# Evaluating time step and resolution sensitivities in the GEOS analysis and forecast system

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# Overview

1. GEOS Model Description
2. NWP sensitivity (25-km reforecast experiments)
3. 13-km Physics Coupling Sensitivity (Monthly Simulations)
4. AGCM Physics Coupling issues
   - Land Surface
   - Radiation
   - Aerosols
5. Atmosphere-Ocean Coupling issues

National Aeronautics and Space Administration

# GEOS: A Scale-Aware Modeling System

*"GEOS is a comprehensive global model for simulation, assimilation, and prediction on weather and climate time-scales"*

## 1. Weather Analysis and Prediction

- *near-realtime analyses, assimilation products, and forecasts*
  - In support of NASA's satellite missions and field experiments
  - Generating 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
  - National Multi-Model Ensemble (NMME) project
  - Chemistry-Climate Model (CCM)
  - Coupled Model Intercomparison Project (CMIP)

## 3. Reanalysis for Climate

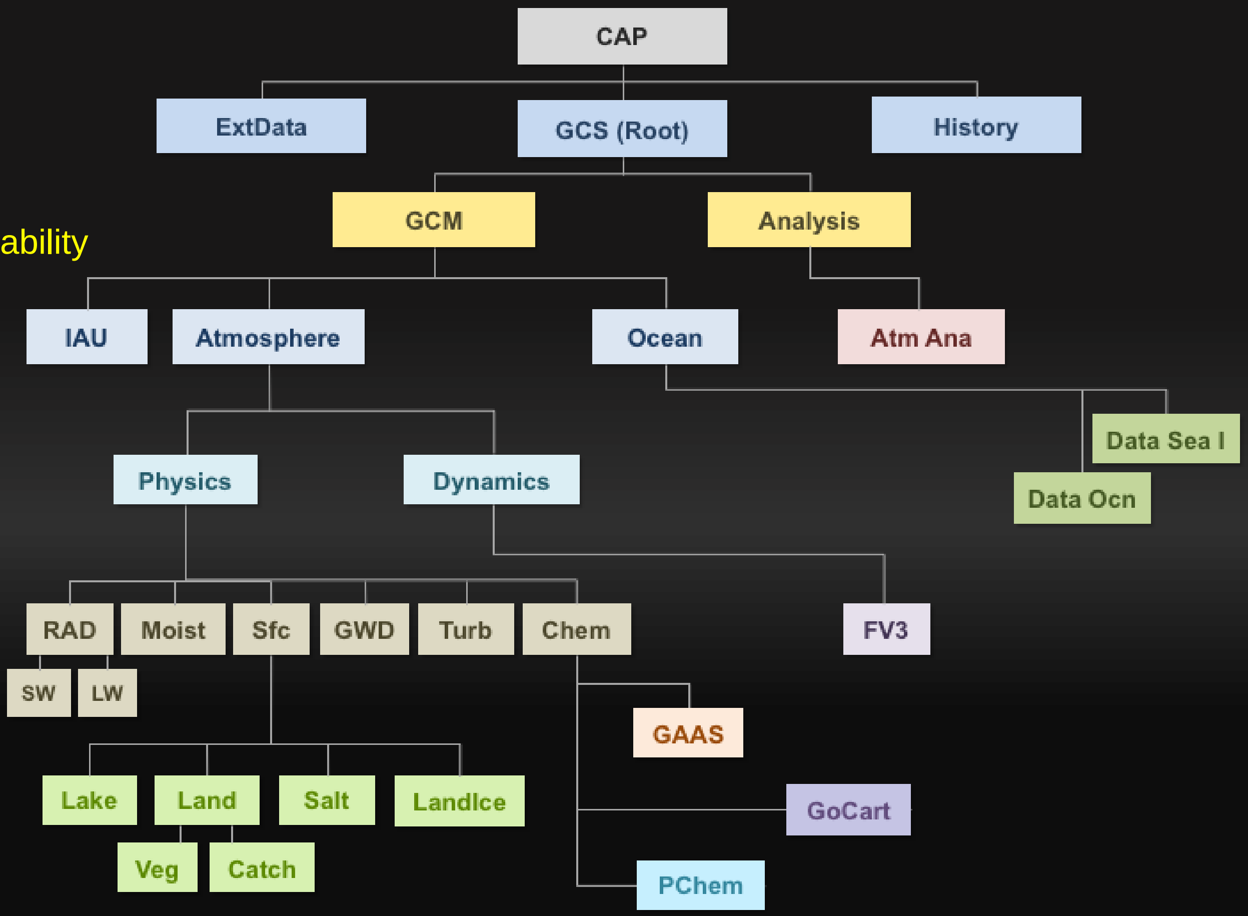
- Modern-Era Retrospective analysis for Research and Applications (MERRA-2)
  - Hi-Resolution global downscaling of reanalyses

## 4. Global Mesoscale Modeling

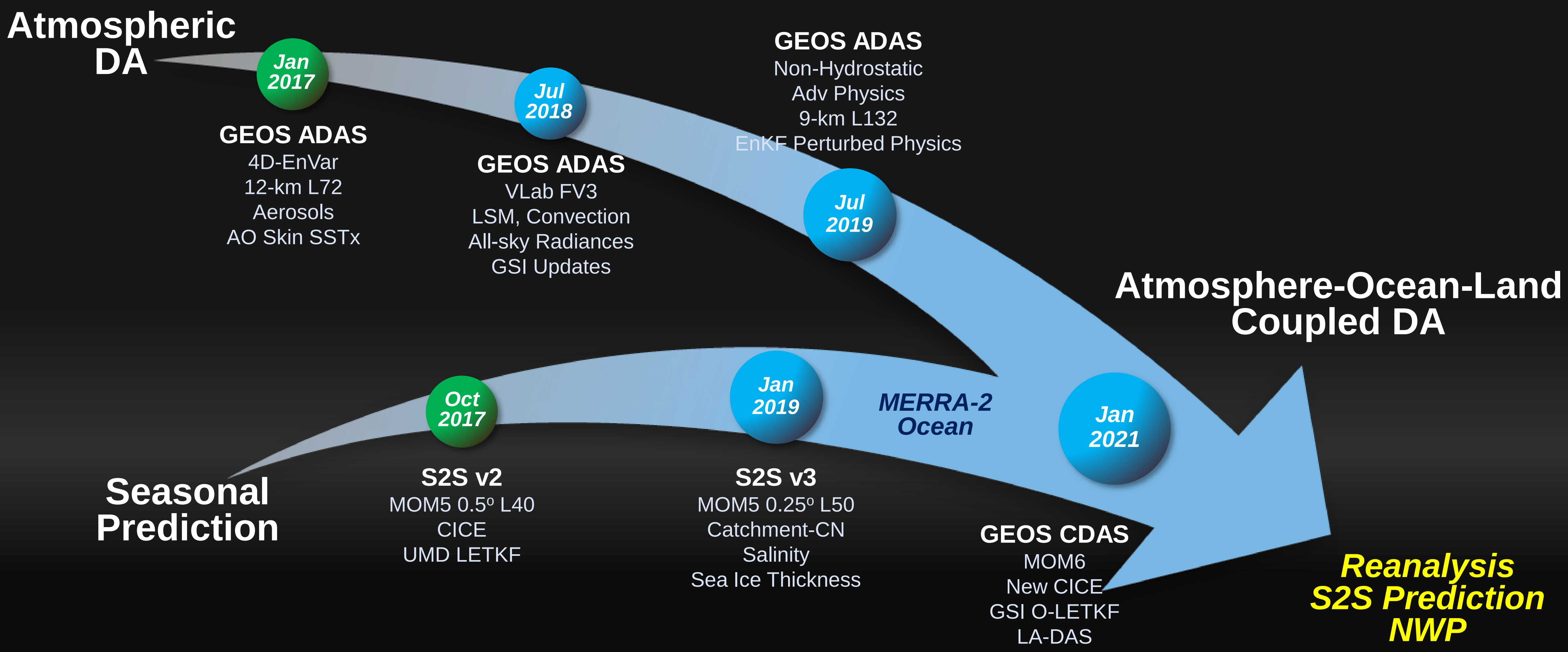
- Global simulations at the forefront of model and computing capability
  - These form the basis for *Observing System Simulation Experiments*.

**GEOS AGCM Model Infrastructure**

Hierarchy of ESMF Gridded Components



# GEOS: Toward a Couple Integrated Earth System Analaysis



# GEOS: Typical 13-km GEOS Configuration

**1. Dynamics - FV3**
- *DT = 450s : remap DT (k_split=2) = 225s : acoustic DT (n_split=12) = 18.75s*

**2. Gravity Wave Drag**
- *DT = 450s*
  - Orographic – McFarlane, 1987
  - Non-Orographic – Garcia and Boville, 1994
  - Rayleigh Friction : 2-day Time-scale

**3. Moist Physics**
- *DT = 450s*
  - Grell-Freitas (GF) Deep Convection (5400s scale-aware deep timescale)
  - Park-Bretherton UW Shallow Convection
  - Bacmeister 1-moment or MG 2-moment cloud microphysics

**4. Surface Physics**
- *DT = 450s*
  - Catchment Land Surface model

**5. Turbulence**
- *DT = 450s*
  - Lock scheme for unstable layers and cloud generated turbulence
  - Louis scheme for stable layers and near surface unstable layers

**6. GOCART Aerosols and PCHEM Chemistry**
- *Split phase: 3600s slow processes and 450s fast processes*
  - GOCART emissions and wet-deposition

**7. Radiation**
- *DT = 3600s*
  - RRTMG LW and SW

**GEOS AGCM Model Infrastructure**

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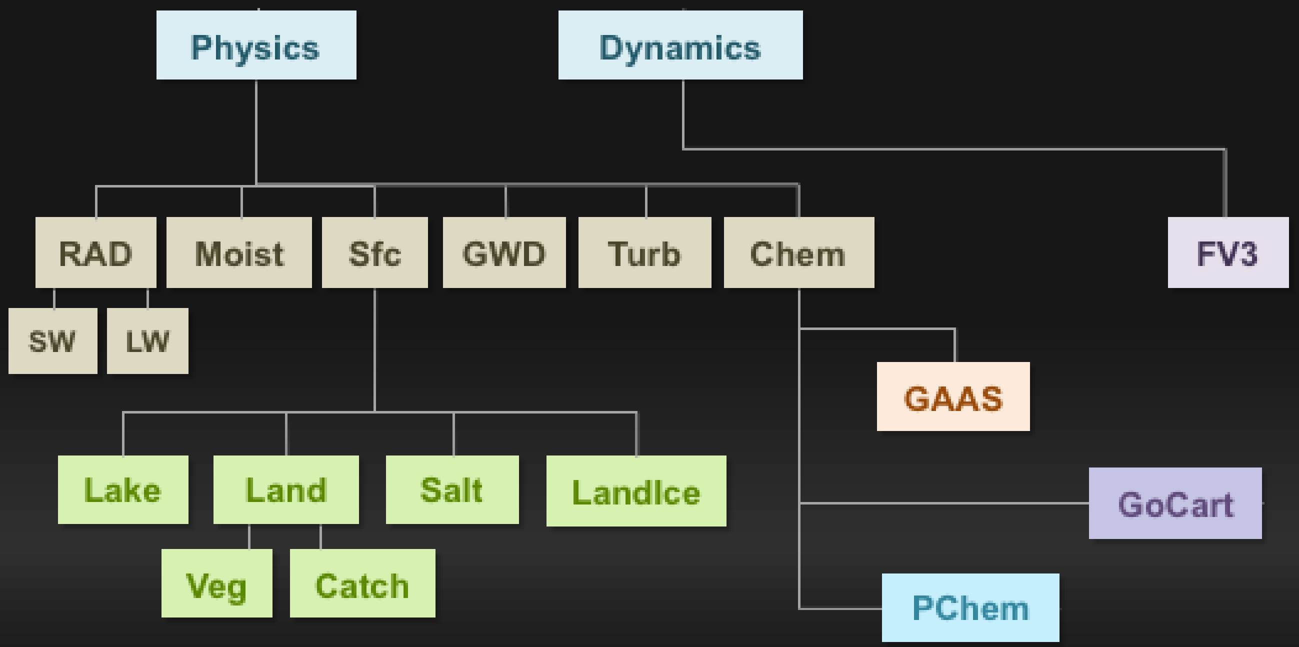


Each component above checks an internal DT so GEOS can easily modify the coupling frequency of each process

