Next Generation Global Prediction System (NGGPS)

Phase 2 Atmospheric Dynamic Core Evaluation

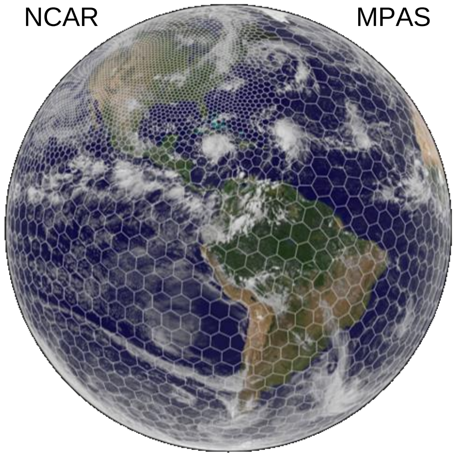
Presentation

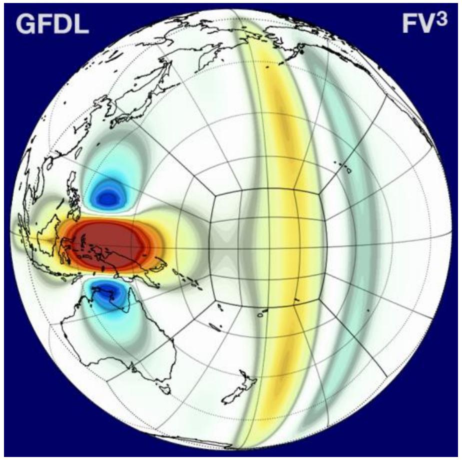
For UMAC

Fred Toepfer/Tim Schneider, Program Manager

Dynamic Core Test Group

June 22, 2016





Outline

- NGGPS Goals and Objectives
- NGGPS Strategy
- Dynamic Core Testing Process and Timelines
- Dynamic Core Assessment (Phase 2)
- DTG Findings

- Back-up
  - GFS Development and Operational Upgrade Plan
  - Detailed Phase 2 Test Results
  - Phase 1 Test and Evaluation
  - Global Modeling Test Bed (GMTB)
  - Common Community Physics Package (CCPP) Strategy

NGGPS Goals and Objectives[1]

- Design/Develop/Implement NGGPS global atmospheric prediction model
  - Non-hydrostatic scalable dynamics
  - Accelerated physics improvement profile
- Improve data assimilation
- Position NWS for next generation high performance computing

World's Best Global Forecast Guidance

1 – From NWS Budget Initiative proposal to OMB

Rationale for Replacing Global Spectral Model (GSM)

- Continued GFS operational performance improvements will require non-hydrostatic resolutions
- Hydrostatic GSM at end-of-life
  - Does not scale well
- Next-Generation computing paradigm will require scaling across potentially 100,000's processors or more
- Semi-Lagrangian spectral cores have significantly poorer effective resolution than competing cores, for same nominal resolution
- Parallel efforts initiated at UKMO and ECMWF

NGGPS Global Atmospheric Prediction Model Technical Strategy

- Reduce implementation time and risk by separating dynamic core and model physics
- Identify and implement optimal core for global weather forecast applications
  - Highly scalable
  - Non-hydrostatic
- Accelerate evolution of model physics
  - Develop/Implement Common Community Physics Package (CCPP)
    - Based on current GFS physics package
    - Integration of best of other existing physics packages
    - Scale aware
  - Employ Global Modeling Test Bed (GMTB) to encourage and facilitate community interaction

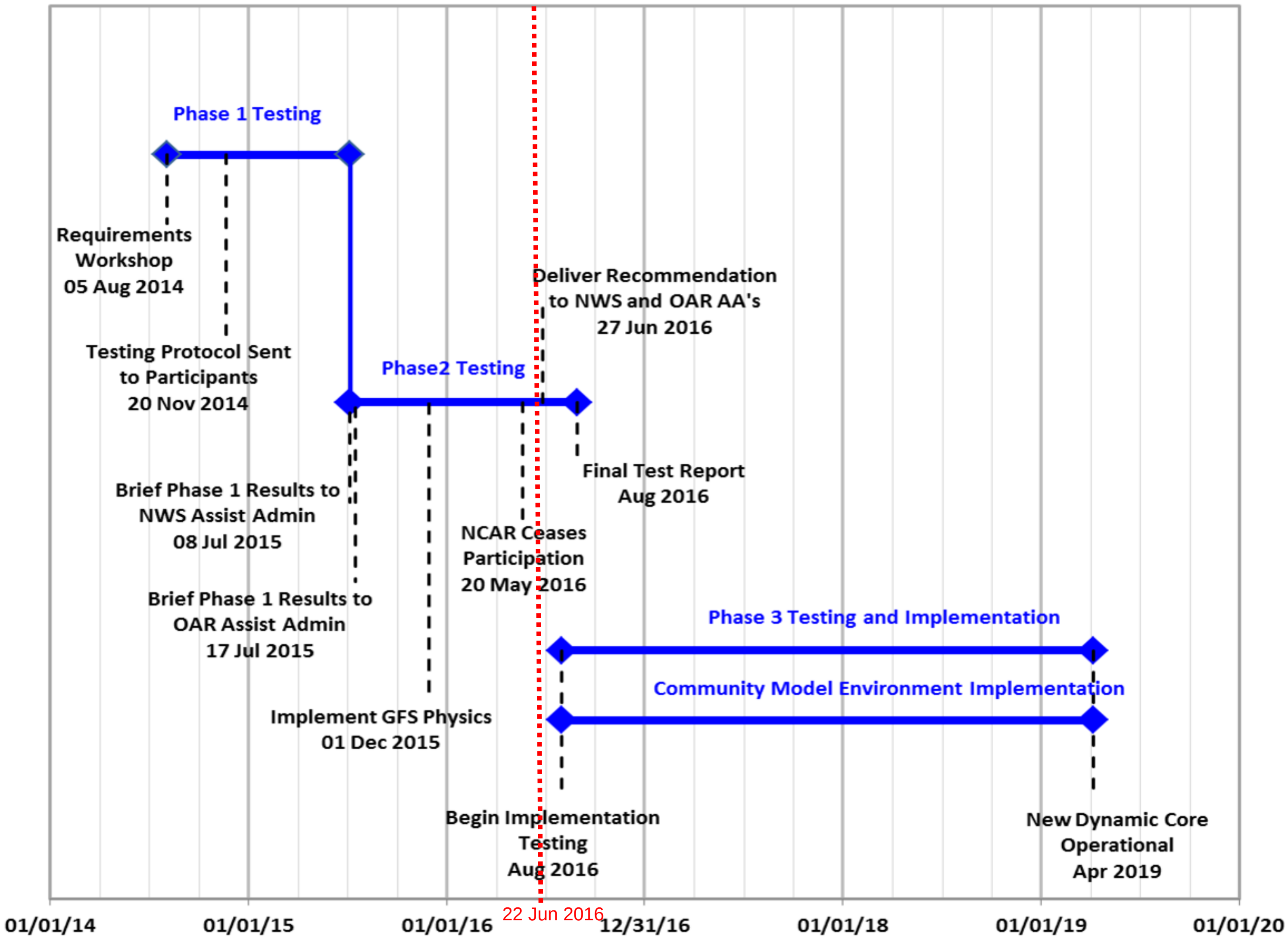
NGGPS Global Atmospheric Prediction Model Implementation Strategy

- Phase 1 – Identify Qualified Dynamic Cores
  - Evaluate technical performance
    - Scalability
    - Integration of scheme stability and characteristics
- Phase 2 – Select Candidate Dynamic Core
  - Integrate with operational GFS Physics/CCPP
  - Evaluate meteorological performance
- Phase 3 – Operational Implementation
  - Implement candidate dynamic core in NEMS
  - Implement Common Community Physics Package
  - Implement data assimilation (4DEnVar with 4D incremental analysis update and stochastic physics)

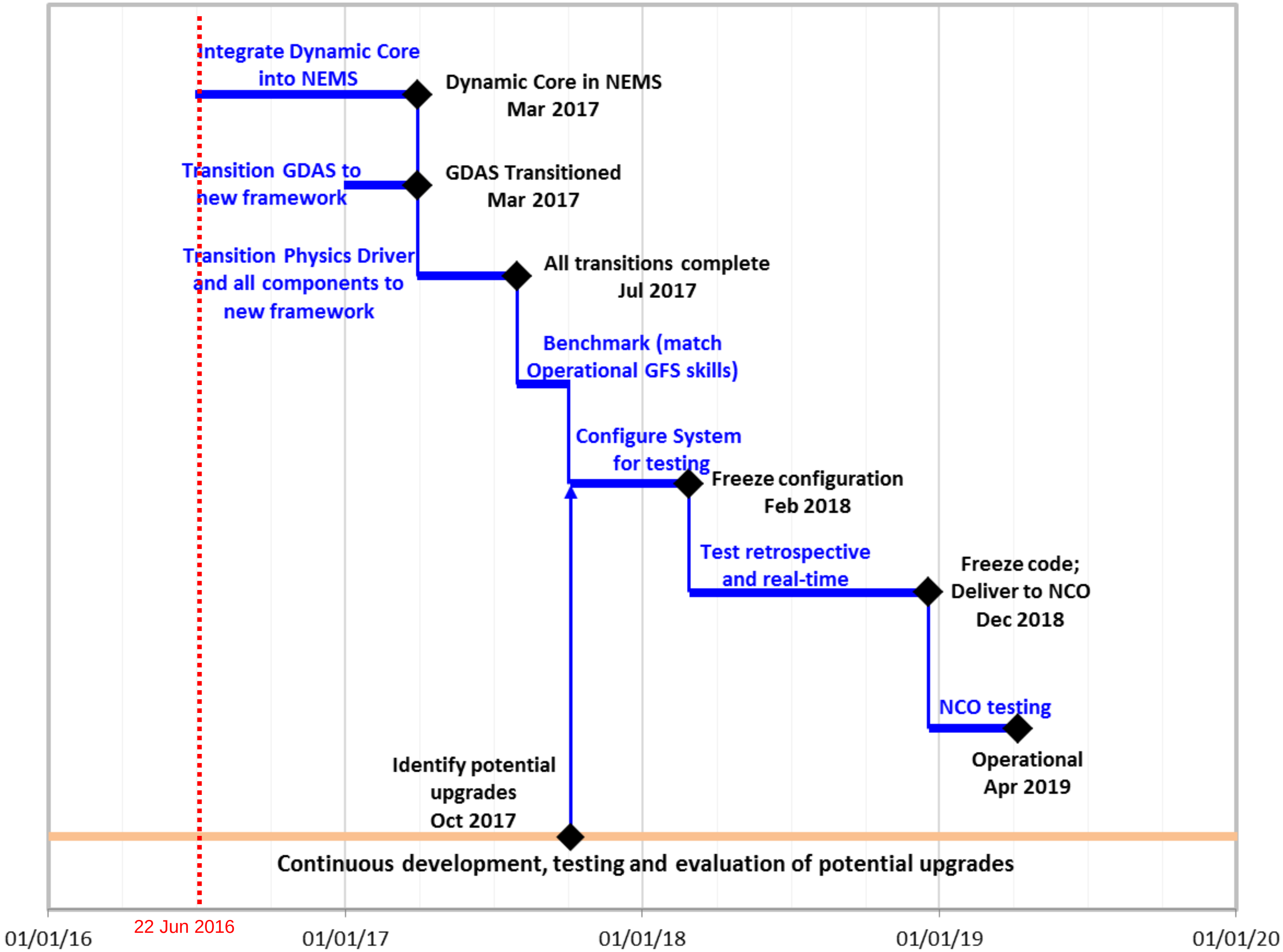
Strategy to Implement Community Model Environment

- Q1FY17: Hold a workshop to collect input on how to structure the community model environment, including:
  - Code hosting environment (e.g. github)
  - Processes for O2R and R2O
  - Governance
  - How will support be provided?
  - What models will be supported (atmosphere dycore, ocean, land…)?
- Develop detailed documentation, include users guide
- Q1FY18: Code released, with documentation
- Q1FY19: First users workshop/tutorial

Dynamic Core Testing and Implementation Timeline



Phase 3 Implementation Detail



Testing and Evaluation Summary

NGGPS Dycore Test Group (DTG) Membership

- Ming Ji, Chair
  - Director, Office of Science and Technology Integration
- Fred Toepfer
  - NGGPS Program Manager
- Tim Schneider
  - Acting NGGPS Program Manager
- Bob Gall
  - Independent Consultant
- Ricky Rood
  - Independent Consultant
- John Thuburn
  - Independent Consultant
- Melinda Peng/Jim Doyle
  - Navy/NRL Monterey
- Ram Ramaswamy/SJ Lin
  - GFDL
- Hendrik Tolman/Vijay Tallapragada
  - NCEP/EMC
- Chris Davis/Bill Skamarock*
  - NCAR/MMM
- Kevin Kelleher/Stan Benjamin
  - ESRL/GSD
- Jeff Whitaker
  - NGGPS Test Manager
- John Michalakes
  - Chair, Advanced Computing Evaluation Committee

* NCAR ceased participation and withdrew from DTG on 20 May 2016

New Dynamic Core Candidate Models

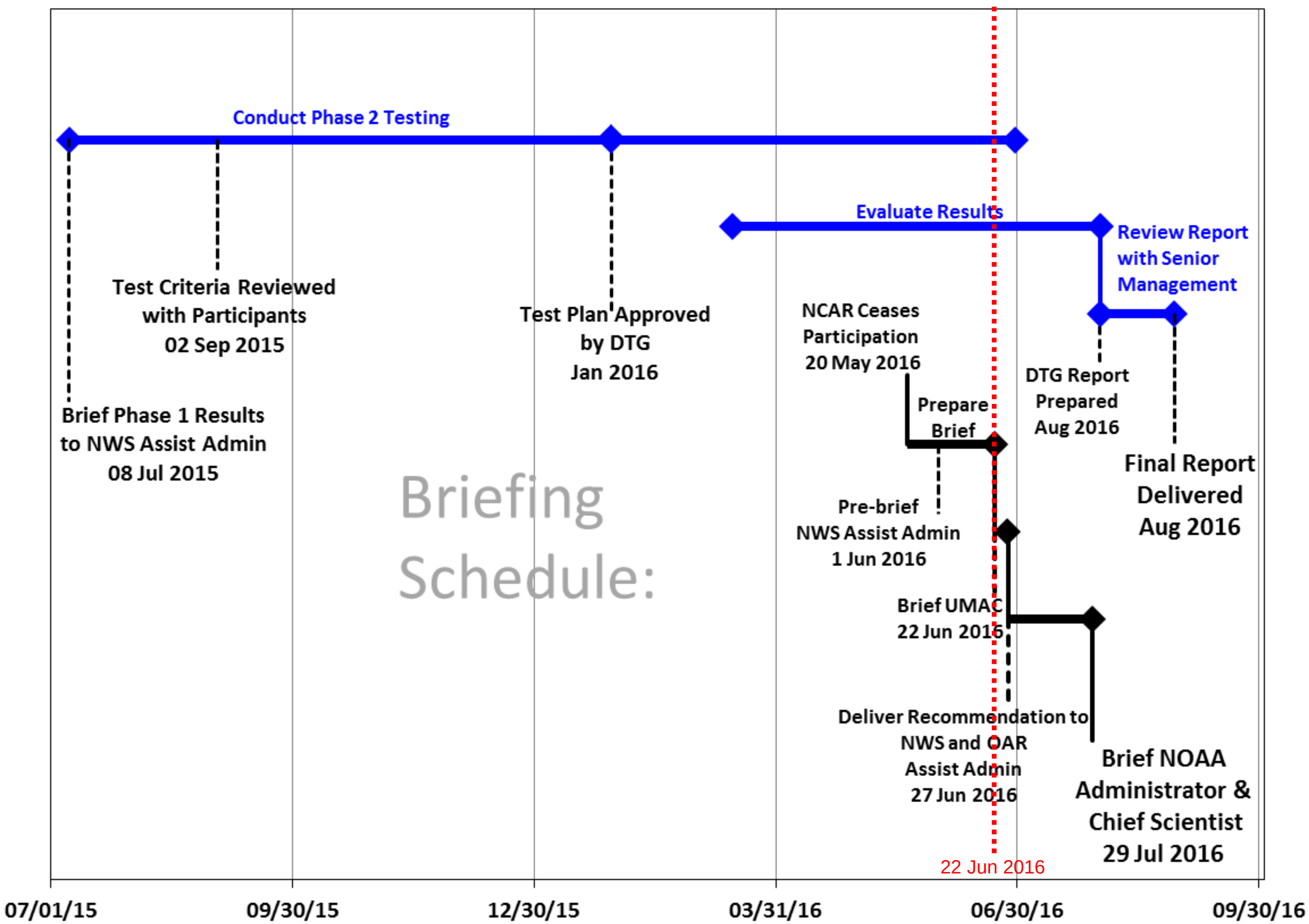
Phase 1 Testing Included*:

*Built upon HIWPP Non-hydrostatic Model Evaluation

- Non-hydrostatic Global Spectral Model (GSM) - EMC
- Global Non-hydrostatic Mesoscale Model (NMM & NMM-UJ) - EMC
- Model for Prediction Across Scales (MPAS) - NCAR
- Non-hydrostatic Icosahedral Model (NIM) – ESRL
- Navy Environmental Prediction System Using the NUMA Core (NEPTUNE) – Navy
- Finite Volume Model version 3 – (FV3) – GFDL

- **FV3 and MPAS selected to advance to Phase 2**

Phase 2 Testing, Evaluation and Reporting Schedule



Phase 2 Test Plan Development Timeline

- Test Plan Developed by DTG between June and December 2015
  - Testing Criteria Finalized by DTG at Face-to-Face Meeting in September 2015
  - Initial Test Plan Developed by November 2015 (including AVEC Test Plan)
- Test Plan Approved by DTG in January 2016

NGGPS Phase 2 Test Plan

#	Evaluation Criteria
1	Plan for relaxing shallow atmosphere approximation (deep atmosphere dynamics)
2	Accurate conservation of mass, tracers, entropy, and energy
3	Robust model solutions under a wide range of realistic atmospheric initial conditions using a common (GFS) physics package
4	Computational performance with GFS physics
5	Demonstration of variable resolution and/or nesting capabilities, including supercell tests and physically realistic simulations of convection in the high-resolution region
6	Stable, conservative long integrations with realistic climate statistics (Complete by 30 June)
7	Code adaptable to NEMS/ESMF
8	Detailed dycore documentation, including documentation of vertical grid, numerical filters, time-integration scheme and variable resolution and/or nesting capabilities
9	Evaluation of performance in cycled data assimilation (Complete by 30 June)
10	Implementation Plan (including costs)

#1: Whole Atmosphere Model (WAM) Suitability

- SWPC WAM development team considered approaches by MPAS and FV3 to SWx requirements:
  - Both dycore teams have adequate plans in place for addressing SWx requirements for the next generation WAM and no preference was given to either dycore
  - Some requirements are not fully addressed by either dycore such as the approach to thermodynamics in a whole atmosphere
  - Significant effort still remains to adapt both dycores to the full atmosphere altitude/pressure domain currently covered by WAM

#2: Conservation Tests

- DCMIP-2012 baroclinic wave idealized test, dry and moist (4.1 and 4.2) run at 13 km resolution. Simple moist physics (large-scale condensation only) included.
- Conservation of total energy, entropy and dry mass measured
- Extra advected tracer added, initialized with θ_e (difference between advected and diagnosed θ_e measured)
- ’Grid imprinting’ (signal of truncation errors at cube corners and pentagons of icosahedral grid) assessed

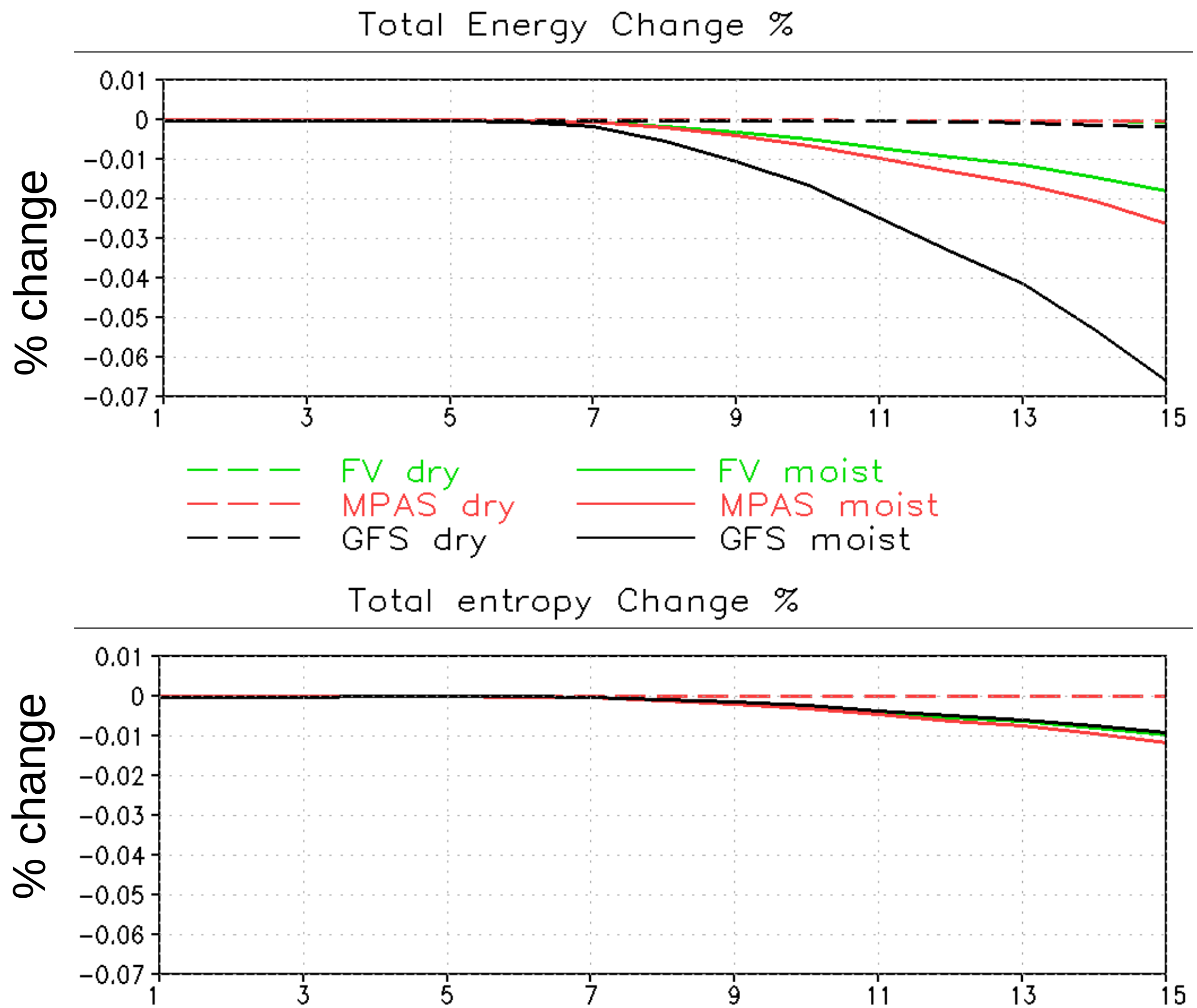
#2: Conservation Tests
Change in Total Energy and Entropy

Change in total energy (top) and entropy (bottom) as a percent change from the initial value. ***Note very tiny range on y axis.***

Energy loss nearly zero in dry case, FV3 and MPAS lose less energy than GFS in moist case.

