GFDL Cloud Micro Physics & consistency with FV3 dynamics

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- **Software**: what's limiting the progress with current modeling frameworks? There is a need to break the rigid boundary between "dynamics" and "physics"

- **Science**:
  1. Back to the 1st principles: making the "dynamics" and "cloud micro-physics" thermodynamically consistent
  2. 2020 FV3: SGO effects on grid-scale "dynamics" and "physics"

2020 FV3 (prototype)

Re-thinking the dynamics-physics interface

- “Dynamics” and “physical parameterizations” are traditionally separated within a modeling framework (*e.g*., GFDL FMS, NCEP NEMS, NCAR ESMF)
- As model resolution increases, particularly when approaching 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 higher computational efficiency (using only small-time-step for “fast physics”)
- FV3 is a non-hydrostatic core designed for all scales. Physics “drivers” should perhaps be rewritten for non-hydrostatic motions (for example, using W, instead of “omega” as input, and without “hydrostatic approximation”?)
- Heating/cooling should be applied to the “moist air”, not “dry air” (as currently in GFS).

Evolution of “GFDL MP”

Lin et al., 1983

↓

Lord et al., 1984

↓

Krueger et al., 1995

↓

Chen and Lin, 2011
Chen and Lin, 2013

↓

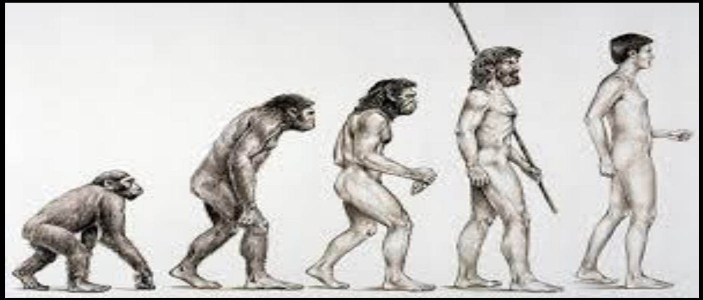
Zhou & Lin, 2018?

- **GFDL Zetac:** Regional simulations (< 20 km)
- **HiRAM**: Seasonal to Sub-seasonal Prediction (10 – 100 km)
- **Super HiRAM**: Global cloud-resolving simulations (< 5 km)
- **NGGPS/UFS**: NWP & S2S (13-km & 3-km)

↓ “Lin-Lin” cloud micro-physics (“**L2 MP**”)

- **“super FV3”: inline MP, for weather, S2S, & climate predictions**

The evolution of FV3



mutation

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

"Super FV3"
(2020 FV3)

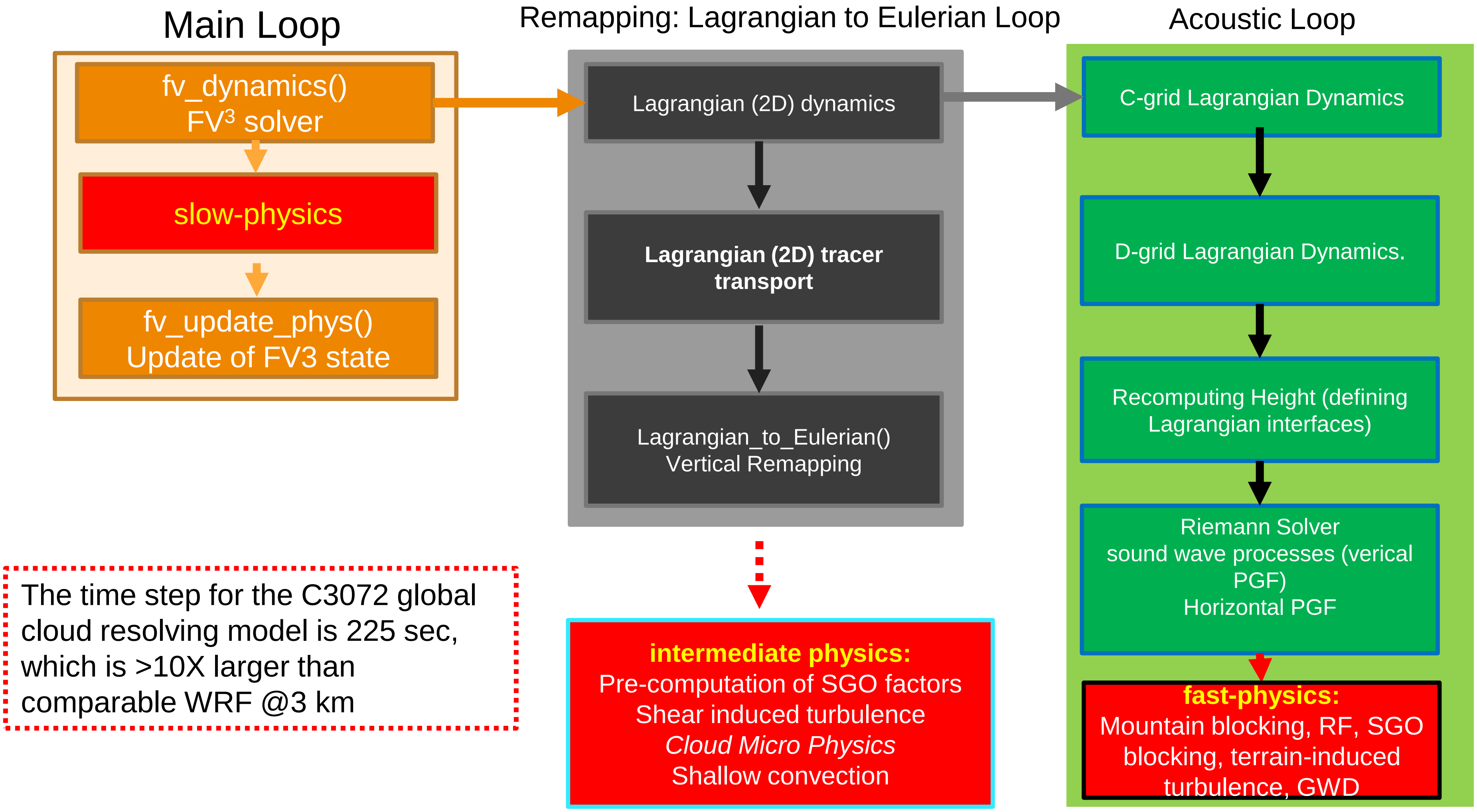
2020 FV3:

- The rigid separation of "Dynamics" and "physical parameterizations" is detrimental to the modeling advancement. To improve physics-dynamics interaction, the legacy modeling system must be torn apart, to enable the "dynamics" to "feel the Sub-Grid Orography" and to "see" better the condensates
- Higher computational efficiency can be achieved by using small-time-step for "fast physics" (separation of timescale)

What's super about "super FV3"?

