The Grell-Freitas Convective Parameterization: Recent developments and applications within the NASA GEOS Global Model

Saulo Freitas[1,2], Georg Grell[3]
[1]Universities Space Research Association, Columbia, MD, USA
[2]Global Modeling and Assimilation Office, NASA/GSFC, Greenbelt, MD, USA
[2]National Oceanic and Atmospheric Administration, Boulder, CO, USA
saulo.r.freitas@nasa.gov

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Contents

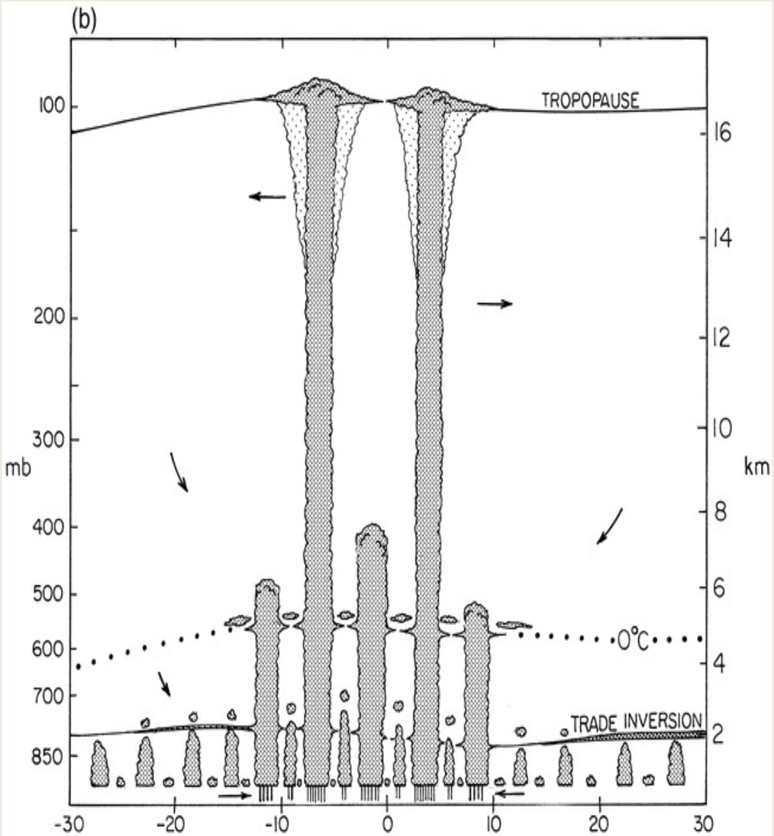
- Partial overview of the GF scheme (see Georg's talk for additional features/applications)
- Applications on regional scale with BRAMS model
- Applications on global scale with NASA GEOS model
- Discussion and planned developments/evaluation

Main characteristics of GF scheme

- Stochastic approach adapted from the Grell-Devenyi (2002) scheme
  - Originally many parameters could be perturbed
  - In 2014 version only 2 were kept (closures and capping inversion thresholds)
- Deep, 'congestus' and shallow (non-precipitating) plumes with an ensemble of closures.
- Scale awareness through Arakawa's 2011 approach or lateral spreading of subsidence.
- Aerosol dependence (experimental)
- Transport of momentum, tracers, water and moist static energy,
- Scavenging for aerosols and trace gases (Henry's law for gases)
- Mass conservative on machine precision, including water and tracers
- New closure from Peter Bechtold et al (2014) => improved the diurnal cycle
- Beta PDFs to emulate the vertical mass flux profiles

Grell and Freitas, ACP 2014, Freitas and Grell, in prep.

A *trimodal* cumulus scheme



Johnson et al (1999):
Trimodal Characteristics of Tropical Convection

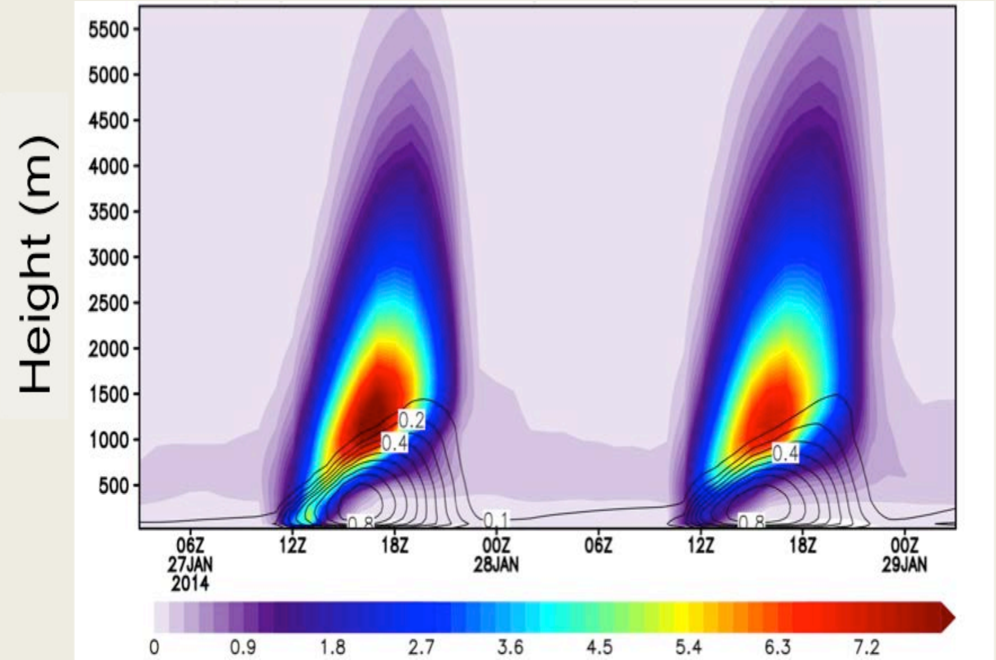
The three predominant convective modes:

- shallow limited by the trade inversion
- congestus by the zero degree inversion layer
- deep with cloud tops well above

1-D simulations using GATE Soundings

Shallow Convection Plume

- Non-precipitating
- entrainment rate constant or with 1/height functional relationship
- Mass flux profile given by a Beta PDF
- Three closures – BLQE (Raymond, 1995), W^*(Grant, 2001) and, convection as natural heat engine (Rennó and Ingersoll, 1996)
- Option for cloud top constrained at 1st inversion layer above PBL height



Diurnal cycle of the PBL and of shallow convective plume. The PBL is shown by the turbulent kinetic energy (m^2 s^{-2}, black contours), while the convective plume with saturated air is represented by the mass flux (10 kg m^{-2} s^{-2}, shaded colors).

’Congestus ’ Convection Plume

- Warm-rain microphysics only.
- entrainment rate constant or with 1/height functional relationship
- Mass flux profile given by a Beta PDF
- Cloud top below at the inversion layer closest to ~ 500 hPa
- Allows convective scale saturated downdrafts
- BLQE (Raymond, 1995), W^*(Grant, 2001) and, like Kain-Fritsh.
- Adapted the diurnal cycle closure (Bechtold et al. 2014) to properly place the cumulus *congestus* occurrence in the diurnal cycle.

Deep Convection Plume

- entrainment rate constant or with 1/height functional relationship
- Mass flux profile given by a Beta PDF
- No limit for cloud top
- Allows convective scale saturated downdrafts
- 4 closures: Grell 1993, Low Level Omega (JBrown_), Moist Convergence (KK), like Kain-Fritsch
- Option for the diurnal cycle closure (Bechtold et al. 2014)

A scale aware convective parameterization

Arakawa et al (2011) propose the following equation for the vertical eddy transport that includes the scale dependence trough σ parameter:

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

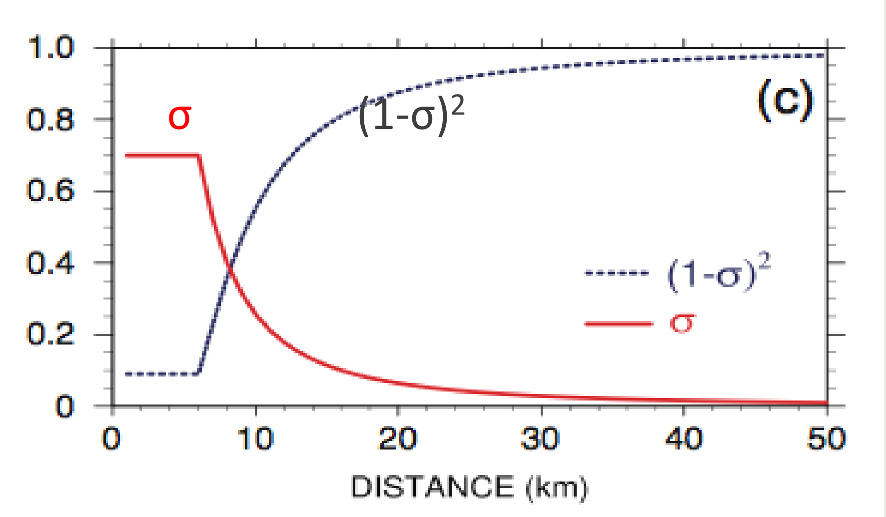
Vertical Eddy transport

Fractional area covered by active cloud drafts.

Eddy transport given by a conventional CP for a full adjustment to a quasi-equilibrium state.