Energy loss in moist case for FV3 and MPAS is consistent with the energy removed along with condensate. Entropy changes for moist case are very small, and consistent with thermodynamic approximations made in entropy definition.

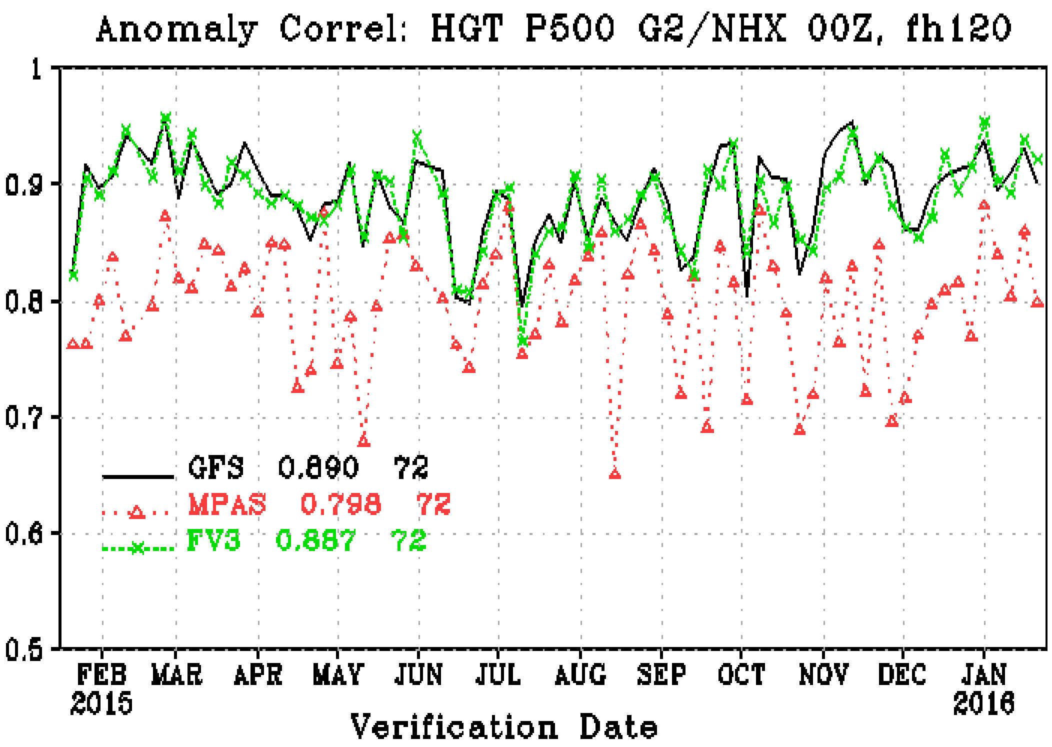
Dry mass (not shown) is conserved exactly in both FV3 and MPAS, GFS gains 0.05 hPa during integration.

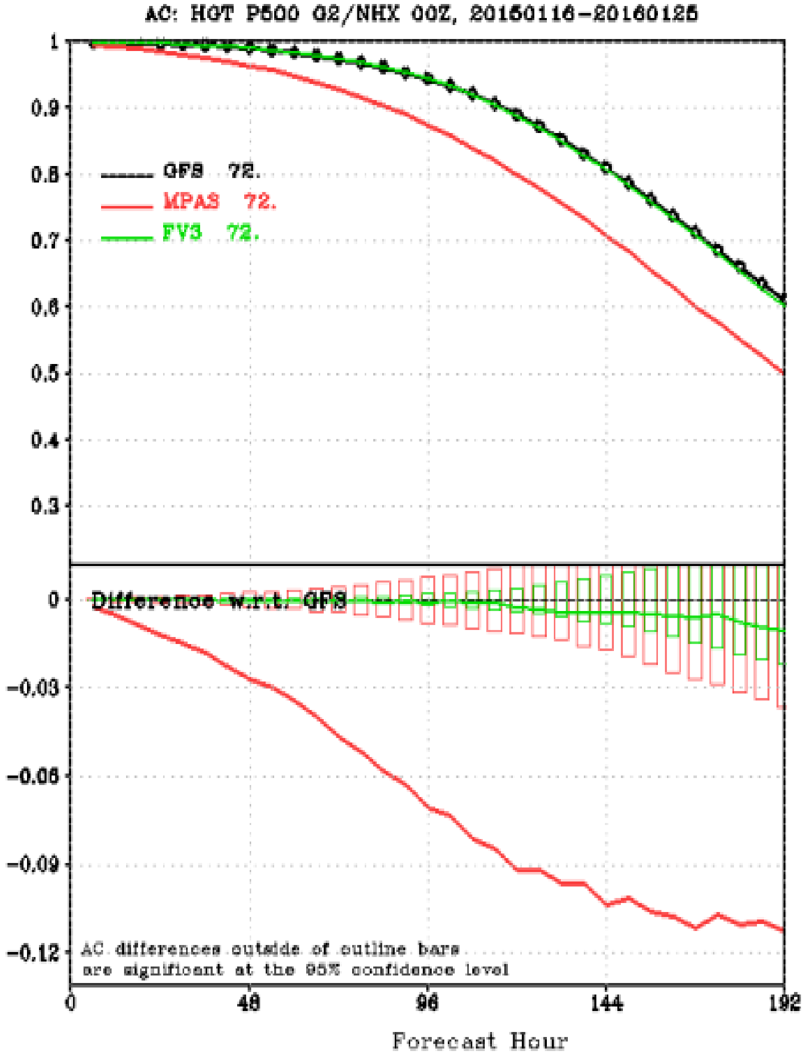


#3: Retrospective 13 km 10-d Forecasts with GFS physics

- GFS physics package (provided by EMC) implemented in both models by FV3 and MPAS development teams
- 74 retrospective 10-d forecasts run at 13 km resolution with 64 vertical levels, initialized from GFS analyses every 5th day for calendar year 2015
- Validated using NCEP verification suite, compared to operational GFS forecasts
- Goals:
  - Assess ‘robustness’ over a wide-range of atmospheric flow conditions
  - Assess work required to replace spectral dycore in operational GFS

#3: Retrospective 13 km Forecast Skill



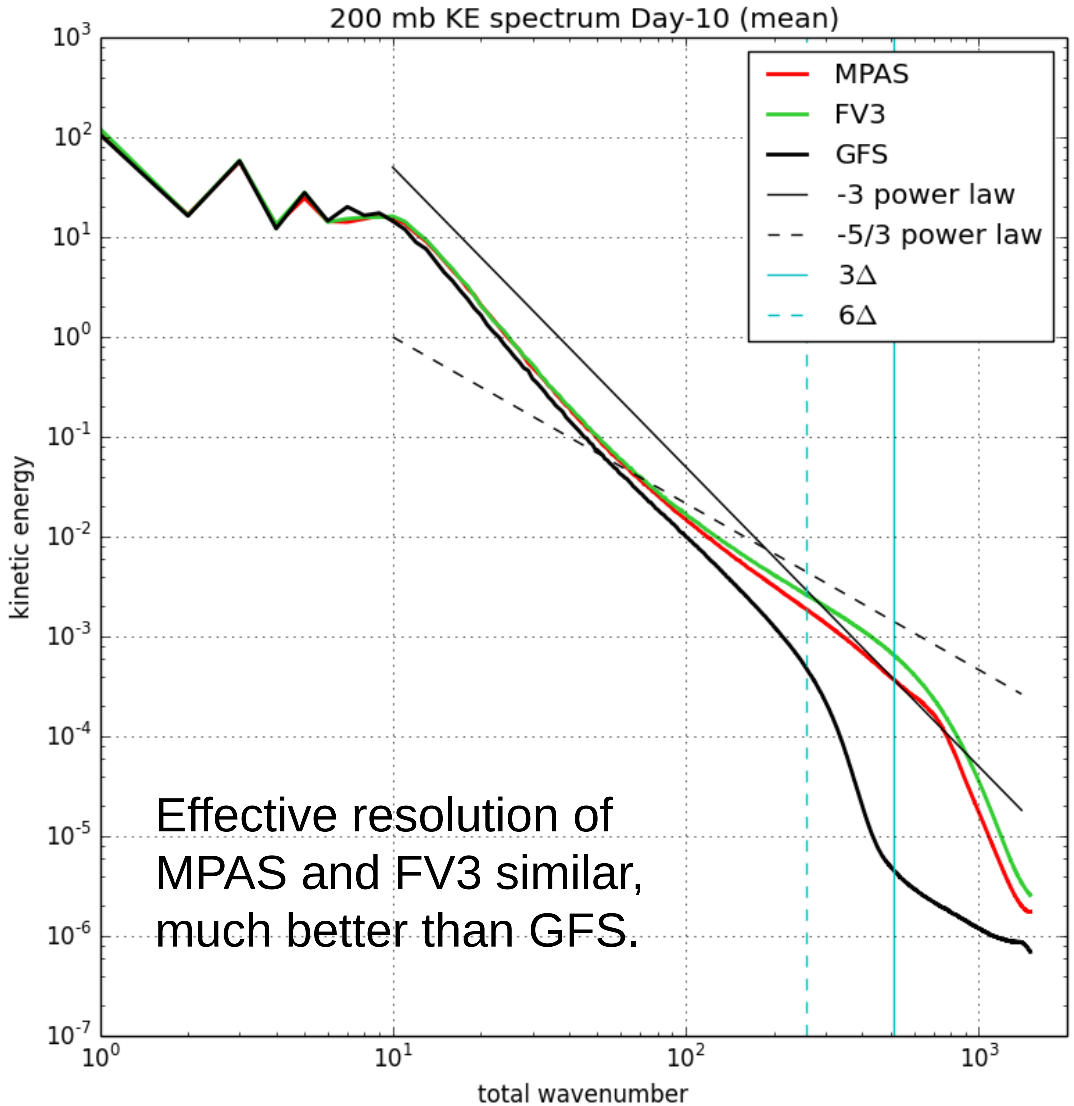


FV3 forecast skill matches the GFS using GFS ICs and GFS Physics

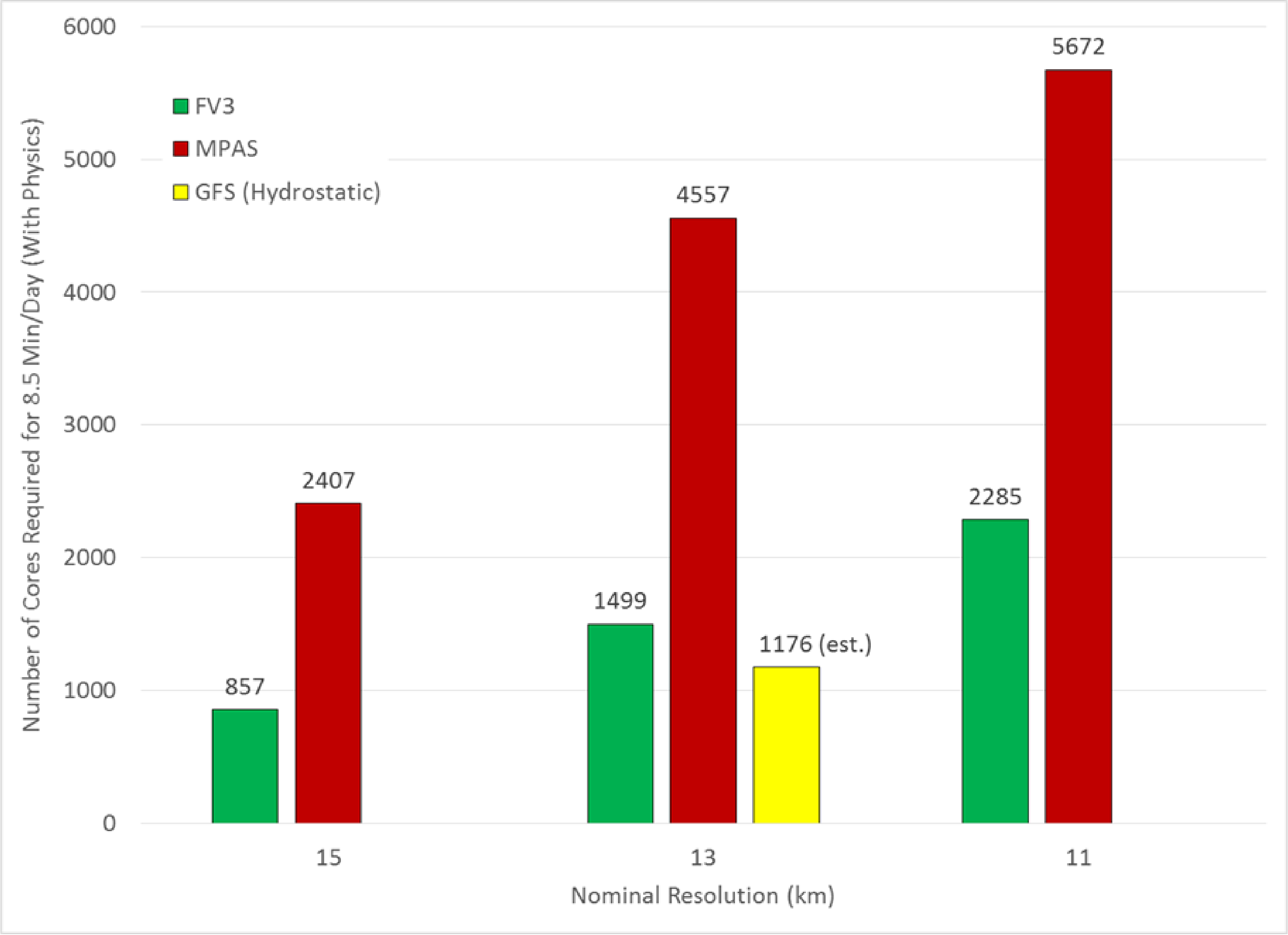
#4: Performance Benchmark: Methodology

- GFS physics runs with double (64b) floating point precision
- Configurations same as for retro forecasts
- 3 nominal resolutions: 15 km, 13 km, 11 km; 63 levels (so differences in effective resolution could be accounted for). Benchmark parameters agreed to by NCAR and GFDL
- Dedicated access to Cori system at NERSC (similar to Luna/Surge); runs conducted on otherwise empty machine
- Metric: Number of processors required to achieve 8.5 minutes per day simulation rate
- Multiple runs varying numbers of processors to straddle 8.5 min/day simulation rate
- Also tested were:
  - Efficiency of mesh refinement strategies (using configuration for criteria #5)
  - Performance with 15 and 30 extra tracers

#4 Performance Benchmark: KE Spectra (Effective Resolution)



#4: Performance Benchmark Results (J. Michalakes)



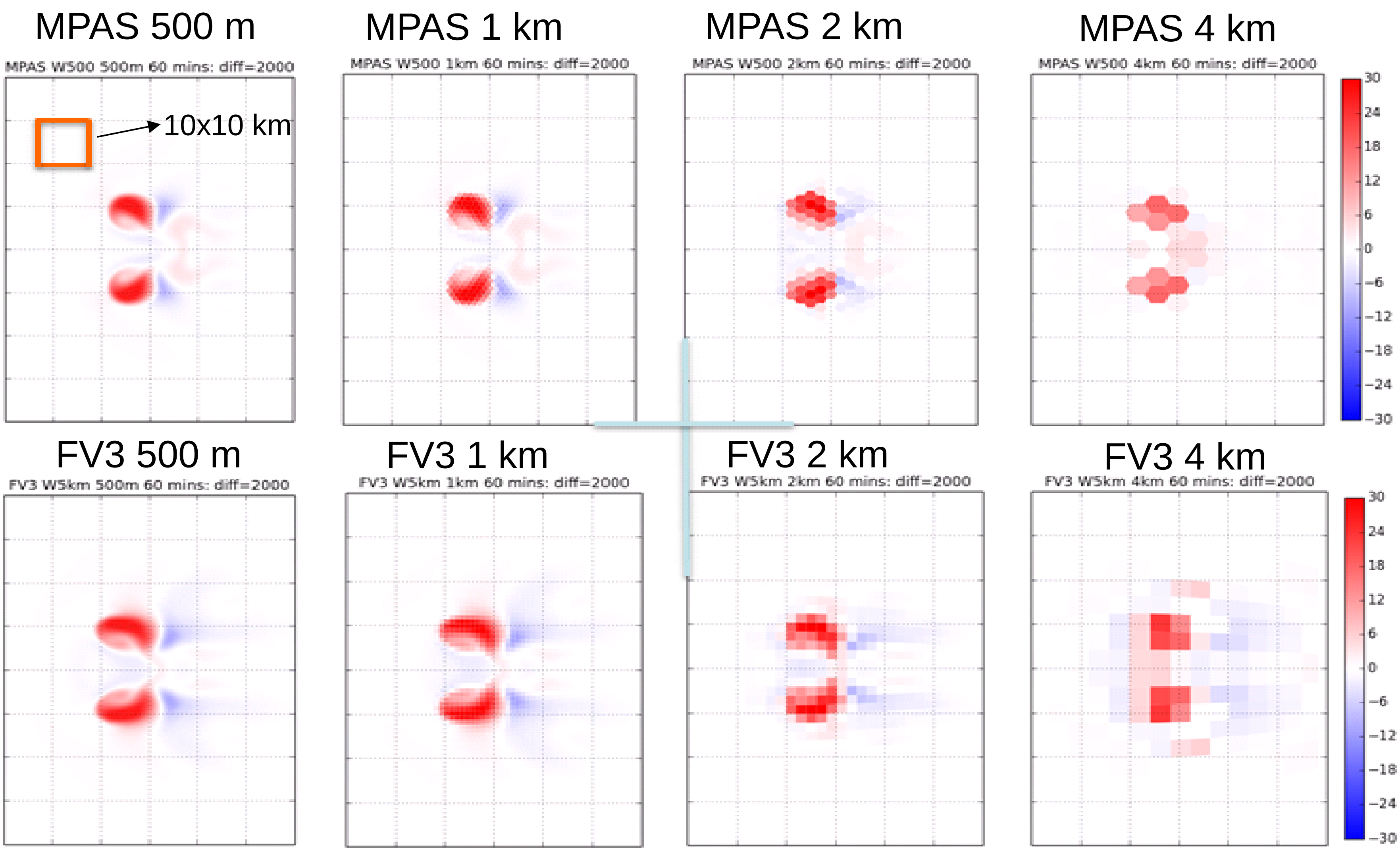
#5: Demonstration of Variable Resolution and Nesting Capabilities

Includes simulations of convection in the high-resolution region, and includes supercell and tropical cyclone (TC) idealized tests

- Real-data forecasts:
  - Mesh varies from 13 km to 3 km over CONUS
  - GFS physics with deep convection disabled
  - Initial conditions for 2013051800 (Moore tornado) and 2012102418 (Hurricane Sandy), forecasts run to 10 days
  - MPAS used a non-uniform mesh, FV3 used a combination of a global stretched grid and a nest
- Idealized tests:
  - Since cases chosen involve severe convection and tropical cyclones, companion idealized tests used to isolate impact of dynamical core on simulations of these phenomena (with highly idealized physics and no mesh refinement)
  - Supercell test (DCMIP-2016, reduced sphere 0.51/2/4 km) also run in Phase I, but not with identical diffusion settings
  - TC test from DCMIP-2012 (full sphere, 13 km)

