GEOS

*the **Goddard Earth Observing System** model*

Bill Putman

Nathan Arnold, Saulo Freitas, and others…

NASA Global Modeling and Assimilation Office

Dan Duffy

NASA Center for Climate Simulation

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 Convection Allowing

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

GEOS (1.5km Resolution) Visible Clouds June 15-18, 2012

Finite-Volume Cubed-Sphere (FV3) Dynamical Core

Finite-Volume transport on a Lat-Lon grid for chemistry transport
Multidimensional Flux-Form Semi-Lagrangian Transport Schemes
Lin and Rood, 1996

Shallow water model development
An Explicit Flux-Form Semi-Lagrangian Shallow Water Model on the Sphere
Lin and Rood, 1997

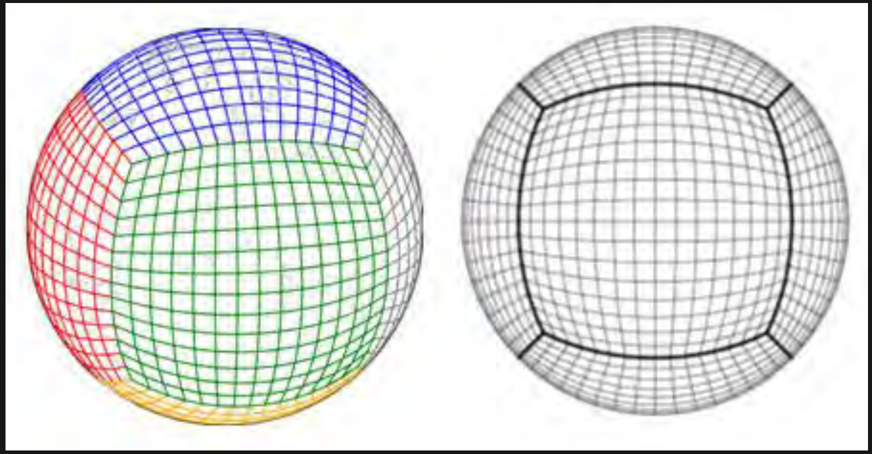
Full 3-dimensional hydrostatic dynamical core
A finite-volume integration method for computing pressure gradient force in general vertical coordinates
Lin, 1997

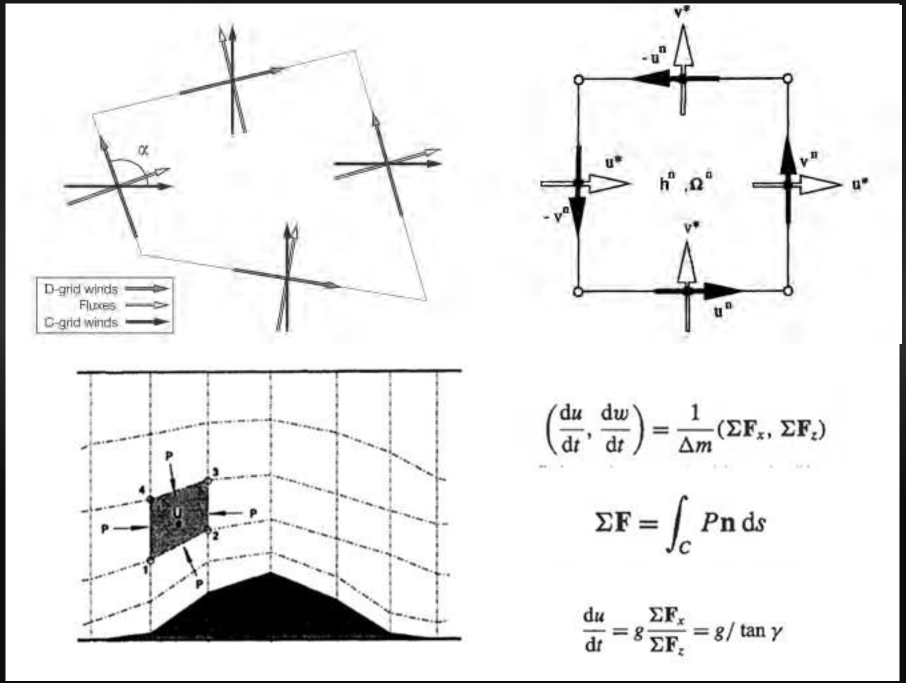
Vertically Lagrangian discretization
A "Vertically Lagrangian" Finite-Volume Dynamical Core for Global Models
Lin, 2004

Cubed-Sphere implementation
Finite-volume transport on various cubed-sphere grids
Putman and Lin, 2007

A non-hydrostatic finite-volume algorithm
A control volume model of the compressible Euler equations with a vertical Lagrangian Coordinate
Chen, Lin, and coauthors, 2013

Global to regional nesting
A two-way nested global-regional dynamical core on the cubed-sphere grid
Harris and Lin, 2014





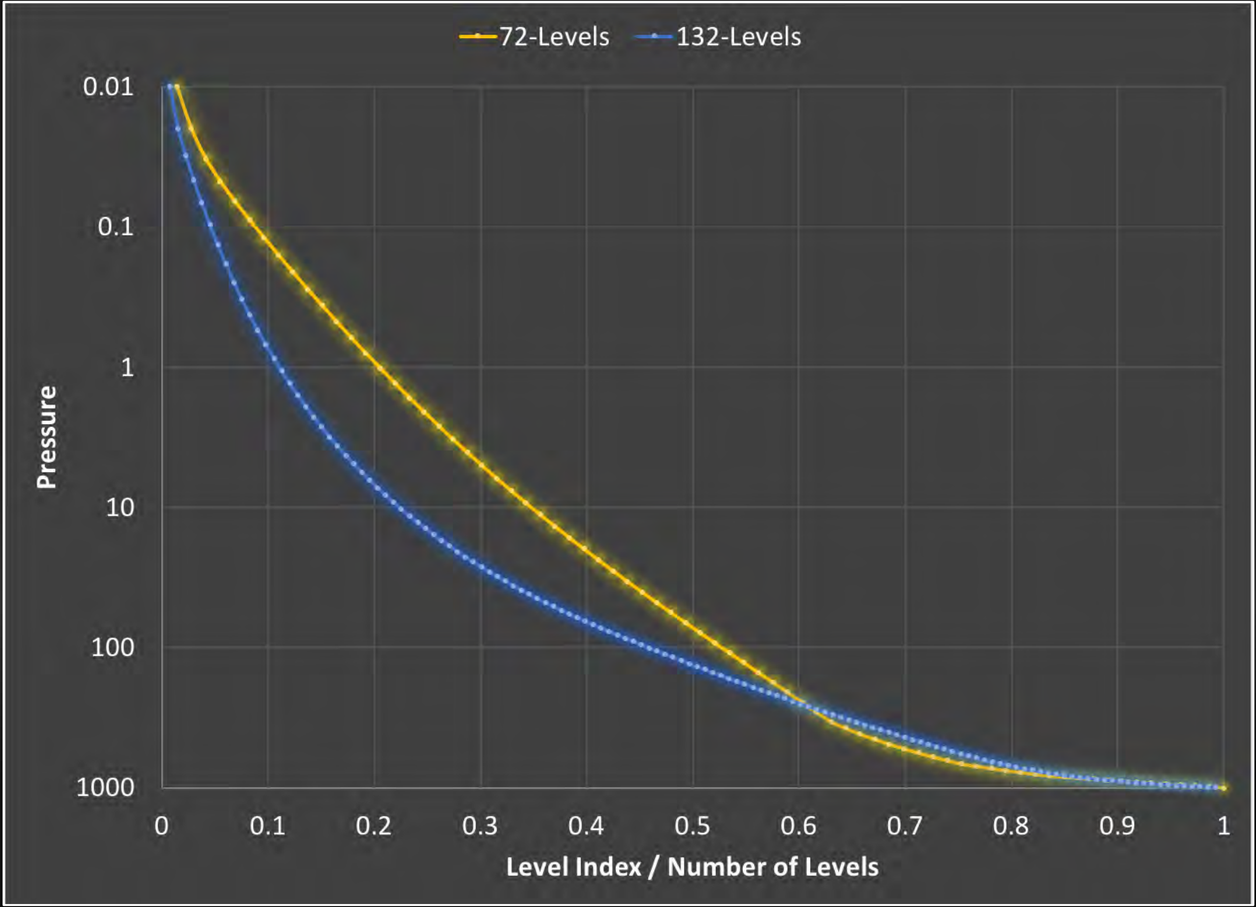
https://www.gfdl.noaa.gov/fv3/

Finite-Volume Cubed-Sphere (FV3) Dynamical Core

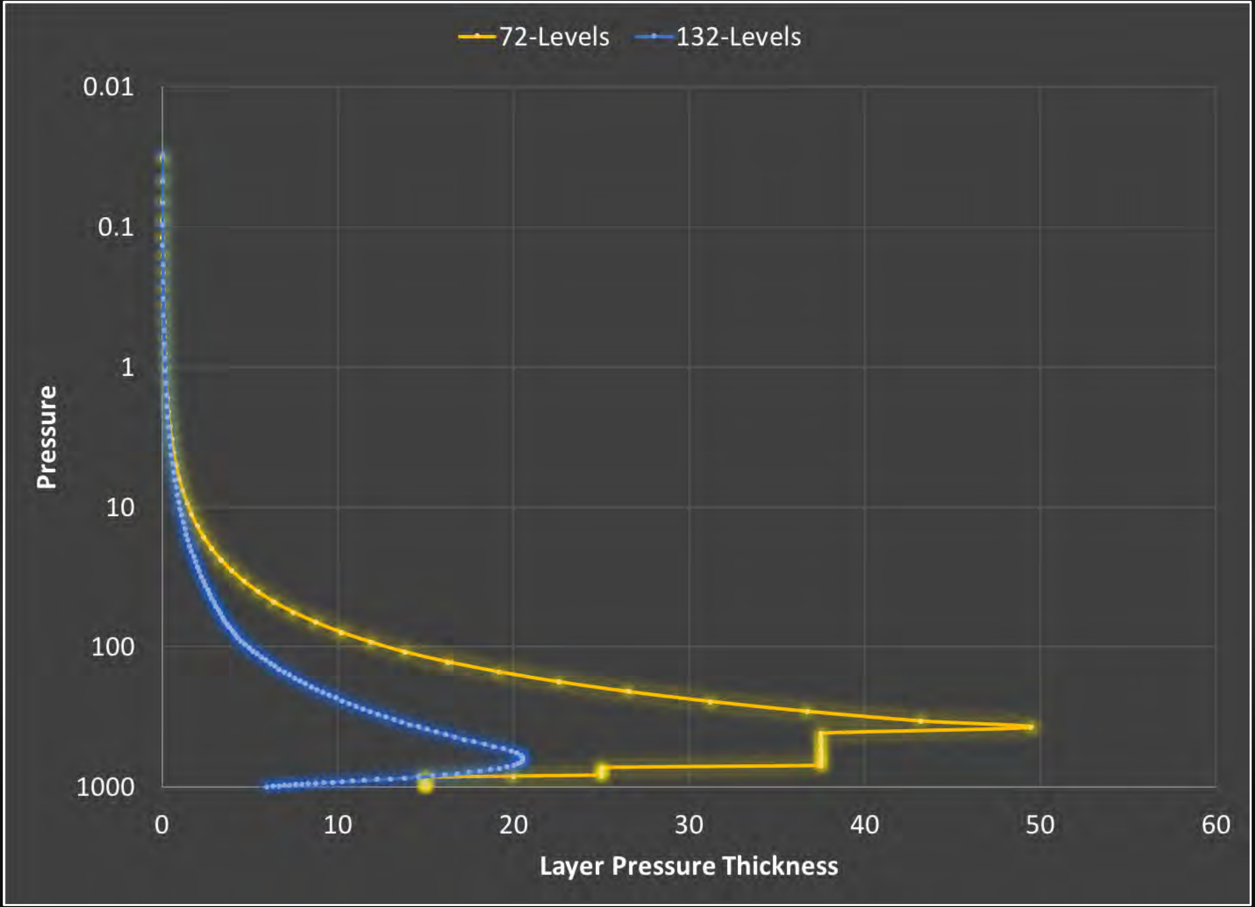
FV3 Namelist Options	NASA (GEOS)				
Horizontal Resolution	c360 (26 km)	c720 (13 km)	c1440 (7 km)	c2880 (3.5 km)	C3072 (3km)
Vertical Resolution	72	72	72	72	132
Fast Physics DT (s)	450	225	150	75	90
Vertical Remap DT (s)	225	112.5	37.5	18.75	15
Acoustic DT (s)	37.5	18.75	9.375	4.6875	3.75
hord_mt ; vt ; t ; p ; tr (horiz advection)	5 ; 5 ; 5 ; -5 ; 8	5 ; 5 ; 5 ; -5 ; 8	5 ; 5 ; 5 ; -5 ; 8	5 ; 5 ; 5 ; -5 ; 8	5 ; 5 ; 5 ; -5 ; 8
kord_mt ; wz ; tr (vertical remap)	9 ; 9 ; 9	9 ; 9 ; 9	9 ; 9 ; 9	9 ; 9 ; 9	9 ; 9 ; 9
dddmp ; d2_bg ; d4_bg (horiz diffusion)	0.1 ; 0.0 ; 0.12	0.1 ; 0.0 ; 0.12	0.1 ; 0.0 ; 0.12	0.1 ; 0.0 ; 0.12	0.1 ; 0.0 ; 0.12
n_sponge ; n_2dzfilter	9 ; 25	9 ; 25	9 ; 25	9 ; 25	9 ; 30
fv_sg_adj (2-dz filter timescale [s])	450	225	150	75	90
vtdm4 (vorticity damping)	0.02	0.02	0.04	0.06	0.08
Compute Cores (Intel Skyake)	1,872	4,068	13,000	20,760	20,640
Throughput (Simulated Days/Day)	180	60	18	8	6

Vertical Resolution

Vertical Level Locations



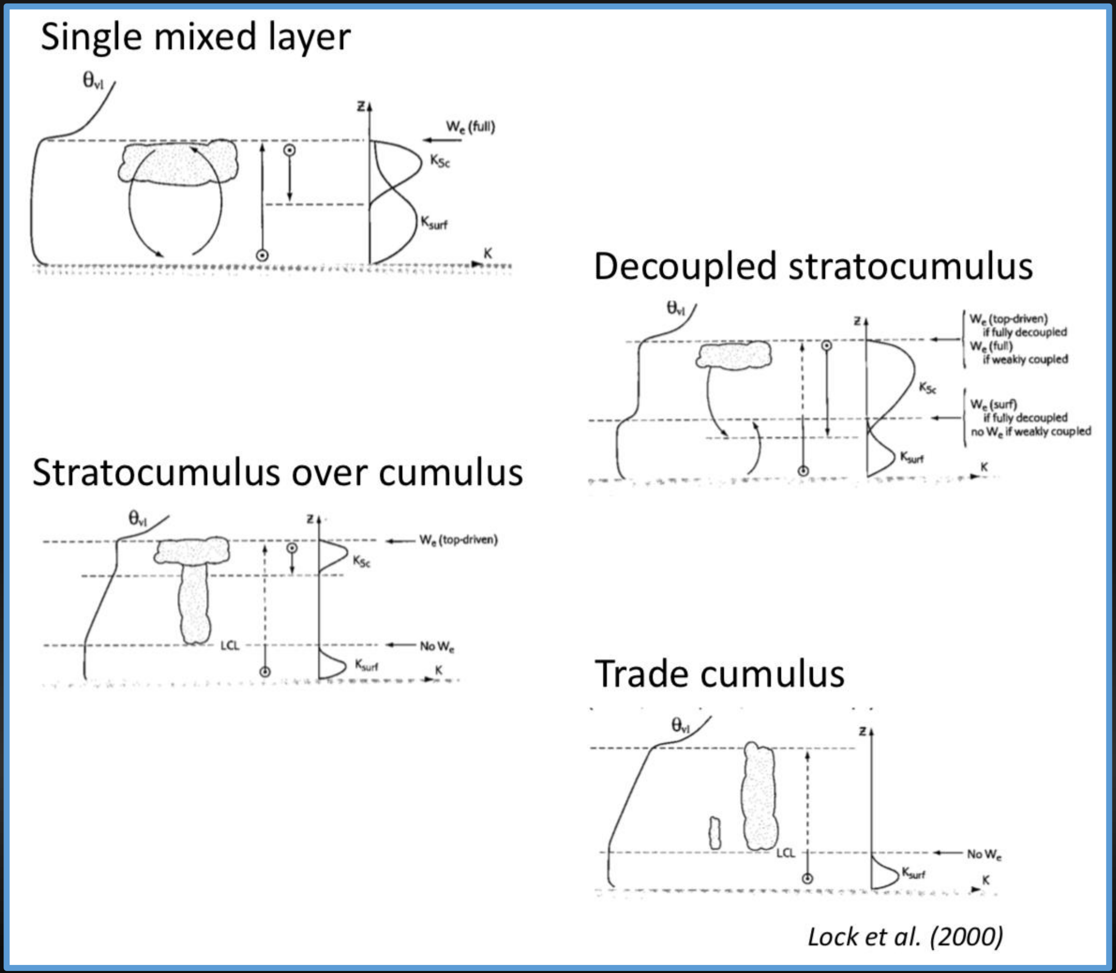
Layer Pressure Thickness



Boundary Layer & Turbulence

The turbulence parameterization is based on Lock et al. (2000) acting together with the Richardson number based scheme of Louis et al. (1982):

- **Lock scheme** represents non-local mixing in unstable layers
  - Computes the characteristics of rising or descending parcels of air ("plumes")
    - Surface (surface bouancy flux)
    - Radiative (cloud top cooling)
  - Includes moist heating in the calculation of buoyancy and a shear-dependent entrainment in the unstable surface parcel calculations
- **Louis scheme** is a first order, local scheme
  - Eddy diffusion coefficients are computed using Richardson number based stability functions for stable and unstable layers
  - State dependent turbulent length scale to add 'memory' to the turbulence parameterization



