FV3 within the NASA GEOS modeling and assimilation system

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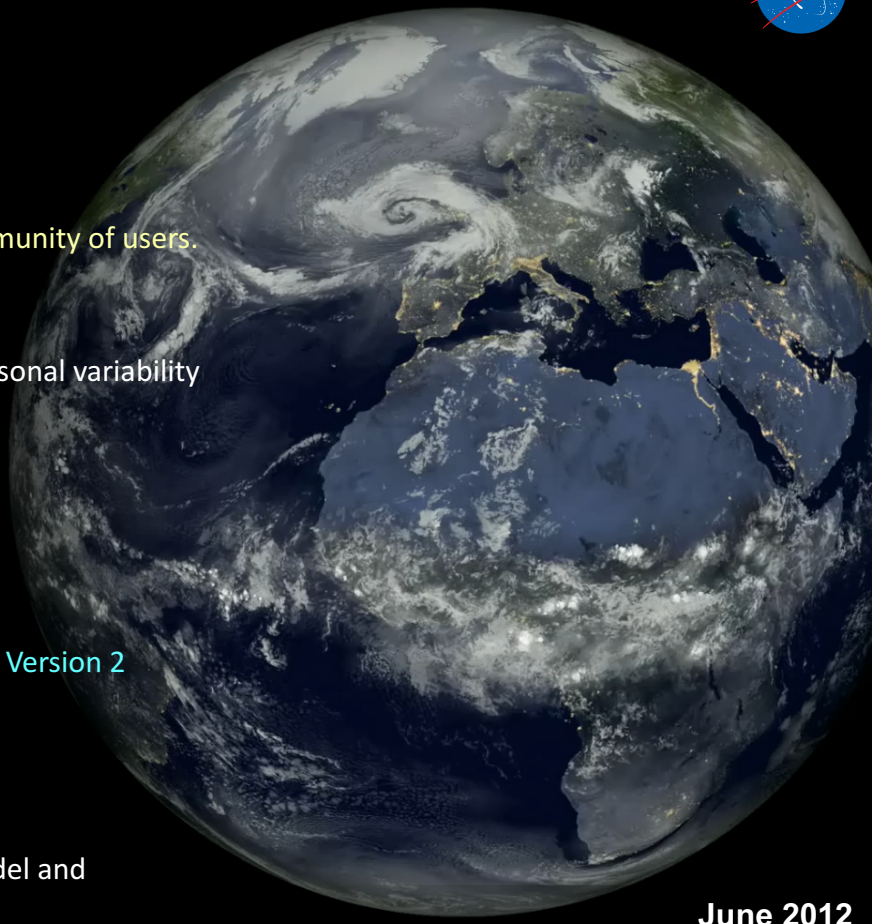
GMAO Modeling Activities

1. Weather Analysis and Prediction
   - *near-realtime analyses, assimilation products, and forecasts*
   - *In* support of NASA's satellite missions and field experiments
   - Generating near-real time atmospheric products for a broad community of users.
2. Seasonal-Decadal Analysis and Prediction
   - Coupled Earth-System models and analyses of subseasonal to seasonal variability in support of:
     - *National Multi-Model Ensemble (NMME)* project
     - Chemistry-Climate Model (CCM)
     - Coupled Model Intercomparison Project (CMIP)
3. Reanalysis for Climate
   - Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)
   - Global downscaling of reanalyses
4. Global Mesoscale Modeling
   - Global simulations with spatial resolutions at the forefront of model and computing capability
     - These form the basis for *Observing System Simulation Experiments*.



June 2012
GEOS 1.5km Cloud Resolving Simulation

GEOS Modeling & Assimilation Portfolio

Forward Processing System	Satellite-Era Reanalysis 1979 - Present	EOS-Era Reanalysis 2000 – Present	Nature Runs (OSSEs)	Seasonal Forecast System	Coupled Simulations (Decadal, CMIP6)
3D-Hybrid Ensemble-Var (25km) 32 ensemble members Hydrostatic FV3 1-Moment Cloud Microphysics *e5131 GEOS-5 FP system Terminated 1Q-2017*	**MERRA (50km) Ending Feb. 2016** 3D-Var Hydrostatic FV-LatLon ~200 TB	**M2R12K (12km)** MERRA2 downscaled to 12 km Aerosols CO_2, CO, SO_2, O_3 Non-Hydrostatic FV3 1-Moment Cloud Microphysics	**G5NR (7km)** Simulated 2005-2007 Aerosols, CO_2, CO, SO_2, O_3 Non-Hydrostatic FV3 1-Moment Cloud Microphysics 4 PB	**GEOS SFS (50km)** MERRA-2 replay 50km, 40L ocean analysis 31 members per month Hydrostatic FV3 Include aerosols, CO, CO_2 *M2-driven EnOI ocean analysis*	**GEOS CMIP (25km)** 25km Atmosphere 25km 50L ocean Include aerosols greenhouse gases Hydrostatic FV3 2-Moment Cloud Microphysics *Planning/discussion* *Align with "MERRA-3" SFS and strategic direction of ESD*
4D-Hybrid Ensemble-Var (12km) 32 ensemble members Atmosphere, ocean surface Hydrostatic FV3 1-Moment Cloud Microphysics *In Production 1Q-2017*	**MERRA-2 (50km)** 3D-Var Hydrostatic FV3 Aerosols and CO, SO_2, O_3 1-Moment Cloud Microphysics ~400 TB	**IESA (12km)** 4D-Hybrid Ensemble-Var 32 ensemble members atmosphere, land, ocean surface Aerosols, CO_2, CO, SO_2, O_3 Non-Hydrostatic FV3 1-Moment Cloud Microphysics 5,000 cores ; 40 simulation days/day 150 days total wallclock ~3 to 4 PB of data	**G5NR-CHEM (12km)** Simulated 2013-2014 Replay to M2R12K Full Reactive Chemistry Non-Hydrostatic FV3 1-Moment Cloud Microphysics 1 PB of data *4Q-FY2016*	**GEOS SFS (25km)** Alignment with "MERRA-3" 25km, 50L ocean analysis System design under review *FY2020 target*	
4D Ensemble-Var (9km) ~100 ensemble members Atmosphere, ocean surface Non-Hydrostatic FV3 2-Moment Cloud Microphysics Grell-Freitas Scale-Aware Convection *FY2018 target*	**MERRA-2 GMI replay (50km)** Replay GMI Chemistry 1 streams, 1,000 cores each 12 to 18 months ~ 1 PB	**IESAR4K (4km)** IESA Downscaled to 4km downscallng evaluation for NCA Aerosols, CO_2, CO, SO_2, O_3 Non-Hydrostatic FV3 2-Moment Cloud Microphysics 5,000 cores ; 40 simulation days/day 150 days total wallclock ~3 to 4 PB of data	**G6NR (1-3km)** Simulated 2015 Aerosols CO_2, CO, SO_2, O_3, CH_4 Non-Hydrostatic FV3 2-Moment Cloud Microphysics ~4 PB *Planning/evaluation*		
	Coupled Reanalysis ("MERRA-3") Atmosphere-land-ocean-cryosphere (alignment with SFS and CMIP6) *FY2020 target*				

Past GMAO core projects

Core GMAO projects in production or evaluation.

Pathfinding projects toward GMAO core efforts.

Projects undergoing GMAO discussion/planning.

GEOS Atmospheric Model

Finite Volume Cubed-Sphere *(FV3 collaboration with NOAA GFDL)*

- Split explicit time-stepping *(C-D grid)*
- Monotonic & Non-Monotonic advection schemes
- Vertically Lagrangian
- Hydrostatic or Non-Hydrostatic

Single-Moment or ***Two-Moment*** moist cloud microphysics options

Relaxed Arakawa Schubert Convection *(stochastic Tokioka entrainment limiter)*

- Grell Freitas and UW shallow convection options

Chou Suarez or ***RRTMG*** radiation options

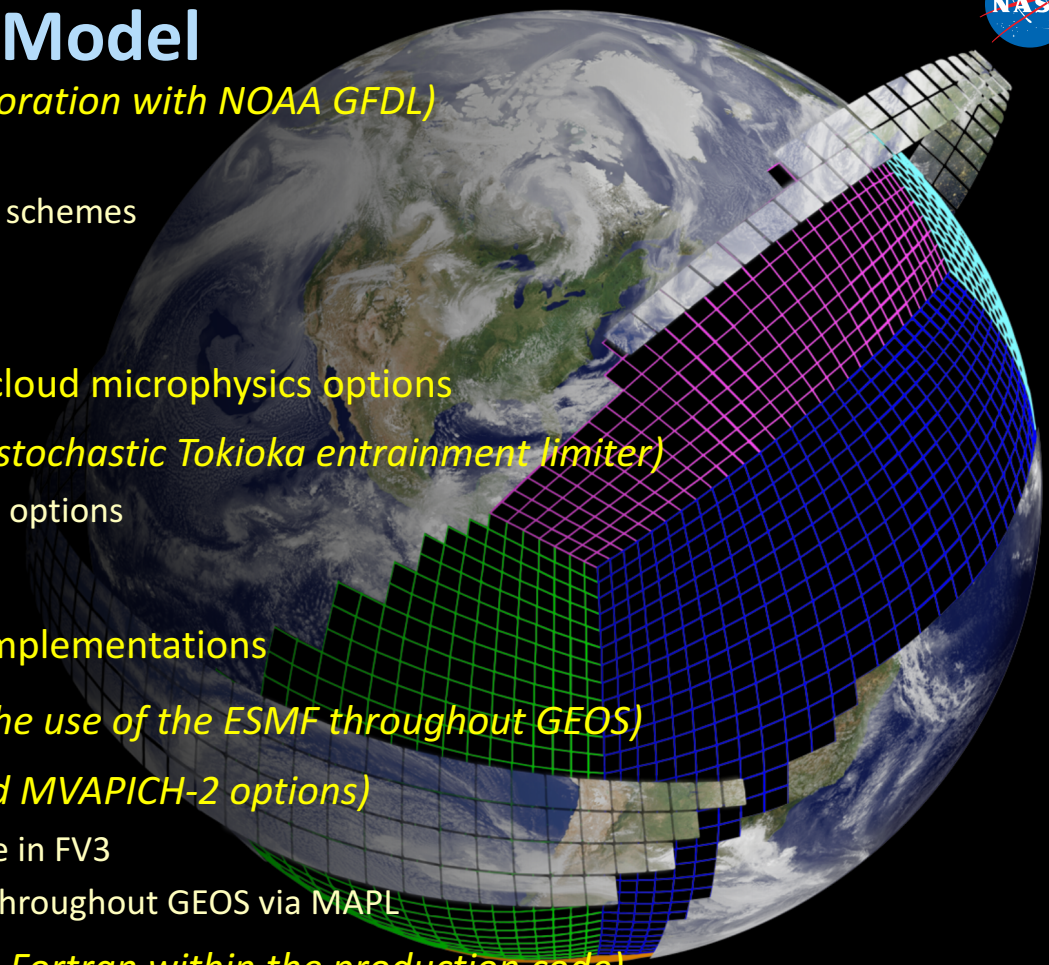
GOCART or ***MAM*** chemistry and aerosol implementations

ESMF compliant *(via MAPL to standardize the use of the ESMF throughout GEOS)*

MPI parallelism *with SGI MPT (Intel-MPI and MVAPICH-2 options)*

- Hybrid MPI+OpenMP directives available in FV3
- Explicit use of SHMEM shared memory throughout GEOS via MAPL

