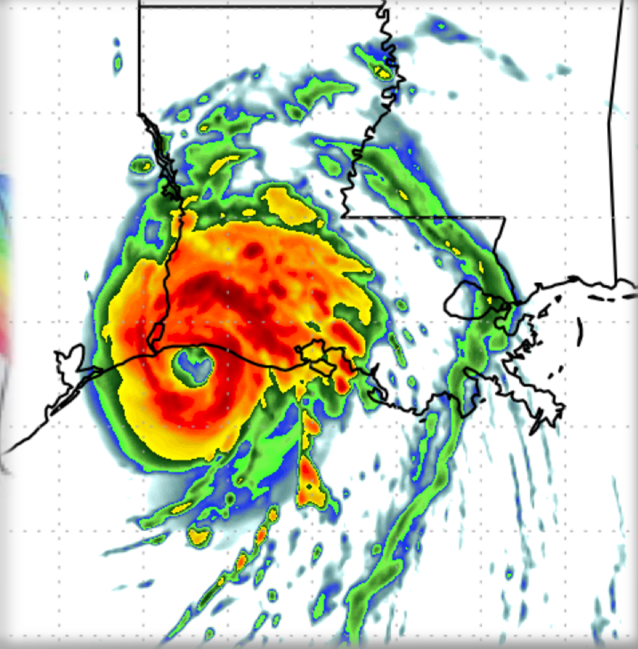


The GFDL Finite-Volume Cubed-Sphere Dynamical Core

Design and Prospects for Global and Unified Modeling

Lucas Harris

for the GFDL FV3 Team

ECMWF Annual Seminar

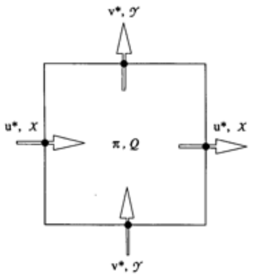
16 September 2020

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

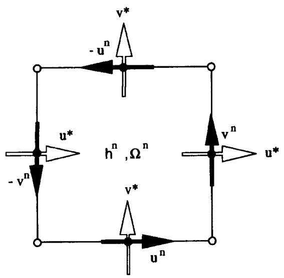
The FV3 Way

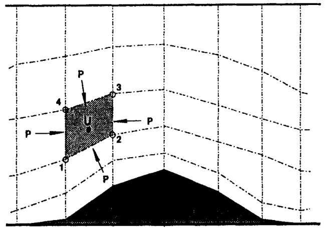
- Physical consistency
- Fully-FV numerics
- Component coupling
- Computational efficiency

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



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

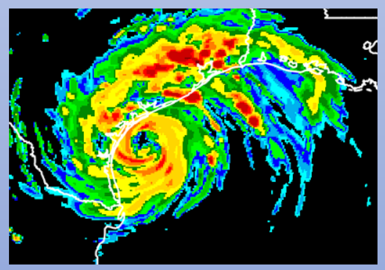


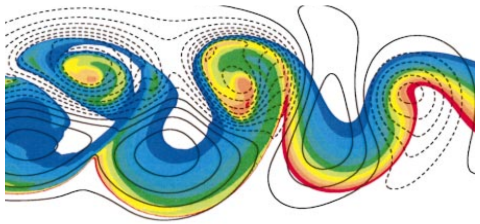


Lin 1997 Efficient, mimetic FV PGF

FV3 for the 2020s

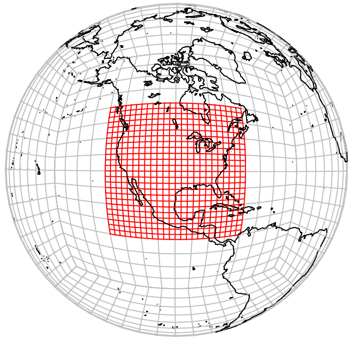
Rigorous Thermodynamics
Flexible dynamics
Adaptable physics interface
Variable-resolution techniques
Regional & periodic domains
Powerful initialization, DA, and nudging functions

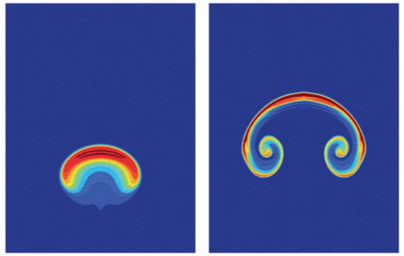




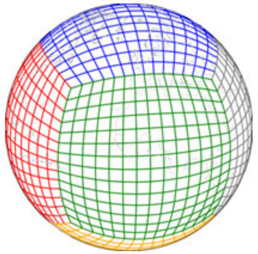
Lin 1998-2004 FV core with “floating” Lagrangian vertical coordinate

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





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

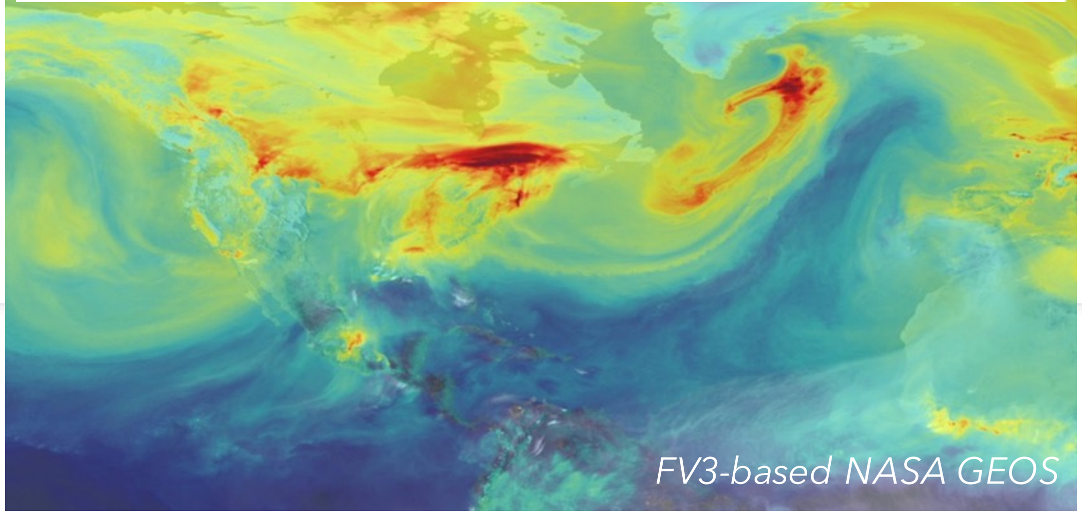


Putman & Lin 2007
Scalable cubed-sphere grid, doubly-periodic domain

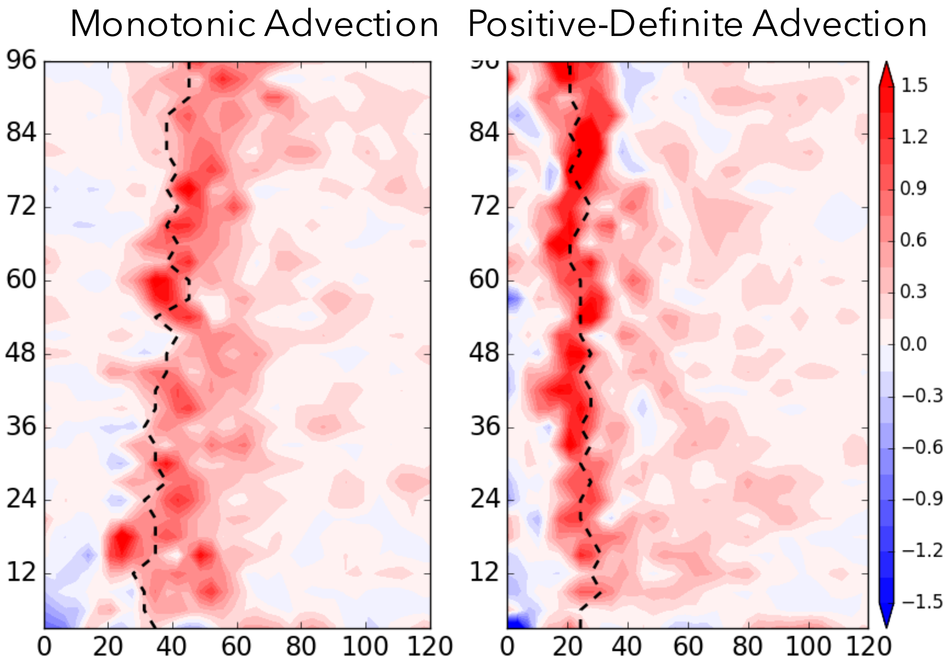
FV Advection

Lin and Rood Advection

$$q^{n+1} = \frac{1}{\pi^{n+1}}\left\{\pi^n q^n + F\left[q^n + \frac{1}{2}g(q^n)\right] + G\left[q^n + \frac{1}{2}f(q^n)\right]\right\}.$$



- "Reverse-engineered" forward-in-time 2D scheme constructed from 1D PPM operators
  - Mass-conservative
  - Correlation-preserving for monotonic limiter
  - Cancels splitting error
  - Separate Courant number limit in x and y
  - Upwinding preserves hyperbolicity and causality
- *All* quasi-horizontal processes, except PGF, can be represented as advection
- Highly adaptable: Positive-definite tracer advection greatly improves hurricane structure



Axisymmetric 5-km W in Hurricane Irma
Harris et al. (2020) JAMES ; K Gao et al., in prep.

Nonhydrostatic Lagrangian Dynamics

```
  for cosz calculations: nswr,deltim,deltsw,dtswh =          10
 180.000000000000        1800.00000000000       0.500000000000000
 anginc,nstp =  1.308996938995747E-002          11
    2016          8          4          5          0          0
ZS      6849.180      -412.0000       231.8707
PS max =     1054.338       min =     441.9276
Mean specific humidity (mg/kg) above 75 mb=   3.994439
Total surface pressure (mb) =     985.8600
mean dry surface pressure =    983.2388
Total Water Vapor (kg/m**2) =   26.56078
--- Micro Phys water substances (kg/m**2) ---
Total cloud water=  6.7240514E-02
Total rain  water=  2.4596382E-02
Total cloud ice  =  3.9533786E-02
Total snow       =  2.1293228E-02
Total graupel    =  1.5756246E-02
---------------------------------------------
TE ( Joule/m^2 * E9) =   2.631335
UA_top max =     144.7256       min =   -42.04172
UA max =     144.7256       min =   -52.63876
VA max =     81.54002       min =   -75.08163
W  max =     37.20443       min =   -10.95220
Bottom w max =     6.904078       min =   -8.178501
Bottom: w/dz max =    0.2614583       min =  -0.3034391
DZ (m) max =     20.60121       min =   -5908.555
Bottom DZ (m) max =   -20.60121       min =   -32.27457
TA max =     317.2014       min =     175.0712
OM max =     94.72382       min =   -140.0013
ZTOP      40.88114       34.03699       39.23885
SLP max =     1097.546       min =     928.5116
ATL SLP max =     1023.925       min =     1000.363
fv_GFS Z500   5696.136       5786.775       5447.827       5867.303
Cloud_top_P (mb) max =   1.0000000E+10  min =     52.47940
Surf_wind_speed max =     28.65420       min =   6.4052401E-05
```

3.25-km X-SHiELD: remap dt = 36 s
→ vertical courant number = [-10.9,9.36]

- Semi-implicit solver extends FV Lagrangian dynamics into nonhydrostatic regime
  - NH solver is a runtime switch
- Vertical motion is entirely implicit.
  - No courant number restriction on vertical velocity.
  - No explicit calculation of vertical transport

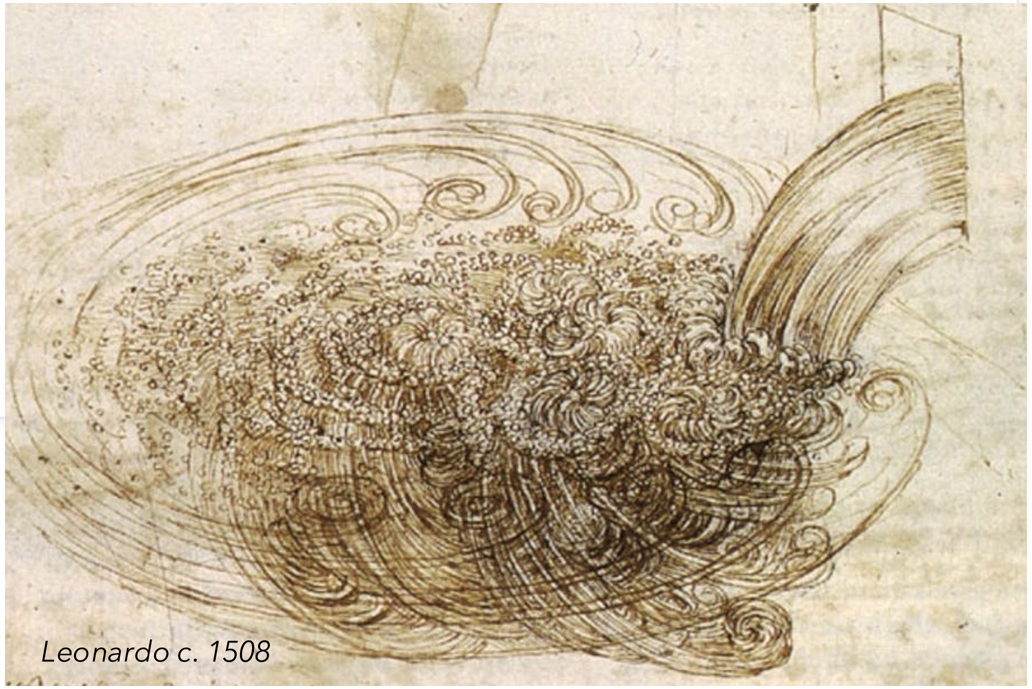
  →Greatly improved numerical efficiency