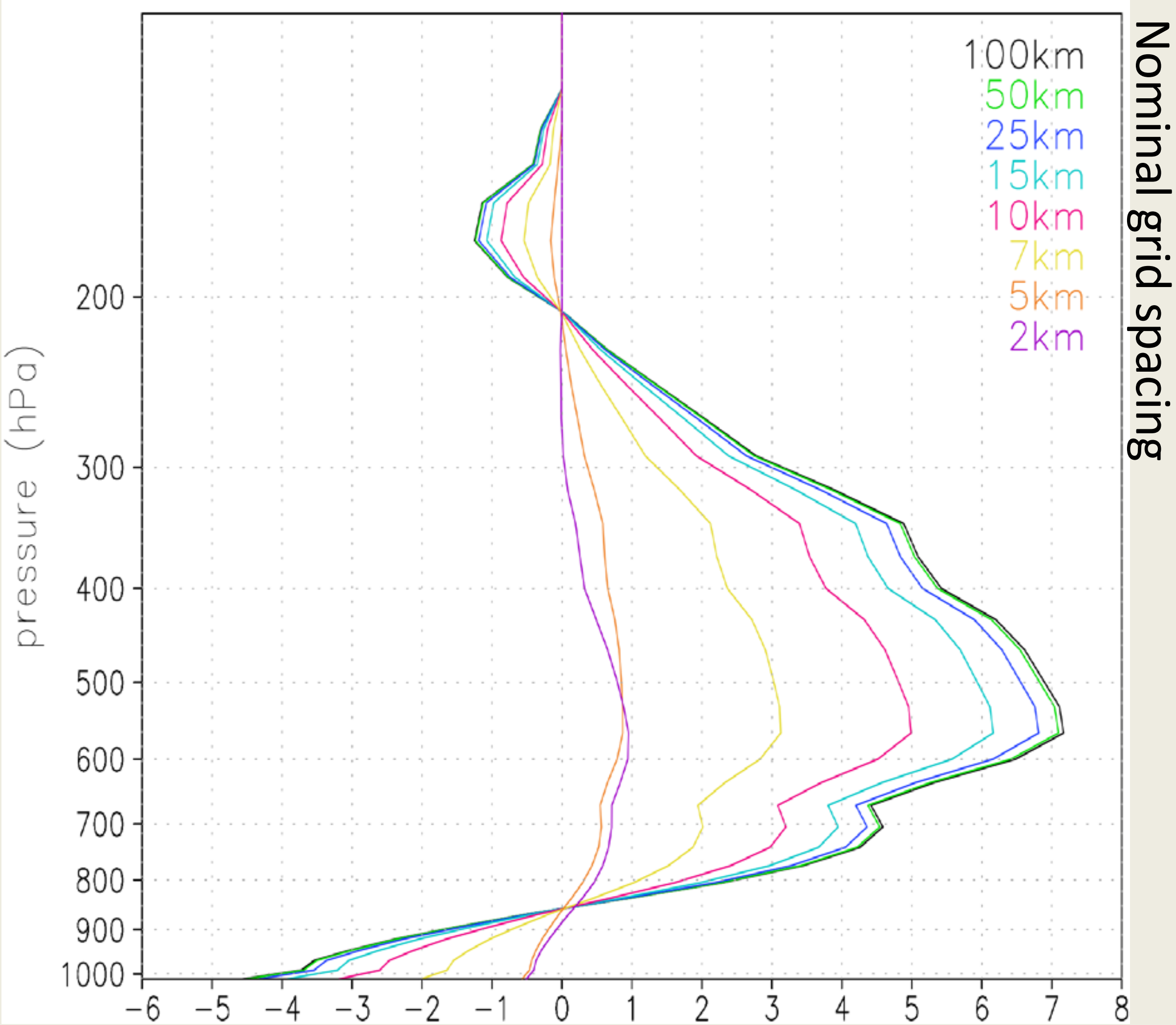
In GF 2014, σ parameter is initially calculated by the entrainment rate (ε) and the local grid area ($\Delta x \Delta y$) by $\varepsilon = 0.2\, R^{-1}$, where R is the effective radius of the updraft. The general formulation for σ is

$$\therefore \sigma = \begin{cases} \dfrac{\pi R^2}{\Delta x \Delta y}, \text{ if } < 0.7 \\ 0.7 \text{ and } \begin{cases} R = \sqrt{0.7 \Delta x \Delta y / \pi} \\ \varepsilon = \dfrac{b}{R} \end{cases} \end{cases}$$



GF scale dependence with GATE soundings

A single column example



Convective heating tendency (K/day)

Average over 160 soundings

GF scale dependence on fully 3-D applications
BRAMS limited area atmospheric model

BRAMS is a Brazilian version of the RAMS model (originally developed at CSU/USA) with a set of improvements, such as

- Besides RAMS's own parameterizations, an updated physics suit: RRTM radiation, GF convection, GT microphysics, NN and based on Taylor theory turbulence, and JULES surface scheme, including carbon cycle and urban surface tiles.
- Walcek's monotonic advection scheme for scalars
- Gas and aqueous phase chemistry with a pre-processor for chemical mechanisms.
- MATRIX aerosol model
- PREP-CHEM-SRC tool for gases/aerosol emission fields.
- Currently, RK-3 time integration scheme and high-order advection operators based on Wicker and Skamarock developments are being implemented.
- Computational scalability up 10,000 cores
- Community model distributed under GNU/GPGPL public license
- See Freitas et al (2017, GMD/EGU) for the latest model description paper.

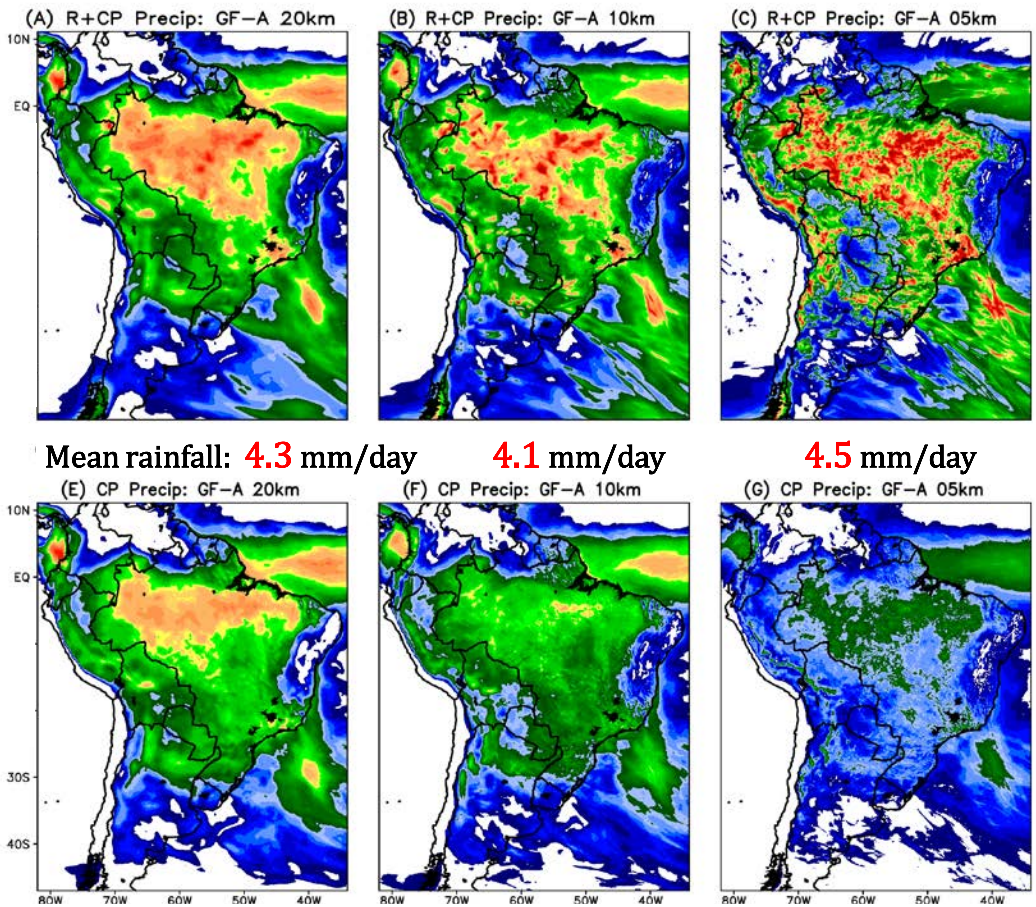
BRAMS has been applied in the Brazilian weather forecast center (CPTEC/INPE) for operational air quality (20km) and weather (5km) forecasts over S. America:
Weather: http://previsaonumerica.cptec.inpe.br/BRAMS5km
Air quality: http://meioambiente.cptec.inpe.br/CCATT-BRAMS20km
BRAMS webpage: http://brams.cptec.inpe.br

Results with BRAMS regional model

Jan 2013 – 15 days w/ 36hr FCT

Total 24h rainfall: resolved + from the parameterization

24 h Rainfall: only from the parameterization



Mean rainfall: 4.3 mm/day 4.1 mm/day 4.5 mm/day

Mean rainfall: 3.5 mm/day 2.5 mm/day 1.0 mm/day

20km **10km** **05km**

with scale dependence

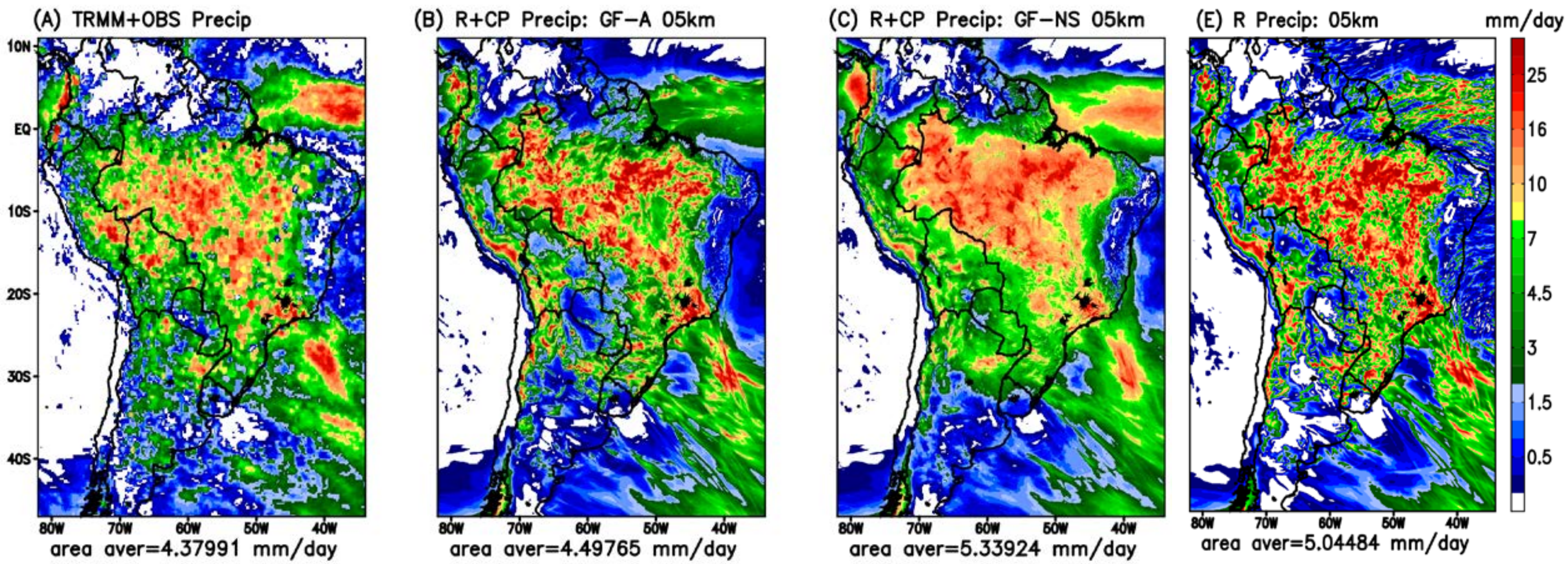
Simulations on 20, 10 and 5 km grid spacing

Grell and Freitas, ACP 2014

BRAMS 5km

January 2013 - monthly mean precipitation (mm/day)

TRMM + OBS	**R+CP: with scale dependence**	**R+CP: without scale dependence**	**Only R**



