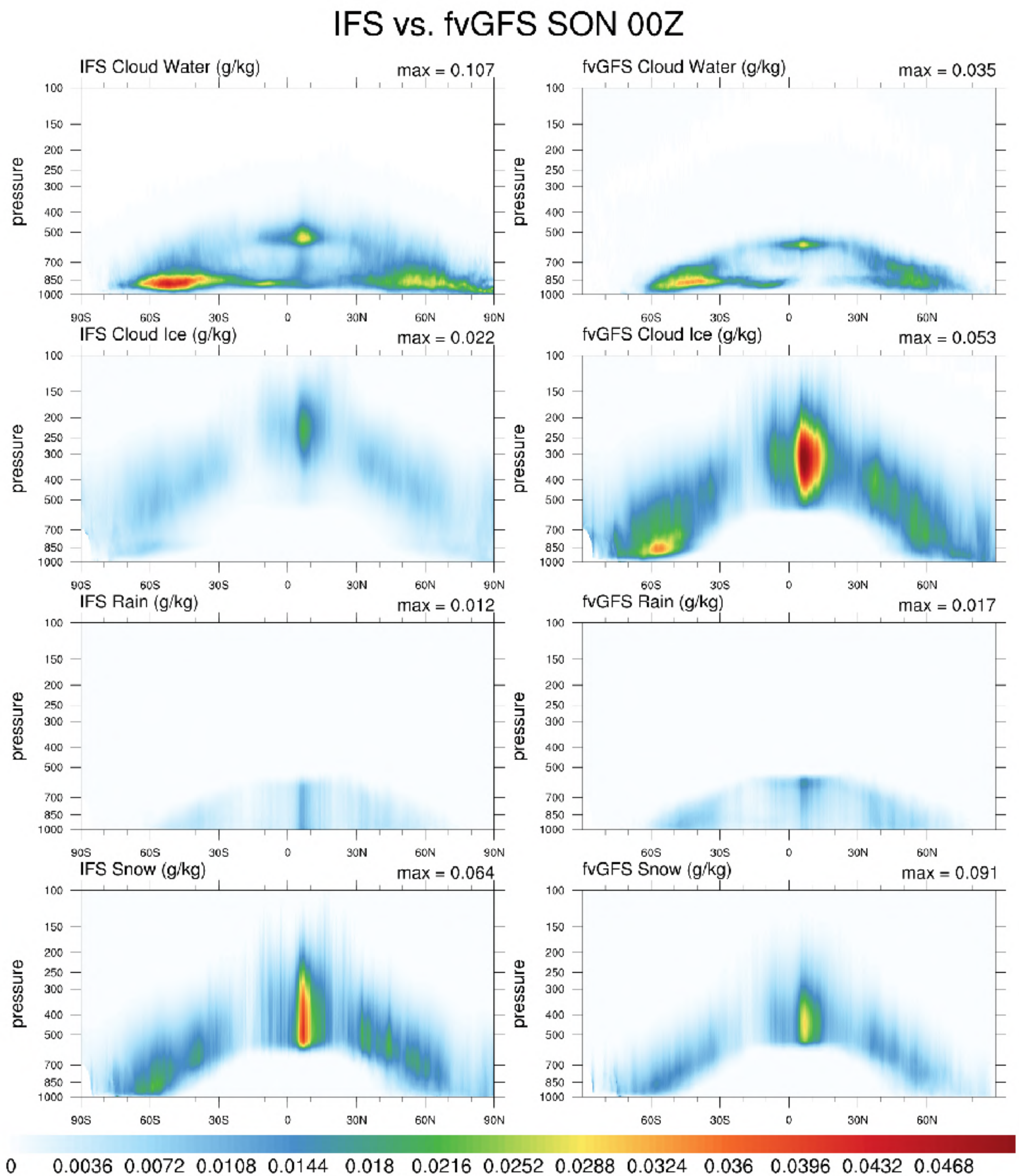
- The *hydrostatic* model for medium-range NWP is near its useful limit
  - It's time to go full non-hydrostatic for all NWP models & DA
- R2O2R: Today's NWP model at NWS could be tomorrow's "high-resolution" climate model at OAR
- Global_2018
  - Boldly step into the NWP gray-zone (~7.5 km) where non-hydro dynamics-microphysics interaction is increasingly more important.
- Regional-global with 2-way nest (GFDL, AOML, OU, and EMC)
  - The Next Generation Hurricane Prediction System with 2.5 km moving nest to replace HWRF
  - CONUS ensemble at 2.5 km with 5 days lead time