FV3 uses a mass- and geopotential-conserving cubic-spline vertical remapping to remap to reference coordinate

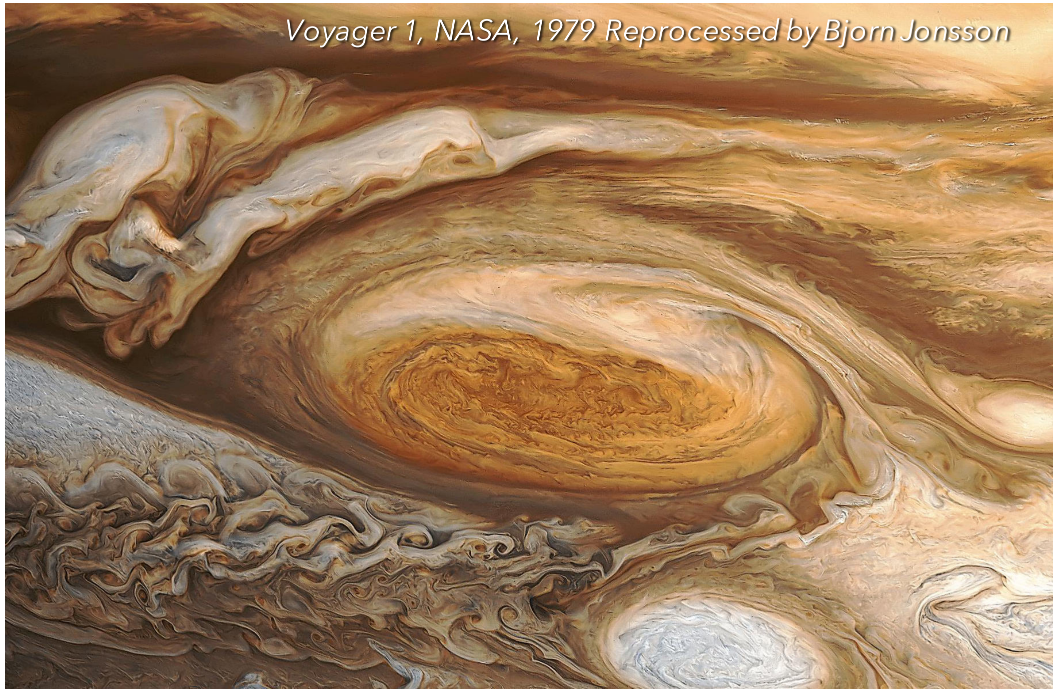
Vorticity Dynamics

Fluids are strongly vortical at all scales. Nearly all intense, long-lived geophysical phenomena are vortical in nature.

FV3's discretization and vector-invariant governing equations emphasizes vorticity: absolute and SW potential vorticity, and updraft helicity, are advected as scalars



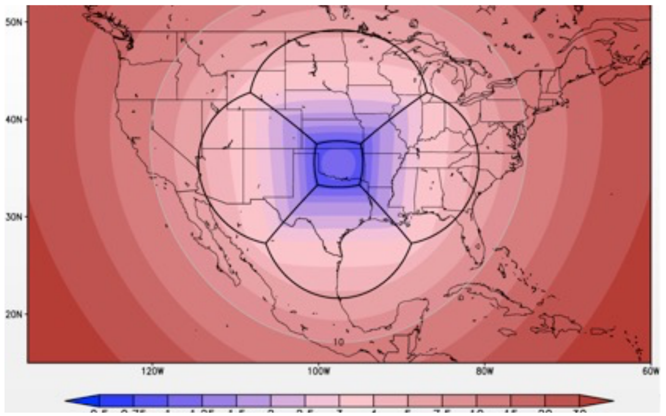
Leonardo c. 1508

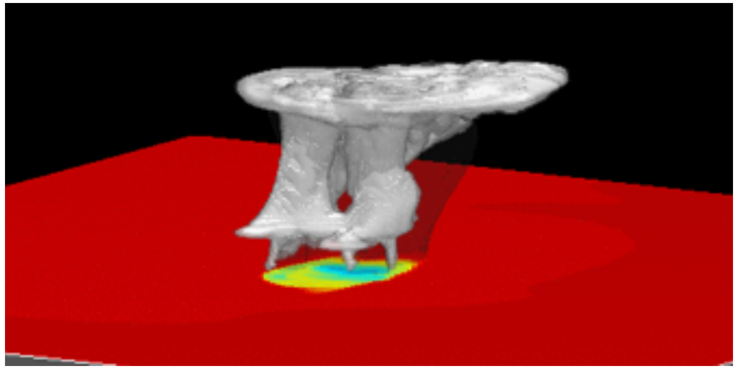


Voyager 1, NASA, 1979 Reprocessed by Bjorn Jonsson

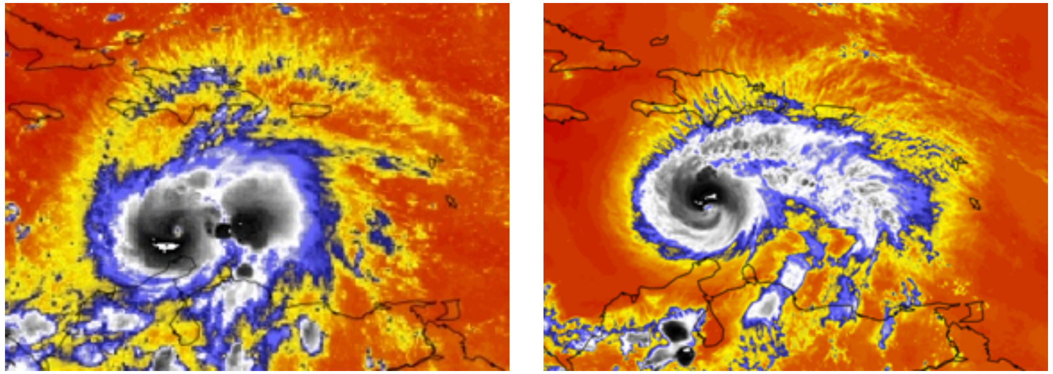
Vorticity Dynamics

- Hybrid C-D grid acts as simplified Riemann solver, permitting accurate computation of both vorticity and advective velocities
- Bonus: divergent modes have *no* implicit dissipation
- Nonlinear vorticity dynamics and mimetic PGF improve representations of small-scale severe weather and hurricane processes





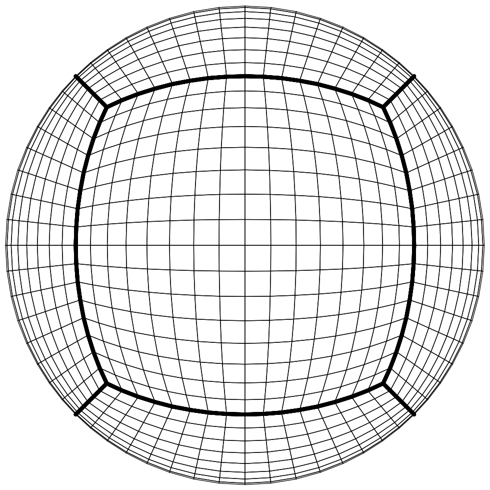
1-km super-stretched global FV3

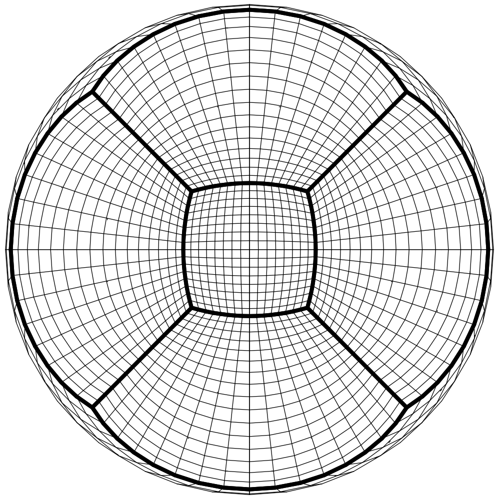


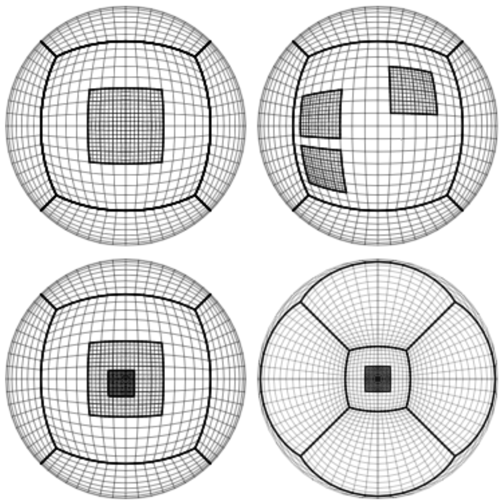
Hurricane Matthew (2016): GOES-13 (left) vs. 2-km T-SHiELD (right)
Courtesy S. Nebuda and J. Otkin, SSEC/UWisc

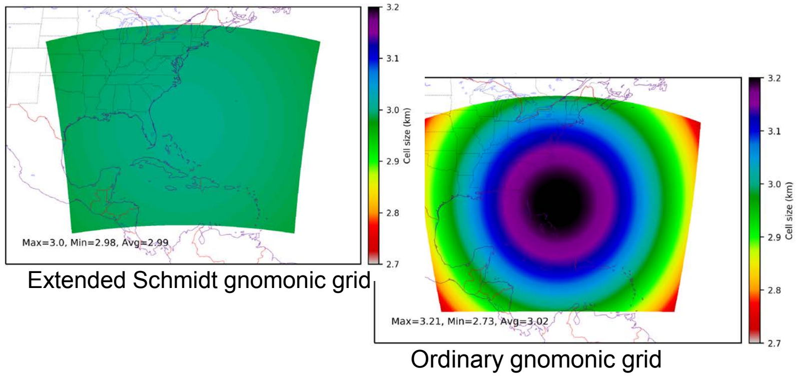
The Cubed-Sphere Grid and Arbitrary Grid Domains

FV3 uses a global cubed-sphere grid **or** any arbitrary regular non-orthogonal quadrilateral grid
This permits Schmidt-stretched grids, two-way nested grids, and uniform regional domains







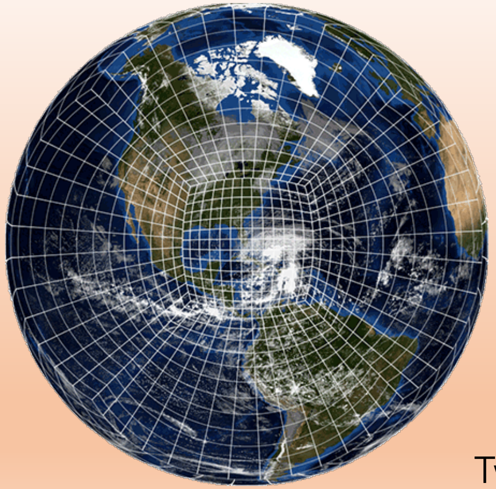


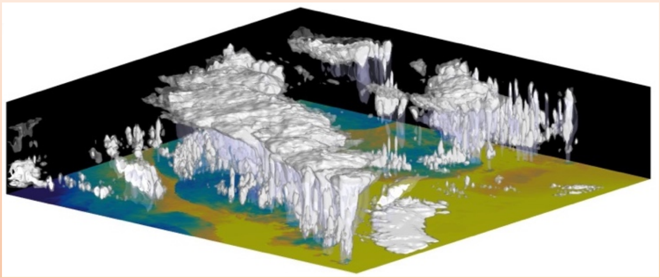
Extended Schmidt gnomonic grid

Ordinary gnomonic grid

Regional-Domain Grid-cell Width
Courtesy Jim Purser and
Chan-Hoo Jeon (NCEP/EMC)

High-resolution domains in FV3



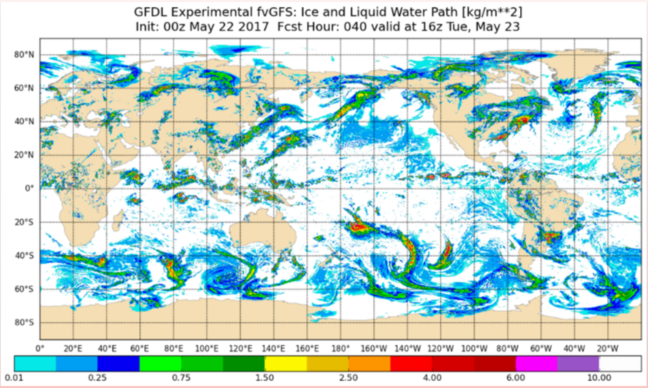


60–90 second
Two-way Interaction
Continual interaction on stretched grid

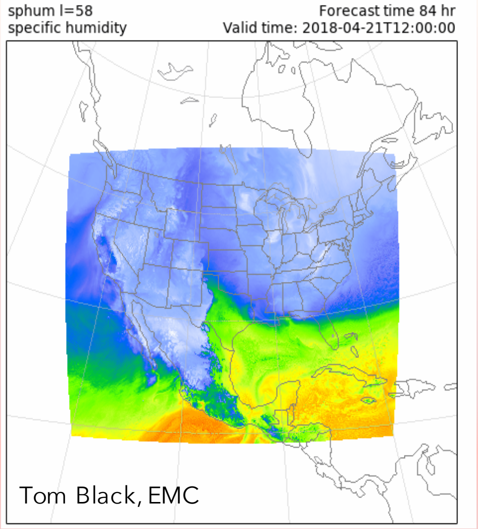
Global-to-regional Refinement

(two-way nesting, or stretching)