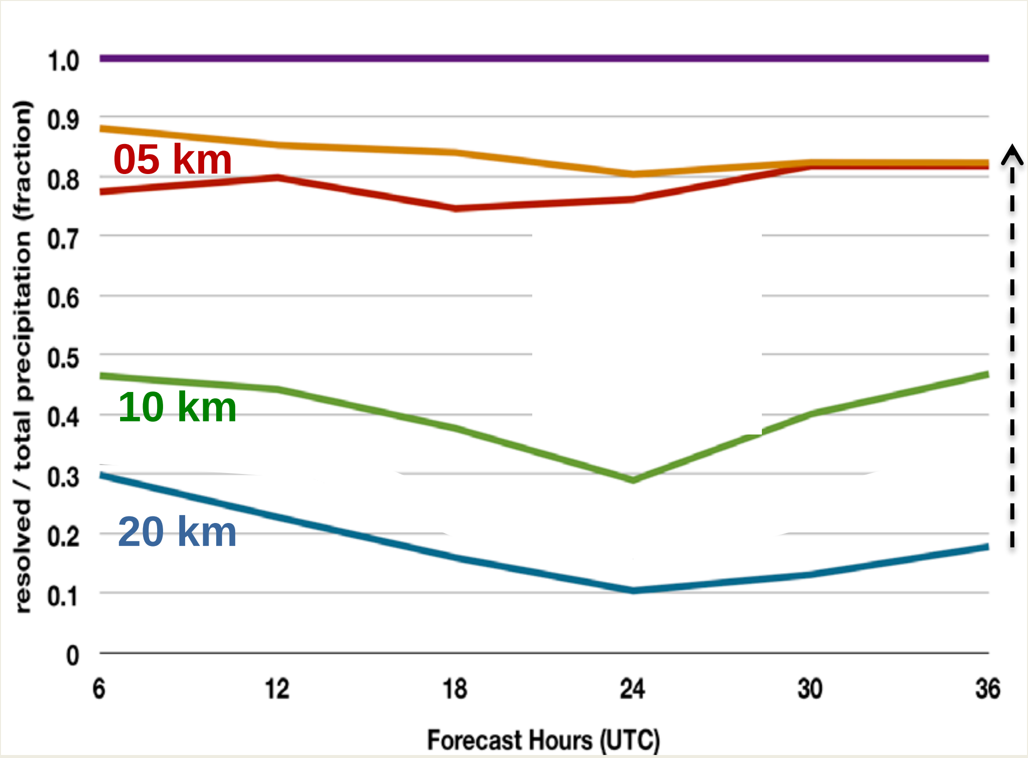
4.38 mm/day	**4.50** mm/day	**5.34** mm/day	**5.04** mm/day

R : resolved precipitation
CP : parameterized precipitation

Grell and Freitas, ACP 2014

Transition from parameterized to resolved precipitation

$$\text{Fraction} = \frac{R}{R + CP}$$



Consistent transition of GF from parameterized to resolved (20 to 5km)

But not for 05km GF-NS, which has similar fraction as the 20km run.

R = resolved precipitation
CP= precip from cumulus parameterization

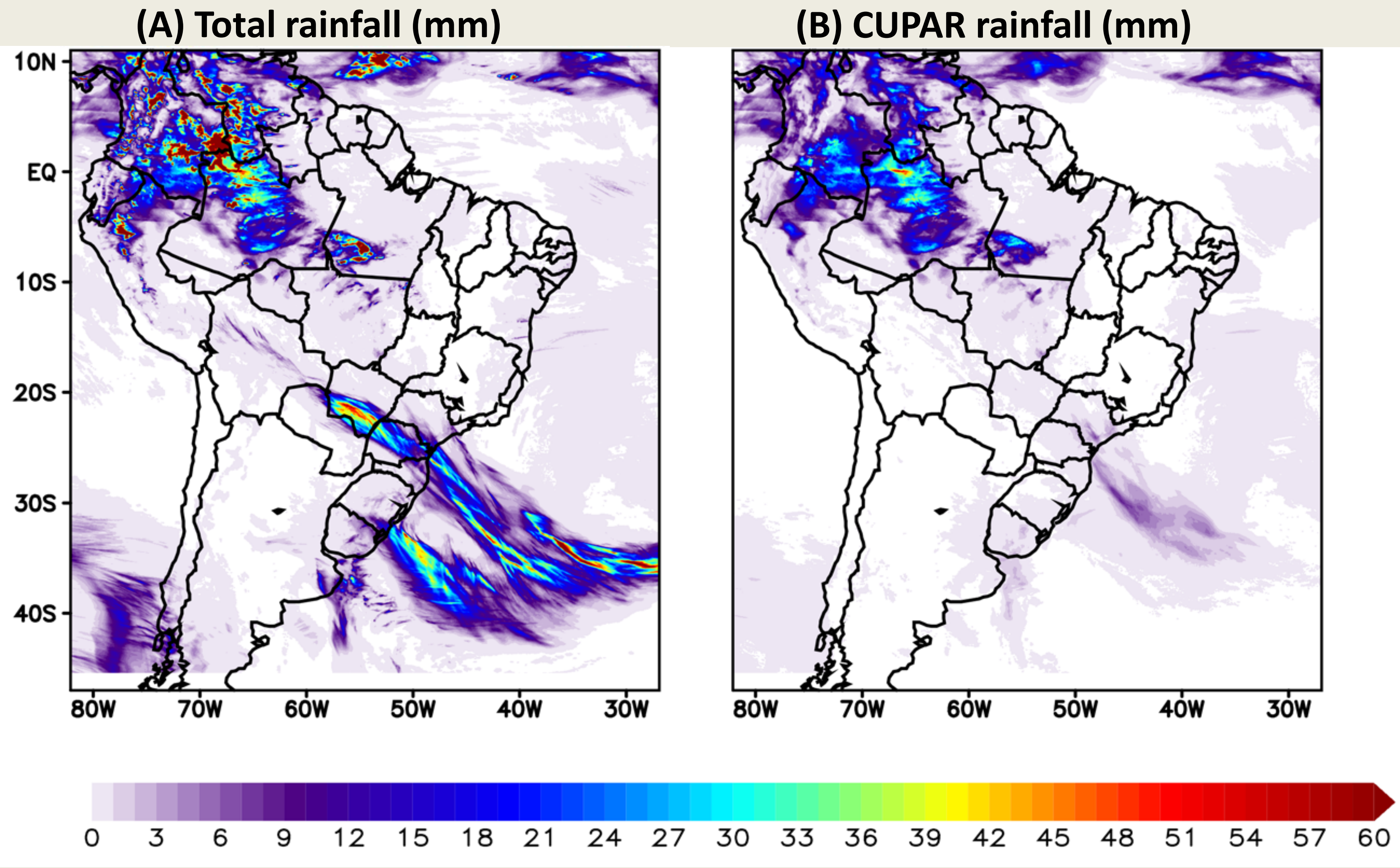
Average over January 2013
36-hour forecast over S. America

20 km – with scale dependence
10 km – with scale dependence
05 km – with scale dependence
05 km – lateral spreading of the subsidence
05 km – no cumulus parameterization
05 km – no scale dependence

Grell and Freitas, ACP 2014

An example of real-time performance of BRAMS

5 km grid spacing operational forecast at CPTEC/INPE – Brazil
24-hour accumulated rainfall for 12 October 2015



Freitas et al. (2017, GMD)

Results with the NASA GEOS Global Model

Exploring the scale-dependence approach applying GF on a cascade of global scale simulations with uniform resolution varying from 50 km to 6 km.

- Apr 15-17 2000
- FV3 with single-moment microphysics, Lock scheme, Chou-Suarez radiation
- Initial condition from MERRA-2 reanalysis
- 3 days run on c180, c360, c720, c1000 and c1440 resolutions
- ~ 50 25 12.5 9 6.25 km

The NASA GEOS Atmospheric Model with FV3

Finite Volume Cubed-Sphere *(FV3 in collaboration with NOAA GFDL)*
- Hydrostatic and Non-Hydrostatic

Cloud microphysics options:
- *Single-Moment*
- *Two-Moment* (Morrison-Gettelman-Barahona)

Convection schemes:
- Relaxed Arakawa-Schubert (with *stochastic Tokioka entrainment limiter*
- Grell-Freitas *trimodal* convection scheme
- UW shallow convection

Turbulence:
- 1st order scheme of Louis (stable PBLs)
- Non-local K-scheme of Lock (cloud topped BLs)

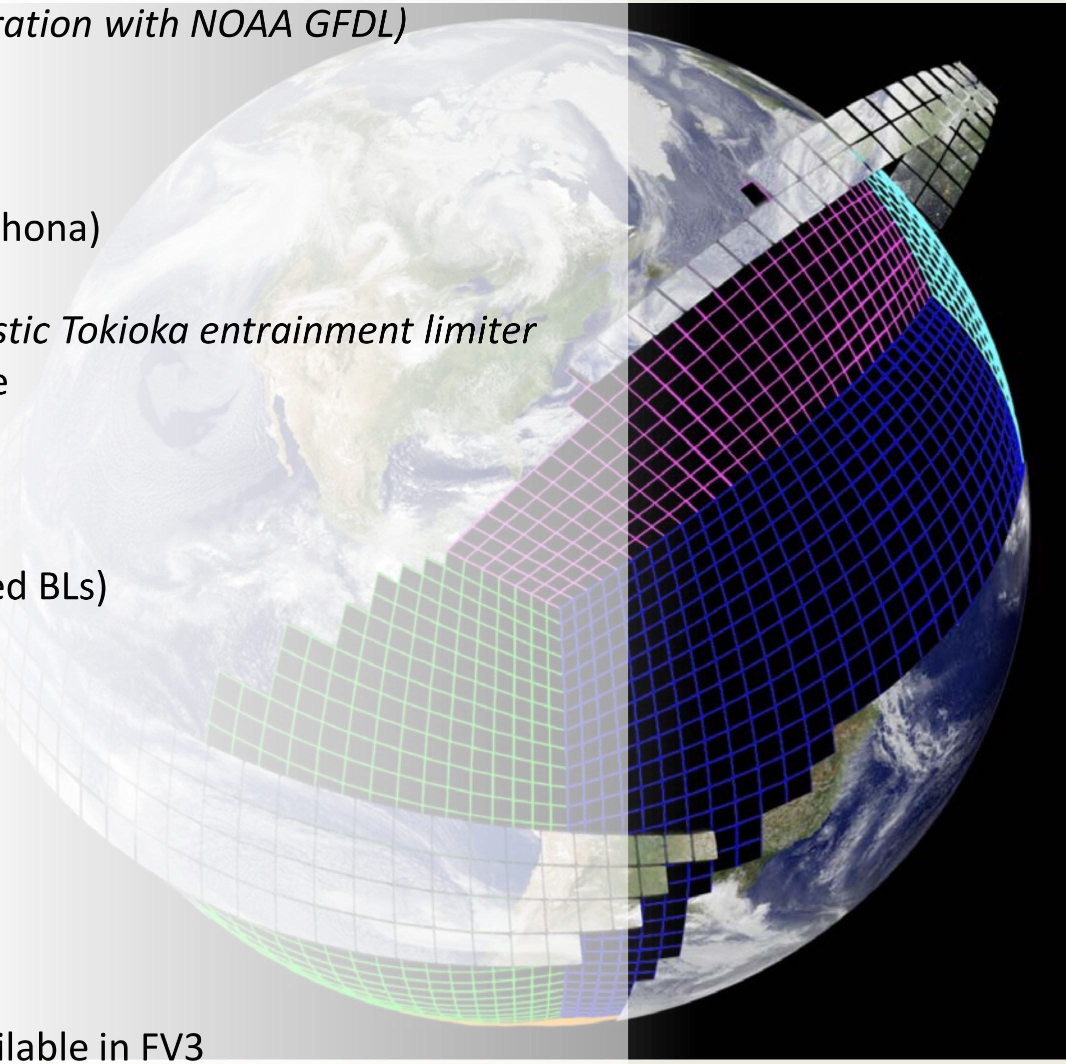
Radiation schemes:
- *Chou-Suarez*
- *RRTMG*