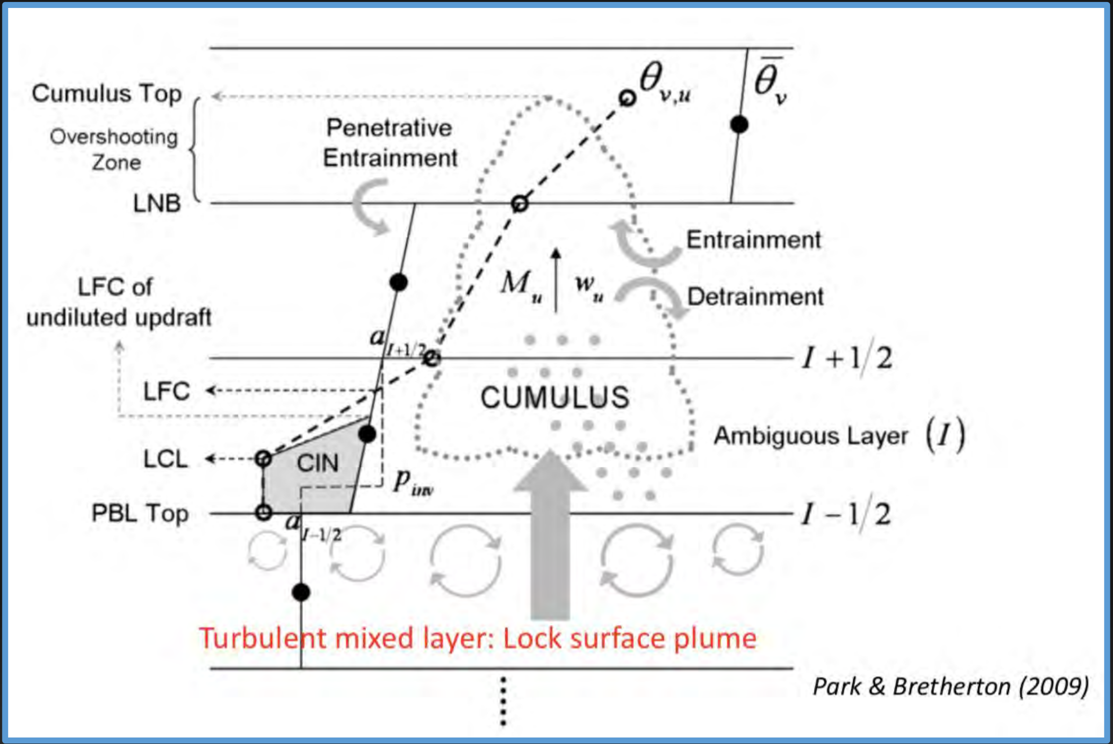
Shallow Convection

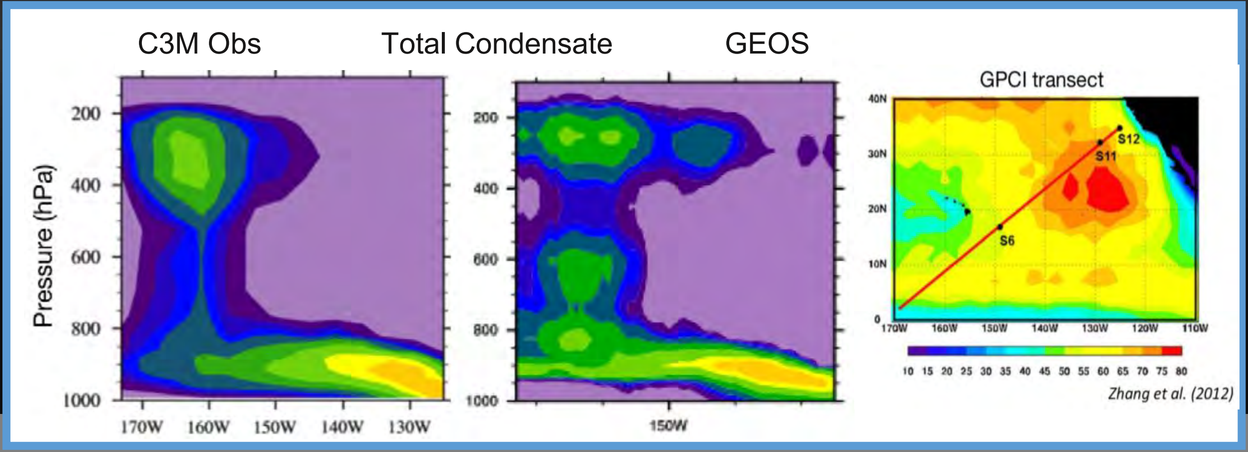
Shallow convection is parameterized with the Park and Bretheron (2009) University of Washington scheme:

- Buoyancy sorting bulk mass flux, closure based on PBL TKE and CIN:

$$M = 0.4\rho\sqrt{e}\exp\left(-\frac{\mathrm{CIN}}{e}\right)$$

- Diagnosed bulk vertical velocity determines overshooting (penetrative entrainment) and affects lateral mixing rates.
- Kessler-type microphysics, with maximum updraft condensate of 1 g/kg.
- Penetrative entrainment allows strong mixing across inversion.
- Shallow cumulus parameterization uses Lock surface plume for sub-cloud mixed layer.





Scale-Aware Deep Convection

Unified physics across model resolutions (from 100- to 3-km):

- Grell-Freitas Deep Convection
  - Scale awareness follows Arakawa et al. (2011)

$$\overline{w'\phi'} = (1-\sigma)^2 \left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$$

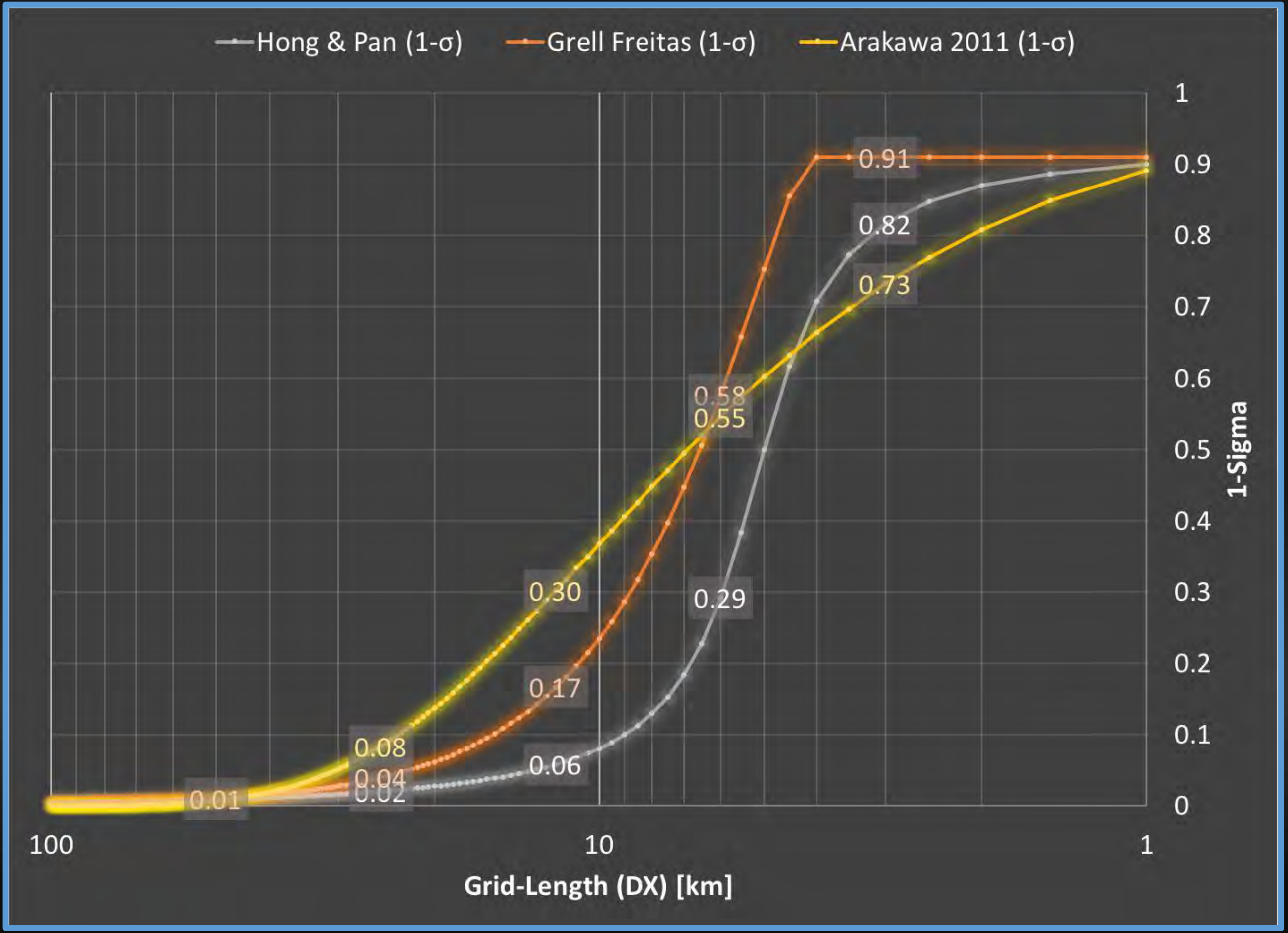
Vertical eddy transport.

Fractional area covered by the active cloud draft.

Eddy transport from Convection for a full adjustment to a quasi-equilibrium state.

  - Stochastic approach adapted from Grell-Devenyi (2002)
  - Trimodal design:
    - Deep: extending to the tropopause
    - Congestus: to the zero degree inversion layer
    - Shallow: limited by trade inversion *[disabled with UW]*
  - Ensemble of closures & convective scale downdrafts
  - Closure for non-equilibrium convection (diurnal cycle land)

Scale-Dependence in the "grey-zone"



Scale-Aware Deep Convection

Unified physics across model resolutions (from 200- to 3-km):

- Grell-Freitas Deep Convection
  - Scale awareness follows Arakawa et al. (2011)

$$\overline{w'\phi'} = (1-\sigma)^2 \left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$$

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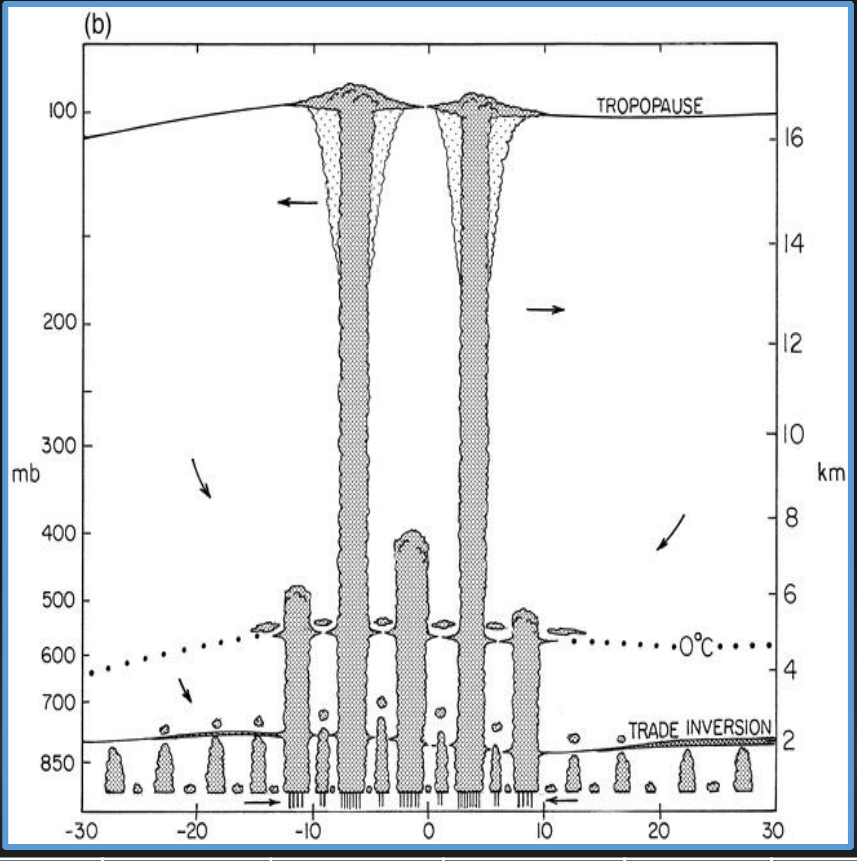
  - Closure for non-equilibrium convection (diurnal cycle land)

Johnson et al (1999):
Tri-modal Characteristics of Tropical Convection



Precip (mm/day)	c90 100-km	c180 50-km	c360 26-km	c720 13-km	c1440 7-km	c2880 3.5-km
Obs Aug-2016	GPM/GSMaP: 2.71 mm/day			GPCP: 2.72 mm/day		
GEOS Total	3.09	3.07	3.11	3.10	3.09	3.07
GEOS LSC	1.06	1.07	1.19	1.70	1.97	2.05
GEOS CNV	2.03	2.00	1.92	1.40	1.12	1.02

GEOS Moist Physics

GEOS single-moment cloud microphysics

[Bacmeister, et al]:

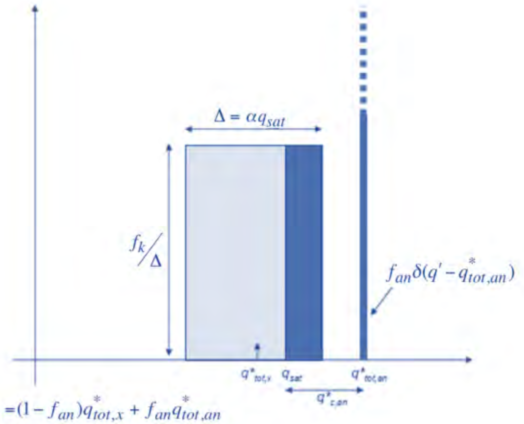
- 3-Phase (water vapor, cloud liquid & cloud ice)
- Source processes for cloud
  - Anvil cloud from detraining convection
  - Large-scale cloud from PDF based condensation
- Loss processes for cloud
  - Evaporation “cloud munching” *[Del Genio et al. (1996)]*
  - Autoconversion of cloud condensate to precipitating condensate *(Sundqvist et al. [1989] and later used by Tiedtke [1993])*
  - Sedimentation of cloud condensate onto falling precipitation
  - Accretion of cloud condensate onto falling precipitation
- Cloud properties informed by aerosol concentrations
  - Liquid and ice cloud effective radii
  - Bergeron processes for mixed phase clouds

Convective Sources

$$\delta f_{an} = {DM}/{\rho \Delta z} \quad \text{and} \quad \delta q_{c,an} = {DC}/{\rho \Delta z}.$$

Detrained Mass (DM) Anvil cloud source

Detrained Condensate (DC) Anvil condensate



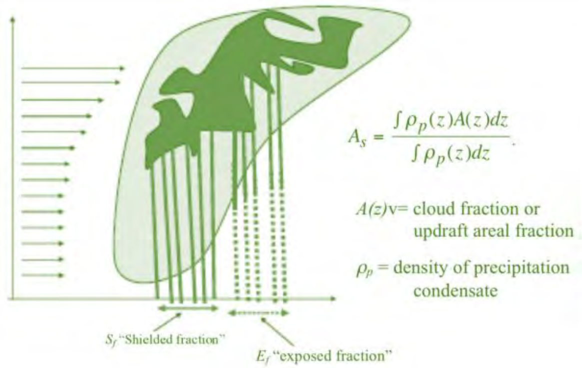
$$\bar{q}_{tot} = (1 - f_{an}) q^*_{tot,x} + f_{an} q^*_{tot,an}$$

$$q^*_{tot,an} = q_{sat}(\bar{T}) + q^*_{c,an} \; ; \; \bar{q}_{c,an} = f_{an} q^*_{c,an}$$

Large-scale bi-modal boxcar PDF

Sundqvist-type autoconversion:

$$G_{p,liq} = c_0 l_c \left\{ 1 - \exp\left[-\left(\frac{l_c}{l_{crit}} \right)^2 \right] \right\},$$



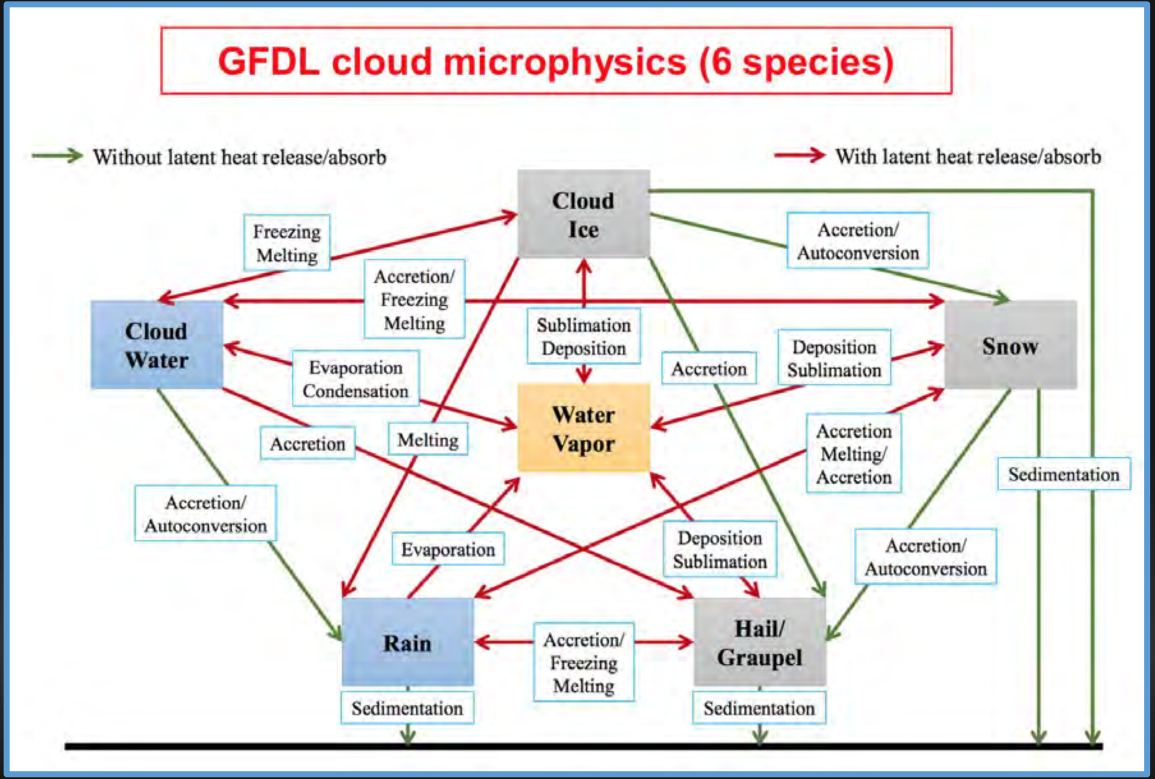
Fallout and Re-evaporation of Precipitation and Accretion of Cloud Condensate