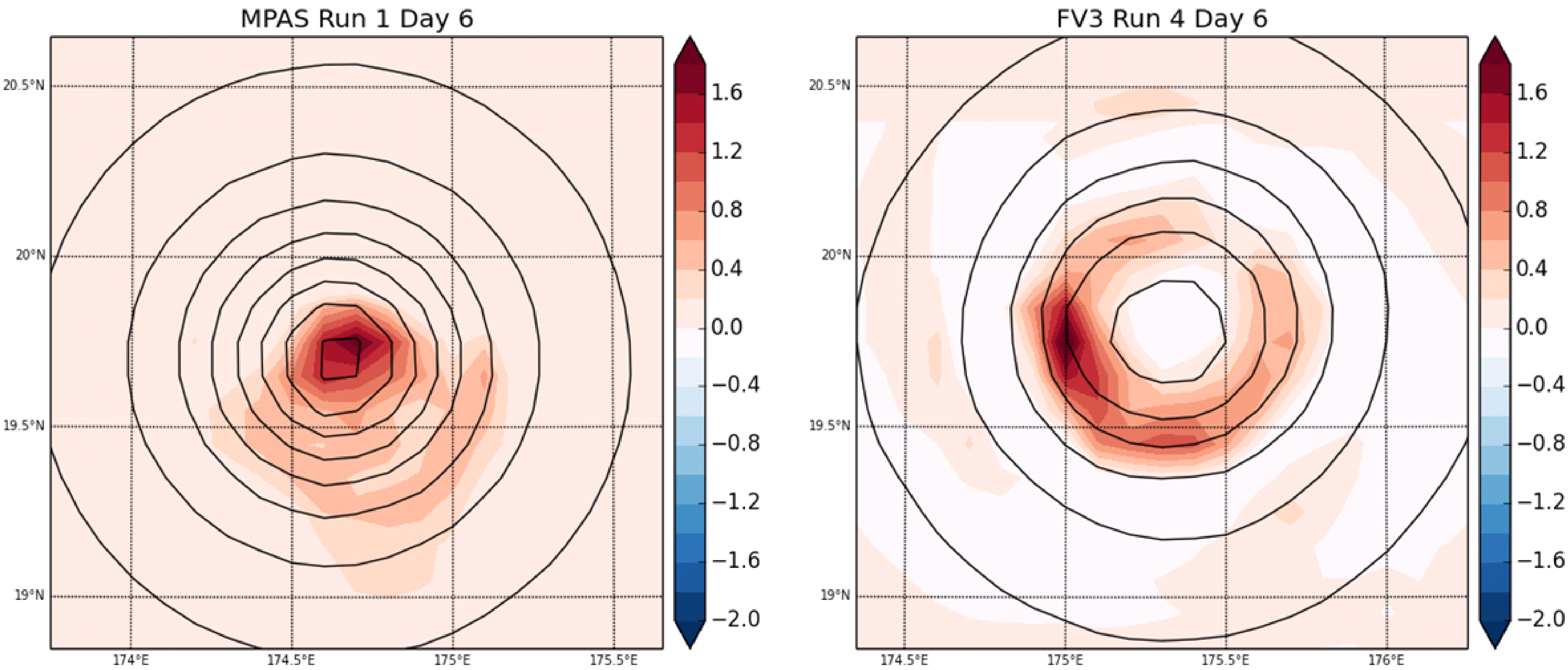
#5: Idealized Supercell Test

500 hPa Vertical Velocity (m/s), All Resolutions



#5: Idealized TC Test

MSLP (black lines), 500hPa Vertical Velocity (color, m/s)



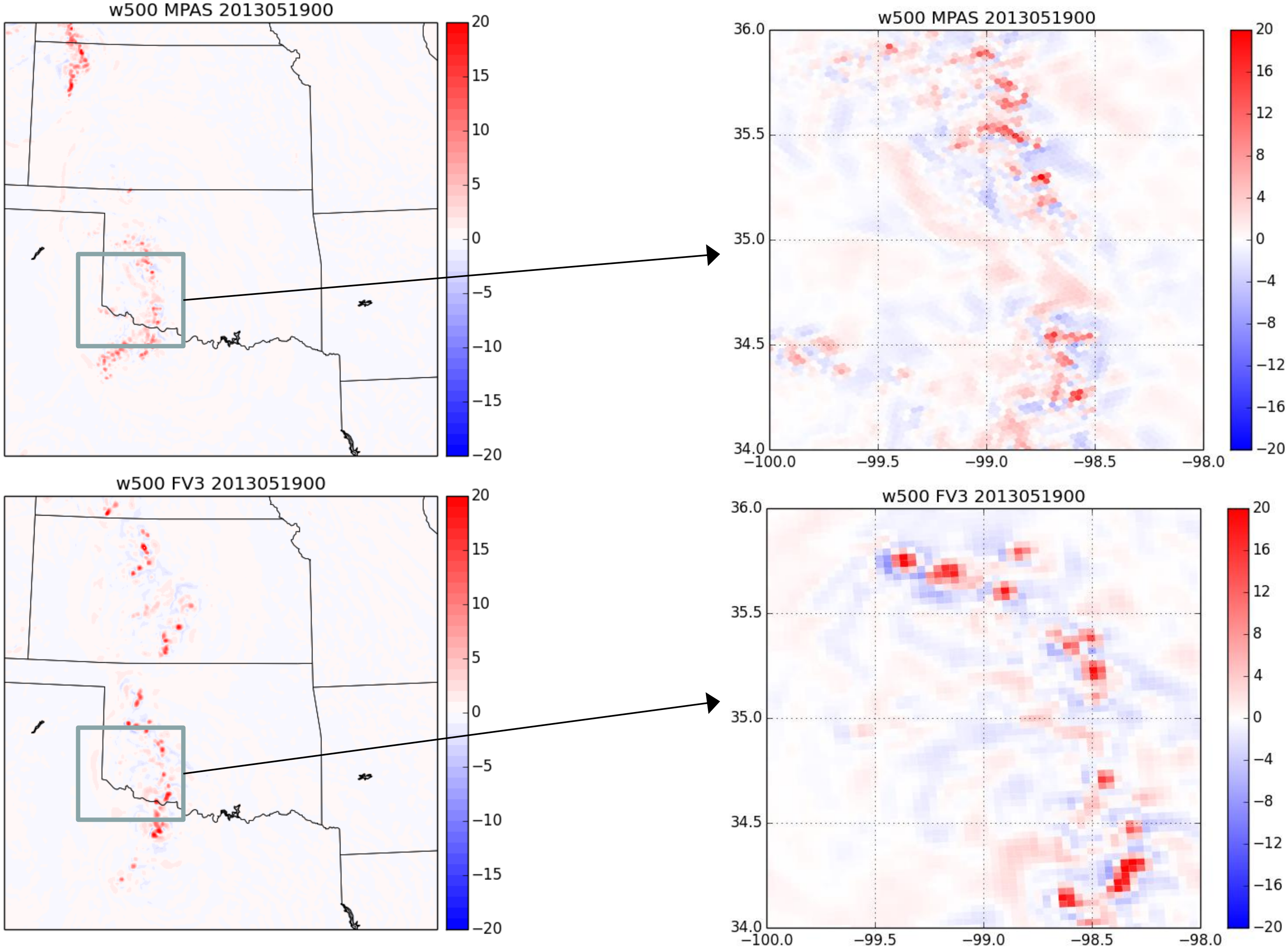
MPAS updraft is maximum in center of storm – no local minimum in eye.
FV3 updraft is still concentric, with subsidence in eye.

***MPAS real-data TC simulations did not have this structure.**

#5: Variable Resolution Tests

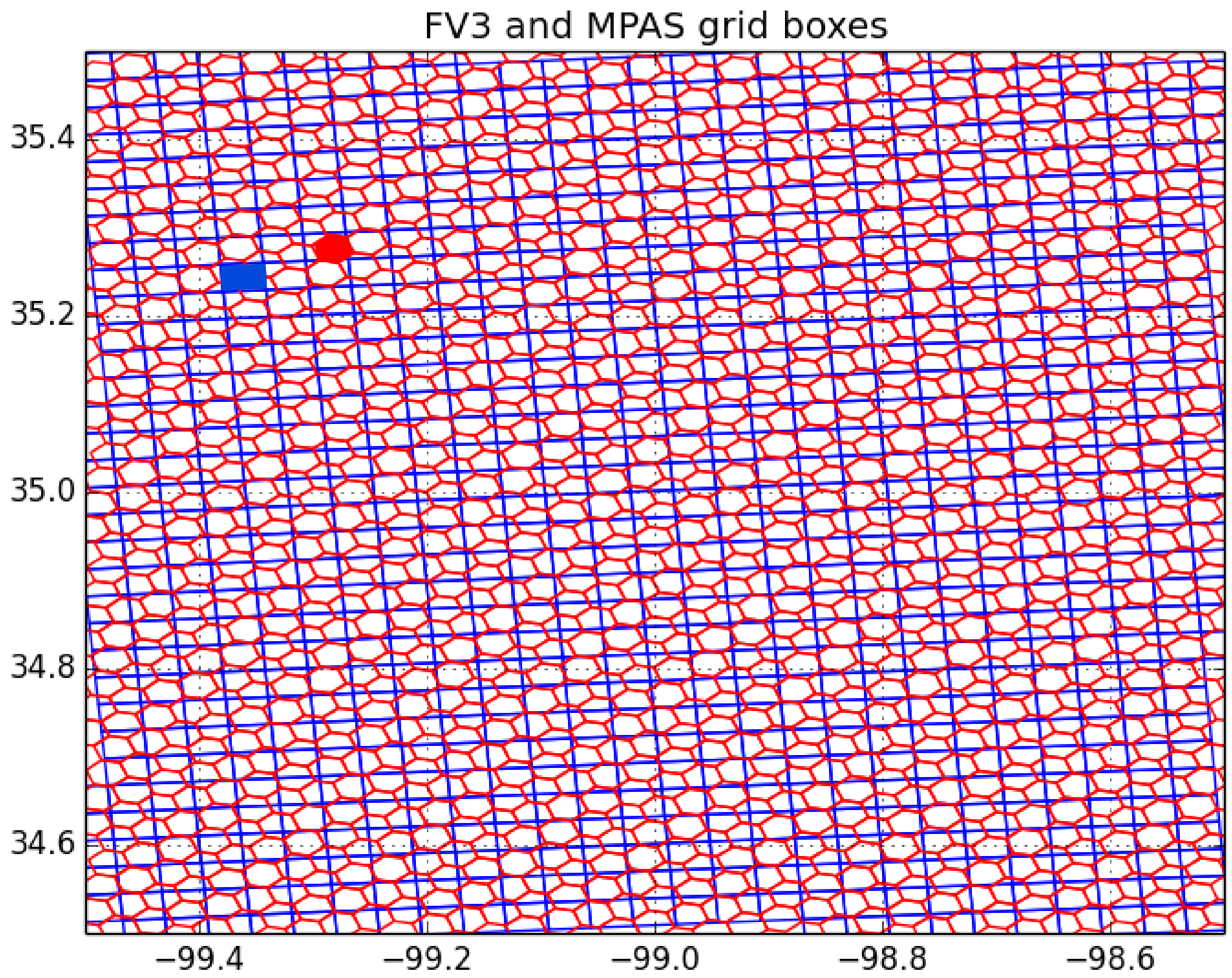
Moore Tornado Case – 24h Fcst Valid 00UTC May 19

500hPa Vertical Velocity (m/s)



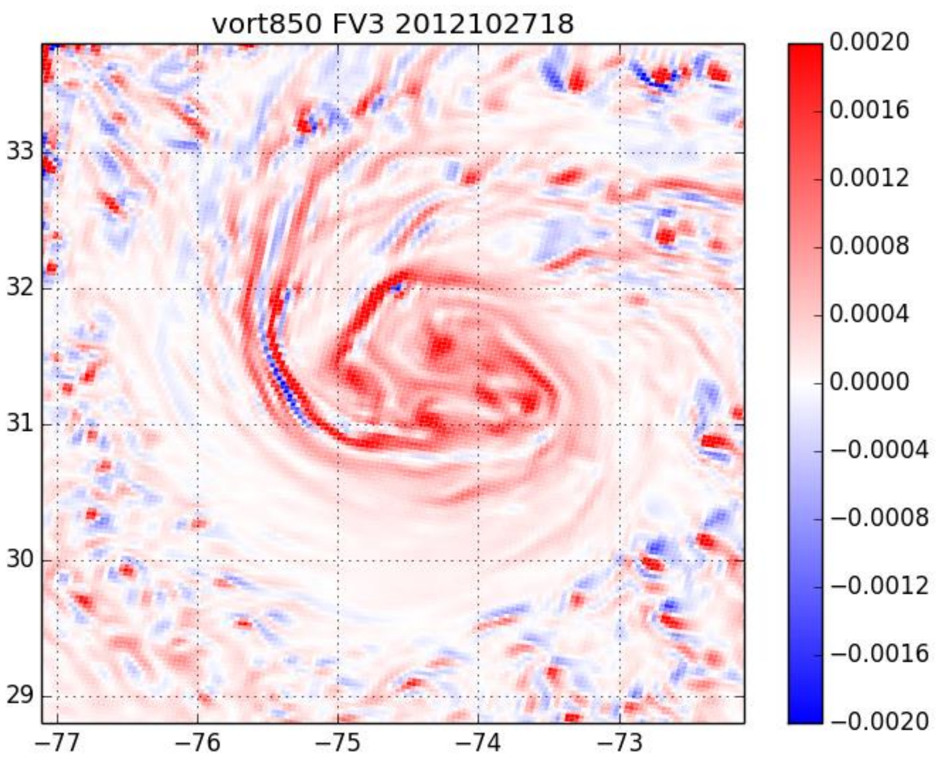
#5: Variable Resolution Tests: Grid Structure in Region of Interest

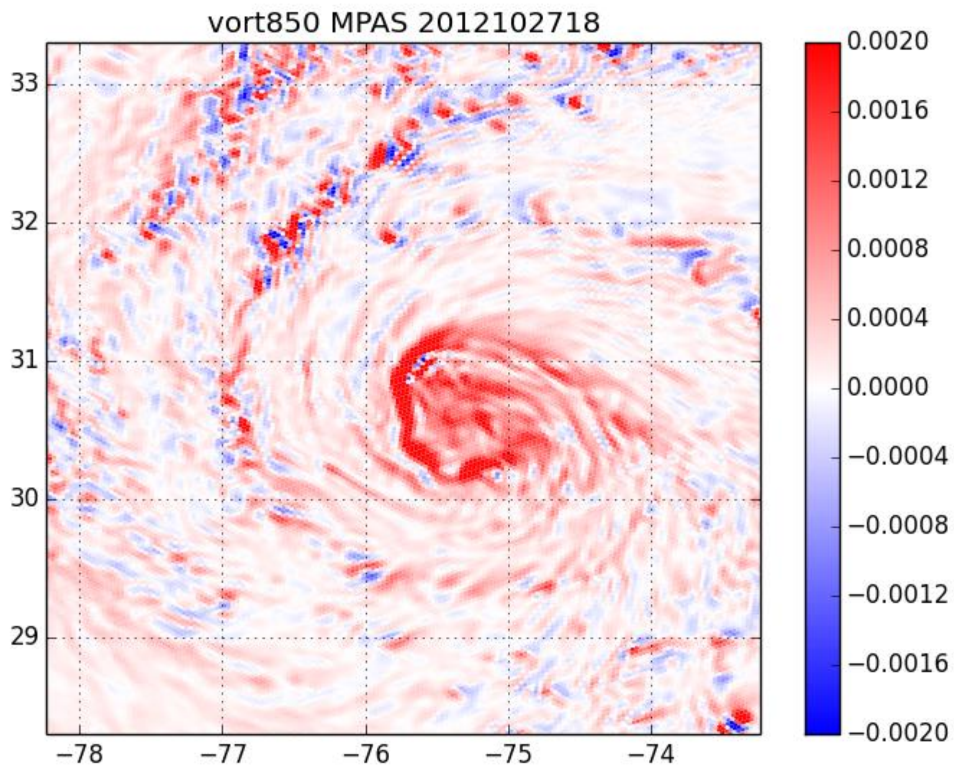
MPAS grid cells (red) are smaller in the region of interest



#5: Variable Resolution Tests:

Hurricane Sandy Case: 72h Fcst Valid 18 UTC Oct 27
850 hPa Vertical Vorticity (s^{-1})

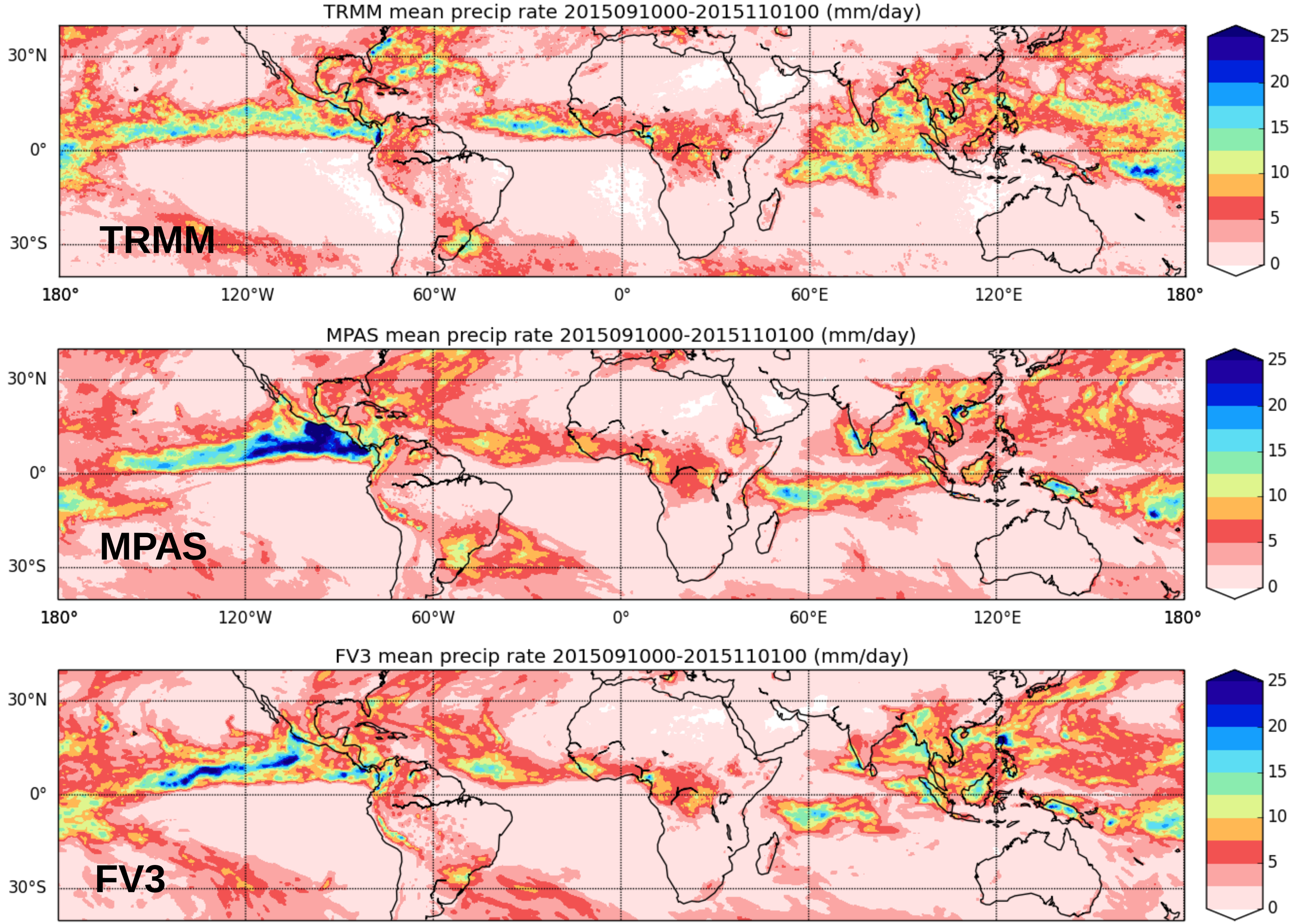




#6: Stable, Conservative Long Integrations with Realistic Climate Statistics

- 90 days runs at reduced resolution (~50 km), from GFS 00UTC Sep 1 2015 analysis, with surface conditions updated every 6 hours
- Assessment will include:
  – 90-day mean statistics
  – Time series of dry mass, energy
  – Detection of 'grid imprint'
- ***Runs are in progress, results are preliminary***

#6: Stable, Conservative Long Integrations with Realistic Climate Statistics (in progress, preliminary) Day 10-60 Mean, IC 2015090100, ~50 km Resolution



Criteria #7 and #8

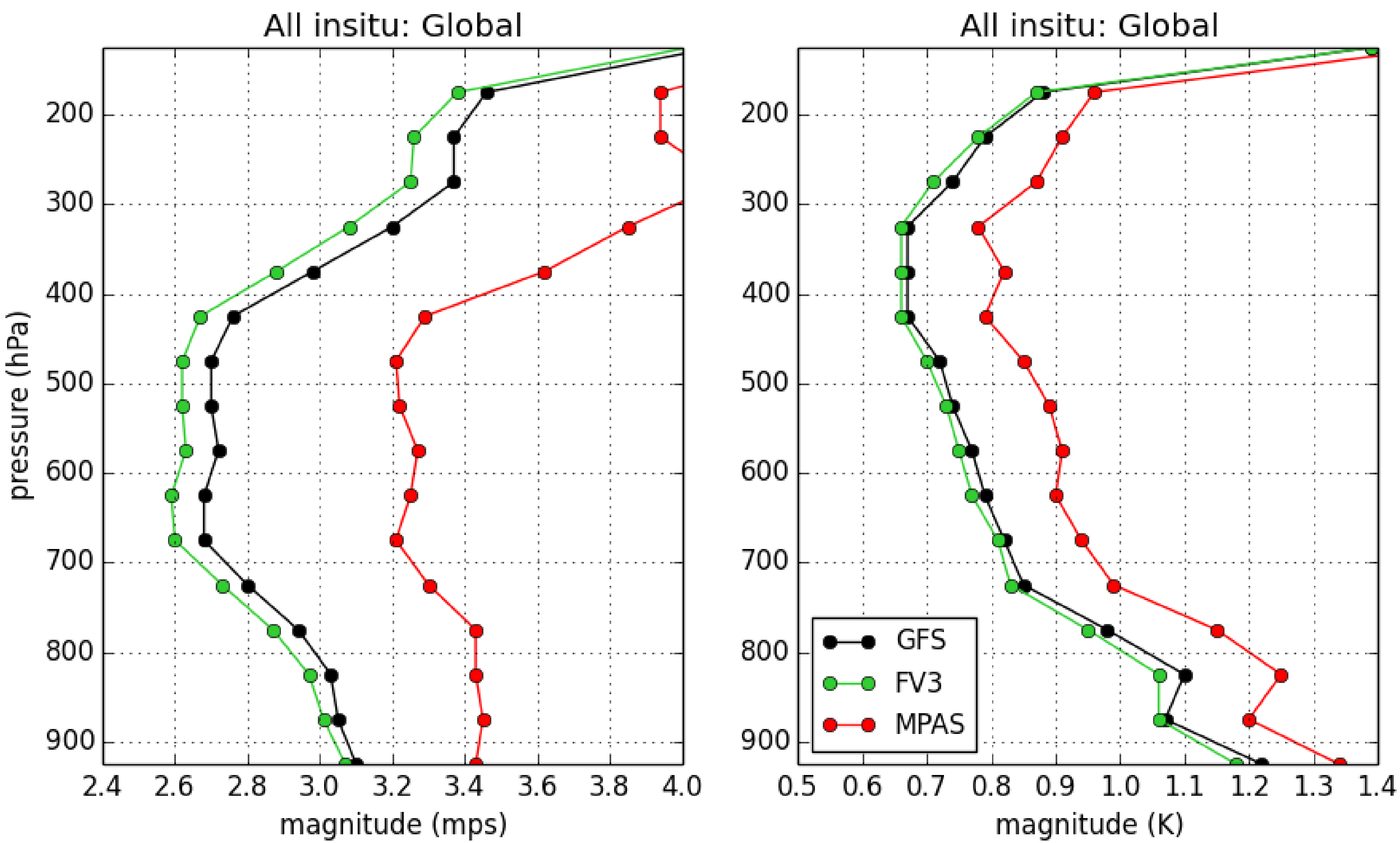
- **#7: Code adaptable to NEMS/ESMF**
  - **Self-reporting on questionnaire from EMC. GFDL completed (no issues) / NCAR incomplete**
- **#8: Detailed dycore documentation**
  - **Complete – Both dycores sufficiently documented for Phase 2 evaluation (but more will be needed for community model environment)**