Aerosol/chemistry models
- *GOCART*
- *MAM*

ESMF compliant *(via MAPL)*

MPI parallelism *with SGI MPT*
  - Hybrid MPI+OpenMP directives available in FV3
  - Explicit use of SHMEM shared memory throughout GEOS via MAPL

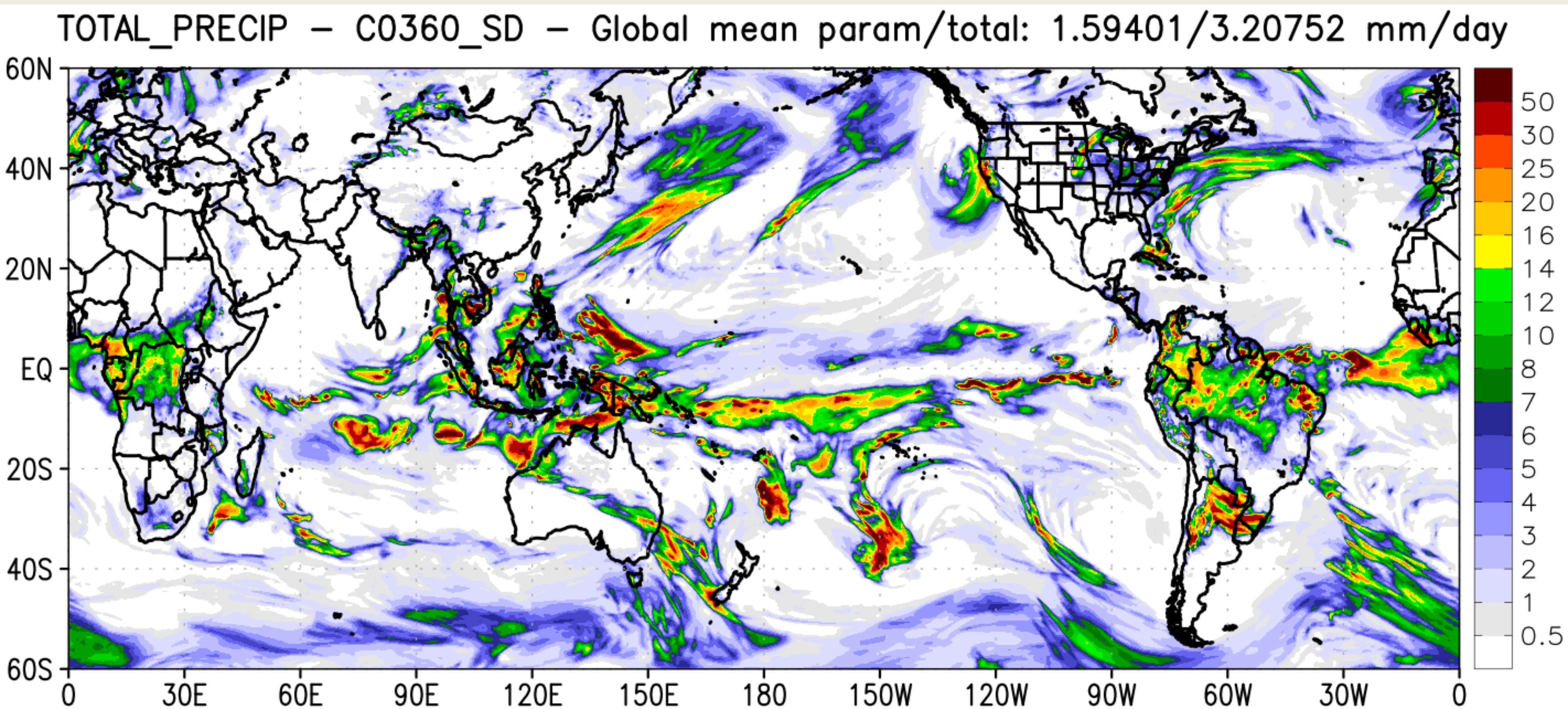
GPU implementation *(optional build via PGI Fortran within the production code)*