GPU implementation *(optional build via PGI Fortran within the production code)*



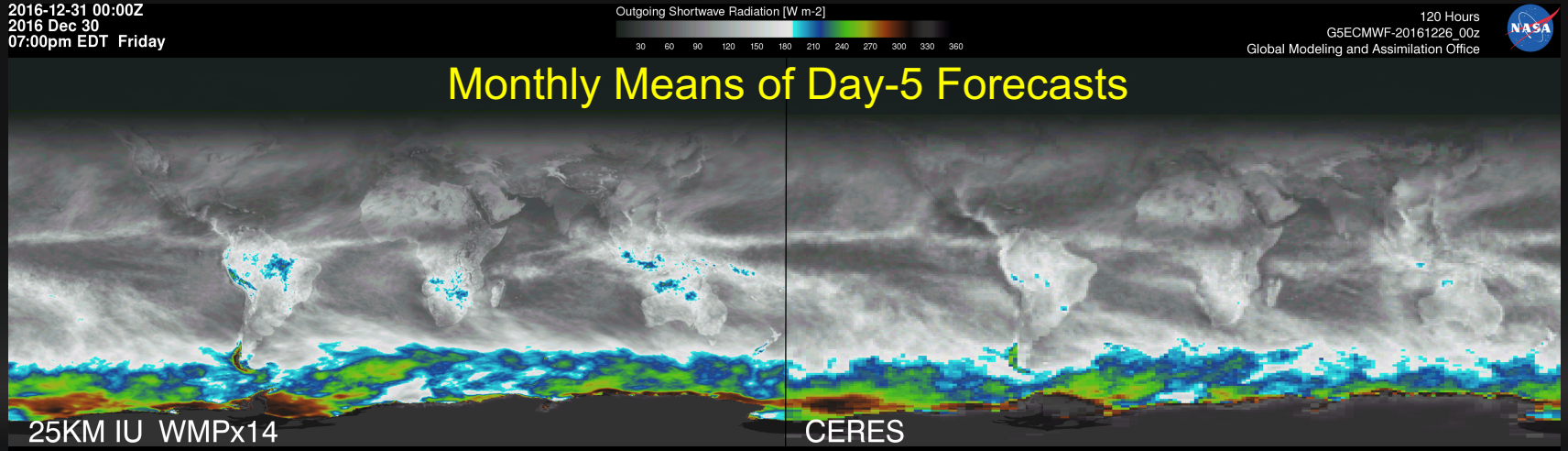
GEOS Modeling Applications

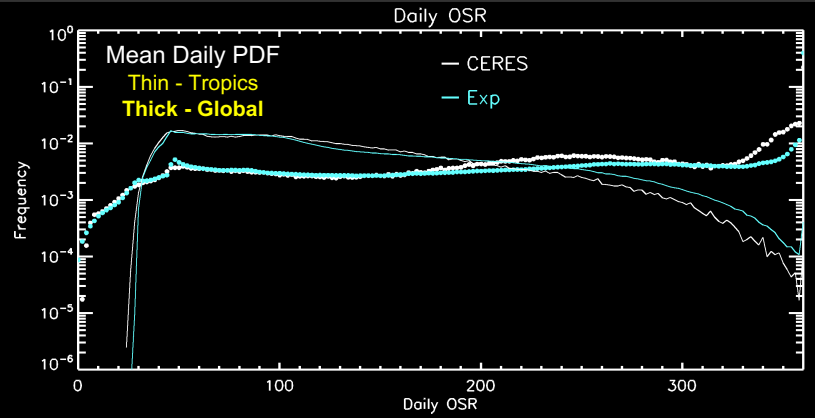
Modeling Component	Current Capability		Year 2020-2025		Year 2025-2030	
	Resolution	*Cores*	*Resolution*	*Cores*	*Resolution*	*Cores*
Single Column	72 Levs	1	132 Levs	1	264 Levs	1
Radiative-Convective-Equilibrium Large-Eddy	500 m	1,000	10-100 m	500,000	1-10 m	1 million
Pioneering Global Embedded-Regional OSSEs	1-5 km *72 Levels*	30,000	500 m – 1 km *132 Levels*	10 million	100-500 m *264 Levels*	1 billion
Deterministic Medium-Range	10-15 km *72 Levels*	6,000	3-7 km *132 Levels*	600,000	1-3 km *264 Levels*	6 million
Seasonal	50 km Ocn 50 km Atm	100	25 km Ocn 25 km Atm	800	10 km Ocn 10 km Atm	16,000
Climate/Reanalysis	50 km	100	10-25 km	8,000	5-10 km	100,000

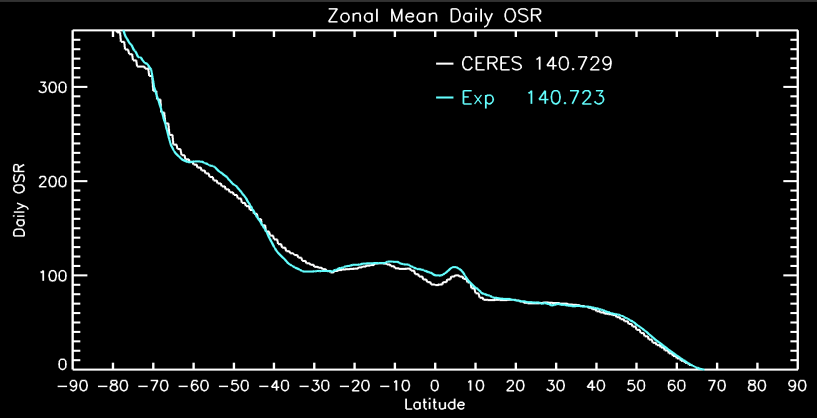
GEOS Tuning Procedures

- Reforecasting
  - 10-day forecasts at 50, 25, and 12-km resolutions
    - Two Seasons (DEC-JAN) and (JUL-AUG)
    - *1200 days of simulation examined at various lead times (1- to 10-days)*
    - *Can finely tune the model*
      - *cloud radiation properties to observations (IR and CERES)*
      - *water vapor and precipitation to observations (SSMI and TRMM)*
      - *looking closely at PDFs on short timescales (30 minutes to daily)*
    - *Examine impact on anomaly correlation and RMS*
- 30-year Ensemble of Seasonal Model Intercomparisons (EMIP)
  - A rapid turnaround on seasonal climate analysis (DJF & JJA) at 50-km resolution
- 30-year AMIP
  - Climate resolution at 50-km resolution
- Fully Cycled DAS
  - At NWP resolutions 25- to 12-km resolutions

GEOS Reforecasting Results







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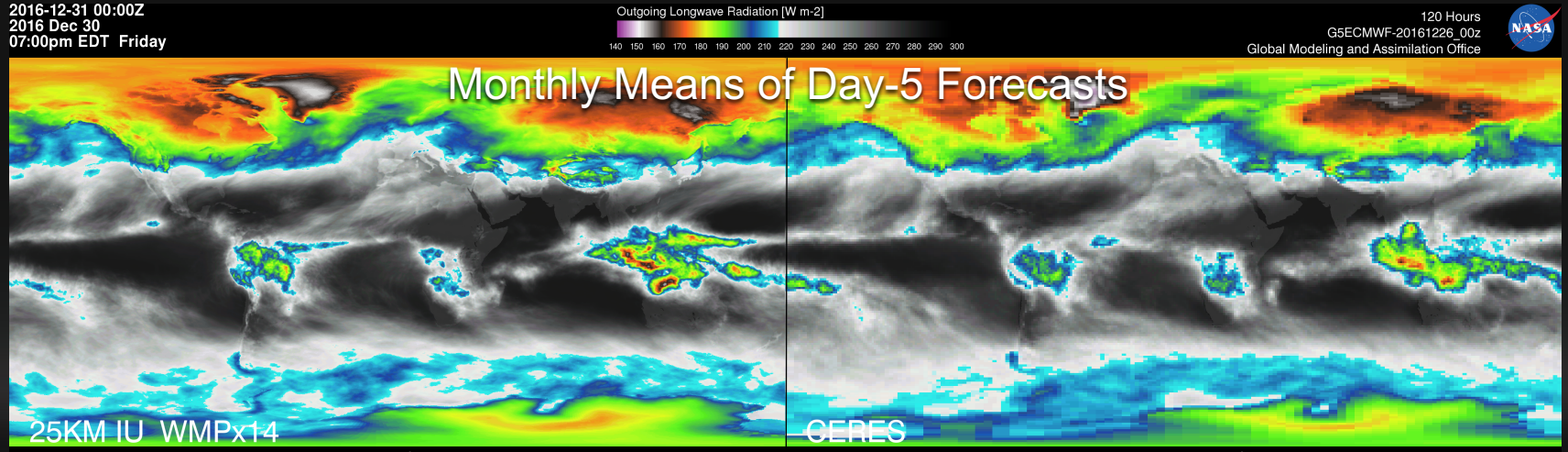

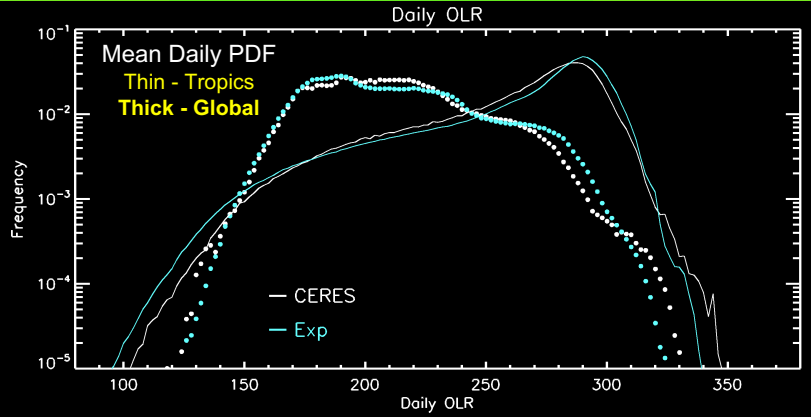

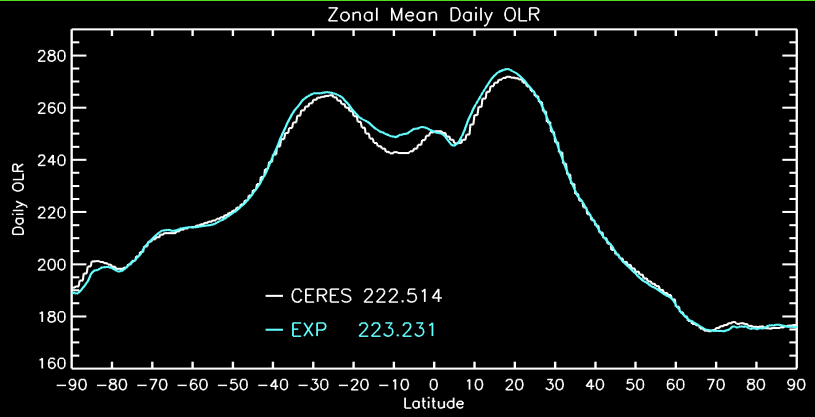

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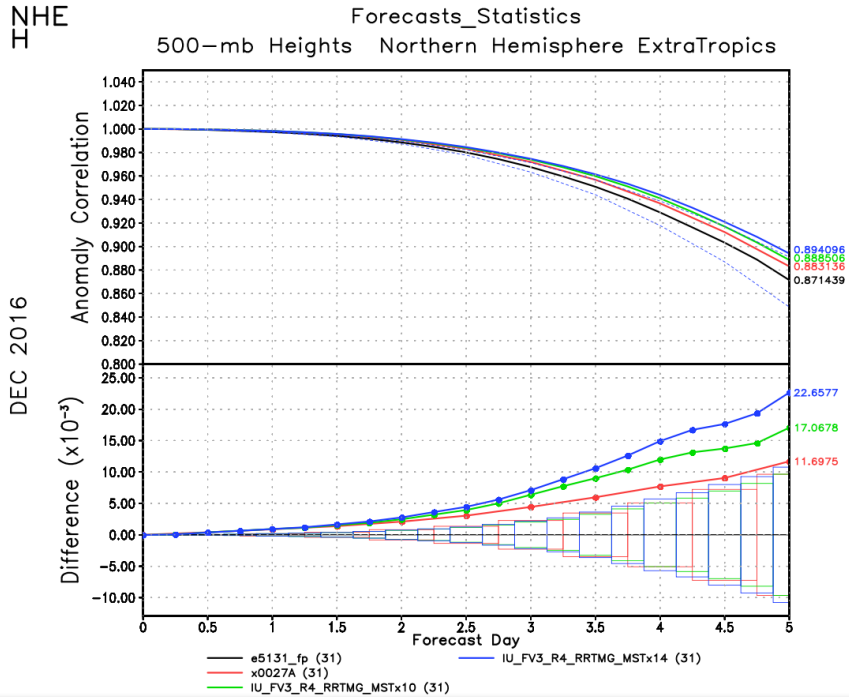
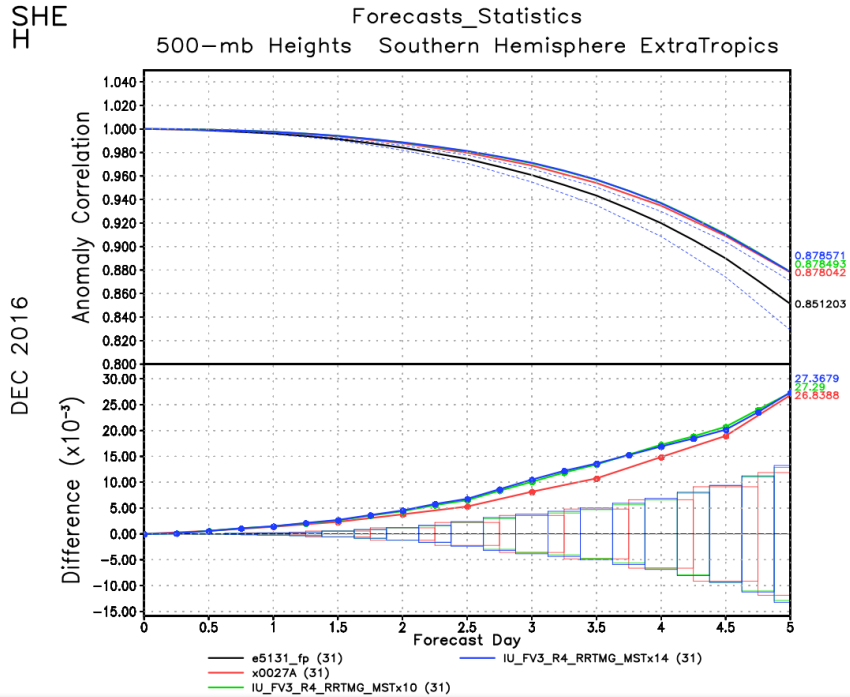