#9: Evaluation of Performance in Cycled Data Assimilation (DA)

- Both models interfaced to operational 4D ensemble-variational DA system
- Due to time and HPC constraints, tests run at reduced resolution (~50 km)
- 80 member ensemble, cycle started at 2015090100 (***In progress, results are preliminary***)
- Differences with operational configuration:
  - No high-resolution control analysis
  - No static background error component (full ensemble used to maximize feedback between dycore and DA)
  - No digital filter or tangent-linear balance constraint
  - No stochastic physics in ensemble (multiplicative inflation increased to compensate)
- Baseline GFS experiment at T382 resolution for reference
- Assessing:
  - Work required to replace spectral dycore in GDAS
  - Whether issues arise that may not be evident when models initialized from ‘foreign’ analysis

#9: DA Cycling: RMS Fit of First-Guess to All In-situ Observations
(in progress, preliminary)

Vector Wind (left) and Temp (right) O-F (2015090500-2015092618)



#10: Implementation Plan - Costs

Initial Implementation (transition to operations) Cost in FTEs (in addition to existing personnel managing O&M for operational GFS)

Activity	FY17		FY18		FY19		FY20		Total	
	MPAS	FV3	MPAS	FV3	MPAS	FV3	MPAS	FV3	MPAS	FV3
Dycore integration into NEMS	3	3	2	2	2	2	2	0	9	7
Physics implementation	2	1	2	1	1	1	1	0	6	3
Physics Driver implementation	1	1	2	1	1	1	1	0	5	3
DA integration	4	2	3	2	3	2	2	0	12	6
Pre/Post	2	2	2	2	1	1	1	0	6	5
Benchmarking	0	0	4	3	4	4	5	0	13	7
Code Management	2	2	2	2	2	2	2	2	8	8
Computational efficiency	2	1	2	1	2	1	2	0	8	3
Transition to operations	0	0	0	0	0	3	3	0	3	3
Total	**16**	**12**	**19**	**14**	**16**	**17**	**19**	**2**	**70**	**45**

Computer Resource Requirements for Initial Implementation (FY17-FY19 for FV3 and FY17-FY20 for MPAS)

	CPU*	CPU Hours**	Disk	Period	% change w.r.t. GFS
GFS	5,150,880	399,840	10 PB	FY17-FY18	0
FV3	6,565,620	509,660	30 PB (2 streams)	FY17-FY19	28%
MPAS	19,959,660	1,549,380	45 PB (3 streams)	FY17-FY20	288%

***CPU* = Y x 4 cycles x 365 days x 3 years, Y is number of cores required for 8.5 min/day**

Y = 1176 (GFS), 1499 (FV3), 4557 (MPAS) based on current operational resolution (~13 km). 1176 1499 4557

Computational requirements for intended implementation configuration TBD

****CPU hours = Y x 8.5 min/day x 10 days x 4 cycles**

HPC resources for Data Assimilation is not included

Availability of computational resources will require development/testing of FV3 in two parallel streams while MPAS would require three parallel streams

Summary

Implementation Costs (Human Resources) for MPAS are 55% more compared to FV3

Implementation Costs (computational resources) for MPAS are 204% more compared to FV3

Summary of Phase 2 Test Results

- Testing yielded sufficient information to evaluate both dynamic cores and produce a low risk recommendation without compromising performance or skill
- Summary of results:
  - Computationally, FV3 is more than twice as fast as MPAS with equivalent resolution
  - FV3 performs comparable to the GFS in cycled data assimilation test (without tuning, at reduced resolution), MPAS performance inferior to GFS
  - Effective resolution for both dynamic cores is found to be similar, and higher than GFS
  - Full forecast experiments with GFS initial conditions and GFS physics showed significant differences between FV3 and MPAS, FV3 almost equivalent to GFS (some stability issues with MPAS forecasts)
  - Supercell tests showed subjectively similar results for both dynamic cores
  - MPAS has unresolved issues in TC and conservation tests

NGGPS Phase 2 Testing Dycore Technical Assessment

Technical Readiness for Operations	MPAS	FV3	Comments
- Computational Performance with GFS Physics	🔴	🟢	FV3 Faster at Equal Nominal Resolution
- Cycled Data Assimilation	🟡	🟢	FV3 (MPAS) performance similar (inferior) to GFS
- Full Experiments w/ GFS Initial Cond's/Physics	🟡	🟢	FV3 as Accurate as GFS; MPAS Significantly Less
- Variable Resolution Testing (Moore Tornado, Hurricane Sandy)	🟡	🟡	Scale-aware Advanced Physics Needed for Either Dycore
- Deep Atmosphere Dynamics Plan/Implementation	🟢/🟡	🟢/🟡	Both Suitable
- Conservation	🟢	🟢	MPAS Less Stable in Tropics
- Supercell Test	🟢	🟢	Both Similar
- TC Simulation	🟢	🟢	Issues with MPAS TC Structure, Likely Related to Simple Physics Configuration
- Long Integrations with Realistic Climate Statistics	🟢	🟢	In Progress/Preliminary
- Next Generation Computing Suitability/Readiness	🟢	🟢	
- NEMS/ESMF Readiness	N/A	🟢	MPAS Incomplete

Technical Readiness:
- 🔴 (Extensive Development Required)
- 🟡 (Modest Level of Development Required)
- 🟢 (Little Additional Development Required)

NGGPS Phase 2 Testing Dycore Cost Assessment

	MPAS	FV3	Comments
Initial Implementation Into Global Forecast System	$ (red)	$ (green)	
- Personnel	$ (red)	$ (green)	
- HPC	$ (yellow)	$ (green)	
Implementation into CFS/GEFS	$ (yellow)	$ (green)	
- Personnel	$ (yellow)	$ (green)	
- HPC	$ (yellow)	$ (green)	
DA	$ (yellow)	$ (green)	
WAM	$ (yellow)	$ (yellow)	

Cost: Low: $ (<1M) Moderate: $ (1-5M) High: $ (>5M)

NGGPS Phase 2 Testing Dycore Risk Assessment

	MPAS	FV3	Comments
Implementation for GFS Global Application	🔴	🟢	
- Technical Performance (Exceeds Current System)	🔴	🟢	
- Schedule (By June 2019)	🔴	🟢	
- Cost Risk (Within Budget Target)	🔴	🟢	
- Computing (Within Available Computing Resources)	🟡	🟢	
Suitability for Future GEFS and CFS Application	🟡	🟢	
Suitability for Future Non-Hydrostatic Applications	🟢	🟢	
Community Modeling	🟢	🟡	
Overall	🔴	🟢	

Risk: Low: 🟢 Moderate: 🟡 High: 🔴

DTG Assessment

The overarching goal of NGGPS is to develop the World's best global numerical weather prediction guidance. FV3's heritage in global applications is a strength, and the test results suggest that FV3 can have cost effective, positive impacts on global products in a relatively short amount of time. The test results have not revealed any deficiencies with FV3 to preclude the representation of convective storms. For MPAS, the test results suggest that the extension to NCEP's global application suite will require more time to provide comparable product quality and the computational costs will be higher.

– Statement of DTG

Summary and Conclusions

- The FV3 Core represents the lowest risk, lowest cost alternative for the new NGGPS atmospheric model
- Adopting FV3 core brings with it a dynamic, vibrant community
  - GFDL is a world-class organization in Global Modeling Applications for Weather and Climate
  - GFDL is a willing partner to the NWS in advancing operational Global weather modeling applications
  - Other Agencies/Entities using Finite Volume Core include NCAR (CESM), NASA (GEOS/GISS), Harvard (GEOS-Chem), Columbia Univ. (pollution studies), U. of Washington (Dale Durran), Chinese Academy of Sciences (IAP), Germany (ECHAM5), Japan (MIROC)
- Integration of FV3 with Common Community Physics Package and GMTB can support interaction with convective weather modeling community
- From the beginning, the NGGPS strategy has been to find and implement the best global model (unification at regional scales/picking the best convective model, while desirable, has not been an objective of NGGPS)
  - Nothing in results precludes eventual global-regional unification based on FV3

DTG Findings

Implementation of the FV3 core into the Global Forecast System to replace the Global Spectral Model represents a high-quality, cost-effective, low-risk option towards implementing a new NGGPS global forecast model

- Compared to the MPAS, FV3:
  - Meets all technical needs
  - Less expensive to implement
  - Higher readiness for implementation
  - Significantly better technical and computational performance
  - Lower risk

Phase 2 Test Results

- Information on NGGPS dycore testing is available at:

  http://www.weather.gov/sti/stimodeling_nggps_implementation_atmdynamics

  - Testing results will be made public at this site as available and on approval by the DTG/Program Manager

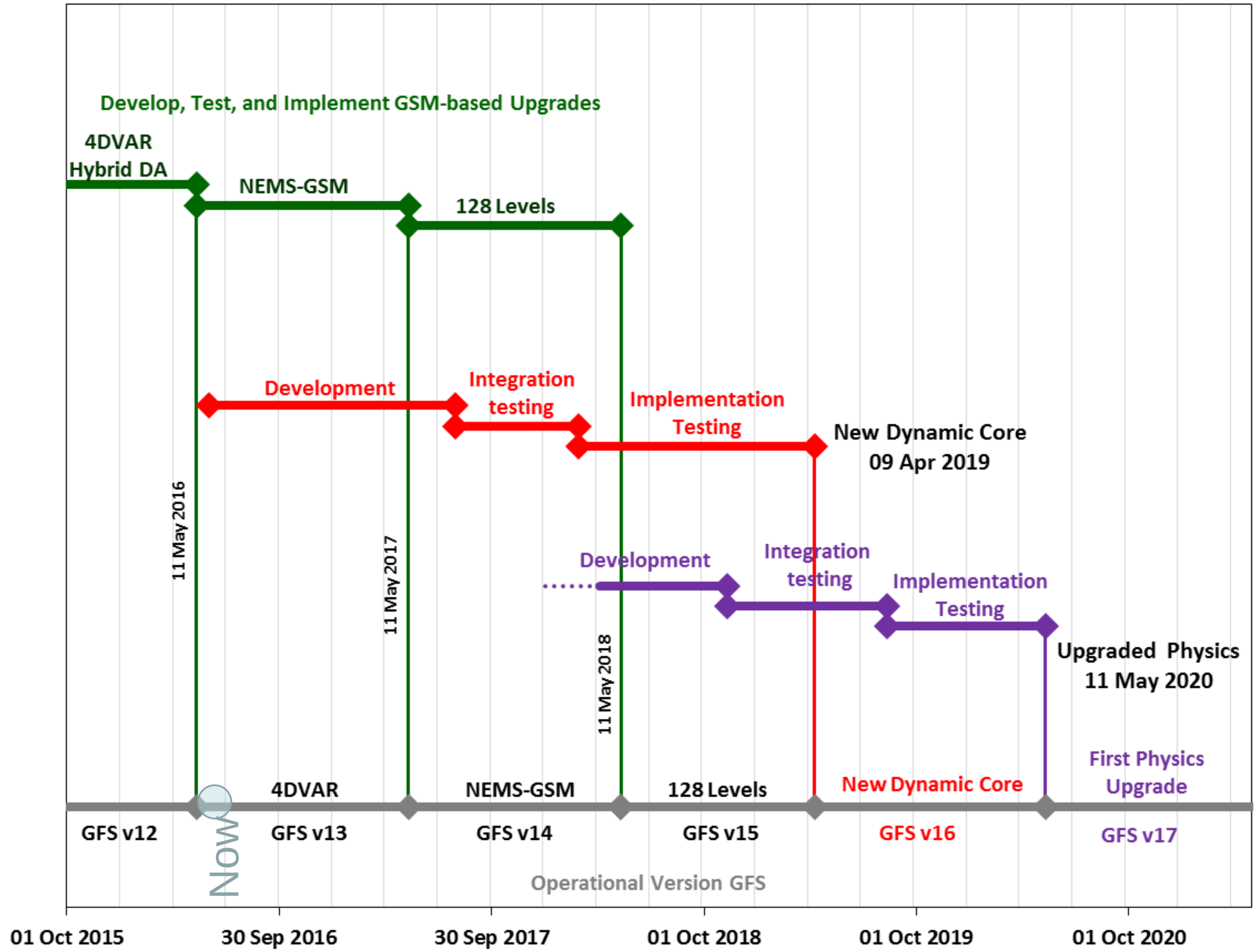
Questions?

NGGPS Website:

http://www.weather.gov/sti/stimodeling_nggps

Back-Up Slides

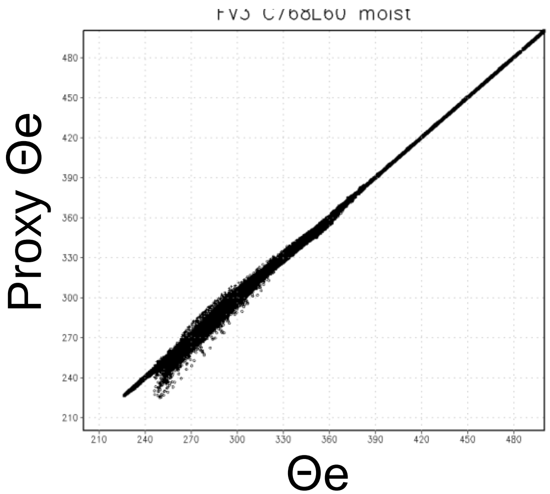
GFS Development and Operational Upgrade Plan



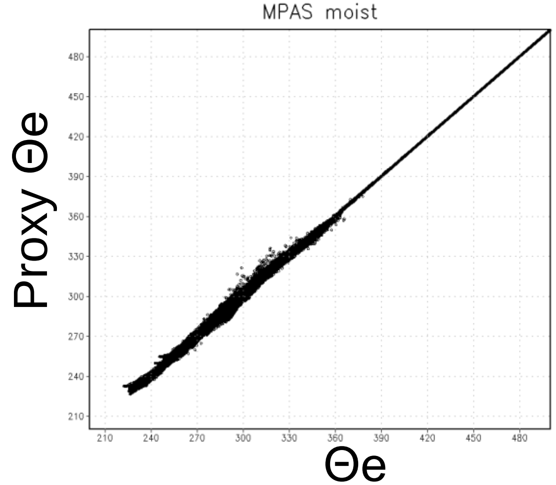
Detailed Phase 2 Test Results

#2: Conservation Test: RMS Difference Between Advected Tracer and Dynamical Field (Day 15)

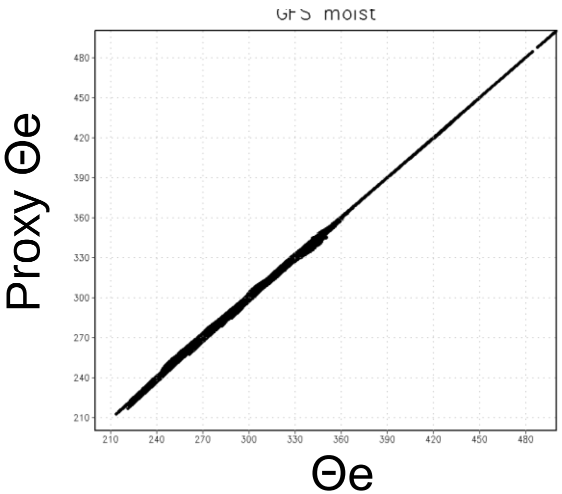
FV3 RMS=0.232



MPAS RMS=0.126



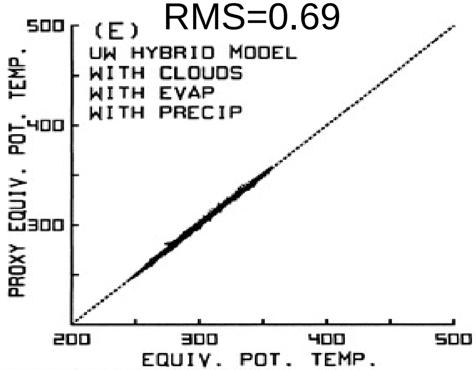
GFS RMS=0.202



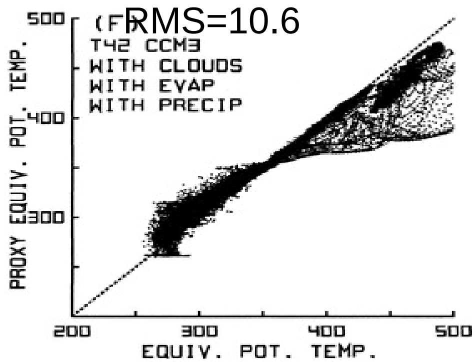
Scatterplots of Θe and proxy Θe (tracer) at day 15 for the moist baroclinic wave (DCMIP test 4.2). Compare with Figure 1 of Johnson et al. 2000.

FV3, GFS and MPAS are similar, much better than CCM3 result from Johnson et al.

UW
RMS=0.69

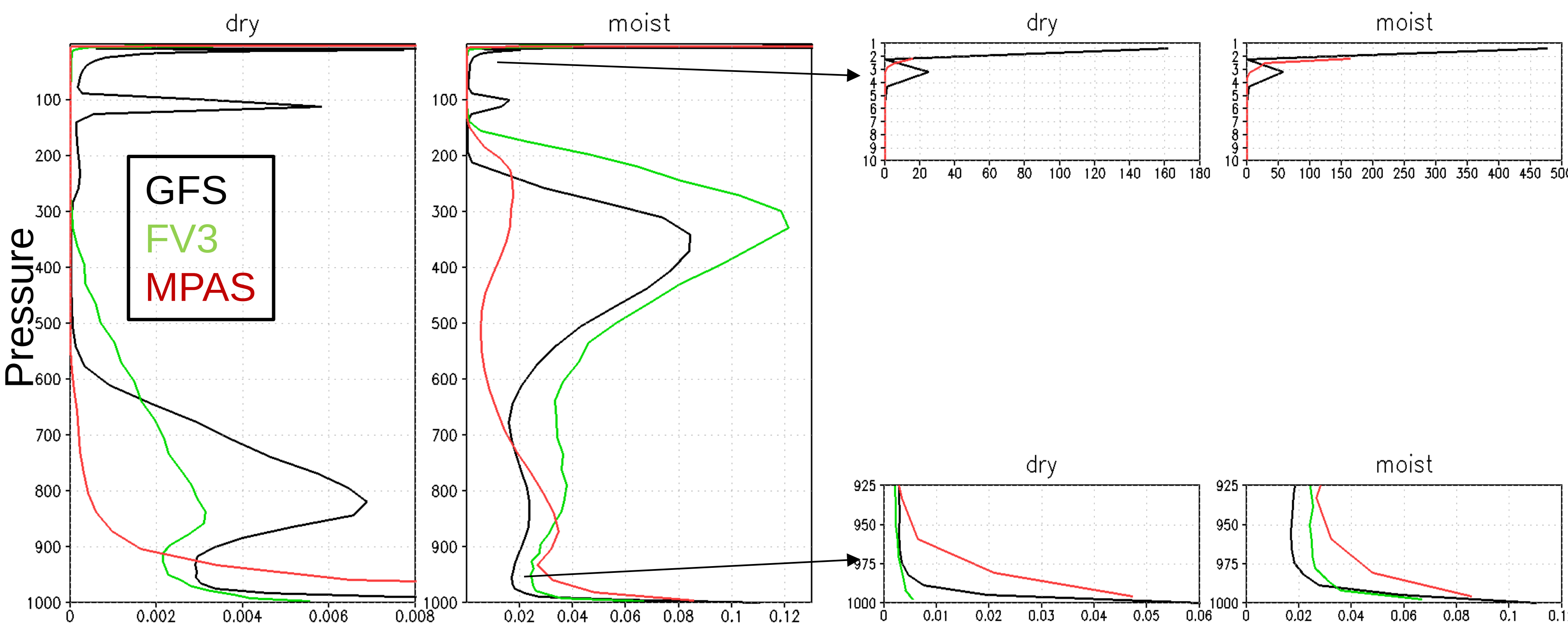


CCM3
RMS=10.6



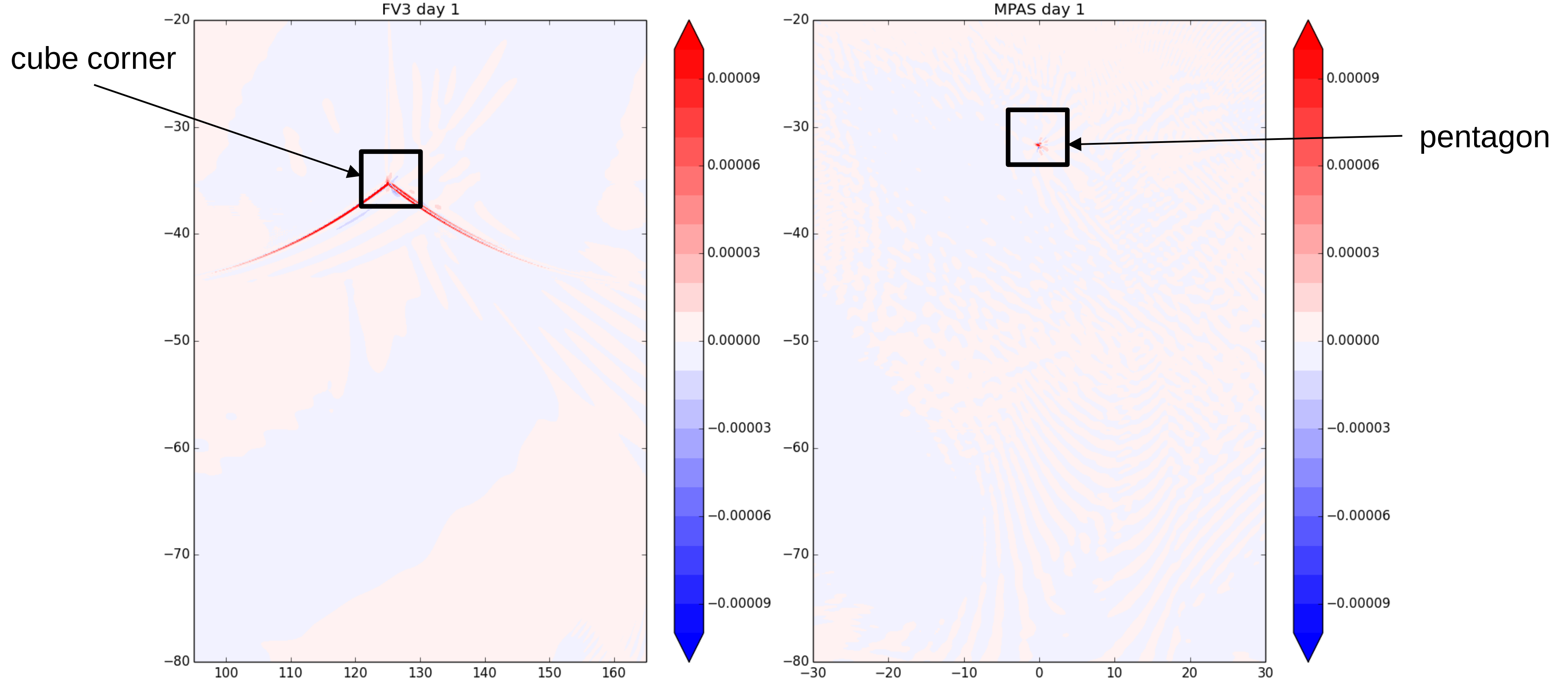
Day-10 scatter plots from Johnson et al. 2000