GFDL Moist Physics

GFDL global cloud microphysics

[Shian-Jiann Lin, Linjiong Zhou, NOAA-GFDL]:

- The algorithms are originally derived from Lin et al. (1983)
  - 6 species microphysics
    - *Water Vapor*
    - *Cloud Water*
    - *Cloud Ice*
    - *Rain*
    - *Snow*
    - *Hail/Graupel*
  - Includes a fast saturation phase adjustment within FV3 following the vertical remapping
  - Time-split between warm-rain and ice-phase (slower) processes
  - Time-implicit monotonic scheme for terminal fall of condensates
- The code at this stage bears little to no similarity to the original Lin MP in zetac

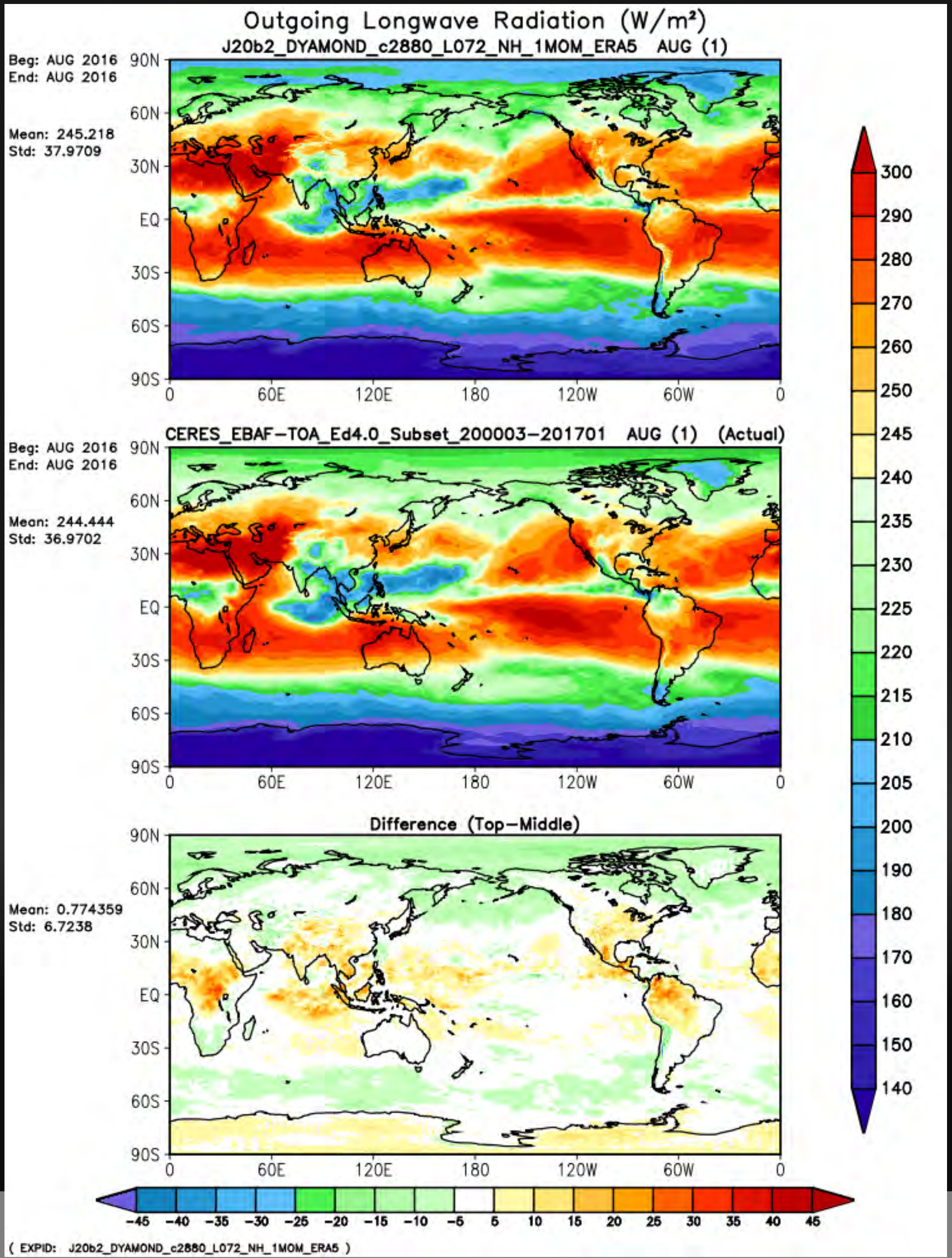


Radiation

RRTMG rapid radiative transfer model

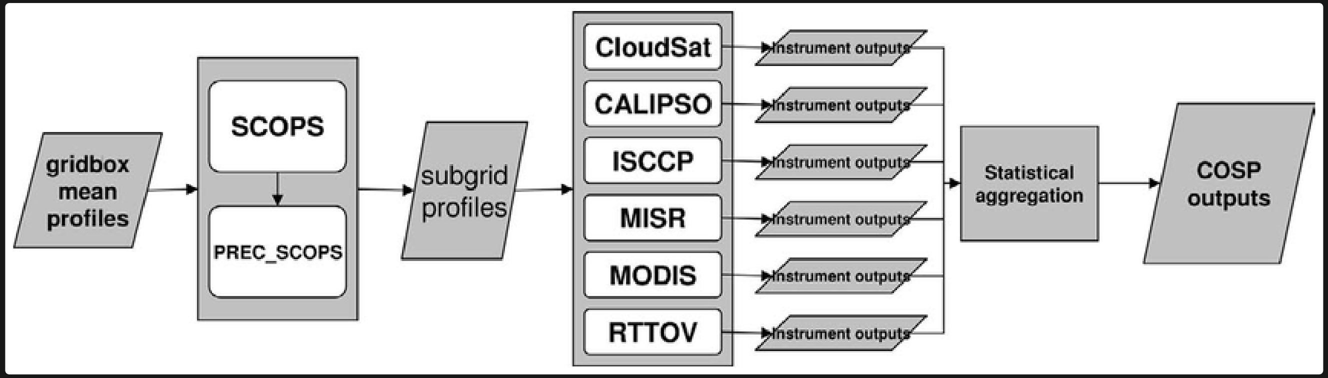
- RRTM is an efficient Correlated k-Distribution (CKD) code from AER, Inc., with g-point extinction interpolation tables derived directly from line-by-line (LBL) calculations with up-to-date validated spectroscopy (LBLRTM), and a modern water vapor continuum model.
- The GCM version, RRTMG, uses a reduced set of 140 g-points in 16 bands in the longwave (10-3250 cm^{-1}) and 112 g-points in 14 bands in the shortwave (820-50000 cm^{-1}). LW flux accuracy cf. LBL is $\lesssim 1.0$ W/m^2. SW flux accuracy cf. RRTM is $\lesssim 3$ W/m2.
- Time frequency of radiation calls:
  - Quick update processes are called on model heartbeat (the physics DT)
  - Full radiation refresh is done 1-hourly

http://rtweb.aer.com/rrtm_frame.html



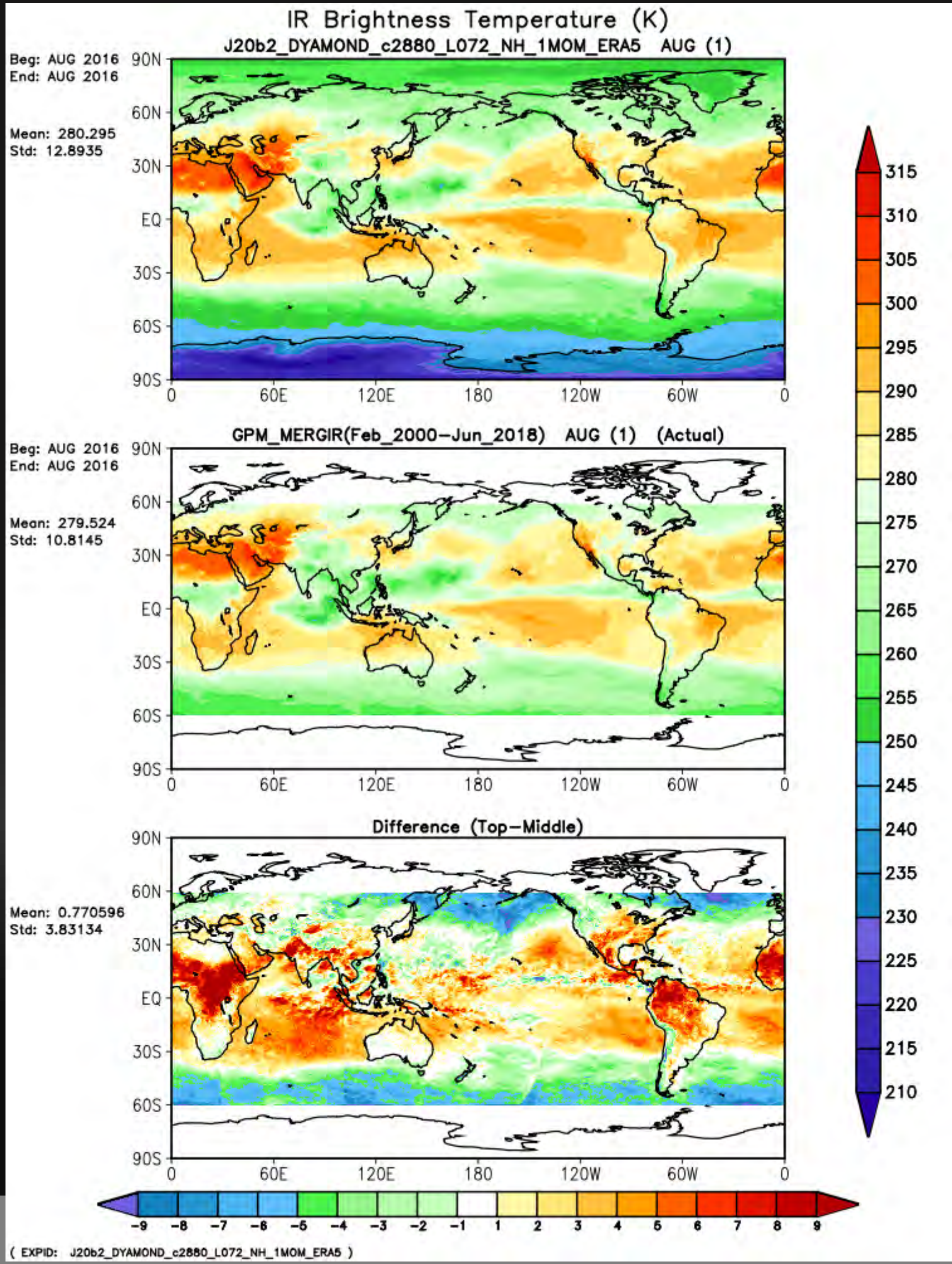
COSP Satellite Simulator

The CFMIP Observation Simulator Package (COSP)



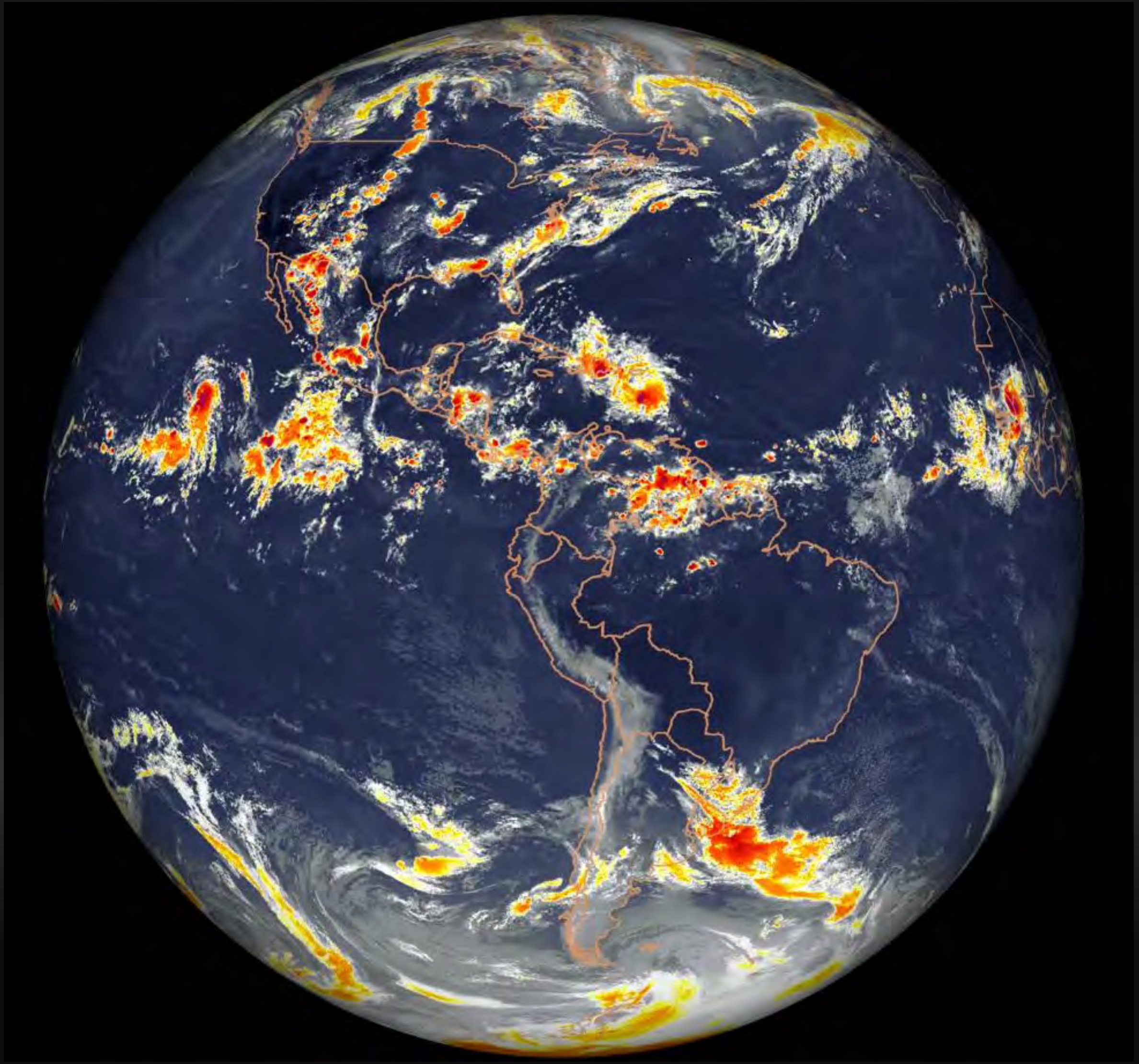
An integrated satellite simulator enabling the simulation from model variables of data from several satellite-borne active and passive sensors. Can be called on the time-frequency of requested model output (every 15 minutes).

https://www.earthsystemcog.org/projects/cfmip/cosp

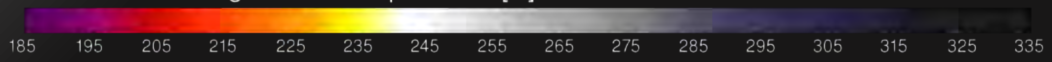


GEOS DYAMOND Experiments

- **GFDL microphysics + scale-aware convection**
  - 3-km (c3072) 132-levels
- **GEOS single-moment microphysics + scale-aware convection**
  - 200-km (c48) 72-levels
  - 100-km (c90) 72-levels
  - 50-km (c180) 72-levels
  - 25-km (c360) 72-levels
  - 12-km (c720) 72-levels
  - 6-km (c1440) 72-levels
  - 3-km (c2880) 72-levels
- **GEOS single-moment microphysics + DeepCU=0**
  - 3-km (c2880) 72-levels
- **GEOS single-moment microphysics + ScaleAware=0**
  - 3-km (c2880) 72-levels
- **GEOS "Replay" to GEOS-DAS and ERA-5**
  - 3-km (c2880) 72-levels



GEOS 3-km DYAMOND Simulation : August 2016



Experiment Data Description Docs

- **GFDL microphysics + scale-aware convection**
  - 3-km (c3072) 132-levels

GEOS File-Spec: Detailed description of model output:
https://portal.nccs.nasa.gov/datashare/G5NR/DYAMOND/03KM_L132/DYAMOND_FileSpec.pdf

- **GEOS single-moment microphysics + scale-aware convection**
  - 200-km (c48) 72-levels
  - 100-km (c90) 72-levels
  - 50-km (c180) 72-levels
  - 25-km (c360) 72-levels
  - 12-km (c720) 72-levels
  - 6-km (c1440) 72-levels
  - 3-km (c2880) 72-levels

GEOS File-Spec: Detailed description of model output:
https://portal.nccs.nasa.gov/datashare/G5NR/DYAMOND/03KM_L072/J20b2_DYAMOND_FileSpec.pdf

- **GEOS single-moment microphysics + DeepCU=0**
  - 3-km (c2880) 72-levels
- **GEOS single-moment microphysics + ScaleAware=0**
  - 3-km (c2880) 72-levels
- **GEOS "Replay" to GEOS-DAS and ERA-5**
  - 3-km (c2880) 72-levels

These cases data reside on the NASA dataportal:
https://portal.nccs.nasa.gov/datashare/G5NR/DYAMOND/

https://portal.nccs.nasa.gov/datashare/G5NR/DYAMOND/03KM_L072/J20b2_DYAMOND_c2880_L072_NH_1MOM_REPLAY/
https://portal.nccs.nasa.gov/datashare/G5NR/DYAMOND/03KM_L072/J20b2_DYAMOND_c2880_L072_NH_1MOM_ERA5/

Using GEOS data

https://geos5.org/wiki/index.php?title=Visualizing_data_in_Cubed-Sphere_grid

Visualizing data in Cubed-Sphere grid

Cubed-Sphere grid background

Several GEOS-5 products are now produced on the native cubed-sphere computational grid. Although this format may be less familiar, this choice has several advantages for some user communities. In particular, the Chemical Transport Modeling (CTM) community can use native mass-flux products to significantly improve conservation properties when running with GEOS-5. To minimize transition difficulties for GEOS-5 data consumers, this page provides instructions for visualizing cubed-sphere data products using a variety of common packages: python, Matlab, IDL, and GRaDS, and Panoply. This page also provides instructions for downloading and building an executable that can regrid cubed-sphere products onto a traditional lat-lon grid.