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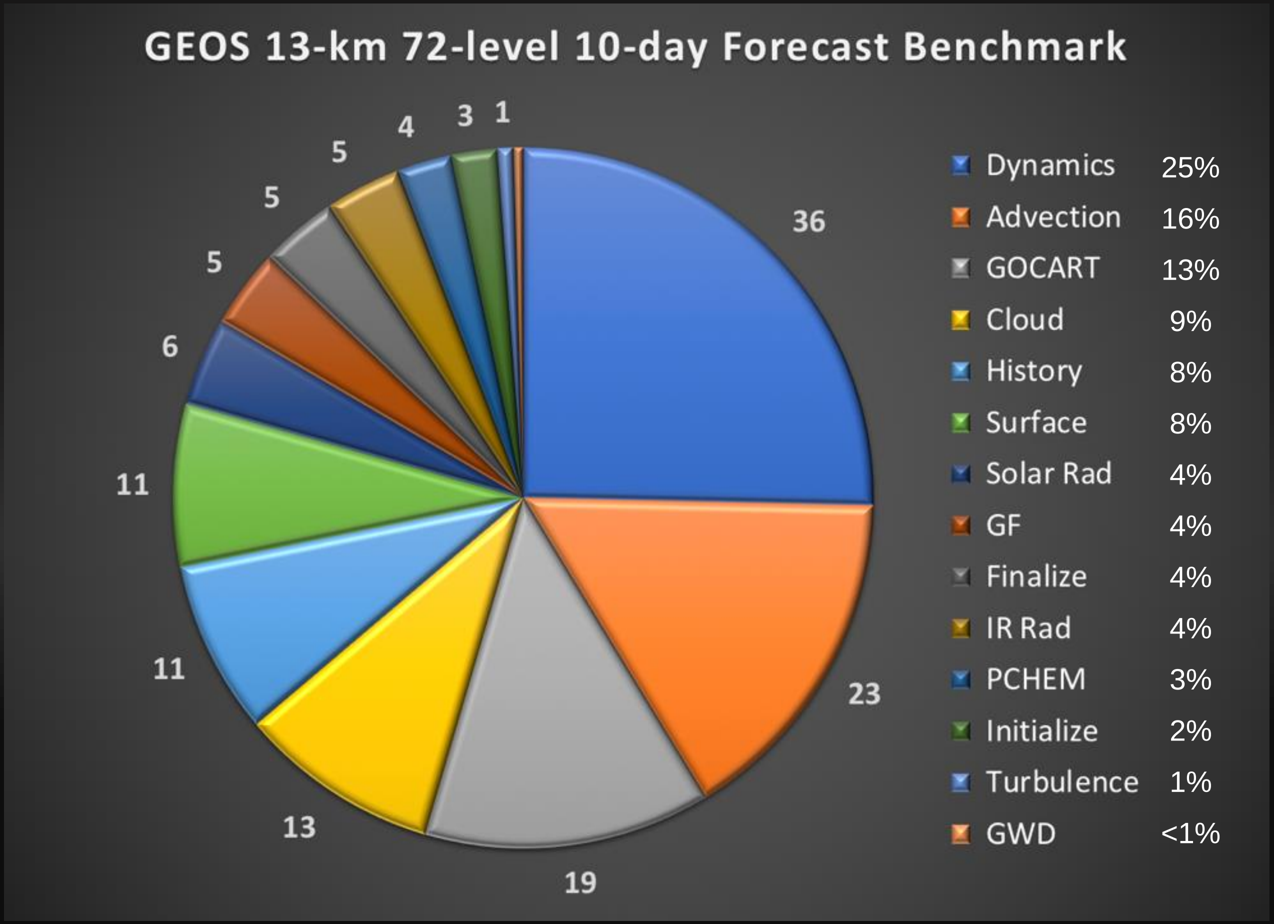
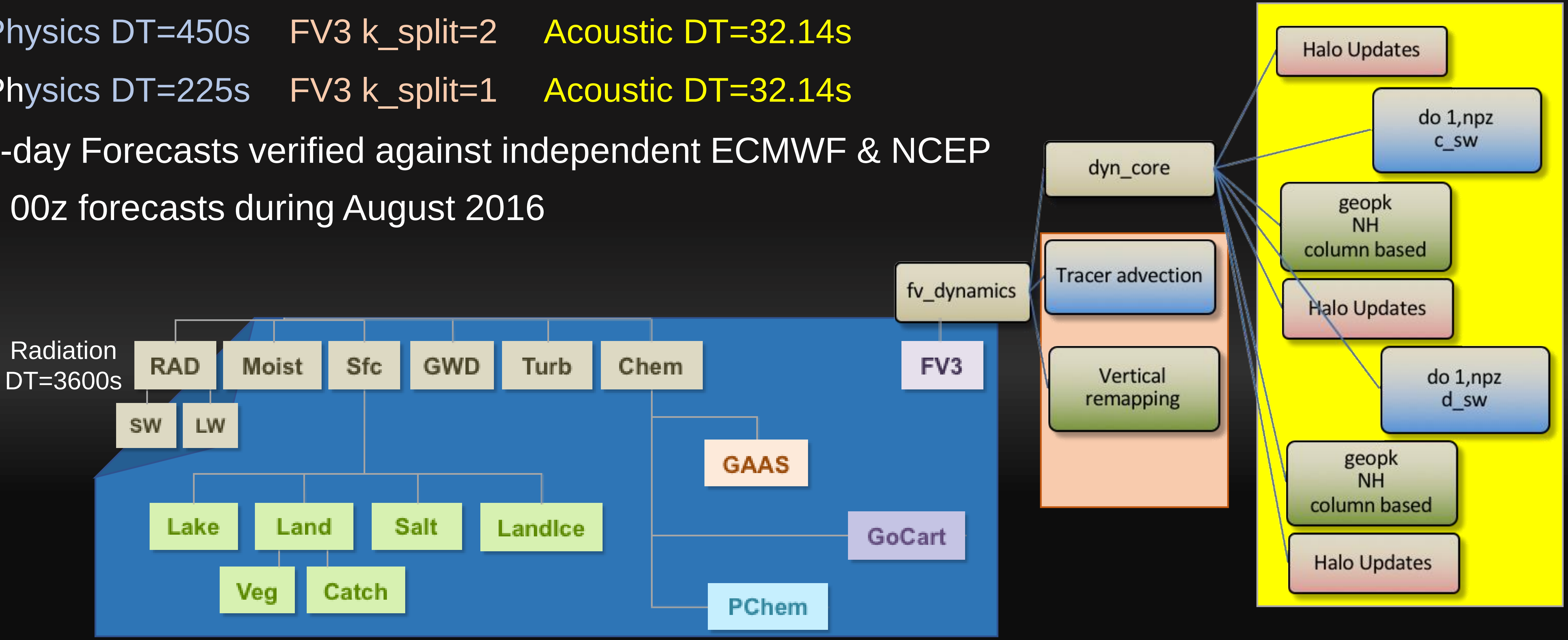
## GEOS AGCM Model Profile

*Component times in minutes*



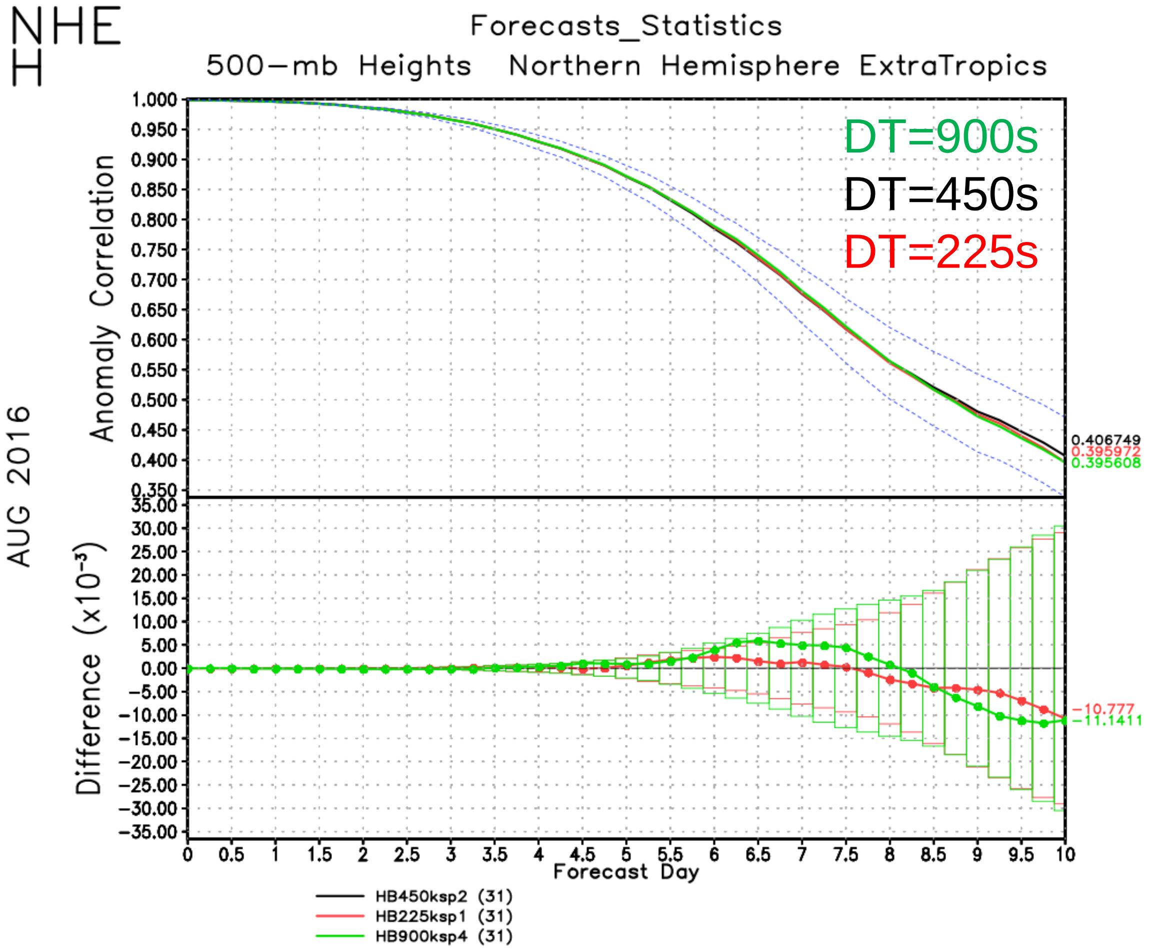
# NWP Experiments

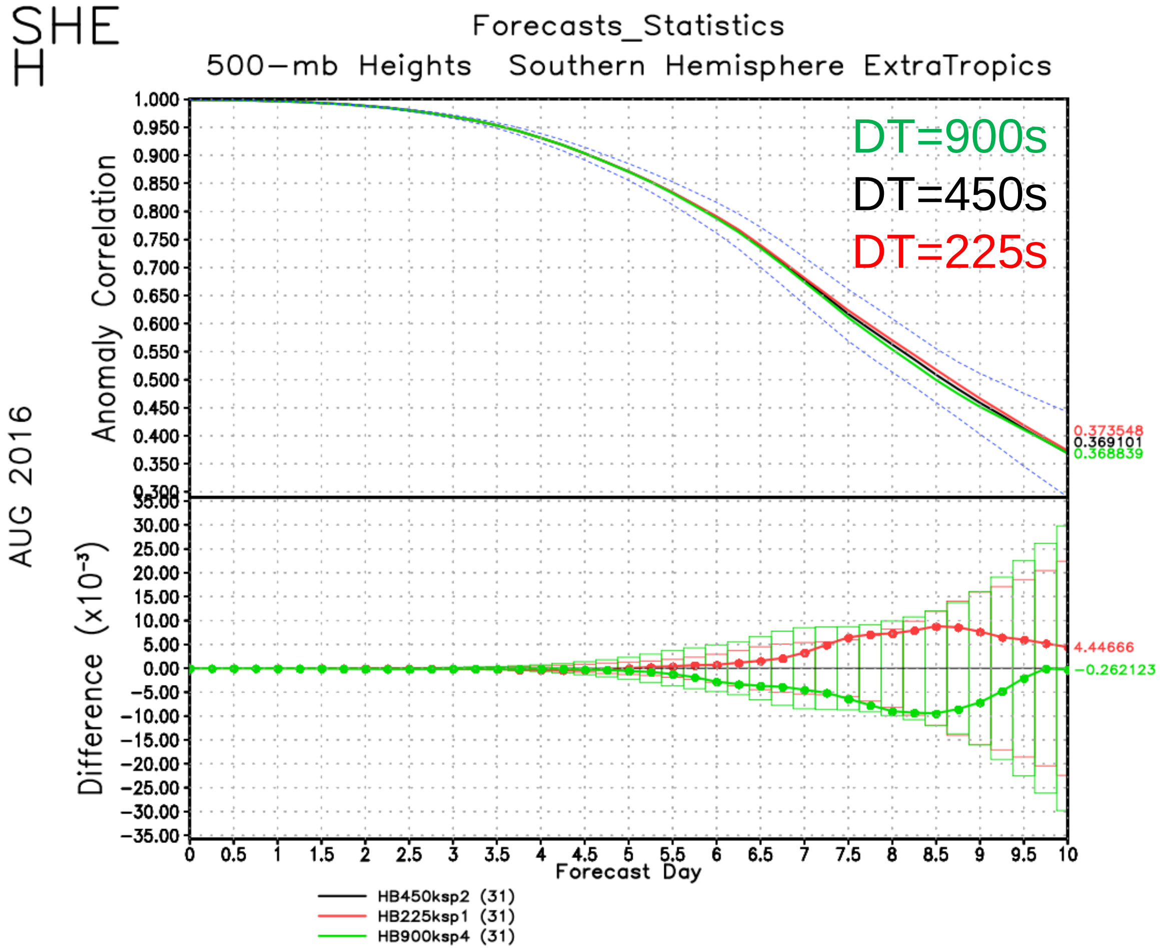
1. We completed a series reforecast experiments from a 25-km 4d-EnvVar GEOS DAS
   - Physics DT=900s FV3 k_split=4 Acoustic DT=32.14s
   - Physics DT=450s FV3 k_split=2 Acoustic DT=32.14s
   - Physics DT=225s FV3 k_split=1 Acoustic DT=32.14s
2. 10-day Forecasts verified against independent ECMWF & NCEP
3. 31 00z forecasts during August 2016