Results with NASA GEOS Global Model

A visual comparison with TRMM rainfall estimation

15-17 April 2000



GF Scale Dependence in NASA GEOS FV3 Model

C0180 (~ 50km) **NO-SD**

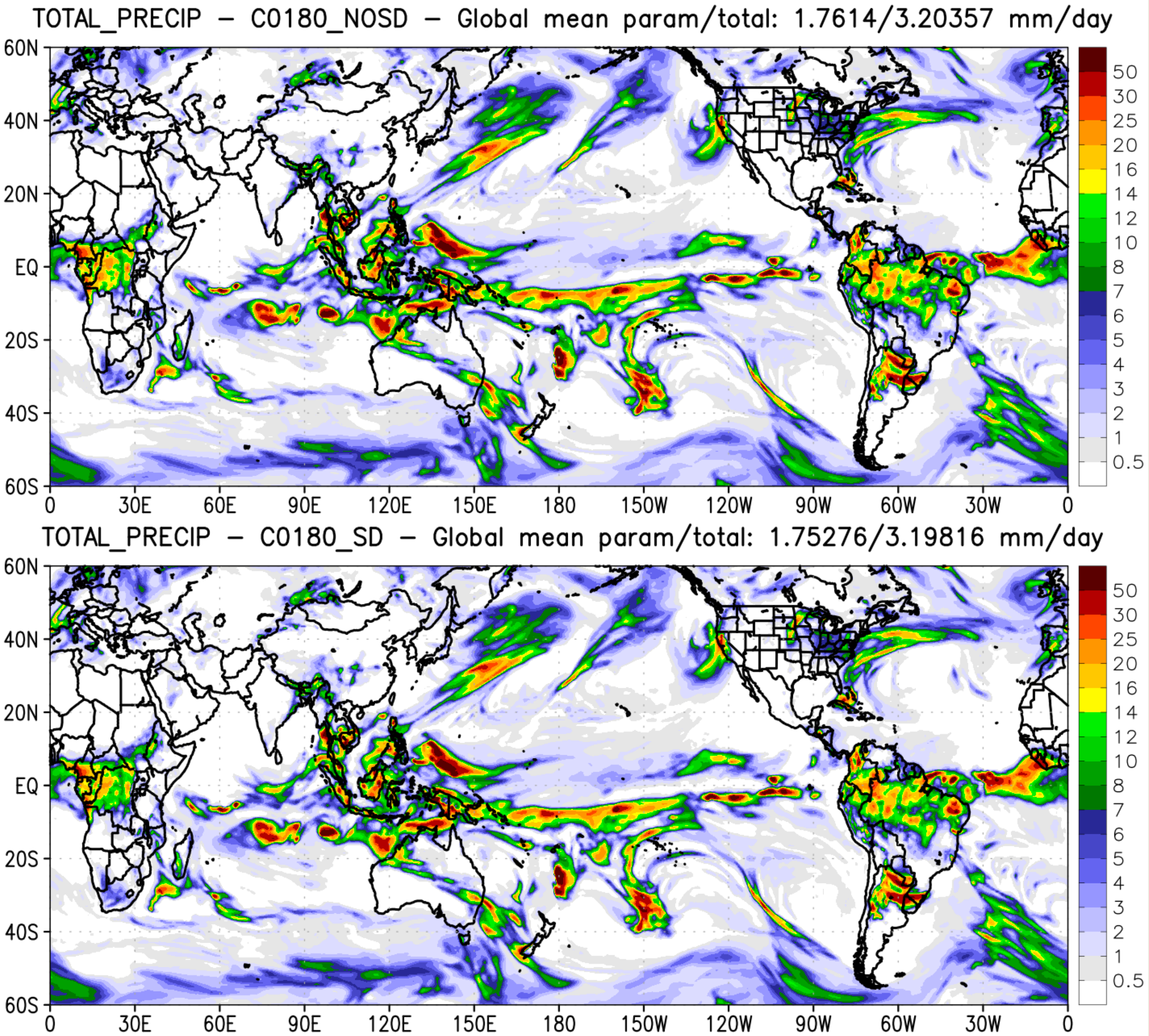
Param. rainfall: 1.8 mm/day

Total rainfall: 3.2 mm/day

C0180 (~ 50km) **SD**

Param. rainfall: 1.8 mm/day

Total rainfall: 3.2 mm/day



GF Scale Dependence in NASA GEOS FV3 Model

C0360 (~ 25km) **NO-SD**

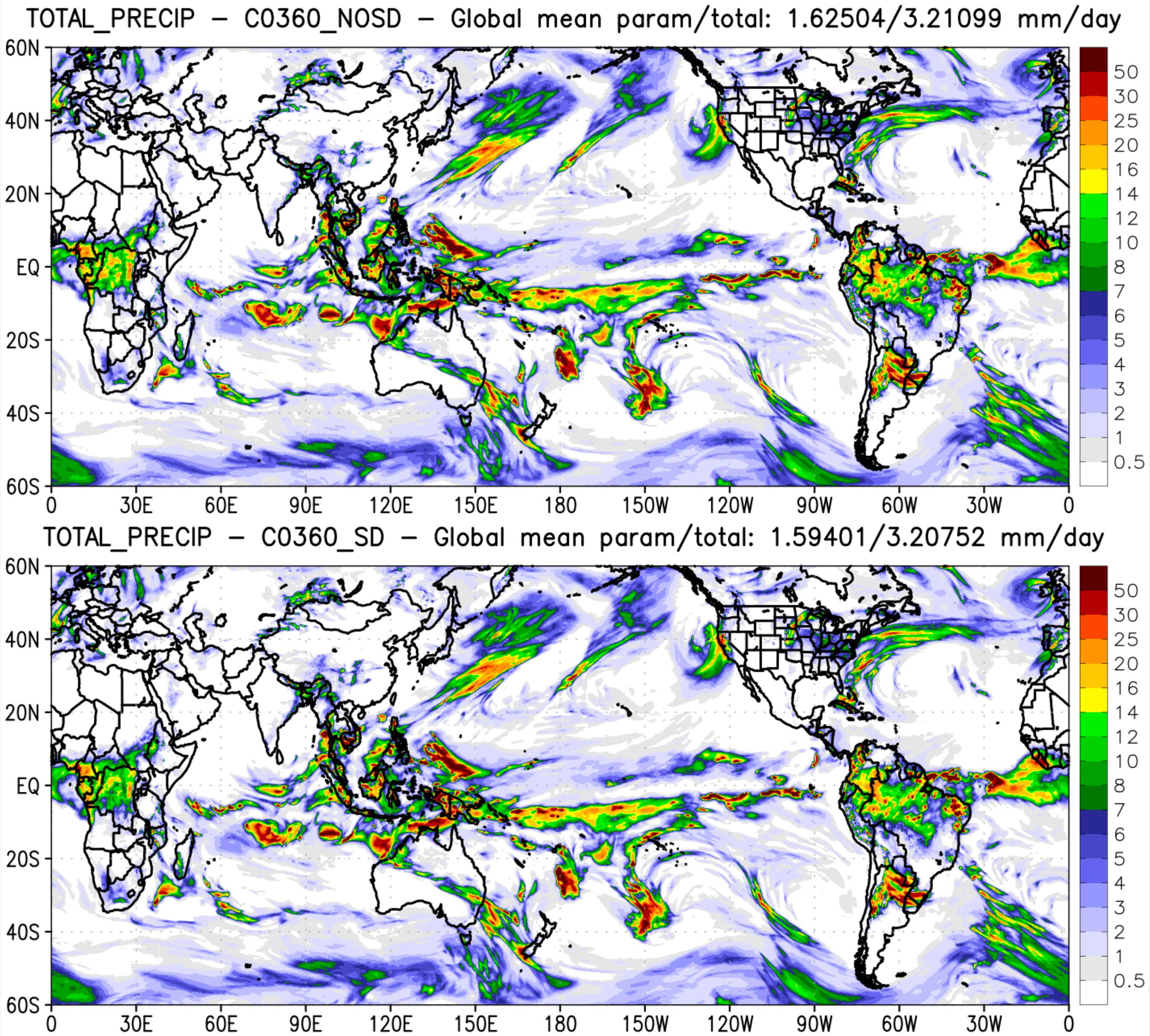
Param. rainfall: 1.6 mm/day

Total rainfall: 3.2 mm/day

C0360 (~ 25km) **SD**

Param. rainfall: 1.6 mm/day

Total rainfall: 3.2 mm/day



GF Scale Dependence in NASA GEOS FV3 Model

C0720 (~ 12.5km) **NO-SD**

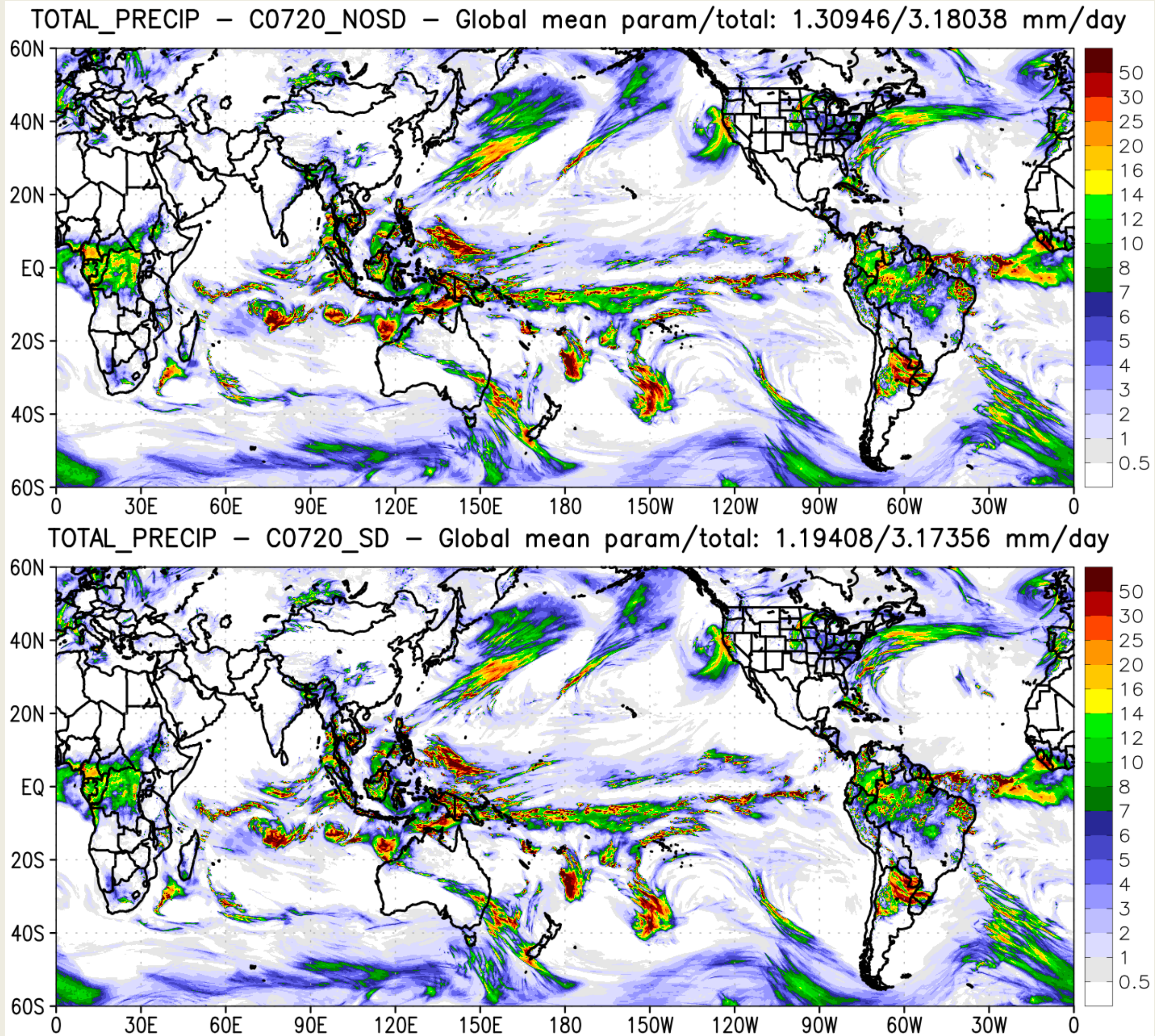
Param. rainfall: 1.3 mm/day

Total rainfall: 3.2 mm/day