The 2016 (NGGPS) FV3 plus

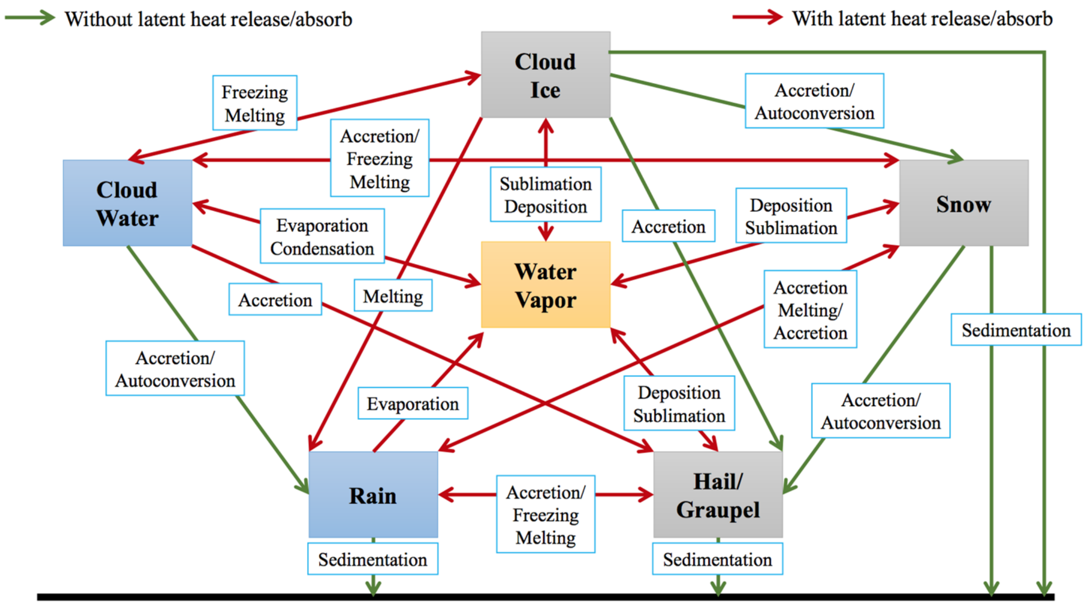
1. Improved "dynamics" : nearly non-diffusive advection scheme, support for moving & static FV3
2. "Fast-physics" (acoustic step):
    - a) "Naturally Scale Aware" (via finite-volume integration) flow-blocking by Sub-Grid Orography (SGO)
    - b) SGO-induced turbulence drag
    - c) SGO forced gravity-wave-drag for non-hydrostatic scale (1-10 km; *work in progress*)
3. "Intermediate-physics" (Lagrangian step):
    - a) Inline cloud microphysics
    - b) Shear-induced turbulence (a vertical mixing parameterization)
4. "Slow-physics": parameterized 3D solar radiation (ongoing collaboration with RCEC, Academia Sinica)



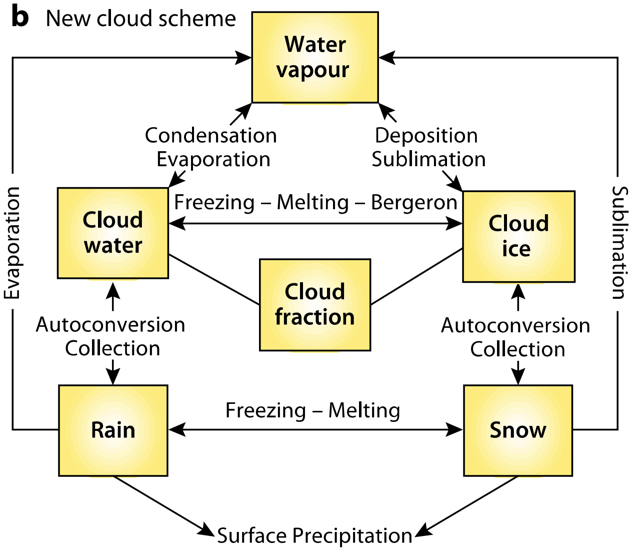
Main Loop
fv_dynamics()
FV3 solver
slow-physics
fv_update_phys()
Update of FV3 state
Remapping: Lagrangian to Eulerian Loop
Lagrangian (2D) dynamics
Lagrangian (2D) tracer transport
Lagrangian_to_Eulerian()
Vertical Remapping
Acoustic Loop
C-grid Lagrangian Dynamics
D-grid Lagrangian Dynamics.
Recomputing Height (defining Lagrangian interfaces)
Riemann Solver
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

GFDL MP is simpler than double moment schemes; but …

GFDL cloud microphysics (6 species)



ECMWF cloud microphysics (5 species)



Some unique attributes of GFDL MP

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

2. **2020 FV3: cloud MP part of the inline "fast physics" called after the "Lagrangian-to-Eulerian" remapping**

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 2nd order FV-type 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**

With Finite-Volume discretization, “dynamics” can be made fully consistent with cloud “micro-physics”, and vice versa

- Momentum equations (Newton’s 2nd law) must include gas, liquid, and ice species
- **Fundamental issues:** cloud condensates (rain, snow, etc.) are not “perfect gas” (equation of state); they are falling “dead weights” (affecting the pressure gradients, nonetheless)

- **Solution**: go back to first law of thermodynamics

$$\delta U = \delta Q - \delta W$$

- ❑ “Dry air” (mainly oxygen O_2 and nitrogen N_2) and vapor form of H_2O are combined together as “air”, treated as “perfect gases”
- ❑ What to do with condensates? Not just deadweights, condensates have much larger heat capacities than “dry air”

The definition of “potential temperature”

The “**dry**” form is defined as:

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{R}{C_p}}$$

Reminder: the “*atmosphere*” is actually not dry!

To derive the moist form, we must go back to the 1st law of thermodynamics, considering the heat content of all species (“dry air”, water vapor, liquid, and ice/snow/graupel)

The <u>correct</u> form of "potential temperature" for moist air

To make progress, and not making the model overly complicated, the assumption here is that **heat capacities** are independent of temperature

Dry:

$$\theta = T\left(\frac{p_0}{p}\right)^{\kappa}, \qquad \text{where} \qquad \kappa = \frac{R_d}{R_d + C_v}$$

Moist:

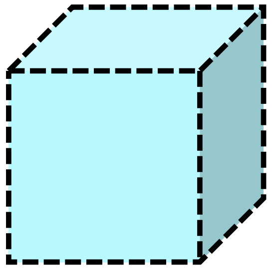
$$\theta = T\left(\frac{p_0}{p}\right)^{\kappa^*}, \qquad \text{where } \kappa^* = \frac{R_d}{R_d + \frac{C^*}{1+\varepsilon q}}\ , \qquad C^* = composite\ \text{“}moist\text{”}\ heat\ capacity,\ \ \varepsilon = \frac{R_v}{R_d} - 1$$

$$C^* = C_{dry\_air} + q_v C_v + q_l C_l + q_r C_r + q_s C_s + q_g C_g + q_i C_i$$

Very fundamental yet often ignored issues in Cloud Micro Physics:

- “Cloud microphysics” (in discrete space) should neither create nor destroy energy: total energy must be locally conserved during phase changes within a grid box (*i.e.*, a “finite-volume”).