# NWP Experiments

## 500mb Height Anomaly Correlation (Verified against ECMWF)

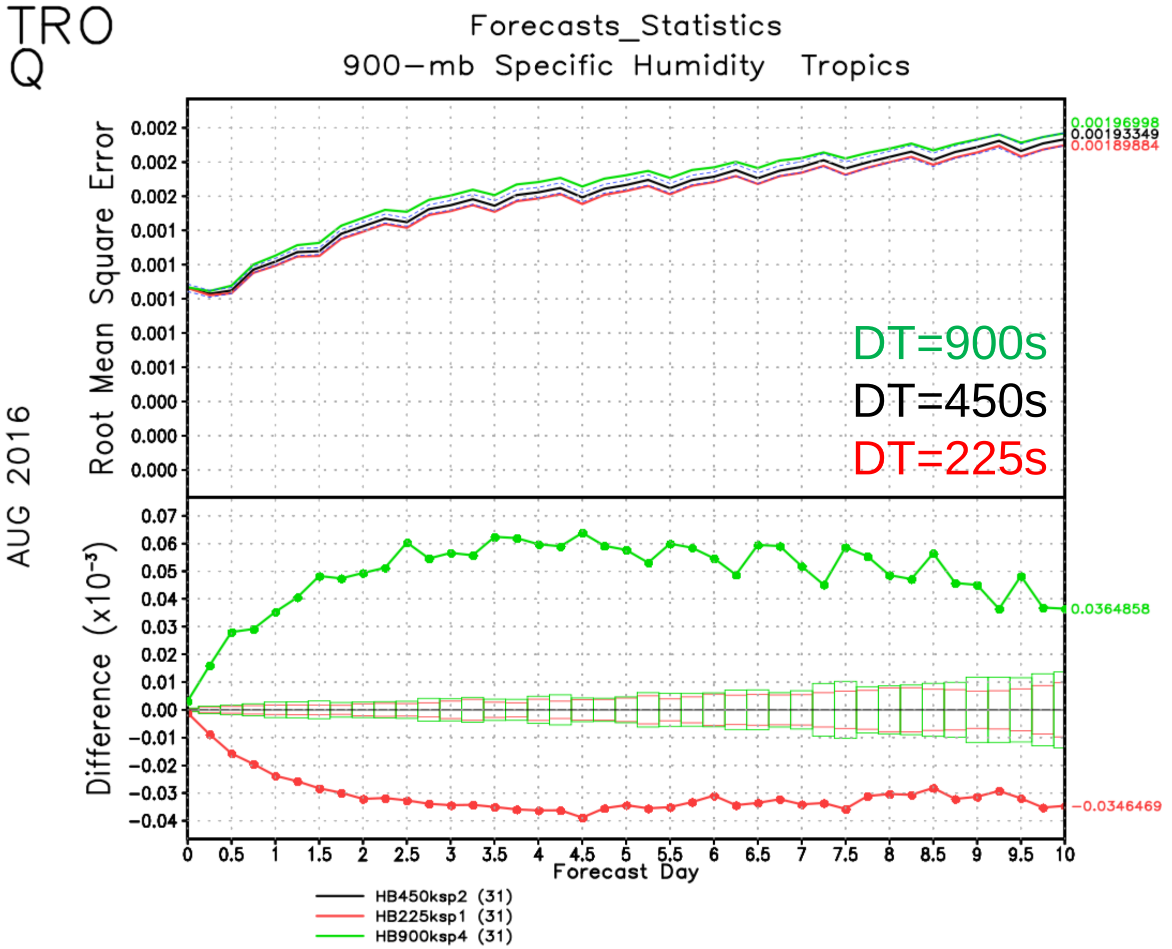


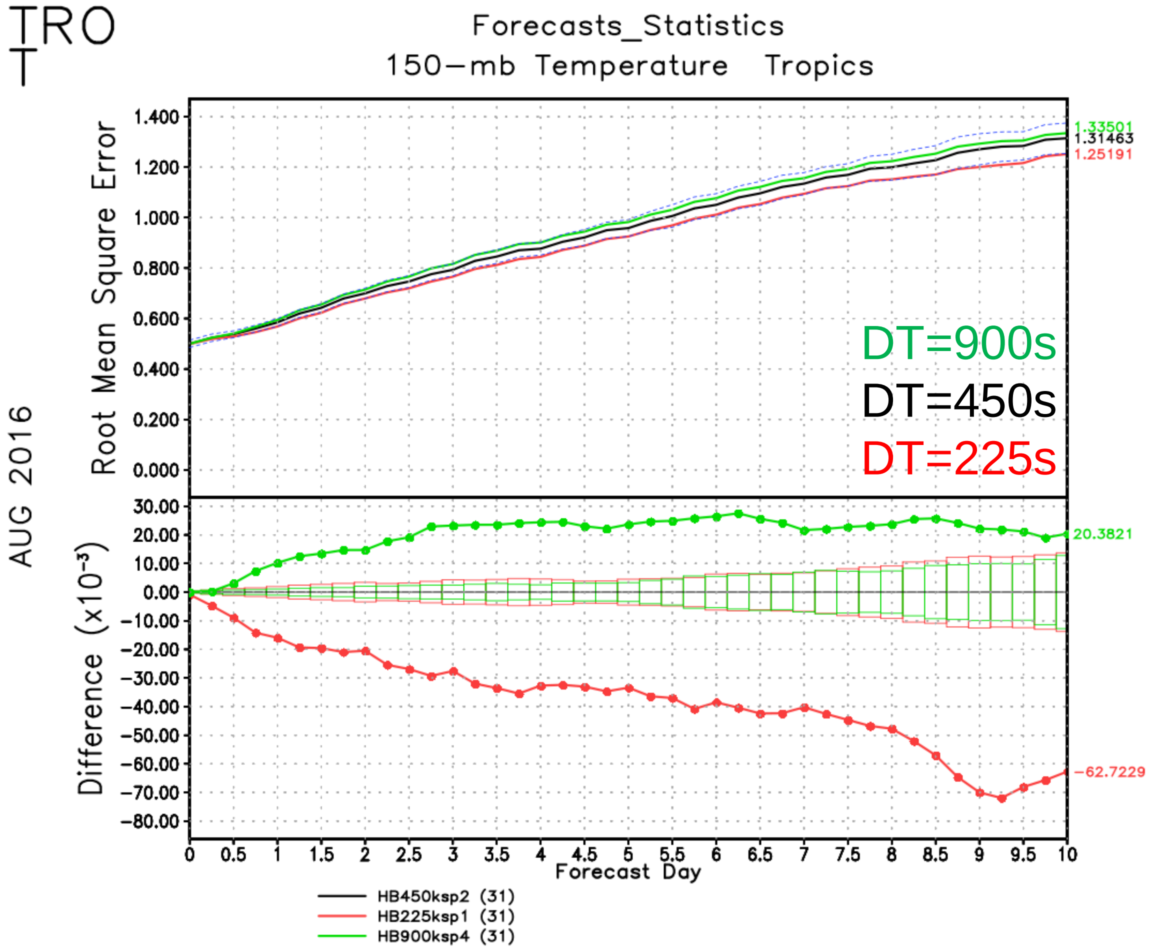




**Heartbeat of GEOS physics has no significant impact**

# NWP Experiments

## 900mb QV and 150mb T RMSE (Verified against NCEP)



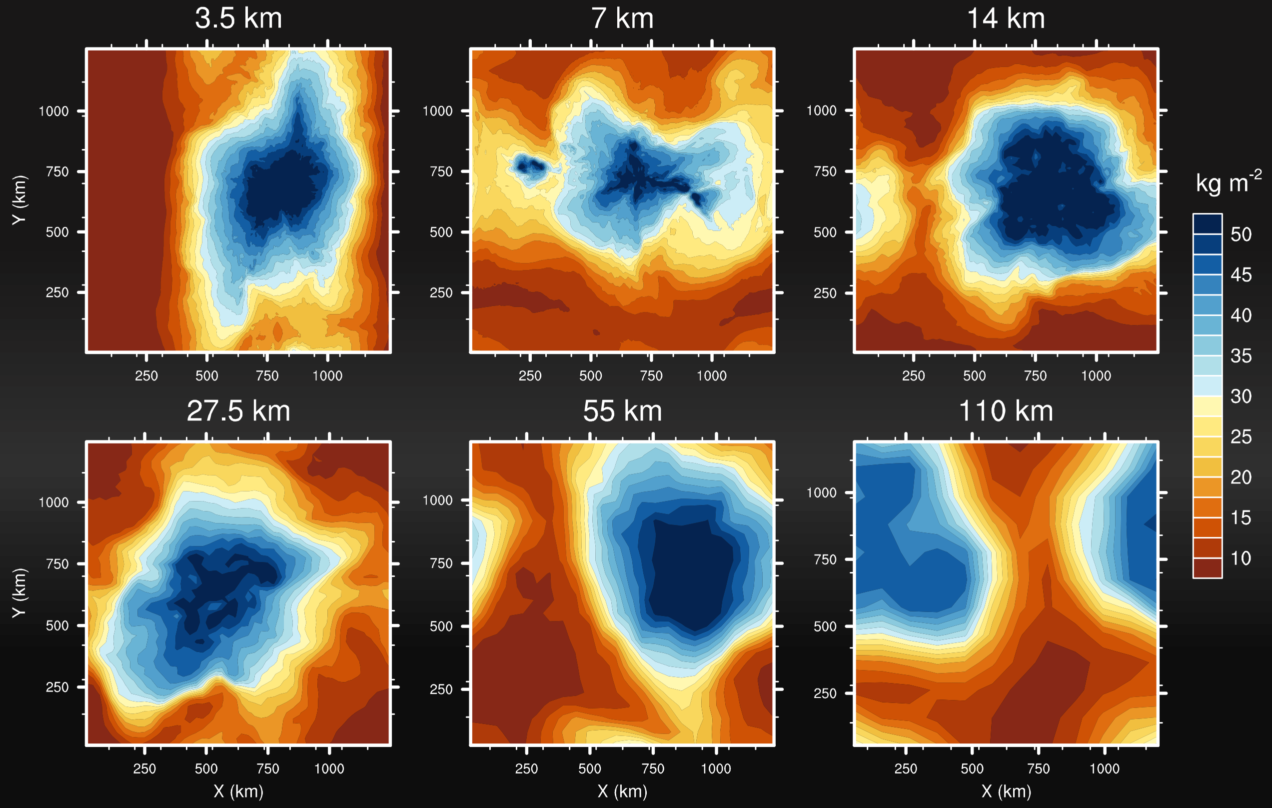

**There is a systematic improvement in tropical low level QV and the tropical tropopause T with smaller DT**

# Doubly-Periodic Radiative Convective Equilibrium Exps

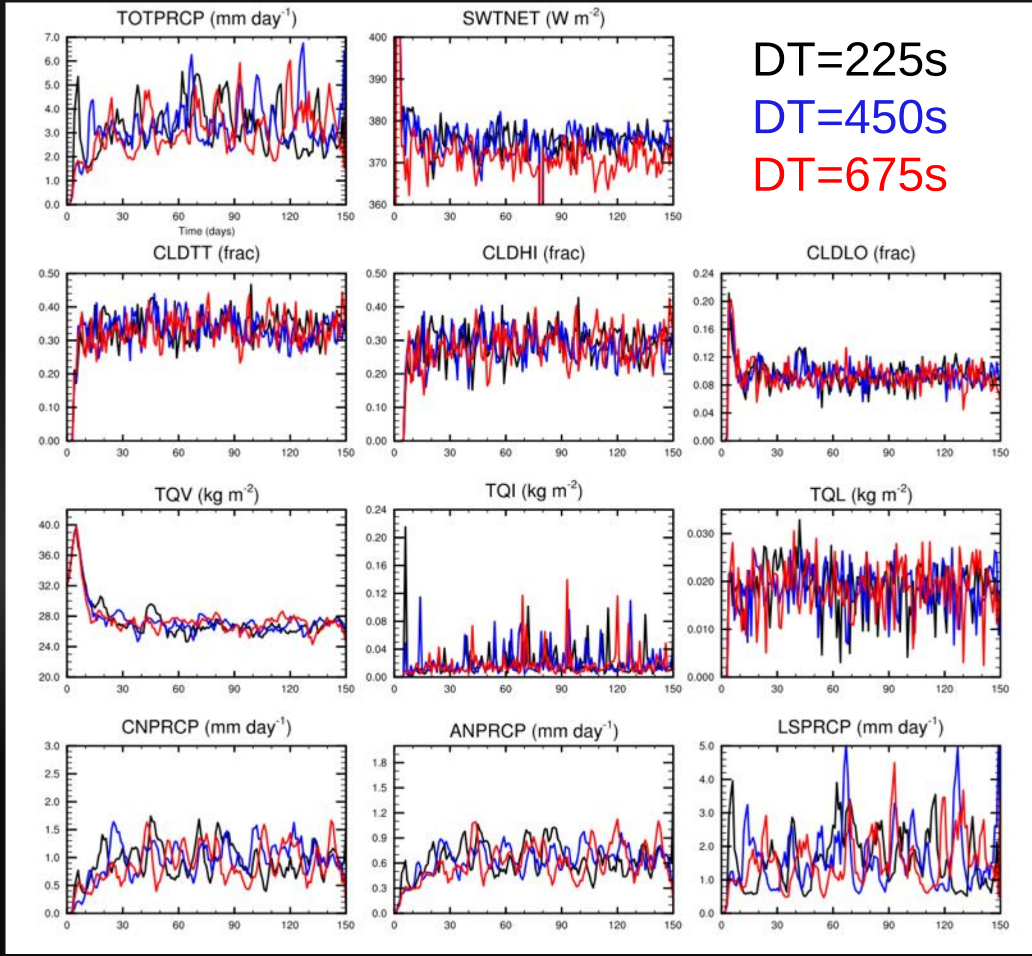
DP Exps can quickly evaluate time-step dependence of GEOS physics:

- unlike Single-Column, DP includes full interaction of physics and dynamics.
- Below is an example of convective aggregation with increasing resolution

## Column water vapor (CWV) after convective aggregation

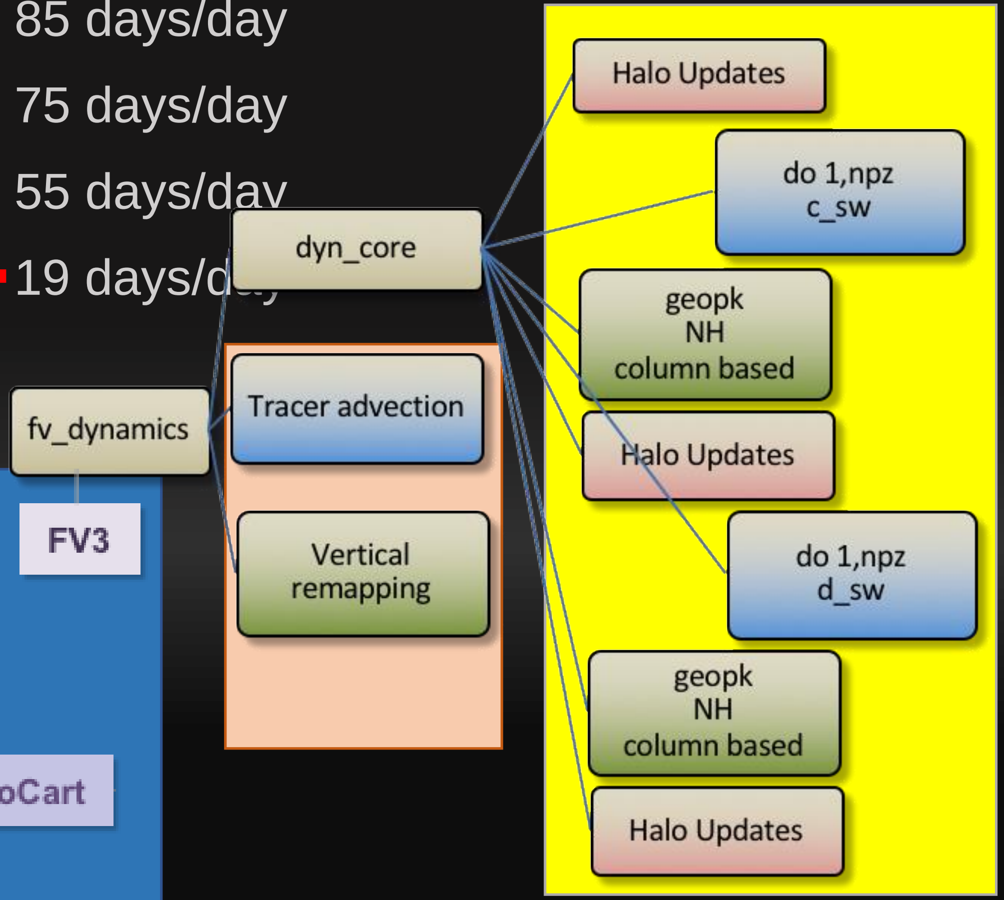


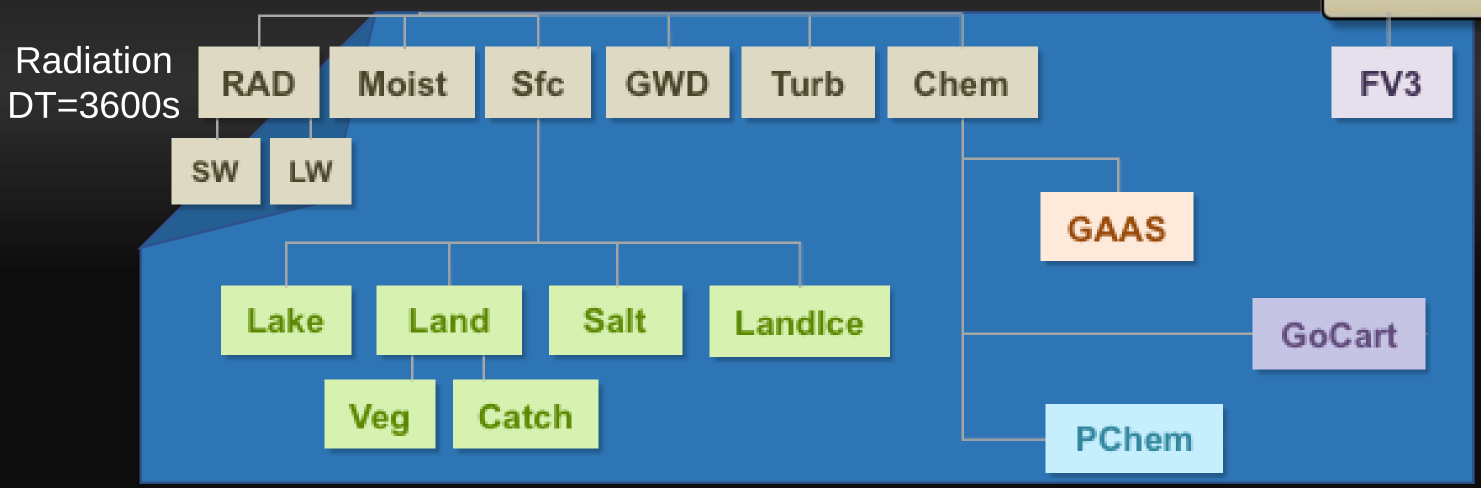

## 14-km DP Exps show very little time-step sensitivity in the UW ShallowCu Component



# 13-km Timestep Sensitivity Experiments

- A sequence of 1-month free-running simulations at 13km (Throughput on 5400 Intel Skylake Cores)
  - Physics DT=900s FV3 k_split=12 Acoustic DT=15s 100 days/day
  - Physics DT=450s FV3 k_split=6 Acoustic DT=15s 85 days/day
  - Physics DT=300s FV3 k_split=4 Acoustic DT=15s 75 days/day
  - Physics DT=150s FV3 k_split=2 Acoustic DT=15s 55 days/day
  - ~~Physics DT= 75s FV3 k_split=1 Acoustic DT=15s~~ 19 days/d
- 40-day simulations covering August 2016

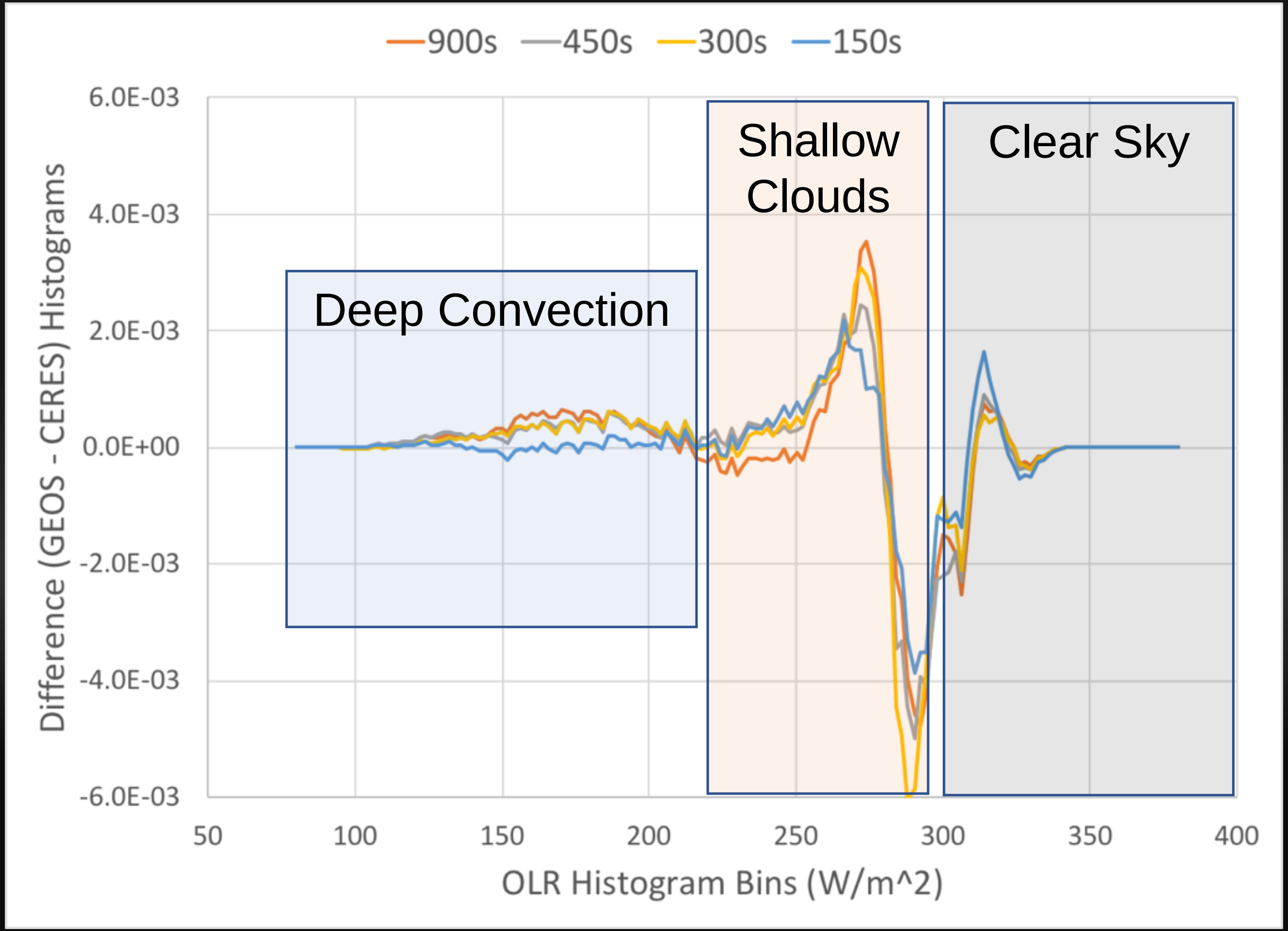


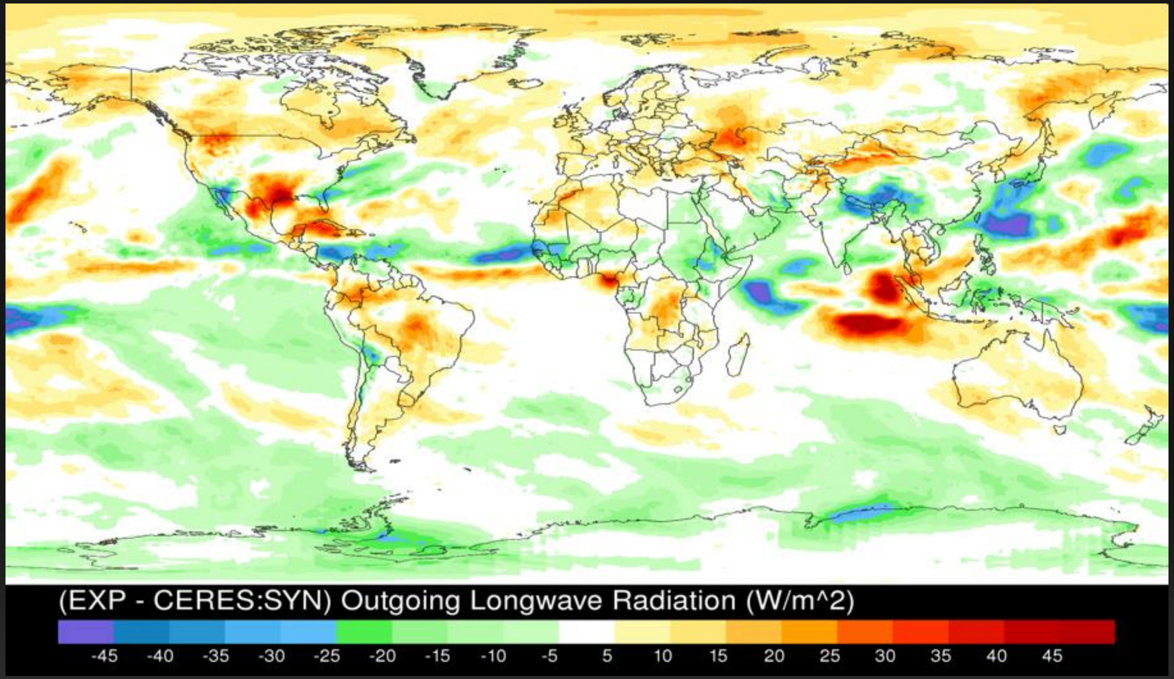
# 13-km Timestep Sensitivity Experiments