C0720 (~ 12.5km) **SD**

Param. rainfall: 1.2 mm/day

Total rainfall: 3.2 mm/day



GF Scale Dependence in NASA GEOS FV3 Model

C1000 (~ 9km) **NO-SD**

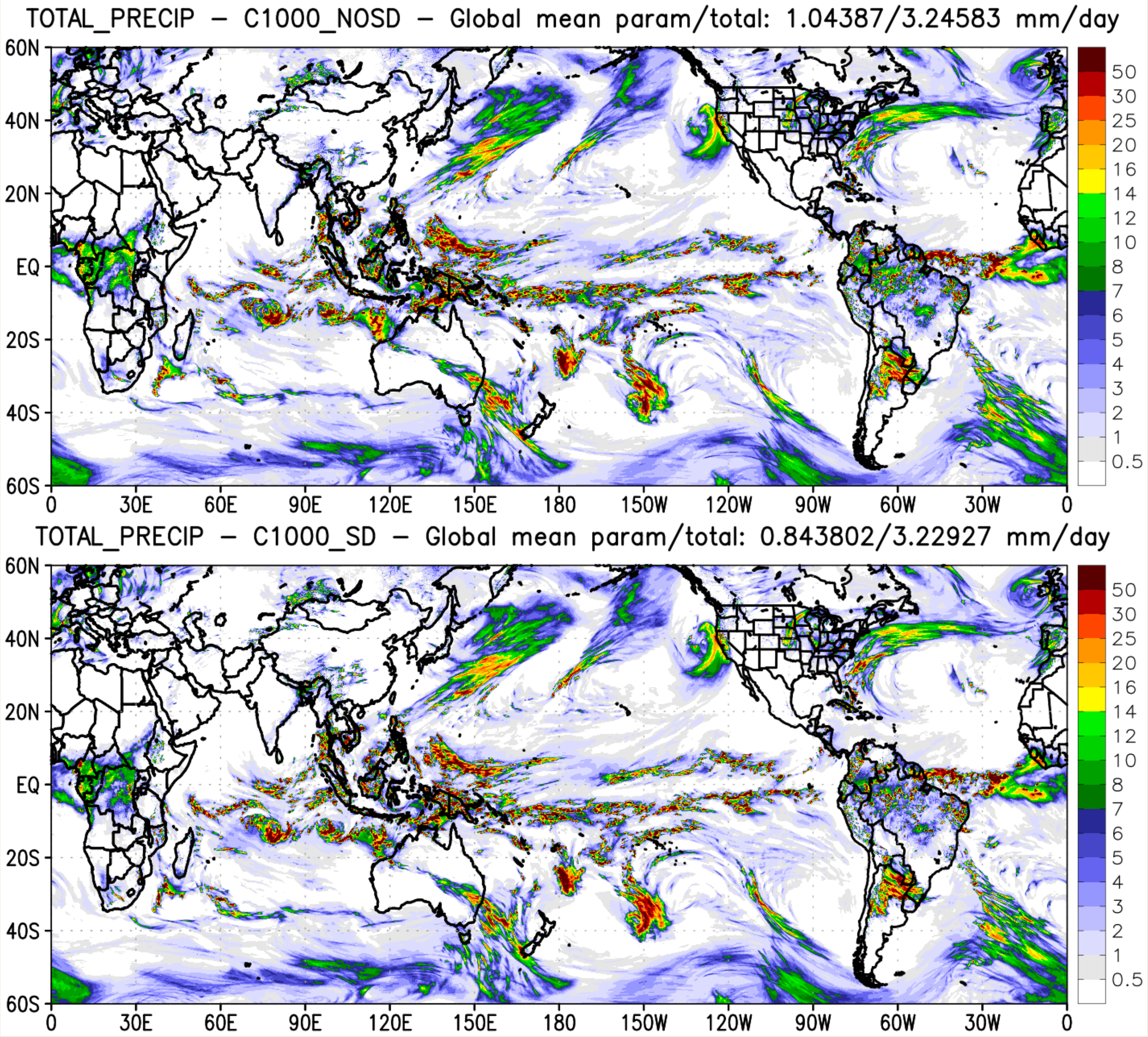
Param. rainfall: 1.0 mm/day

Total rainfall: 3.2 mm/day

C1000 (~ 9km) **SD**

Param. rainfall: 0.8 mm/day

Total rainfall: 3.2 mm/day

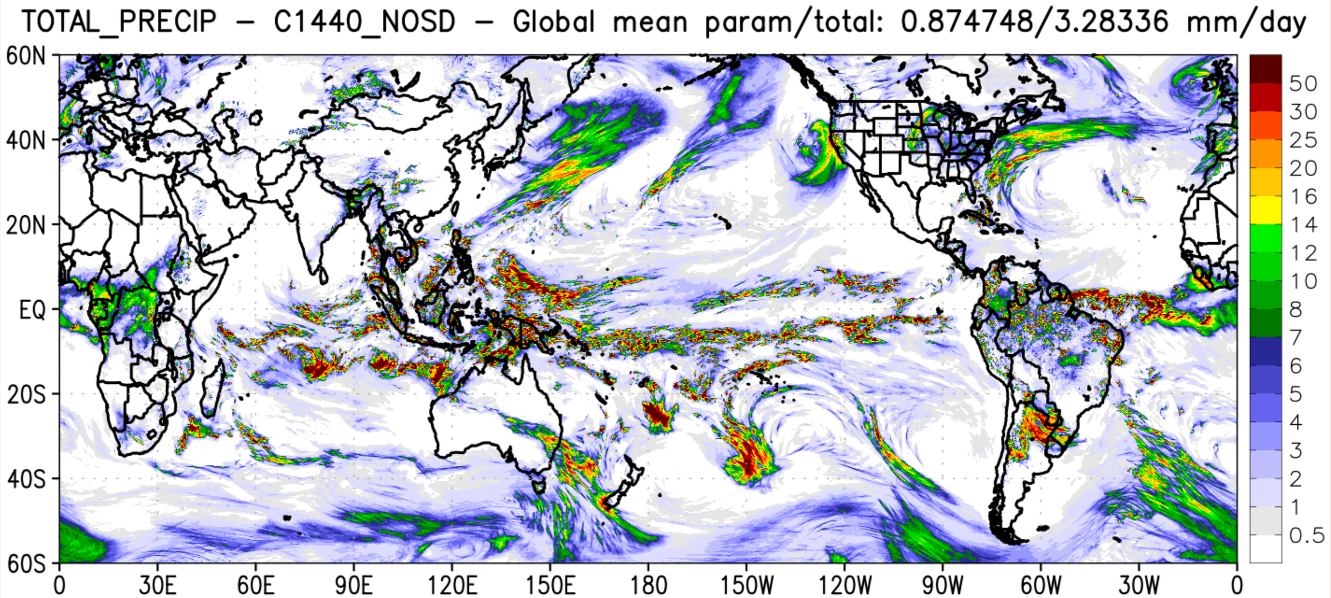


GF Scale Dependence in NASA GEOS FV3 Model

C1440 (~ 6.25km) **NO-SD**

Param. rainfall: 0.9 mm/day

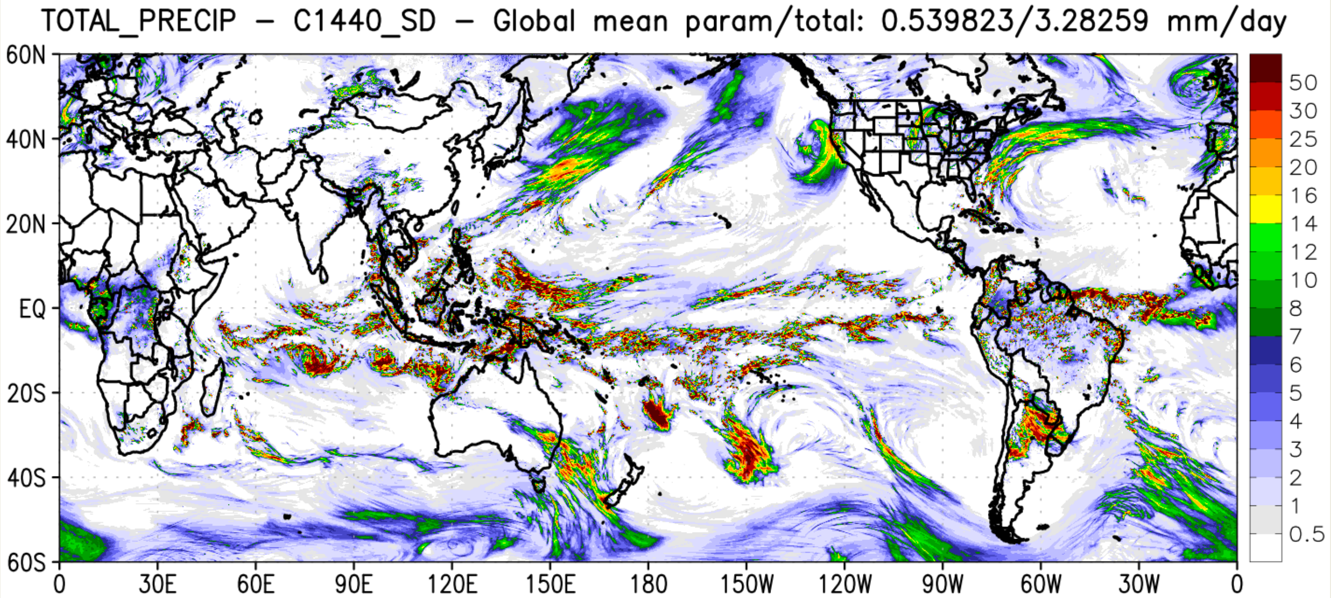
Total rainfall: 3.3 mm/day



C1440 (~ 6.25km) **SD**

Param. rainfall: 0.5 mm/day

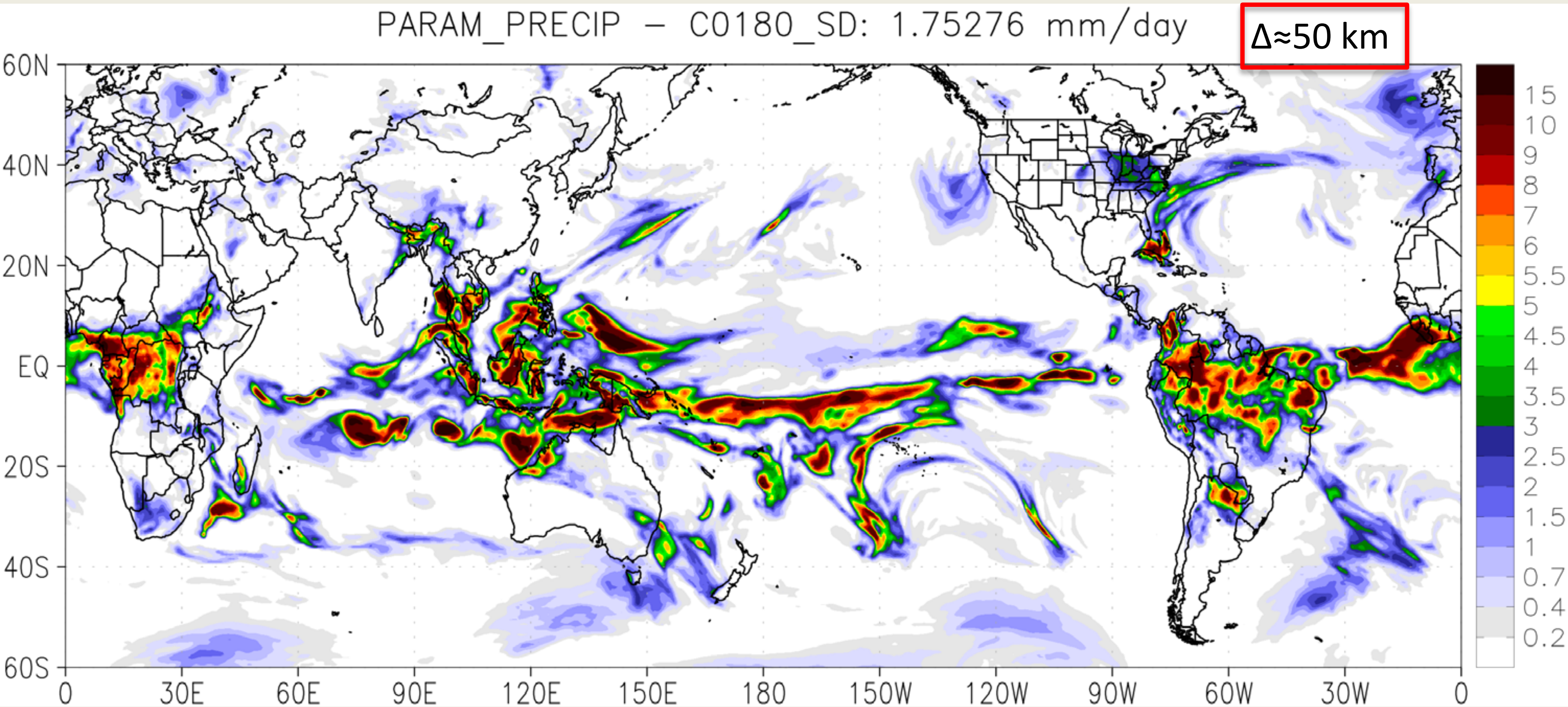
Total rainfall: 3.3 mm/day



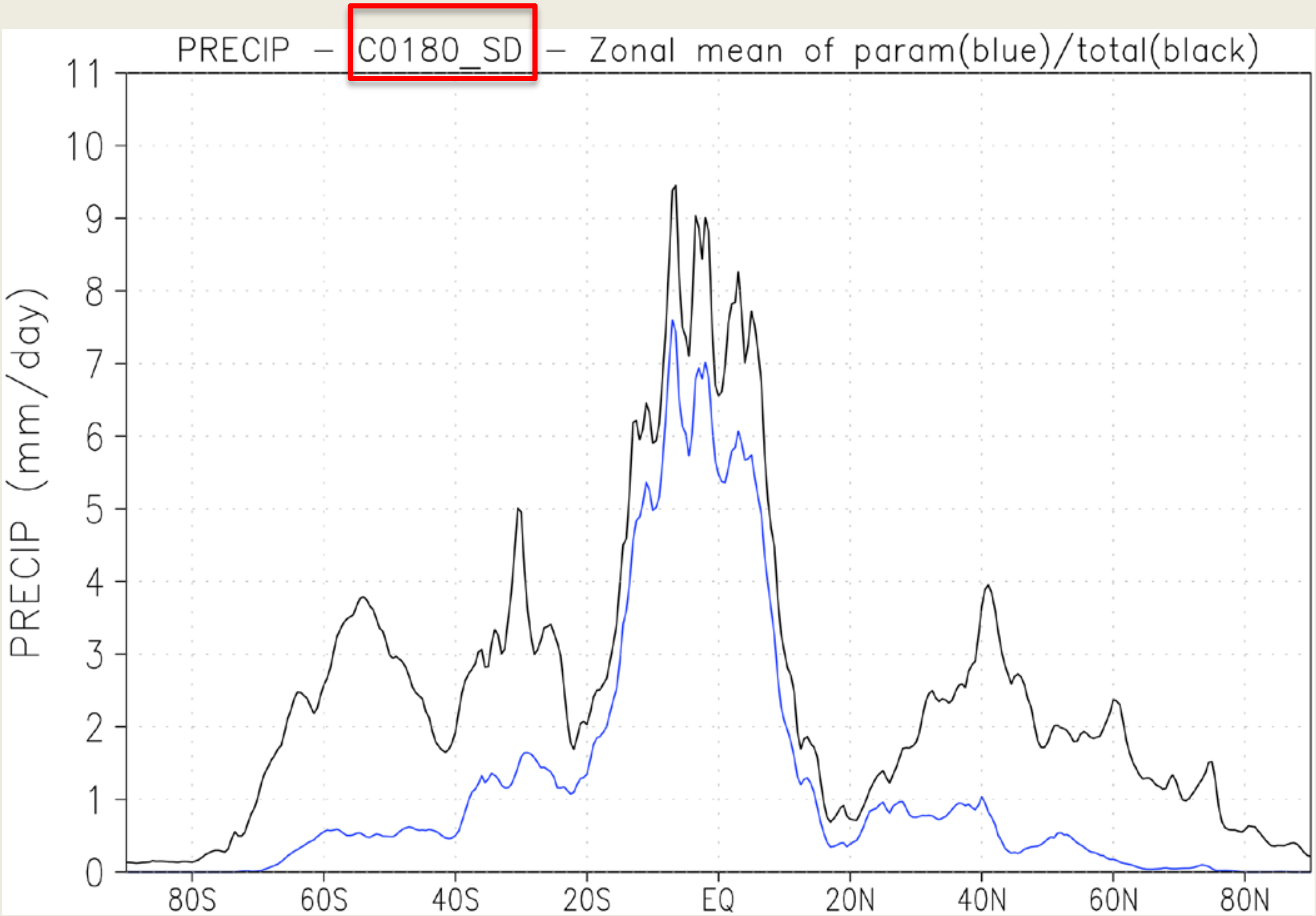
GF Scale Dependence in NASA GEOS FV3 Model