Contents [hide]

GEOS files are generated with the Network Common Data Form (NetCDF-4) library, which uses Hierarchical Data Format Version 5 (HDF-5) as the underlying format.

NetCDF-4 is an open-source product of UCAR/Unidata (https://www.unidata.ucar.edu/software/netcdf/) and HDF-5 is developed by the HDF Group (http://www.hdfgroup.org/). One convenient method of reading GEOS-5 files is to use the netCDF library, but the HDF-5 library can also be used directly.

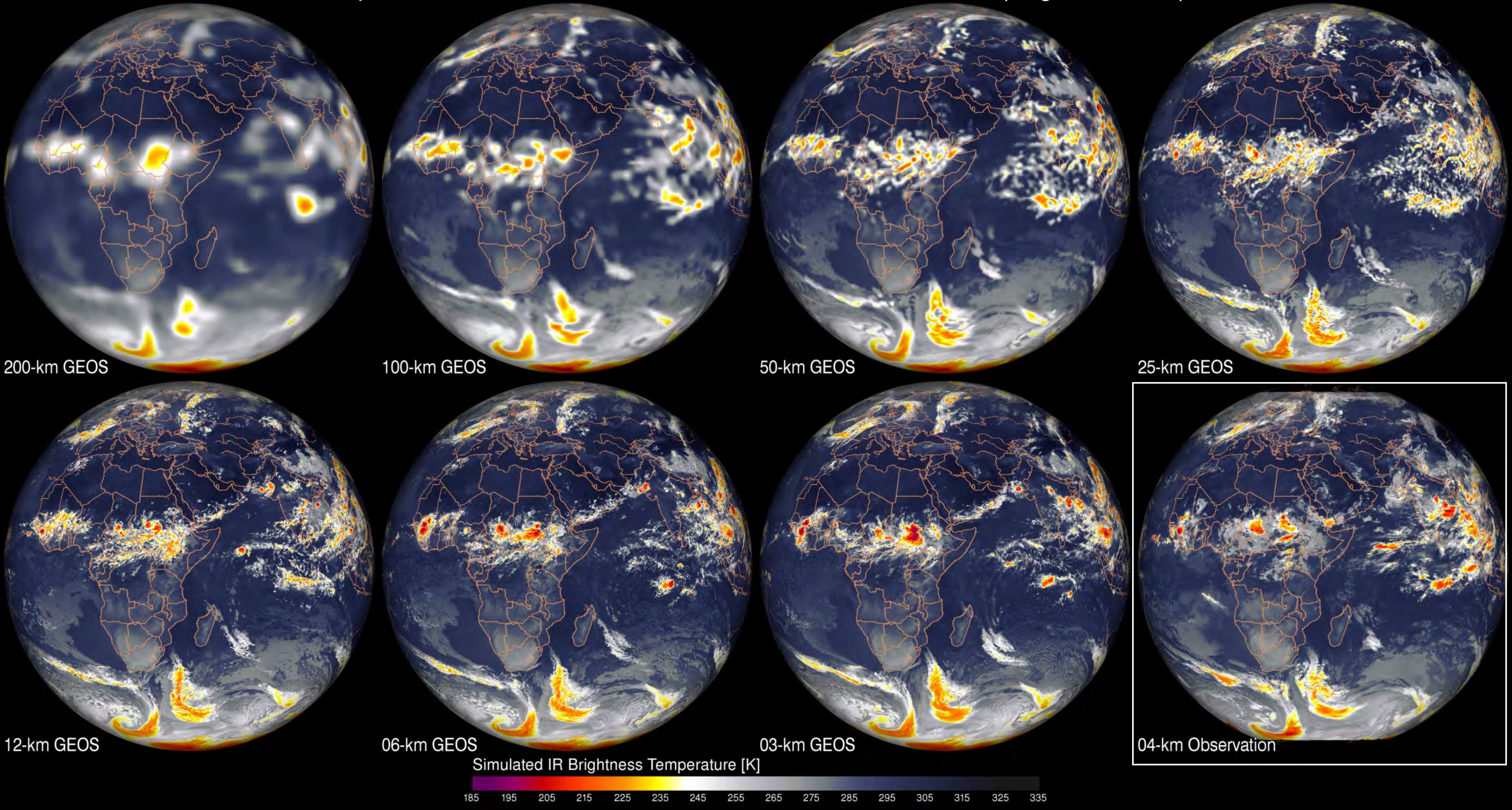
Observations

- **Global Precipitation**
  - **0.1-Deg : ½ hourly** GPM – IMERG : Global Precipitation Measurement
    - Rainfall estimates combining data from all passive-microwave instruments in the GPM Constellation
    - *https://pmm.nasa.gov/data-access/downloads/gpm*
  - **0.1-Deg : 1 hourly** GSMaP : Global Satellite Mapping of Precipitation
    - Rainfall estimates combining data from all passive-microwave instruments in the GPM Constellation
    - *https://sharaku.eorc.jaxa.jp/GSMaP*
- **Infrared Brightness Temperature (~11 microns)**
  - **4-km : ½ hourly** IMERGE
    - Globally-merged, full-resolution (~4 km) IR data
    - GMS-5, GOES-8, Goes-10, Meteosat-7 and Meteosat-5
    - *https://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.full_res.shtml*
  - **8-km : 3 hourly** NOAA Climate Data Record (CDR)
    - Gridded Satellite (GridSat-B1)
    - International Satellite Cloud Climatology Project (ISCCP) B1
    - *https://catalog.data.gov/dataset/noaa-climate-data-record-cdr-of-gridded-satellite-data-from-isccp-b1-gridsat-b1-infrared-channel*
- **Radiation - Clouds and the Earth's Radiant Energy System (CERES)** - *https://ceres.larc.nasa.gov/order_data.php*
  - **1-Deg : Monthly** Energy Balanced and Filled (EBAF)
    - Climate Data Record (CDR) of monthly TOA fluxes
    - Monthly and climatological
  - **1-Deg : 1 hourly** Synoptic TOA and surface fluxes and clouds (SYN)
    - 1-Hourly gridded observed TOA and Fu-Liou RT surface fluxes and clouds
    - Suitable for regional diurnal and process studies

Global Modeling and Assimilation Office

Depiction of clouds/convection in GEOS from 200- to 3-km (August 4, 2016)

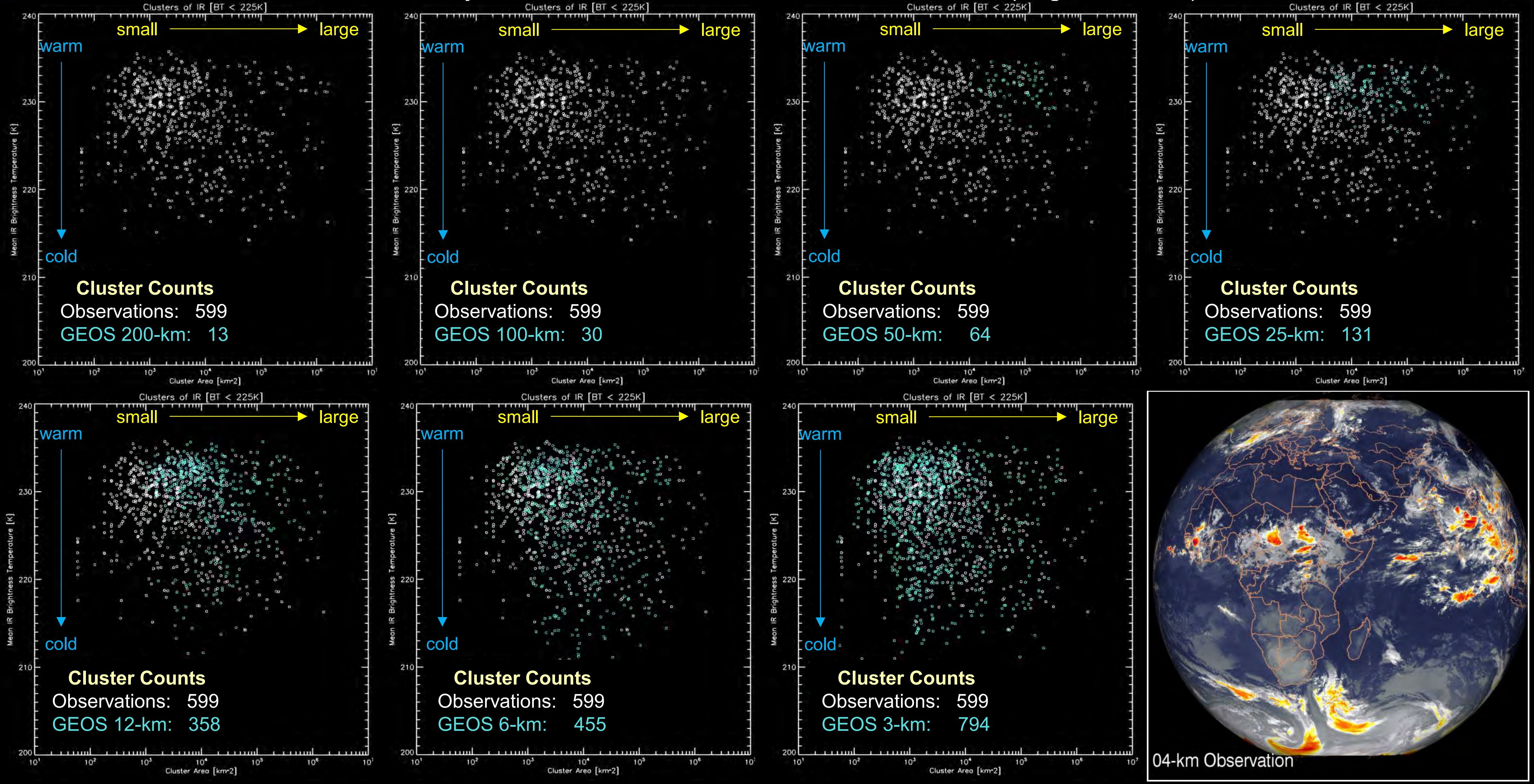
GMAO



Global Modeling and Assimilation Office

Cluster analysis of convection in GEOS from 200- to 3-km (August 4, 2016)

GMAO



Global Modeling and Assimilation Office

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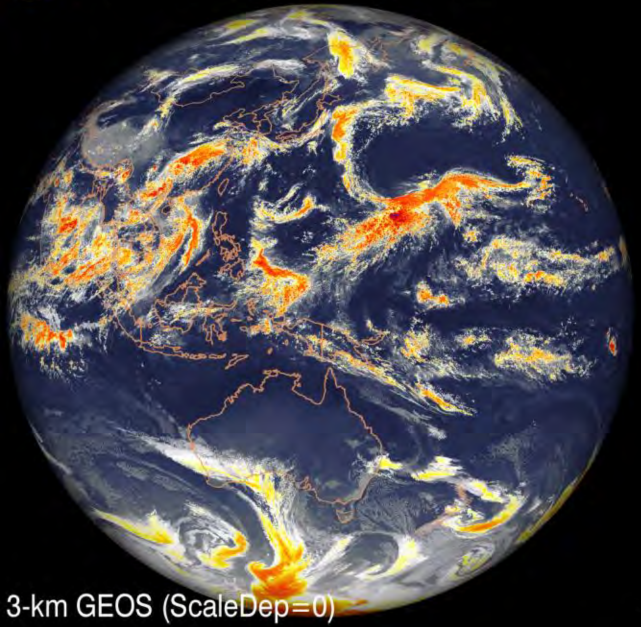
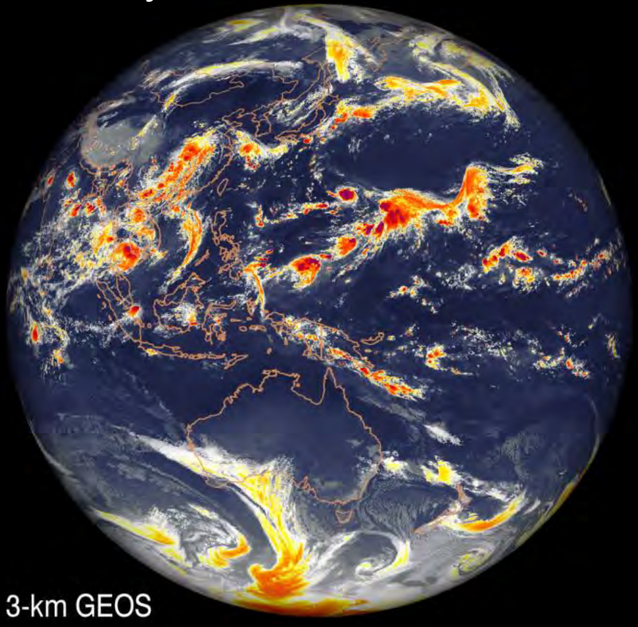
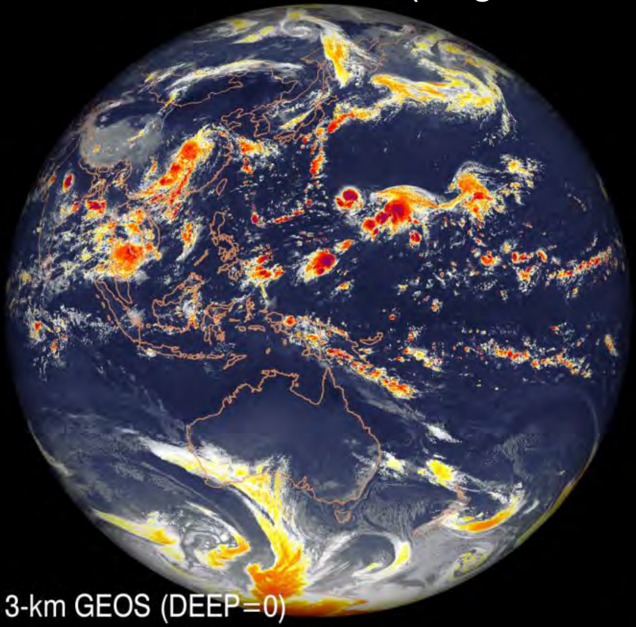


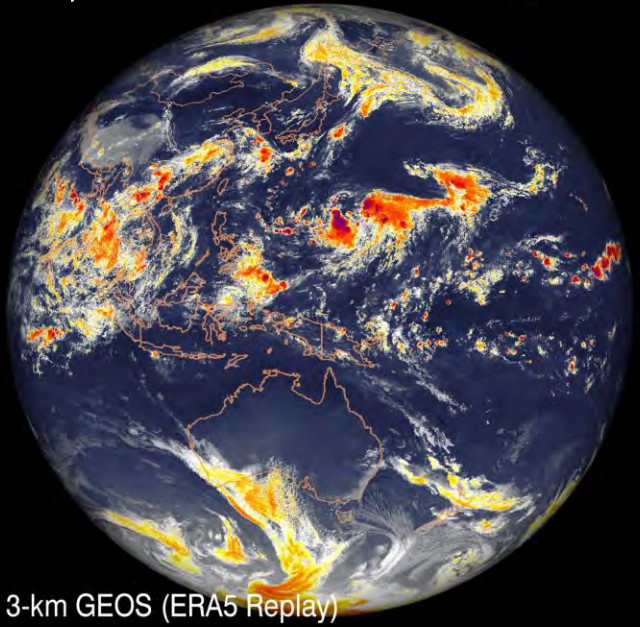
3-km GEOS (ScaleDep=0)



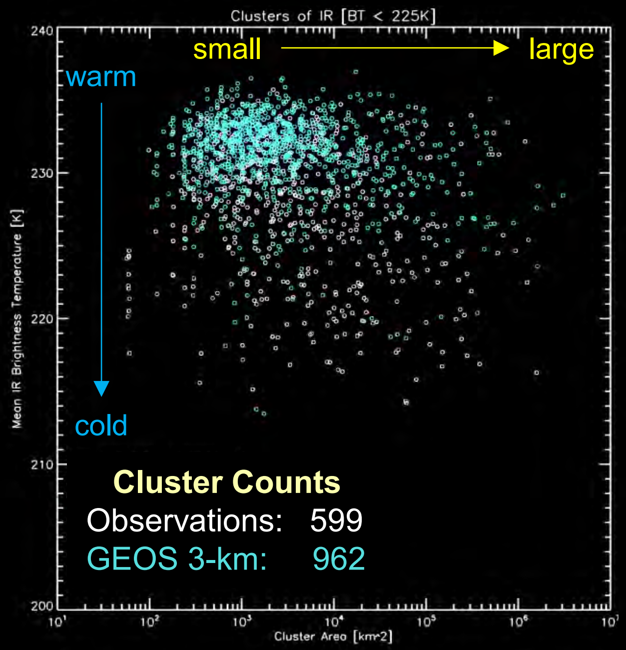
3-km GEOS

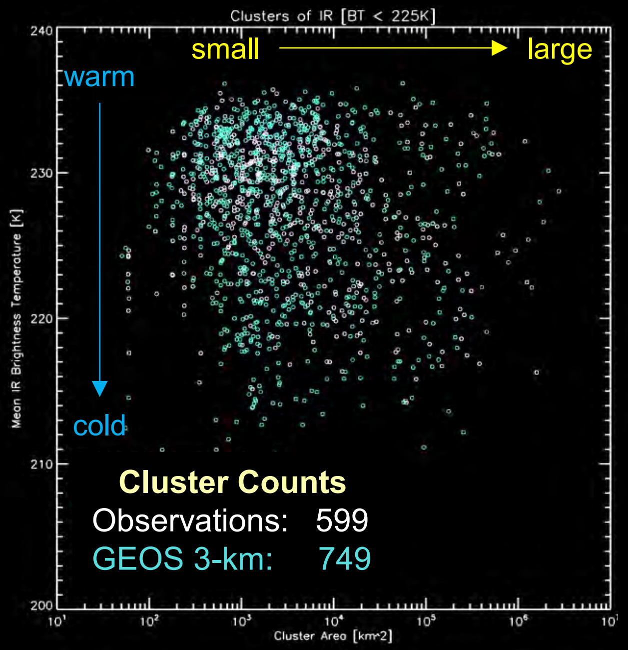


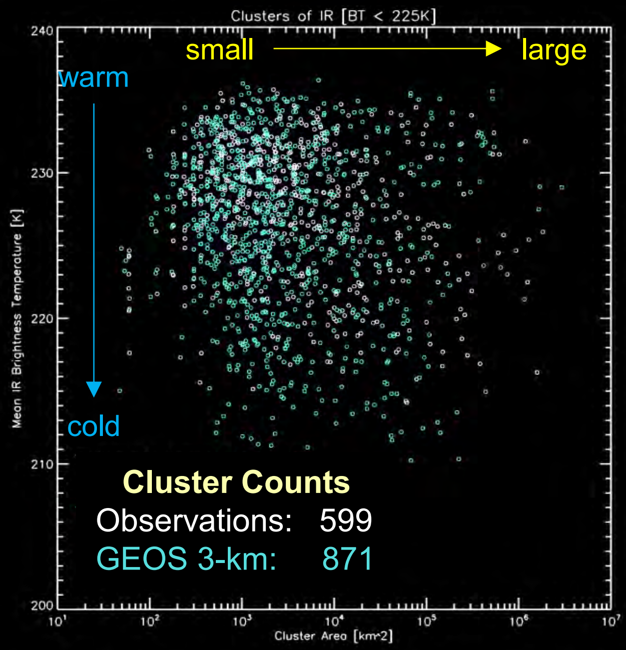
3-km GEOS (DEEP=0)