# Supplemental Slides

# KE spectrum from GFDL "Super HiRAM"

**(FV3 with modified GFDL AM4 physics at globally uniform ~3.2 km)**



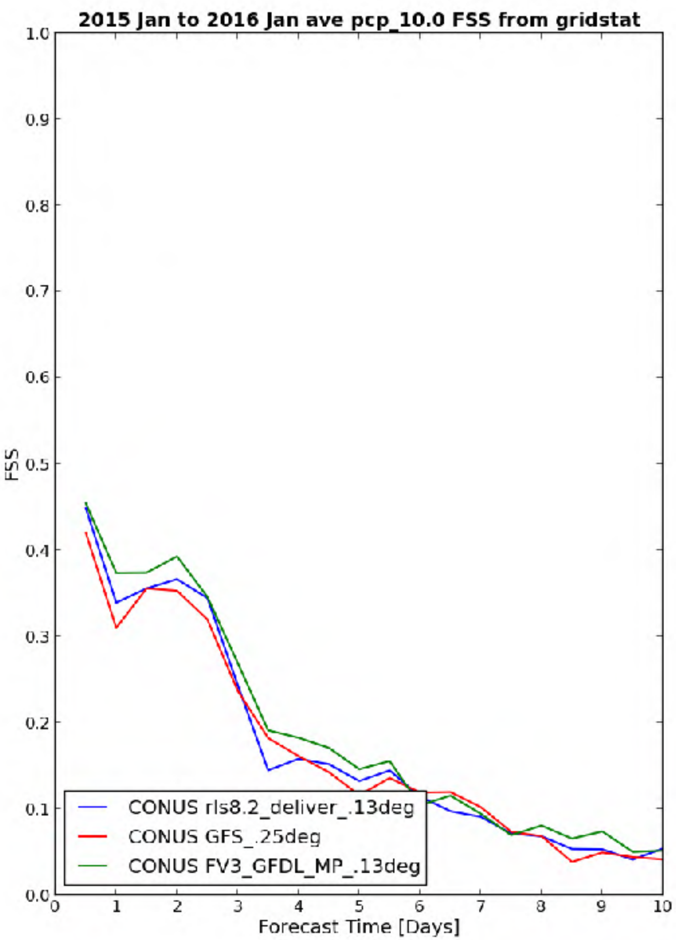

IFS vs. fvGFS SON 00Z
IFS Cloud Water (g/kg)
max = 0.107
fvGFS Cloud Water (g/kg)
max = 0.035
IFS Cloud Ice (g/kg)
max = 0.022
fvGFS Cloud Ice (g/kg)
max = 0.053
IFS Rain (g/kg)
max = 0.012
fvGFS Rain (g/kg)
max = 0.017
IFS Snow (g/kg)
max = 0.064
fvGFS Snow (g/kg)
max = 0.091
pressure
100
150
200
250
300
400
500
700
850
1000
90S
60S
30S
0
30N
60N
90N
0
0.0036
0.0072
0.0108
0.0144
0.018
0.0216
0.0252
0.0288
0.0324
0.036
0.0396
0.0432
0.0468

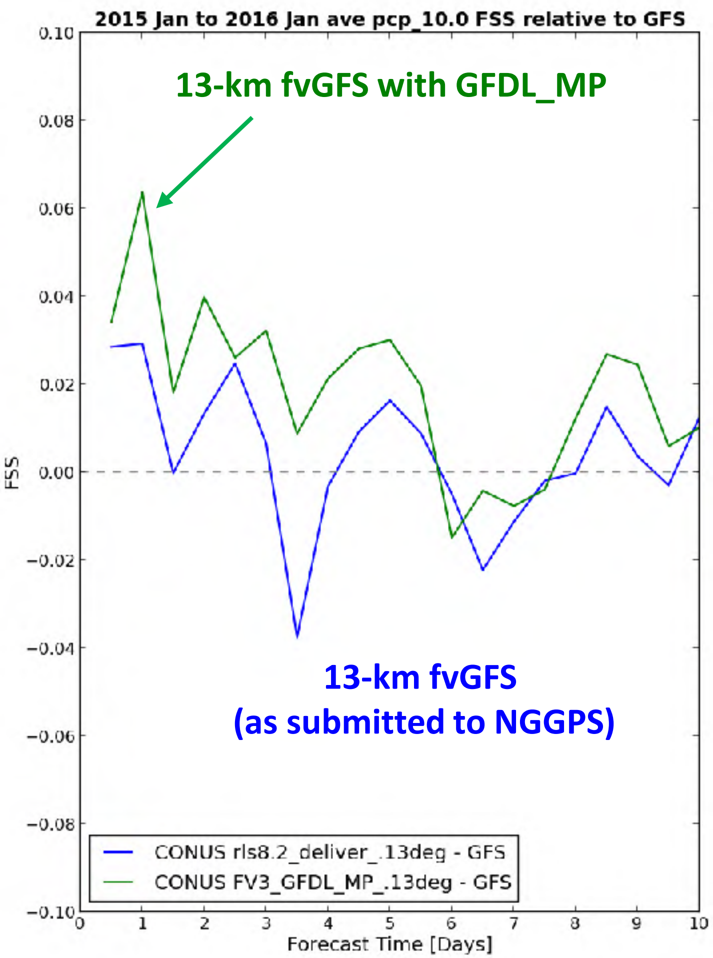
# Fractions Skill Score over CONUS

## (based on NGGPS 74 cases)

## GFDL_MP made a significant improvement

**Precipitation Events >= 10.0mm/6hr**



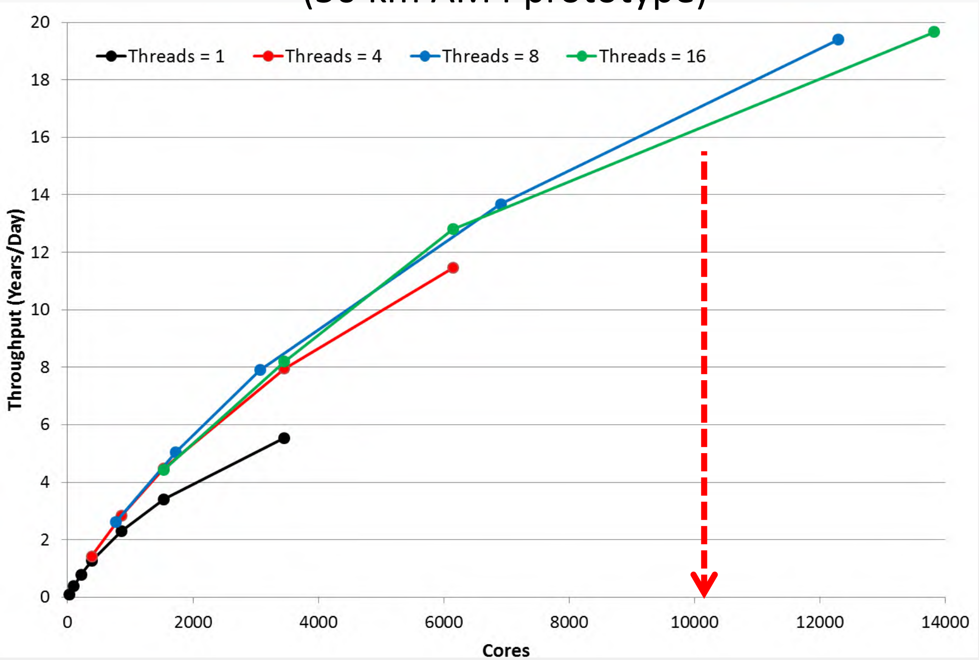

FSS by MET tool, using Stage IV data

# Million-core scalability *via* hybrid programming

- **The AM4 prototype (50 km with 30 tracers) scales beyond 10,000 cores (left)**
- **A global cloud-resolving prototype (3.5 km) scales beyond 1 million cires (right)**