Consider a “Finite-Volume” of “**moist air**”

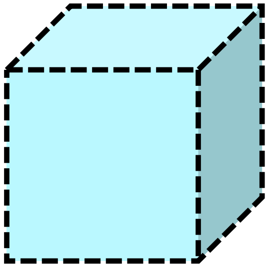


(one of roughly 50 billion “finite volumes” in a 3-km global cloud-resolving model)

Note: the latent heat, when released, should be applied to all constituents within the finite-volume, not just “dry air” as is usually done in most models (such as GFS)

How to conserve moist energy exactly during phase changes?

As an illustration, consider only phase-change from vapor (q_v) to cloud liquid water (q_l) (ice-phase is analogous)



Kirchhoff's law

$$\frac{\partial L_v}{\partial T} = C_{p\_vapor} - C_{liquid}$$

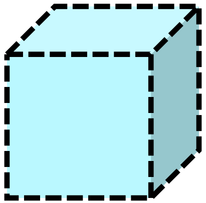
Total thermal Energy = Internal (sensible) Energy + Latent Energy

condensation

"Before" (n) → "After" (n+1)

$$C_m^n T^n + L_0 q_v^n = C_m^{n+1} T^{n+1} + L_0 q_v^{n+1}$$

The 1st principles:



- Moist energy conservation:

$$C_m^n\ T^n + L_0\ q_v^n = C_m^{n+1}\ T^{n+1} + L_0\ q_v^{n+1}$$

- Mass conservation:

$$q_v^n + q_l^n = q_v^{n+1} + q_l^{n+1}$$

After some algebra:

$$\Delta T = \frac{1}{C_m^{n+1}}\left[L_0 \Delta q_v + (C_m^n - C_m^{n+1}) T^n\right]$$

Versus "Kirchhoff law":

$$\frac{\partial L_v}{\partial T} = C_{p\_vapor} - C_{liquid}$$

Summary:

The thermodynamically consistent form that conserves moist energy:

$$\Delta T = \frac{1}{C_m^{n+1}}\left[L_0 \Delta q_v + (C_m^n - C_m^{n+1})T^n\right] = \frac{\Delta q_v}{C_m^{n+1}}\left[L_0 + \left(C_{vap} - C_{liq}\right)T^n\right]$$

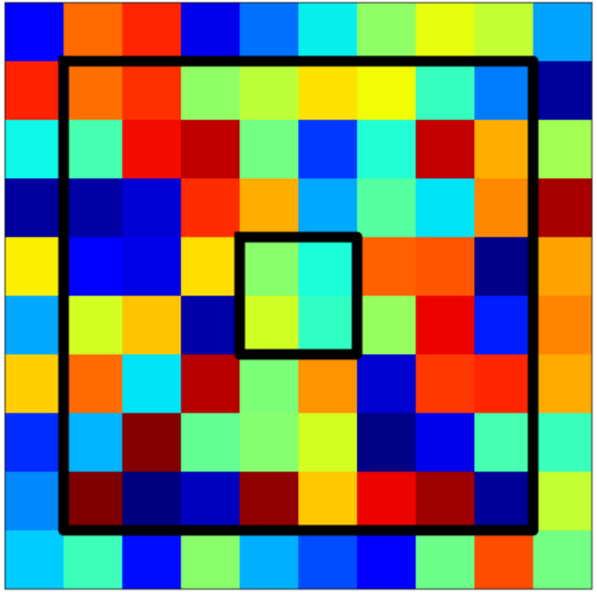
The simple form used by most models (all water substance ignored):

$$\Delta T = \frac{\Delta q_v}{C_{dry\_air}} L_f$$

$L_0 = Latent\ Heat\ at\ absolute\ zero\ (0\ K)$

$L_f = Latent\ Heat\ at\ freezing\ point\ (\sim 273\ K)$

Horizontal Sub-grid Variability



Horizontal sub-grid variability is a function of cell area:

Over land: $$h_{var} = \min\left\{0.2, \max\left[0.01, D_{land}\left(\frac{Ar}{10^{10}}\right)^{0.25}\right]\right\}$$

Over ocean: $$h_{var} = \min\left\{0.2, \max\left[0.01, D_{ocean}\left(\frac{Ar}{10^{10}}\right)^{0.25}\right]\right\}$$

Where ***Ar*** is cell area. ***D_land*** and ***D_ocean*** are base values for sub-grid variability over land and ocean.

Larger sub-grid variability appears in larger area.

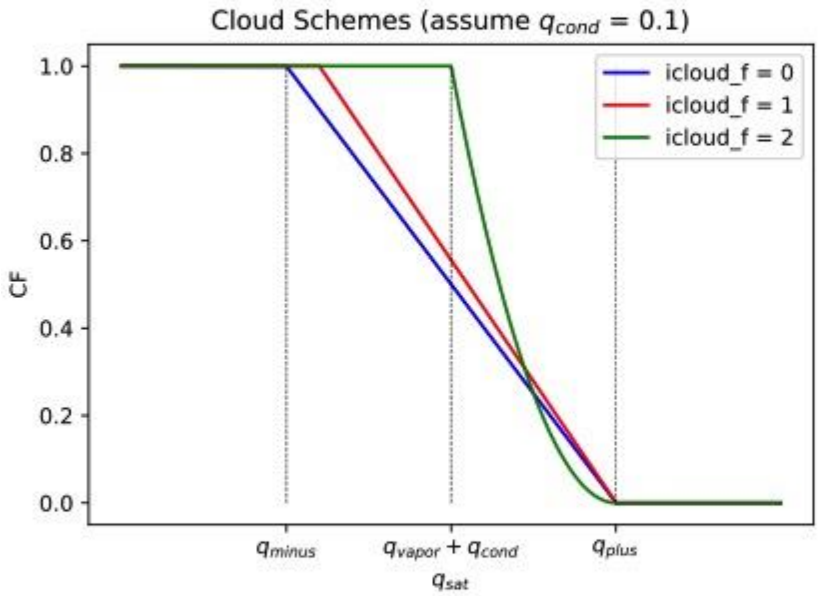
Horizontal sub-grid variability is used in cloud fraction, relative humidity calculation, evaporation and condensation processes.