- Consistent, rapid interaction
- Improved BCs
- Large-scale interaction (great for TCs)
- Enables medium-range/S2S convective-scale prediction



Three-hour
BC Update Frequency



Limited-Area Regional Model

- Low computational overhead: Ideal for resource-limited users
- Simple and easy for short-term
- Good for extremely high resolutions
  LES, urban-scale, Warn-on-Forecast
  (3-km is not the end)

Rigorous Thermodynamics and Physics-Dynamics Coupling

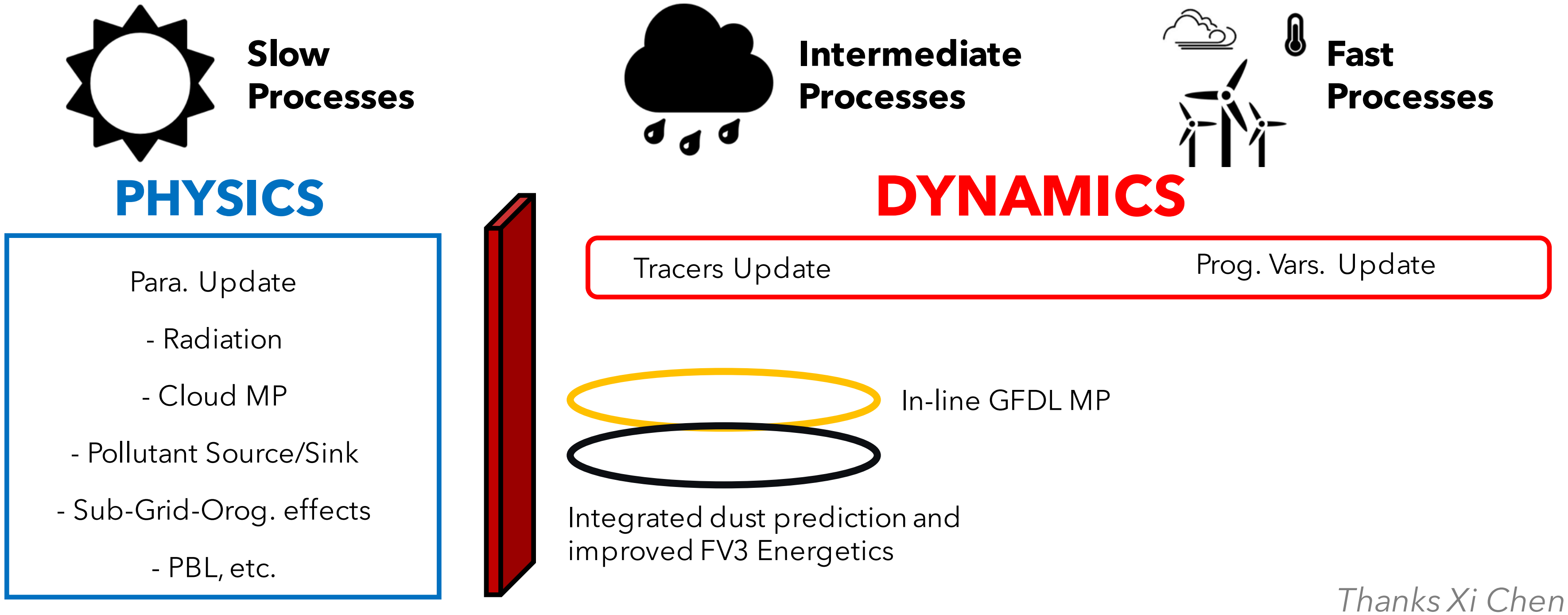
- Mass in FV3 includes water vapor and all condensates. Condensate loading and moist-mass effects baked-in.
  - Physics tendencies are tricky however
- FV3 incorporates the heat content of water vapor and condensates

- The GFDL microphysics is directly in-lined within FV3 and takes advantage of the numerics
  - Implicit Lagrangian sedimentation
  - Subgrid variability for fractional autoconversion
  - Sedimentation transports momentum and the heat of tracers
  - Consistent masses and energetics with dynamics.

J-H Chen and Lin, 2013 JClim
Harris et al. 2020, JAMES
Courtesy S-J Lin and Linjiong Zhou

Rethinking Physics-Dynamics Coupling

- Moving modeling forward requires breaking the strict separation of physics and dynamics.
- Partially-resolved and fast processes can be integrated directly into FV3 for better dynamical consistency, energy conservation, and efficiency



Thanks Xi Chen + Yuan Ma

Applications of FV3

The Global FV3 Community

github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere

UFS
UNIFIED FORECAST SYSTEM

GFDL
AM4 CM4 ESM4
SHiELD SPEAR

NATIONAL WEATHER SERVICE
GFSv15 v16 GEFSv12
MRW SRW HAFS …

NOAA 50 YEARS RESEARCH
NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION

GFDL FV3

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

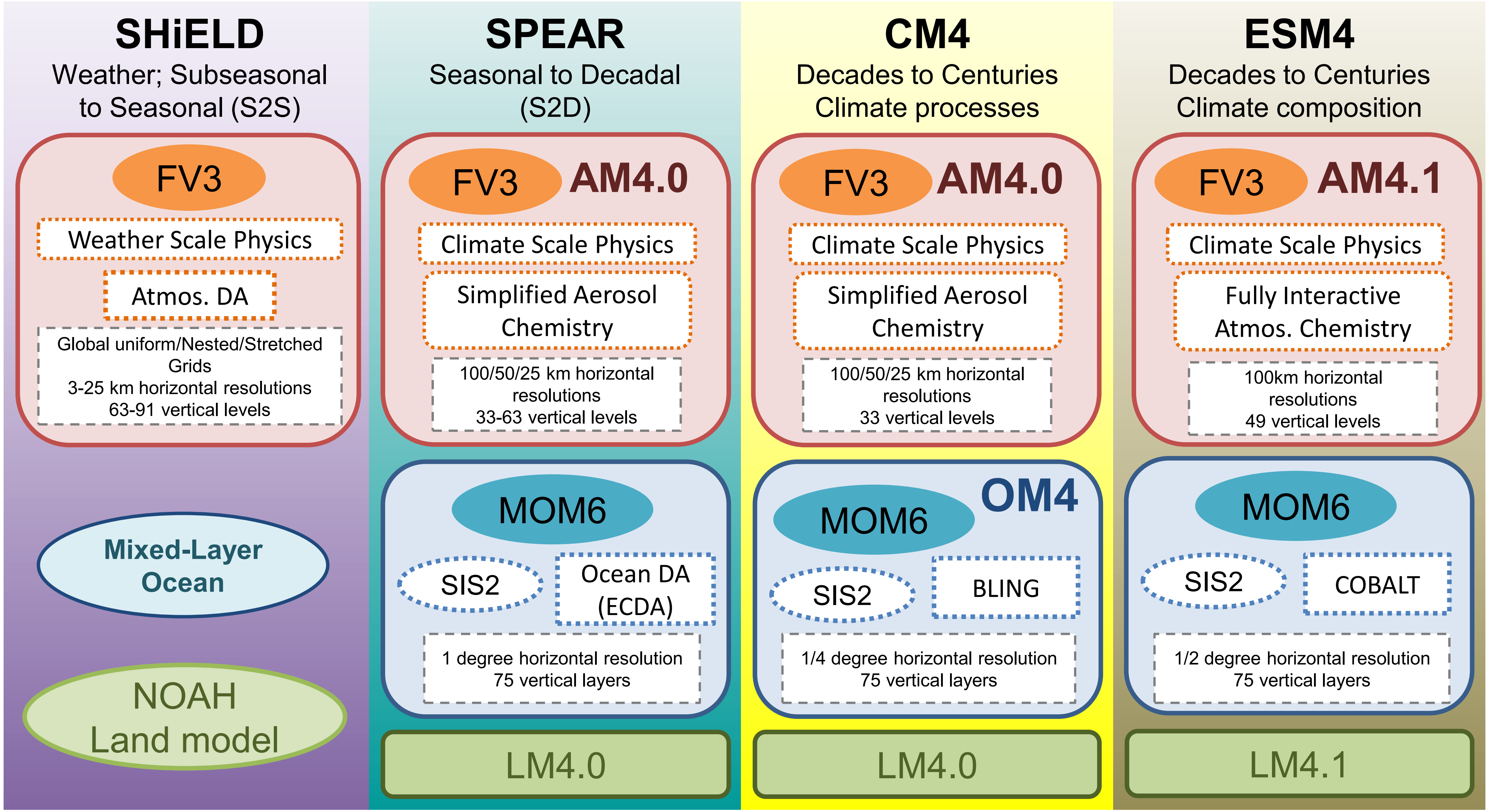
HARVARD
GEOS Chem
GEOS-Chem High-Performance

NCAR
CAM-FV
CAM-FV3

IAP
Chinese Academy of Sciences
LASG FAMIL

Taiwan Central Weather Bureau
CWBGFS

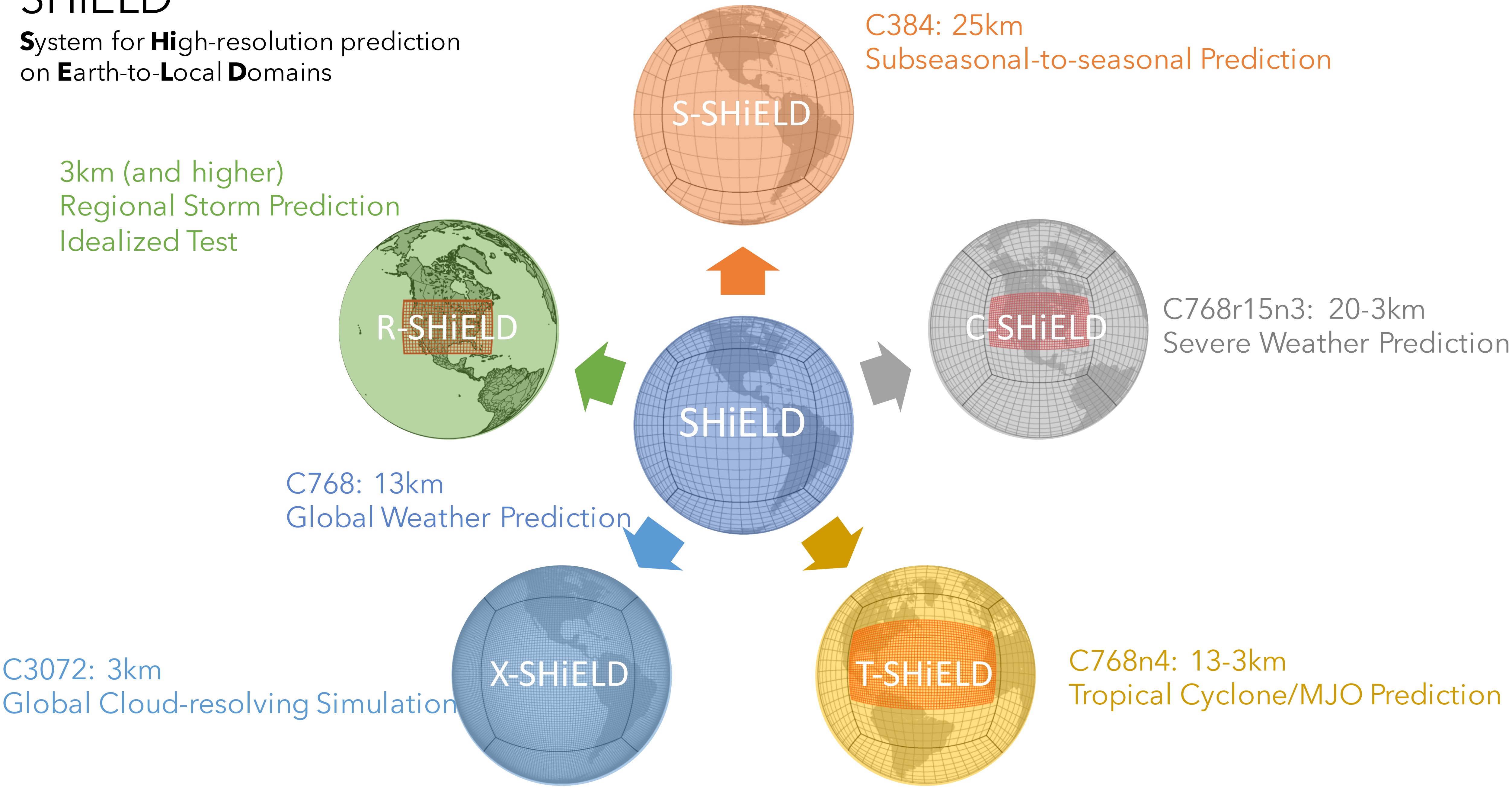
The GFDL Fourth-Generation Unified Modeling Suite



