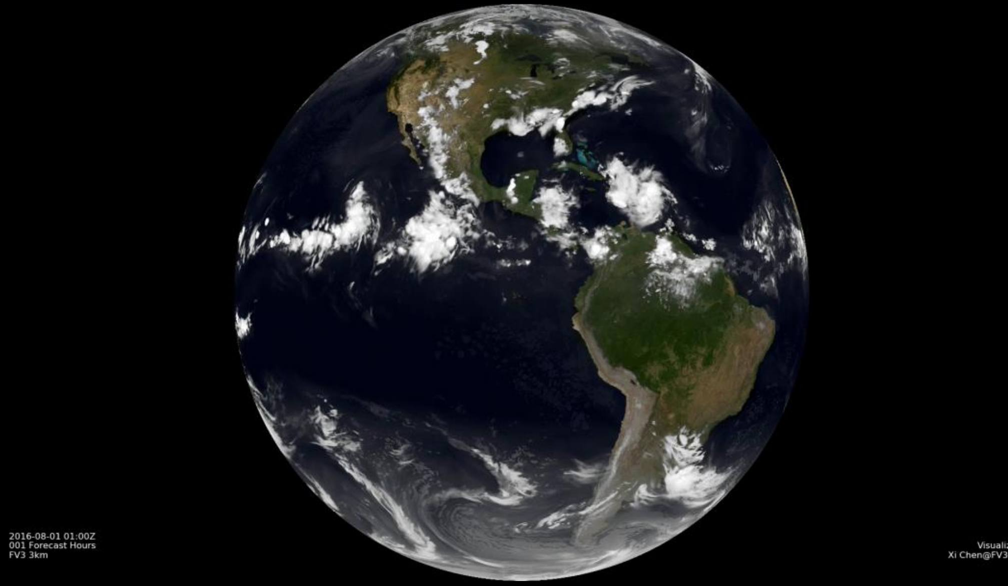
An Efficient Integrated Dynamics-Physics Coupling Strategy for Global Cloud-Resolving Models

S.-J. Lin, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton
The concept of "Super Dynamics developed while sabbatical at RCEC, Academia Sinica, Taipei

- ❖ **Feasibility, fidelity, and accuracy of FV3-GCRM for 10-day NWP (with 2016 FV3)**
- ❖ **The "Super Dynamics" project (2020 FV3)**
  - ➢ An optimal combination of "grid-scale" dynamics with built-in "sub-grid" processes - embedding "column physics" within "dynamics"
  - ➢ To improve dynamics-physics interaction, and to enhance computational efficiency (enabling large-time-step integration, and better use of CPU-cache or accelerator)

Large-Time-Step demo: 2020 FV3 (3-km, Δt=225 sec)



Status of the "2016 FV3"

Weather Applications:

- The GFDL FV3 "dynamical core" was selected in **2016** as the "engine" for the Next Generation Global Prediction System (NGGPS)

- Since Jan 2018, NOAA is developing a Unified Forecast System (UFS) based on FV3 – **the unification between the Global models for 1) weather, 2) space weather, 3) S2S, and 4) regional forecast systems**

Climate Applications:

- NASA GEOS and **all** NOAA/GFDL models for **IPCC** are based on the FV3

FV3: physically representing the atmosphere by finite control-volumes

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

2. Physically based forward-in-time "horizontal" transport (only "2D" between two Lagrangian surfaces)
    - Locally conservative and (optionally) monotonic via constraints on sub-grid distributions (Lin & Rood 1996; Putman & Lin 2007) – particularly good for aerosols and cloud micro-physics
    - Space-time discretization is non-separable -- hallmark of a physically based FV algorithm

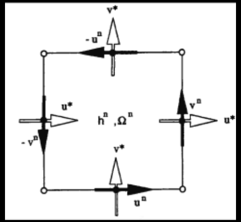
3. Combined use of C & D staggering with optimal **Potential Vorticity** advection and **Helicity** representation

→ important from TC-permitting (100-km) to tornado-permitting (1-km) 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

5. Non-hydrostatic extension: the vertically Lagrangian discretization reduces the sound-wave solver into a 1-D problem (solved by either a Riemann-Invariant method or a semi-implicit solver)

The FV3's C-D grid works like Yin-Yang

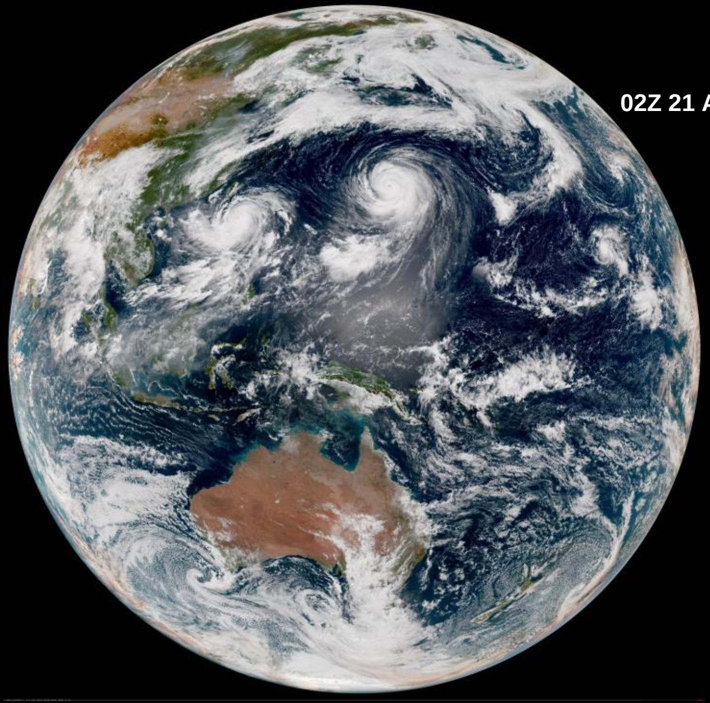


Helicity

A glimpse into the future of Numerical Weather Prediction?

Global cloud-resolving (3-km resolution, equivalent to 56 megapixels) prediction with FV3

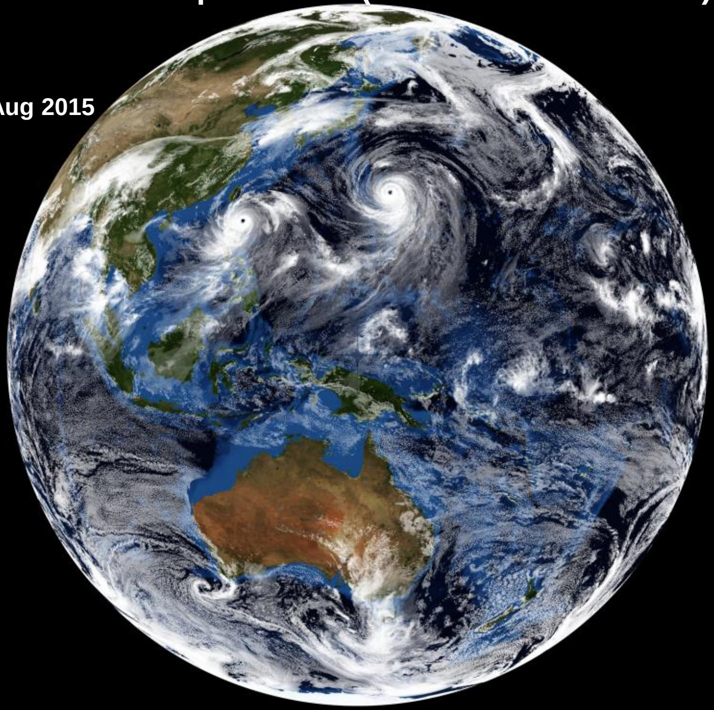
Himawari Satellite



Source: http://www.jma.go.jp

02Z 21 Aug 2015

50-hour prediction (INIT: 00Z 19AUG 2015)



FV3 initialized with IFS IC (courtesy of Linus Magnusson, ECMWF)

Can a FV3-powered GCRM compete with the best NWP model in the synoptic scale (200 km or larger)?

Experiment with ECMWF-IFS initial conditions (~ 9 km)

Period:

- **20150814** – **20160809** (twice per months, 24 cases total). IFS data at **9-km L137** data, courtesy of Linus Magnusson, ECMWF

Initialization:

- Only the atmospheric state from the IFS is used
- The land properties and IC are interpolated from GFS

Model tuning:

- A climate-oriented tuning was performed with the GFDL cloud Micro-Physics

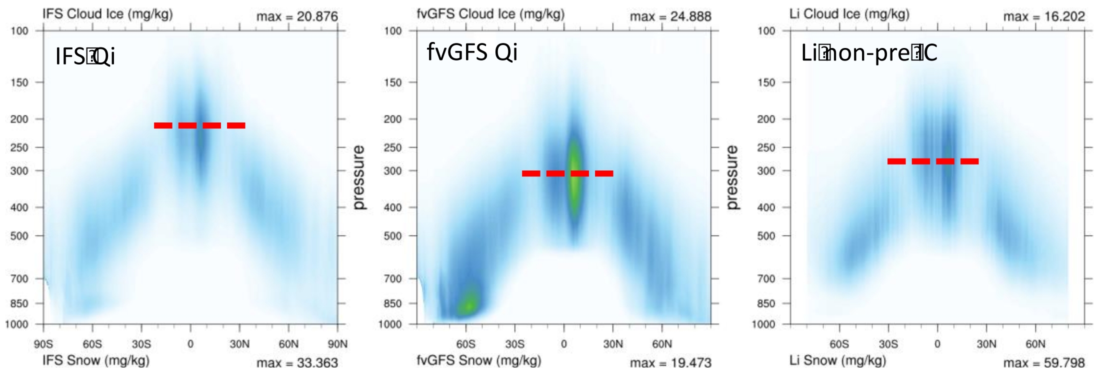
- ### Metrics for evaluation?