e5131_fp – 25km 3d-Hybrid + FV3 *(Production system at the time)*

x0027A – 25km 4d-Hybrid EnsVar + GMTED topography & GWD tuning

x10/x14 – Reforecasting with RRTMG + NGGPS FV3 + Moist cloud tuning



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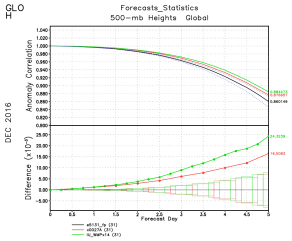
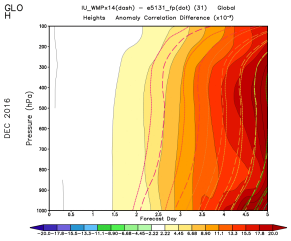
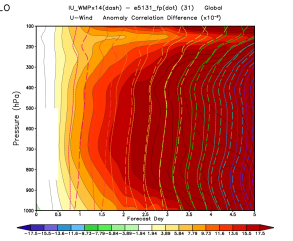
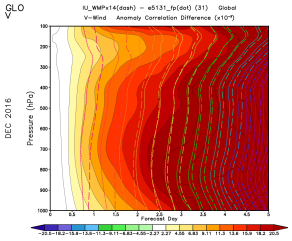
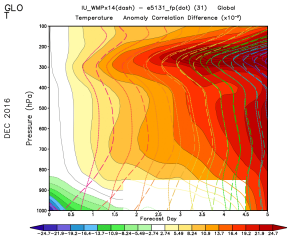
GEOS Reforecasting Results

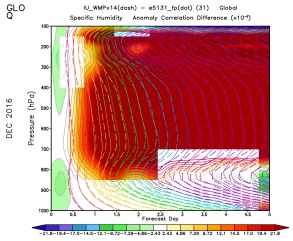


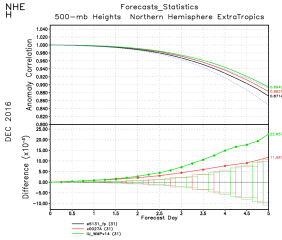


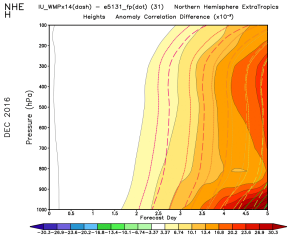


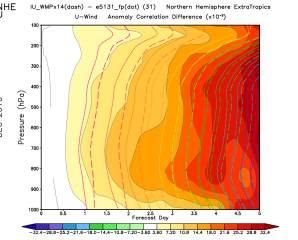


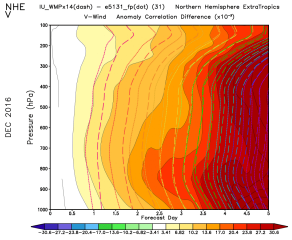


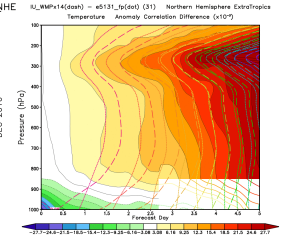


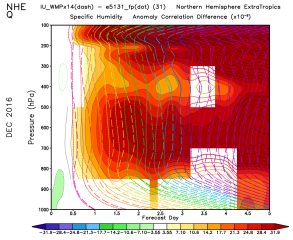


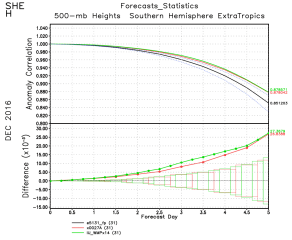


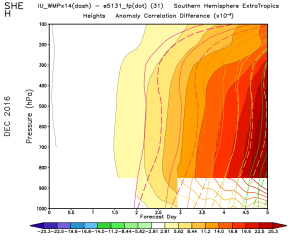


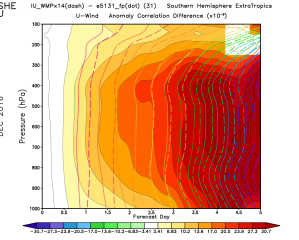


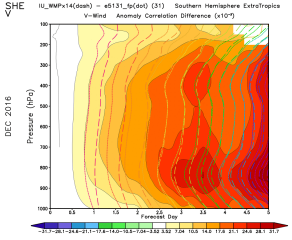


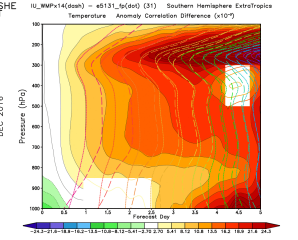


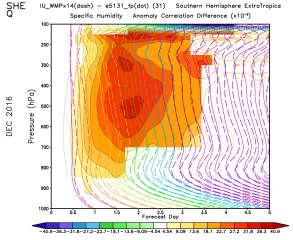


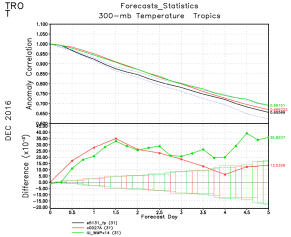


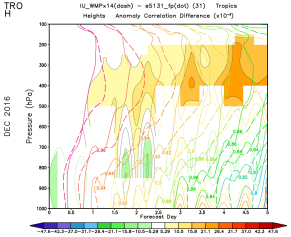


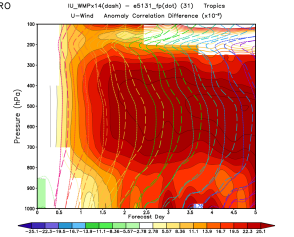


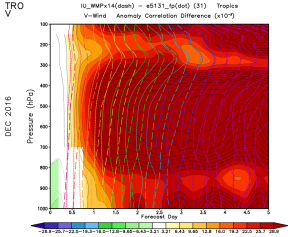


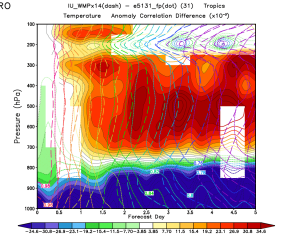


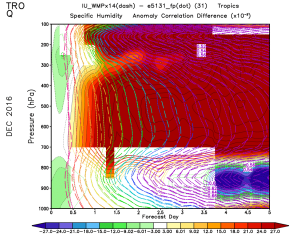








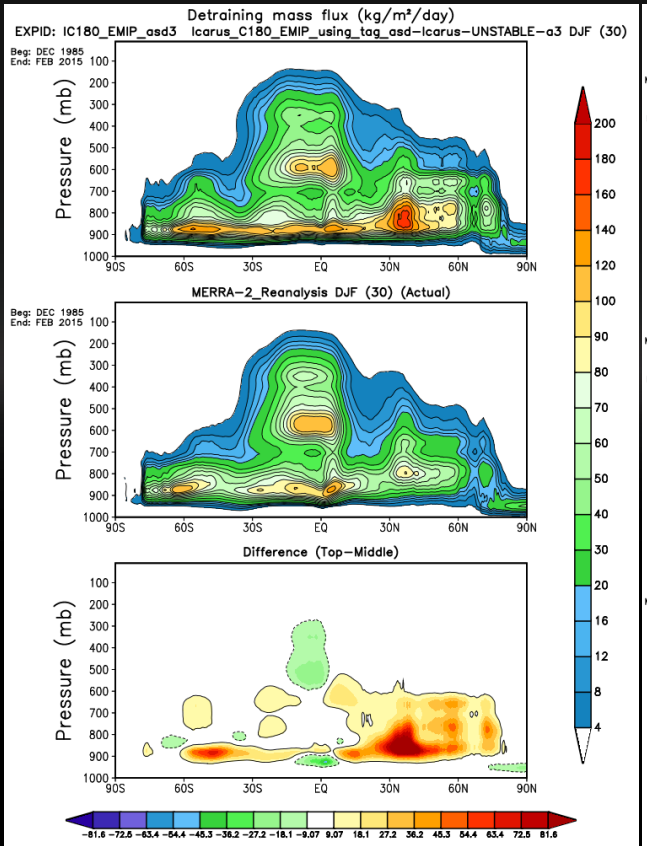


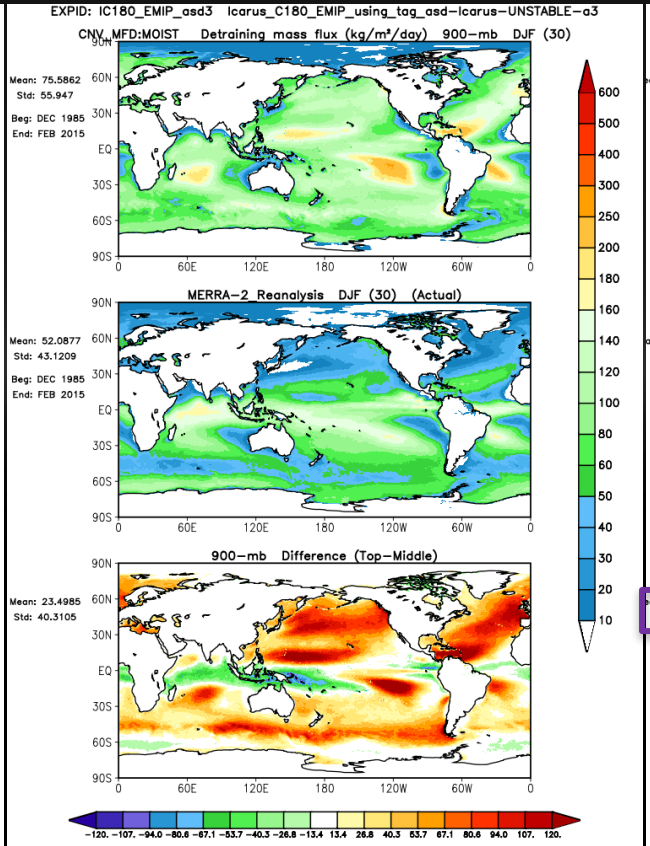


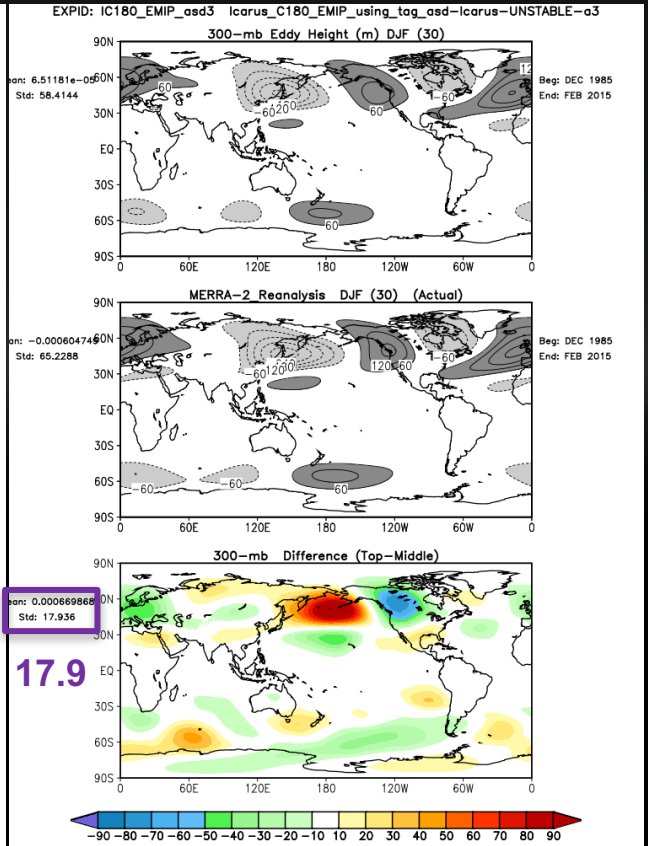
GEOS 30-Year Ensemble AMIP Results (MERRA-2 to x0027A)