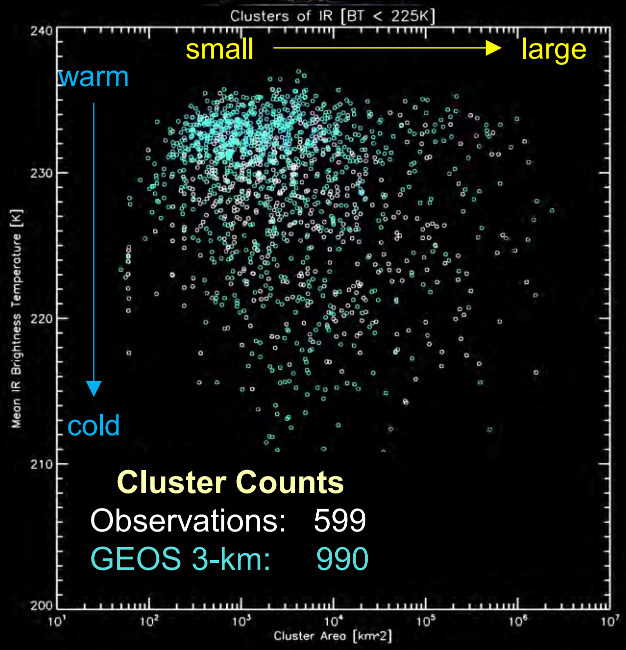


3-km GEOS (ERA5 Replay)







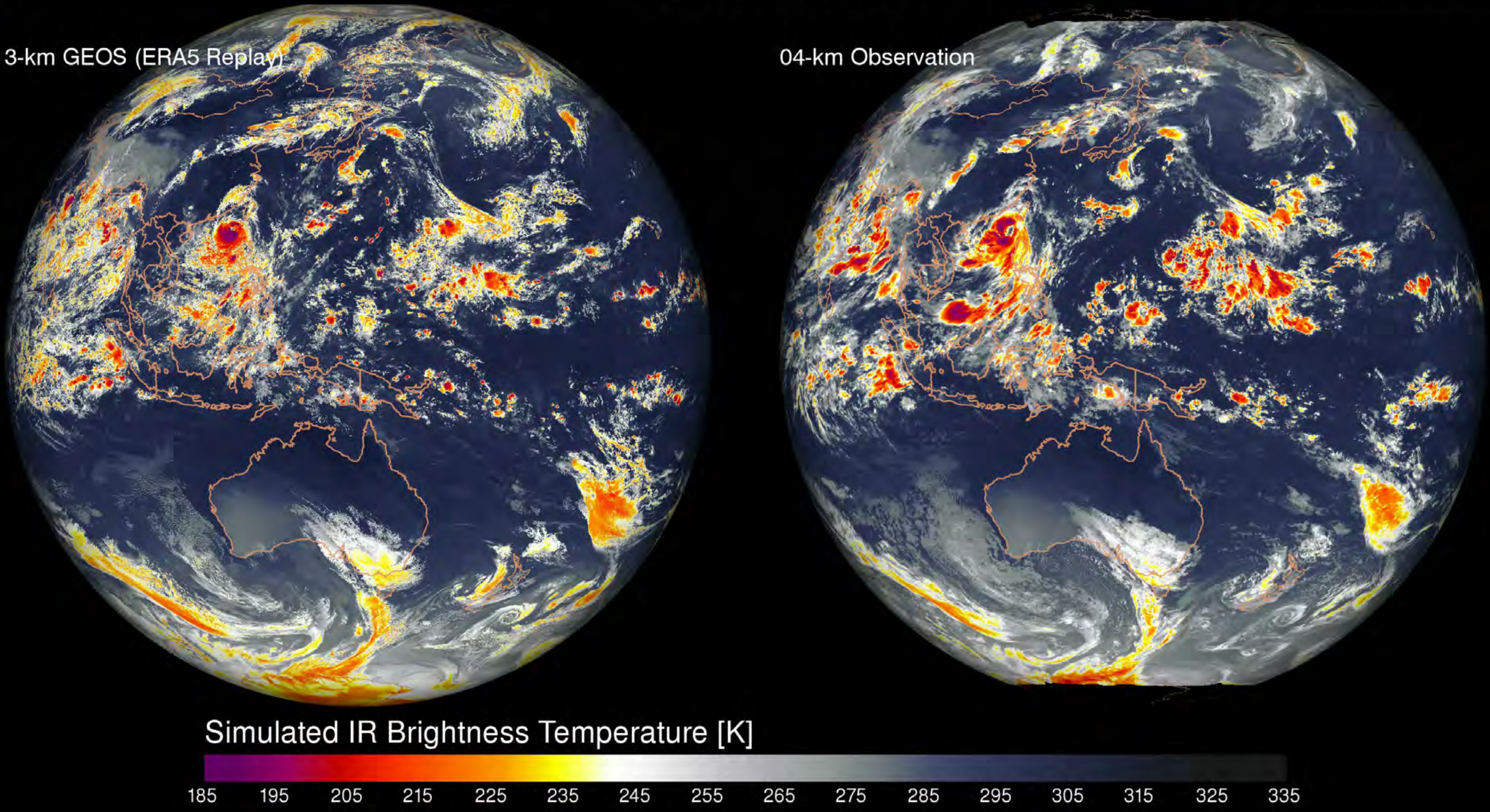


GEOS 3-km Replay to ERA5

[Increments filtered to T60]

20160801_0000

GMAO

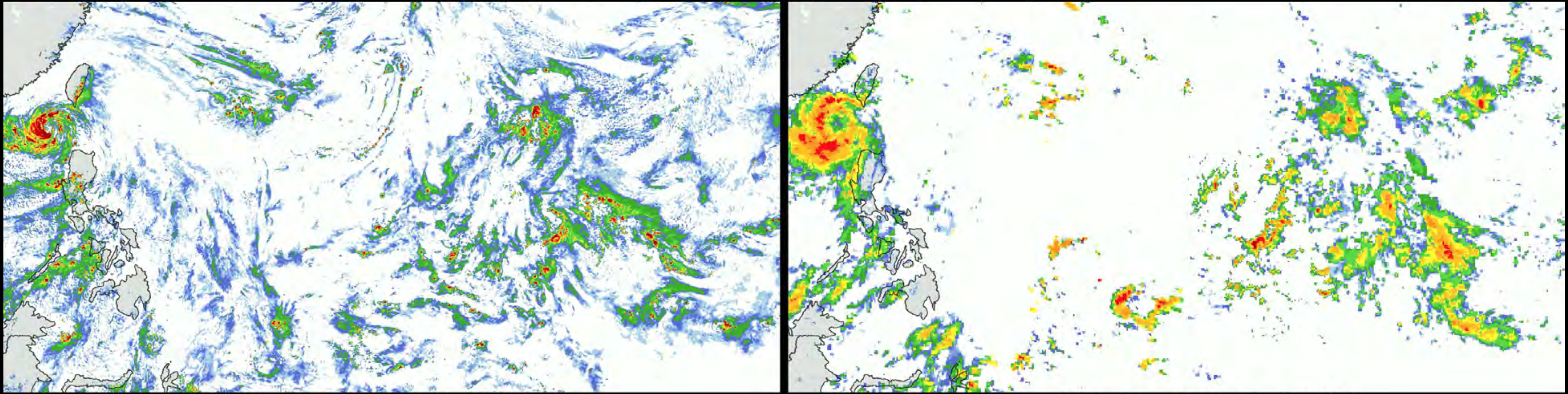


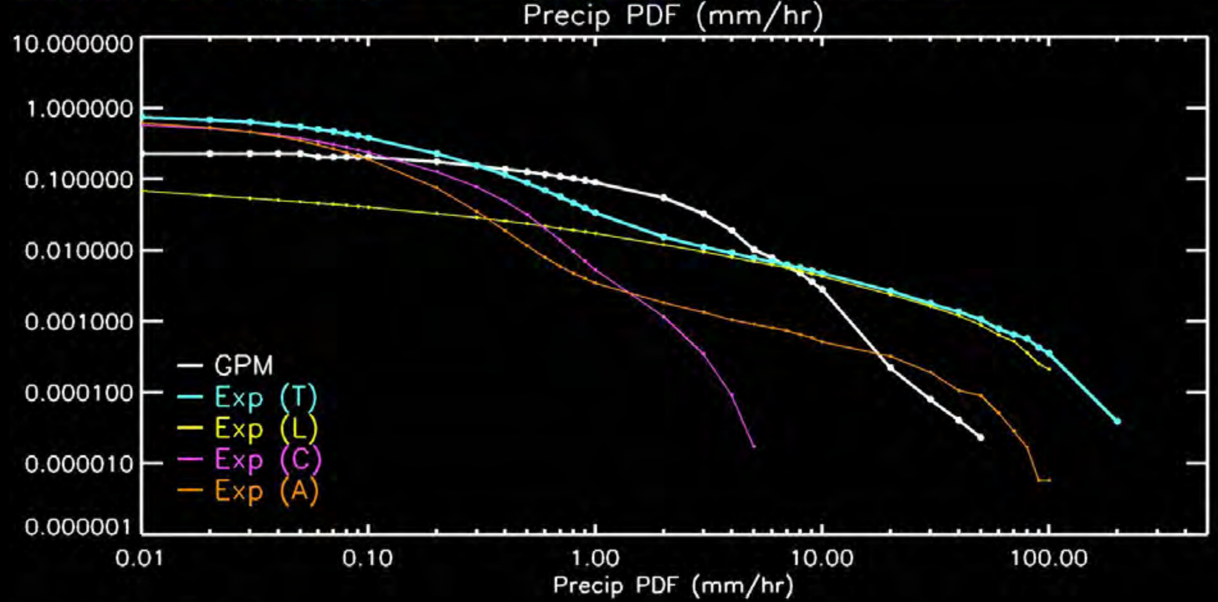
GEOS 3-km Replay to ERA5
[Increments filtered to T60]

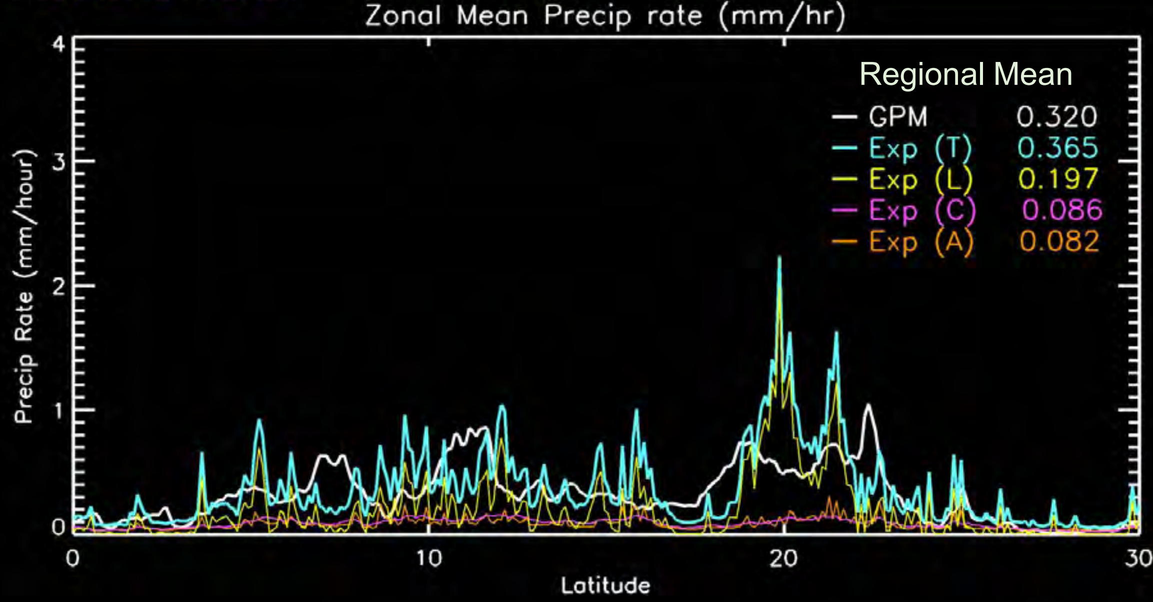
Precipitation Rate [mm/hr]
0.1 0.2 0.3 0.5 1 2 3 5 10 20 50

GPM Observations
[0.1-degree]

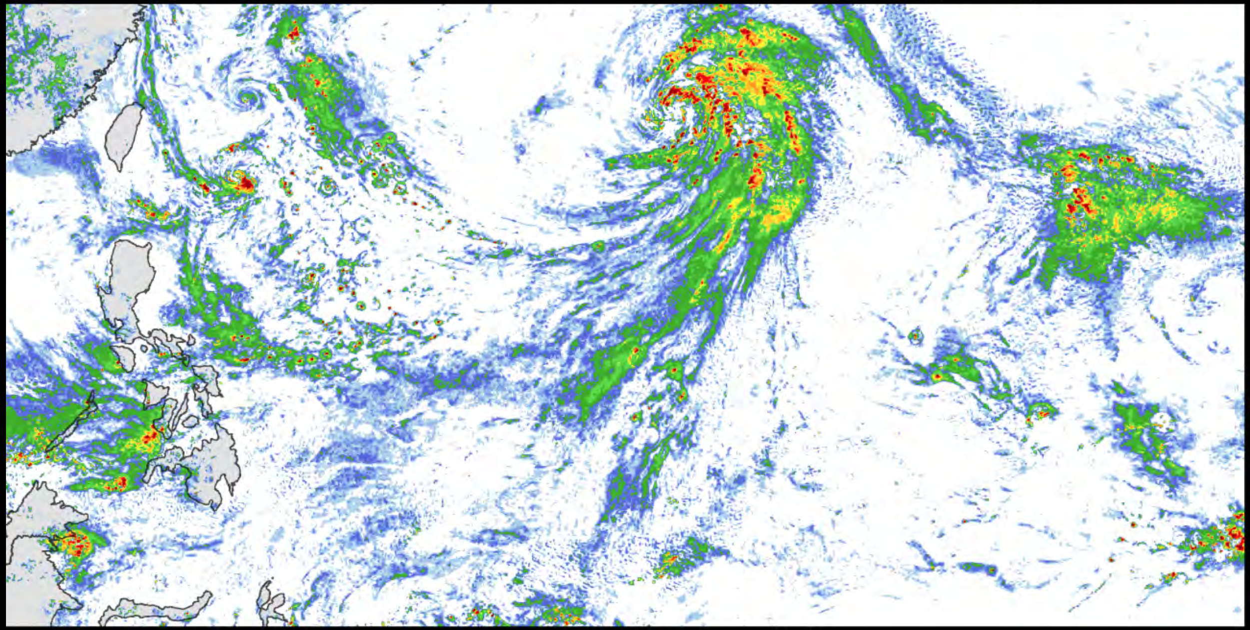
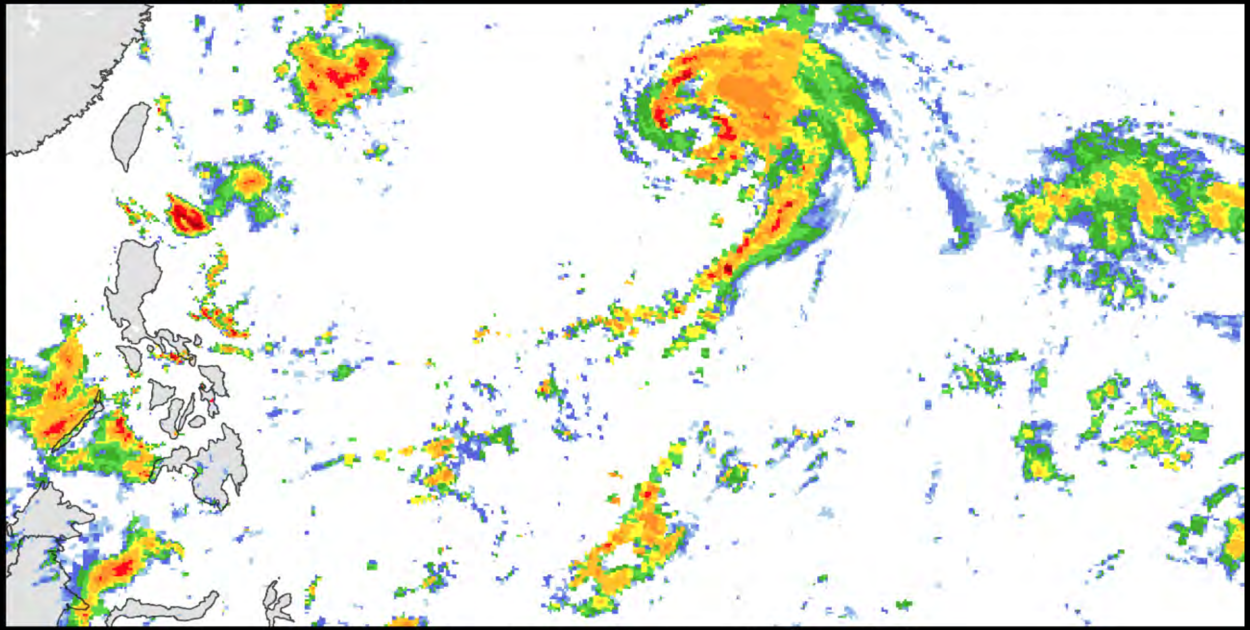
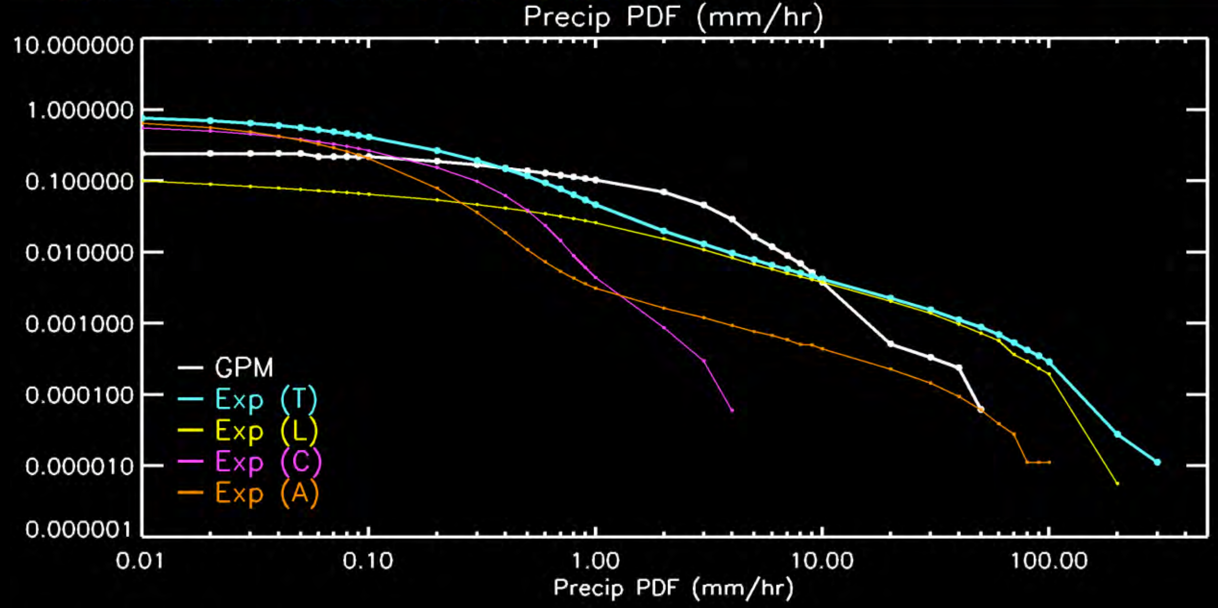
GMAO