- **Let's start with the usual suspect: the Anomaly Correlation Coefficient of 500mb Height**

"Calibrating" cloud condensates with ECMWF analyses and CloudSat

Cloud ice (zonal mean)

IFS analyses (Aug2015-Aug2016) | **13-km FV3 forecasts (Aug2015-Aug2016)** | **CloudSat (Li, et al., JGR, 2012)**



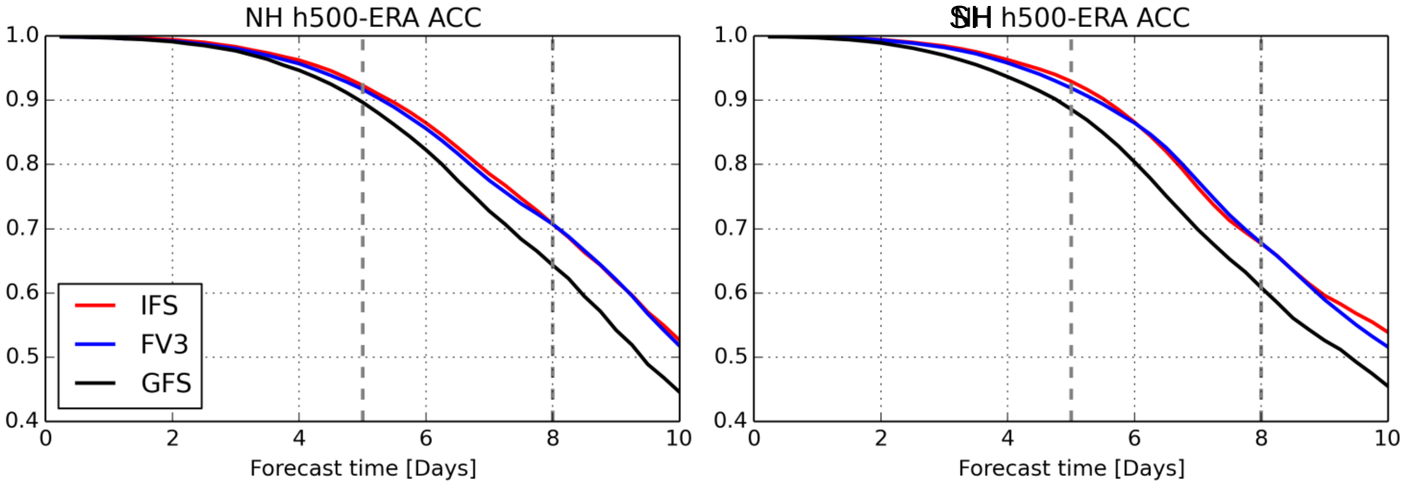
(IFS data courtesy of Linus Magnusson, ECMWF)

500-mb Height ACC (synoptic scale >200 km)

Global Cloud-Permitting FV3-GFS (C3072_L63) vs. NCEP-GFS and ECMWF-IFS

Skill Comparison (24 cases, twice per month for a full year)

Anomaly Correlation Coefficients (ACC) of 500-mb Height

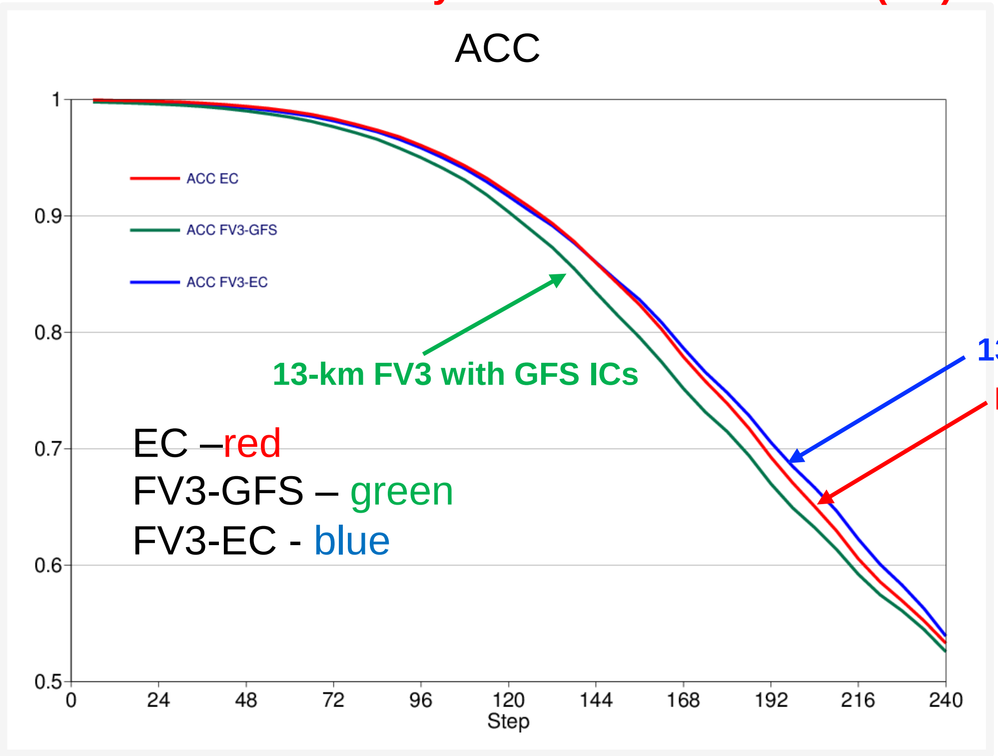


Note: FV3-GFS at 13-km has slightly higher scores

2016 FV3: Forecast Experiment with GFS and ECMWF ICs

(August 2015 to August 2016, every 5th day = 73 cases)

500-mb Anomaly Correlation Coefficient (NH)

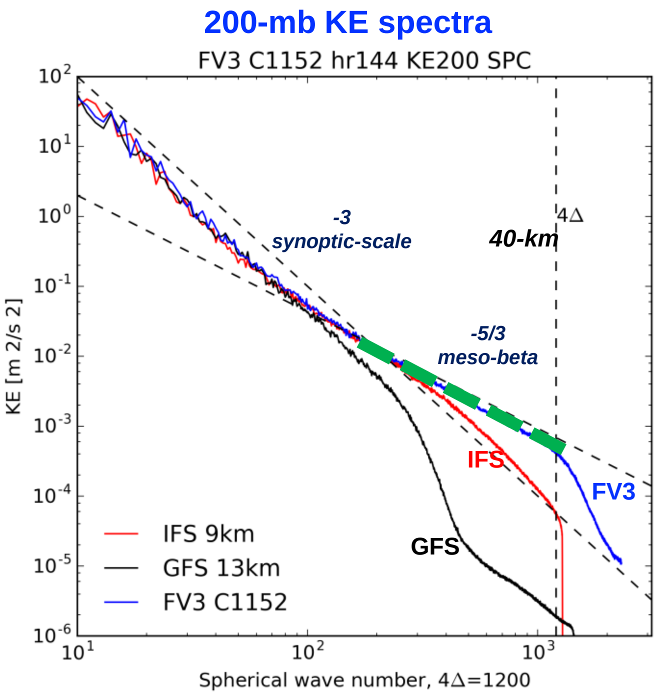


13-km FV3 with ECMWF ICs

ECMWF official forecasts

(ACC computed using EC method by Linus Magnusson, ECMWF)

- **How well do ECMWF-IFS (9-km), NCEP-GFS (13-km), and FV3-GFS (9-km) actually resolve the “meso-scale”?**



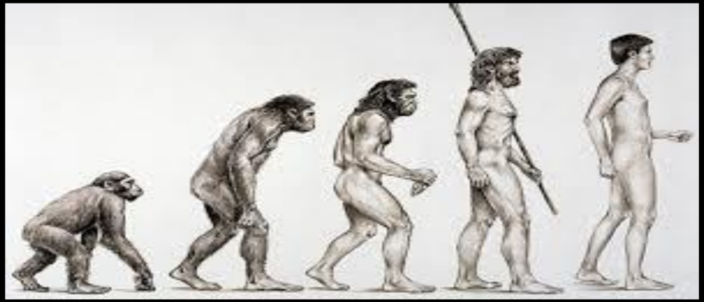
- FV3 at C1152 (9-km) near perfectly catpures the“-5/3” meso-beta (20-200 km) spectrum to 4-Δx
- The IFS has lower energy in the meso-scale; but it does follow “-3” spectrum (synoptic scale) well
- The GFS has the least amount of energy in the mesoscale (3 orders of magnitude smaller than FV3 and the theoretical value)

Super Dynamics project: A total redesign of the dynamics-physics coupling

- "Dynamics" and "physical parameterizations" are traditionally separated within a modeling framework
- Near the gray-zone (1-10 km), the dynamics needs to "see & feel" the water species (e.g., rain, snow, cloud water/ice) to allow better physics-dynamics interaction and for higher computational efficiency (by using only small-time-step for "fast physics")
- Traditional "column physics" should be (completely) rewritten without the "hydrostatic approximation"
- Heating/cooling should be applied to the "moist air", not "dry air" (as currently in GFS and GFDL AM-2/3/4), and in constant-volume, not constant pressure (isobaric)

Going for the extra mile: embedding "column physics" directly into the dynamics

The evolution of FV3



1996 Lin & Rood CTM
NASA GOCART, MOZART
ECHAM 4,5
MRI, BCC climate models

→

1998 FV
NASA GEOS-4
GFDL CM2.1
MCAR CESM1,2

→

2016 FV3
NGGPS
GFDL AM4
NASA GEOS-5

mutation →

"Super FV3"

Project: 2020 FV3

2020 FV3:

- The rigid separation of "Dynamics" and "physical parameterizations" is detrimental to the modeling advancement. To improve physics-dynamics interaction, the legacy modeling system should be torn apart

- To achieve higher computational efficiency by using small-time-step for "fast physics" - calling the sub-grid physics at the right place and with the right frequency

What’s super about “super FV3”?