## Hydrostatic C192L63 with 30 tracers on GAEA

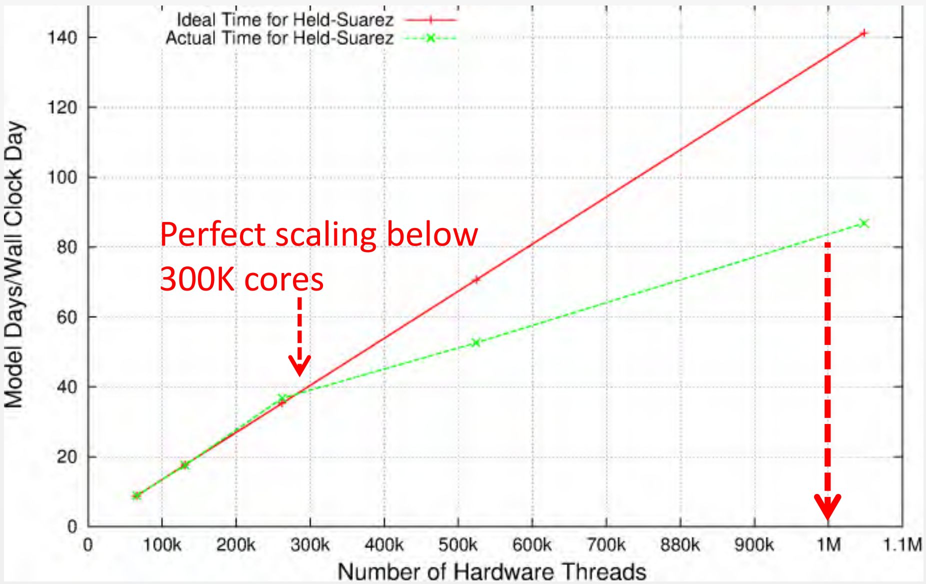
(50 km AM4 prototype)




**10,000 cores**

## Non-hydrostatic C2560L32 on IBM B/G

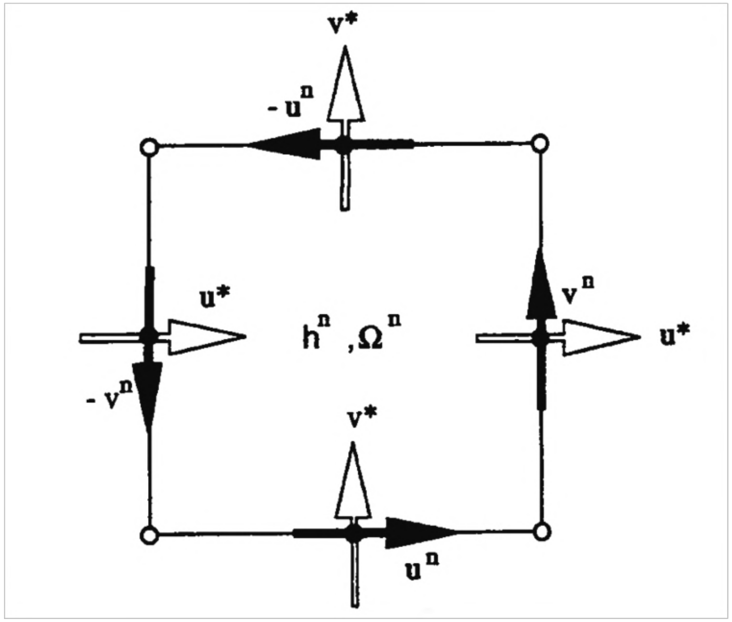
(3.5 km global cloud-permitting prototype)




**1 million cores**

# A balanced approach to "horizontal" grid staggering:

The C+D grid (Lin & Rood 1997)




C & D could work together, like Yin-Yang

## Pressure gradient (linear):

- C grid requires no averaging (best)
- D grid requires averaging in both directions (worst); can be drastically improved with 4$^{th}$ order FV scheme

## Geostrophic balance (linear):

- C grid requires averaging in both directions (worst)
- D grid requires NO averaging (best)

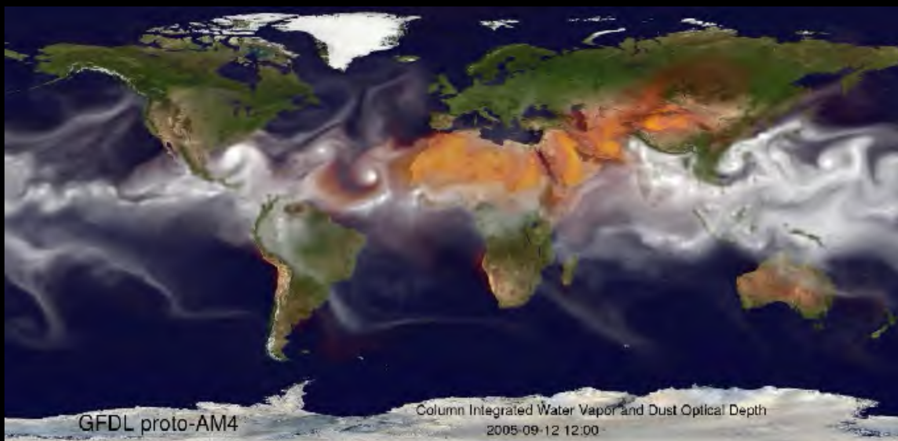
## Potential Vorticity & Helicity (nonlinear):

- C grid is the worst grid for vorticity & helicity
- D grid is the best for vorticity advection and the representation of updraft helicity (severe storms)