All models use the Flexible Modeling System (FMS) framework and are part of the Unified Forecast System

SHiELD

System for **Hi**gh-resolution prediction on **E**arth-to-**L**ocal **D**omains



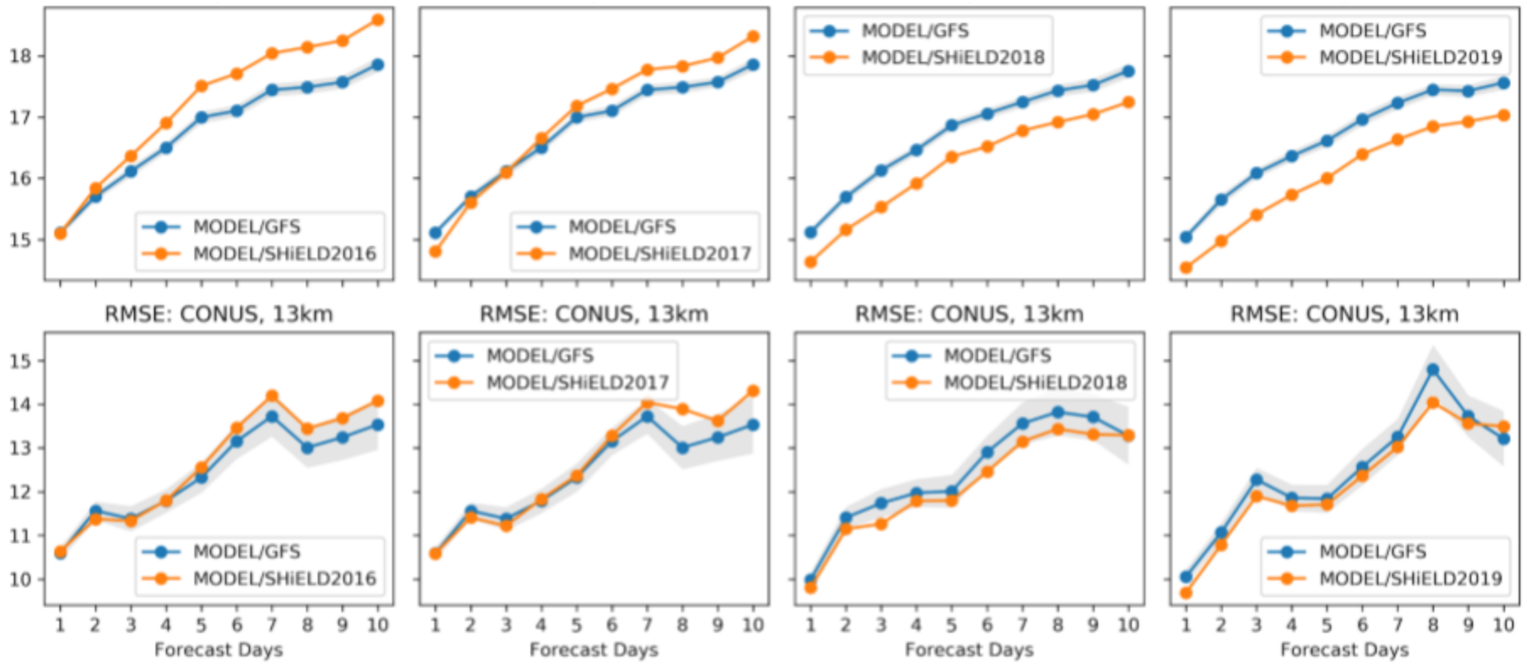
Courtesy of Linjiong Zhou, Kun Gao, and Kai-Yuan Cheng

13-km SHiELD Evolution

2016	2017	2018	2019	2020
Tuned NGGPS GFS Physics	GFDL Cloud Physics EMC SA-SAS	Inline GFDL MP Pos-Def Advection YSU Turbulence Mixed-layer Ocean	Updated FV3 Revised GFDL MP URI-GFDL Sea State	Overhauled GFDL MP New cloud-radiation UW-EMC TKE-EDMF

Tropical Precipitation vs. TRMM
25-km data

CONUS Precipitation vs. StageIV

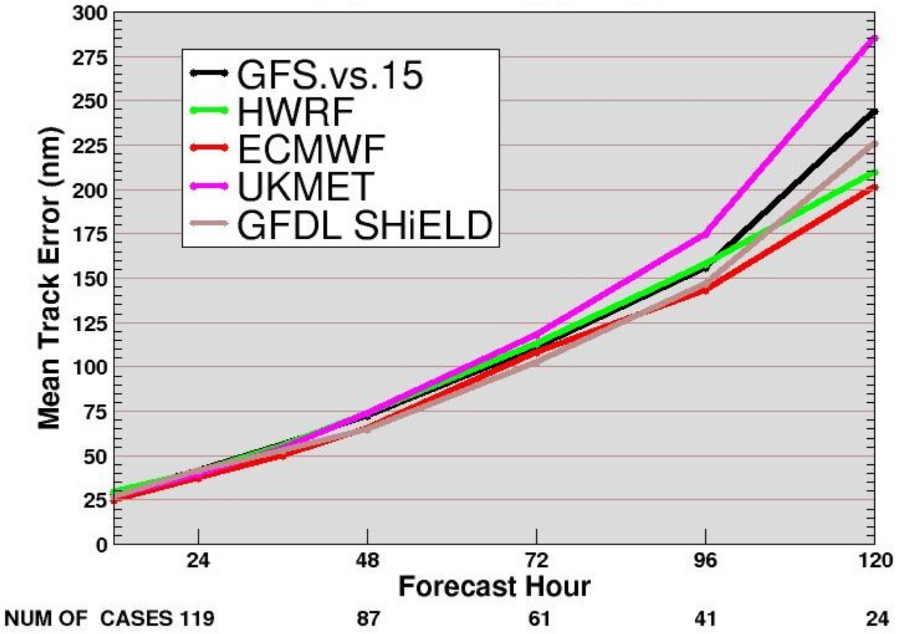


RMSE: Lower is Better

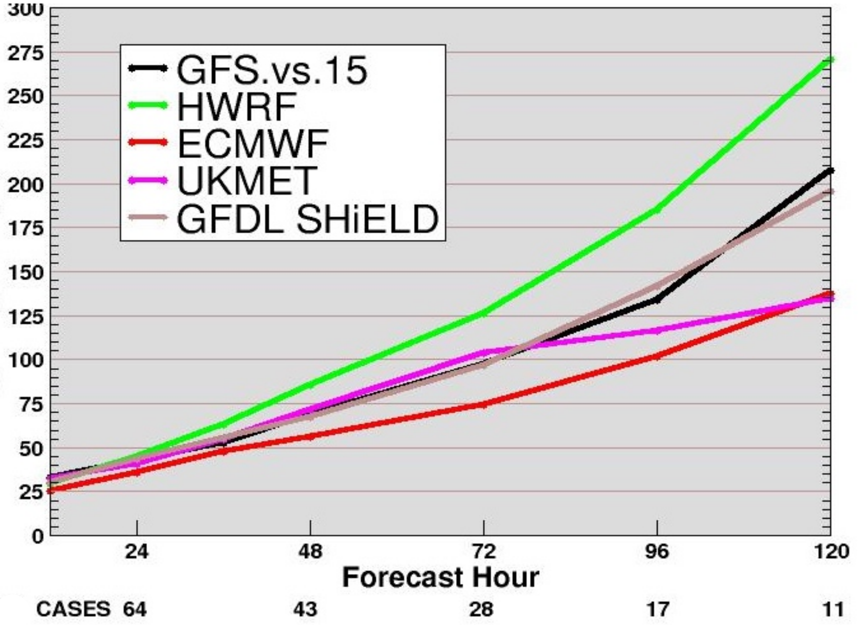
Courtesy Linjiong Zhou; Harris et al, 2020, JAMES

SHiELD Hurricane Tracks

Atlantic Track Model Error

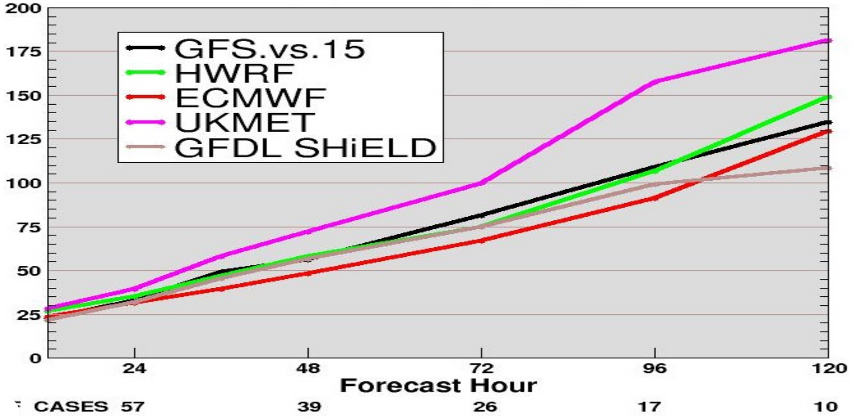


Eastern Pacific
Track Model Error



Western Pacific
Track Model Error

Y-axis squashed to match other plots



Results as of 00Z 14 September

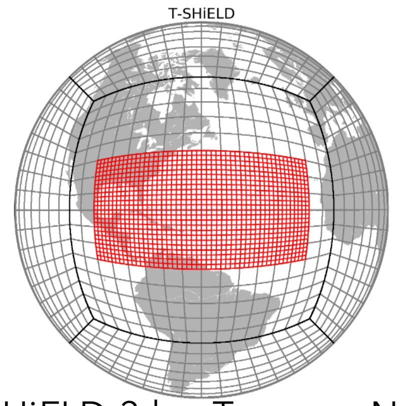
See shield.gfdl.noaa.gov
for real-time forecasts

WARNING

Season still ongoing
Skill subject to change

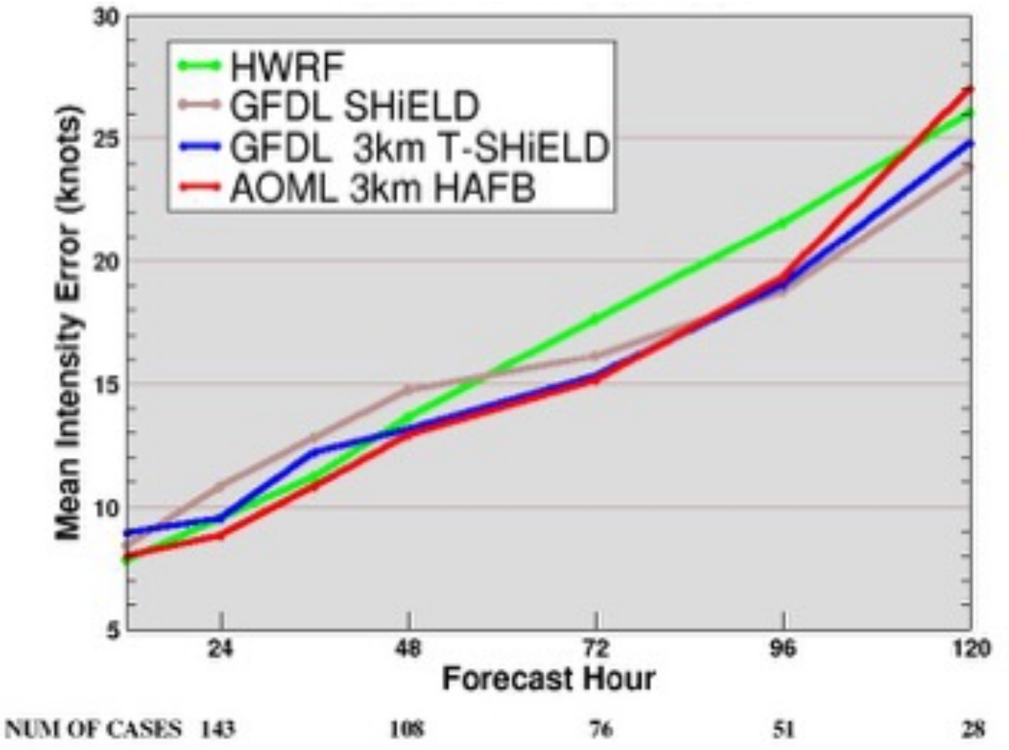
Courtesy Kun Gao & Morris Bender

SHiELD & T-SHiELD Intensity

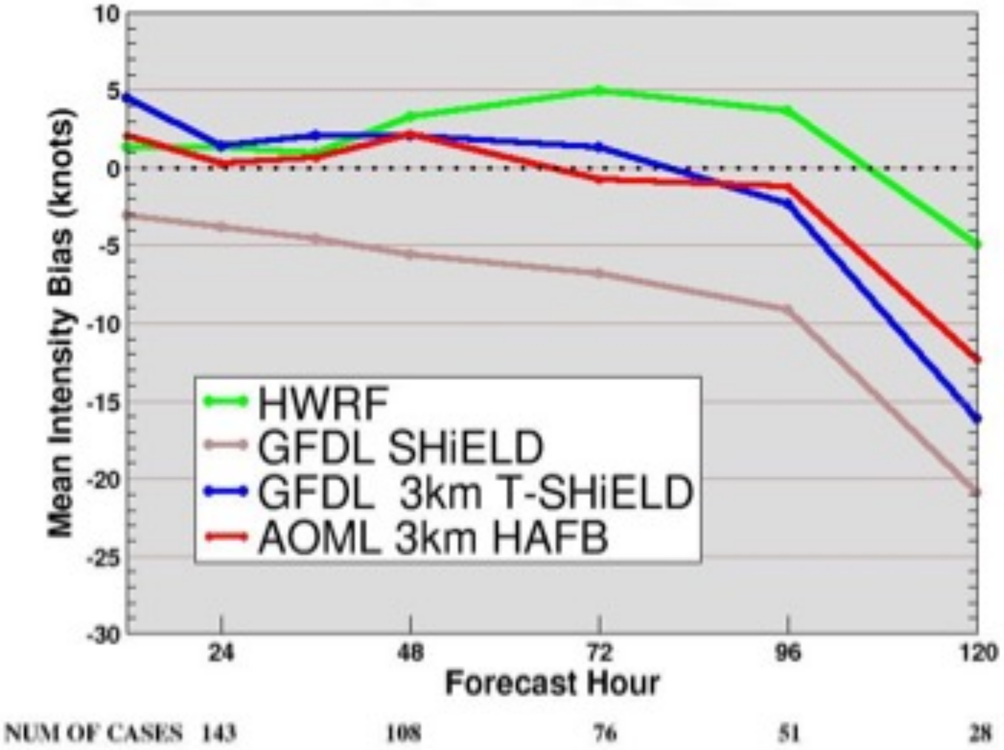


T-SHiELD:3-km Two-way Nest
("HAFS-B" is similar)