The 2016 (NGGPS) FV3 plus

1. Improved “dynamics”: nearly non-diffusive advection scheme with a 2Δ-filter in physical space

2. “Fast-physics” (acoustic step):

   a) “Naturally Scale Aware” (via finite-volume integration) flow-blocking by Sub-Grid Orography (SGO)

   b) SGO-induced turbulence drag

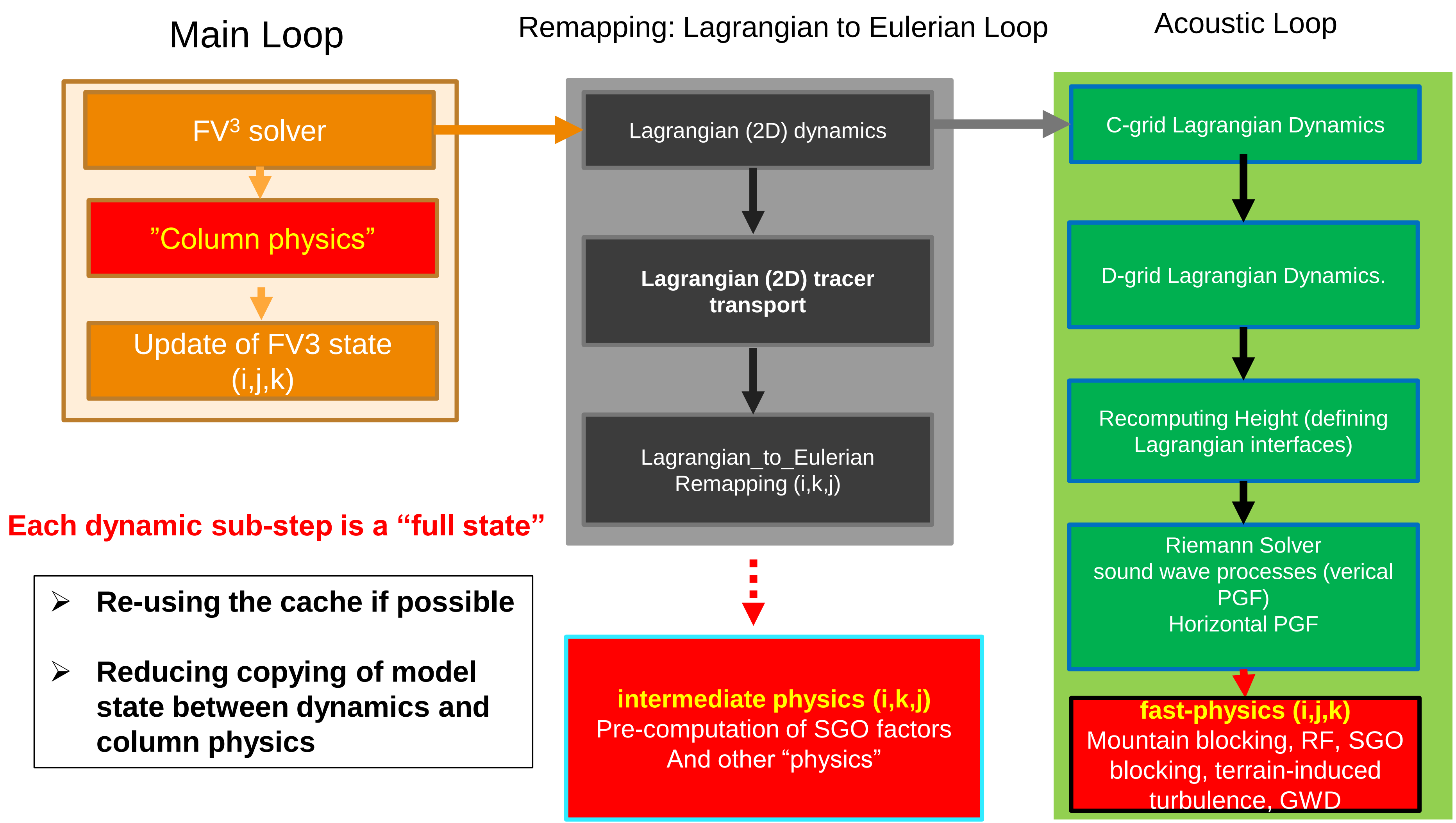
   c) SGO forced gravity-wave-drag for non-hydrostatic scale (work in progress)

3. “Intermediate-physics” (Lagrangian step):

   a) Cloud microphysics with SGO effects (work in progress)

   b) Shear-induced turbulence (a vertical mixing parameterization)

4. “Slow-physics”: parameterized 3D solar radiation (work in progress)

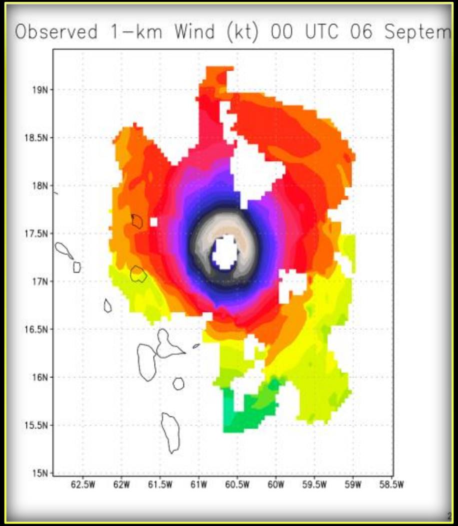

Main Loop
Remapping: Lagrangian to Eulerian Loop
Acoustic Loop
FV³ solver
"Column physics"
Update of FV3 state (i,j,k)
Lagrangian (2D) dynamics
Lagrangian (2D) tracer transport
Lagrangian_to_Eulerian Remapping (i,k,j)
C-grid Lagrangian Dynamics
D-grid Lagrangian Dynamics.
Recomputing Height (defining Lagrangian interfaces)
Riemann Solver
sound wave processes (verical PGF)
Horizontal PGF
fast-physics (i,j,k)
Mountain blocking, RF, SGO blocking, terrain-induced turbulence, GWD
Each dynamic sub-step is a "full state"
Re-using the cache if possible
Reducing copying of model state between dynamics and column physics
intermediate physics (i,k,j)
Pre-computation of SGO factors
And other "physics"

Hurricane Irma (2017)

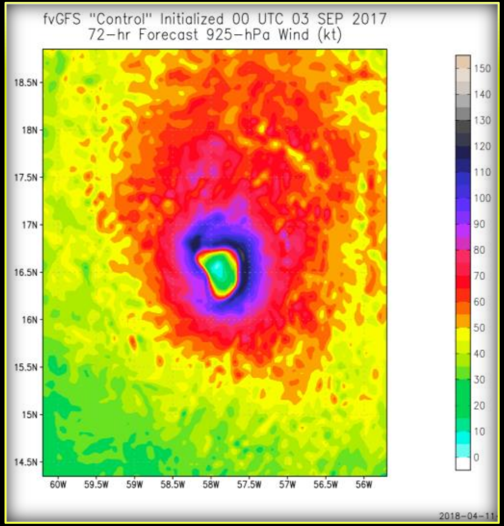
72-hour forecast

Valid 00Z
6 Sep 2017

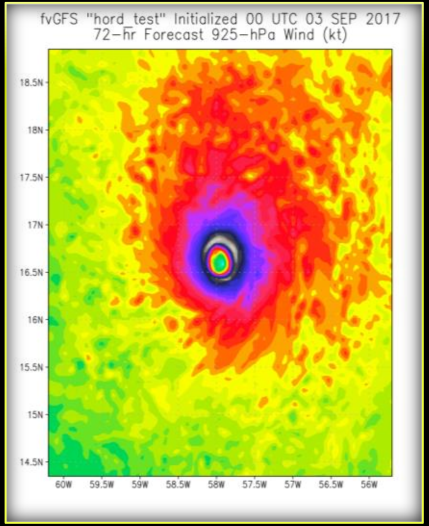
Observations



2016 FV3
RMW = 54 km



$PD + 2\Delta\_filter$ tracer advection
RMW = 28 km



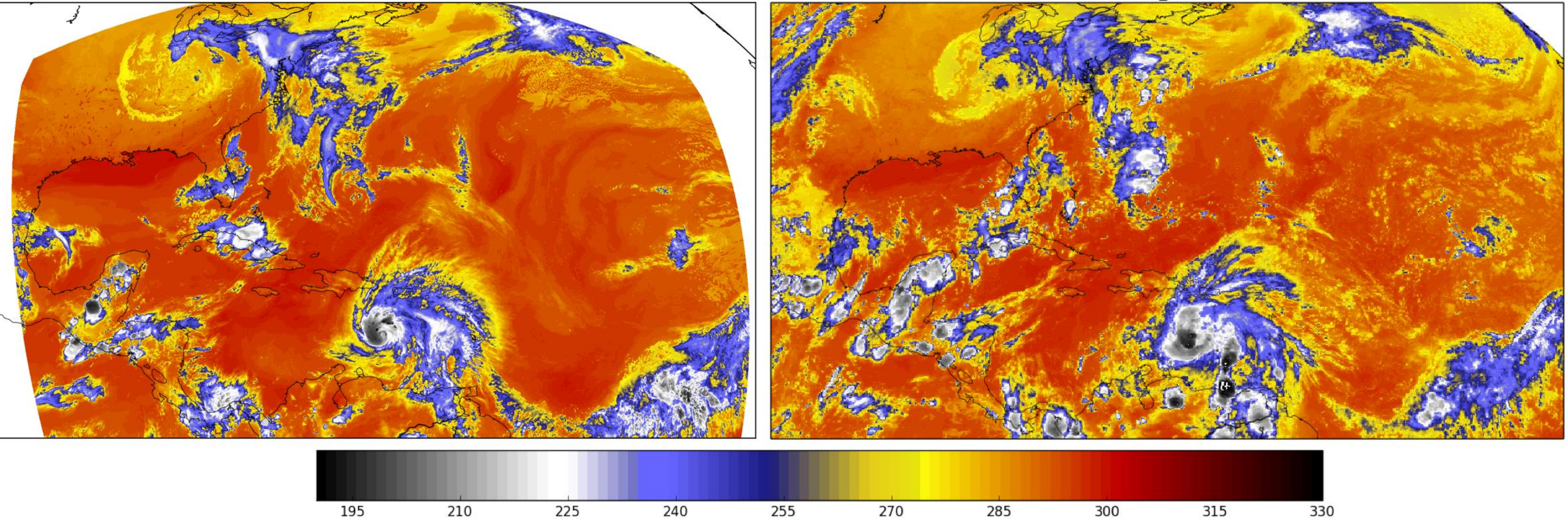
A 2-way interactive 2-km nest, running parallel-in-time, with the global model at 13-km