#2: Conservation Test: RMS Difference Between Advected Tracer and Dynamical Field (Day 15)

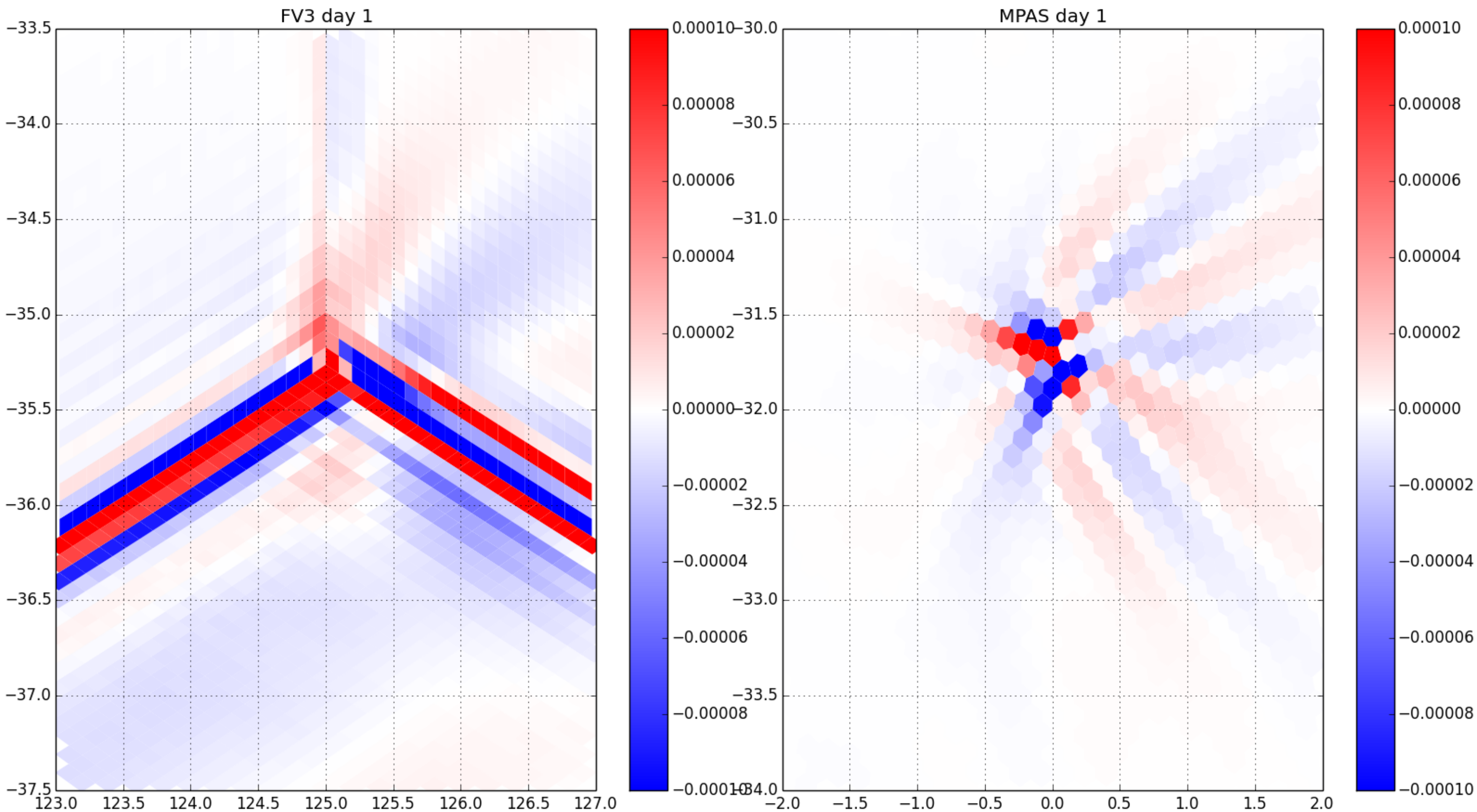


Global average RMS difference between prognostic equivalent potential temperature and tracer equivalent potential temperature calculated for each model level. Insets on right show detail at lower and upper levels of model, note that x-axes scales are much larger in insets.

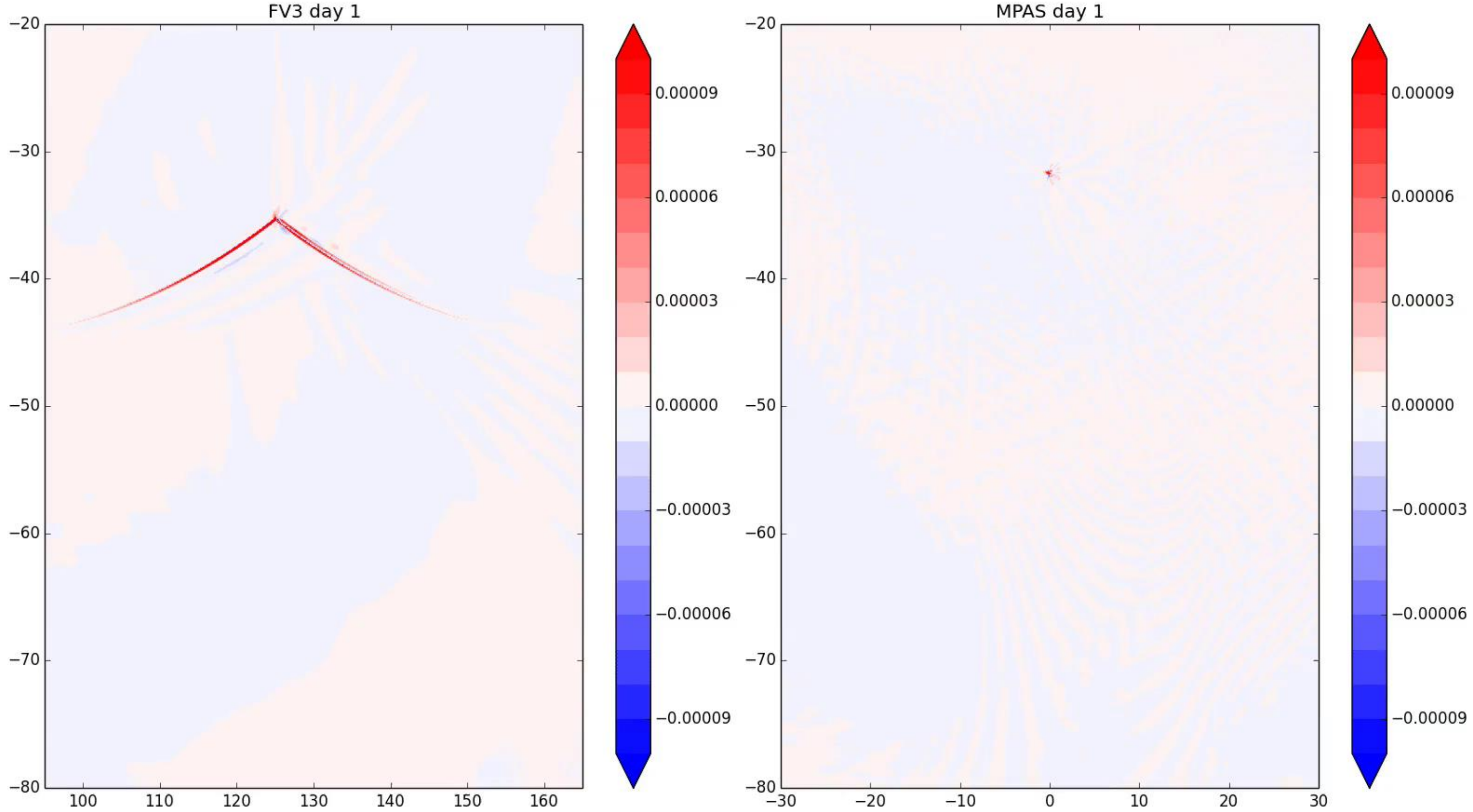
#2: Conservation Test Case (Grid Imprint Assessment): *Dry Case* (Southern Hem) Vertical Velocity at Lowest Level, Day 1 (Zonal Mean Removed)



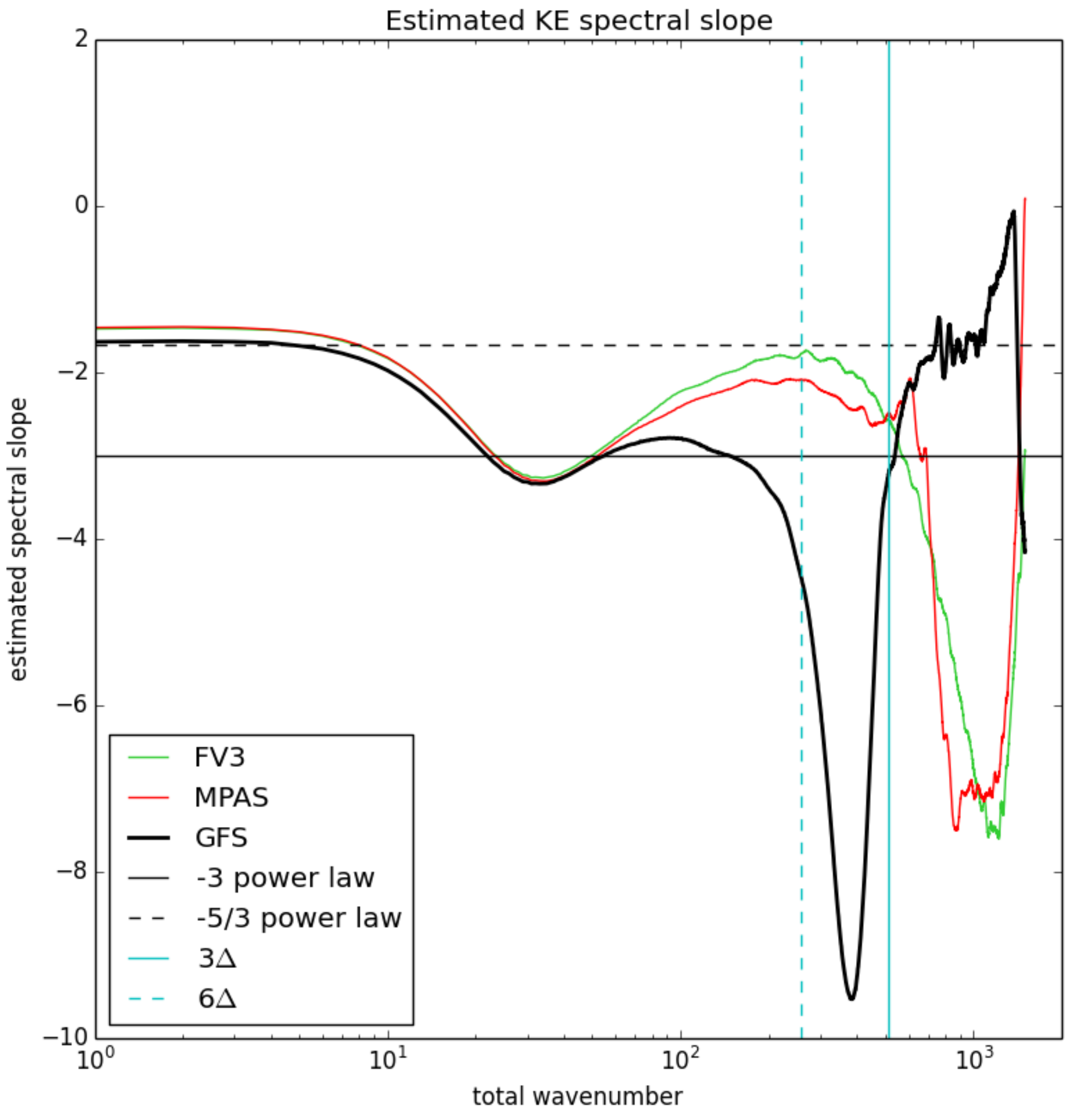
#2: Conservation Test (Grid Imprinting Assessment): Zoom-in on Cube Corner, Pentagon (Level 1 w)



#2: Conservation Test (Grid Imprinting Assessment): Animation of Level 1 w



#4: Performance Benchmark Results: Estimated Spectral Slope



#4: Performance Benchmark Results: Configurations

Eval. Criterion #4 -- Performance with GFS Physics	FV-3	MPAS
Nominal resolution (km)	13.03 (equat.), 12.05 (avg.)	13
Grid Points	3,538,944	3,504,642
Vertical Layers	63	63
Time Step (sim. sec)	112.5 (dyn.), 18.75 (acous.)	75 (transport), 37.5 (dynamics), 18.75 (acoustic)
Radiation Time Step	3600	3600
Physics (other) Time Step	225	225
Tracers	3	3

Coarser than nominal resolution (km)	15.64 (equat.), 14.46 (avg.)	15
Grid Points	2,547,600	2,621,442
Vertical Layers	63	63
Time Step	225 (dyn.), 22.5 (acous.)	90 (transport), 45 (dynamics), 22.5 (acoustic)
Radiation Time Step	3600	3600
Physics Time Step	225	180

Finer than nominal resolution (km)	11.72 (equat.), 10.34 (avg.)	11
Grid Points	4,816,896	4,858,092
Vertical Layers	63	63
Time Step	112.5 (dyn.), 16.07 (acous.)	60 (transport), 30 (dynamics), 15 (acoustic)
Radiation Time Step	3600	3600
Physics Time Step	225	180

#4: Performance Benchmark Results: Tracer advection performance

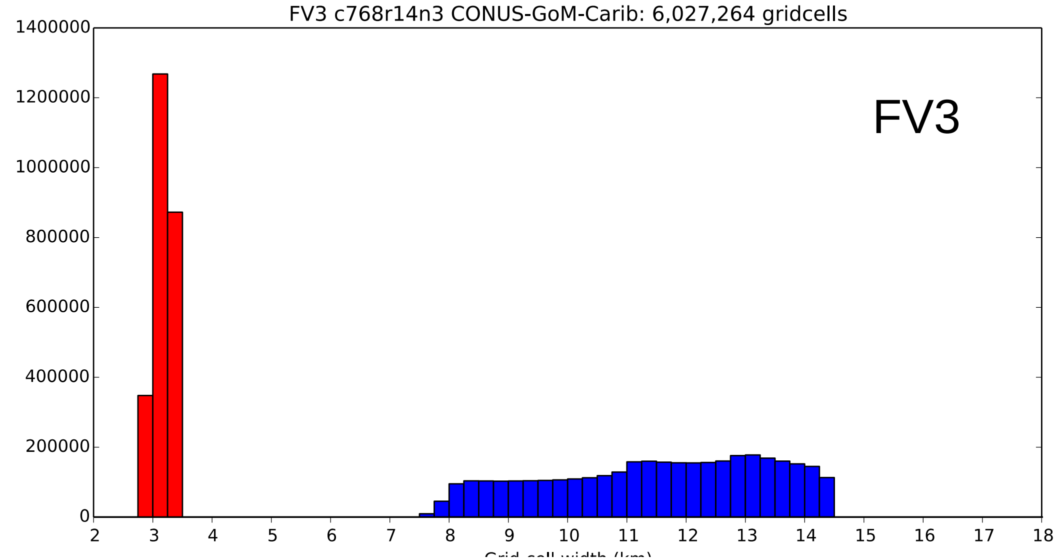
- Tracer advection benchmarks on Cori
  - Measure cost as a function of number of 3D tracer fields
    - Workloads and configuration:
      - 13 km case on number of cores needed for 8-8.5 min/day
    - Baseline: 3 tracer fields
    - Add 15 and 30 artificial tracers
  - Result: cost for full tracer load increased by factor of 2.5 for MPAS versus 1.53 for FV3 compared to baseline.

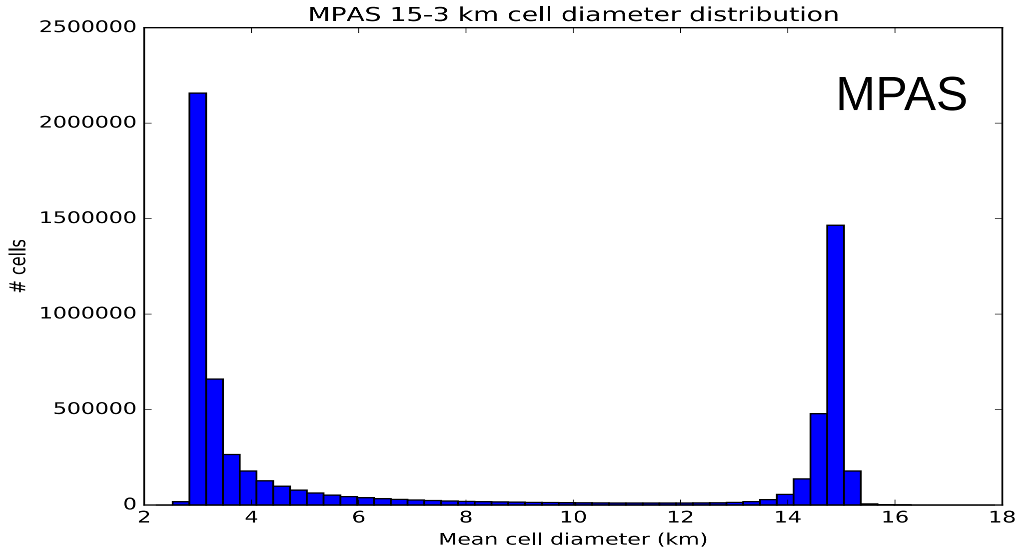
	Cores	Number of tracers / Minutes			Factor (lowest to highest)
MPAS	4800	3 / 8	18 / 14.6	33 / 19.8	2.5
FV3	1536	3 / 8.14	15 / 9.8	30 / 12.0	1.5 (1.53 adjusted)

Adjustment for FV3 workloads using 15 and 30 tracers **total** *instead of 15 and 30* **additional** *tracers per Test Plan.*

#4: Performance Benchmark Results: Refinement Configuration

Histograms of grid cell size





#4: Performance Benchmark Results: Refinement Efficiency

- Part of Criterion #5 evaluation
- How efficient is non-uniform at saving cost compared with uniform 3 km resolution on same number of processors?
- Benchmark and adjust for differences in resolution and area of refinement
- FV3's nesting scheme was more efficient than MPAS's in-place mesh refinement

Definition of nesting efficiency E:

a_g = area of domain (5.101e14 m^2)

a_h = area of refinement (FV3: 2.52e13 m^2 ; MPAS: 2.82e13 m^2)

$r = a_h / a_g$ fraction of domain at high resolution (for uniform res. Domain, r = 1)

dx_L = lowest resolution

dx_H = highest resolution

$C = r\,(dx_L / dx_H)^3\, C_{cellstep} + (1-r)\, C_{cellstep}$ *(C is "cost")*

$$S_{ideal} = \frac{(dx_L / dx_H)^3}{r\,(dx_L / dx_H)^3 + 1 - r} \quad \begin{matrix} \leftarrow C_{uniform} \\ \leftarrow C_{refined} \end{matrix}$$

(Note: $C_{cellstep}$ factors out)

$$S_{measured} = \frac{T_{uniform}}{T_{refined}}$$

$$E = S_{measured} / S_{ideal}$$

#4: Performance Benchmark Results: Refinement Efficiency (continued)

- Part of Criterion #5 evaluation
- How efficient is non-uniform at saving cost compared with uniform 3 km resolution on same number of processors?
- Benchmark and adjust for differences in resolution and area of refinement
- FV3's nesting scheme was more efficient than MPAS's in-place mesh refinement