## (GEOS – CERES) OLR Histograms (30S:30N)

Monthly Mean (Aug 2016) of Daily Histograms




150s Exp – CERES OLR




**Error in the Global Mean OLR (GEOS-CERES)**

| Physics DT | GEOS-CERES |
|---|---|
| 900s | -2.395 |
| 450s | -2.067 |
| 300s | -1.546 |
| 150s | -0.466 |

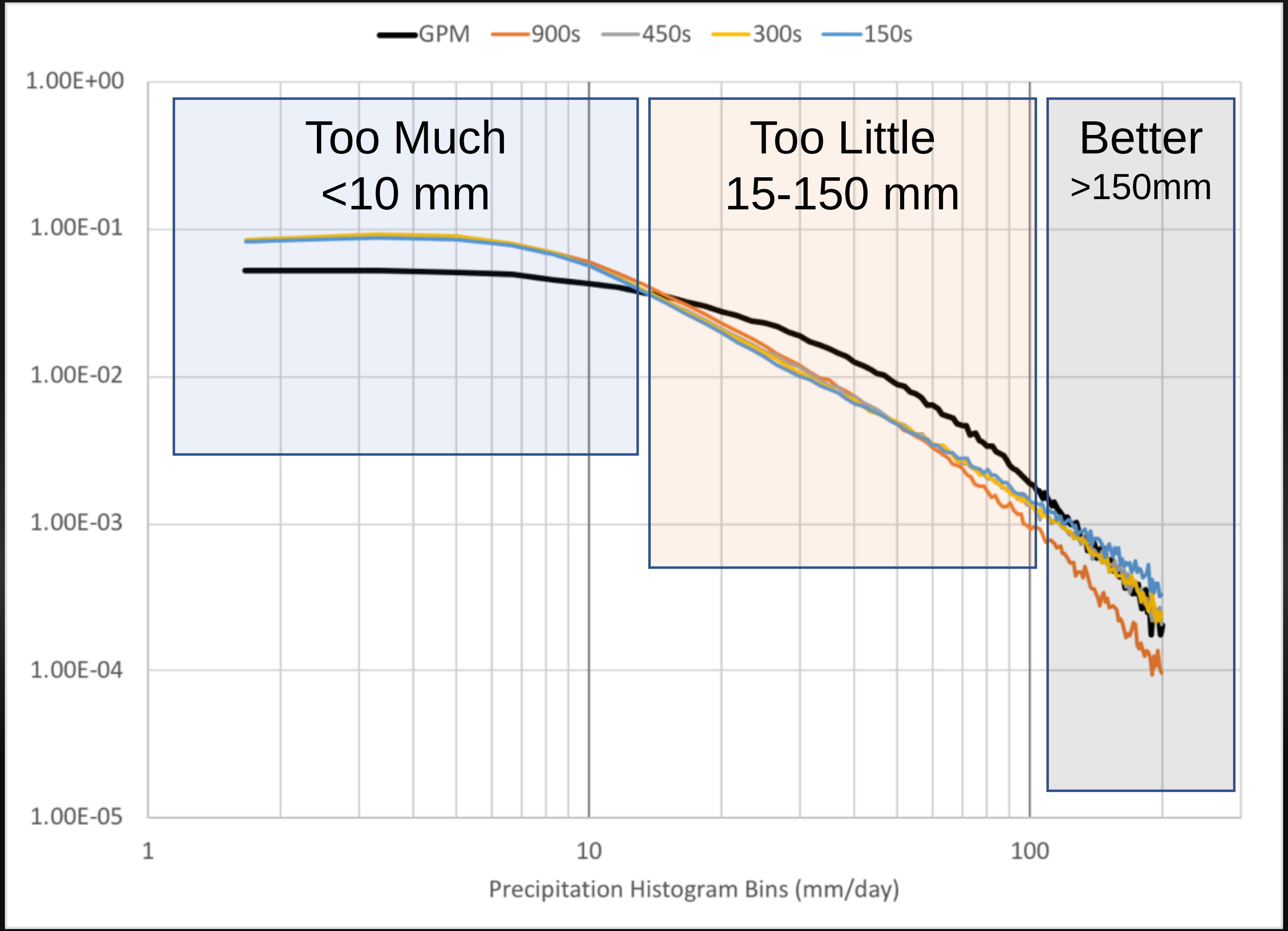
GEOS OLR is converging to CERES with shorter Physics DT

# 13-km Timestep Sensitivity Experiments

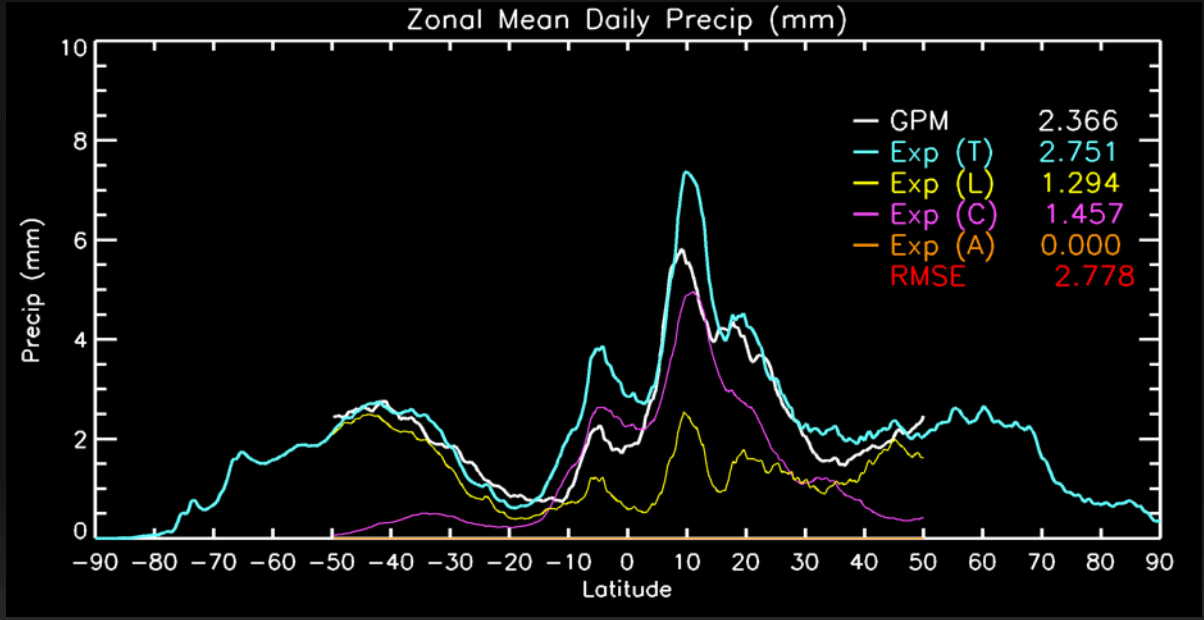
Using GF+UW Convection

**(GEOS & GPM) Precip Histograms (60S:60N)**

Monthly Mean (Aug 2016) of Daily Histograms




150s (GF+UW Convection) Exp Zonal Mean vs GPM




**Fraction of Large-Scale / Total Precipitation**

| Physics DT | LSC/TOT |
|---|---|
| 900s | 0.427 |
| 450s | 0.451 |
| 300s | 0.457 |
| 150s | 0.470 |

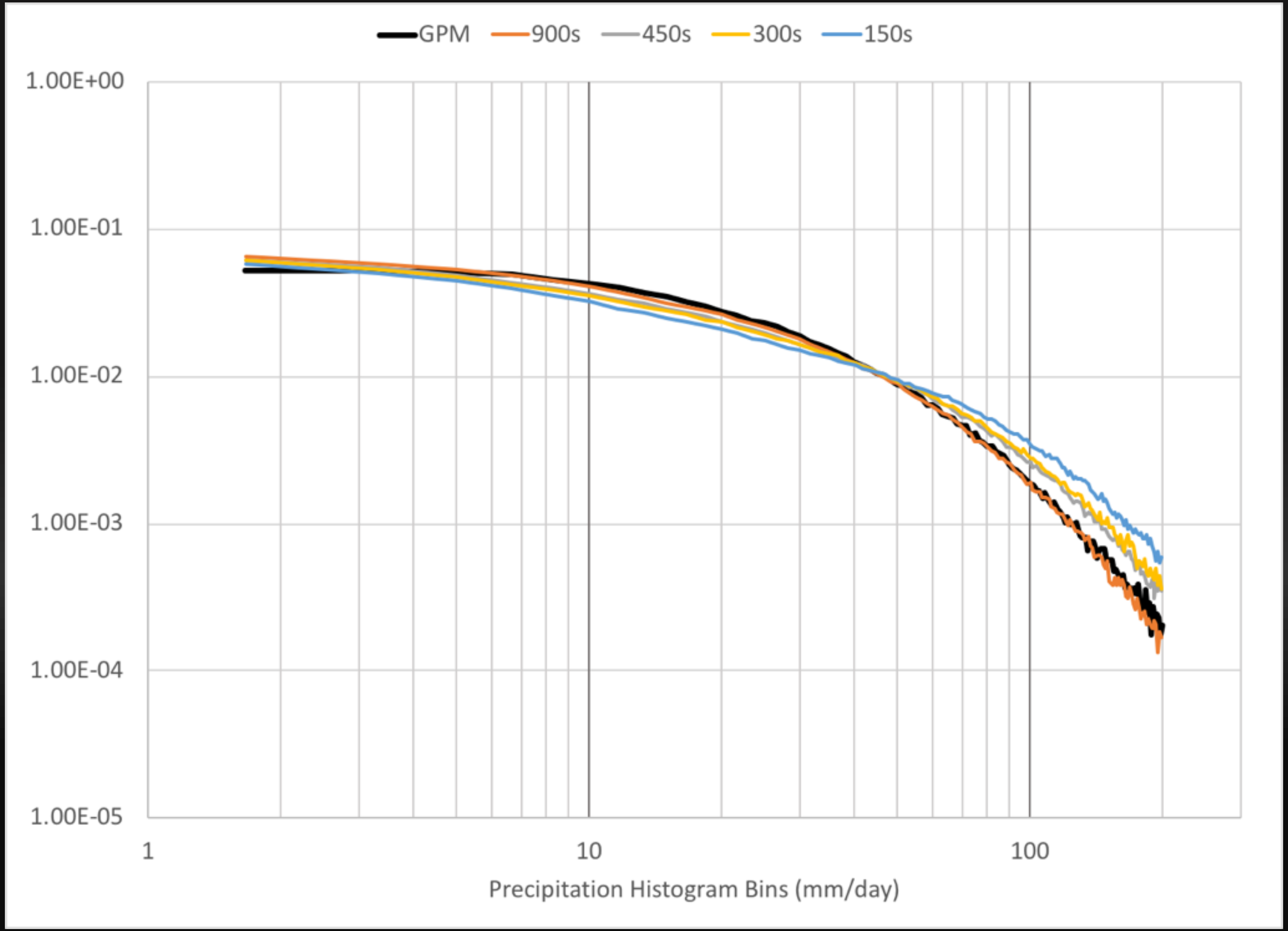
Large-scale Precip is increasing with small DTs but not significantly