Detraining Mass Flux from RAS

Stationary Wave Pattern







GEOS 30-Year Ensemble AMIP Results (x0027A to x14)

Detraining Mass Flux from RAS

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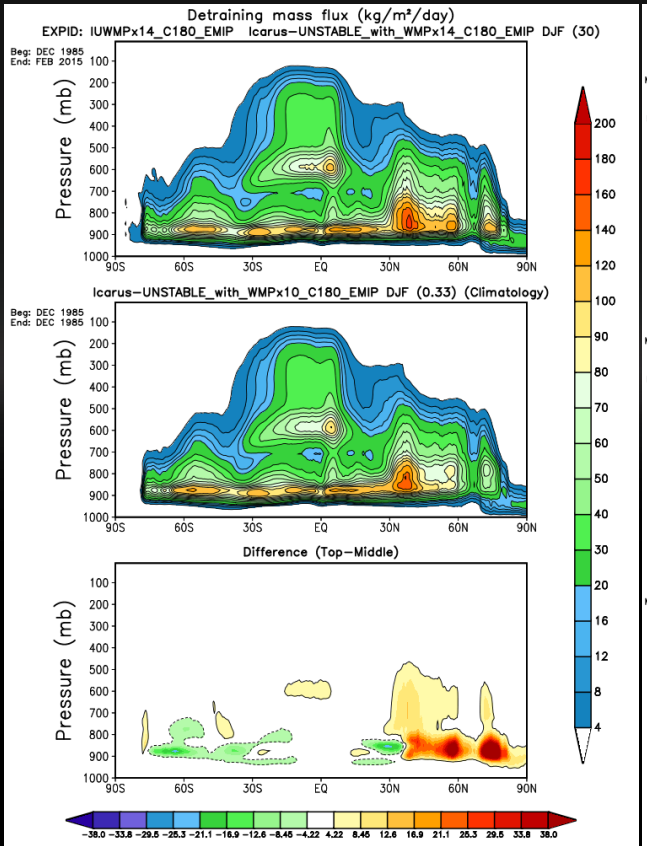
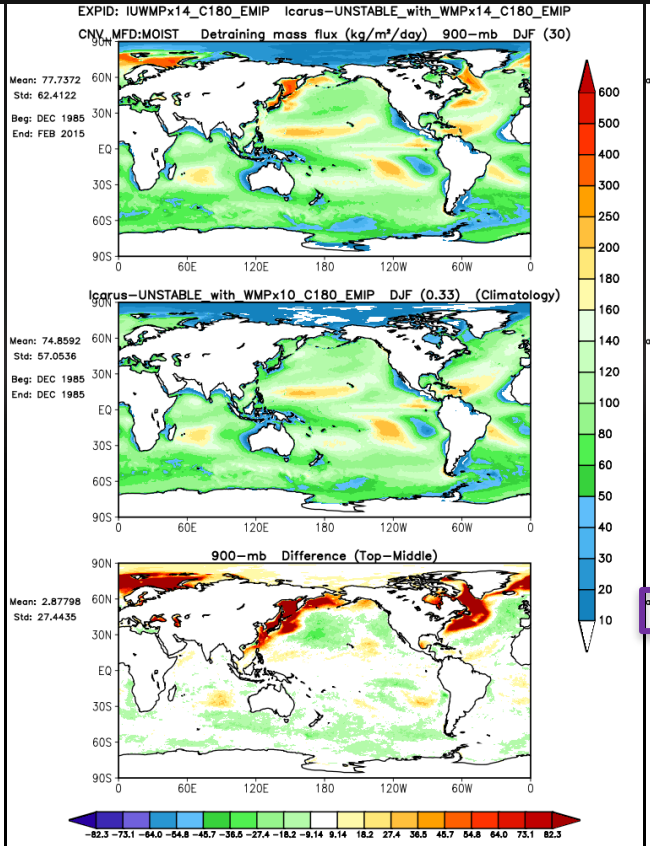
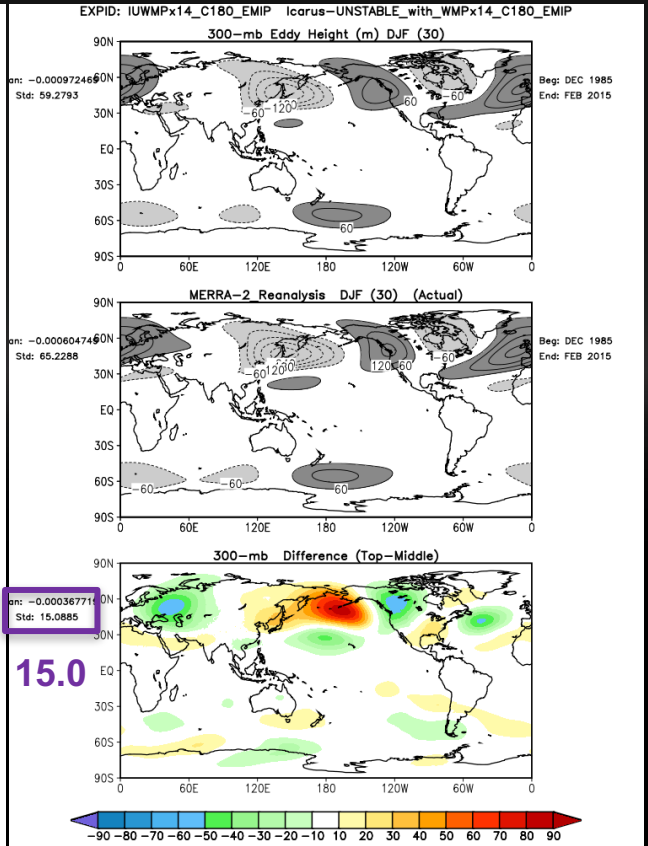






FV3 c720 Namelist Settings in GEOS

hydrostatic = .T.

Hydrostatic FV3

(112.5s Adv/Remap DT)

(18.75s small DT)

dt = 225s
k_split = 2
n_split = 6

tau = 0.
rf_cutoff = 8.e2

Rayleigh Friction off
(done in GEOS moist physics)

n_sponge = 9
d2_bg_k1 = 0.16
d2_bg_k2 = 0.02
fv_sg_adj = 0.0

9 Sponge Layers
Disabled Dry Conv Adj

z_tracer = .T.
fill = .T.

Tracer Courant Limit by Level
(Filling negative tracers)

gmao_cubic = .T.
kord_tm = 9
kord_mt = 9
kord_wz = 9
kord_tr = 9
consv_te = 1.

Cubic Spline Total Energy Conservative Vertical Remapping
(using GMAO_CUBIC)

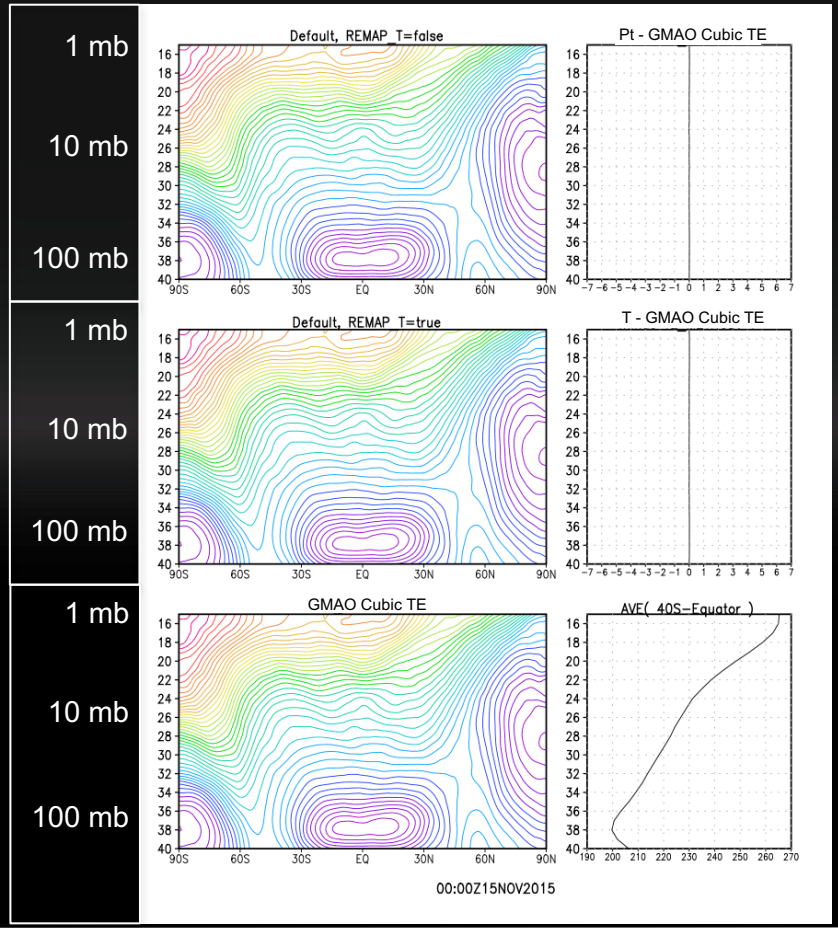
hord_mt = 8
hord_vt = -8
hord_tm = -8
hord_dp = -8
hord_tr = -8

Monotonic Advection Schemes

nord = 2
dddmp = 0.2
d4_bg = 0.15
d2_bg = 0.0
d_ext = 0.0
vtdm4 = 0.0
do_vort_damp = .F.
d_con = 0.

6^{th} order divergence damping
(No Vorticity Damping)

FV3 GMAO Cubic TE Remapping

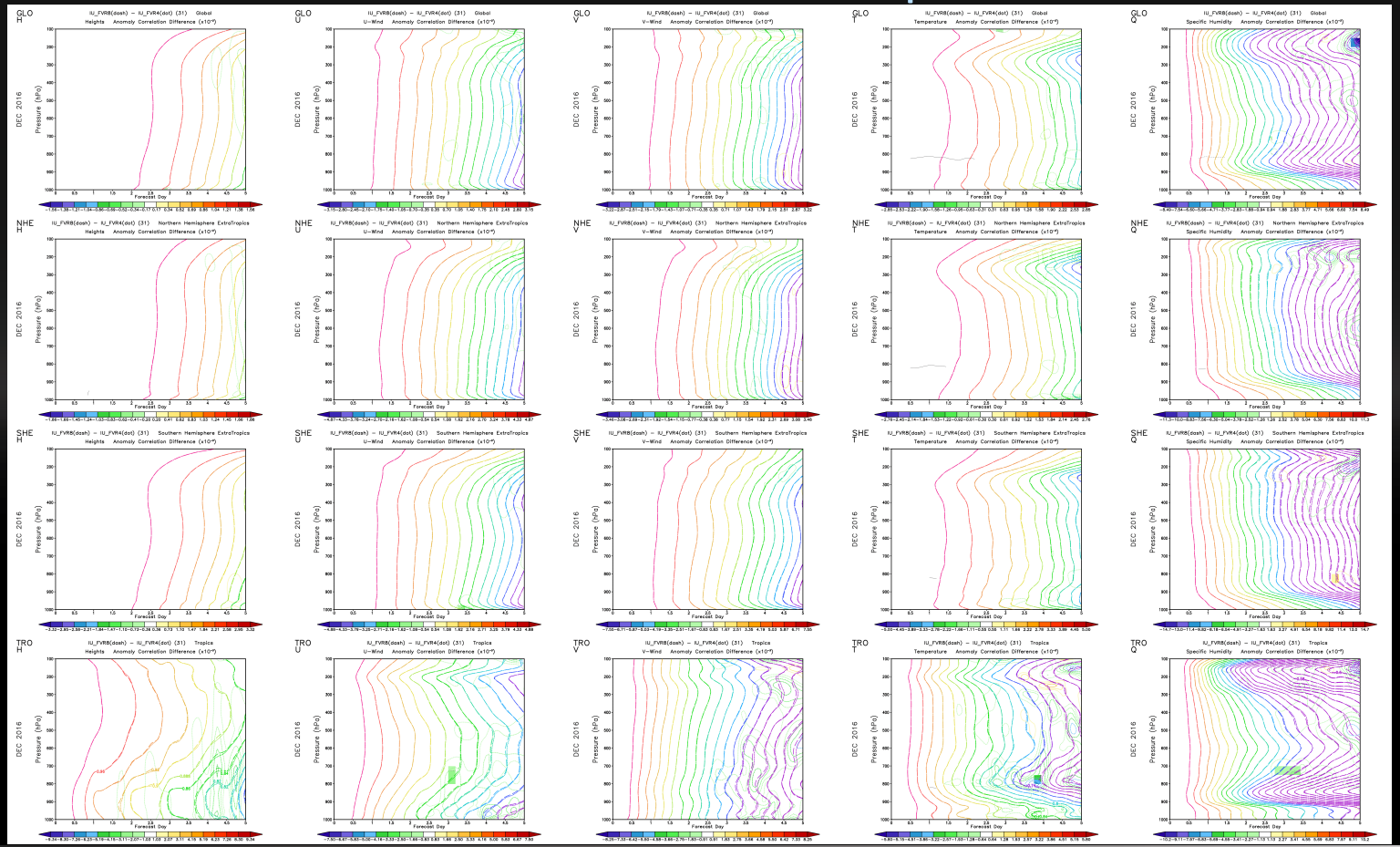


FV3 Cubic PT Remap
DZ noise

FV3 Cubic T Remap
DZ noise

GMAO Cubic TE Remap
No DZ noise

FV3 R4 vs R8 Skill Comparison



The GEOS 12-km Forward Processing System

GOES forward processing assimilation and deterministic forecast system

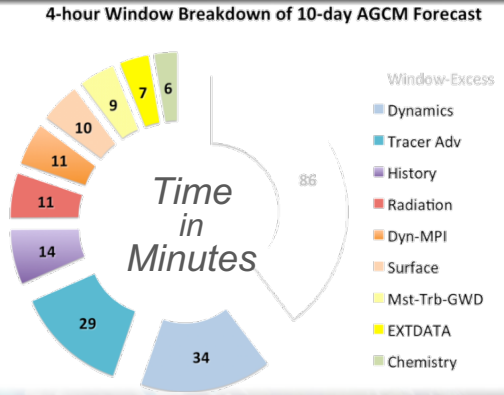
Production Configuration:

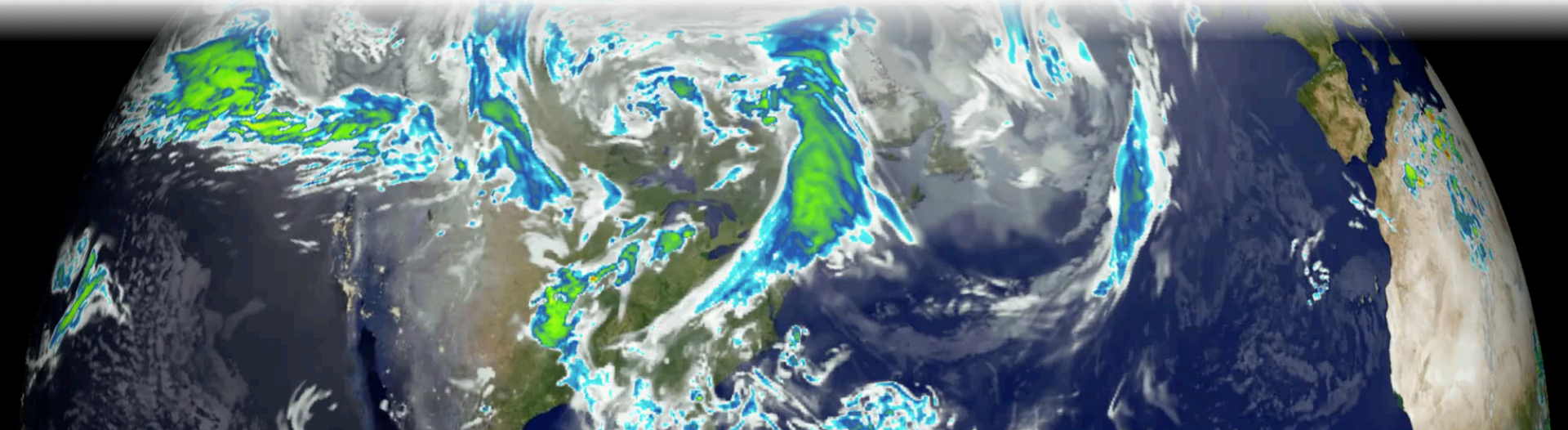
12-km with 72-levels on 5400 Xeon Haswell Cores

4-D Hybrid Ensemble-Variational Data Assimilation

Hydrostatic FV3 Dynamics

GOCART Aerosols Assimilation with GAAS (57 tracers)





The MERRA-2 Reanalysis

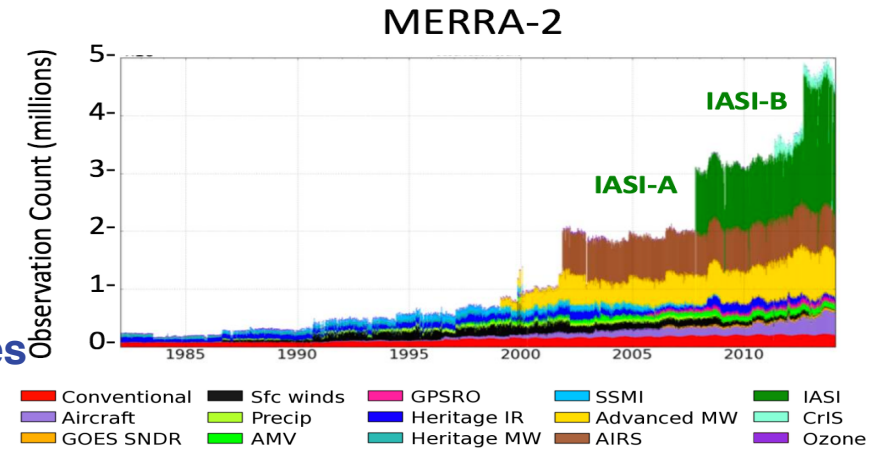
Modern-Era Retrospective Analysis for Research and Applications

[MERRA-2 1980-present]

Production Configuration:

50-km with 72-levels in 4 streams of 100 Xeon Cores

3-D Variational Data Assimilation



An intermediate reanalysis of the satellite era

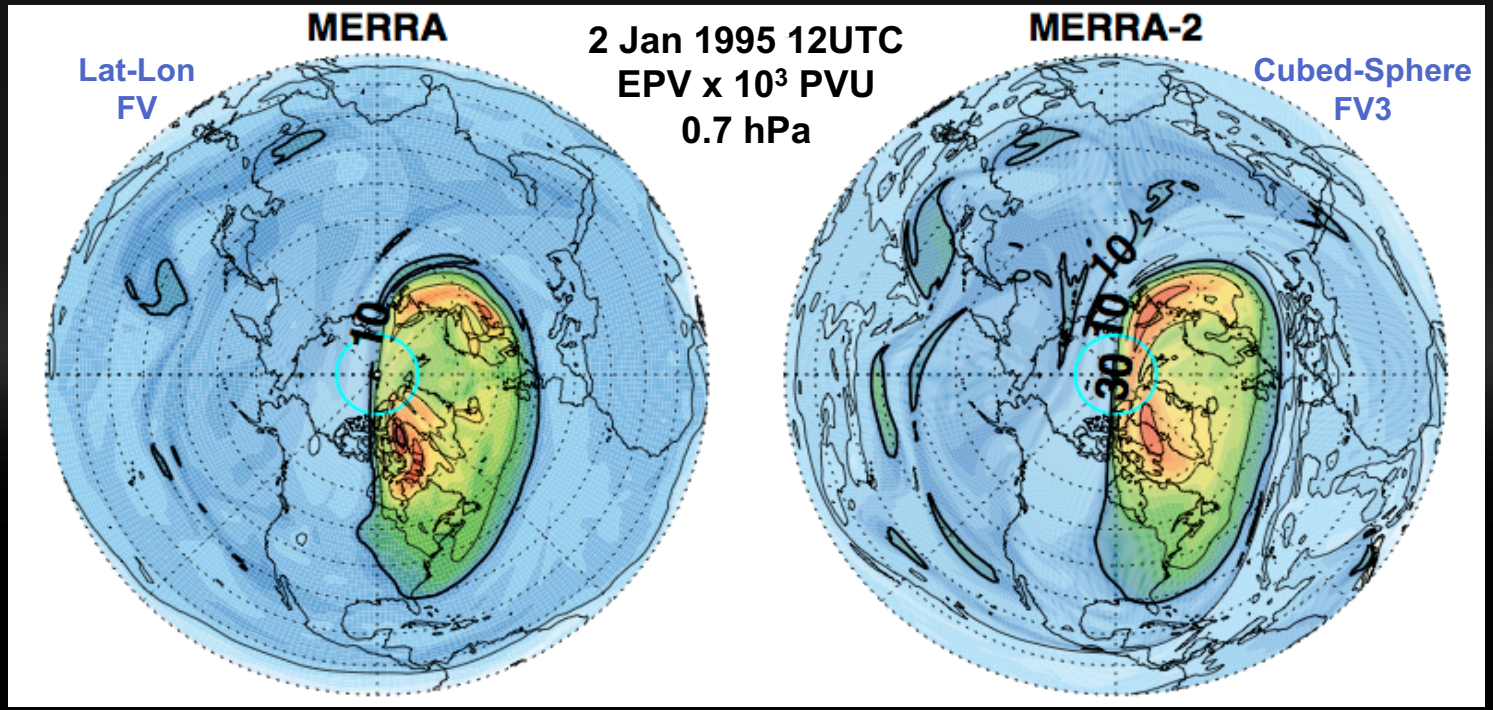
- Includes new satellite observations not available to MERRA
- Reduces biases and imbalances in the water cycle
- Reduces some spurious trends and jumps related to changes in the observing system

Progress toward an Integrated Earth System Reanalysis

- Joint assimilation of meteorological and aerosol observations
- Improves aspects of the stratosphere, including ozone
- Improves aspects of the cryosphere, including glaciated surfaces

The MERRA-2 Reanalysis

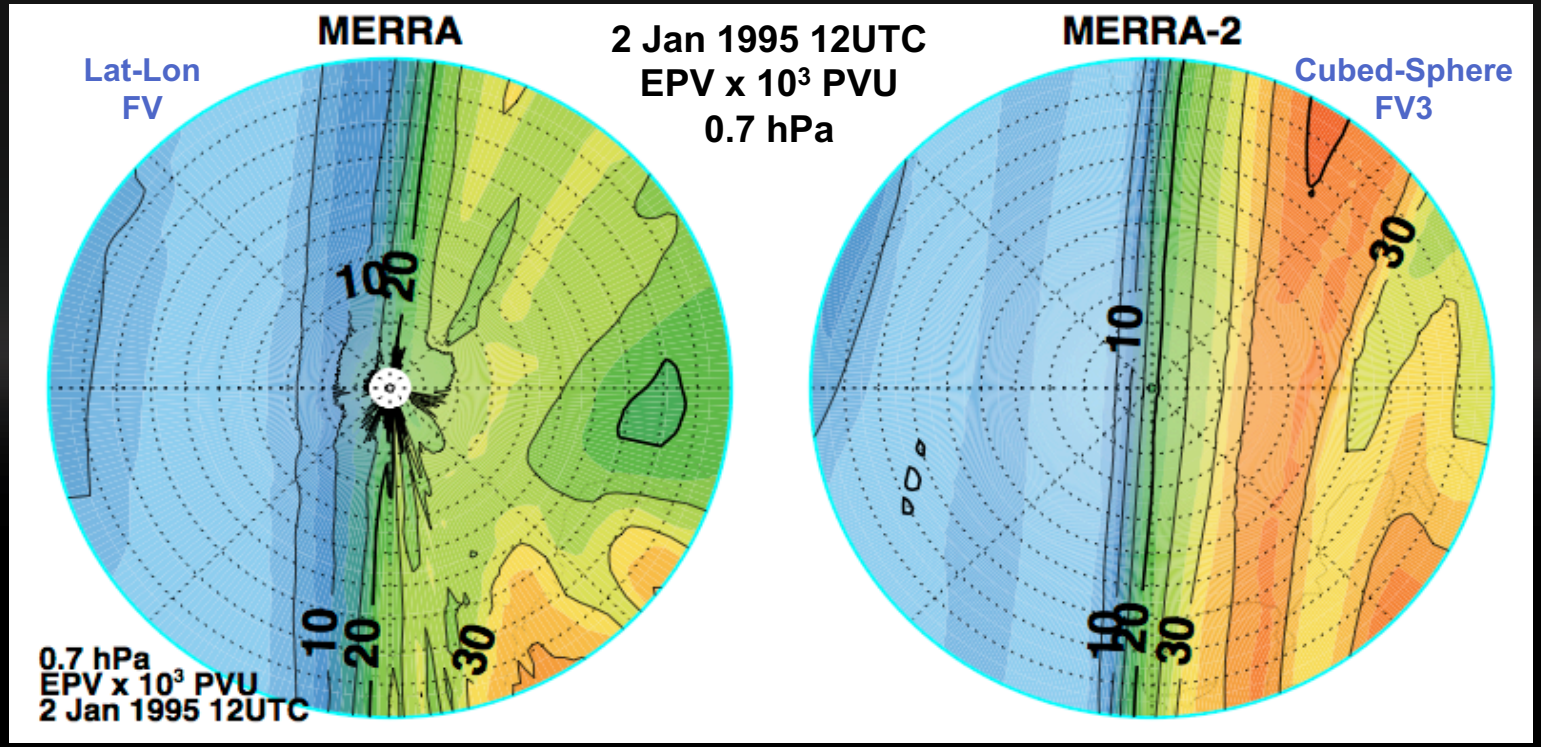
Cross Polar Flow (Polar Wind > 170 ms^{-1}) Influence of of the Pole on EPV



MERRA-2 has two high EPV regions (red) merging over the pole, created by downward motion, While MERRA has two weaker EPV regions with low EPV values at the pole.