Simulated precipitation from the <u>cumulus parameterization</u>

From 50 => 12 => 6 km



GF Scale Dependence in NASA GEOS FV3 Model



Global zonal mean precipitation: from 50 =>	25	=> 12.5 =>	6.25 km
	C180	C360	C720	C1440

Blue = from the cumulus scheme **Black**= total precipitation

Results with the NASA GEOS Global Model

Exploring the simulation of the diurnal cycle convection over the Amazonia Basin including
Bechtold et al (2014) closure for non-equilibrium convection

- NASA GEOS model configured as a single column model
- Jan-Feb 1999
- IC/BC (including advection tendencies) from MERRA-2 reanalysis

Diurnal cycle of convection over the Amazon Basin (LBA-TRMM case)

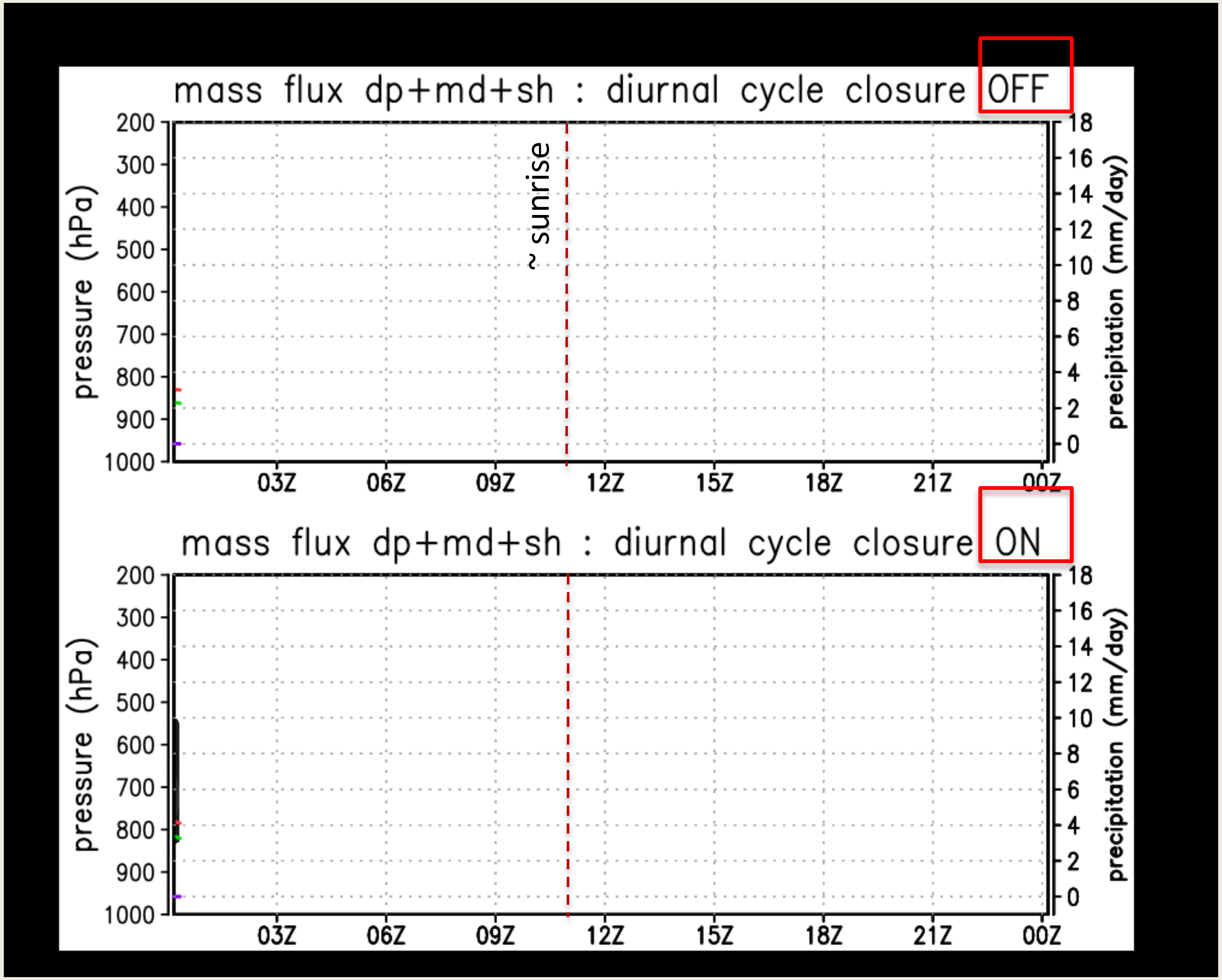
Shaded is the total updraft mass flux (deep+congestus+shallow)

Color contours show the simulated rainfall (mm/day)

- **Total**
- **Parameterized**
- **Parameterized (congestus)**

NASA GEOS model with GF

- Single Column model
- Average over Jan-Feb 1999
- IC/BC from MERRA-2 reanalysis



UTC time (LT=UTC-4h)

Diurnal cycle of convection over the Amazon Basin (LBA-TRMM case)

Shaded is the total updraft mass flux (deep+congestus+shallow)

Color contours show the simulated rainfall (mm/day)

- **Total**
- **Parameterized**
- **Parameterized (congestus)**

NASA GEOS model with GF

- Single Column model
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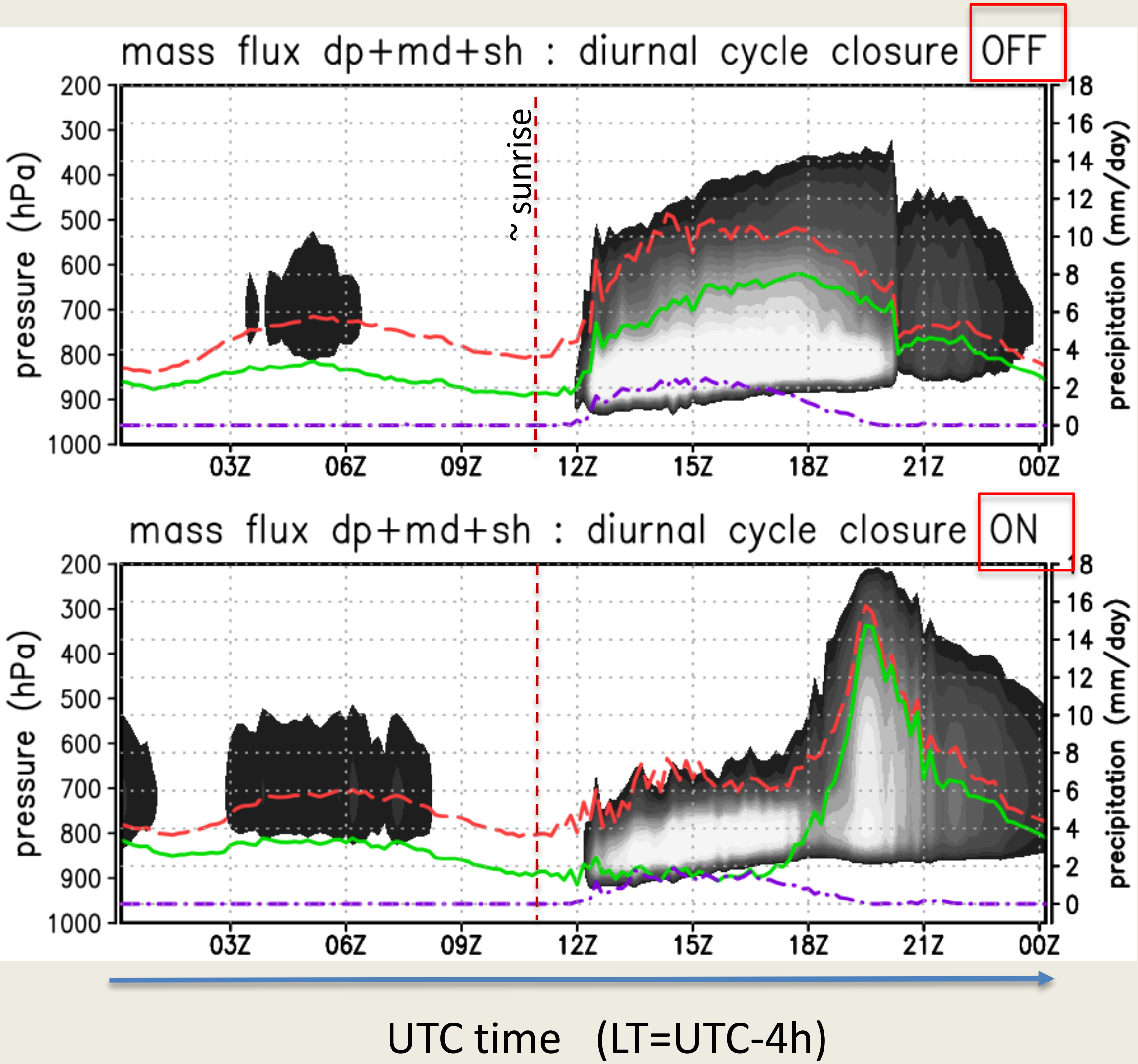
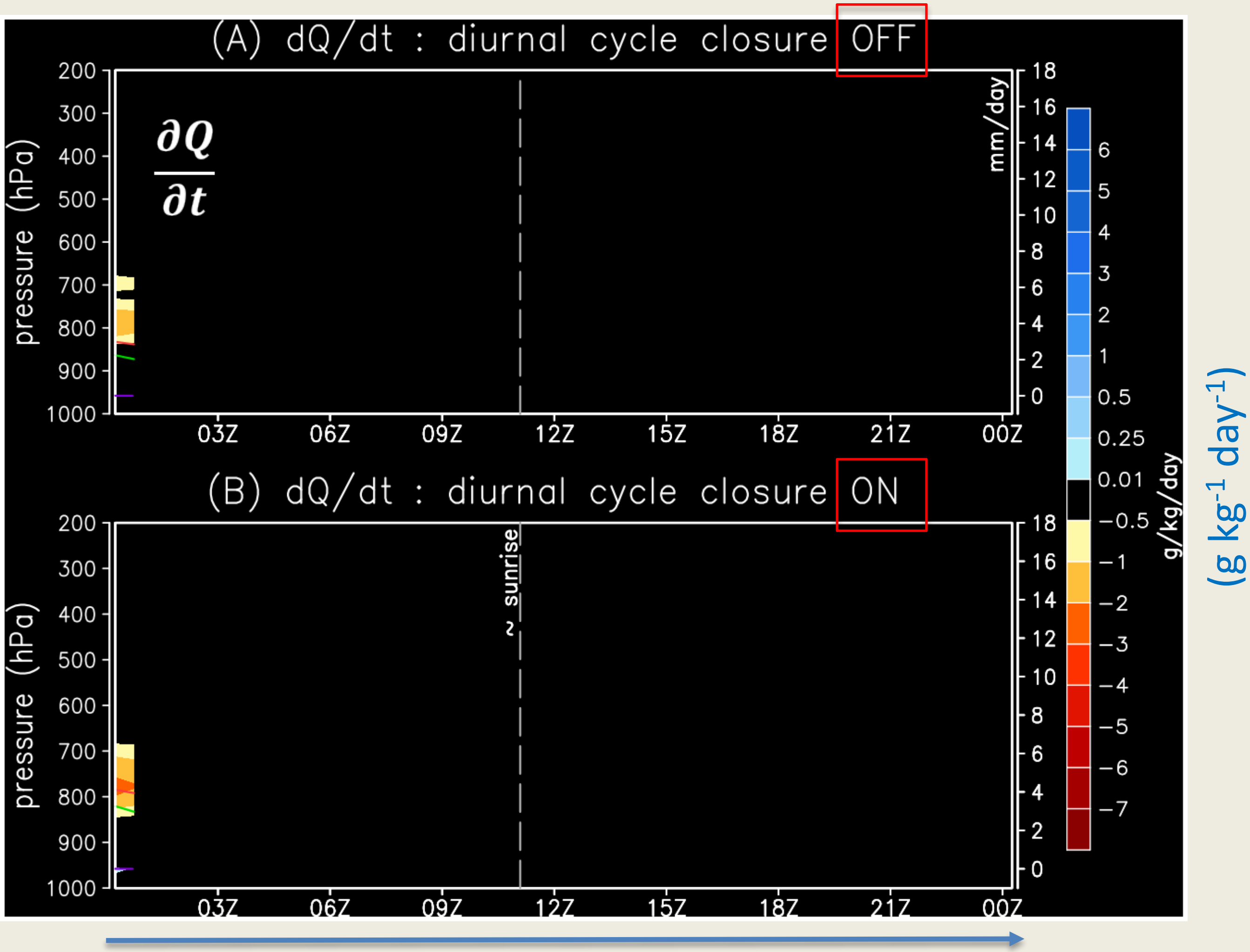