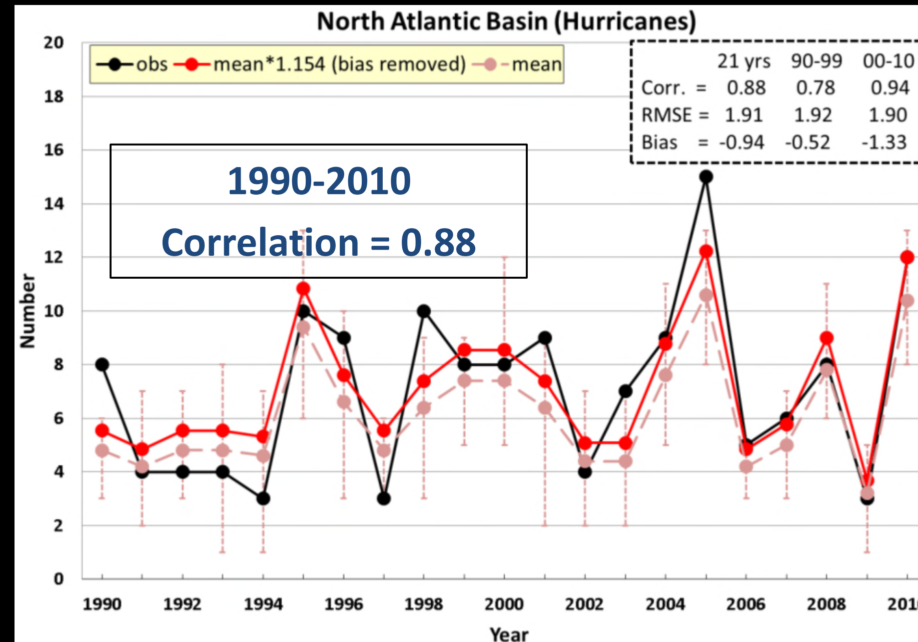
**A combination of C and D is better than a pure C or a pure D grid**

# GFDL's research on Predictions for all-scale

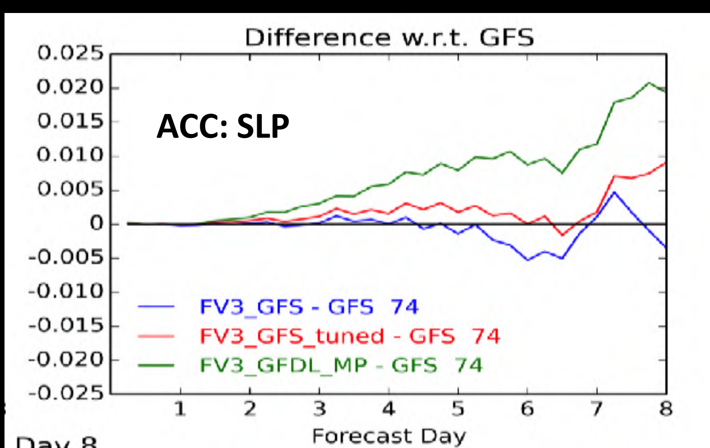
Dust (orange) and water vapor (white)
GFDL 50-km AM4 for IPCC