The MERRA-2 Reanalysis

Cross Polar Flow (Polar Wind > 170 ms^{-1}) Influence of of the Pole on EPV



80°N to the North Pole

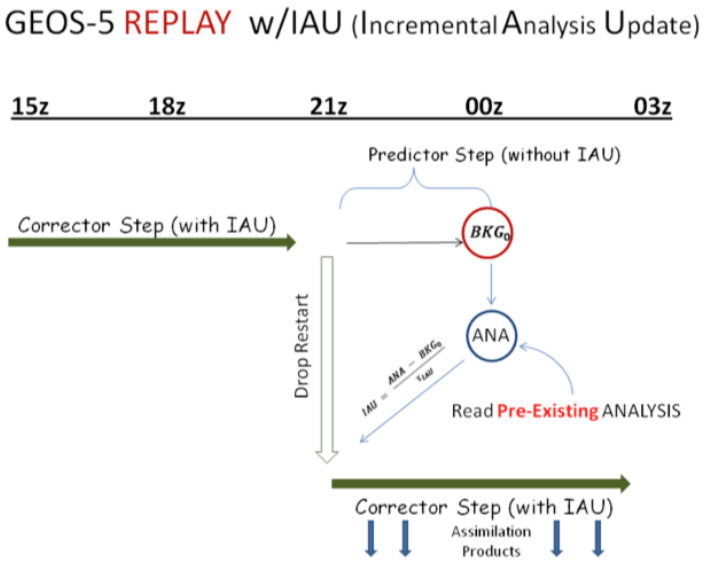
MERRA diagnostic EPV contains small-scale structures radiating from the pole.

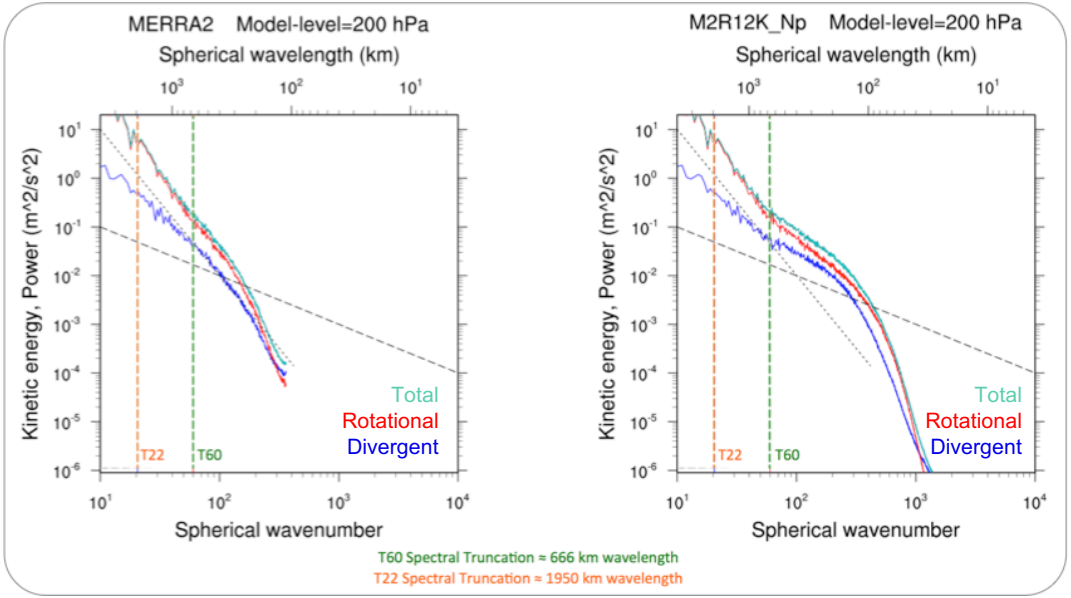
MERRA-2 12-km Global Downscaling (2000-2016)

MERRA-2 Replay at 12.5-Km (M2R12K)

‘Replay’ Using MERRA-2 with IAU

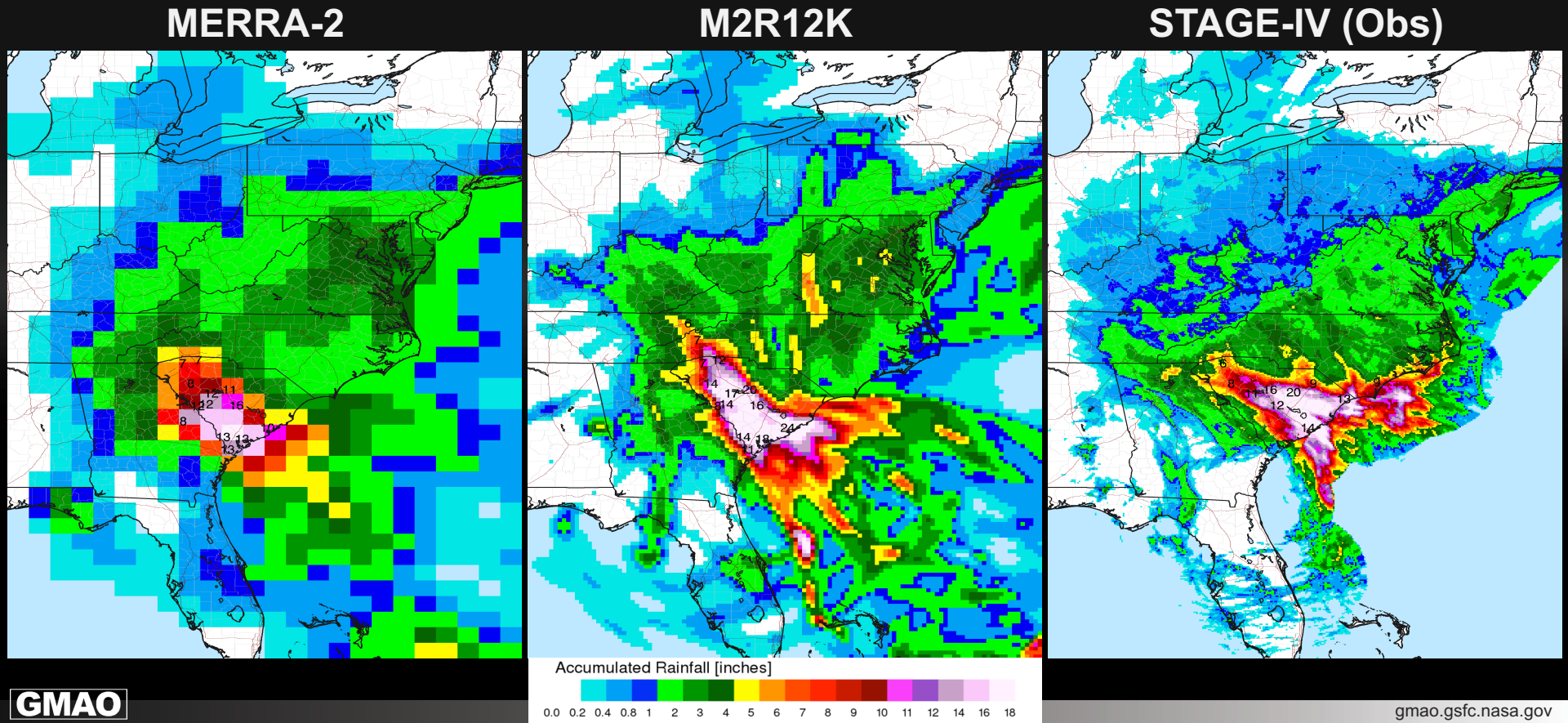
Only forcing at scales T60 and longer





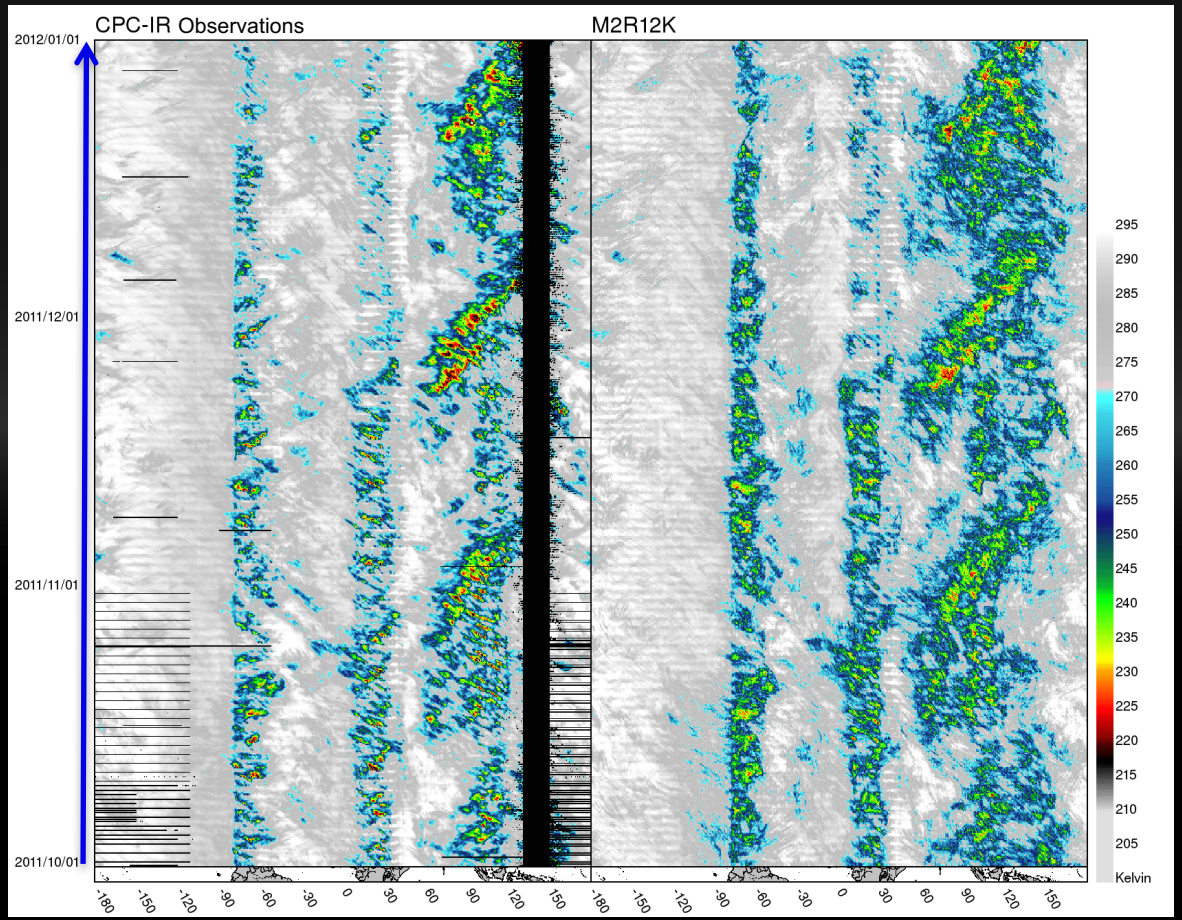
MERRA-2 12-km Global Downscaling (2000-2016)

October 2-5, 2015 South Carolina Floods



MERRA-2 12-km Global Downscaling (2000-2016)