Atlantic Model Intensity Error



Atlantic Model Intensity Bias



Courtesy Kun Gao, Andy Hazelton, and Morris Bender

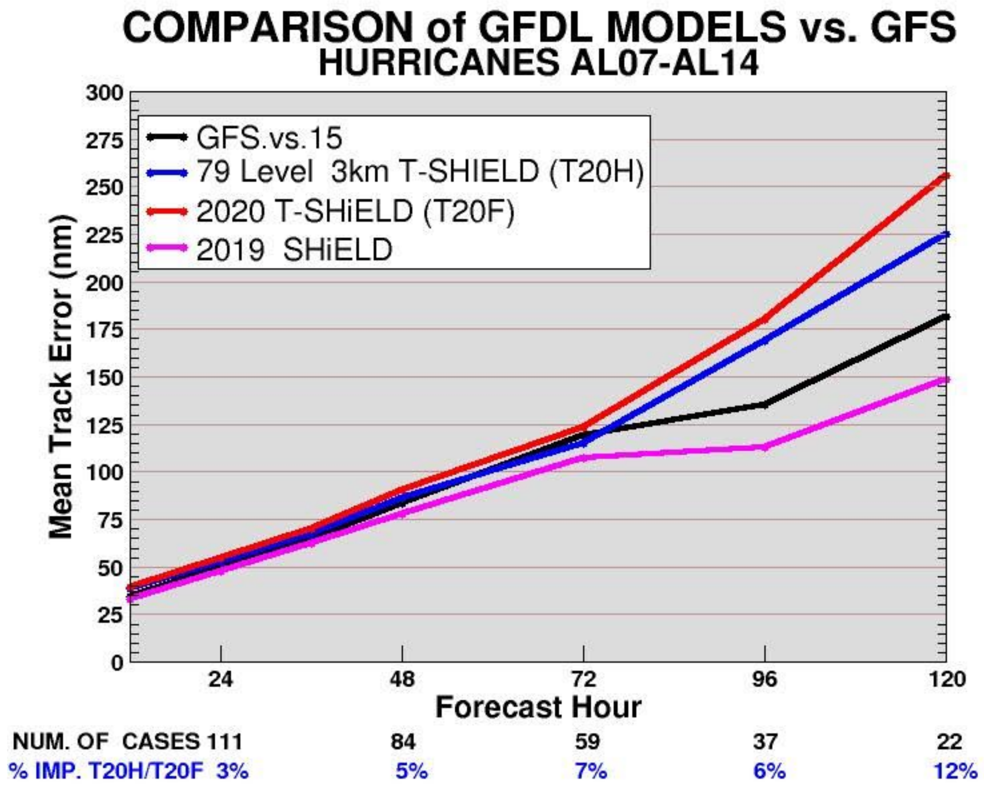
Vertical Resolution and Vertical Nesting

SHiELD uses 91 levels while T-SHiELD uses only 63. May be limiting representation of shear distorting hurricane vortices.

Vertical nesting: increase T-SHiELD to 79 levels on the nest *only*. Runtime increases by only 5%.

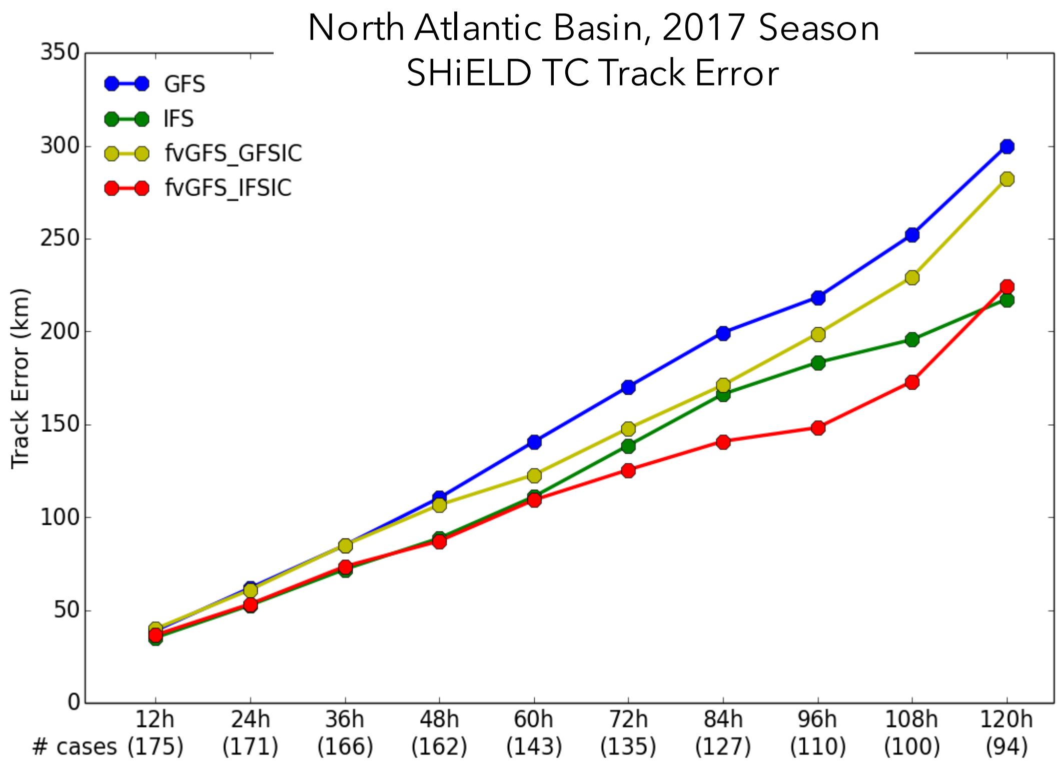
→12% lower track error at day 5.

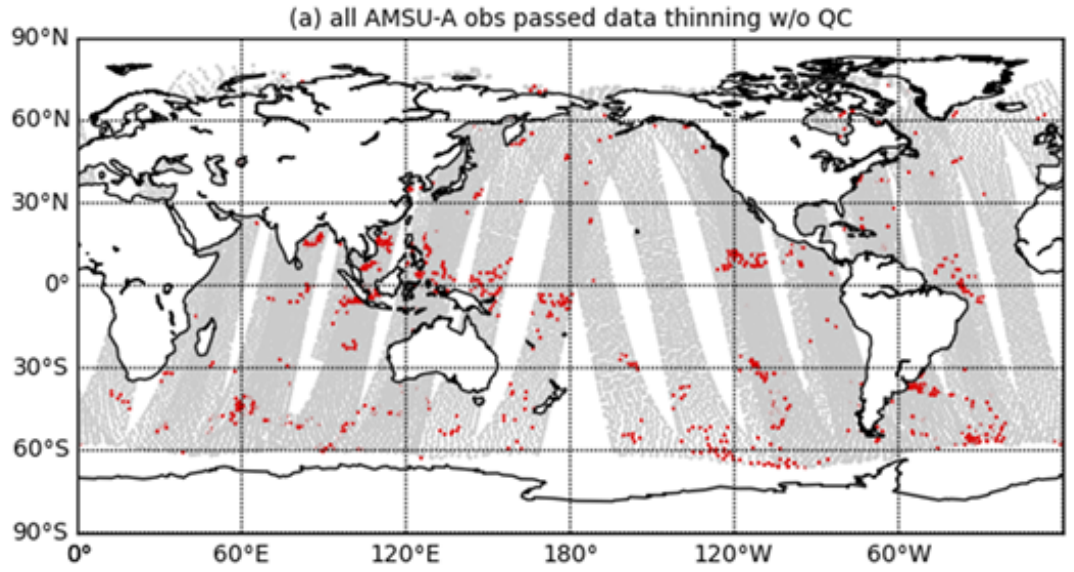
Also investigating role of interactions with topography.



Courtesy Kun Gao & Morris Bender

Better forecasts? Better ICs!





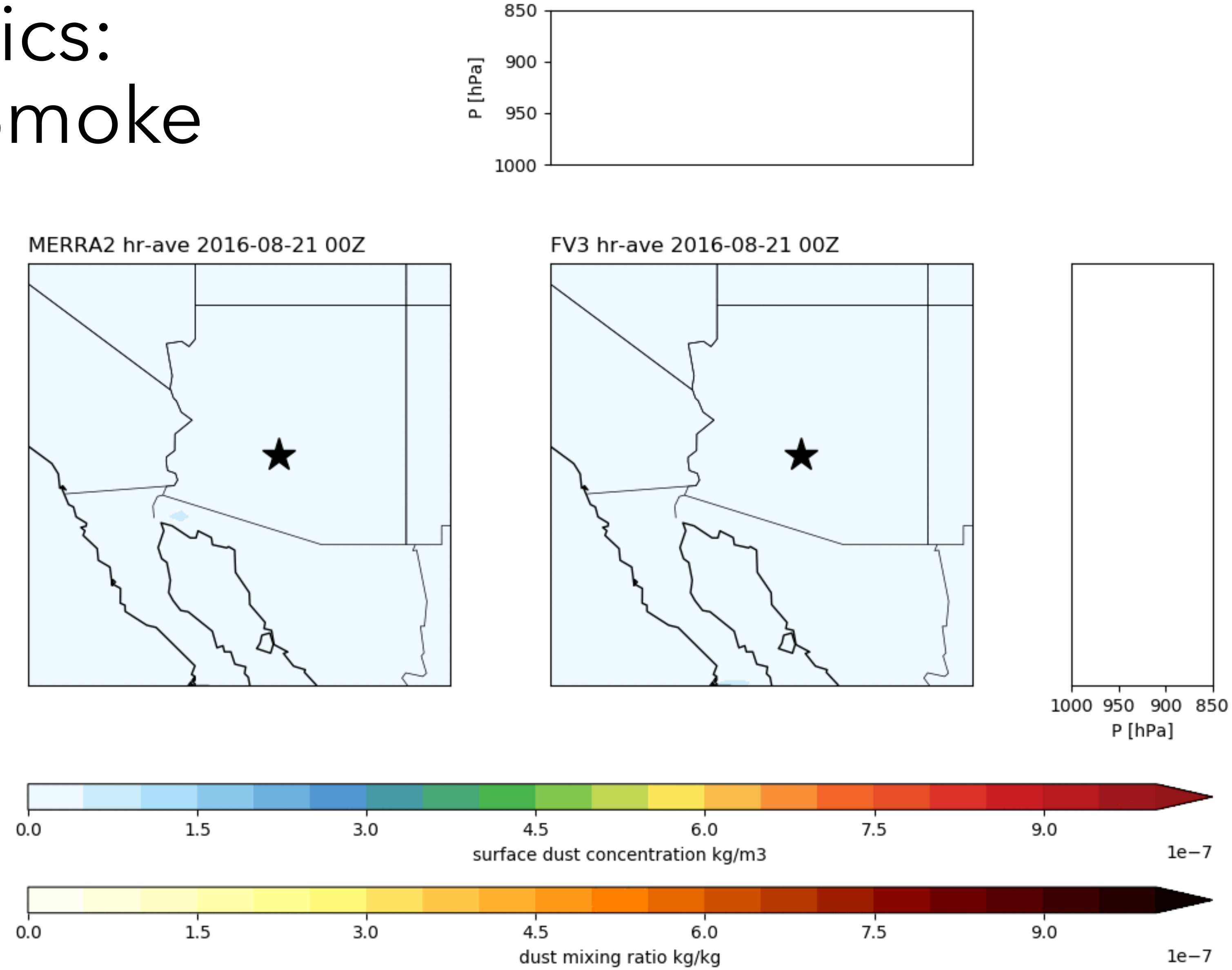
Collaborations with ECMWF

- J-H Chen et al. 2019, GRL
- Magnusson et al. 2019, QJ
- Ongoing Dimosic Project