# 13-km Timestep Sensitivity Experiments

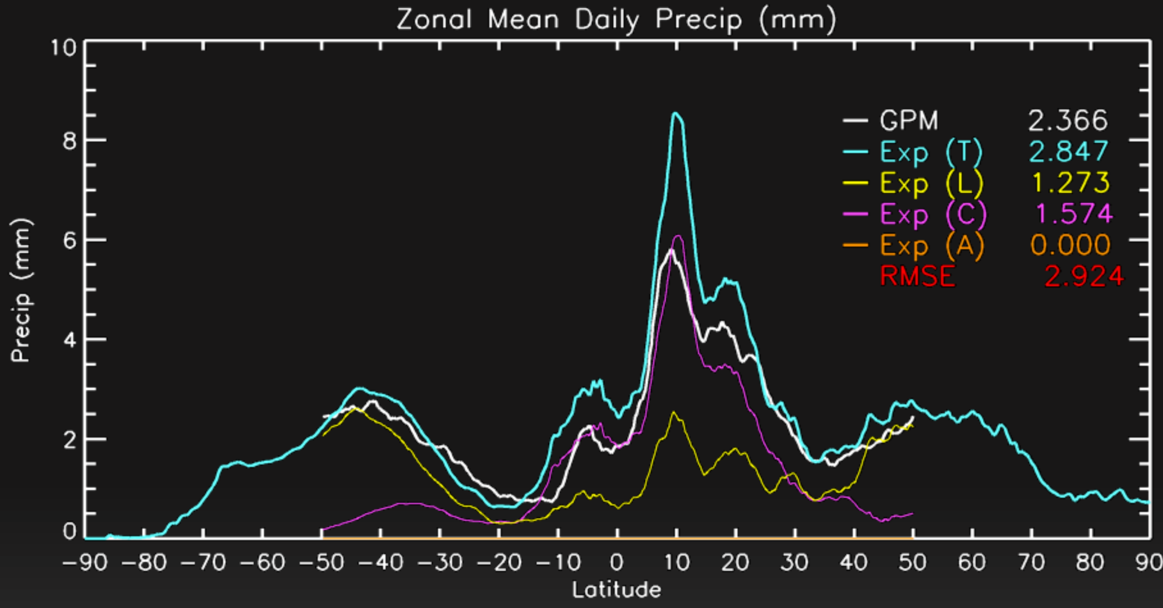
Using RAS Deep Convection

**(GEOS & GPM) Precip Histograms (60S:60N)**

Monthly Mean (Aug 2016) of Daily Histograms




900s (RAS Convection) Exp Zonal Mean vs GPM




**Fraction of Large-Scale / Total Precipitation**

| Physics DT | LSC/TOT |
|---|---|
| 900s | 0.447 |
| 450s | 0.469 |
| 300s | 0.484 |
| 150s | 0.506 |

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   - Land Surface
   - Radiation
   - Aerosols
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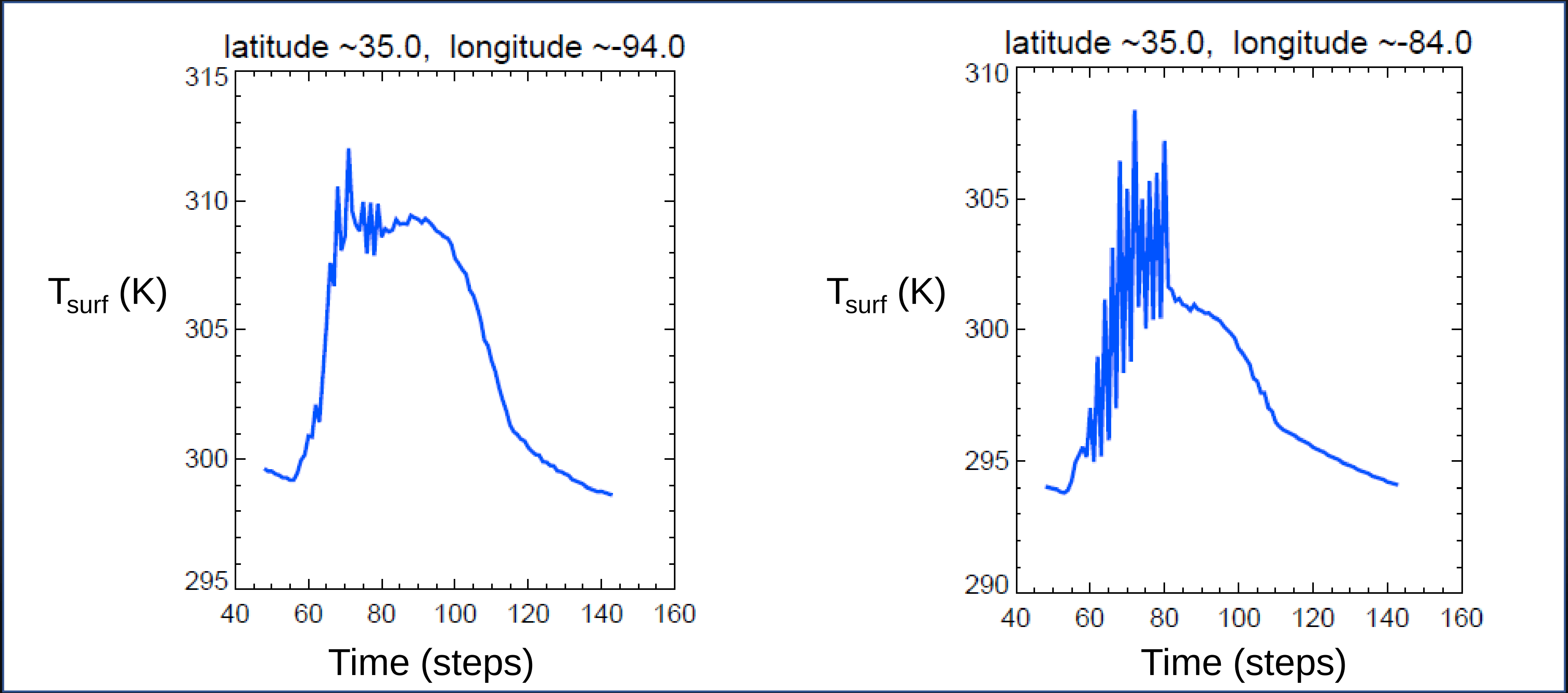
# Land Surface Instabilities

Oscillations in the land surface temperature sometimes appear in the coupled system…

… and occasionally these oscillations are egregious.




(15-minute time steps used in these coupled simulations)

# Land Surface Instabilities

## Three approaches for reducing/removing these oscillations:

1. Decrease time step. The above oscillations were produced with a 15-minute time step, whereas the current system is run with a 7.5 minute time step. The shorter time step should at least reduce the magnitudes of the oscillations.

2. Improve tendency terms provided to land surface energy balance calculations. Sensible heat flux, for example, is forced to satisfy:

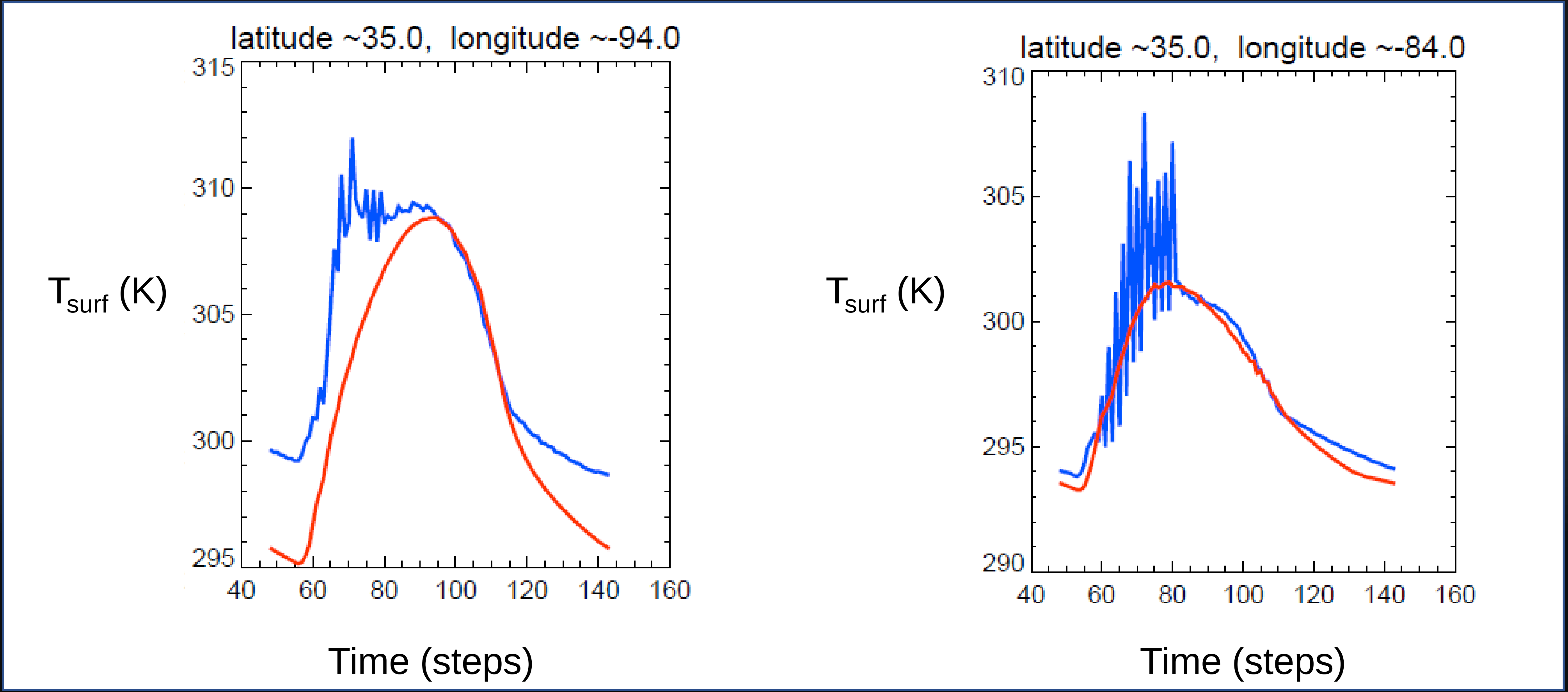
$$H = [H]_{old} + \left[\frac{\partial H}{\partial T_c}\right]_{old} \Delta T_c + \left[\frac{\partial H}{\partial e_a}\right]_{old} \Delta e_a$$

These tendency terms, which are provided by the atmospheric model, do not currently account for the derivatives of aerodynamic resistance with respect to temperature and vapor pressure.

# Land Surface Instabilities

## Three approaches for reducing/removing these oscillations:

3. Increase heat capacity associated with the surface energy balance calculation.




The oscillations are generally eliminated across the globe.

# Radiation Issues

## Radiation on Fast and Slow timescales as in current version of GEOS (changes coming…)

## 1. On the slow refresh() timescale: 3600s

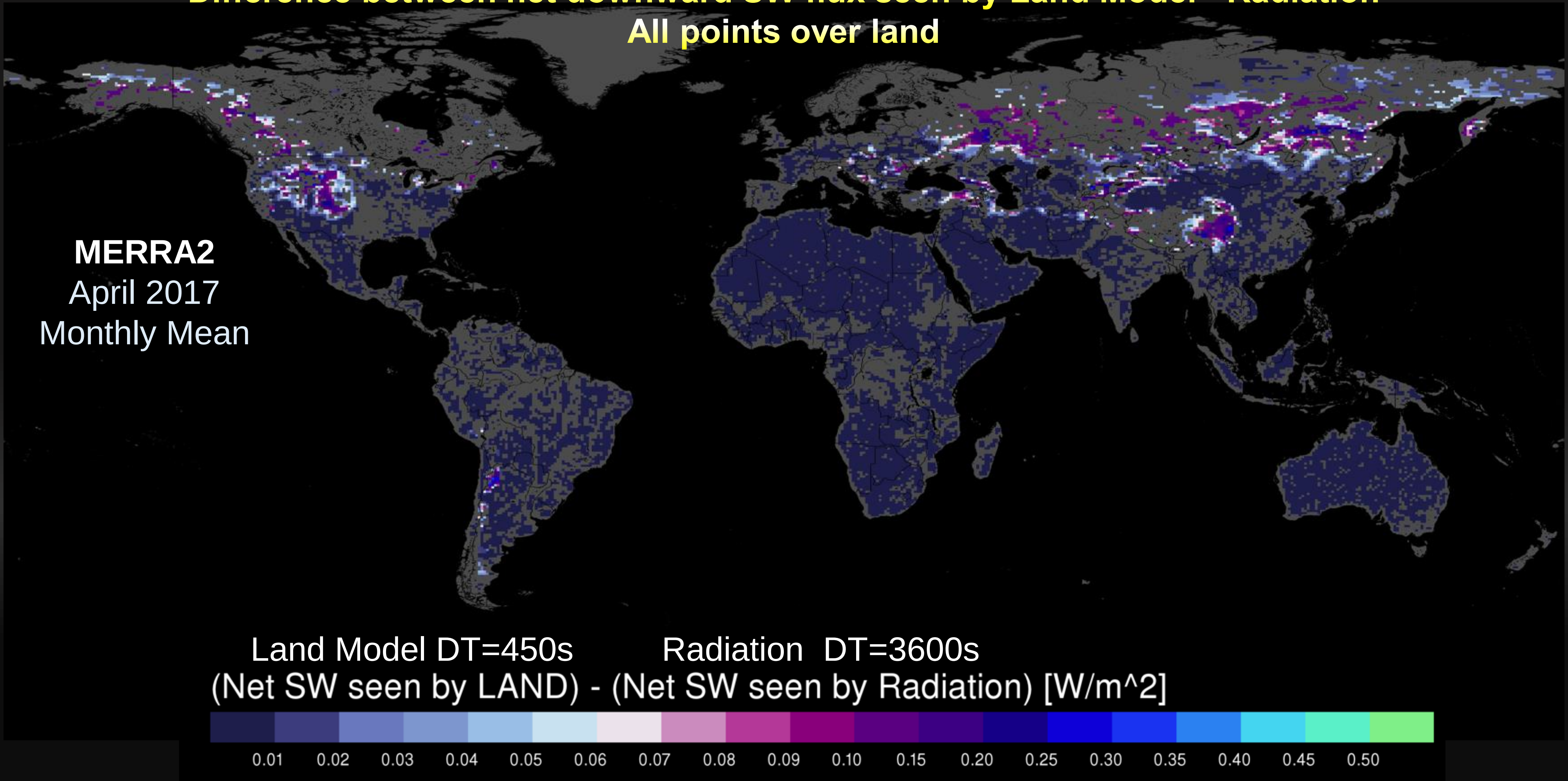
- *Longwave*
  - A full radiation calculation is performed with the current instantaneous surface and atmospheric properties (T, Q, Clouds, Aerosols)
  - The derivatives of all layer upward fluxes with respect to surface temperature are also calculated
- *Shortwave*
  - A full radiation calculation is performed with the current instantaneous surface and atmospheric properties (T, Q, Clouds, Aerosols)
  - The calculation is performed for the mean TOA insolation and insolation-weighted cosine of solar zenith angle for the refresh period
  - All fluxes are normalized by this TOA insolation and saved in the internal state