Hurricane Matthew

0000 UTC 30 Sept 2016 (24 hour forecast) Infrared

FV3 2-km regional nest

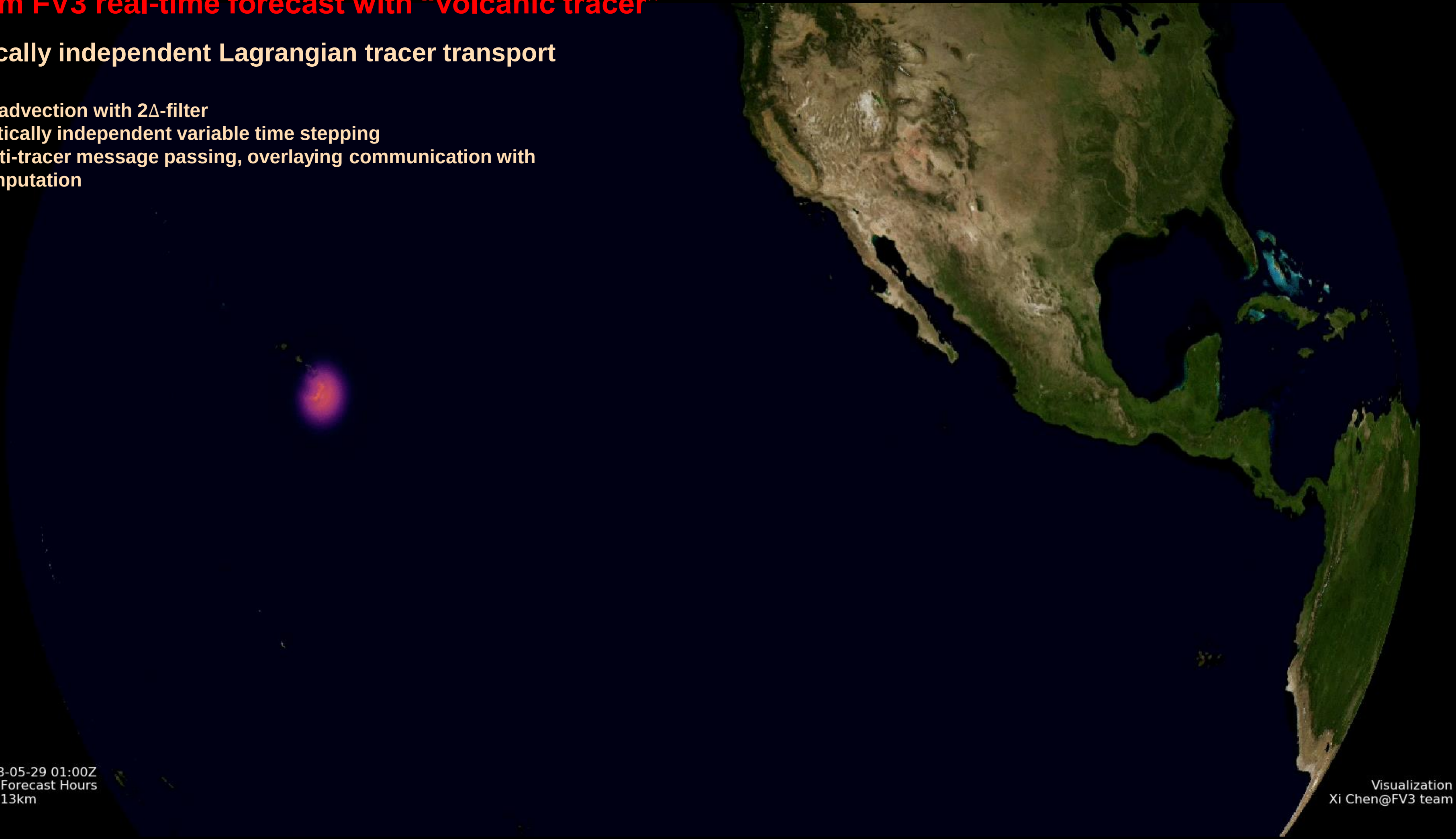
GOES Infrared (credit: Jason Otkin)



13-km FV3 real-time forecast with “volcanic tracer”

Vertically independent Lagrangian tracer transport

- PD advection with 2Δ-filter
- Vertically independent variable time stepping
- Multi-tracer message passing, overlaying communication with computation



Other considerations

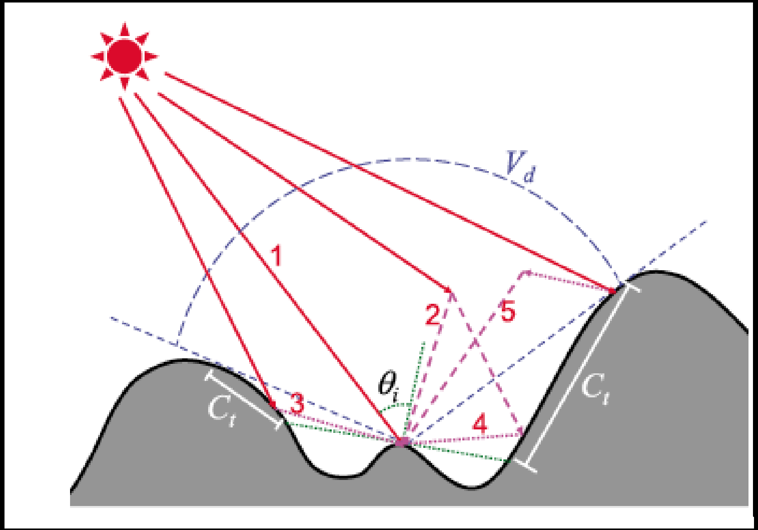
- Sub-grid "parameterization" should operate directly on the **native grid** used by the dynamics → less re-gridding, less errors (and enhanced stability!)

- Traditional gravity wave drag parameterizations are not optimal, or perhaps wrong, if the horizontal resolution is between 1-10 km; let the non-hydrostatic core do its job !

- Hydrostatic vs non-hydrostatic physics: constant volume heating can better simulate vertically propagating gravity waves

Goal: utilizing the Sub-Grid Orography (SGO) to its fullest extent

- The Earth's orography is precisely known to meter scale. We should be able to take advantage of the Sub-Grid Orography at any model horizontal resolution



(Lee, Liou, and Hall, 2011, JGR)

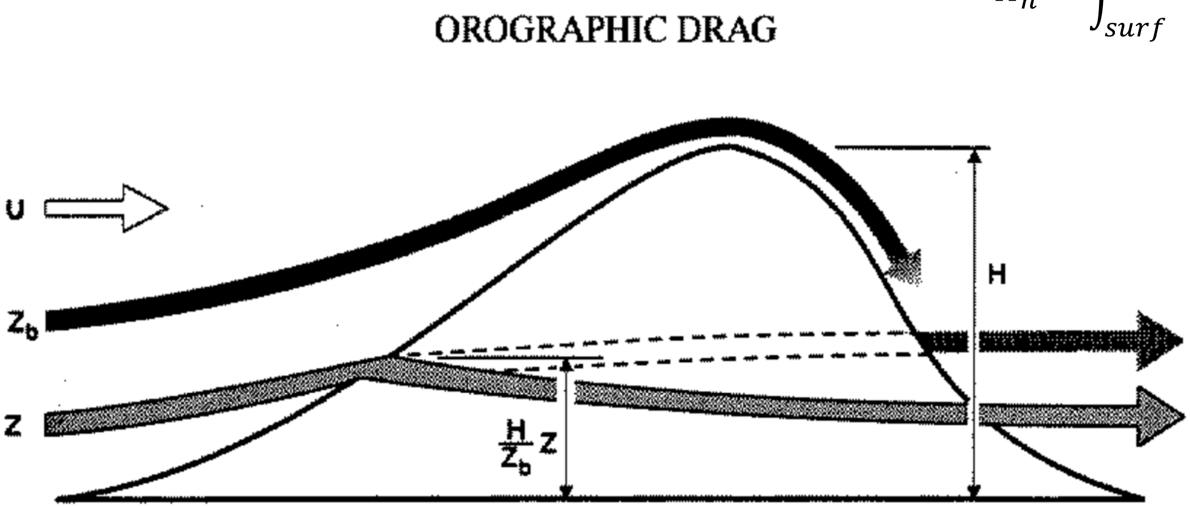
- The inline-SGO processes in the super FV3 is conceptually analogous to that of Lee, Liou, and Hall 2017 for "3D radiation"
- The "mountain blocking" was inspired by Lott and Miller (1997), but with more precise finite-volume integration (instead of making assumption on shape and blocking height)
- The FV3's SGO-induced turbulence was inspired by Beljaars et al. 2004: "A new parameterization of turbulent form drag". However, the FV3 SGO turbulent form drag is derived with the aide of "Buckingham Pi theorem"

Where did the "SGO blocking" idea come from?