2nd-order FV-type vertical reconstruction refers to Lin et al. (1994)

Cloud Fraction Calculation

Similar to auto-conversion, calculation of cloud fraction is based on horizontal sub-grid variability. Cloud fraction calculation includes all hydrometeors.

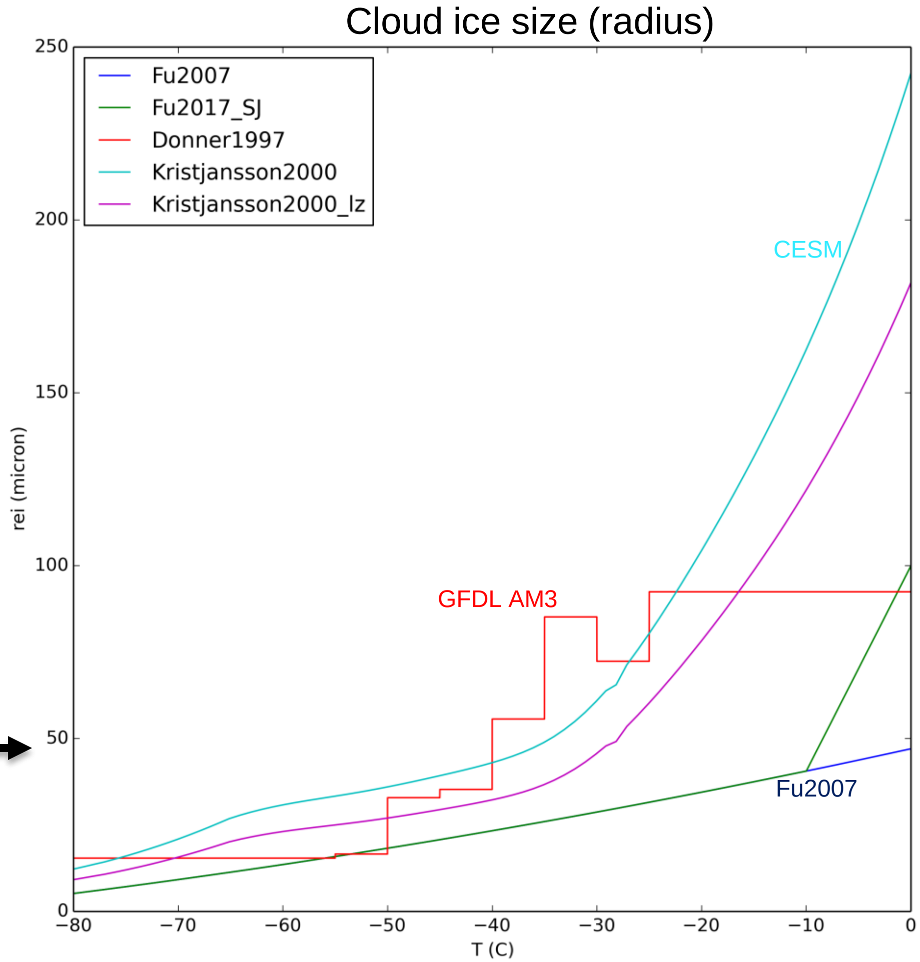
$$CF = \max\left[0, \min\left(1, \frac{q_{plus} - q_{sat}}{q_{plus} - q_{minus}}\right)\right]$$



Cloud Radii Diagnosis

- Current Method
  - Cloud water: temperature dependent algorithm
  - Cloud ice: Heymsfield and McFarquhar (1996)

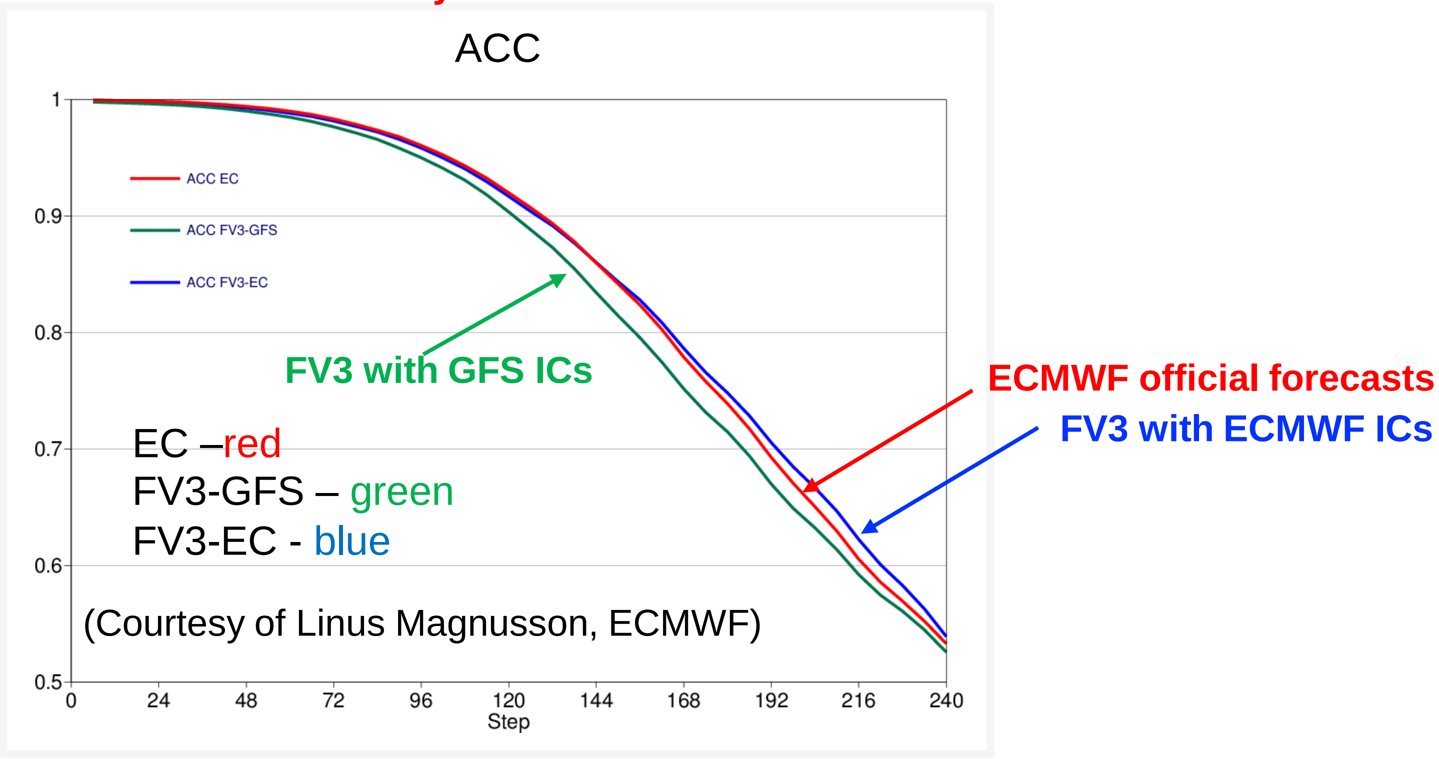
- New Method at GFDL
  - Cloud Water: Martin et al. (1994)
  - Cloud Ice:
  - Rain, Snow, Graupel: Derived from Lin et al. (1983)