DA in FV3-based GFSv15 prototype
New radiances available for assimilation from high-impact areas in all-sky data assimilation

M Tong et al. 2020, MWR

Integrated Physics: In-Line Dust & Smoke

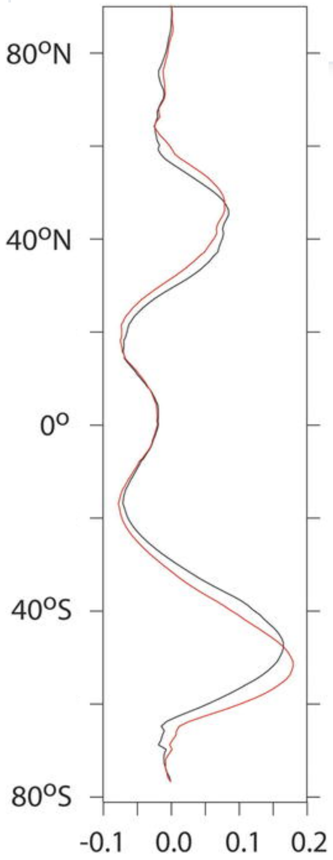


Dust emission in-line with FV3 advection

Wet deposition and prognostic drop number can be implemented within in-line GFDL MP

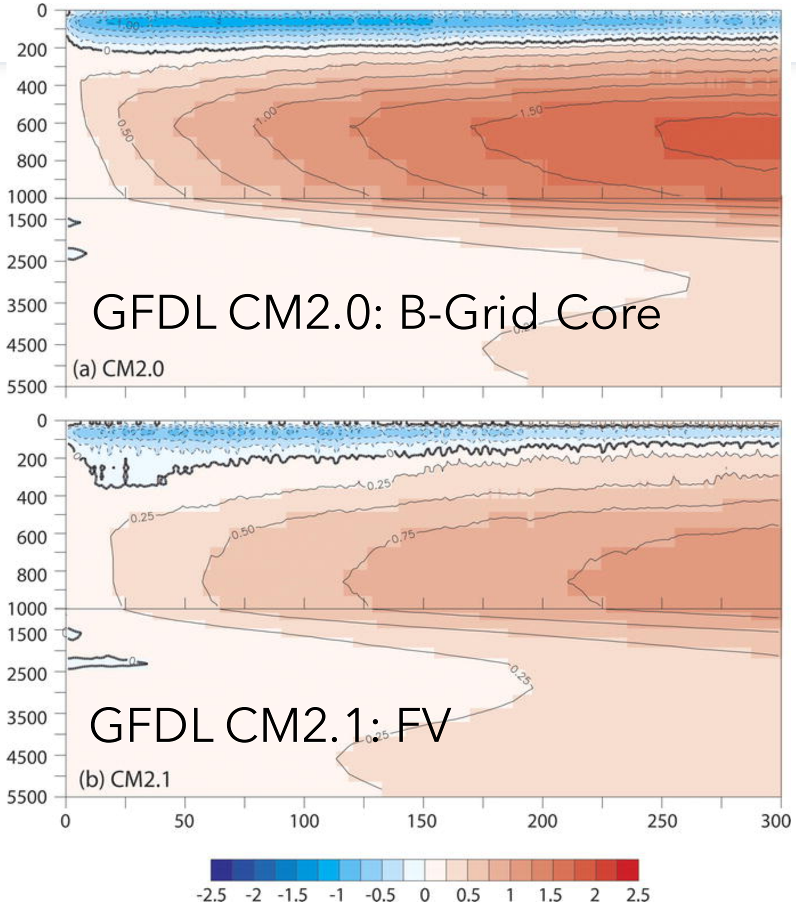
Courtesy Xi Chen and Paul Ginoux

Seamless Modeling: Vorticity Dynamics

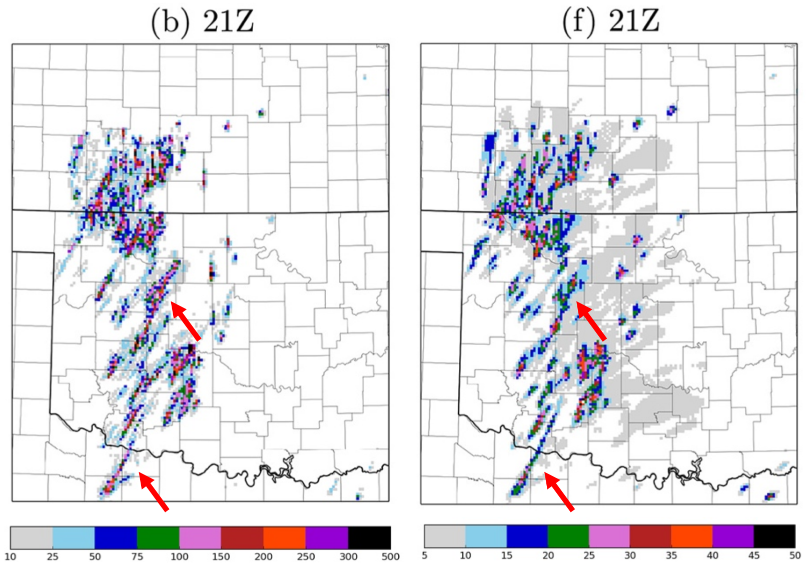


Zonal-mean wind stress: **CM2.0** vs. **CM2.1**

Delworth et al. 2006 JClim



Global-mean Ocean Temp diff. (K) in control-climate integrations

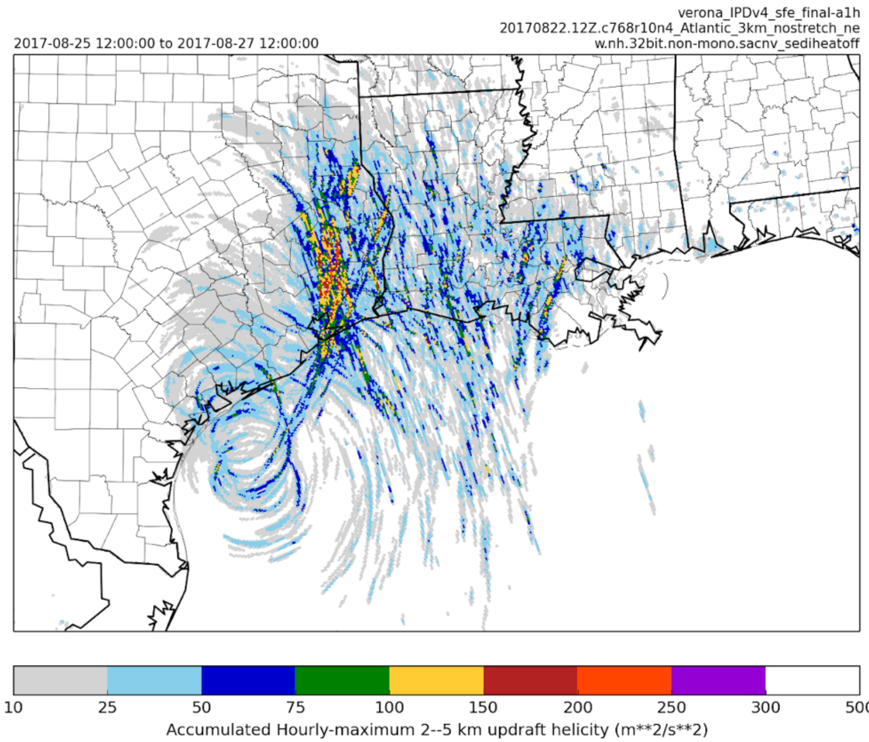


Hourly-Maximum UH (w x ζ, m^2s^{-2})

Hourly-Maximum column-max w (m^1s^{-1})

C-SHiELD (3-km US nest)
Oklahoma severe weather
16 May 2017

Harris et al. 2019, JAMES

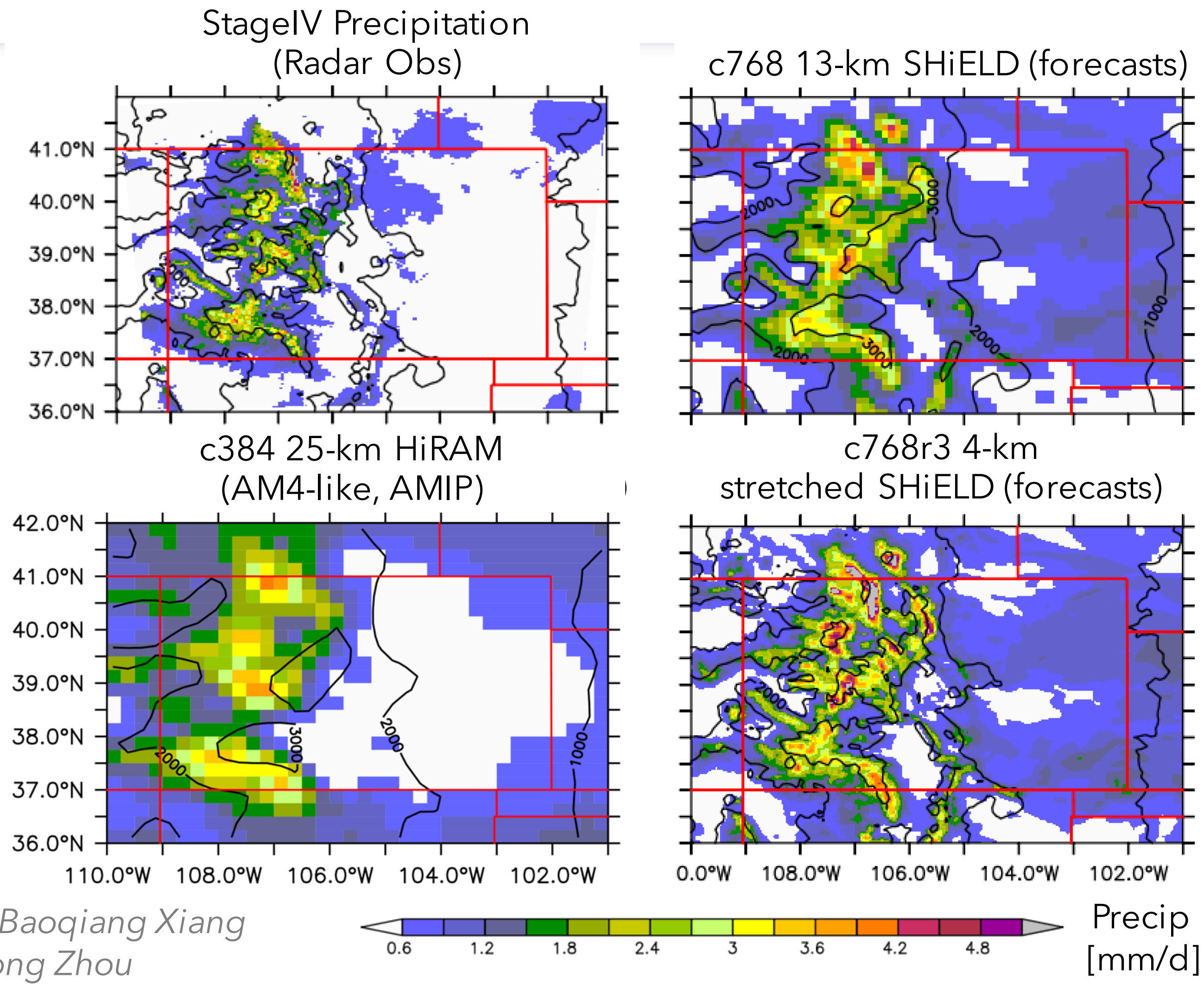


T-SHiELD (3-km Atlantic nest)
48-hour max

Updraft Helicity
Initialized 00Z
22 August

Hazelton et al. 2018b Wea. Forecasting

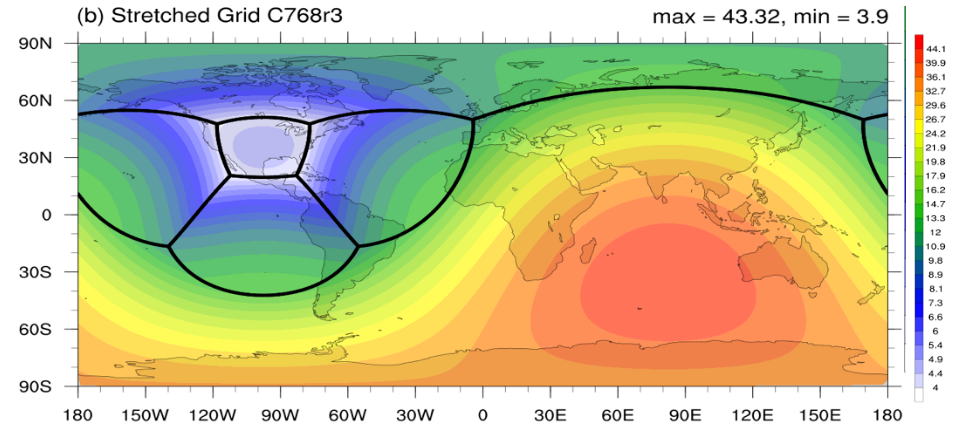
Seamless Modeling: Orographic Precipitation



Courtesy Baoqiang Xiang and Linjiong Zhou

Relevant mountain features captured even at 25-km resolution become very well-represented at 4-km.