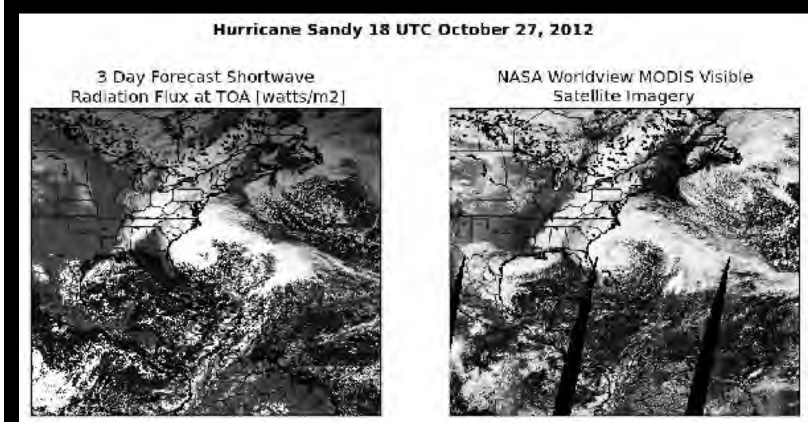

**Seasonal Hurricane Prediction** (25-km HiRAM)



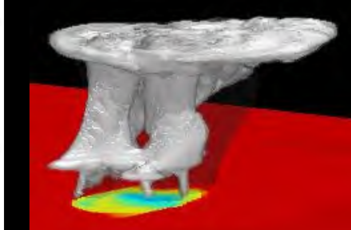

**Medium-range NWP** (13-km, phase-2 NGGPS)




**Global cloud-permitting Predictions**
(3-km, phase-1 NGGPS)




**Severe Storm prediction**
(1 km, Super HiRAM)



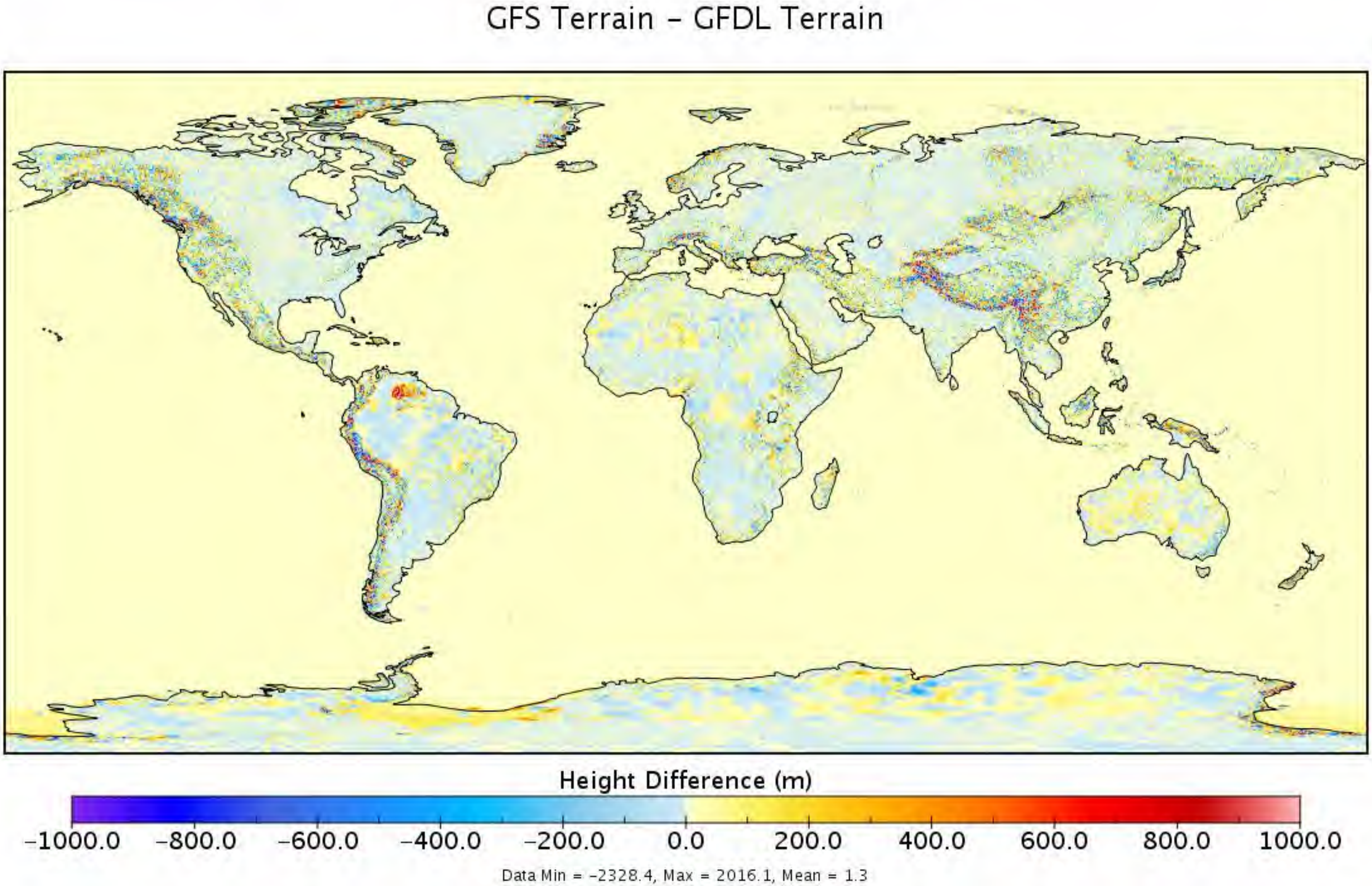
# NGGPS phase-2 benchmarks: FV3 vs MPAS

http://www.weather.gov/media/sti/nggps/Phase%202%20Dycore%20Evaluation%20Briefing%2022%20June%202016%20UMAC%20%234%20v1_0.pdf

- Base configuration (13-km): 3.04 X
- With 30 more tracers (MP + aerosols): 1.63 X
- Variable resolution efficiency: 1.53 X

**Net (multiplicative) result: 7.5 X**

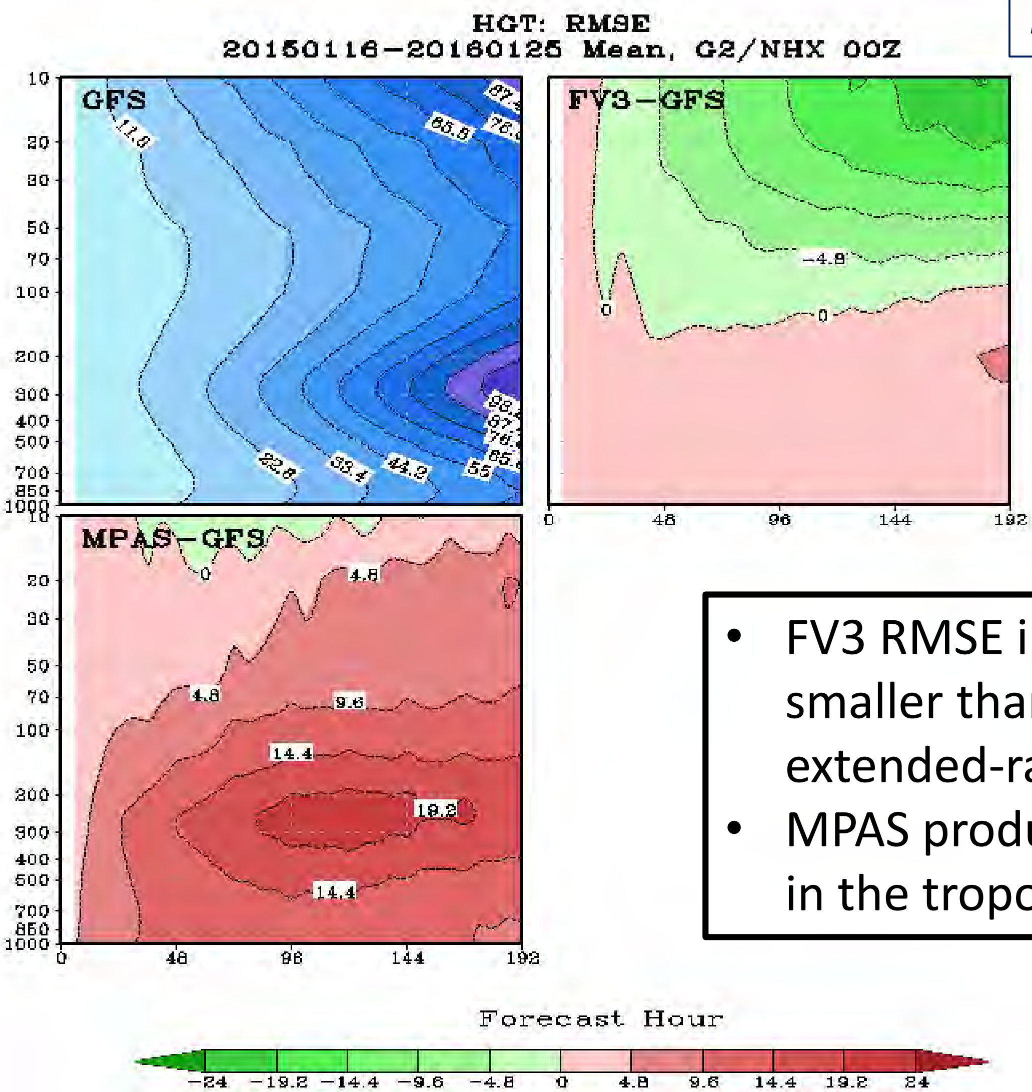
- **FV3 can afford to have 7X more ensemble members at the same cost**
- **The difference likely to be more dramatic with higher vertical resolution**