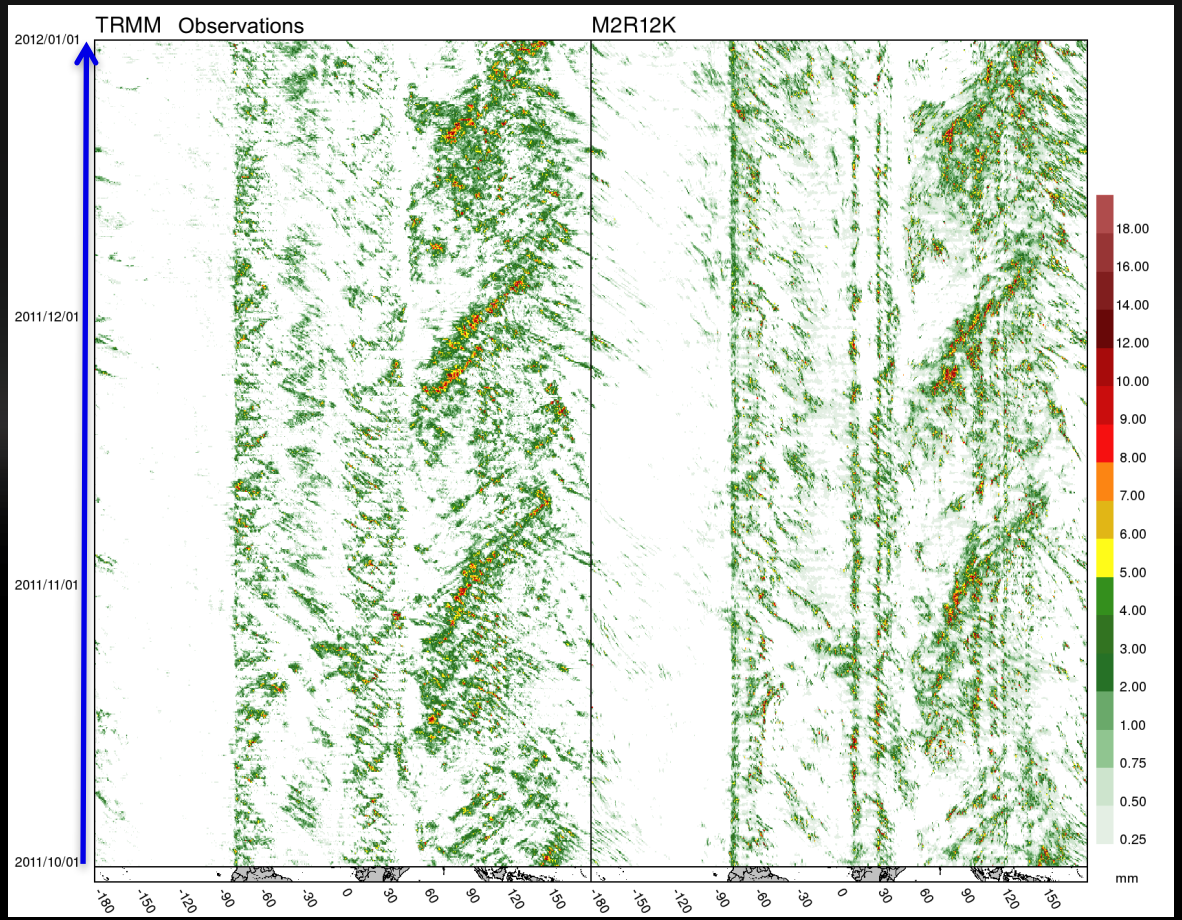
2011-12
DYNAMO
MJO



11-micron
Brightness
Temperature
5S : 5N

MERRA-2 12-km Global Downscaling (2000-2016)

2011-12
DYNAMO
MJO



Hourly
Precipitation
5S : 5N

7-km GEOS-5 Nature Run (2005 & 2006)

Must produce realistic weather and variability

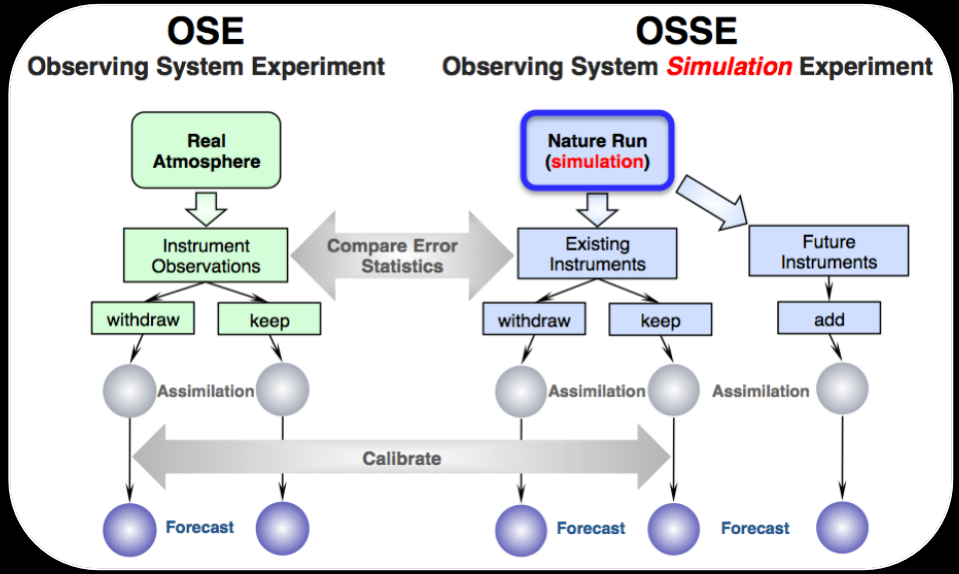
- *High impact / Extreme events*
  - *Mid-latitude storms*
  - *Tropical cyclones*
  - *Organized convective clusters*

These must form in a free running simulation

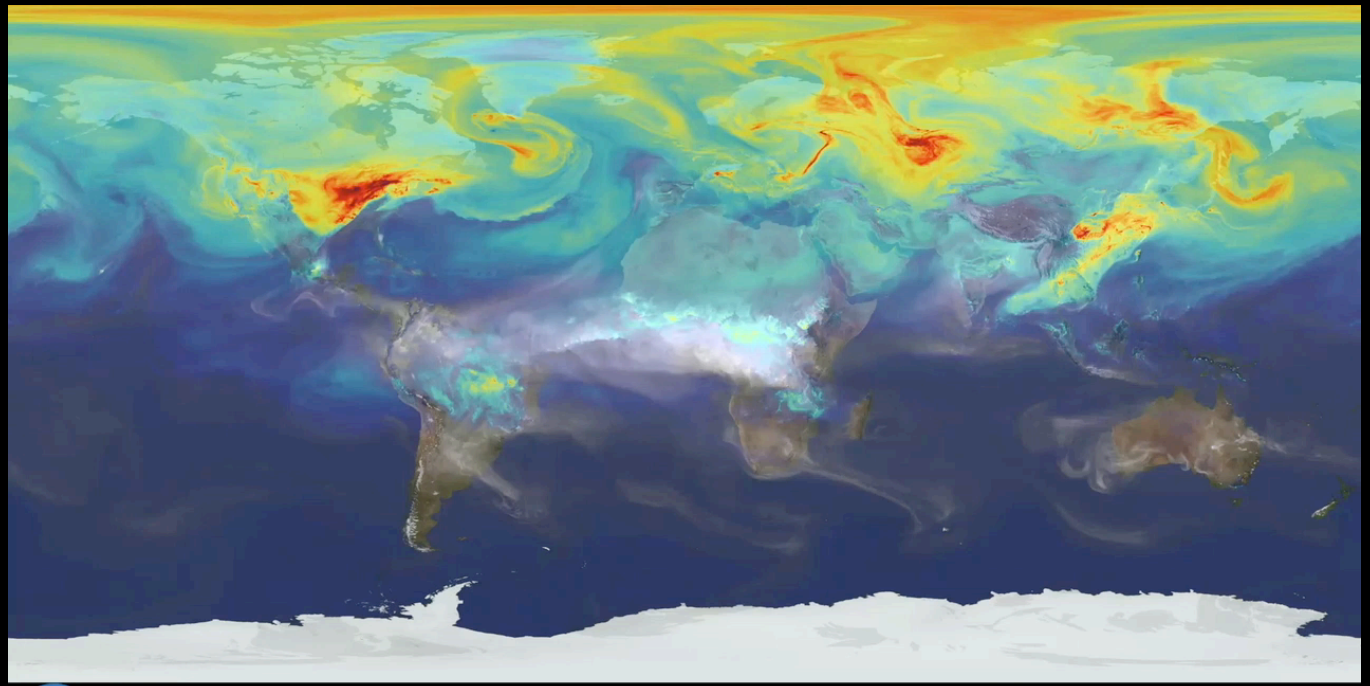
- *No constraints to observed meteorology*
  - *It will not produce specific weather events*
  - *But it will produce similar events*

Climatology must be representative of Nature

- *It must resemble the real atmosphere*
  - *Statistically viable climatology*
  - *An acceptable level of variance for the climate of Earth*
- *While it will not be exactly the climate of the period simulated, it must be a statistically possible scenario*



7-km GEOS-5 Nature Run (2005 & 2006)



7km-G5NR details:

2-Year Nature Run (2005-2007)

Non Hydrostatic FV3

30-minute output

Aerosols

CO_2

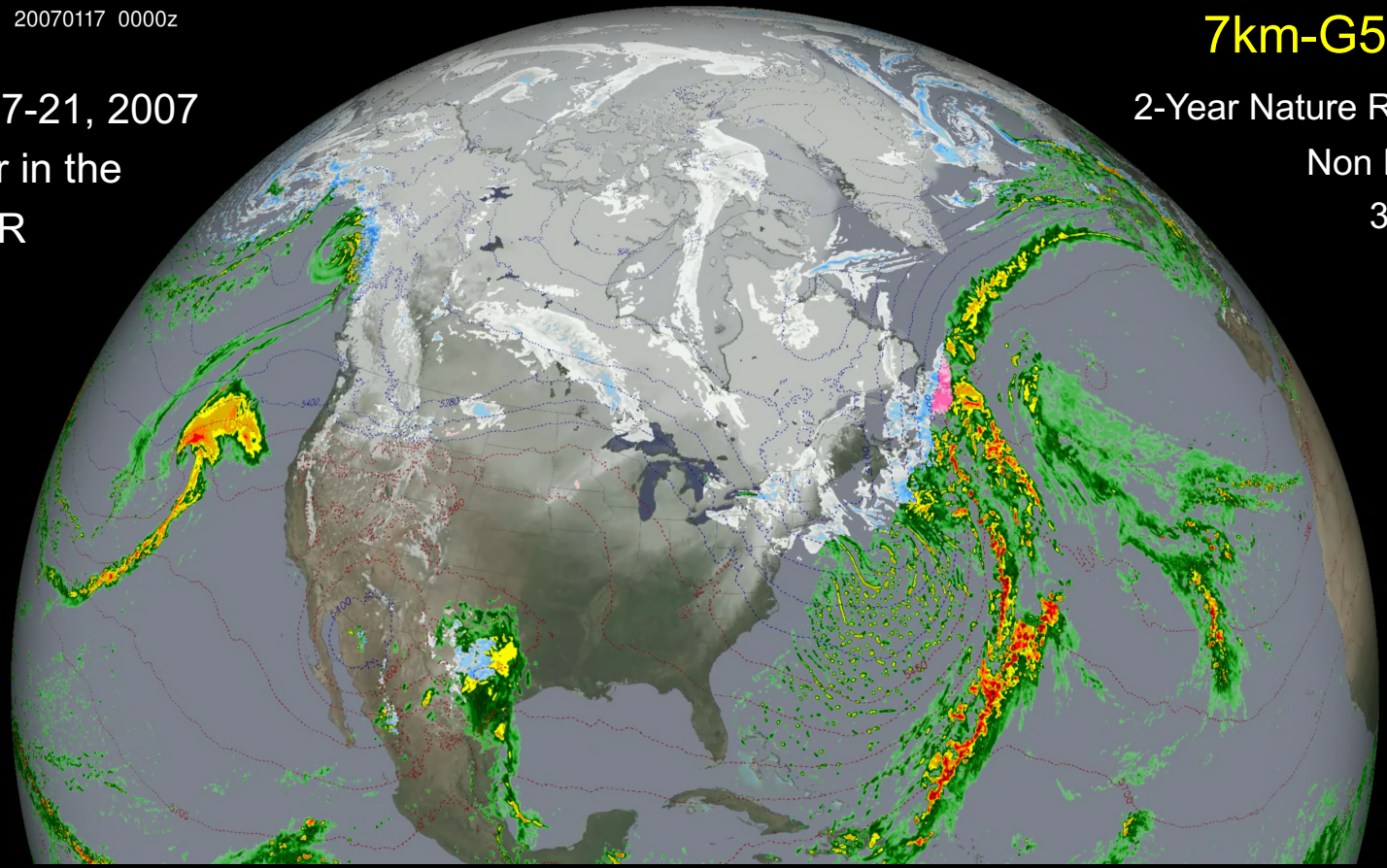
Surface Boundary Conditions & Emissions

- *1/8-degree Reynolds/OSTIA SST*
- *10-km EDGAR CO_2 emissions*
- *CASA-GFED at 10-km with MODIS EVI CO_2 land fluxes*
- *daily QFED fire emissions*
- *AEROCOM SO_2 emissions and injection heights*
- *GOCART mixing, and deposition*