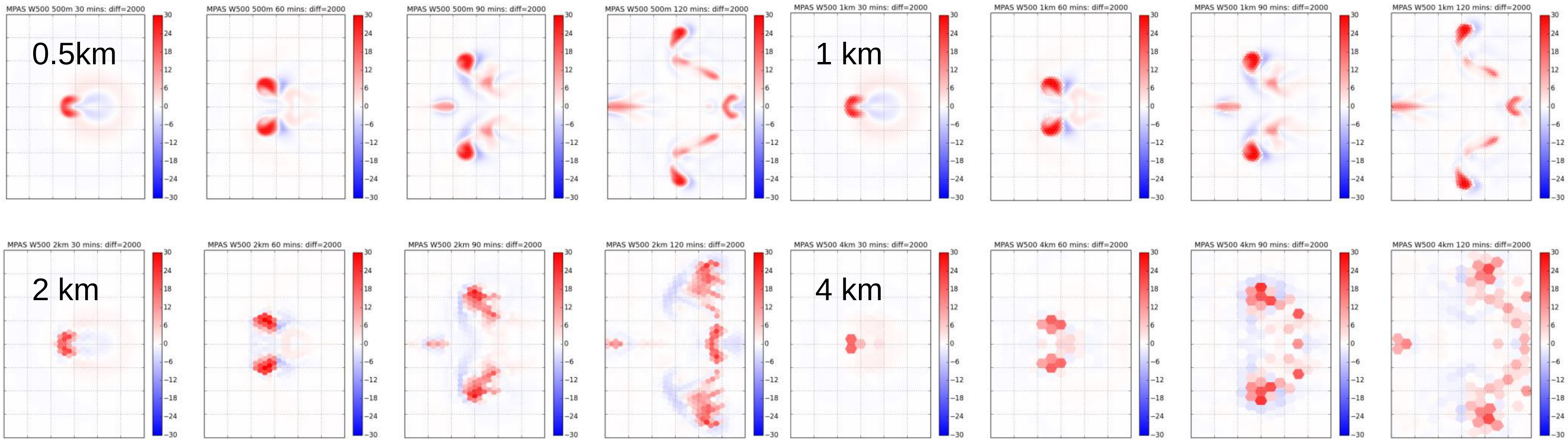
	FV3	MPAS
ag (global domain area m^2)	5.101E+14	5.101E+14
ah (high res area m^2)	2.52E+13	2.82E+13
percent of domain in high res r = ah/ag	4.94E-02	5.53E-02
dx low	14	15
dx high	3	3
dx l / dx h	4.67	5.00
(dx l / dx h) ^ 3	101.63	125.00
T-uniform (ideal)	101.63	125.00
T-reduced (ideal)	5.97	7.86
ideal speedup from refinement	17.02	15.91
T_uniform (measured)	345.93	344.65
T_refined (measured)	20.98	34.10
observed speedup from refinement	16.49	10.11
Efficiency	96.9%	63.5%

#5: Modifications to Phase 1 Supercell Test Case Configuration

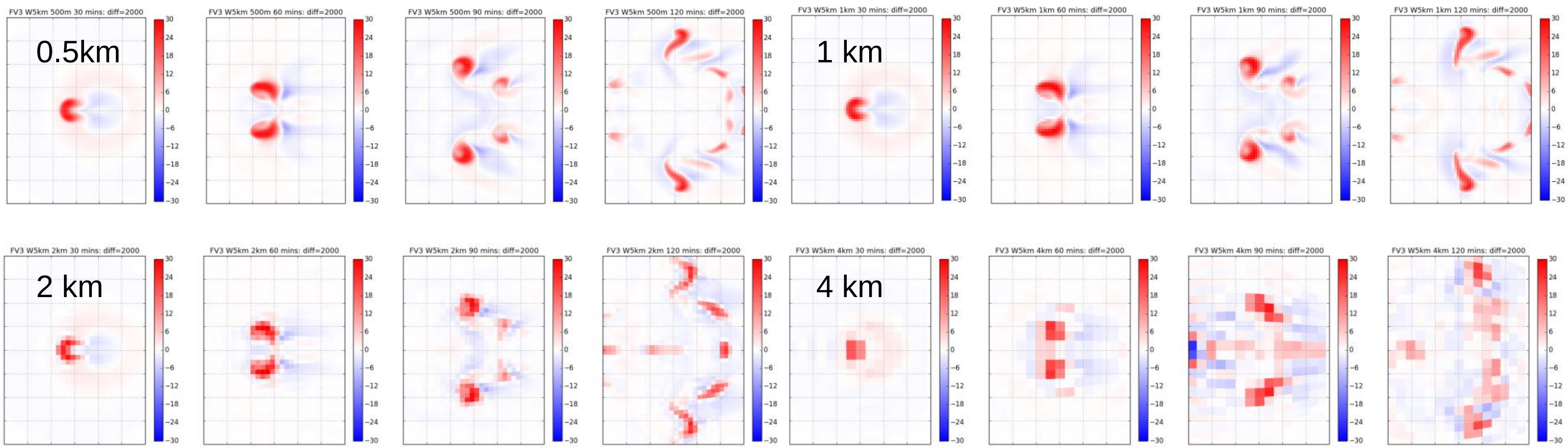
- MPAS
  - Disable vertical diffusion
  - Set Prandtl number to 1 (so that horizontal diffusion coefficient is same for all variables)
  - Physics timestep same as large RK step
  - Large RK step set to 3,6,12,24 seconds for 500m,1km,2km,4km resolutions
  - Number of acoustic timesteps per large RK step set to 6 in all cases
- FV3
  - Disable Smagorinsky diffusion by setting dddmp=0
  - Disable monotonic horizontal transport
  - Turn on 2nd order horizontal diffusion of tracers (using inline_q=.T. to ensure that tracers are integrated on the same time step as other prognostic variables)
  - Physics timestep set to 20,20,20,25 secs for 500m,1km,2km,4km resolutions
  - Number of vertical remaps per physics timestep (k_split) set to 8,5,2,1 for 500m,1km,2km,4km resolutions
  - Number of acoustic time steps per vertical remap (n_split) set to 5 in all cases

- With these mods, both models use constant 2nd order horizontal diffusion for all variables, no vertical diffusion. A horizontal diffusion coefficient of 2000 m^2/s is used, since it appears to produce a converged solution at 500 m for both models.

#5 Supercell Test: MPAS 500 hPa w

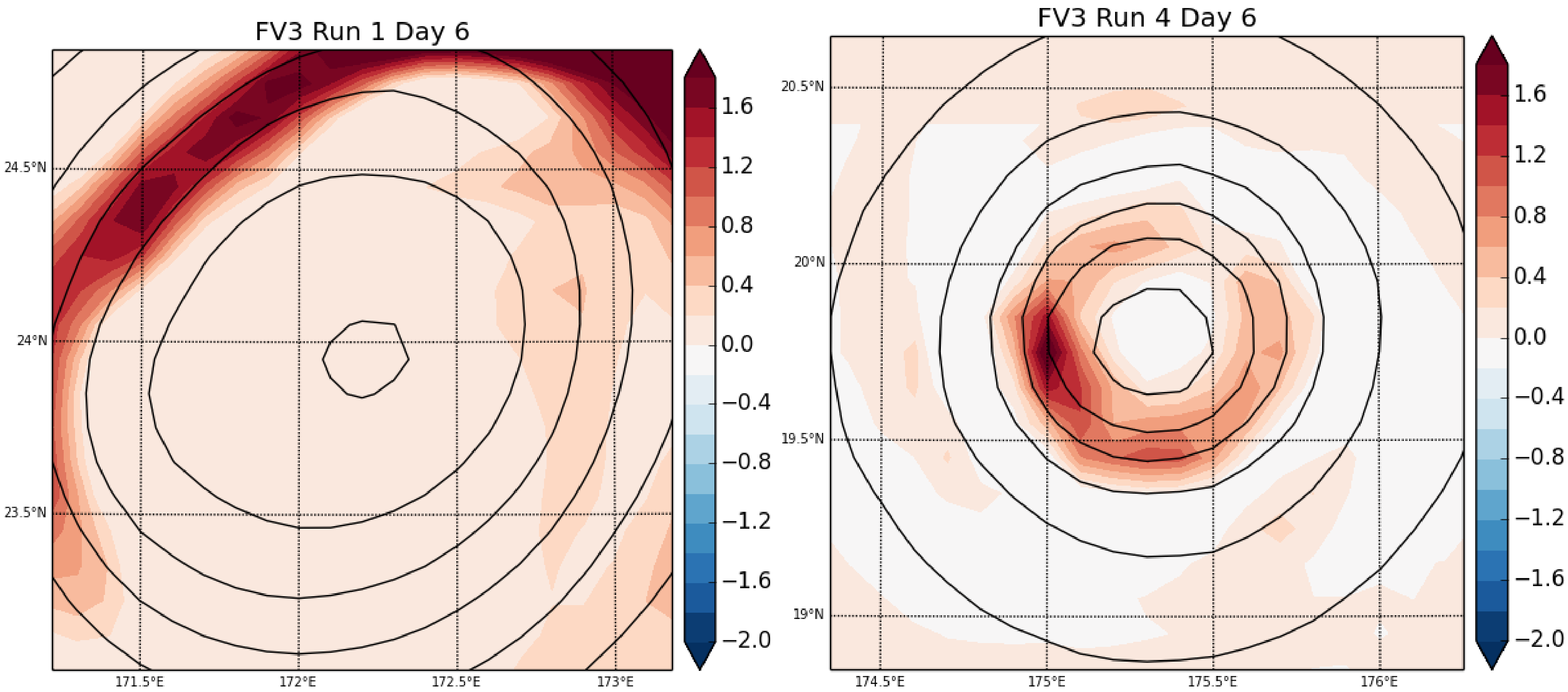


#5: Supercell Test: FV3 500 hPa w



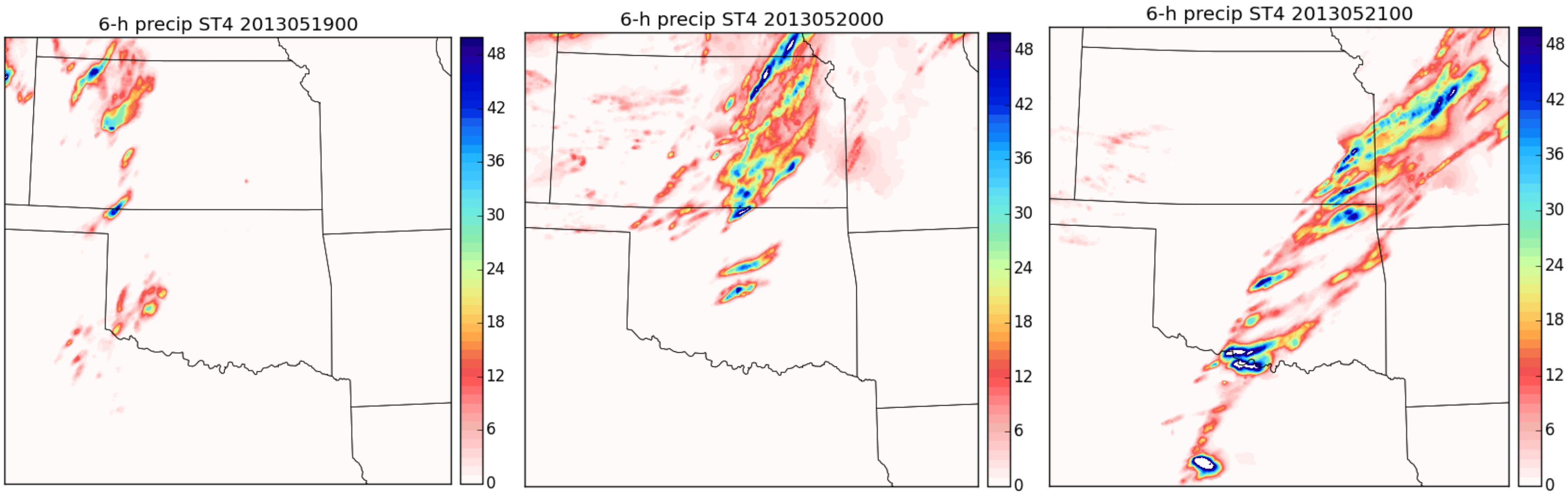
#5: Idealized TC Test

MSLP (Black Lines), 500hPa Vertical Velocity (color, m/s)

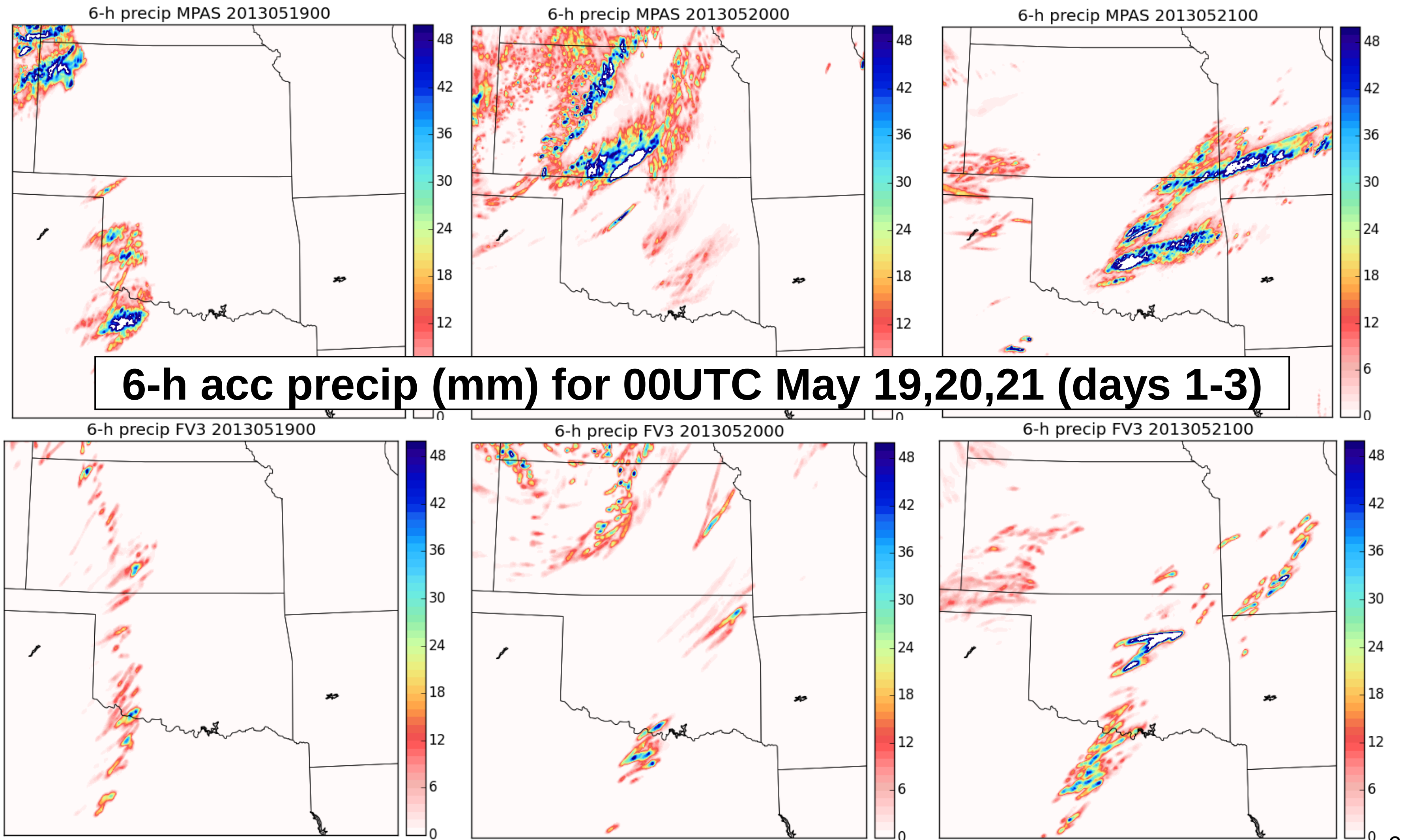


FV3 as originally configured has a huge eye (left); removing the vertical 2dz filter produced a much smaller, more realistic storm structure (right).

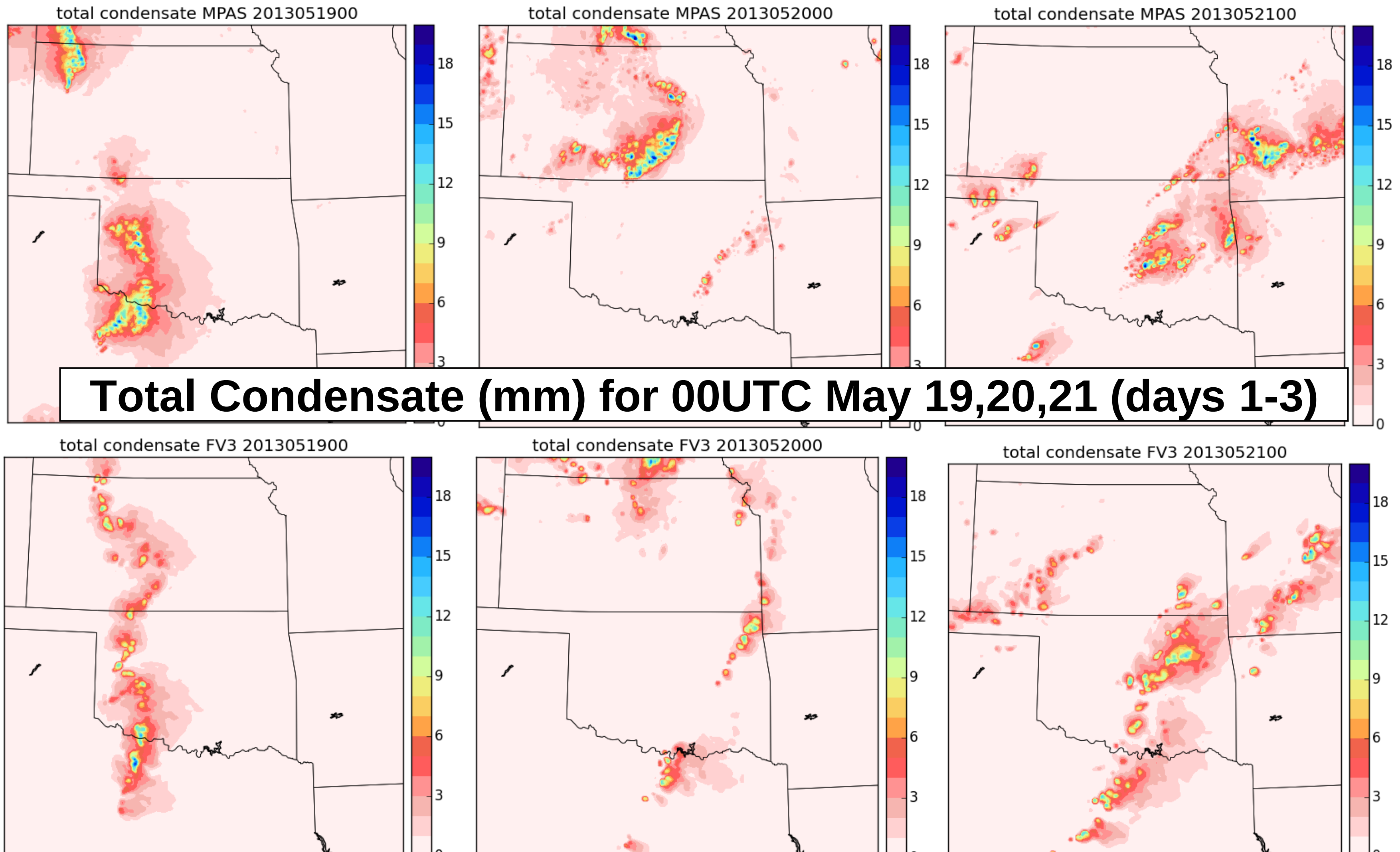
#5: Moore Tornado Case: Stage IV Precipitation Analyses



#5: Moore Tornado Case: Simulated Precipitation



#5: Moore Tornado Case: Simulated Total Cloud Condensate



Total Condensate (mm) for 00UTC May 19,20,21 (days 1-3)

Phase 1 Test and Evaluation

Selecting a New Operational Atmospheric Dynamic Core

- Evaluate, select and implement a replacement to current Global Spectral Model
- Parallel efforts initiated at UKMO and ECMWF
- Next-Generation computing paradigm will require scaling across potentially 100,000’s processors or more
- Candidate dynamic core testing is being conducted in two phases

Atmospheric Model Dynamic Core Testing Overview

Phase 1 Testing

Status	Activities
Complete	HIWPP Idealized Tests
Complete	Computational performance and scalability testing and software evaluation by Advanced Computing Evaluation Committee (AVEC)
Complete	HIWPP 3-km, 3-Day Simulations
Complete	Phase 1 Testing Report
Complete	Dycore Test Group (DTG) assessment of Phase 1 testing results
Complete	Phase 1 testing results briefing to NCEP (Dr. Bill Lapenta)

Note: Specific details on Phase 1 testing and associated criteria provided later in brief

NGGPS Phase 1 Testing

- AVEC
  - Benchmarks Testing
  - Software Evaluation
- HIWPP
  - Idealized Tests
  - 3-km, 3-Day Simulations

Incorporated Non-hydrostatic Dynamic Core Testing from HIWPP

NGGPS Phase 1 Dycore Test Candidate Model Dynamic Cores

- FV3 (GFDL): Cubed-sphere finite-volume with flexible Lagrangian vertical coordinate (z or p base) with nesting or stretched grid capability
- MPAS (NCAR): Finite-volume C-grid staggering, icosahedral (z coordinate) with unstructured mesh refinement capability.
- NIM (ESRL): Icosahedral unstaggered A-grid mesh, finite-volume (z coordinate)
- NMM-UJ (EMC): Finite-difference, cubed-sphere version of Non-hydrostatic Mesoscale Model (p coordinate); Uniform Jacobian cubed sphere grid replaced lat/lon grid version with staggered B-grid (NMMB)
- NEPTUNE (Navy): Spectral-element (horizontal and vertical) cubed-sphere grid (z coordinate) with adaptive mesh refinement