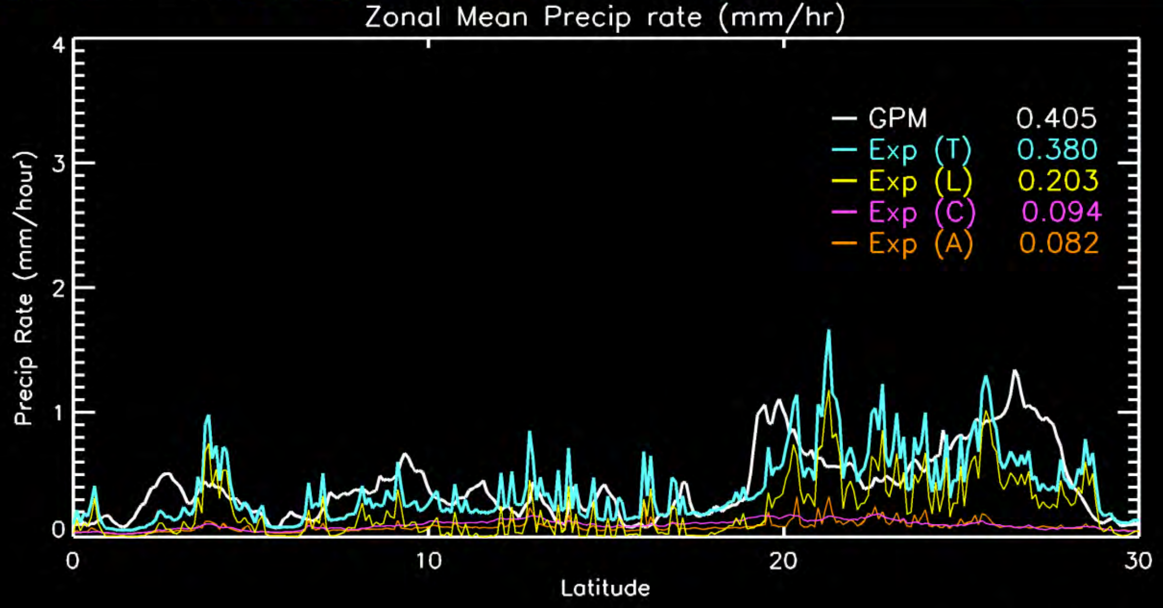




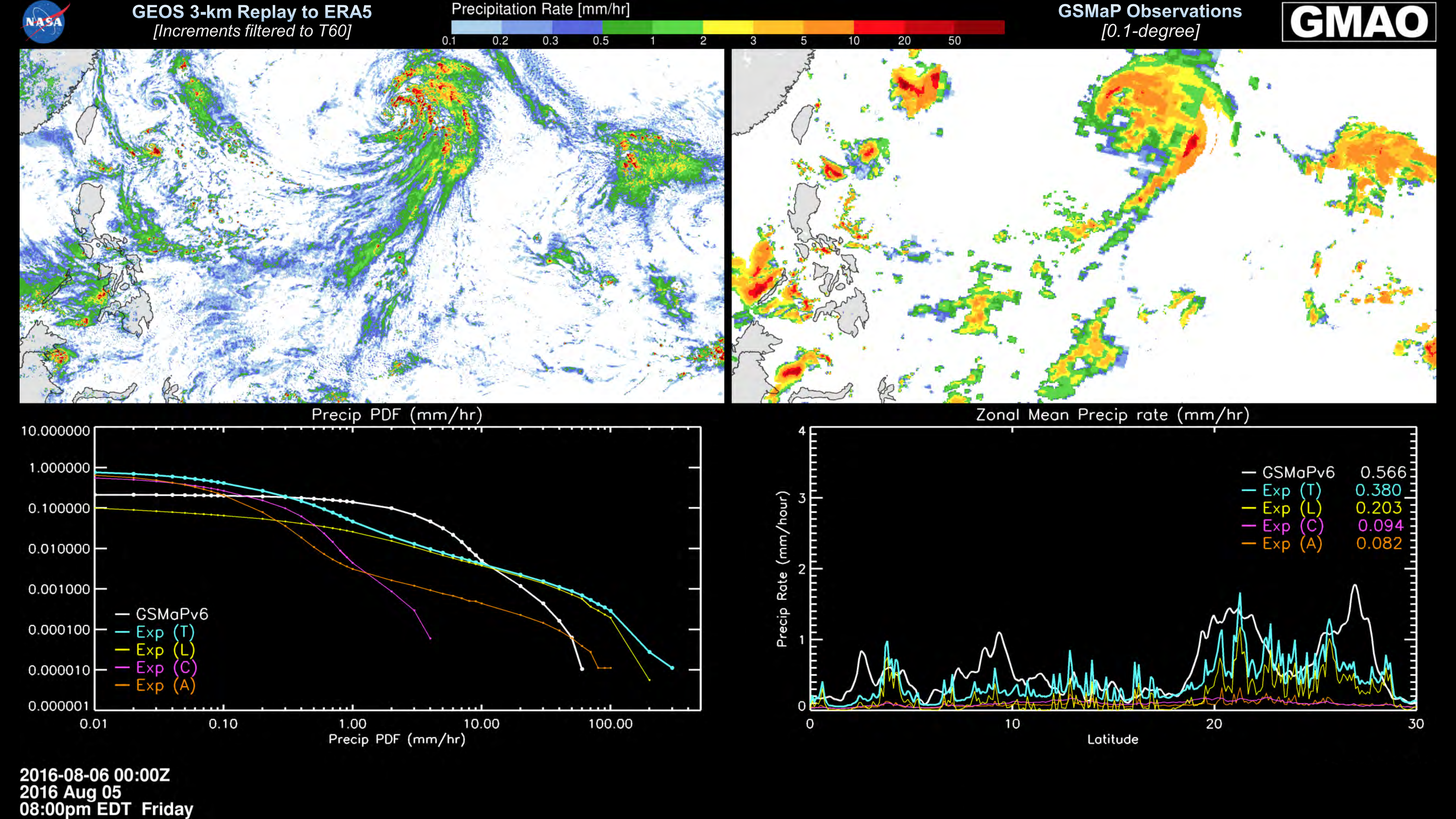


2016-08-01 00:00Z
2016 Jul 31
08:00pm EDT Sunday

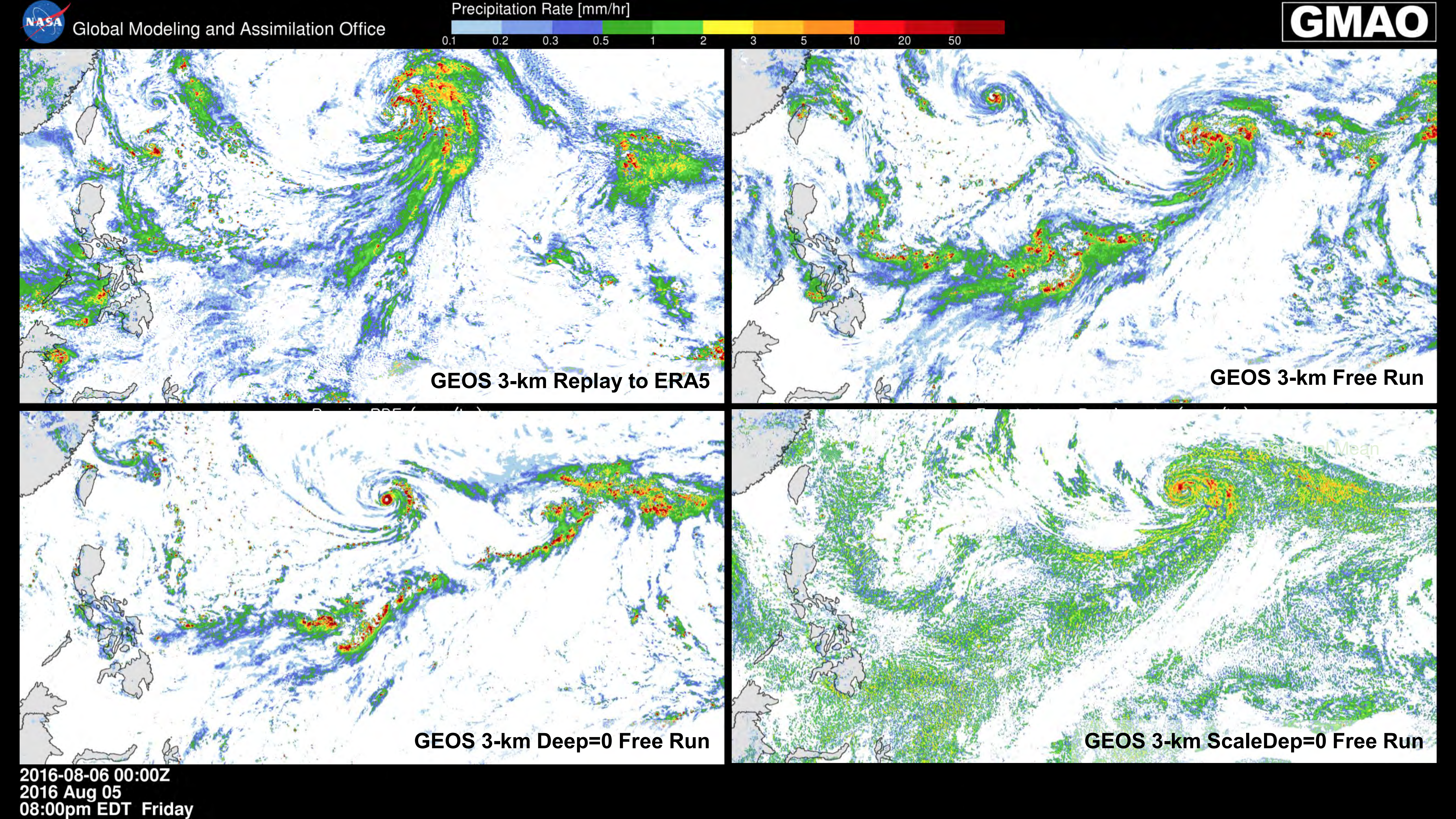






2016-08-06 00:00Z
2016 Aug 05
08:00pm EDT Friday



NASA
GEOS 3-km Replay to ERA5
[Increments filtered to T60]
Precipitation Rate [mm/hr]
0.1 0.2 0.3 0.5 1 2 3 5 10 20 50
GSMaP Observations
[0.1-degree]
GMAO
Precip PDF (mm/hr)
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.000001
0.01 0.10 1.00 10.00 100.00
Precip PDF (mm/hr)
GSMaPv6
Exp (T)
Exp (L)
Exp (C)
Exp (A)
Zonal Mean Precip rate (mm/hr)
Precip Rate (mm/hour)
4 3 2 1 0
GSMaPv6 0.566
Exp (T) 0.380
Exp (L) 0.203
Exp (C) 0.094
Exp (A) 0.082
0 10 20 30
Latitude
2016-08-06 00:00Z
2016 Aug 05
08:00pm EDT Friday

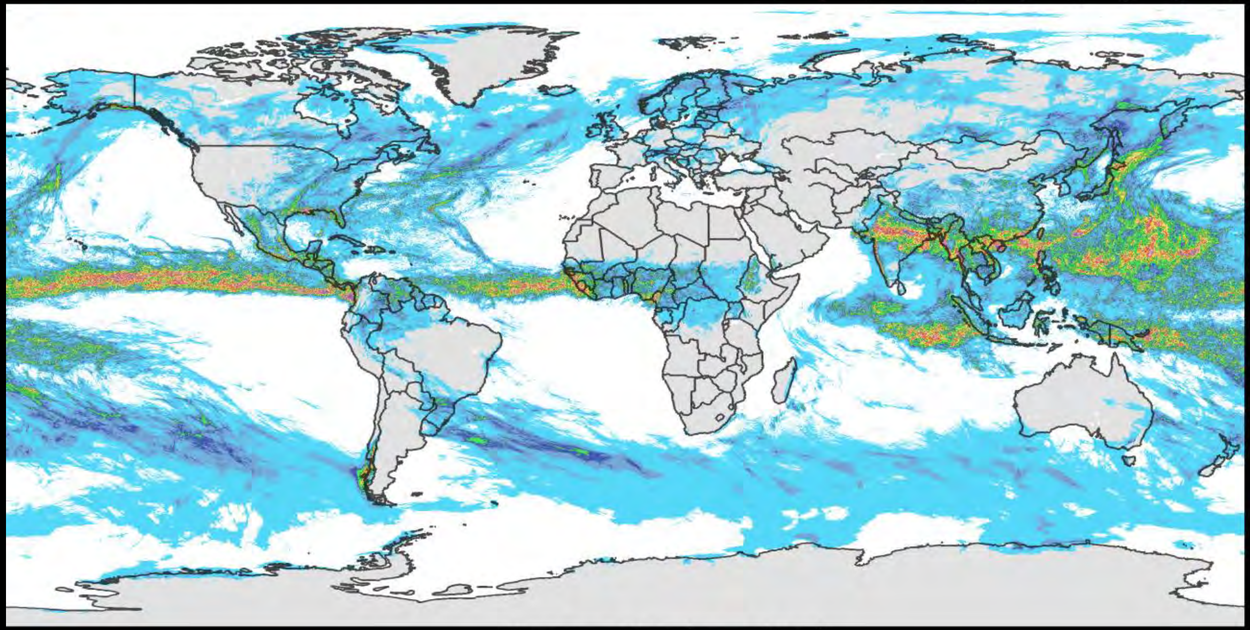

NASA
Global Modeling and Assimilation Office
Precipitation Rate [mm/hr]
0.1
0.2
0.3
0.5
1
2
3
5
10
20
50
GMAO
GEOS 3-km Replay to ERA5
GEOS 3-km Free Run
GEOS 3-km Deep=0 Free Run
GEOS 3-km ScaleDep=0 Free Run
2016-08-06 00:00Z
2016 Aug 05
08:00pm EDT Friday

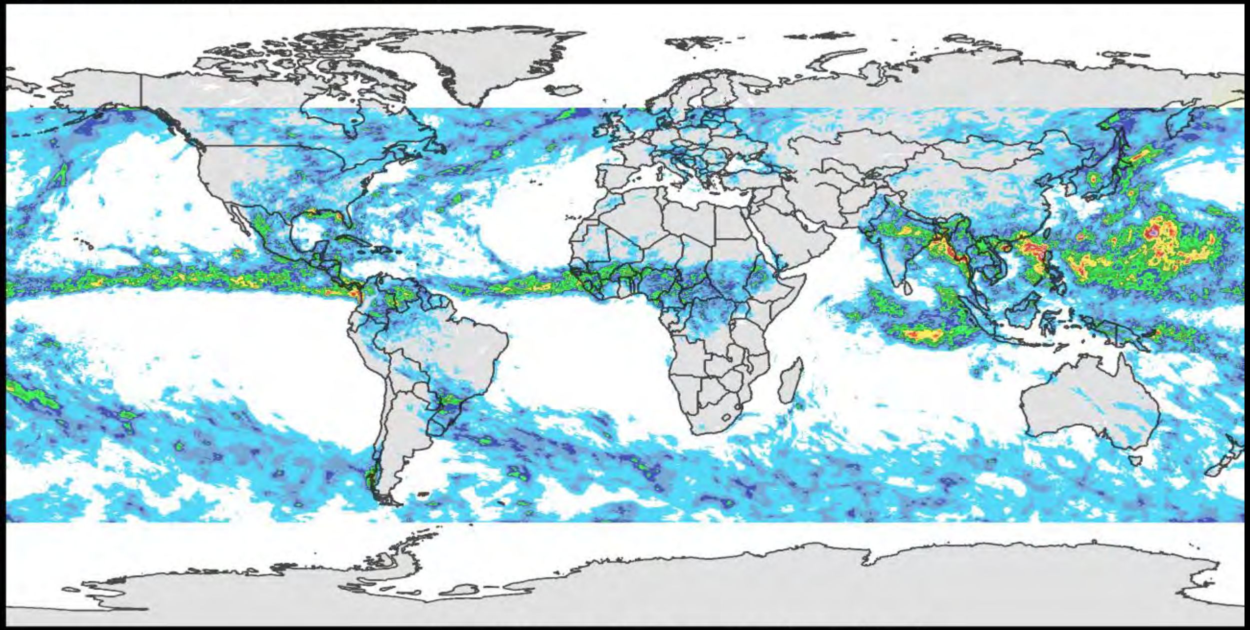
GEOS 3-km Replay to ERA5
[Increments filtered to T60]