The mountain drag (original idea developed by Lott & Miller 1997)

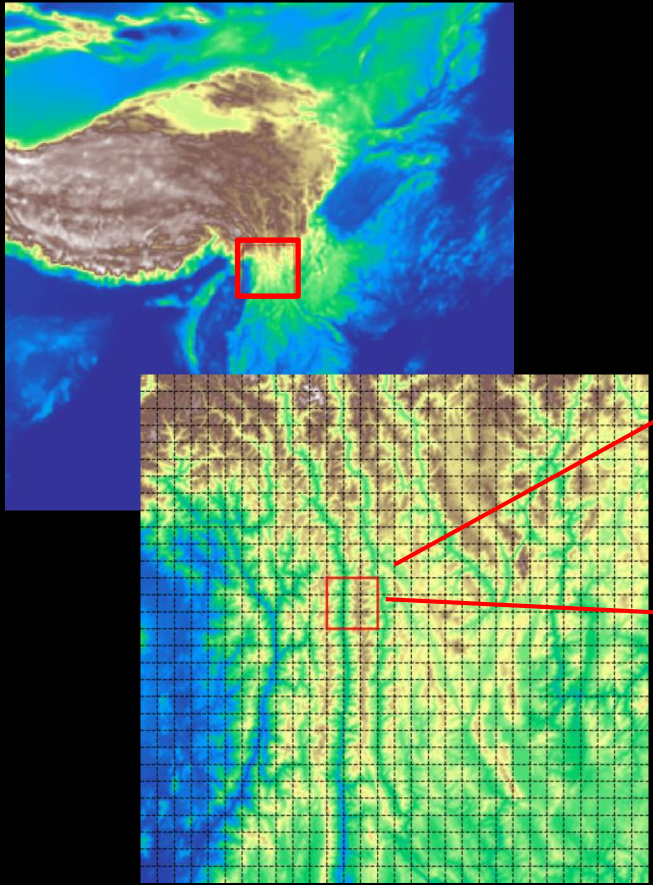
- Designed for hydrostatic model with hydrostatic assumption
- It is a "dynamical replacement" of the "envelop mountain" (Wallace 1983). The sub-grid terrain shape is assumed to be elliptical
- The flow goes over the mountain - if $H_n < 1$
- The flow is blocked - if $H_n > 1$

$$H_n = \int_{surf}^{Z\_peak} \frac{N}{u} dz$$



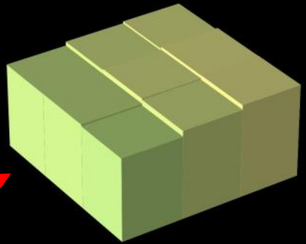
(Lott & Miller 1997)

The “super FV3” uses the 1-km sub-grid orography, regardless of the true resolution



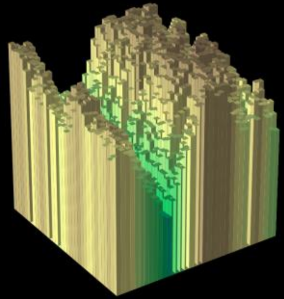
$$\Phi_{actual} = \phi_{mean} + \phi_{sub-grid}$$

C768 (Δx ~12 km) model Mean orography



For each 12x12 (km) ”finite-volume” (grid box), there are 12x12=144 sub-grid columns

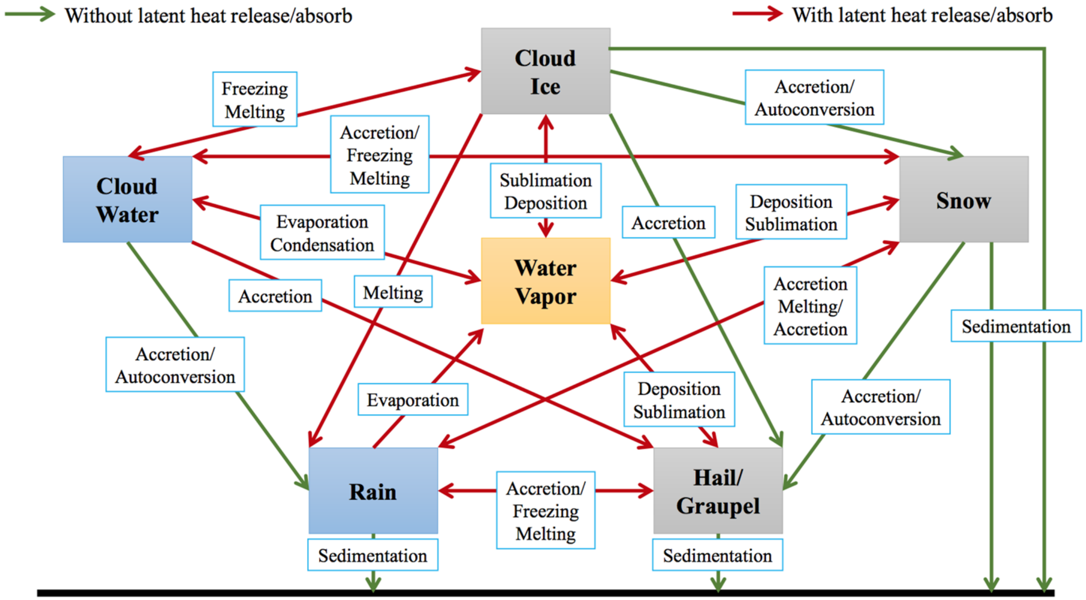
Hi-resolution orography (1-km)



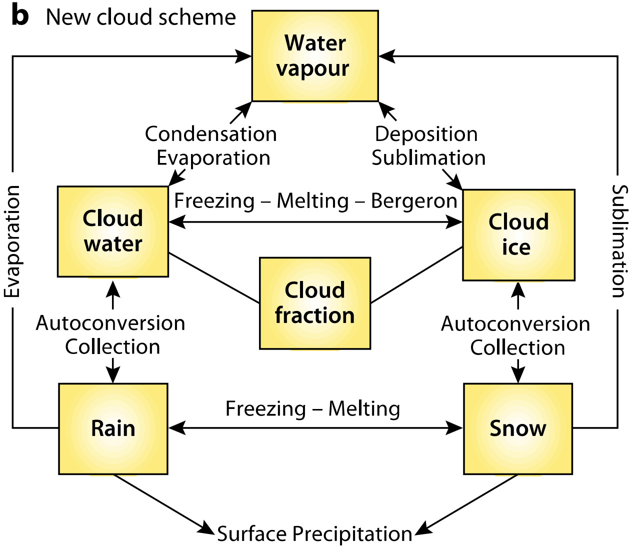
$$Drag = \frac{\rho}{2} C_d A V^2$$

GFDL MP is simpler than double moment schemes; but …

GFDL cloud microphysics (6 species)



ECMWF cloud microphysics (5 species)



Some unique attributes of GFDL Cloud MP

1. **2016 FV3: phase-changes called after the "Lagrangian-to-Eulerian" remapping**

2. **2020 FV3: cloud MP fully embedded, becoming part of "Super FV3"**

3. **Time-split between warm-rain and ice-phase (slower) processes**

4. **Time-implicit monotonic scheme for terminal fall of condensates**

5. **"Scale-awareness" achieved by an assumed horizontal sub-grid variability and a 2^{nd} order FV vertical reconstruction for auto-conversions (ice ▸ snow)**

6. **Thermodynamic consistency between the dynamics and cloud micro physics:**

   * **exact local moist energy conservation between phase changes**

   * **condensates carry heat & 3D momentum**

Mechanisms by which "sub-grid" mountains/hills affect precipitating clouds (Houze 2012)