Global Spectral Model not included – Non-hydrostatic version not available

Phase 1 Dycore Testing Overview

Evaluation Criteria	How evaluation was done
Bit reproducibility for restart under identical conditions	Query model developers (AVEC)
Solution realism for dry adiabatic flows and simple moist convection	Perform series of idealized tests and evaluate solutions
High computational performance and scalability	Benchmarks run by AVEC
Extensible, well-documented software that is performance portable	Subjective evaluation of source code by AVEC
Execution and stability at high horizontal resolution (3 km or less) with realistic physics and orography	72-h forecasts with realistic physics and orography using operational GFS initial conditions (Moore tornado and Hurricane Sandy)
Lack of excessive grid imprinting	Evaluate idealized test case solutions

NGGPS Phase 1 Dycore Testing Test Personnel

- NGGPS Test Manager – Jeff Whitaker (OAR)
- AVEC Test Manager – John Michalakes (NWS Contractor)
- FV3 Test Manager – Shian-Jiann Lin (GFDL)
- MPAS Test Manager – Bill Skamarock (NCAR)
- NMM-UJ Test Manager - Geoff DiMego (EMC)
- NEPTUNE Test Manager – Jim Doyle (Navy)
- NIM Test Manager – Jin Lee (ESRL)

NGGPS Phase 1 Testing Ground Rules

- Each candidate model's configurations – resolution, number of points, number of levels, and time step were reviewed and agreed upon by other modeling groups
- Strict schedules with deadlines were followed
  - Candidate dycore development paths not in sync with NGGPS timeline in all cases
- Any dycore testing modifications during test were approved by the NGGPS Manager, Test Manager and other dycore leads
  - Included substitution of NMM-UJ for NMMB and additional runs of dycores at single vs double precision
  - Both AVEC testing and idealized testing used same versions of code – modifications required re-running some tests for standardization

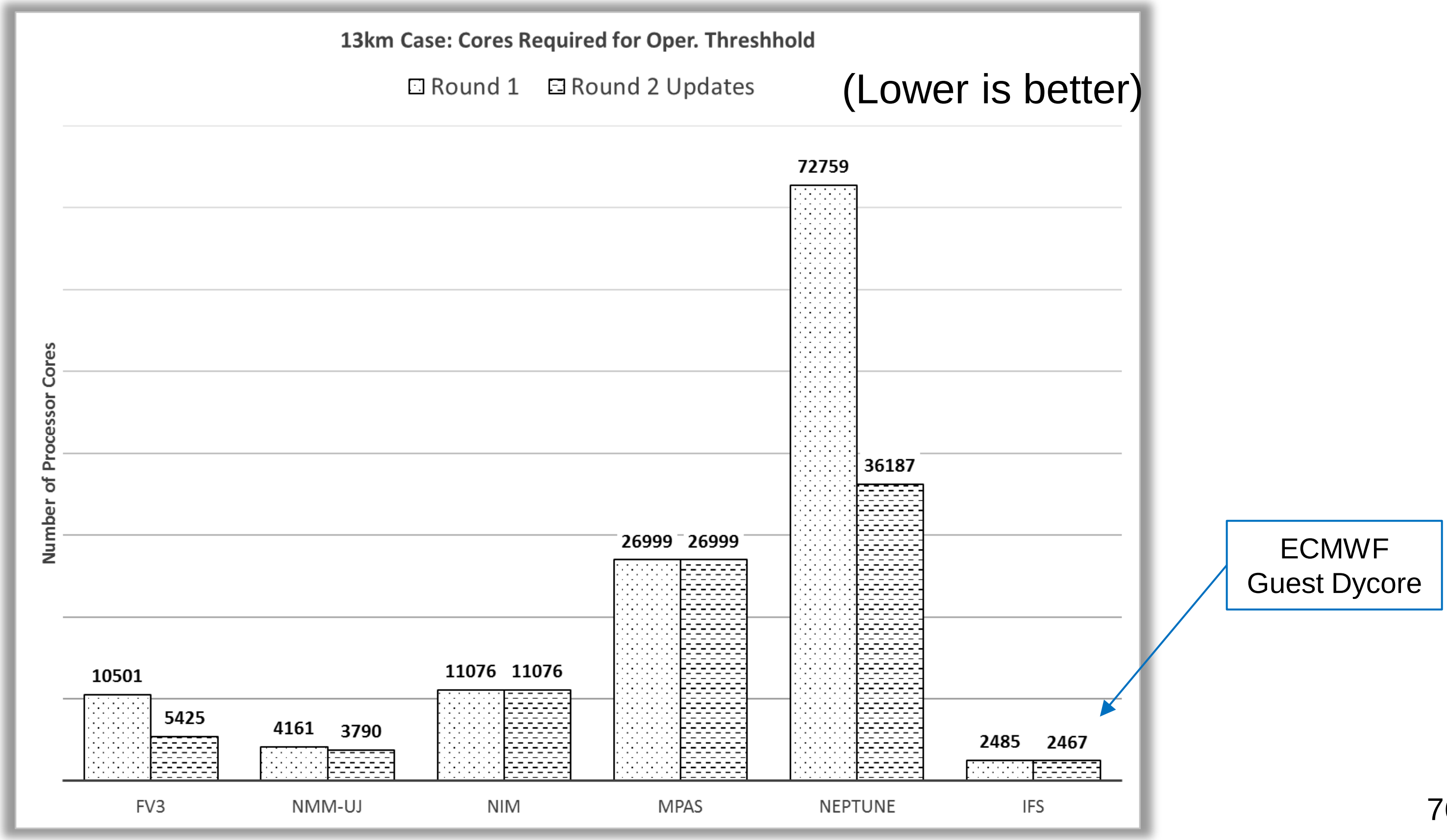
AVEC Phase 1 Evaluations

AVEC Phase 1 Evaluations

- Advanced Computing Evaluation Committee formed August 2014 to evaluate and report on performance, scalability and software readiness of five NGGPS candidate dycores
- Reports
  - NGGPS Phase 1 Benchmarks – April 30, 2015
  - NGGPS Phase 1 Software Evaluation (addendum to above) – May 28, 2015
- Benchmarks on 130-thousand core HPC system at DOE: “Edison”
  - 13-km and 3-km workloads based on HIWPP non-hydrostatic test case
  - Model groups agreed on each others’ configurations
  - Time step and other configuration options were “best guesses”
  - Groups that changed codes or configurations to improve benchmark performance were required to resubmit results for HIWPP test case
- Round 2 benchmarks in Phase 1 afforded groups the opportunity to make adjustments (single vs double precision, run with additional higher processor counts, 3rd vs 4th order, and improvements in MPI communications)

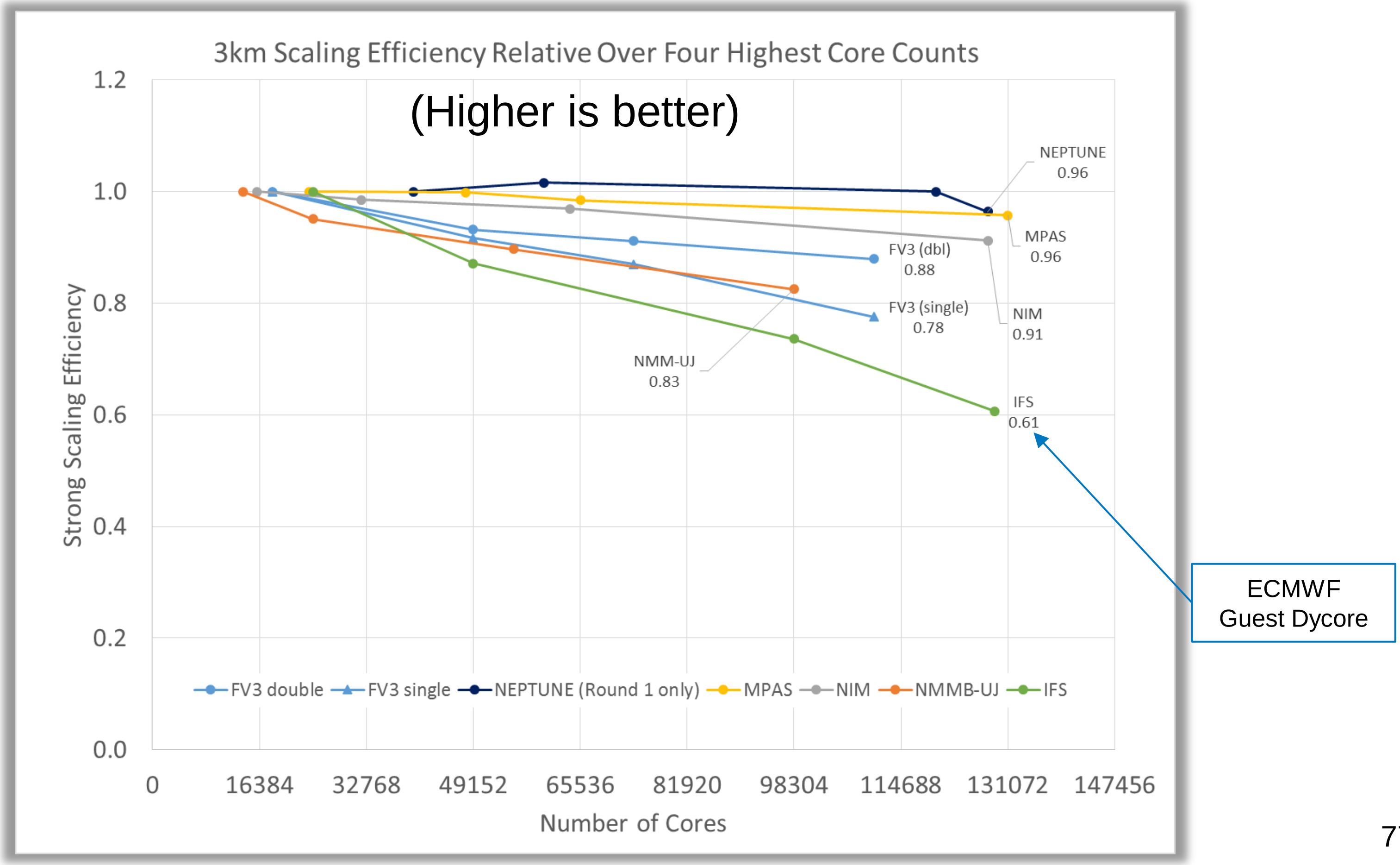
AVEC Phase 1 Evaluations: Performance

- Performance:
  - Number of processor cores needed to meet operational speed requirement with 13-km workload
  - Rankings (fastest to slowest): NMM-UJ, FV3, NIM, MPAS, NEPTUNE



AVEC Phase 1 Evaluations: Scalability

- Scalability: ability to efficiently use large numbers of processor cores
  - All codes showed good scaling
  - Rankings (most to least scalable): NEPTUNE, MPAS, NIM, FV3, NMM-UJ



AVEC Phase 1 Evaluations: Software

- Software evaluations intended to highlight strengths and weaknesses of codes to be ready for NGGPS
  - Note: snapshot in time, all codes under active development
- Phase 1 results based on self-reports from AVEC questionnaire*:
  - Software maturity: FV3, NIM, MPAS, NEPTUNE, NMM-UJ
  - Nesting or mesh refinement: FV3, MPAS, NEPTUNE, NMM-UJ, NIM
  - Support for thread parallelism: FV3, NIM, NMM-UJ, MPAS, NEPTUNE
  - Reproducibility: FV3, NIM, NMM-UJ, MPAS, NEPTUNE
  - Advanced architectures: NIM, FV3; NMM-UJ, NEPTUNE, MPAS
- Additional evaluation including detailed code inspection and review of documentation will continue into Phase 2 testing

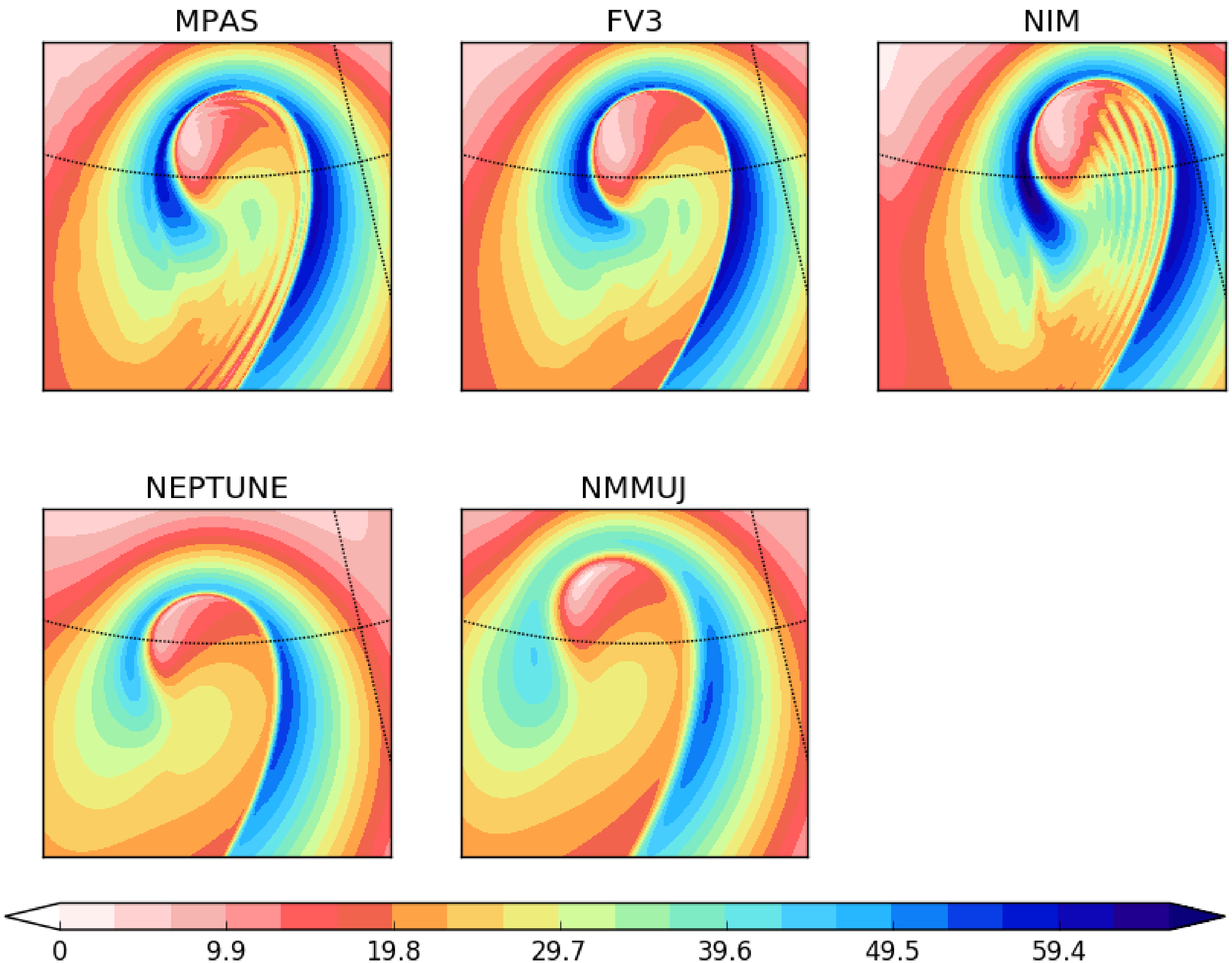
*Stoplight color coding by AVEC Chair, John Michalakes (not full AVEC)

HIWPP Tests Supporting NGGPS Phase 1 Testing

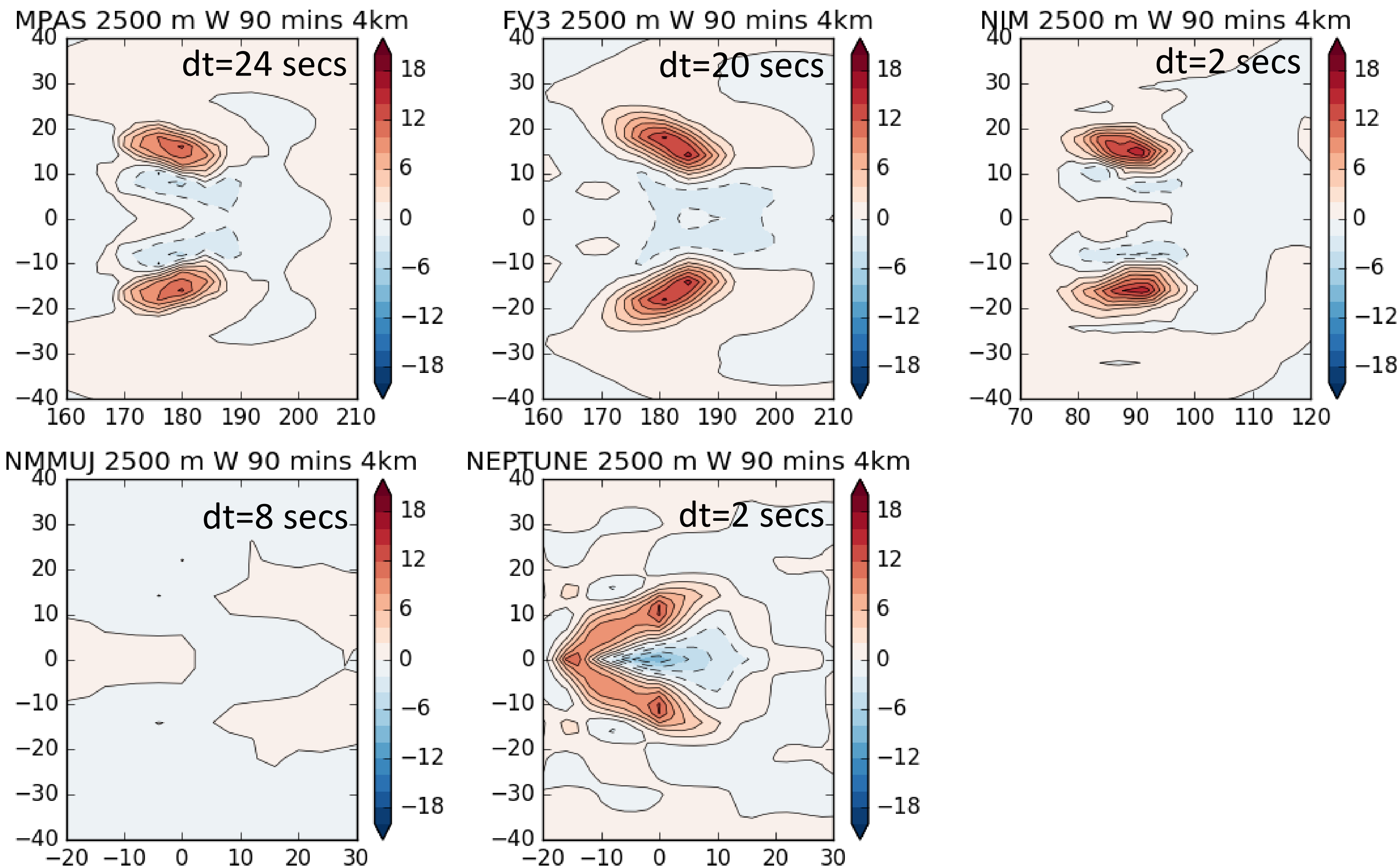
Idealized Tests

- **Baroclinic wave test with embedded fronts** (DCMIP 4.1)
  - Dynamics strongly forces solution to shortest resolvable scales
  - Shows impact of truncation error near quasi-singular points on computational grid ("grid imprinting")
  - 15/30/60/120 km horizontal resolutions with 30 and 60 vertical levels
- **Non-hydrostatic mountain waves on a reduced-radius sphere** (like DCMIP 2.1/2.2)
  - Shows ability to simulate non-hydrostatic gravity waves excited by flow over orography
  - 3 tests: M1 (uniform flow over a ridge-like mountain), M2 (uniform flow over circular mountain), M3 (vertically sheared flow over a circular mountain). Solutions are all quasi-linear
- **Idealized supercell thunderstorm on a reduced-radius sphere**
  - Convection is initiated with a warm bubble in a convectively unstable sounding in vertical shear
  - Simple Kessler warm-rain microphysics, free-slip lower boundary (no boundary layer)
  - Splitting supercell storms result after 1-2 hours of integration
  - 0.5/1/2/4 km horizontal resolutions

Baroclinic Wave (Sfc Wind Speed at Day 9, 15-km resolution)