Too much drizzle due to SAS shallow convection.



Grid-cell Width in Stretched Grid: Zhou et al. 2018, BAMS

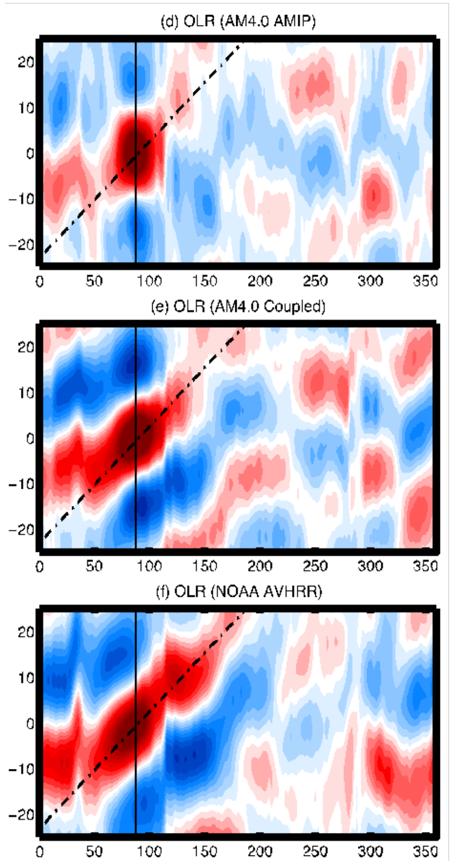
Seamlessness in the GFDL Modeling Suite: The Madden-Julian Oscillation

CMIP Earth-System Models

CM4 Coupled Climate Model

100-km AM4 Atmosphere
(C96 FV3 + GFDL Climate Physics)
+ 25-km MOM6 + LM4

Even at 100-km good MJO propagation is found…if coupled to an ocean



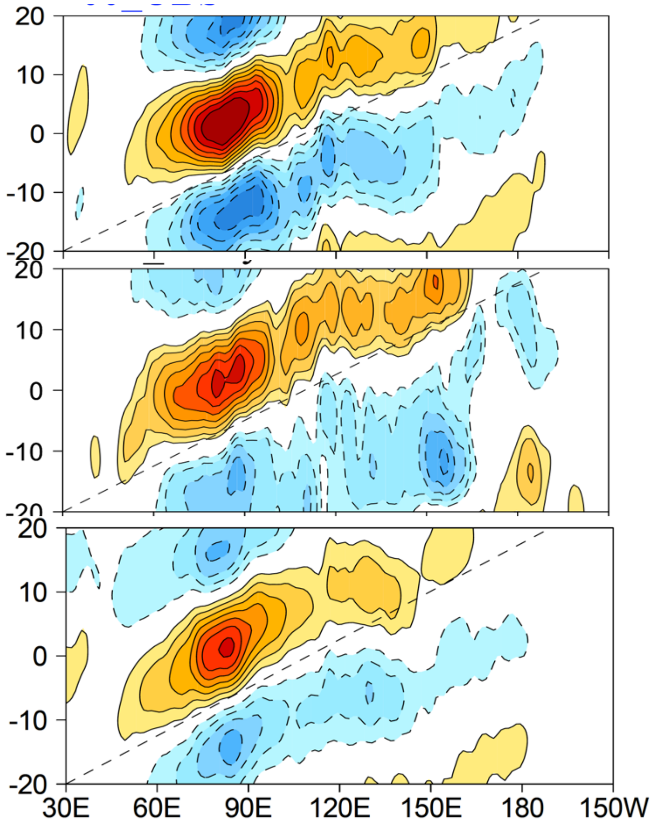
Zhao et al. 2018a,b

S2S & S2D Prediction Models

Observations

25-km S-SHiELD
Atmos. w/ MLO

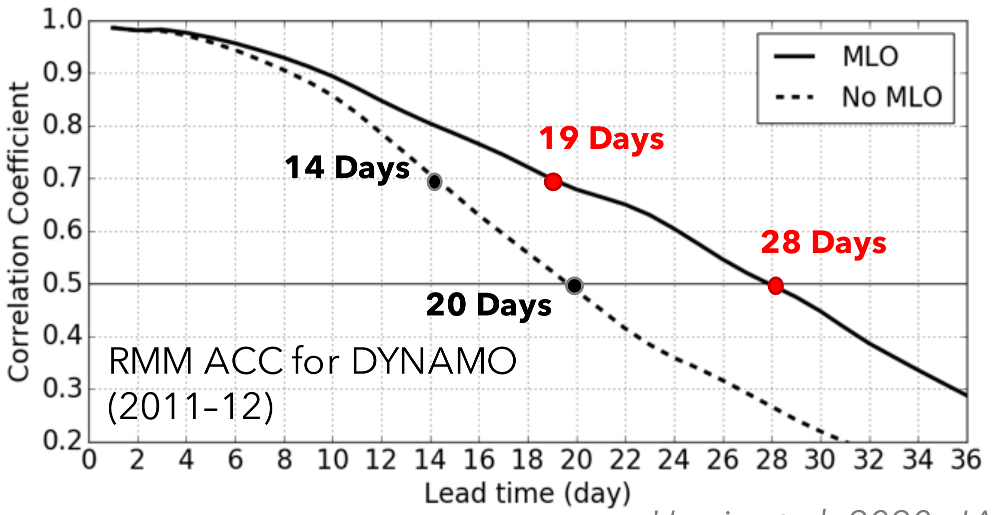
50-km SPEAR
MOM6-Coupled S2D



Courtesy Baoqiang Xiang

Seamlessness in the GFDL Modeling Suite: MJO Prediction Skill

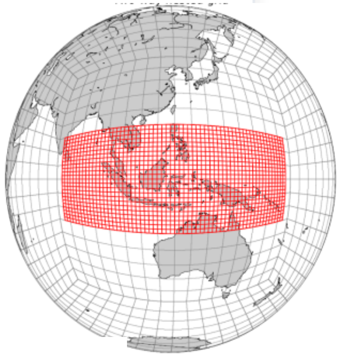
25-km S-SHiELD

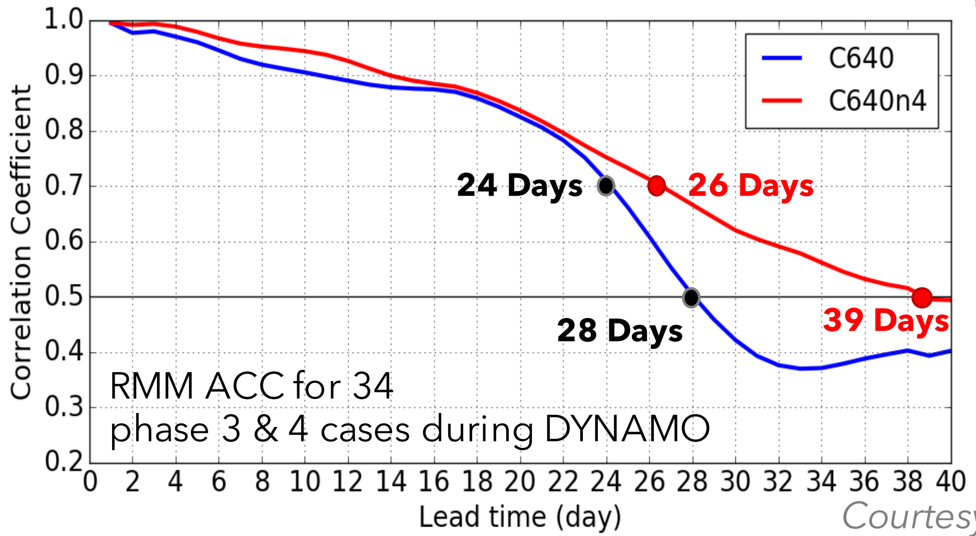


Harris et al. 2020, JAMES

Mixed-layer ocean adds 8 days of useful skill

4-km nested T-SHiELD





Courtesy Kun Gao

4-km Maritime Continent Two-Way Nest improves predictability and propagation of MJO compared to **16-km uniform**

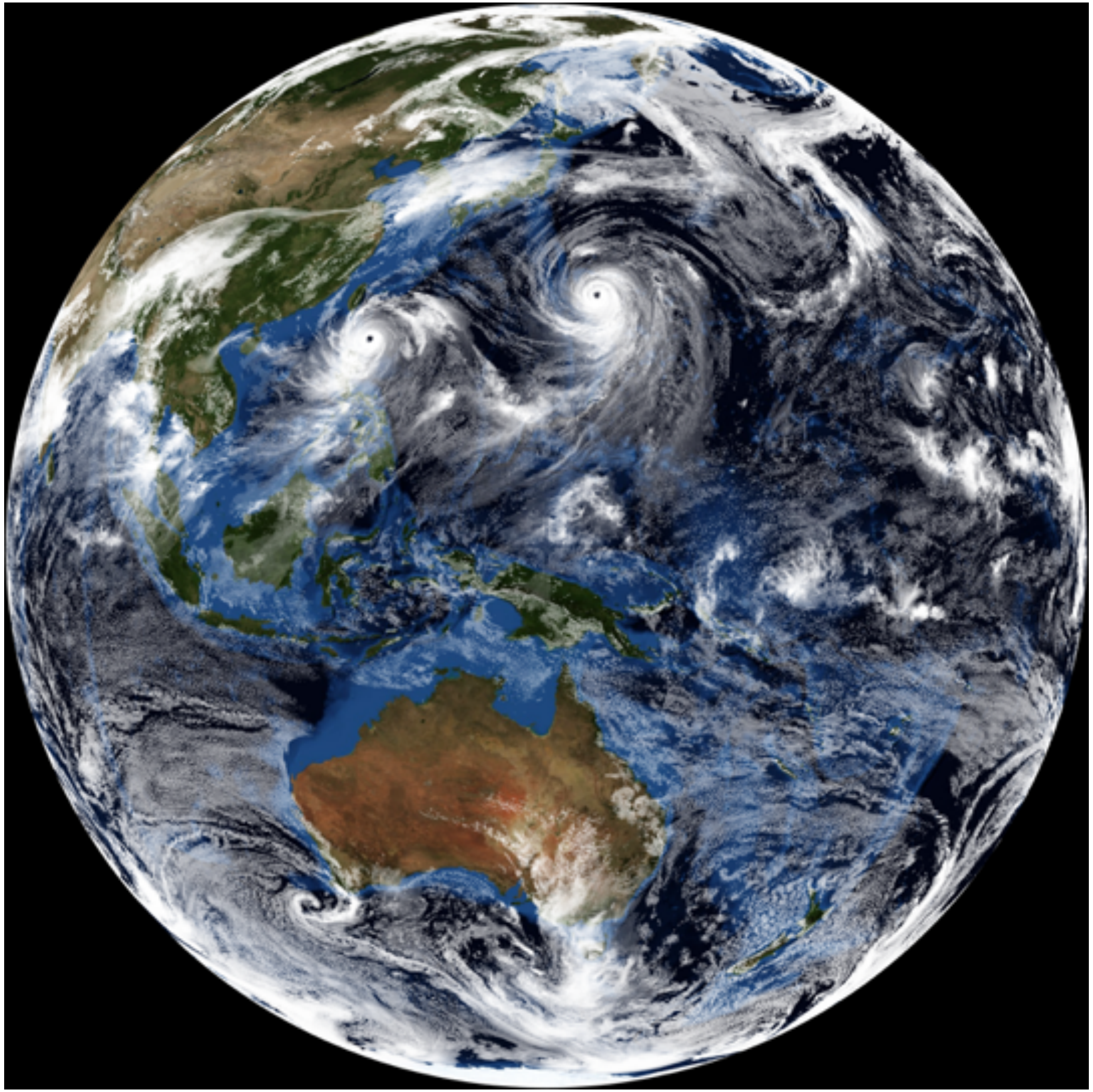
X-SHiELD

3.25-km (C3072) GCRM seamlessly integrated with other GFDL models

Partnering with Vulcan, Inc and the University of Washington to build a hybrid ML model to emulate X-SHiELD in a cheap low-resolution model

VULCAN

GFDL



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

X-SHiELD Performance

- X-SHiELD is efficient but still too slow for everyday use.
- Previous NASA Goddard port of FV3 to CUDA found large speedups, but very labor-intensive
- Public-Private-Academic Partnership to port FV3 and GFS Physics into GridTools DSL through GT4Py

Goal: Practical 1-km global model

X-SHiELD C3072 L79		
Gaea c4	13482 CPUs	75 min/day
Orion (MSU)	12288 CPUs	68 min/day
Courtesy Rusty Benson	27648 CPUs	33 min/day
	36864 CPUs	26 min/day

(Timing does not include I/O)

GridTools

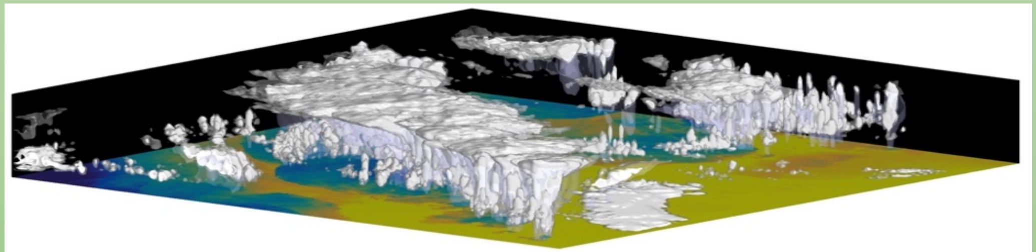
CSCS Centro Svizzero di Calcolo Scientifico Swiss National Supercomputing Centre