[sulfates, dust, and black carbon]

aerosols radiatively coupled

7-km GEOS-5 Nature Run (2005 & 2006)

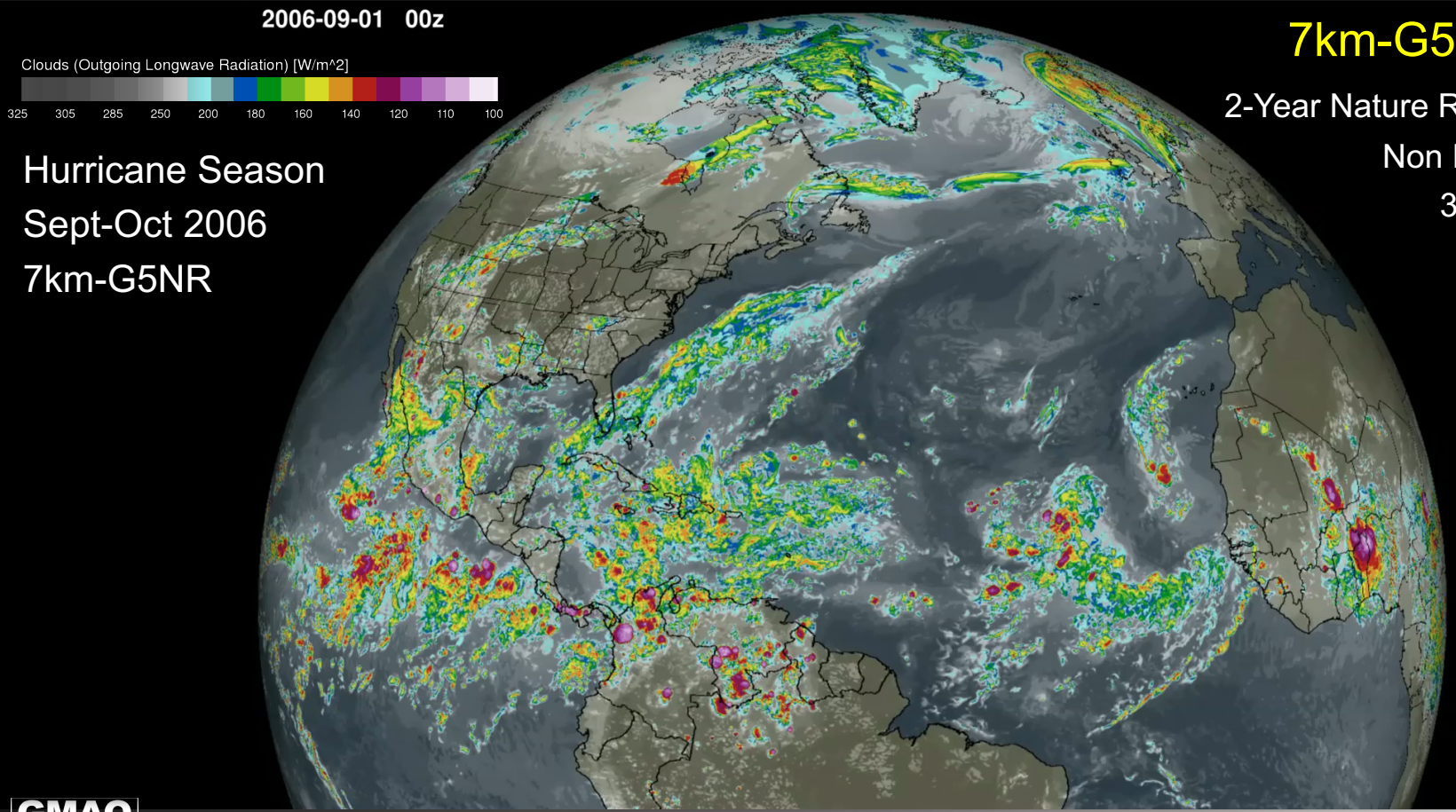


January 17-21, 2007
Nor'easter in the
7km-G5NR

7km-G5NR details:

2-Year Nature Run (2005-2007)
Non Hydrostatic FV3
30-minute output
Aerosols
CO_2

7-km GEOS-5 Nature Run (2005 & 2006)



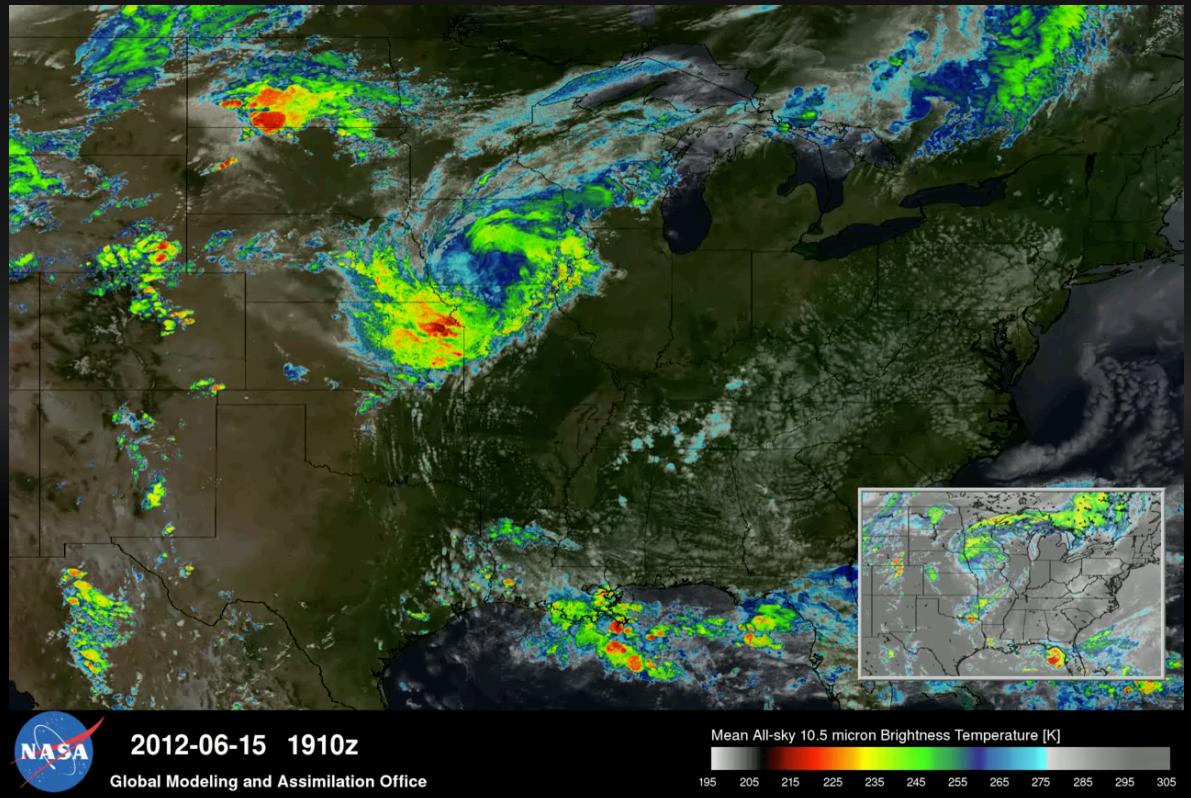
Hurricane Season
Sept-Oct 2006
7km-G5NR

7km-G5NR details:

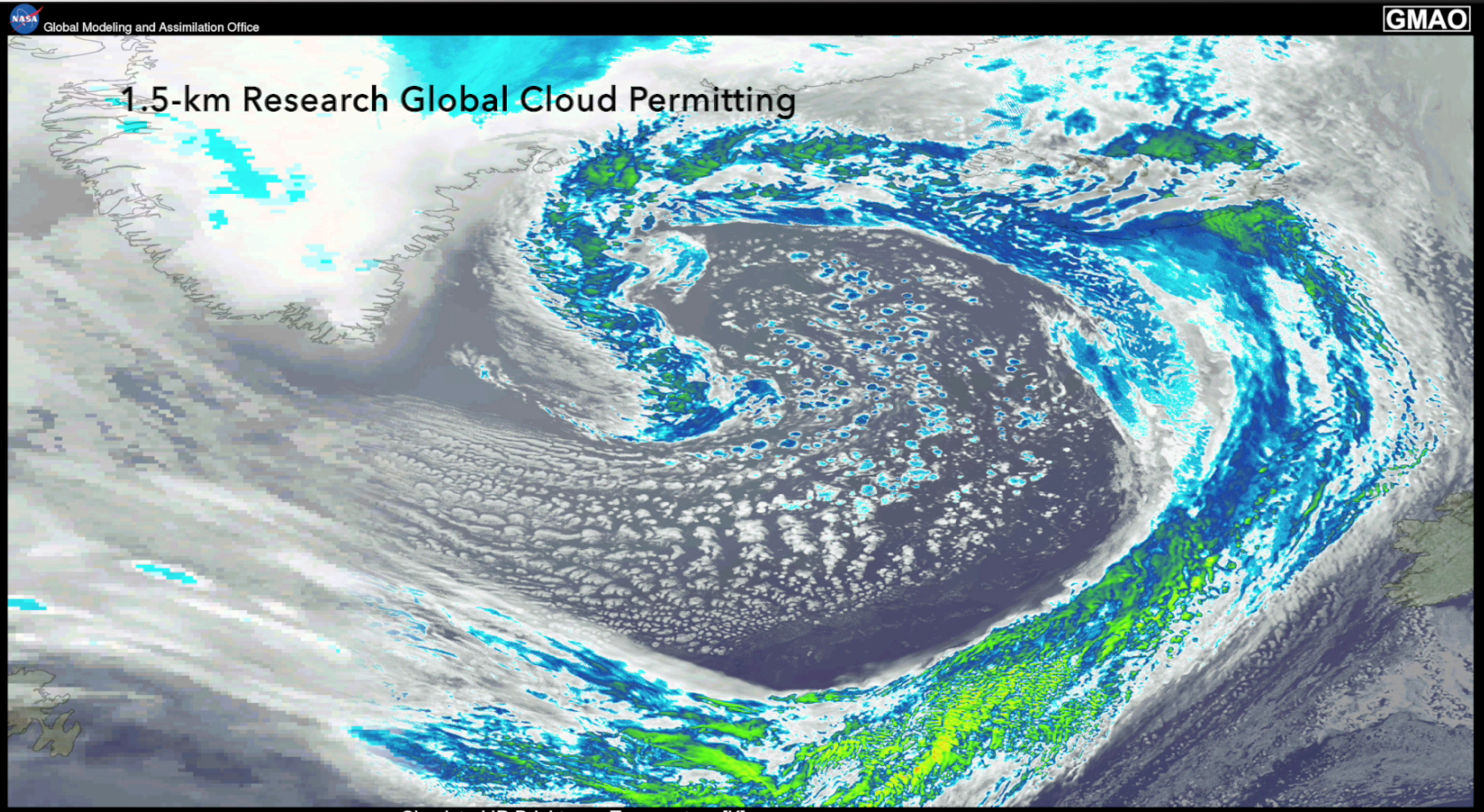
2-Year Nature Run (2005-2007)
Non Hydrostatic FV3
30-minute output
Aerosols
CO_2

1.5km GEOS Convection Allowing Model

- Non-Hydrostatic FV3 dynamics
  - Non-monotonic advection schemes
  - 6th order divergence damping
  - Explicit vorticity damping
- Morrison Gettelman Barahona
  - 2-moment cloud microphysics
- RAS convection
  - reduced to just shallow convection
- Turbulence
  - 1st order scheme of Louis (stable PBLs)
  - Non-local K-scheme of Lock (cloud topped BLs)
- GOCART aerosol and chemistry transport
- Extensive GEOS infrastructure development
  - Memory optimization (SHMEM)
  - I/O server development
    - Asynchronous writing
    - Efficient reading of boundary conditions



Run on 30,240 Intel Xeon Haswell cores Throughput of 3.5 days/day


Global Modeling and Assimilation Office
GMAO
1.5-km Research Global Cloud Permitting
2017-04-28 12:00Z
2017 Apr 28
07:00am EDT Friday
Simulated IR Brightness Temperature [K]
180 190 200 210 220 230 240 250 260 270 280 290 300 310 320
024 Forecast Hours
20170427_12z
GEOS 1.5-km