GFS Terrain - GFDL Terrain
Height Difference (m)
−1000.0 −800.0 −600.0 −400.0 −200.0 0.0 200.0 400.0 600.0 800.0 1000.0
Data Min = −2328.4, Max = 2016.1, Mean = 1.3

# Retrospective forecasts at 13-km:

## zonal mean RMSE of Height: FV3 and MPAS vs. GFS

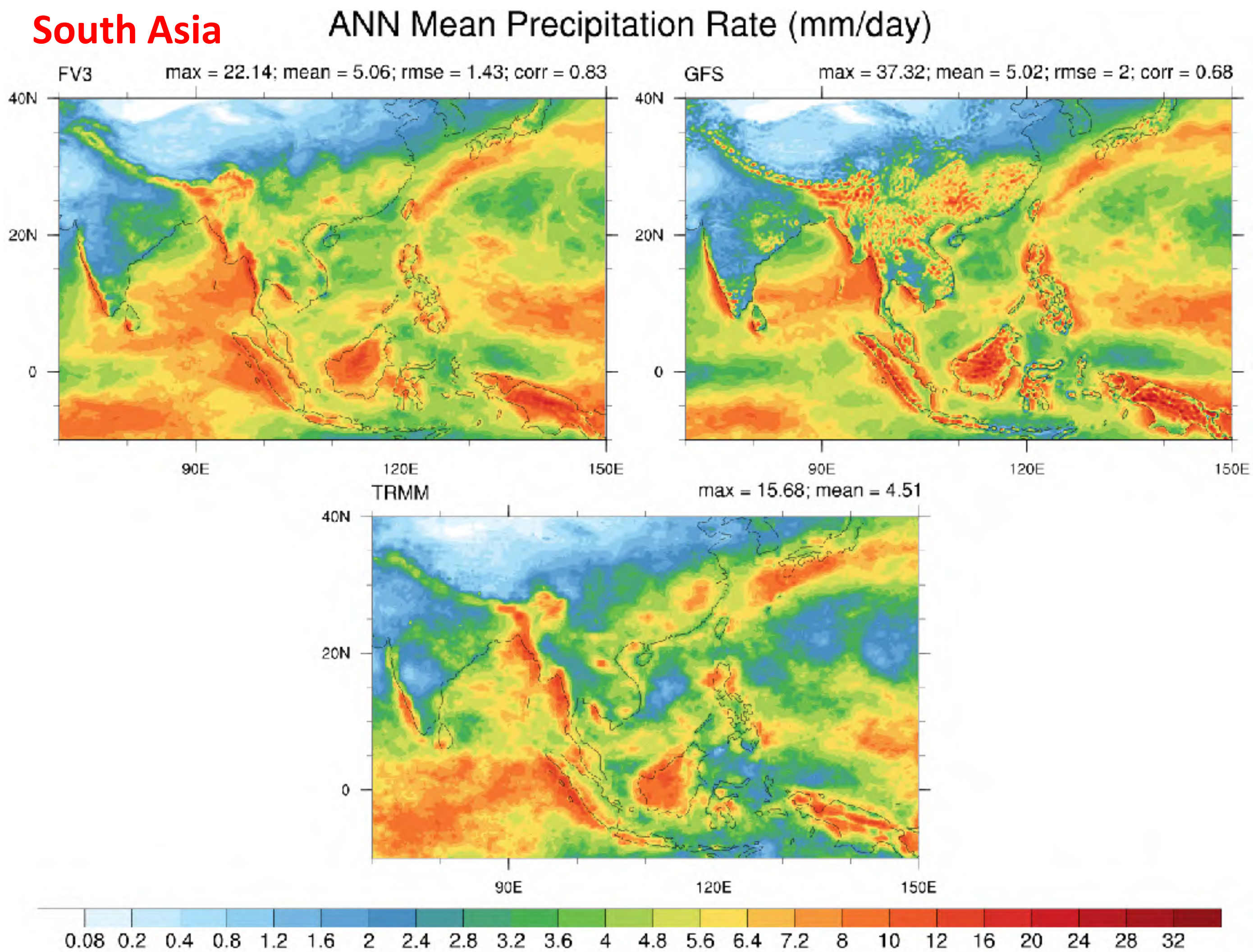
*No tuning of the physics was performed*