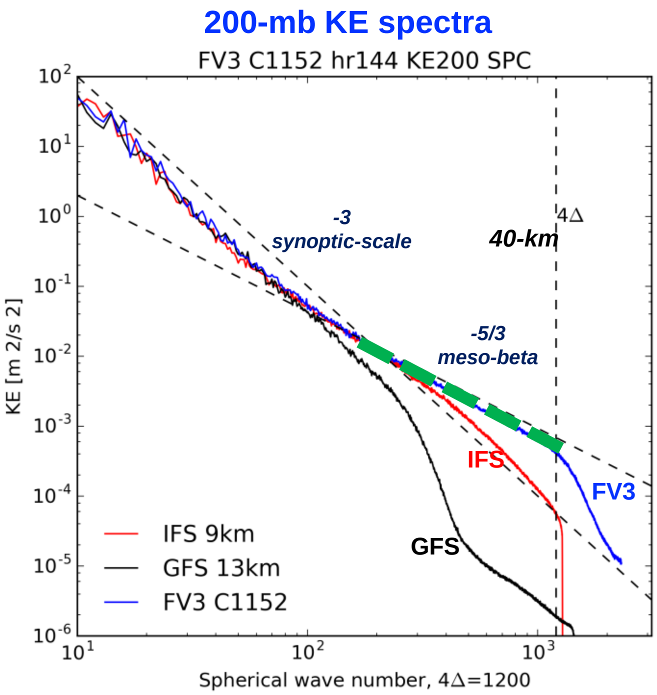
NGGPS: Forecast Experiment with GFS and ECMWF ICs

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

500-mb Anomaly Correlation Coefficient



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



- FV3 at C1152 (9-km) near perfectly represents the“-5/3” meso-beta (20-200 km) spectrum
- 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)

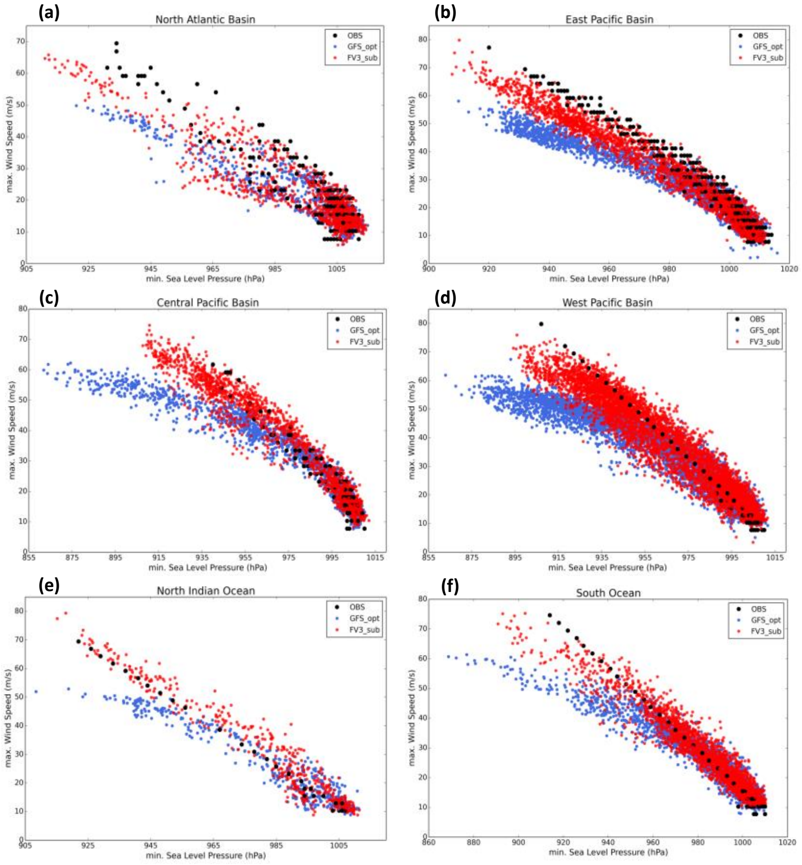


Figure 4. The relationship of maximum 10-m wind (ms^{-1}) and minimum sea-level-pressure (hPa) for TCs in (a) North Atlantic Ocean, (b) North East Pacific basin, (c) North Central Pacific basin, (d) North West Pacific basin, (e) North Indian Ocean and (f) South Ocean at every 6 hour. The observations from ATCF best-track data are donated in black dots. TCs of GFS_opt are in blue dots, and of FV3_sub are in red.

Wind –SLP correlation

- Blue dots: operational GFS (13 km)
- Red dots: FV3 (13 km)
- Black dots: observations (best track)

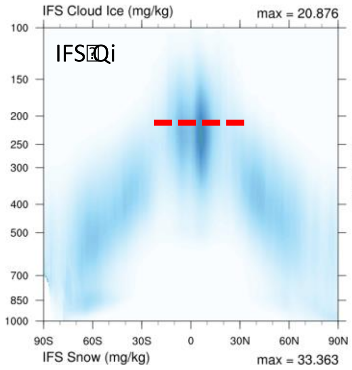
GFS produced too low SLP (relative to 10-m wind)

(Credit: Jan-Huey Chen)