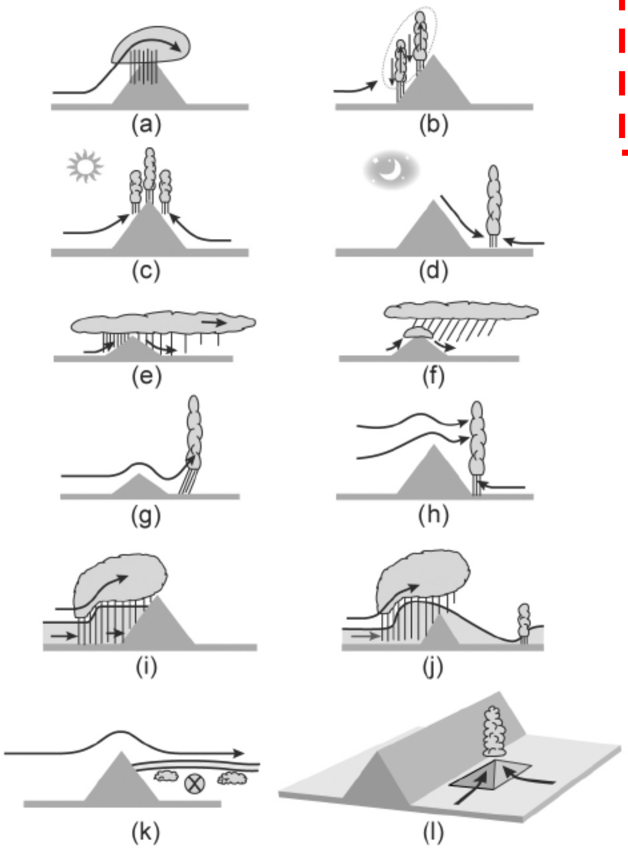
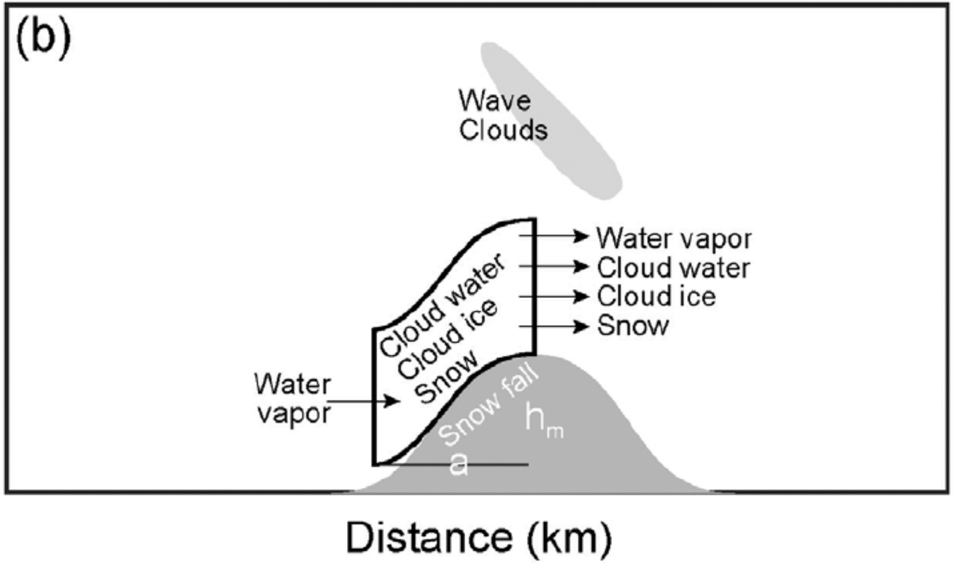
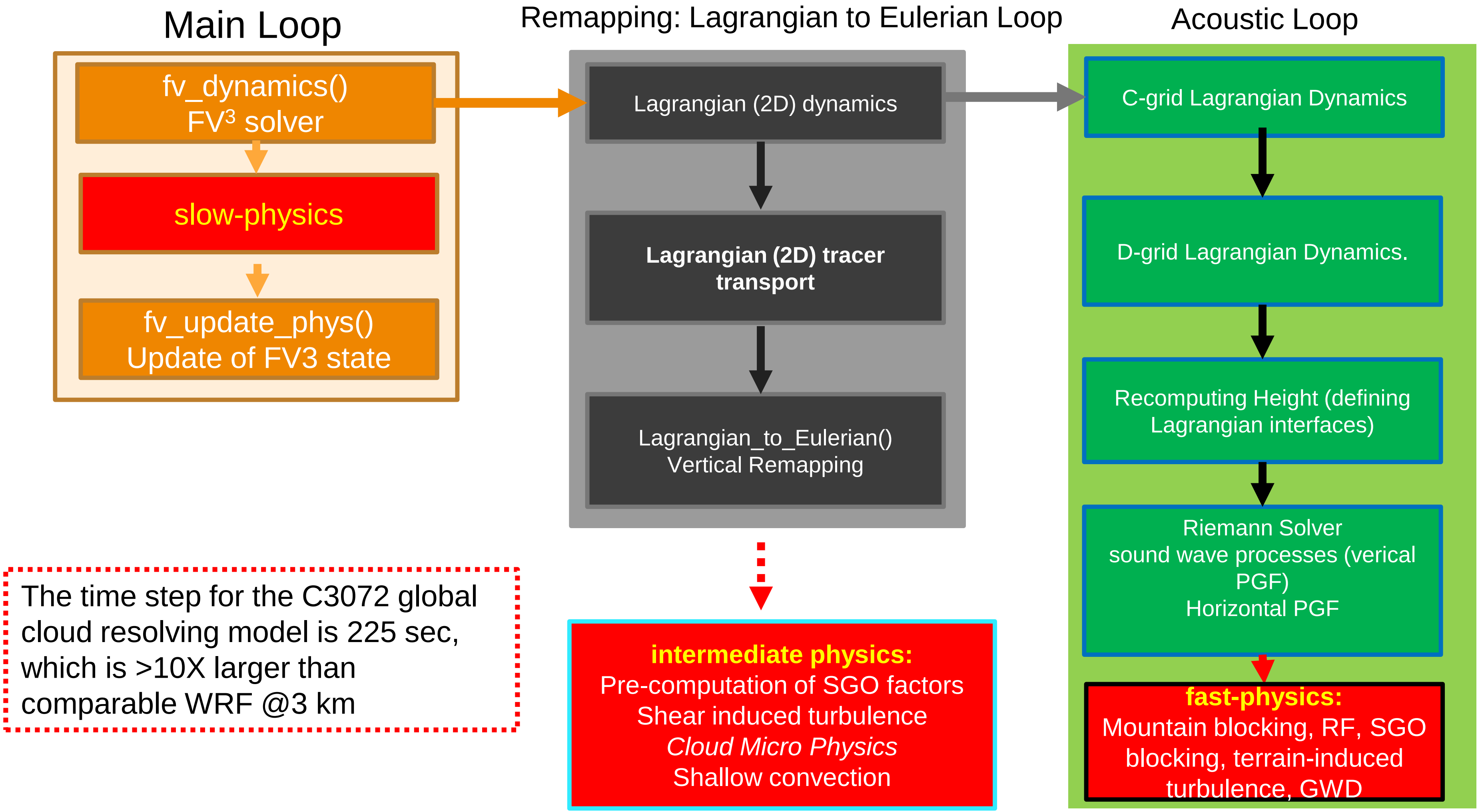


Figure 3. Mechanisms by which mountains and hills affect precipitating clouds.

Sub-Grid-Orography induced condensation/precipitation





Main Loop
fv_dynamics()
FV3 solver
slow-physics
fv_update_phys()
Update of FV3 state
Remapping: Lagrangian to Eulerian Loop
Lagrangian (2D) dynamics
Lagrangian (2D) tracer transport
Lagrangian_to_Eulerian()
Vertical Remapping
Acoustic Loop
C-grid Lagrangian Dynamics
D-grid Lagrangian Dynamics.
Recomputing Height (defining Lagrangian interfaces)
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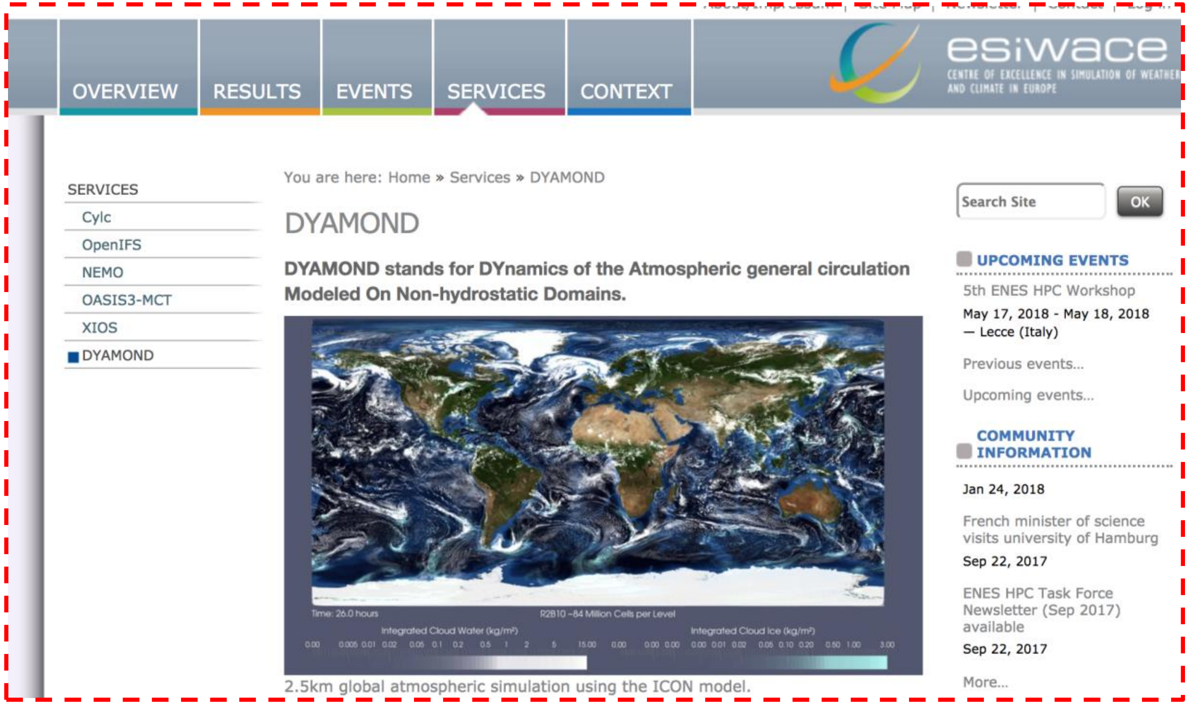
sound wave processes (verical PGF)
Horizontal PGF
fast-physics:
Mountain blocking, RF, SGO blocking, terrain-induced turbulence, GWD
intermediate physics:
Pre-computation of SGO factors
Shear induced turbulence
Cloud Micro Physics
Shallow convection
The time step for the C3072 global cloud resolving model is 225 sec, which is >10X larger than comparable WRF @3 km

Evaluating the “Super FV3” across the Gray-Zone

The “DYAMOND Project” *(https://www.esiwace.eu/services/dyamond)*

- First International inter-comparison of global cloud-resolving models
- Participants:

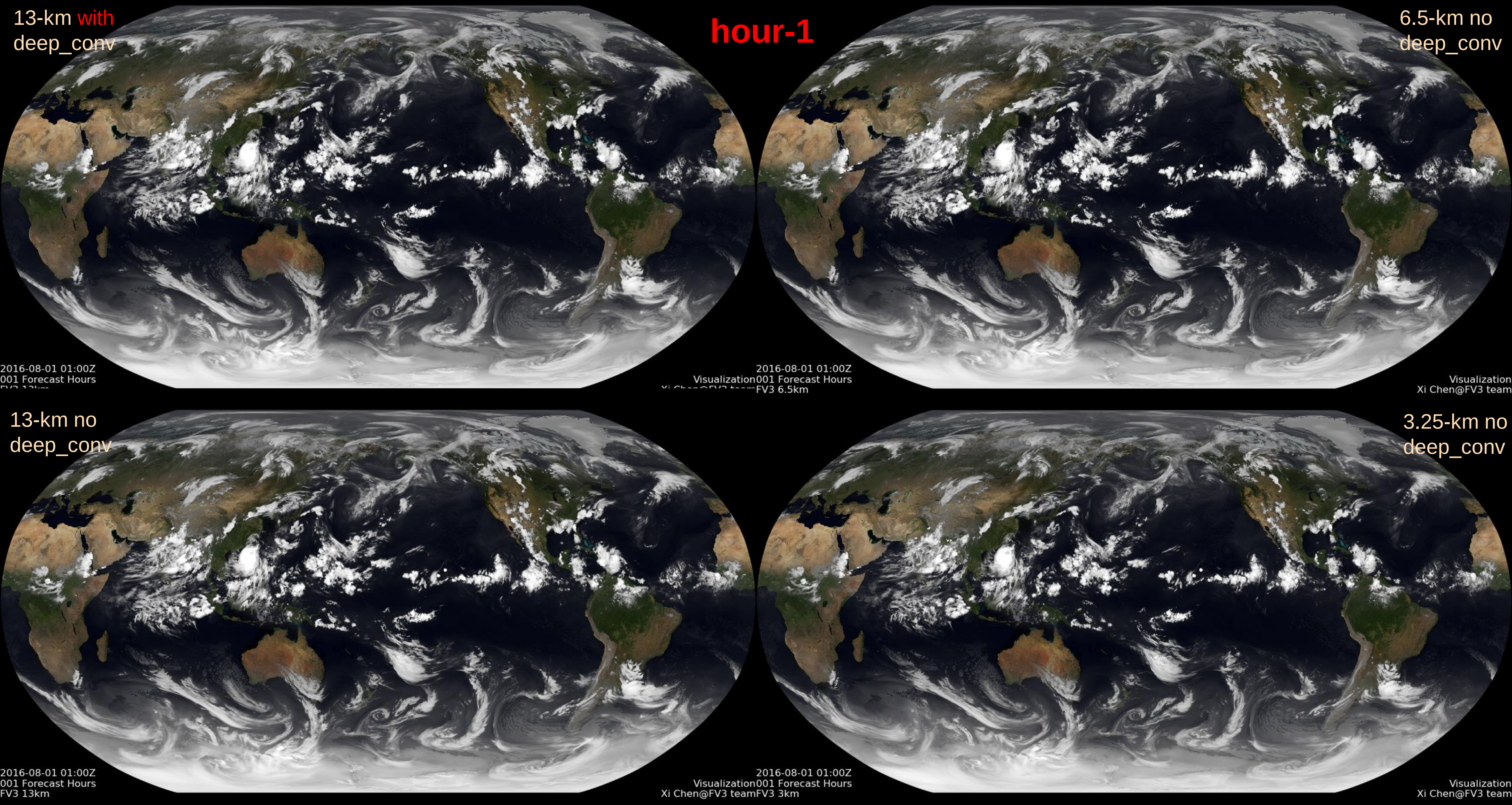
  FV3 (GFDL)
  FV3 (NASA/GMAO)
  NICAM
  ICON
  UM (UKMO)
  MPAS
  ARPEGE-NH
  SAM



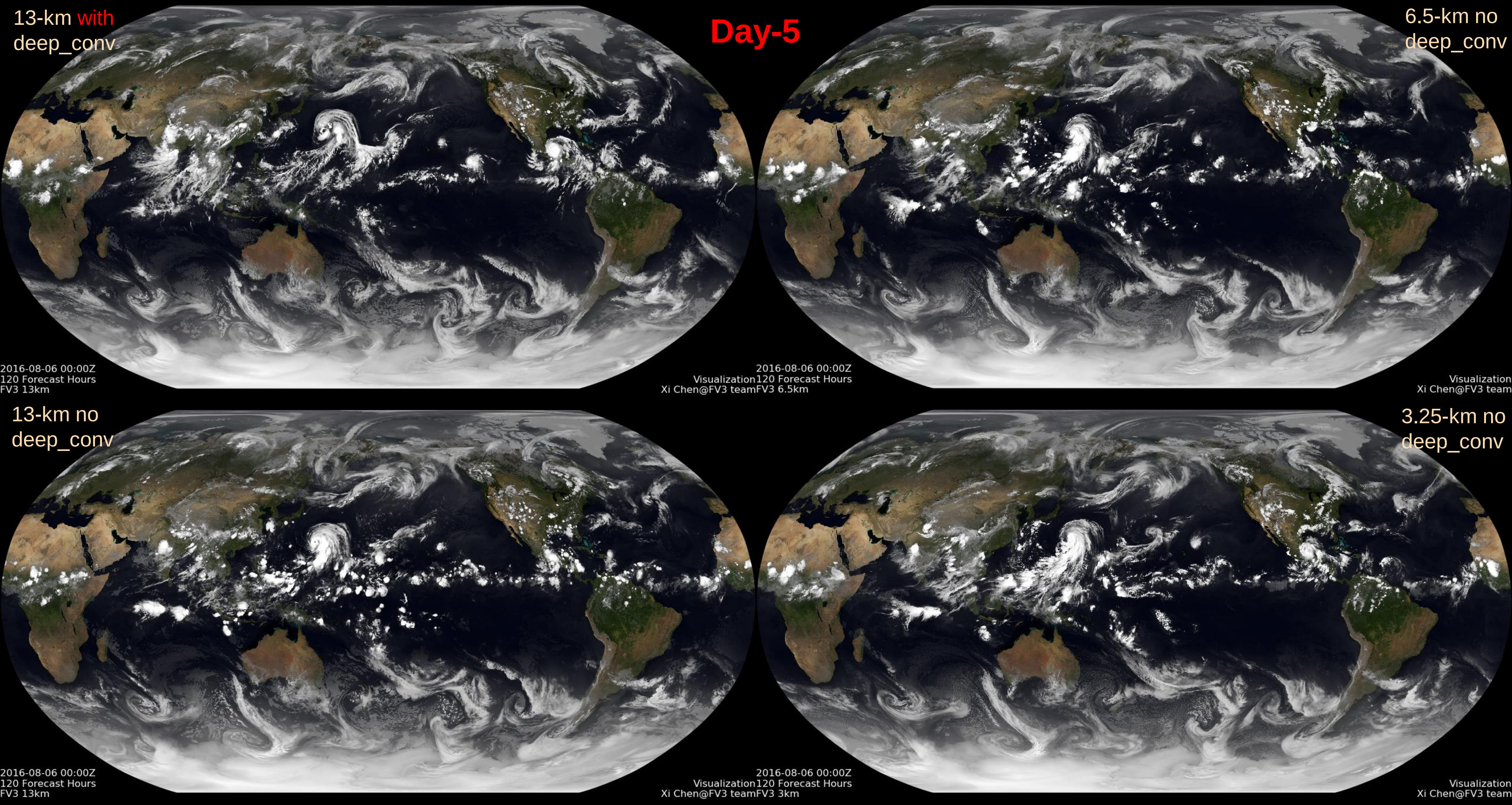
DYAMOND model configurations (32-bit, Cray XC40)

	Δx (km)	deep Conv	big_Δt (sec) (Slow physics)	L2E (sec) (intermediate physics)	Acoustic (sec) (Fast-physics)	Cores needed to meet NWP requirement* (estimated, minimal I/O)
C768_L63*	13	ON	225	225	18.75	3,000
C768_L63	13	OFF	225	225	18.75	3,000
C1536_L91	6.5	OFF	225	112.5	9.375	30,000
C3072_L91	3.25	OFF	225	56.25	4.5	240,000

*Assumed NWP requirements: 10 days forecast in less than 100 min.


hour-1
13-km with deep_conv
6.5-km no deep_conv
13-km no deep_conv
3.25-km no deep_conv
2016-08-01 01:00Z
001 Forecast Hours
2016-08-01 01:00Z
Visualization001 Forecast Hours
FV3 6.5km
Visualization
Xi Chen@FV3 team
2016-08-01 01:00Z
001 Forecast Hours
FV3 13km
2016-08-01 01:00Z
Visualization001 Forecast Hours
Xi Chen@FV3 teamFV3 3km
Visualization
Xi Chen@FV3 team