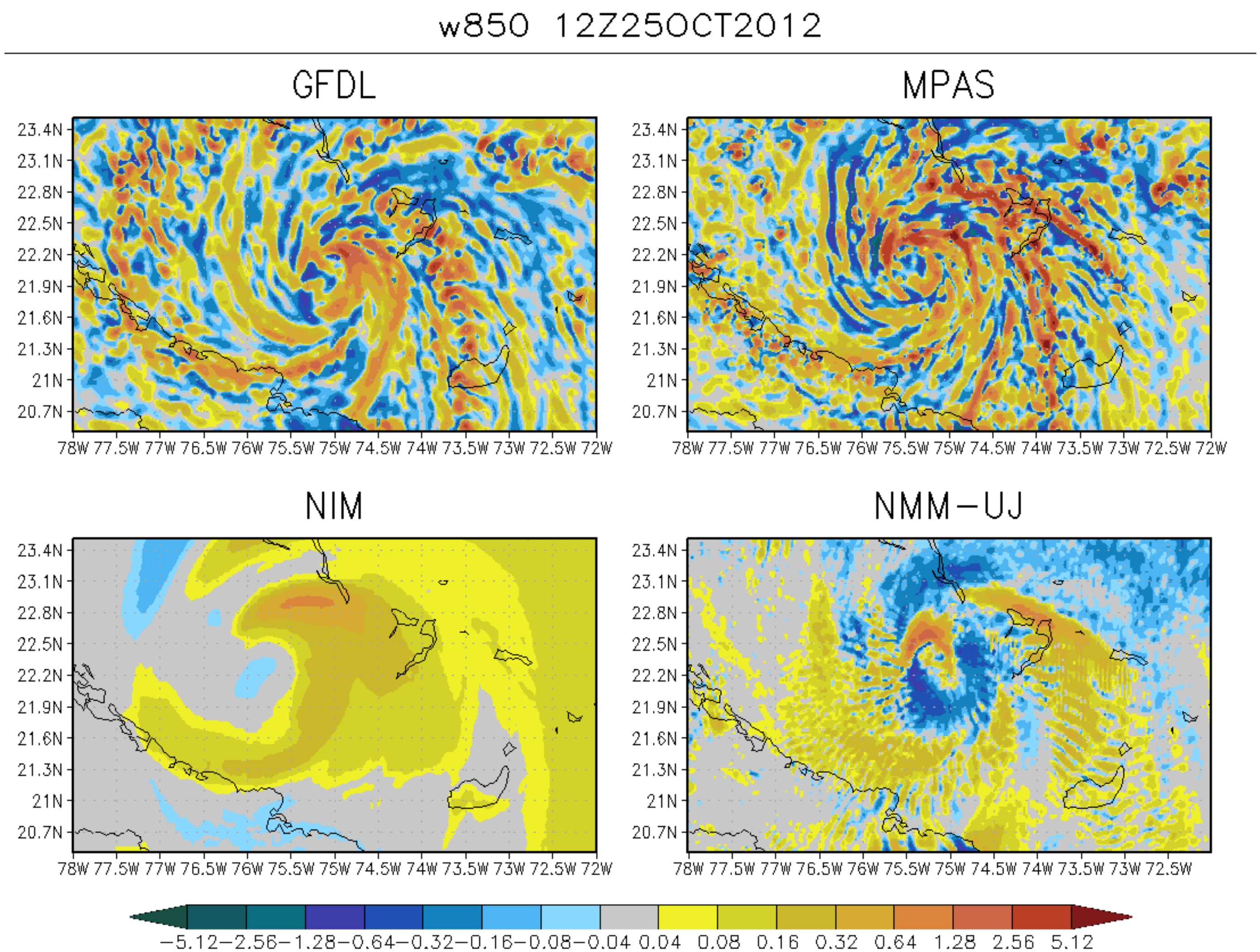
Supercell (2500-m w at 90 mins, 4-km resolution)



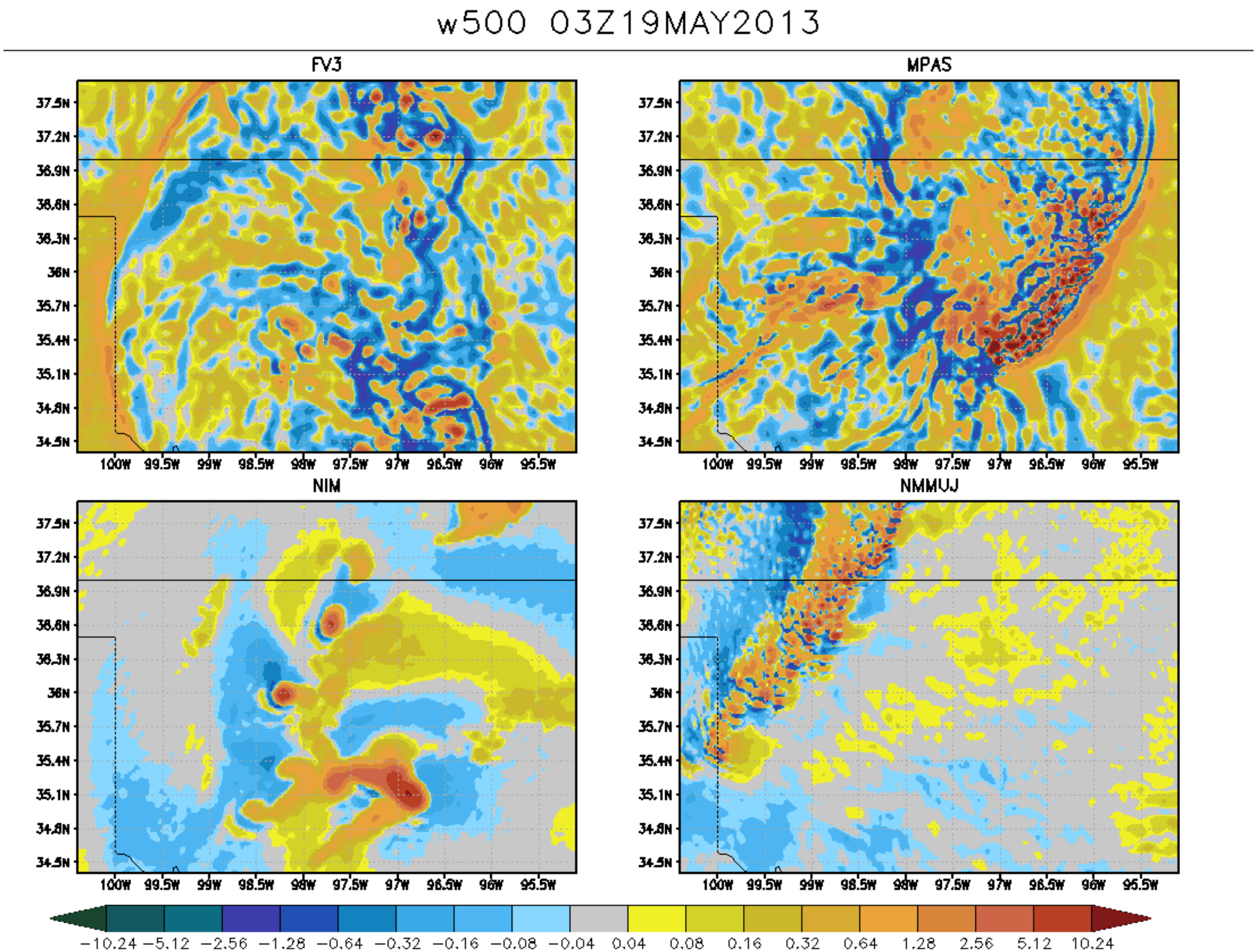
72-h 3-km Forecast Test

- ‘Stress-test’ dycores by running with full-physics, high-resolution orography, initial conditions from operational NWP system
  - Different physics suites used in each model
- Two cases chosen:
  - Hurricane Sandy 2012102418 (also includes WPAC typhoon)
  - Great Plains tornado outbreak (3-day period beginning 2013051800). Includes Moore OK EF5 tornado around 00UTC May 19
- Focus not on forecast skill, but on ability of dycores to run stably and produce reasonable detail in tropical cyclones and severe convection
  - Also look at global quantities like KE spectra, total integrated precipitation/water vapor/dry mass

Hurricane Sandy (w at 850 hPa)



Moore Tornado (w at 500 hPa)



Idealized Testing Summary

- **FV3, MPAS** produced highest quality solutions overall
  - More similar to each other than other models for all tests
- **NIM** produced reasonable mountain wave and supercell solutions
  - Excessive noise near grid scale in baroclinic wave solution
  - Full physics forecasts excessively damped
- **NEPTUNE** was not able to produce full physics 3-km forecasts
  - Baroclinic wave too smooth, 4-km supercell not split by 90 mins
- **NMM-UJ** did not produce realistic solutions for the mountain wave and supercell tests
  - Vertical velocity fields from full physics forecasts did not show signatures expected from resolved convection

Dycore Test Group (DTG) Membership

- Chair: Ming Ji (Director, Office of Science and Technology Integration)
- Fred Toepfer (NGGPS Program Manager)
- Bob Gall, Ricky Rood, John Thuburn (Independent Consultants)
- Melinda Peng (Navy – NEPTUNE)
- Venkatachala Ramaswamy (GFDL - FV3)
- Hendrik Tolman (EMC – NMM-UJ)
- Chris Davis (NCAR – MPAS)
- Kevin Kelleher (ESRL – NIM)

NGGPS Phase 1 Testing DTG Assessment

- Several dycores identified that consistently produced solutions of higher quality and/or were more mature than other dycores - low technical risk
- Low Risk Decision - Sufficient information is available to proceed with fewer dycores to Phase 2 testing
  - No additional testing required to remove programmatic risk
  - No unique quality lost in any models not moving forward
- Majority agreed
  - FV3 and MPAS were ready to move Phase 2 testing
  - Additional development needed for other NMM-UJ, NIM, and NEPTUNE

NGGPS Phase 1 Testing Project Summary Assessment

	Idealized Tests	3-km, 3-day forecasts	Performance	Scalability	Nesting or Mesh Refinement	Software Maturity
FV3	🟢	🟢	🟢	🟢	🟢	🟢
MPAS	🟢	🟢	🟡	🟢	🟢	🟢
NIM	🟡	🔴	🟢	🟢	🔴	🟢
NMM-UJ	🔴	🟡	🟢	🟢	🟡	🔴
NEPTUNE	🟡	🔴	🔴	🟢	🟢	🔴

🟢 Meets or exceeds readiness for needed capability
🟡 Some capability but effort required for readiness
🔴 Capability in planning only or otherwise insufficiently ready

Dycore Readiness Project Risk Assessment

	Overall Risk	Comment
FV3	Low	None
MPAS	Mostly Low	Computational Performance
NIM	Moderate	Maturity – Nesting, high resolution
NMM-UJ	Moderate	Maturity – Idealized Testing
NEPTUNE	High	Maturity

Neither readiness for potential future computing architectures (fine-grain computing) nor future computing relative scarcity/abundance judged to be overarching requirements at this time

Project Manager Assessment

- Relative dycore performance in testing results
  - FV3 and MPAS achieved both acceptable and highest quality testing results
  - MPAS markedly slower than FV3 but MPAS team anticipates significant improvement available and achievable
  - Significant additional development (months to years) potentially needed for other cores to achieve comparable (not better) performance
- Significant long-term schedule risk added if we delay for additional dycore development and/or Phase 1 testing
  - No guarantee of relative improvement between dycores
  - Potential for open-ended development across multiple models
- Cost - Limited resources, both in personnel and funding, and should be focused on development or readiness of top dycore candidates for operations
- Must consider planned model develop

NGGPS Project Manager Recommendation

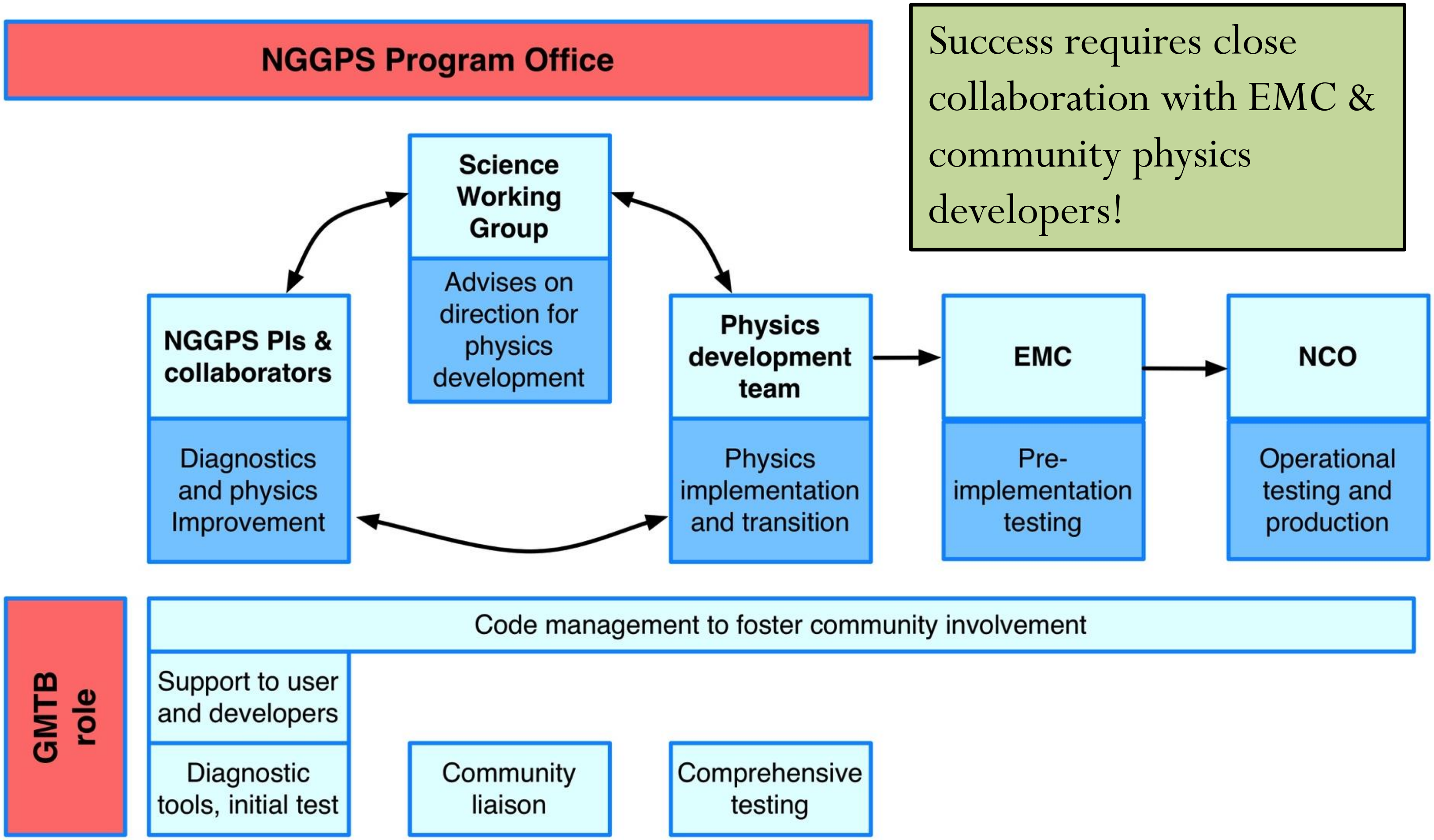
- Proceed to Phase 2 testing on schedule with two dycores:
  - FV3 and MPAS

Global Modeling Test Bed (GMTB)

GMTB – Role

- Extension of current DTC (NCAR and GSD partnership)
- Developmental testing of new functionality
- Facilitates community involvement in ongoing development of operational modeling systems
  - Community code management
  - Facilitates use of code in non-NOAA platforms
  - Provides necessary infrastructure for community to interact with code system
  - Supports code system to external developers
  - Independent test and evaluation of proposed upgrades to operational system from external community

Global Model Test Bed (GMTB): Facilitating NGGPS physics development



Success requires close collaboration with EMC & community physics developers!

GMTB – Current Focus

- Atmospheric physics
  - Create and support a Common Community Physics Package (CCPP) with carefully vetted physics suites for global modeling at various resolutions
  - Develop a design and implementation plan to evolve current Interoperable Physics Driver (IPD) to meet the needs of NGGPS
  - Implement a testbed for innovations
  - NGGPS Physics Workshop
- Sea ice model
  - Participate in efforts to create a plan for fostering community collaboration in Los Alamos Sea Ice Model (CICE) development

GMTB – DTC Support

- Cases for each hierarchy tier, from idealized tests using a single-column model, through more complex tests using a full global dynamic core. Including:
  - Initialization data
  - Forcings
  - Relevant observation datasets
- Benchmarks
  - Output of operational models for each case
- Analysis tools, such as,
  - Model Evaluation Tools (MET)
  - Tools shared from community
  - Scripts
  - Diagnostic plot-making capabilities

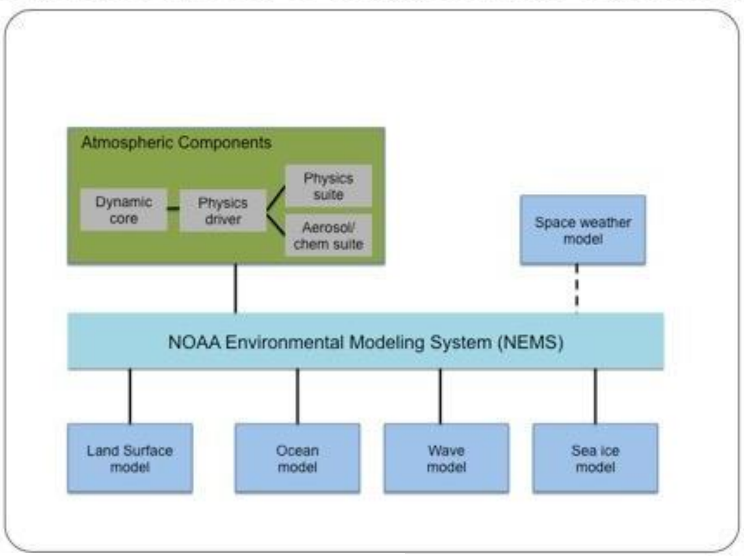
Common Community Physics Package (CCPP) Strategy

Driver and CCPP in NGGPS context

Dycore/CCPP/Driver

are elements of the atmospheric modeling component

Proposed NGGPS Components Schematic

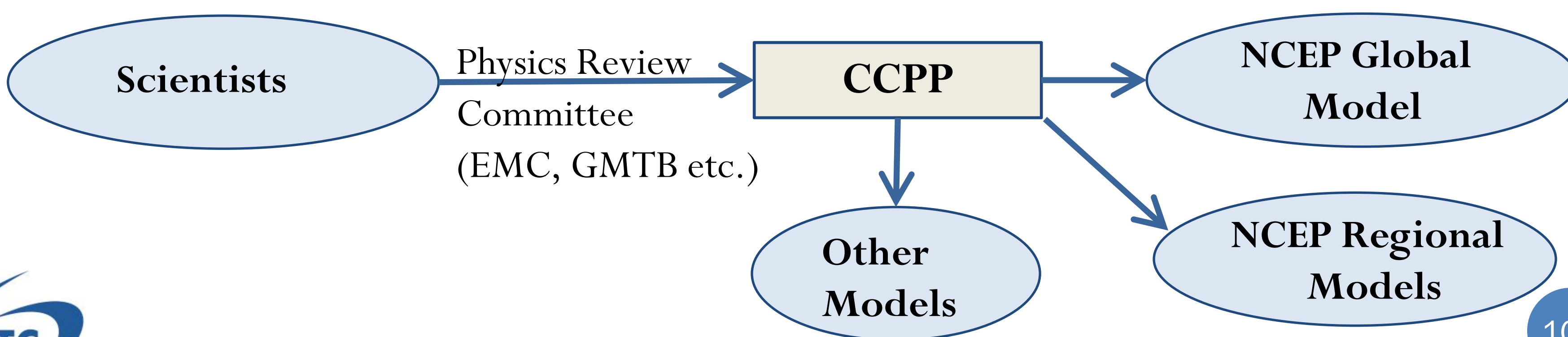


History and Status

- NUOPC Physics Interoperability Team created requirements for driver and parameterizations (modified Kalnay rules)
- In support of NGGPS, a driver was developed to facilitate connection of GFS physics to other dycores
- This driver meets needs of NGGPS dycore test but does not follow all requirements put forth by the NUOPC PI Team

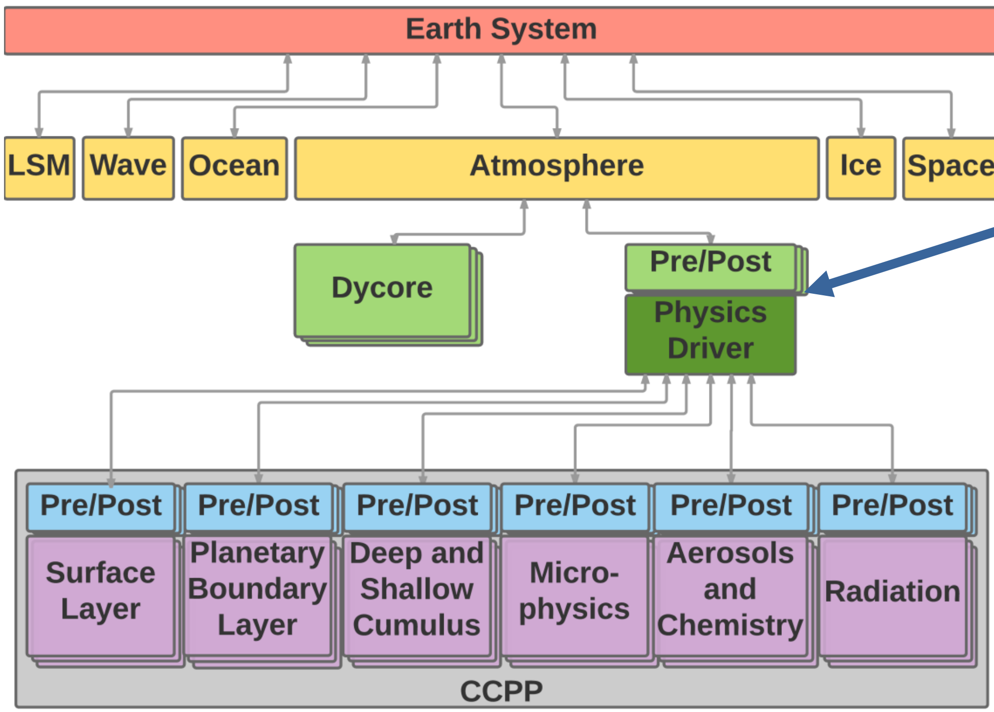
Proposed Vision for Driver & CCPP

- CCPP is a library of dycore-agnostic atmospheric physical parameterizations to be used by NCEP models
  - Start with global, but can be used by regional models as well
  - CCPP can be used with any dycore that connects to the Driver
- Various parameterizations of each category can co-exist in the CCPP, but a Physics Review Committee constrains options based on objective and transparent criteria



Schematic for Driver & CCPP

GMTB PRELIMINARY SCHEMATIC



Pre/Post Physics interfaces and Driver

Needed for CCPP to connect with dycore (EMC has created initial version and will lead further development with GMTB's input of requirements)

CCPP

GMTB takes the lead in creating it, in close collaboration with EMC and Physics Review Committee

CCPP Initial capability is GFS operational physics

GMTB does not engage substantial software changes initially.
Primary role for GMTB is documentation and support.