## 2. On the fast update() timescale: 450s

- *Longwave*
  - Upward layer fluxes are linearly updated for the new surface temperature
  - Downward fluxes are currently held constant
- *Shortwave*
  - The internal state normalized fluxes are multiplied by the mean TOA solar insolation for the current heartbeat period
  - No adjustment for changing surface or atmospheric properties is currently made
  - The renormalization is effectively due to the changing projection of the incoming solar beam in the vertical as the sun moves

# Radiation Issues

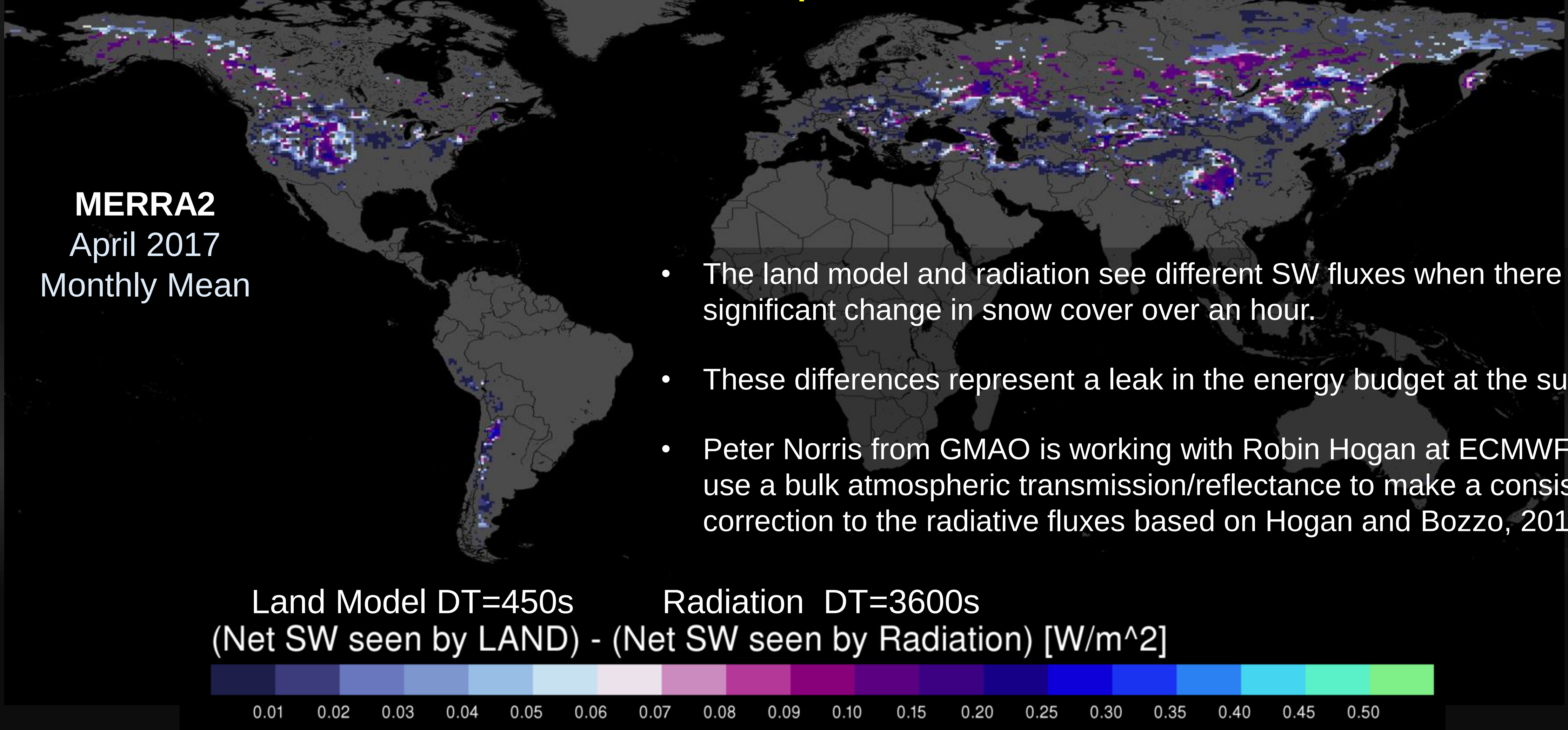
## Difference between net downward SW flux seen by Land Model - Radiation
## All points over land



# Radiation Issues

## Difference between net downward SW flux seen by Land Model - Radiation
## All snow covered points over land

**MERRA2**
April 2017
Monthly Mean




- The land model and radiation see different SW fluxes when there is significant change in snow cover over an hour.
- These differences represent a leak in the energy budget at the surface.
- Peter Norris from GMAO is working with Robin Hogan at ECMWF to use a bulk atmospheric transmission/reflectance to make a consistent correction to the radiative fluxes based on Hogan and Bozzo, 2015

# Aerosol 2-Phase Coupling

Aerosols and species advection cost more than dynamics in the 13-km GEOS configuration. Consuming nearly 30% of a 10-day forecast.

## Phase 1:

Processes executed on Physics DT=450s

1.1 Emissions

## Phase 2:

Processes executed on GOCART_DT=3600s

2.1 Chemistry production

2.2 Gravitational settling and dry deposition

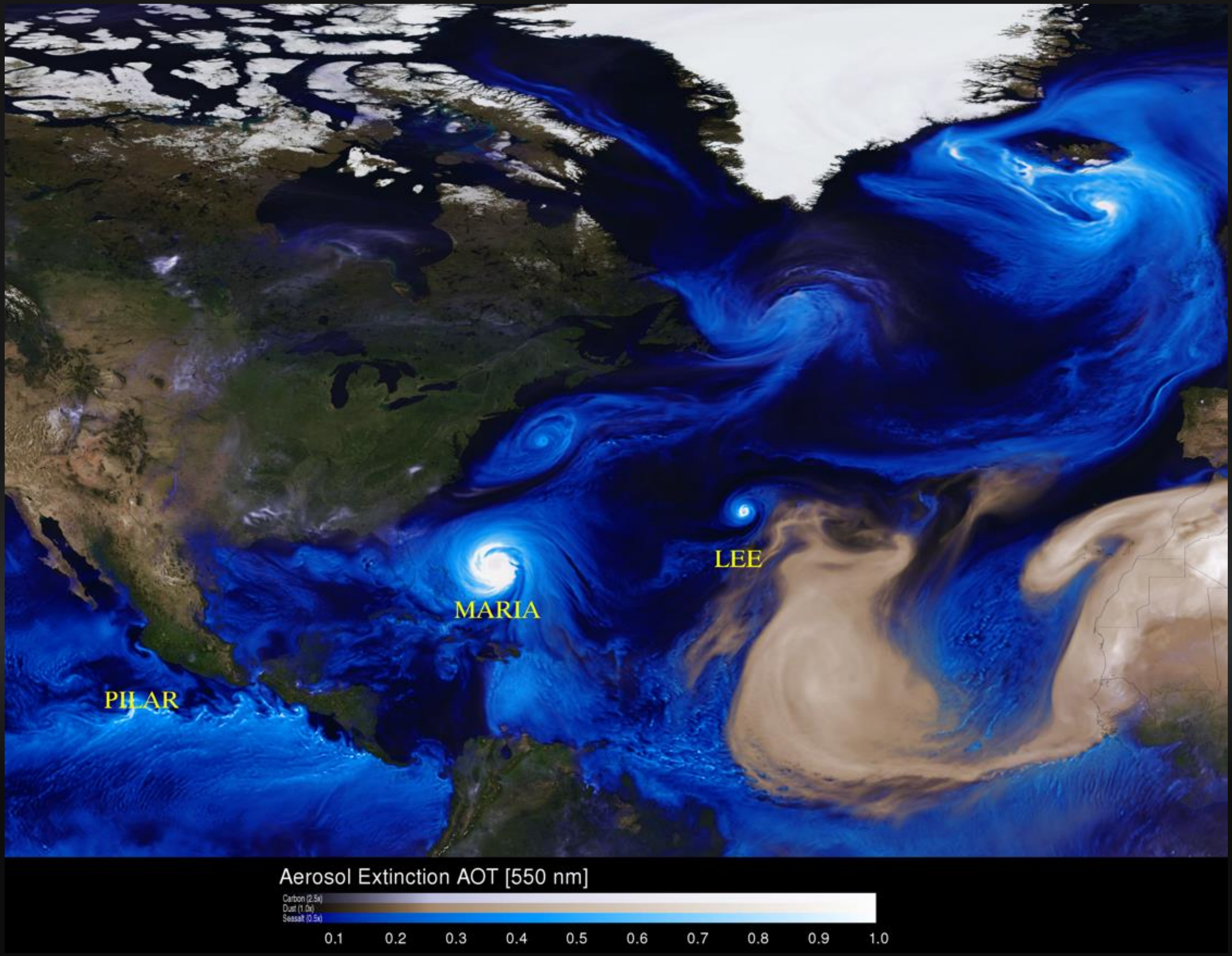
2.3 Large-scale wet removal

2.4 Convective-scale mixing and wet removal

Diagnostics updated on heartbeat DT=450s

2.5 Aerosol diagnostics

This split-phase approach can reduce the aerosol timing by more than 75%. The impact at higher resolutions (with smaller DTs) is even greater than this.



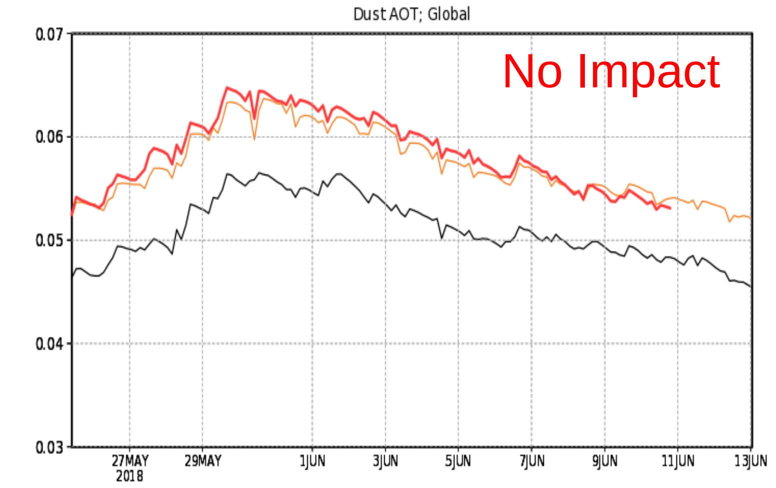
# Aerosol 2-Phase Coupling

## 13-km 4d-EnsVar GEOS DAS Experiments

Examining the impact of 2-phase aerosol processes in GEOS
versus aerosol coupling on the 450s Physic DT