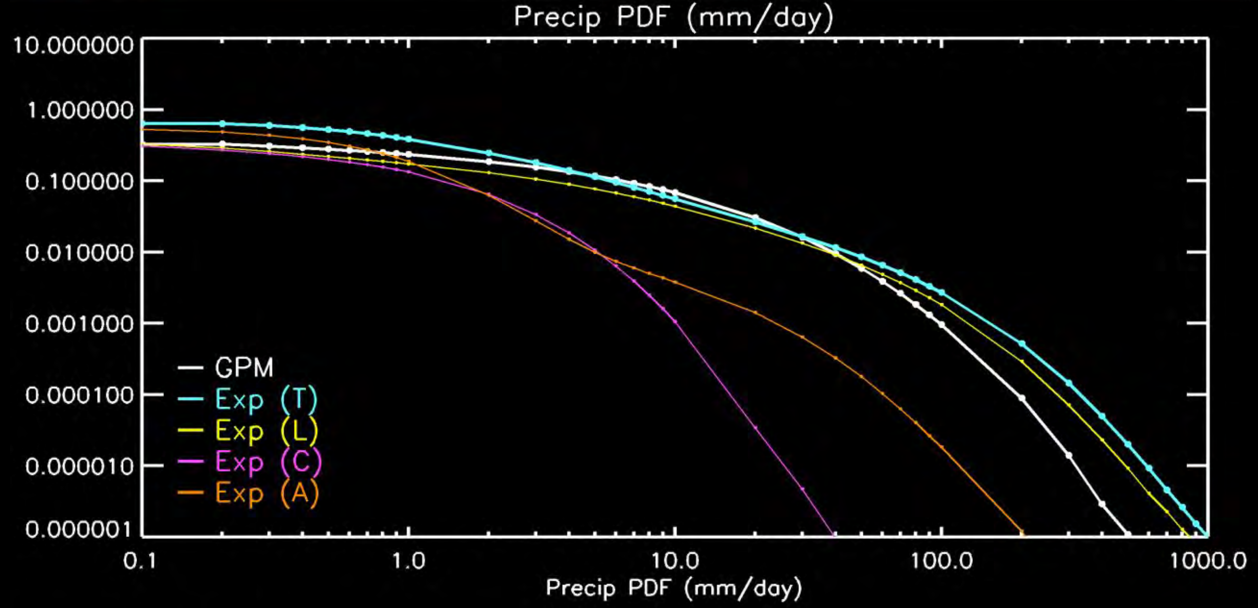
31-Day Mean Precipitation Rate [mm/day]
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

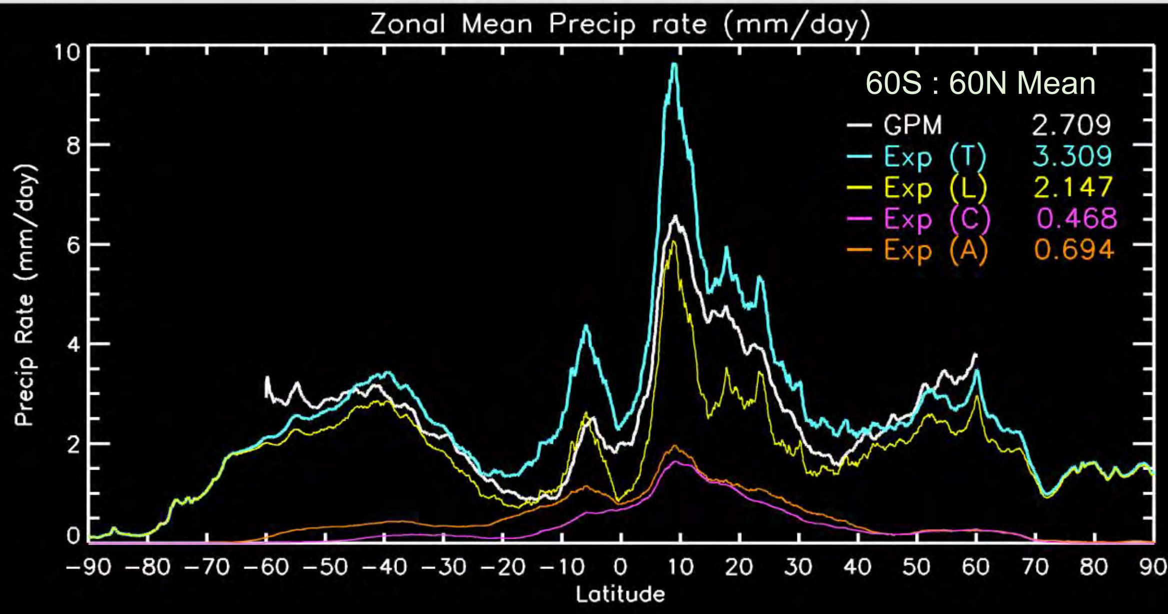
GPM Observations
[0.1-degree]

GMAO







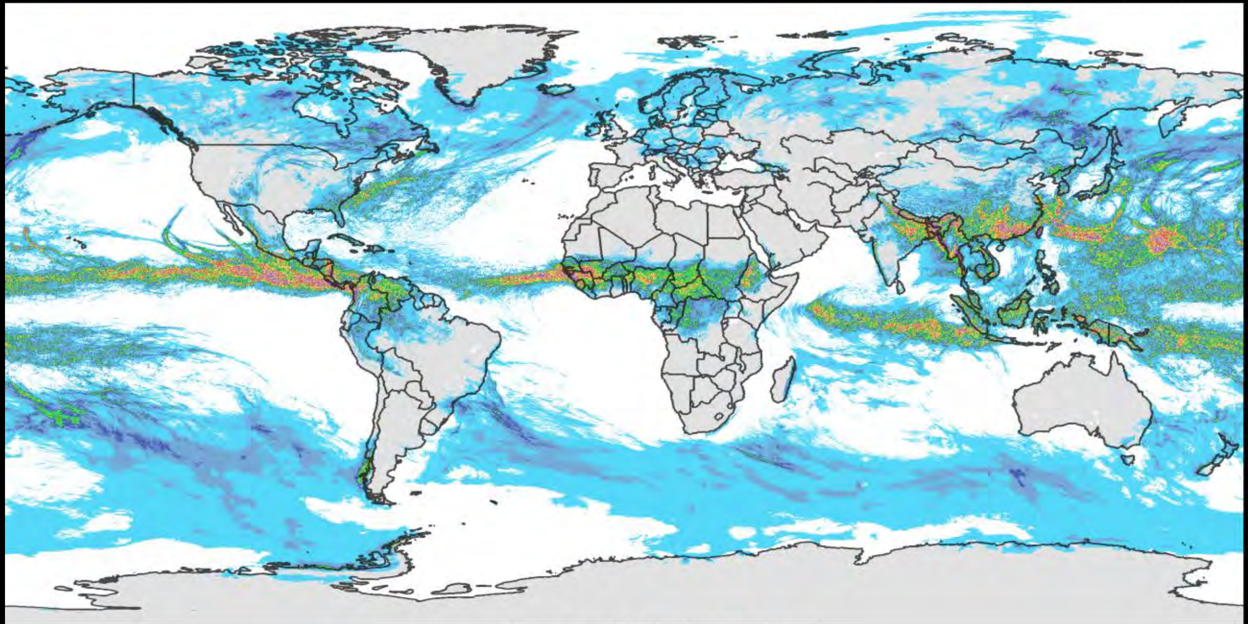


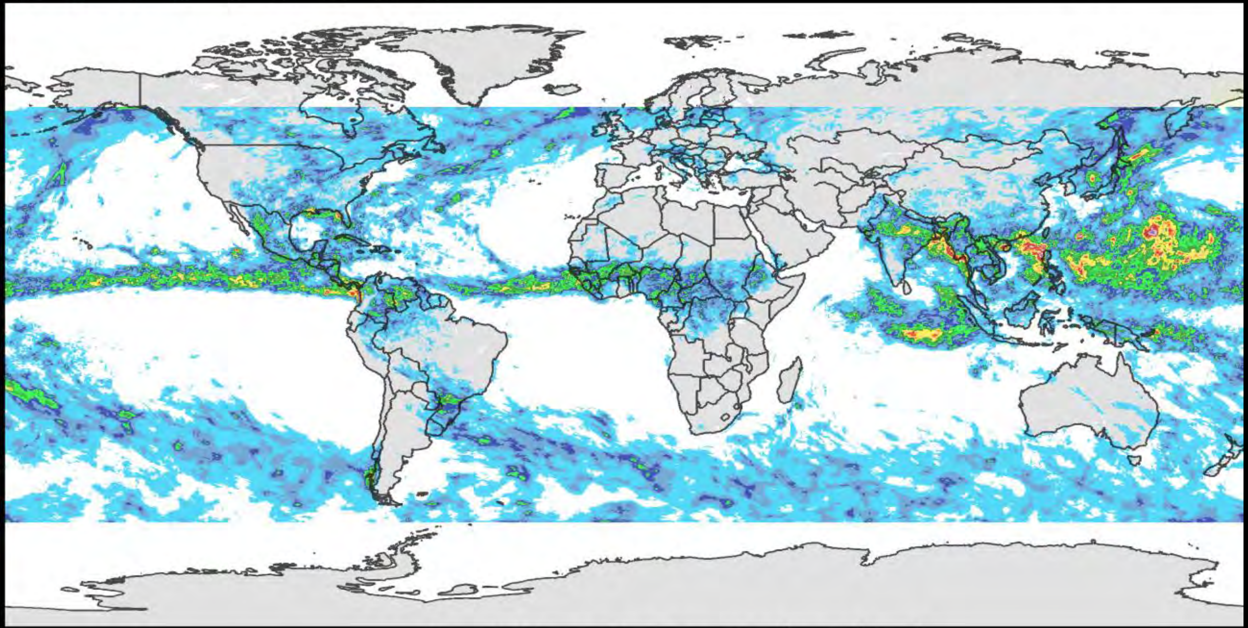
2016-09-01 00:00Z
2016 Aug 31
08:00pm EDT Wednesday

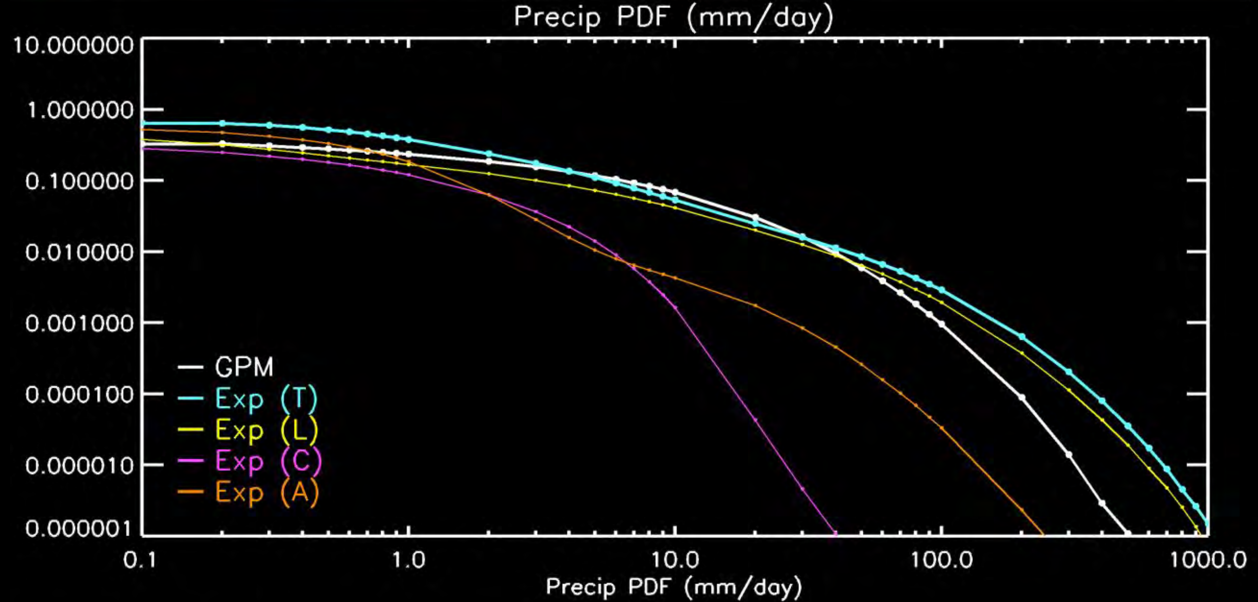
GEOS 3-km Free-Run
[Increments filtered to T60]

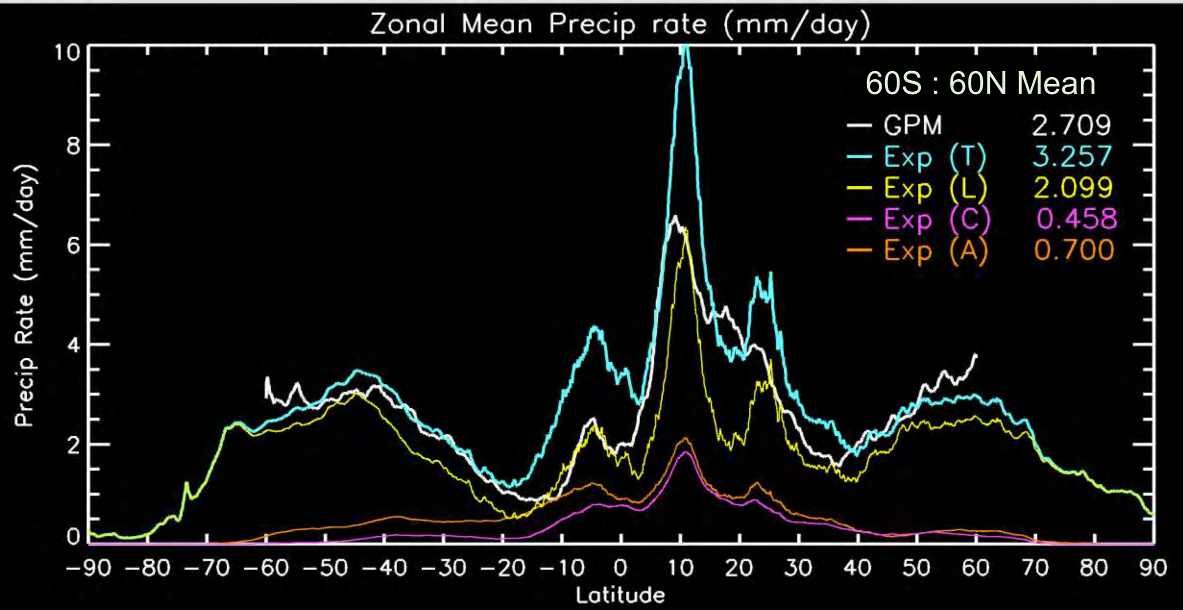
31-Day Mean Precipitation Rate [mm/day]
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

GPM Observations
[0.1-degree]









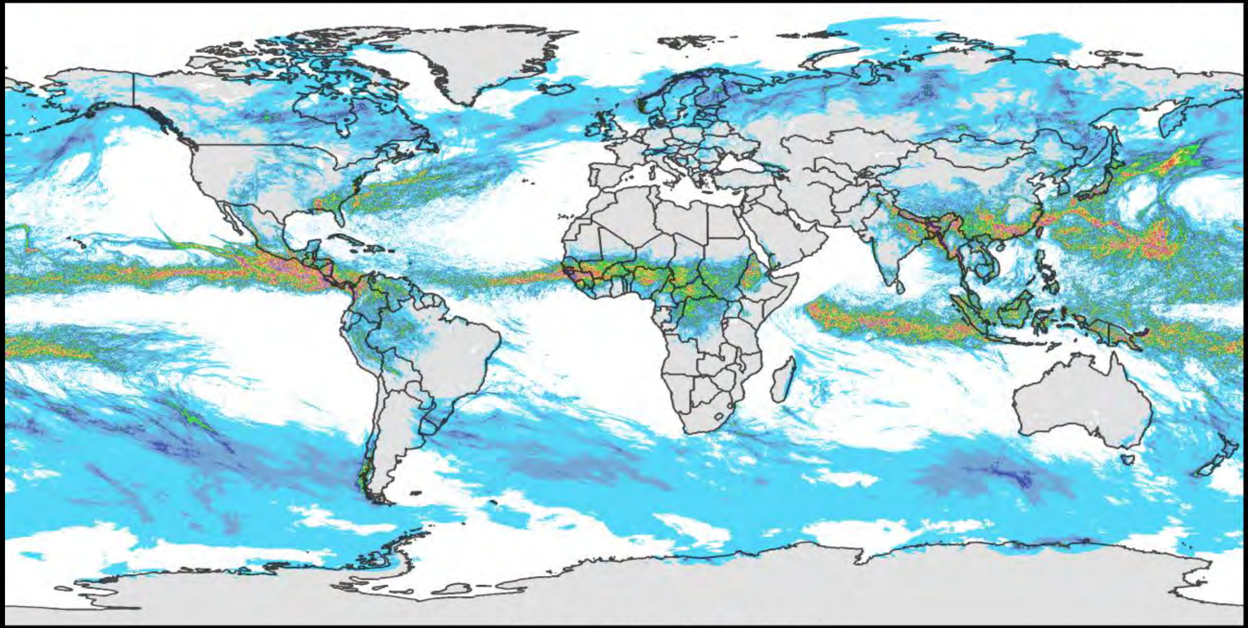
2016-09-01 00:00Z
2016 Aug 31
08:00pm EDT Wednesday