Green: better than GFS
Red: worse than GFS

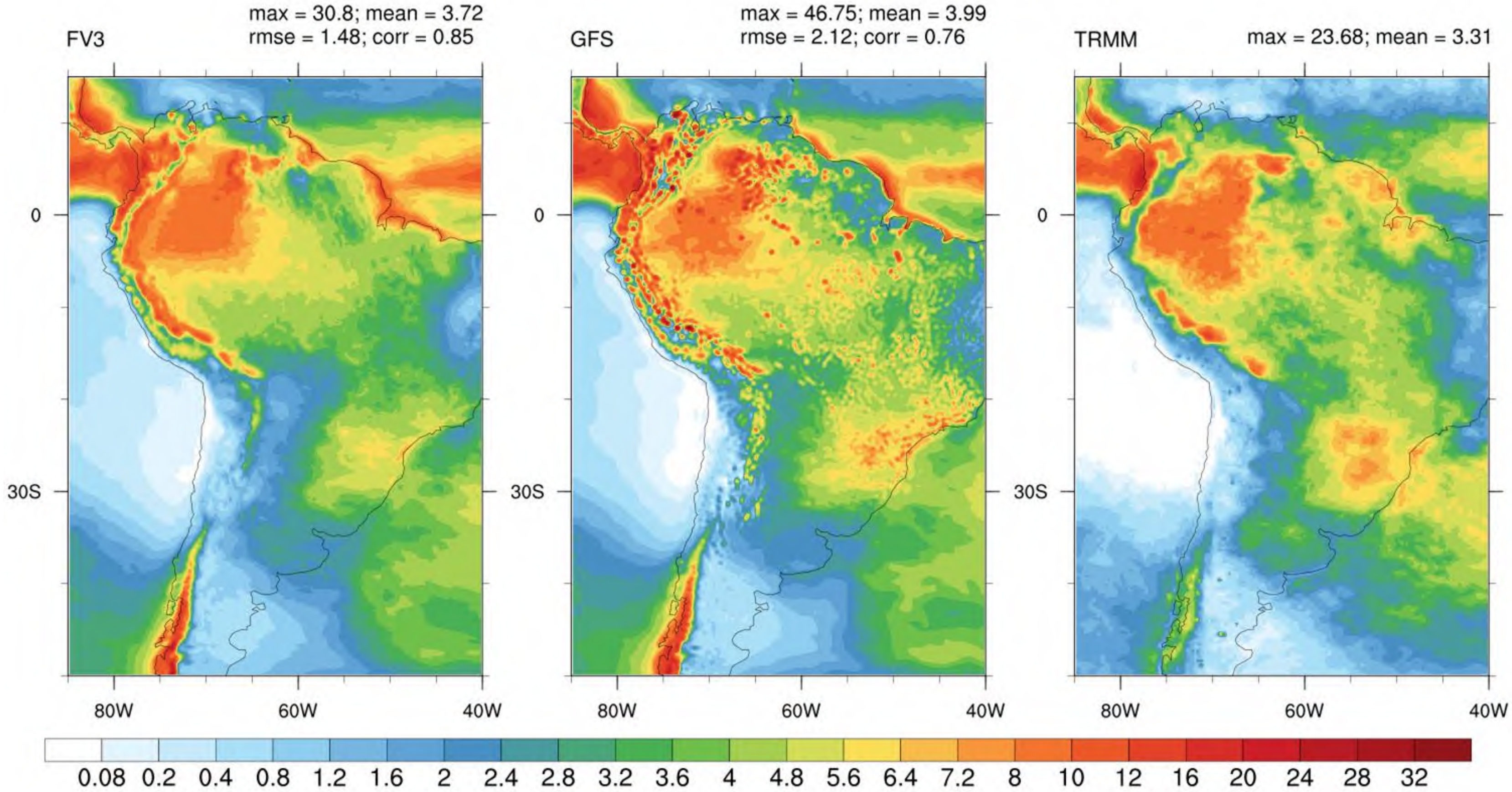
- FV3 RMSE in the stratosphere is much smaller than GFS (and IFS) – source of extended-range predictability
- MPAS produced anomalously large error in the troposphere

**South Asia**

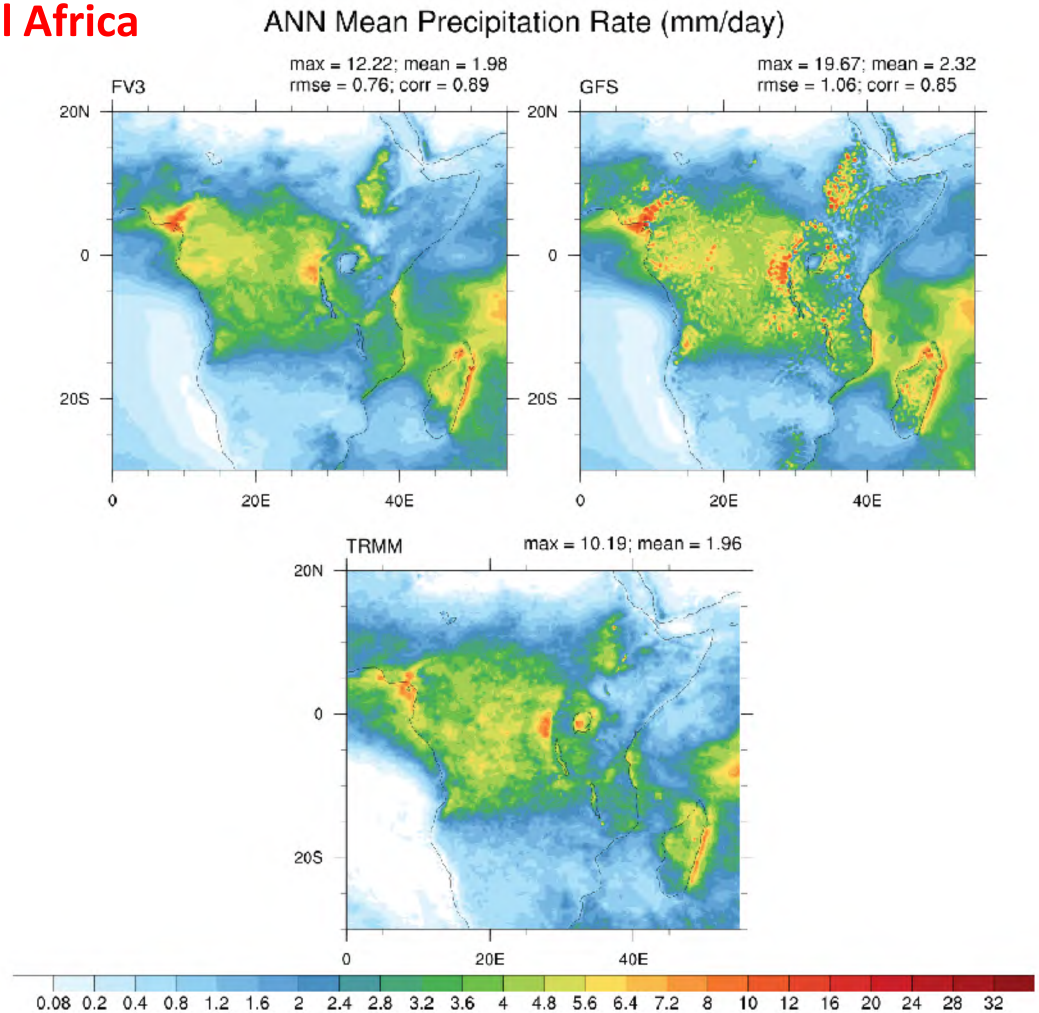

ANN Mean Precipitation Rate (mm/day)
FV3
max = 22.14; mean = 5.06; rmse = 1.43; corr = 0.83
GFS
max = 37.32; mean = 5.02; rmse = 2; corr = 0.68
TRMM
max = 15.68; mean = 4.51
40N
20N
0
90E
120E
150E
0.08 0.2 0.4 0.8 1.2 1.6 2 2.4 2.8 3.2 3.6 4 4.8 5.6 6.4 7.2 8 10 12 16 20 24 28 32