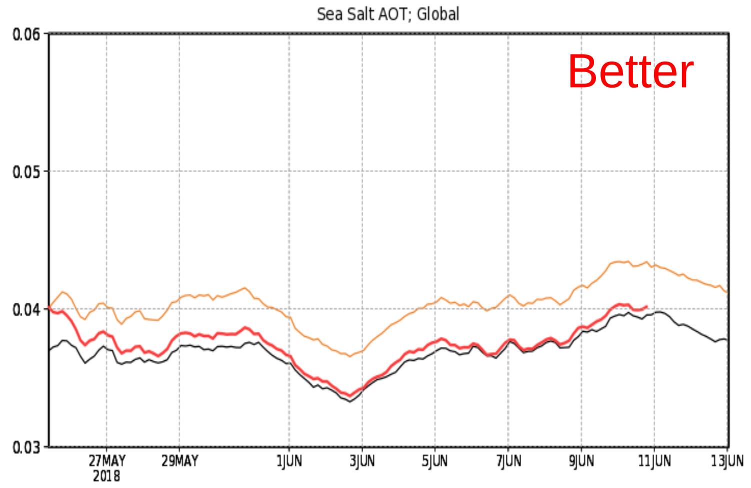
### *Dust*

2-Phase Aerosols Aerosols 450s Control:Target AOT



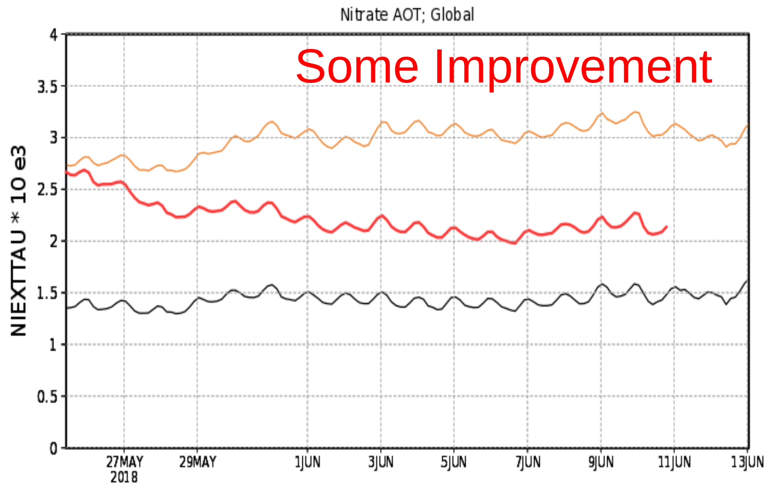

### *Sea Salt*

2-Phase Aerosols Aerosols 450s Control:Target AOT




### *Nitrate*

2-Phase Aerosols Aerosols 450s Control:Target AOT

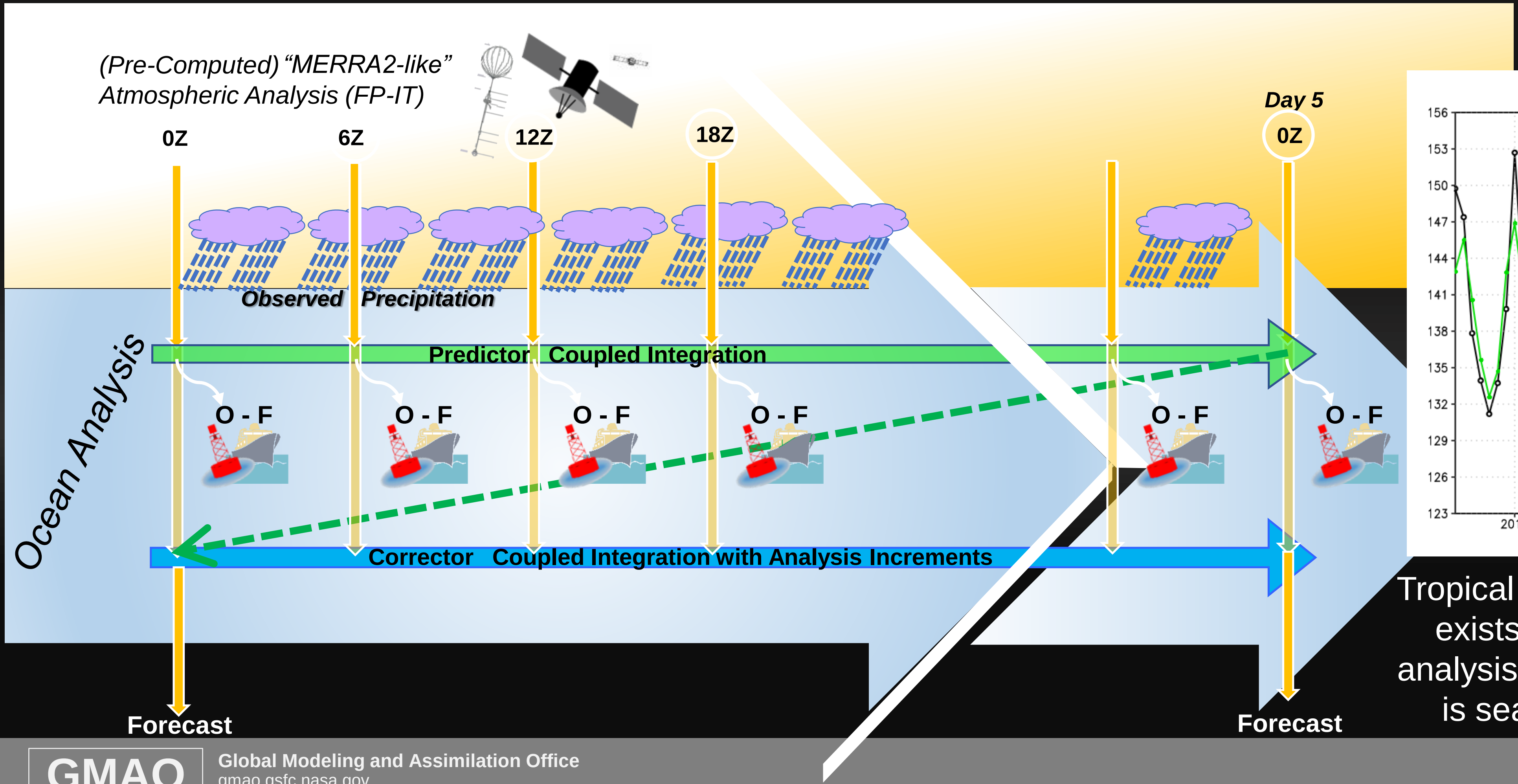


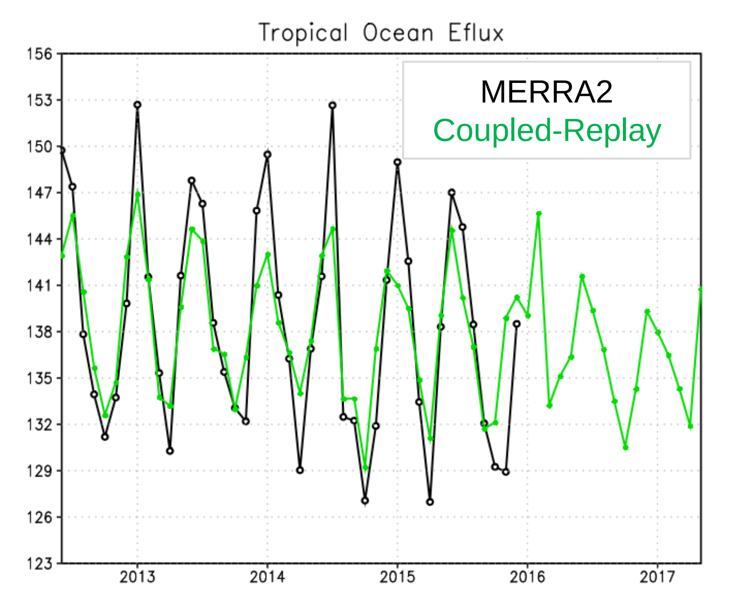

This sensitivity will be enhanced as we adapt aerosol aware cloud microphysics packages like MG and will impact clouds and radiation more directly

# Ocean Coupling Challenges

The GEOS S2S forecast system requires a 'coupled-replay' to an existing GEOS atmospheric analysis (FP-IT)

- Issues exist at the Atmosphere-Ocean interface through inconsistent SSTs and evaporative fluxes
- The ultimate solution is a fully coupled Atmosphere-Ocean Integrated Earth System Analysis



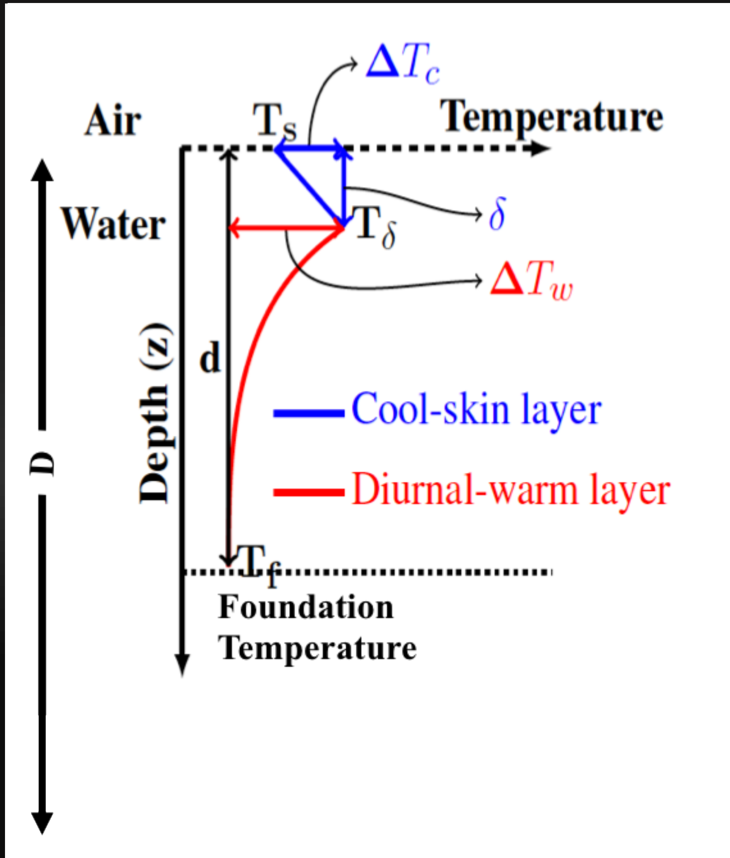



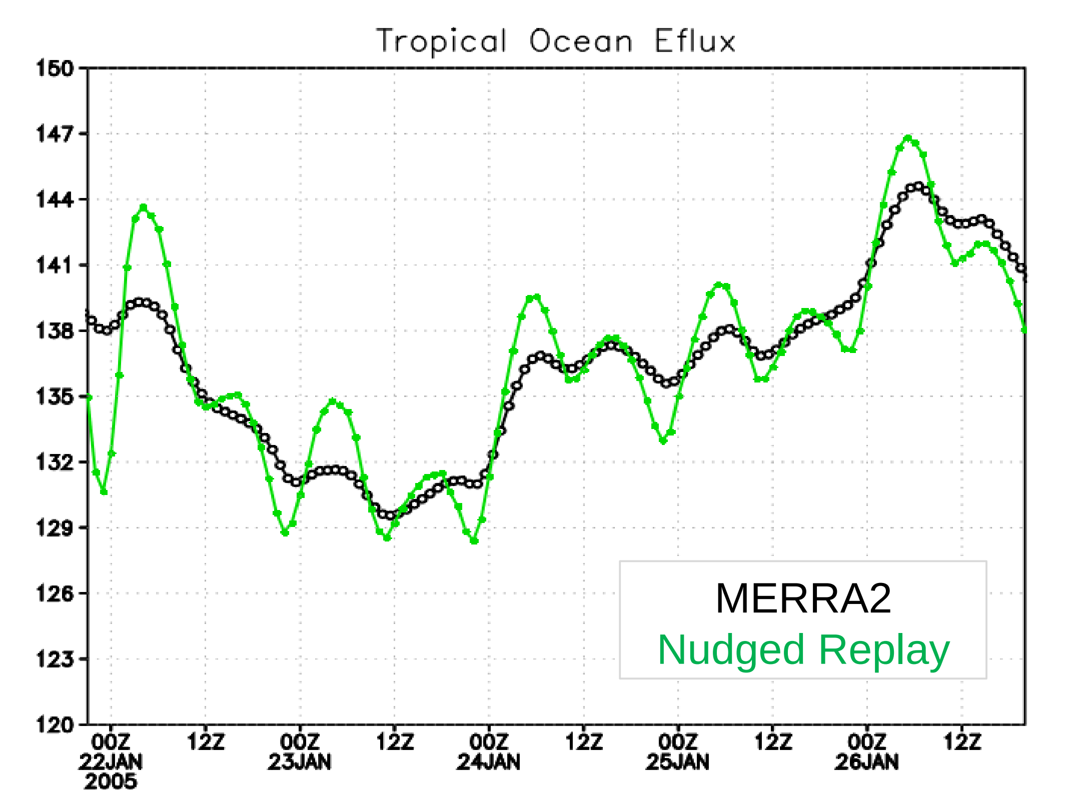

Tropical ocean Eflux is 70-75% of what exists in the replayed atmosphere analysis leading to an uncontrolled rise is sea-level in the coupled-replay

# Ocean Coupling Challenges

An updated Atmosphere-Ocean Interface Layer (AOIL) is being including in GEOS for the S2S Version 3 system

- The model for near-sea surface diurnal warming and cool-skin layers acts as a coupler between the atmosphere and ocean components
- This AOIL includes a nudging of SST and sea ice fraction from MERRA-2 boundary conditions




Tropical Ocean Eflux now follows MERRA2 in the ”coupled-replay”

# Conclusions

1. NWP Experiments show improved tropical QV & T biases with shorter physics DT (Using GF+UW)
2. UW ShallowCu shows very little DT sensitivity in 14-km RCE experiments
3. OLR comparison with CERES is improved with GF+UW convection at shorter physics DTs
4. Precipitation issues comparing GF+UW with GPM are not resolved by physics DT
   - RAS precipitation PDFs compare well with GPM using longer physics DTs
5. Several minor coupling issues exist in the land-surface and radiation
6. Aerosol coupling issues will become important with MG microphysics
   - GOCART computational costs are significant
7. Atmosphere-Ocean “Coupled-Replay” issues with latest S2S systems are resolved
   - Looking toward fully coupled Ocean-Atmosphere-Land DA in 2021