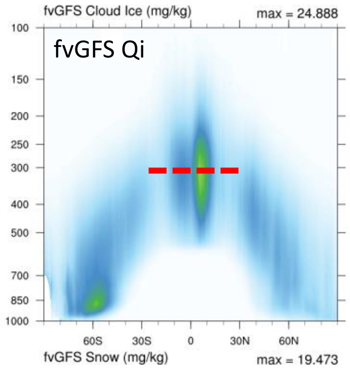
Calibrating “cloud condensates” with ECMWF analyses and Cloud_Sat

non-precipitating ice

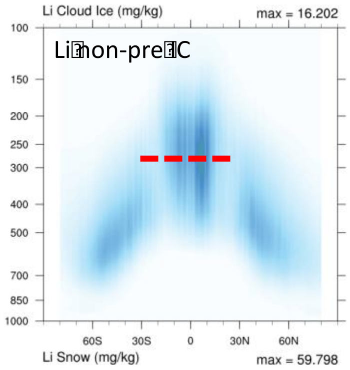
**IFS analyses
(Aug2015-Aug2016)**



**13-km FV3 forecasts
(Aug2015-Aug2016)**



**CloudSat
(Li, et al., JGR, 2012)**

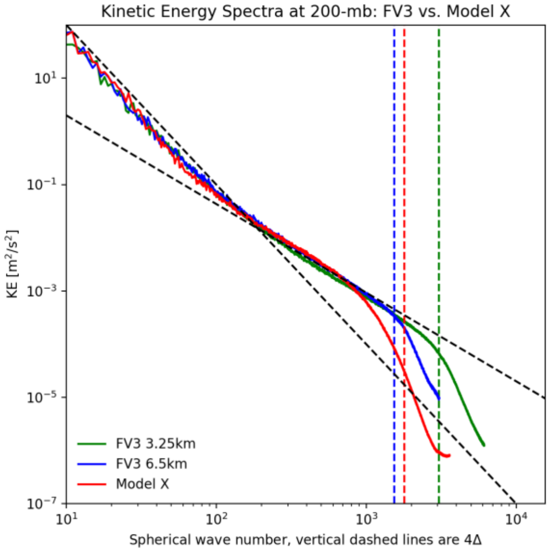


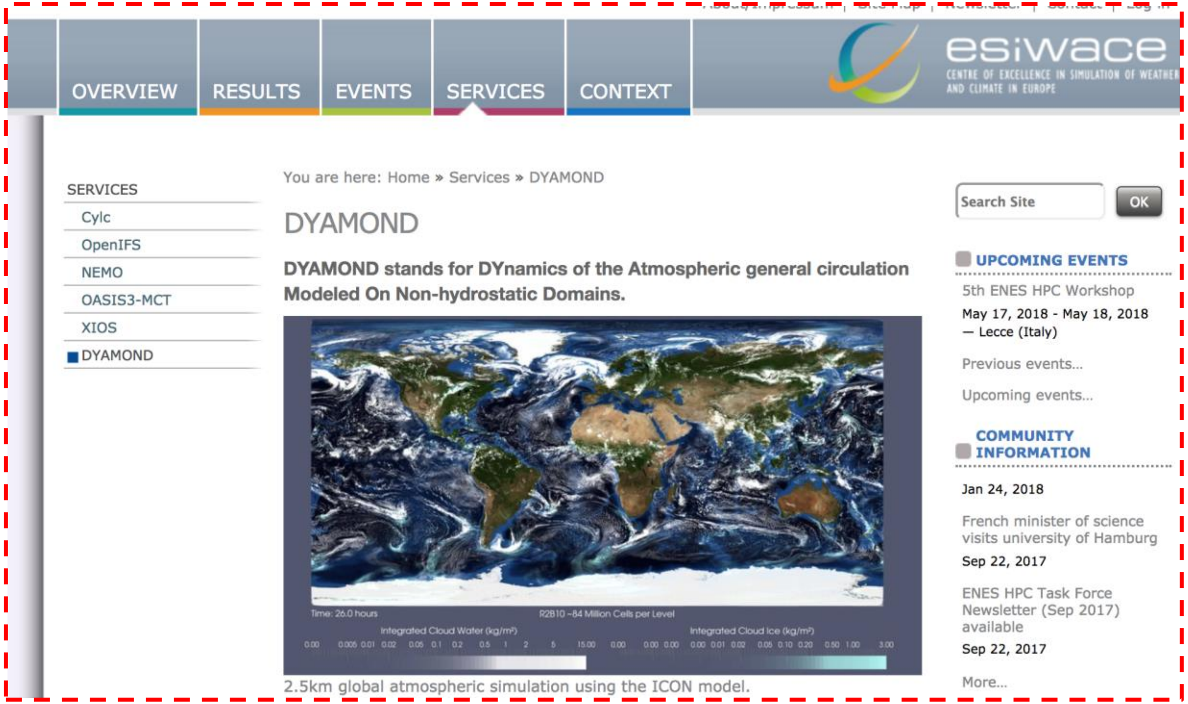
(IFS data courtesy of Linus Magnusson, ECMWF)

Evaluating the "Super FV3" in the Gray-Zone

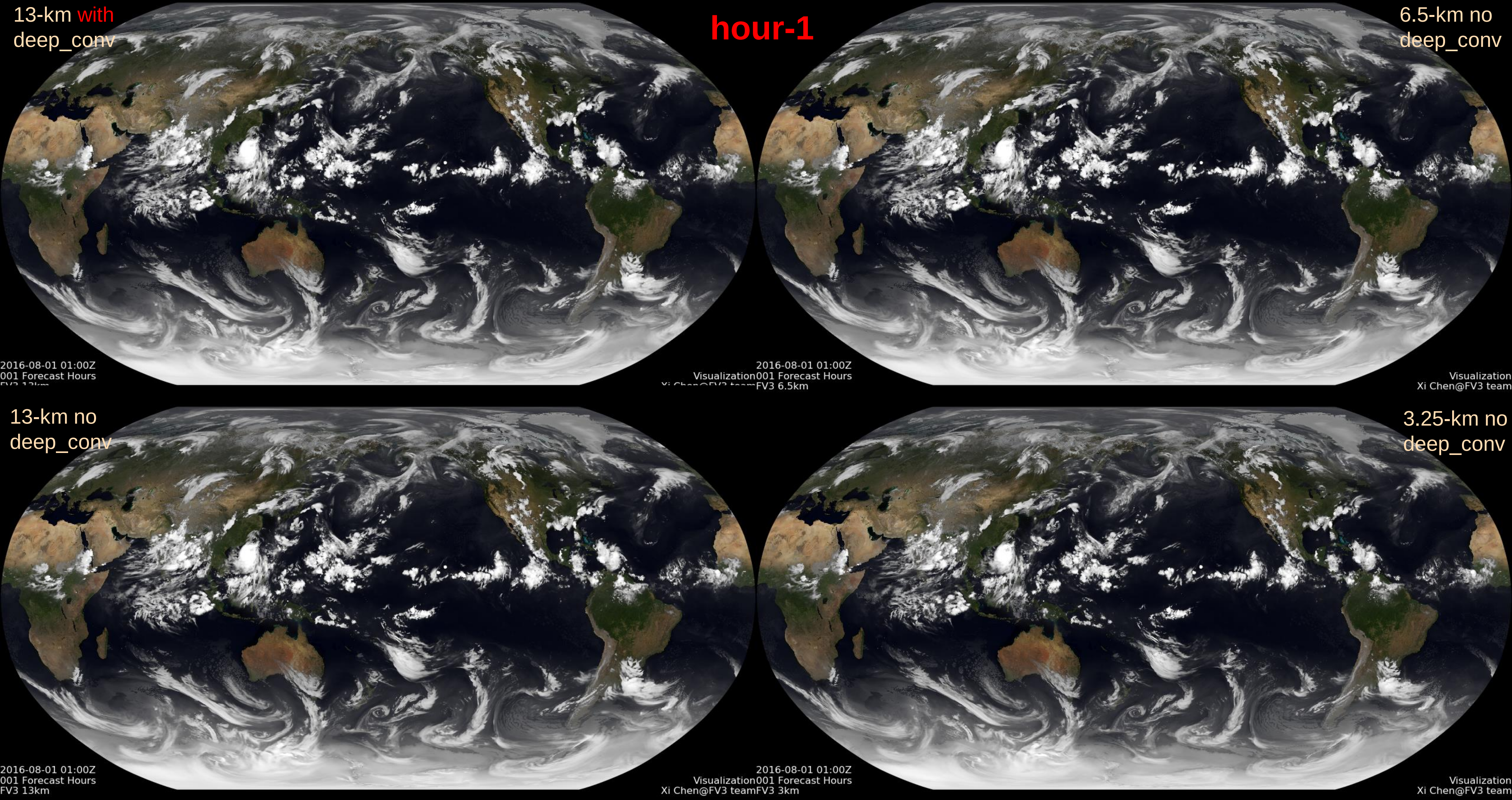
The "DYAMOND Project" *(https://www.esiwace.eu/services/dyamond)*