ETH zürich

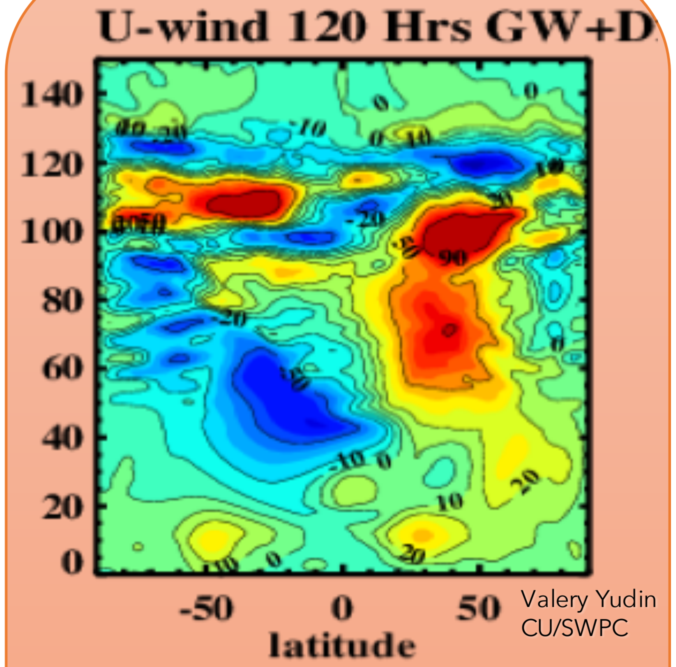
VULCAN

GFDL

Coming Attractions



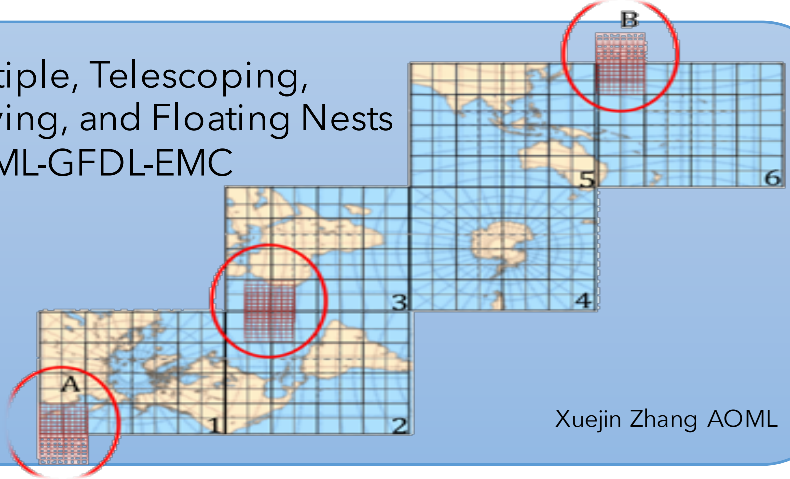
Process-study framework for Physics-Dynamics Interactions



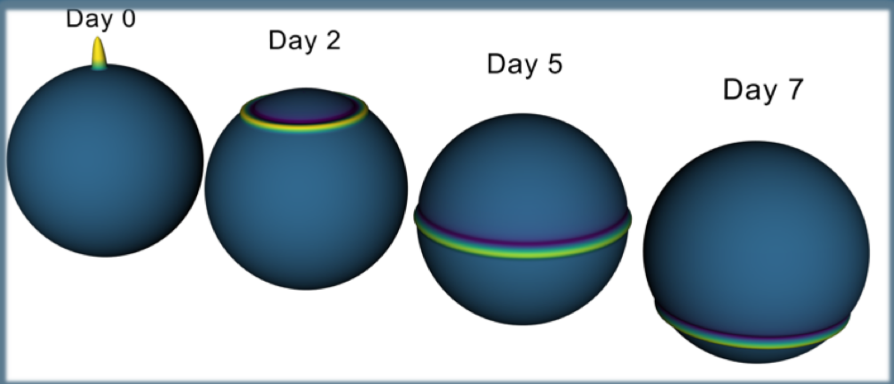
Deep atmosphere for Space Weather and Whole Atmosphere EMC-GFDL-SWPC

Unified Physics & Dynamics

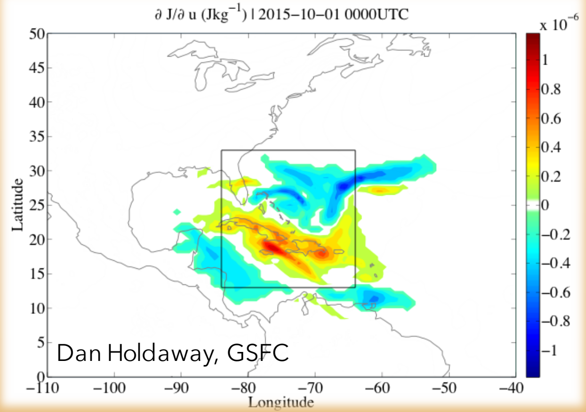
Multiple, Telescoping, Moving, and Floating Nests AOML-GFDL-EMC



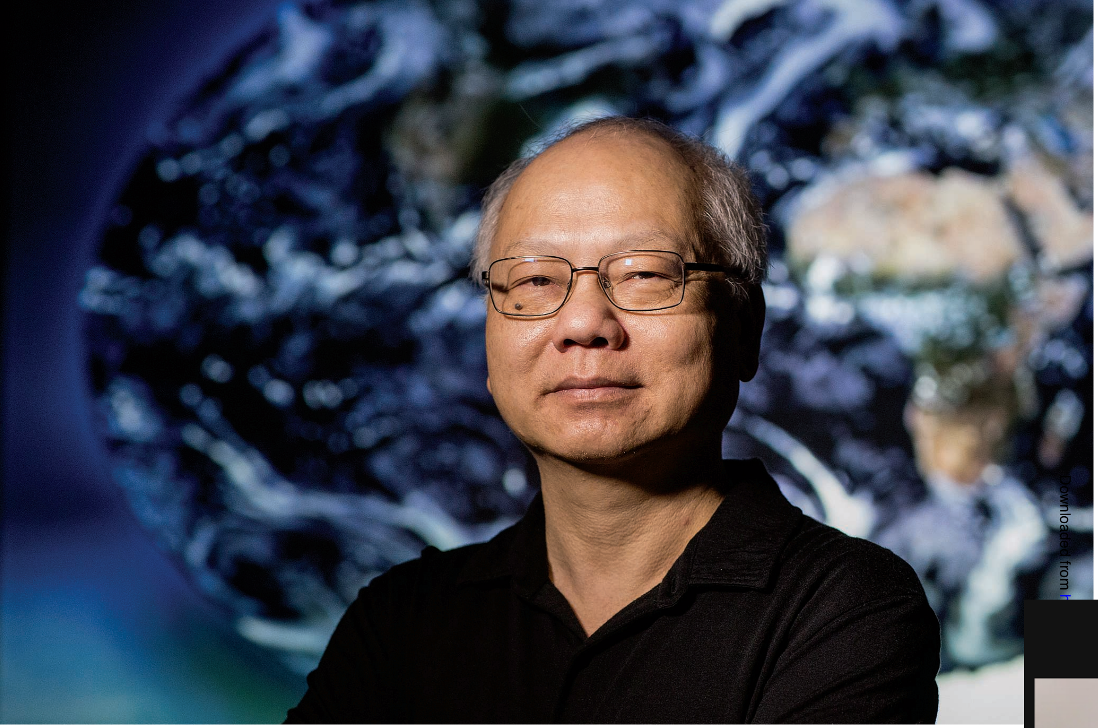
Xuejin Zhang AOML



LMARS Simplified Riemann Solver
X. Chen et al 2013, 2018, 2020
Li and X. Chen 2019



FV3 Adjoint: NASA Goddard



THE WEATHER MASTER

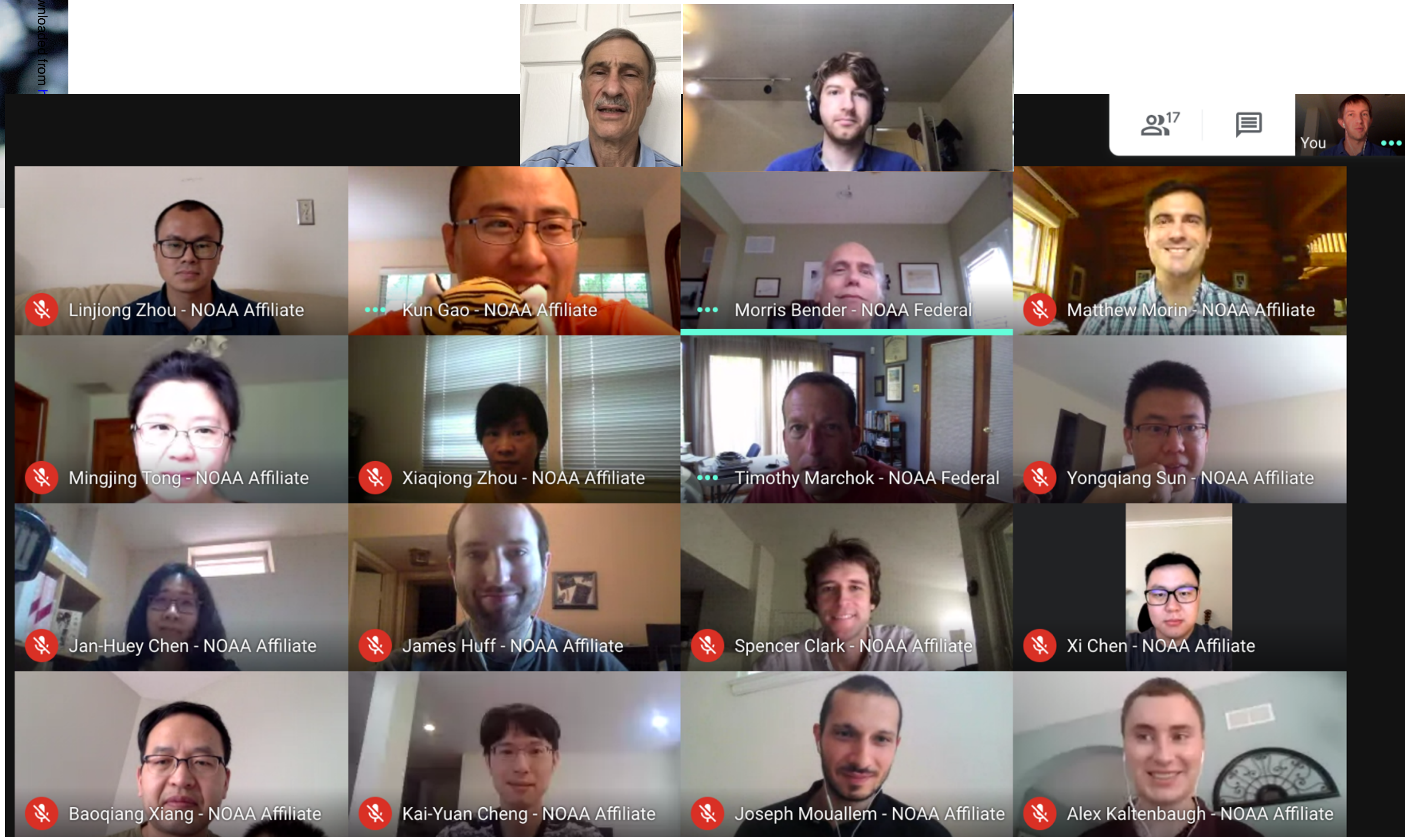
How Shian-Jiann Lin's atmospheric grids could unify weather forecasts and climate models

By **Paul Voosen**

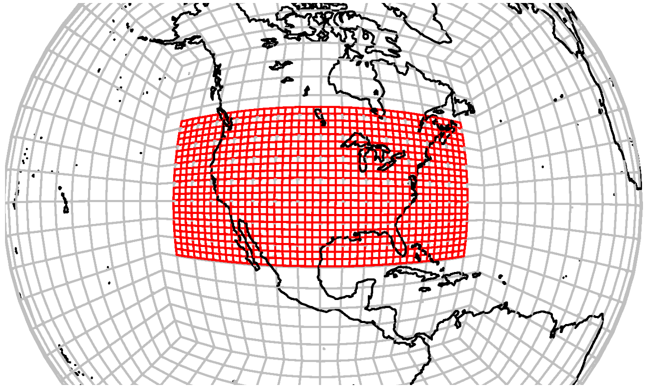
www.gfdl.noaa.gov/fv3

shield.gfdl.noaa.gov

github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere



C-SHiELD
Severe Storm Forecasts



- Leverages advances from other SHiELD configurations
    - Revised diffusion and shallow convection, updated GFDL microphysics and PBL
- Submitted to 2020 Spring Forecasting Experiment at the NOAA Hazardous Weather Testbed in Norman, OK
    - Received high marks for pre-storm environment and cold pools
    - FV3-NSSL (diff. MP, PBL, LSM) does very well with storm structure every year
- Further evaluation is forthcoming