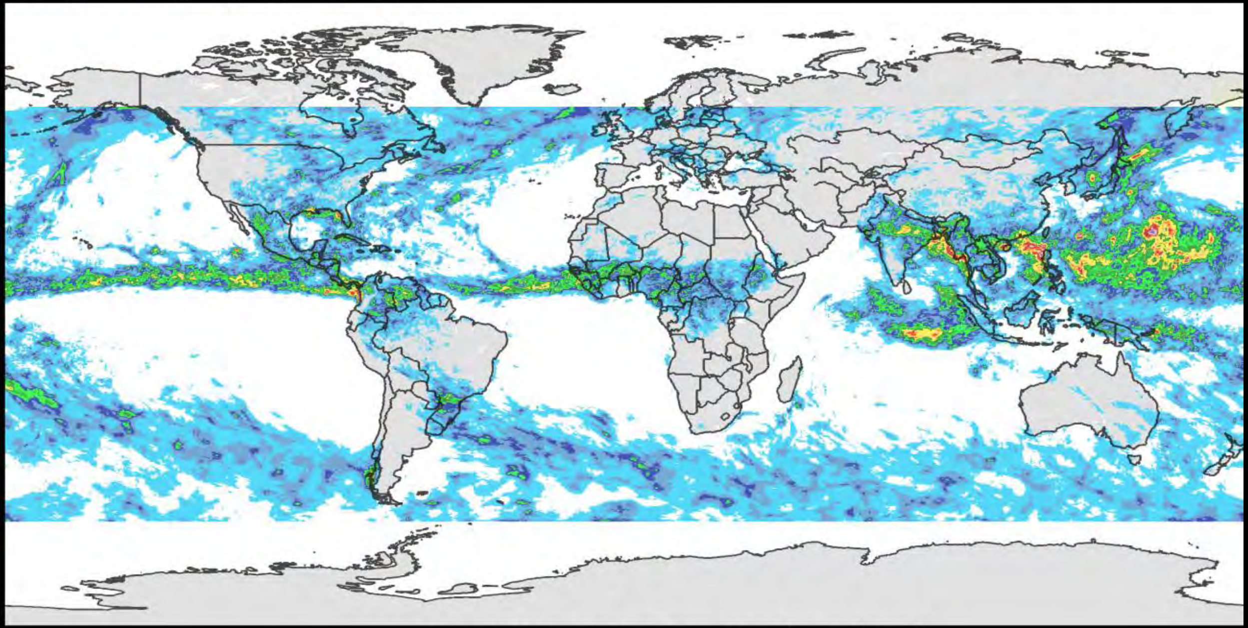
GEOS 3-km Deep=0 Free-Run
[Increments filtered to T60]

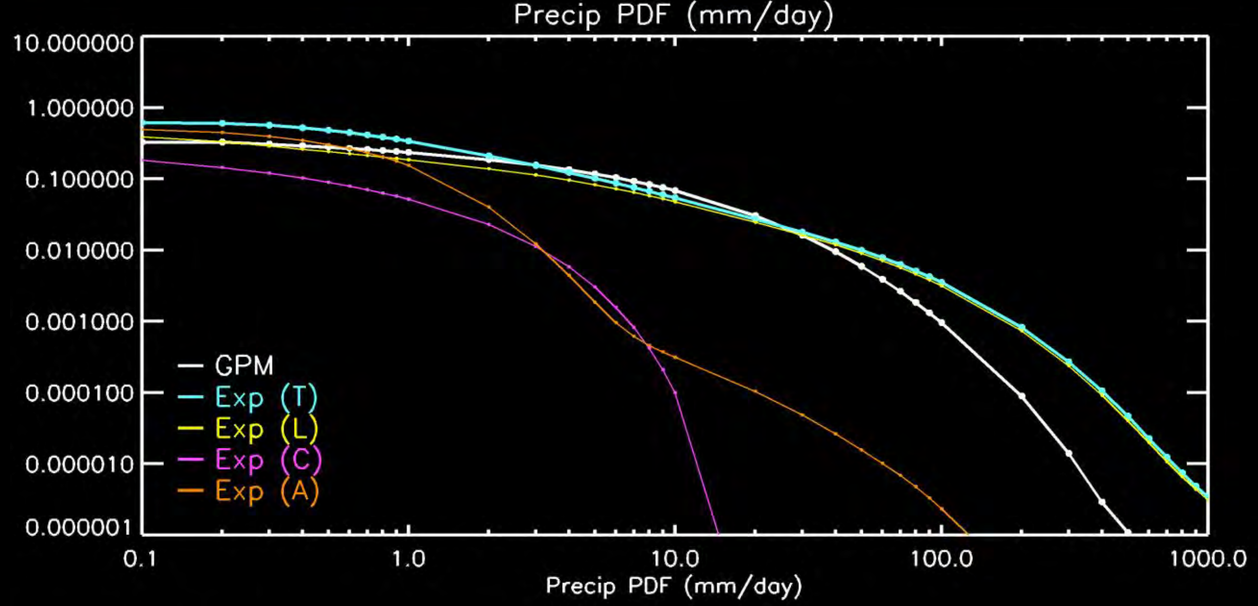
31-Day Mean Precipitation Rate [mm/day]
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

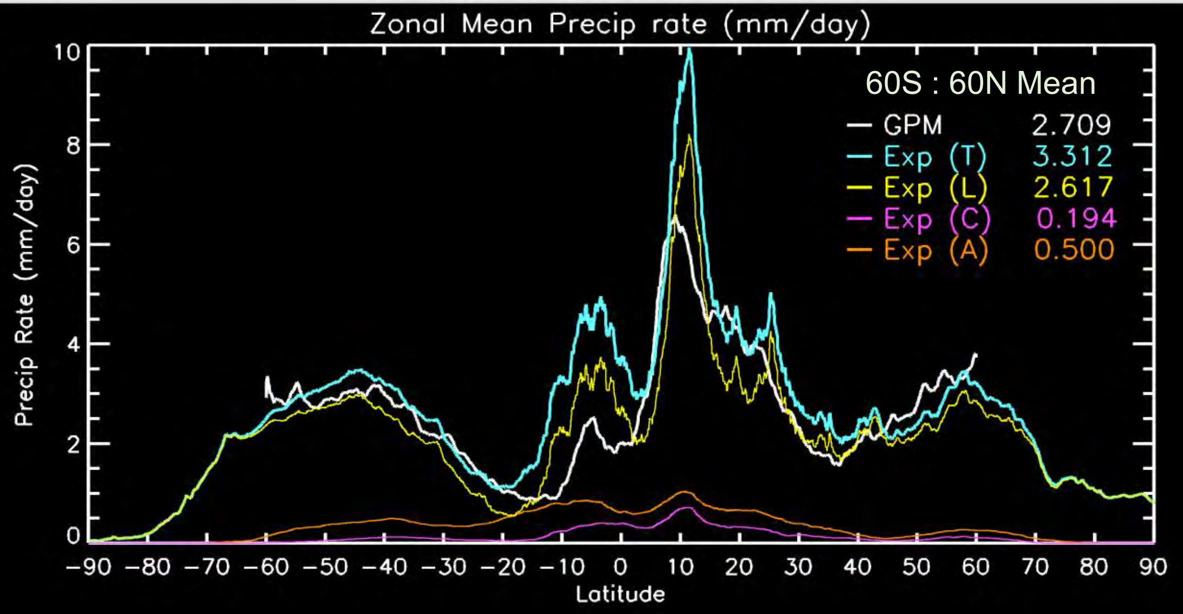
GPM Observations
[0.1-degree]

GMAO









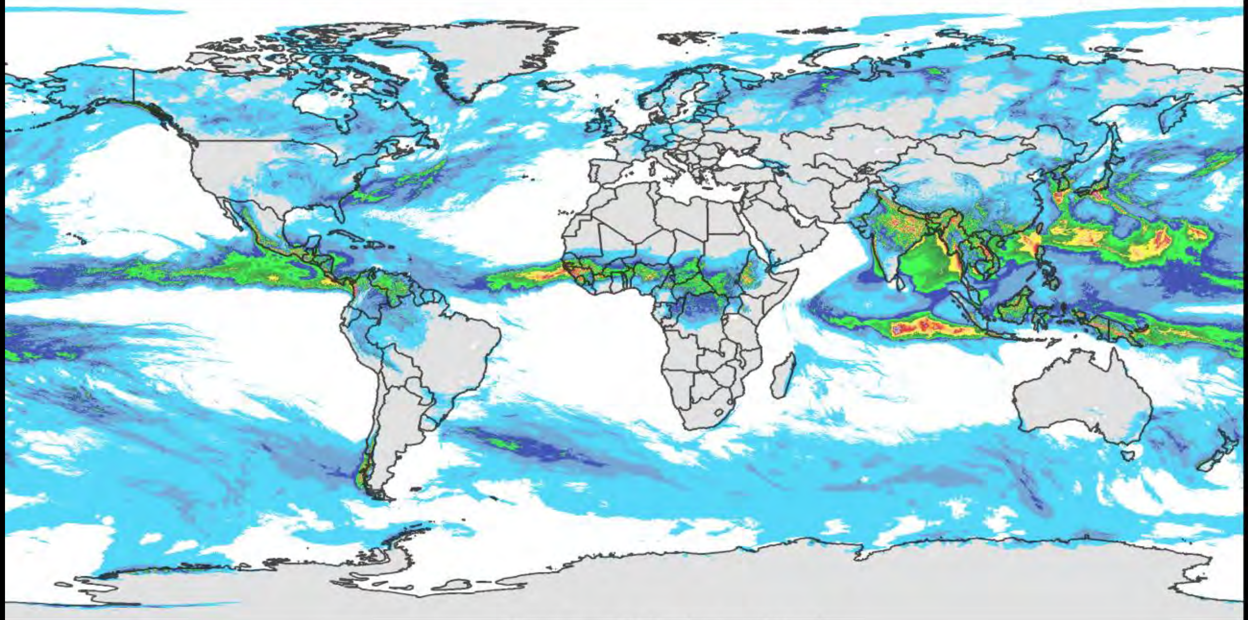
2016-09-01 00:00Z
2016 Aug 31
08:00pm EDT Wednesday

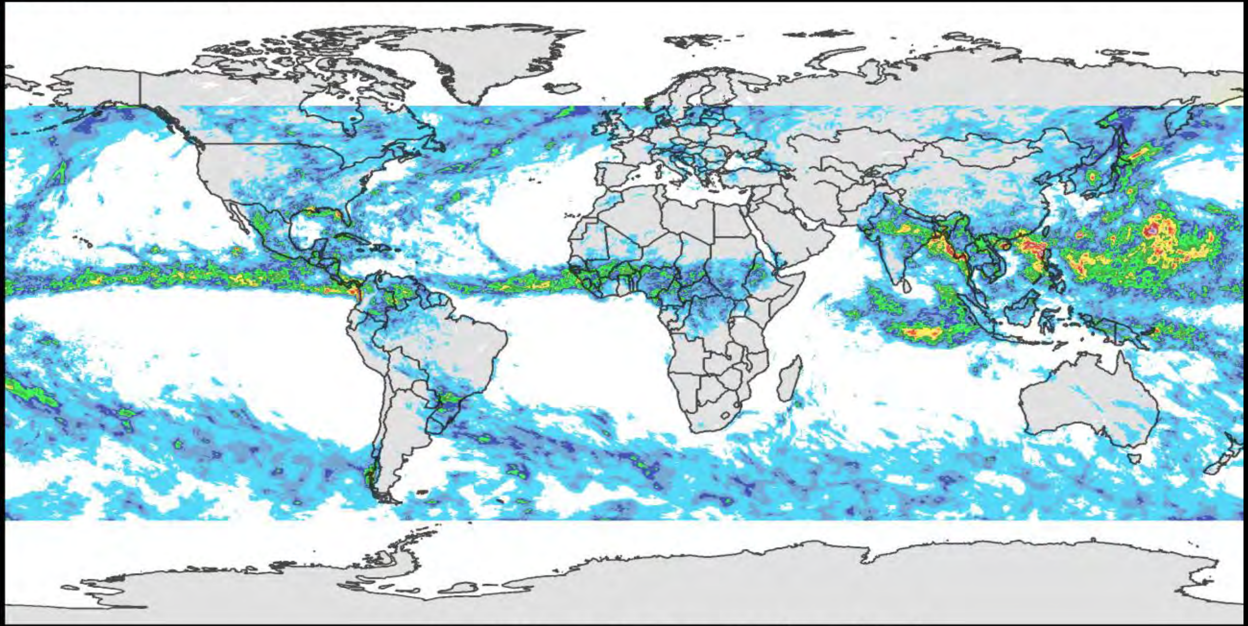
GEOS 3-km ScaleDep=0 Free-Run
[Increments filtered to T60]

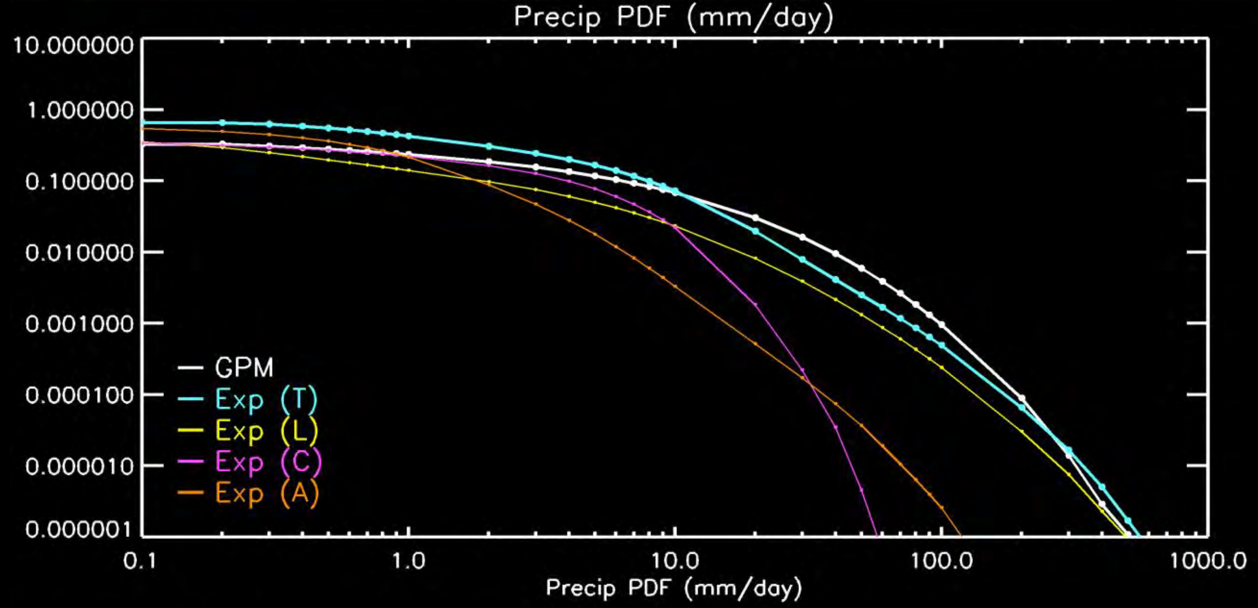
31-Day Mean Precipitation Rate [mm/day]
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

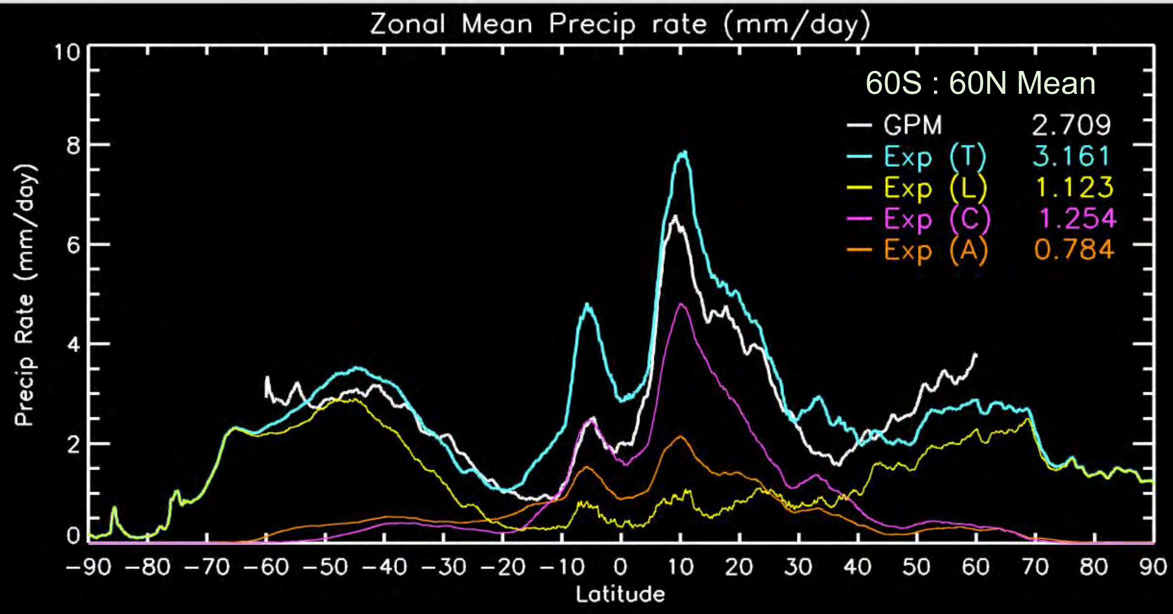
GPM Observations
[0.1-degree]

GMAO









2016-09-01 00:00Z
2016 Aug 31
08:00pm EDT Wednesday

Questions

For more information on the GEOS system and applications:

https://gmao.gsfc.nasa.gov

https://gmao.gsfc.nasa.gov/GEOS_systems/

https://geos5.org/wiki/index.php?title=GEOS-5_public_AGCM_Documentation_and_Access

https://www.nccs.nasa.gov

https://www.hec.nasa.gov