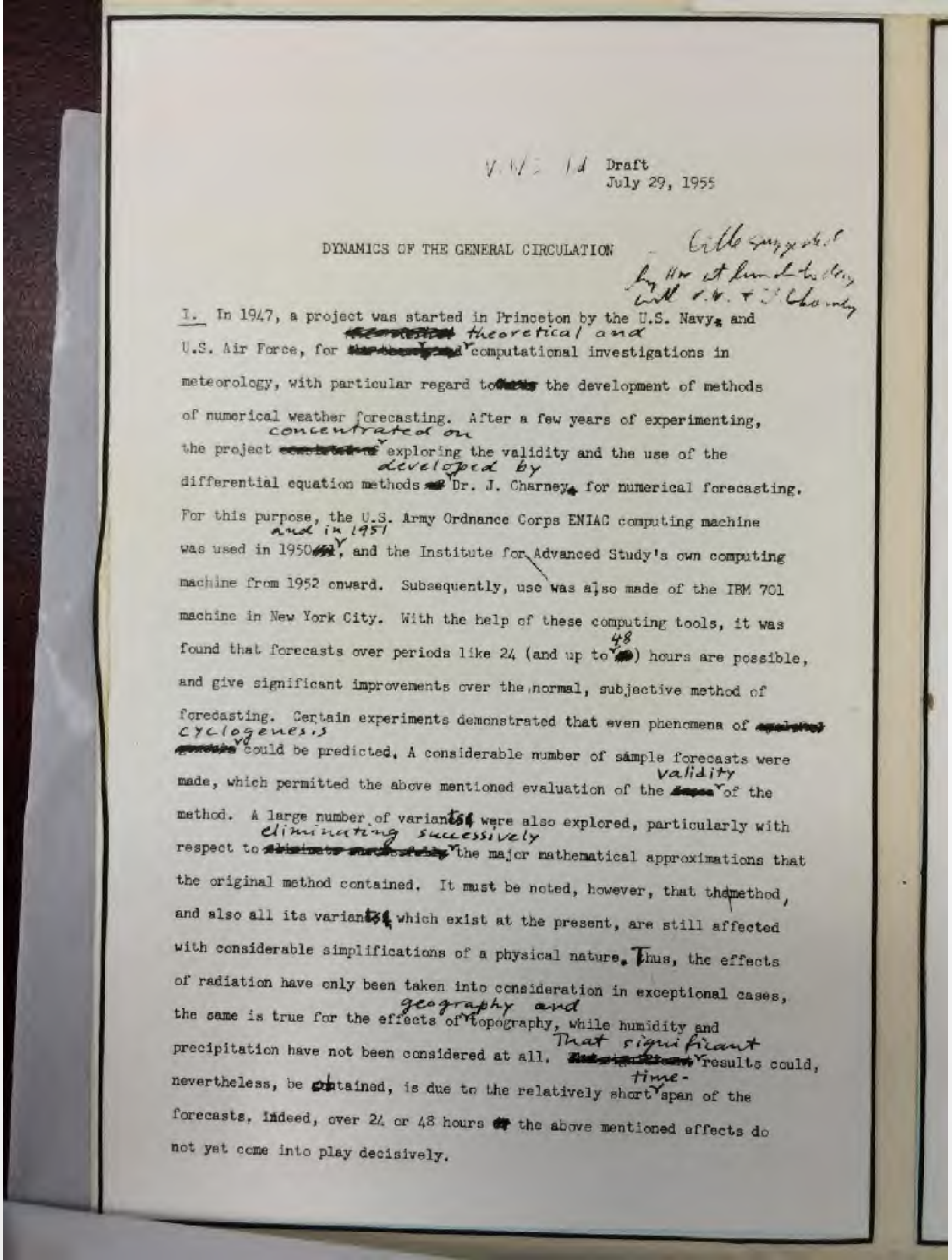
**South America**

# ANN Mean Precipitation Rate (mm/day)



# Central Africa





Draft
July 29, 1955

DYNAMICS OF THE GENERAL CIRCULATION

1. In 1947, a project was started in Princeton by the U.S. Navy, and U.S. Air Force, for theoretical and computational investigations in meteorology, with particular regard to the development of methods of numerical weather forecasting. After a few years of experimenting, the project concentrated on exploring the validity and the use of the differential equation methods developed by Dr. J. Charney, for numerical forecasting. For this purpose, the U.S. Army Ordnance Corps ENIAC computing machine was used in 1950 and in 1951, and the Institute for Advanced Study's own computing machine from 1952 onward. Subsequently, use was also made of the IBM 701 machine in New York City. With the help of these computing tools, it was found that forecasts over periods like 24 (and up to 48) hours are possible, and give significant improvements over the normal, subjective method of forecasting. Certain experiments demonstrated that even phenomena of cyclogenesis could be predicted. A considerable number of sample forecasts were made, which permitted the above mentioned evaluation of the validity of the method. A large number of variants were also explored, particularly with respect to eliminating successively the major mathematical approximations that the original method contained. It must be noted, however, that the method, and also all its variants which exist at the present, are still affected with considerable simplifications of a physical nature. Thus, the effects of radiation have only been taken into consideration in exceptional cases, the same is true for the effects of geography and topography, while humidity and precipitation have not been considered at all. That significant results could, nevertheless, be obtained, is due to the relatively short time-span of the forecasts. Indeed, over 24 or 48 hours the above mentioned effects do not yet come into play decisively.

# NWP is in GFDL's DNA

**A 1955 document recently found at GFDL:**

"Dynamics of the general circulation"

***"It was found that forecasts** (using a simplified model) **over 24 hours are possible".***