Day-5

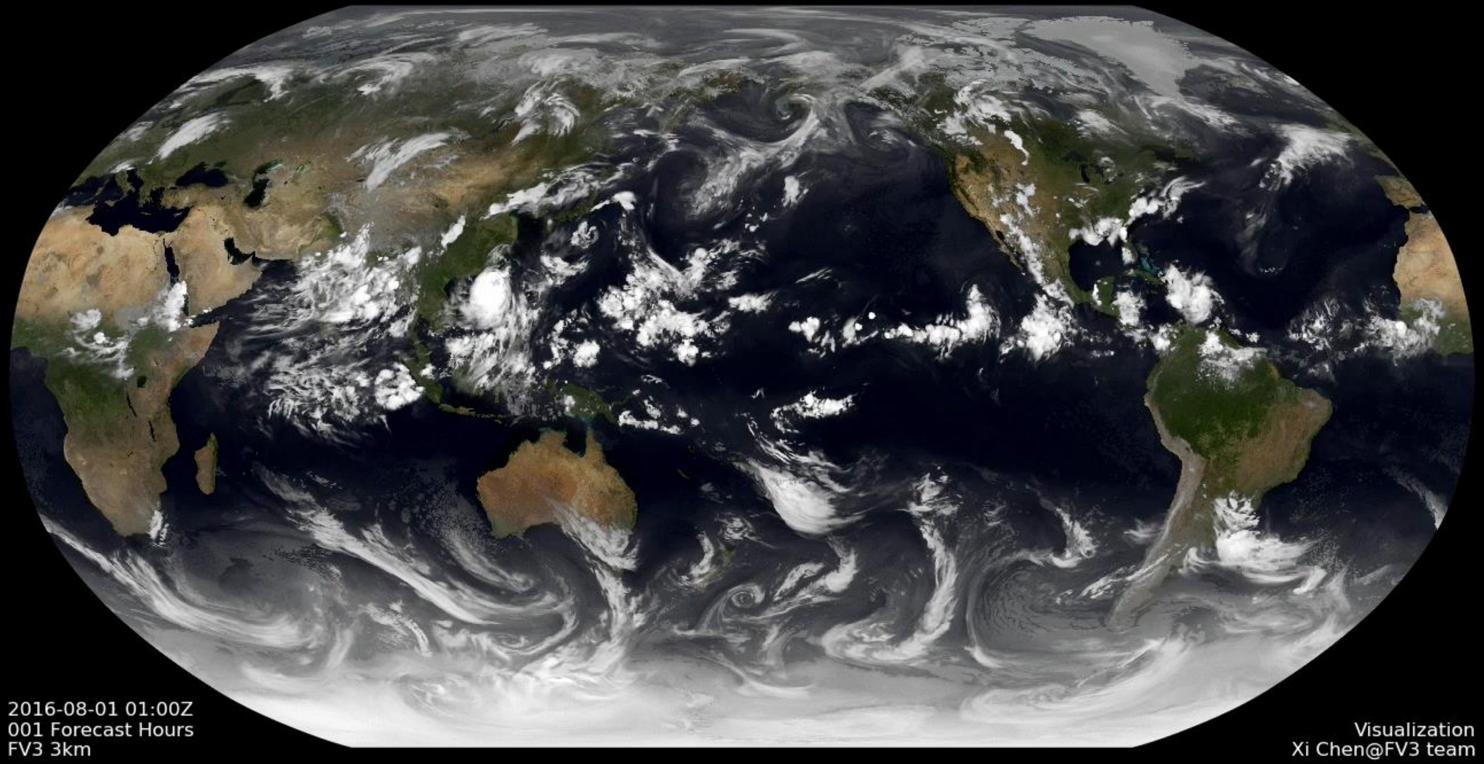


13-km with deep_conv
2016-08-06 00:00Z
120 Forecast Hours
FV3 13km
6.5-km no deep_conv
2016-08-06 00:00Z
Visualization120 Forecast Hours
Xi Chen@FV3 teamFV3 6.5km
Visualization
Xi Chen@FV3 team
13-km no deep_conv
2016-08-06 00:00Z
120 Forecast Hours
FV3 13km
3.25-km no deep_conv
2016-08-06 00:00Z
Visualization120 Forecast Hours
Xi Chen@FV3 teamFV3 3km
Visualization
Xi Chen@FV3 team

“Super FV3” project (2020 FV3)

A 40-day sub-seasonal prediction experiment at global 3.25 km resolution

OLR: 20180801-20160910

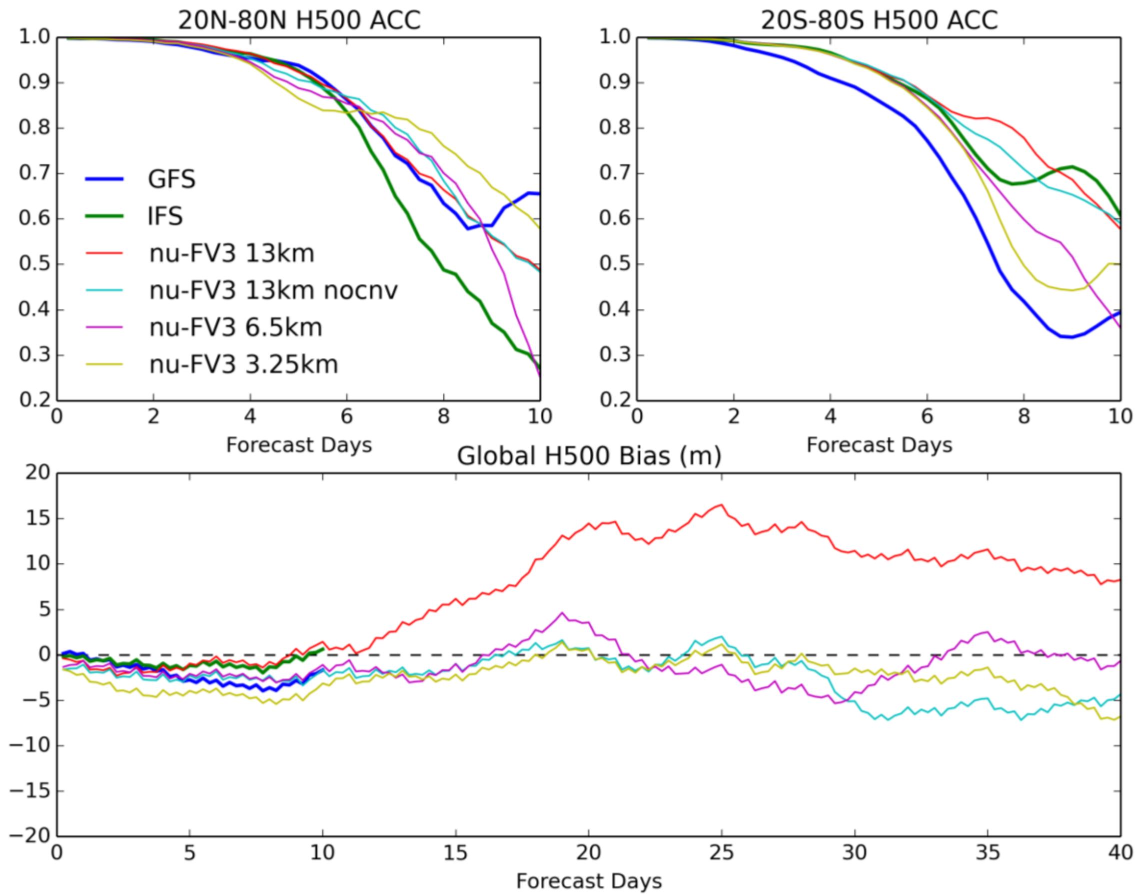


Anomaly Correlation Coefficient (ACC): 500-mb Height

Initialization: 1 Aug 2016

ACC

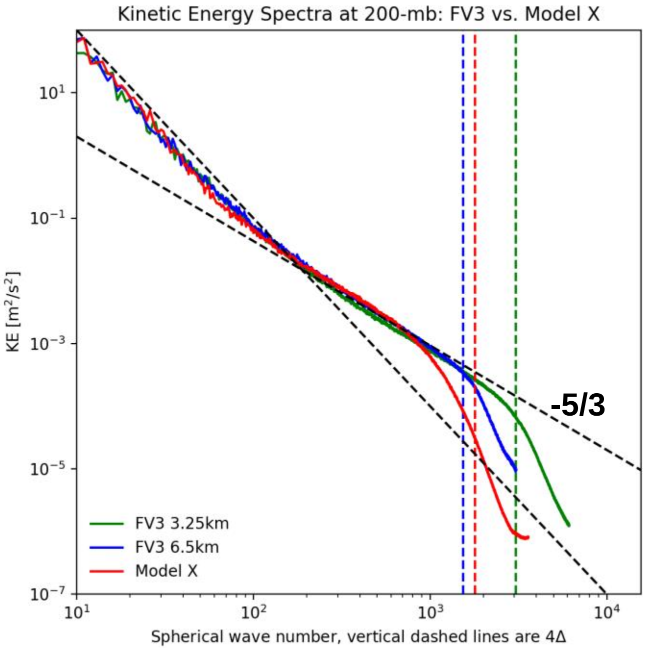
Mean Bias



The C1536 (6.5 km) has the smallest bias in 500-mb HGHT over the 40-day period

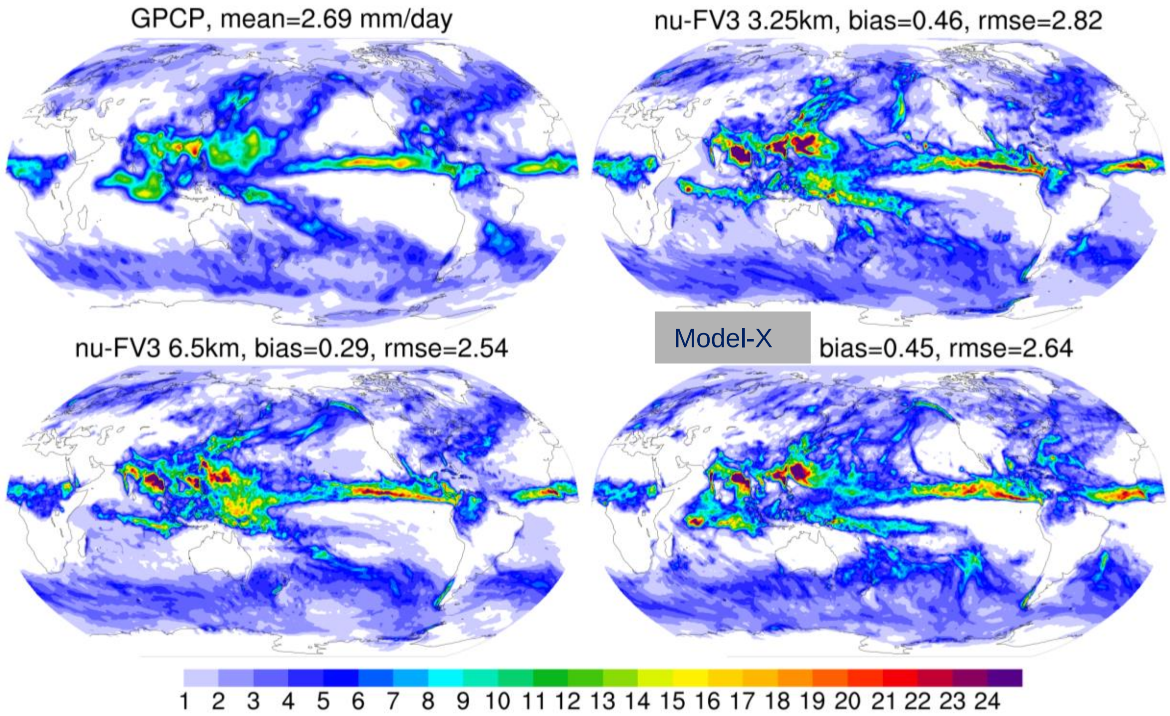
DYAMOND Project: comparison between FV3 (at 3.25-km and 6.5-km), and Model-X (at 5-km)

200-mb Kinetic Energy Spectra



hyper-diffusion:
- **6.5-km: 8th order**
- **3.2-km: 6th order**

Average precipitation over the last 30 days



Future development path of FV3:

- **The "2020 FV3" project:**
  we are developing a nearly self-contained "super dynamics" with built-in Sub-Grid physics suitable for gray-zone (1-10 km), with a physics-dynamics interface re-designed for non-hydrostatic model

- With the "super dynamics", a global cloud-resolving model can be competitive (in large-scale) with today's best NWP model, and it may meet the computational requirement for operation in 3-5 years