- First International inter-comparison of global cloud-resolving models
- Participants: nu-FV3, NASA-GOES-5, NICAM, ICON, UK HadGEM3, MPAS, and SAM



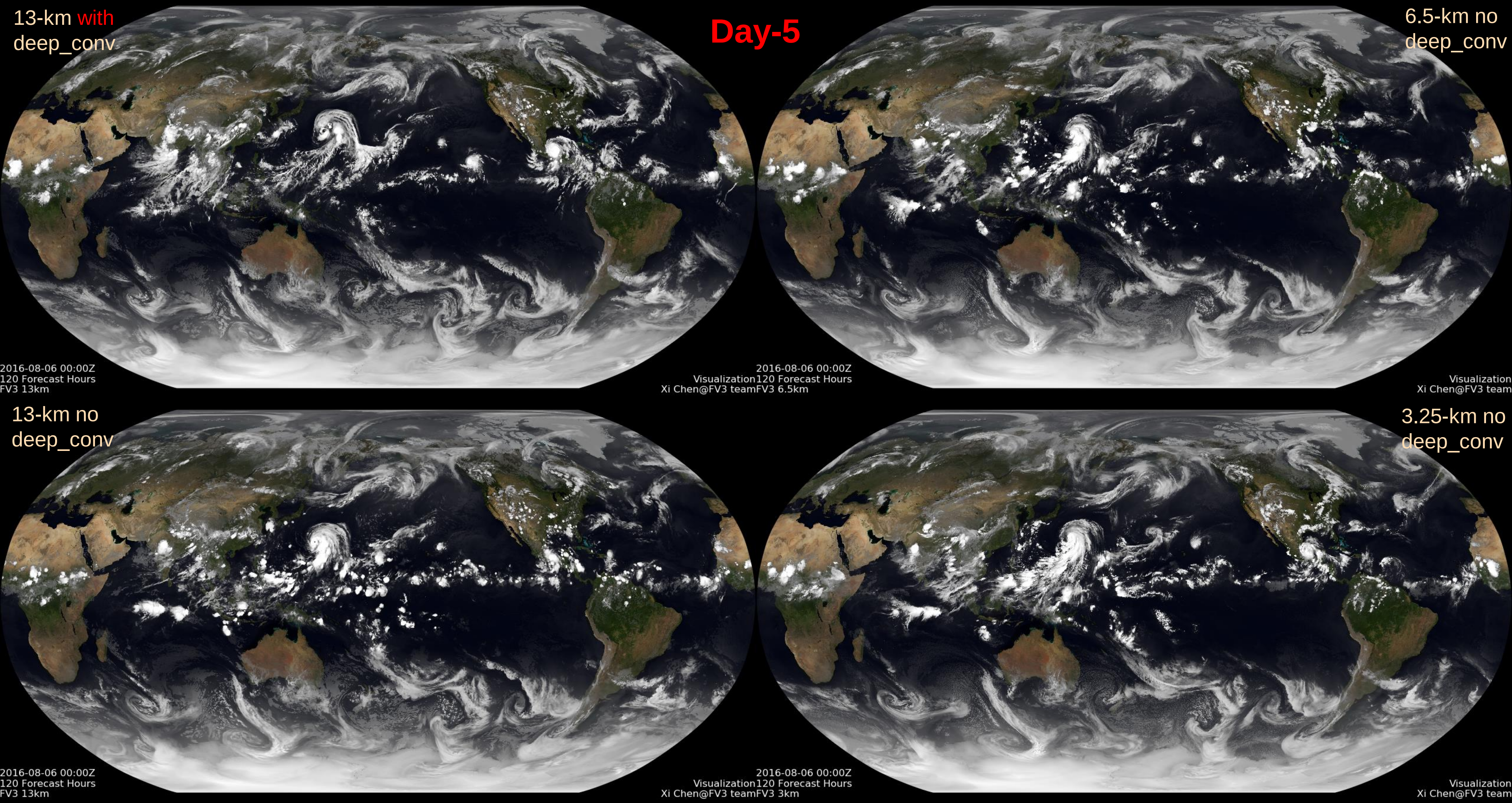


hour-1



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

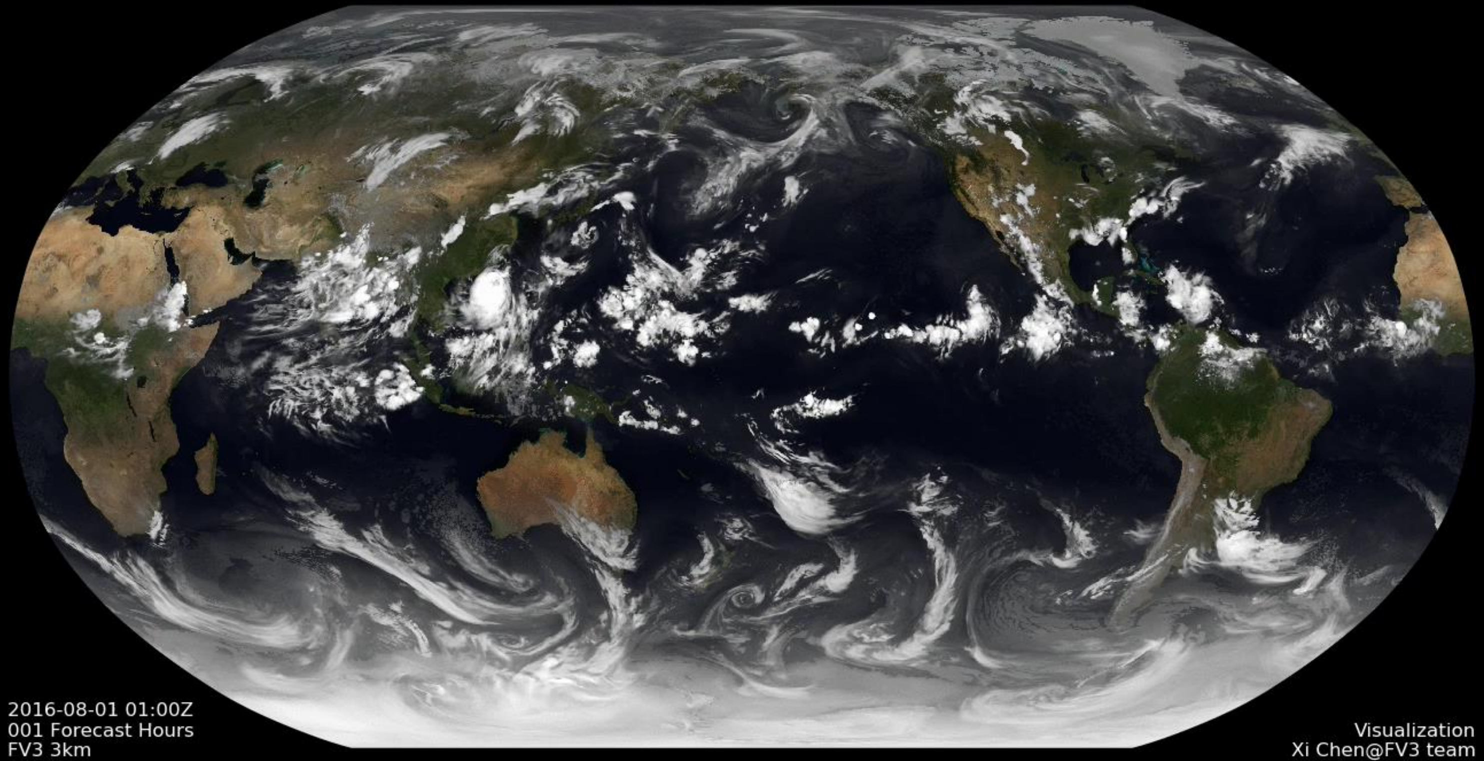
Day-5


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

The “2020 FV3” prototype

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

OLR: 20180801-20160910

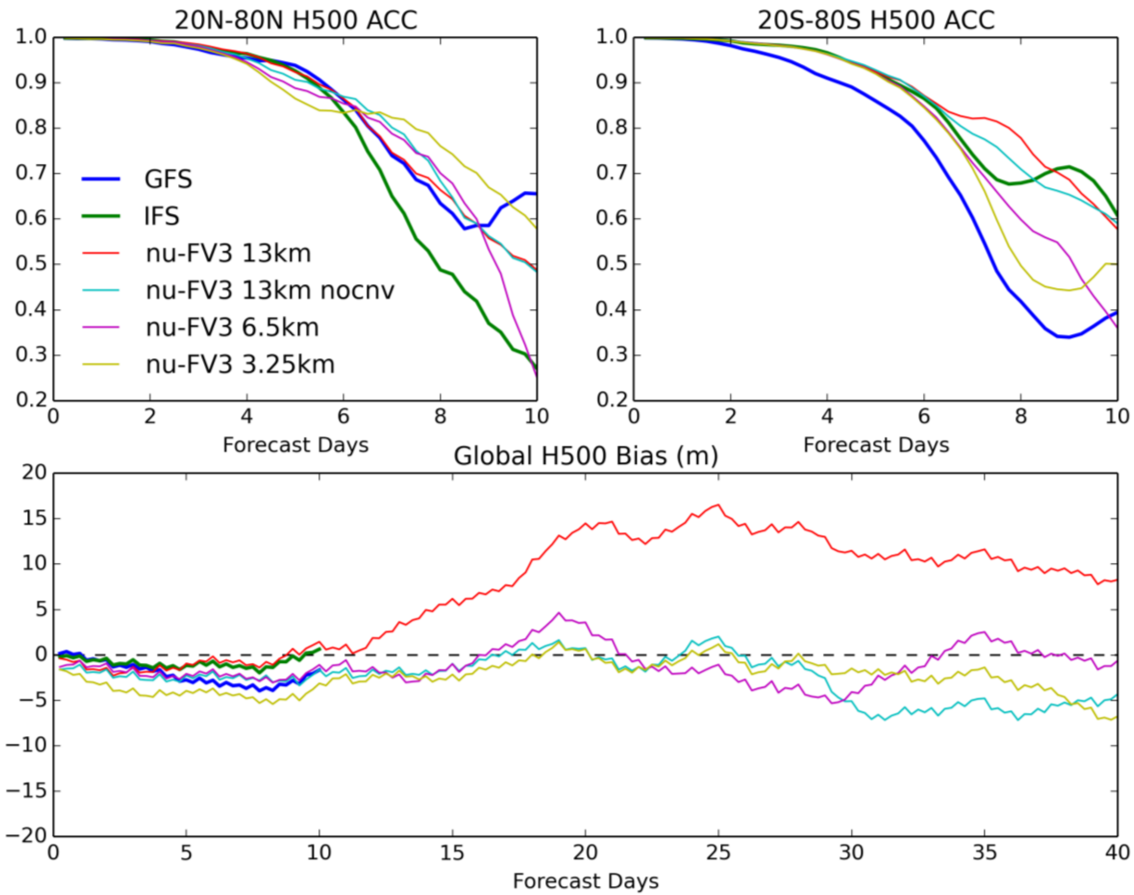


Anomaly Correlation Coefficient (ACC): 500-mb Height

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

Future development path of FV3:

- **The "2020 FV3" will be an evolution, not a revolution:**
  we are developing a nearly self-contained "super dynamics" (2020 FV3) with built-in Sub-Grid physics (including the inline cloud micro-physics) suitable for gray-zone (1-10 km)

- A global cloud-resolving/permitting configuration that relies very little on cumulous parameterization may be feasible for operational NWP in a few years

- Computational performance of the 6.5 km C1536L79: 6 hours with ~55K cores (Cray XC40) to finish a 40-day sub-seasonal prediction