Diurnal cycle of convection over the Amazon Basin

Convective moistening tendency

Simulated Rainfall (mm/da
- **Total**
- **Parameterized**
- **Parameterized (congest**

NASA GEOS model with GF
- Single Column model
- Jan-Feb 1999
- IC/BC from MERRA-2 reanalysis



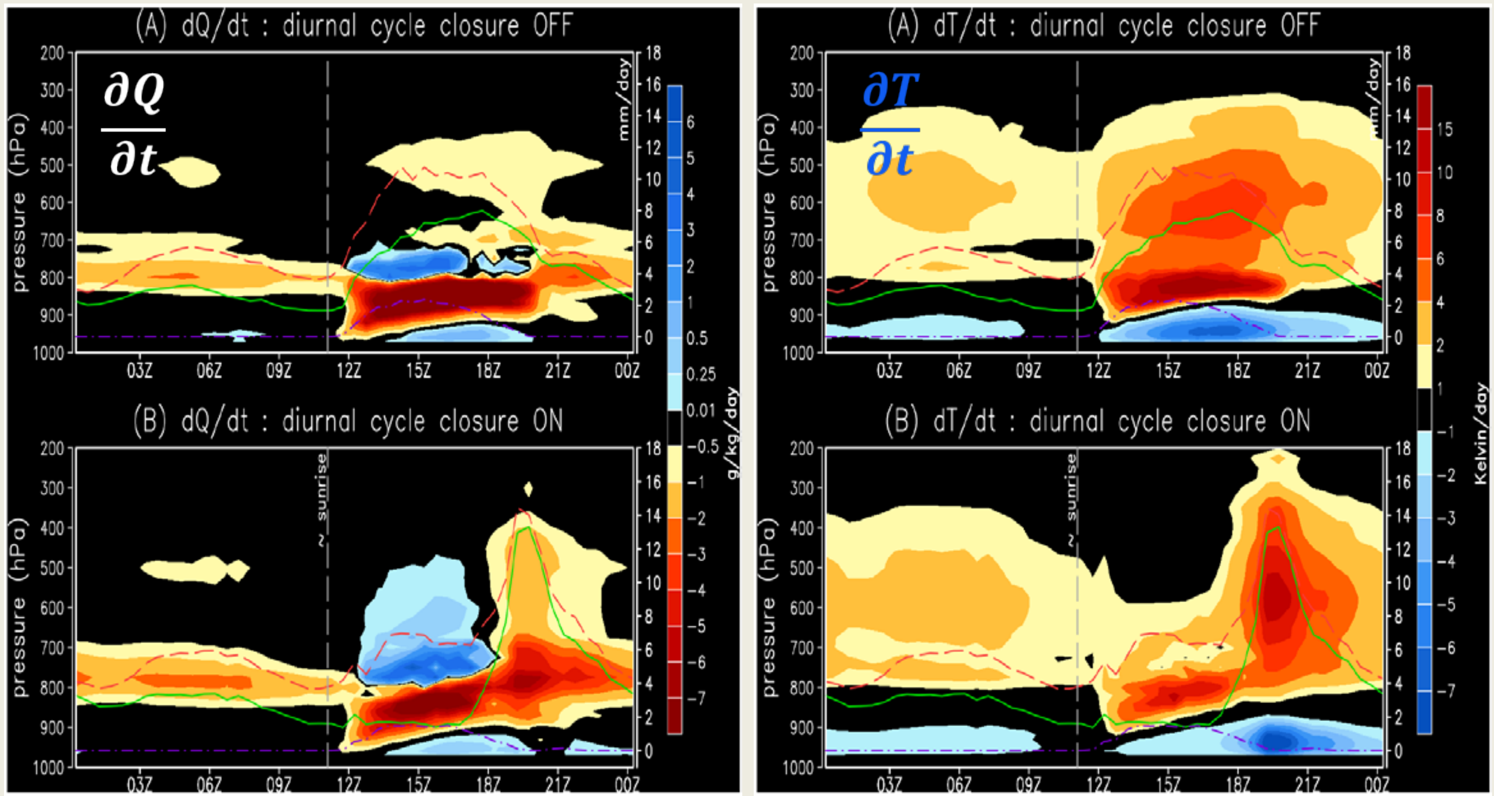
UTC time (LT=UTC-4h)

Diurnal cycle of convection over the Amazon Basin

Convective moistening and heating tendencies

NASA GEOS model with GF

- Single Column model
- Jan-Feb 1999
- IC/BC from MERRA-2 reanalysis



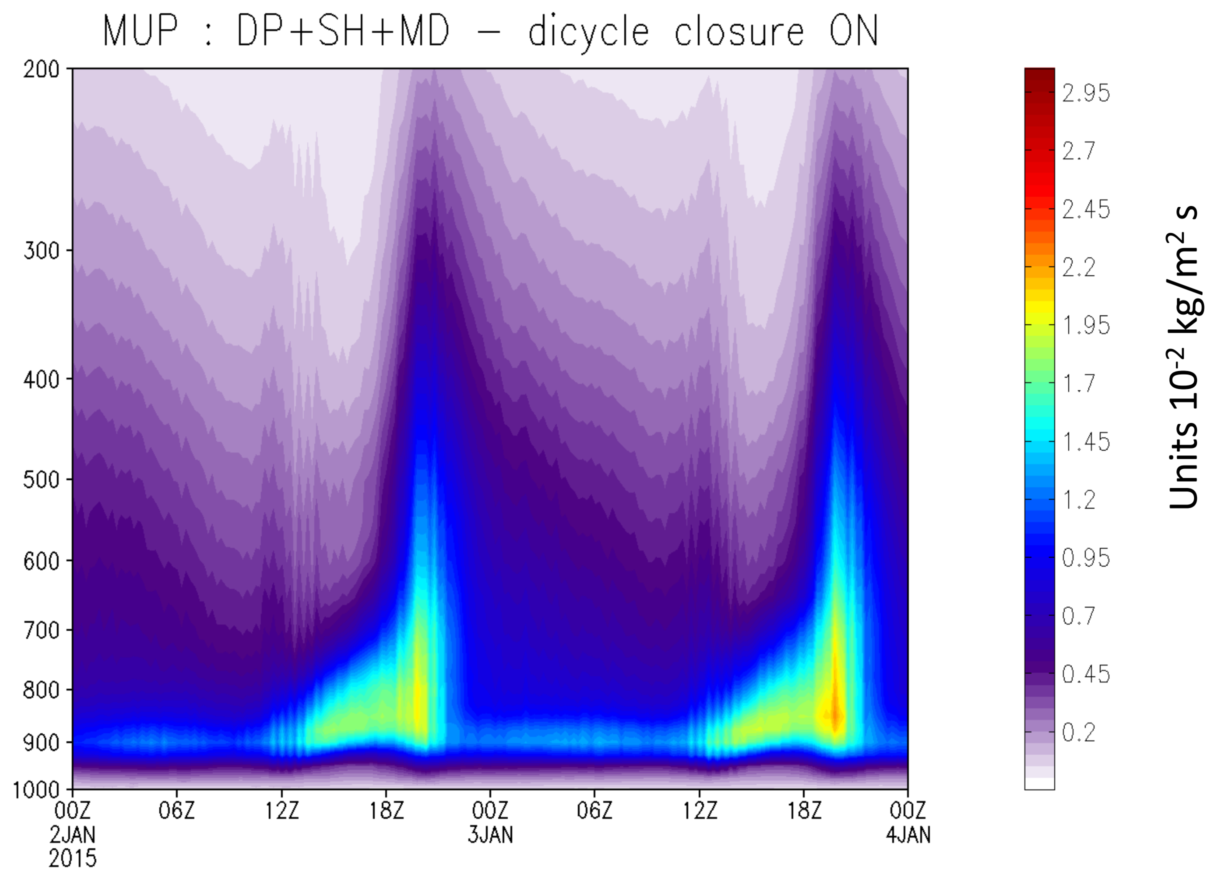
UTC time (LT=UTC-4h)

Diurnal cycle of convection over the Amazon Basin

Mass flux of the three updrafts

NASA GEOS

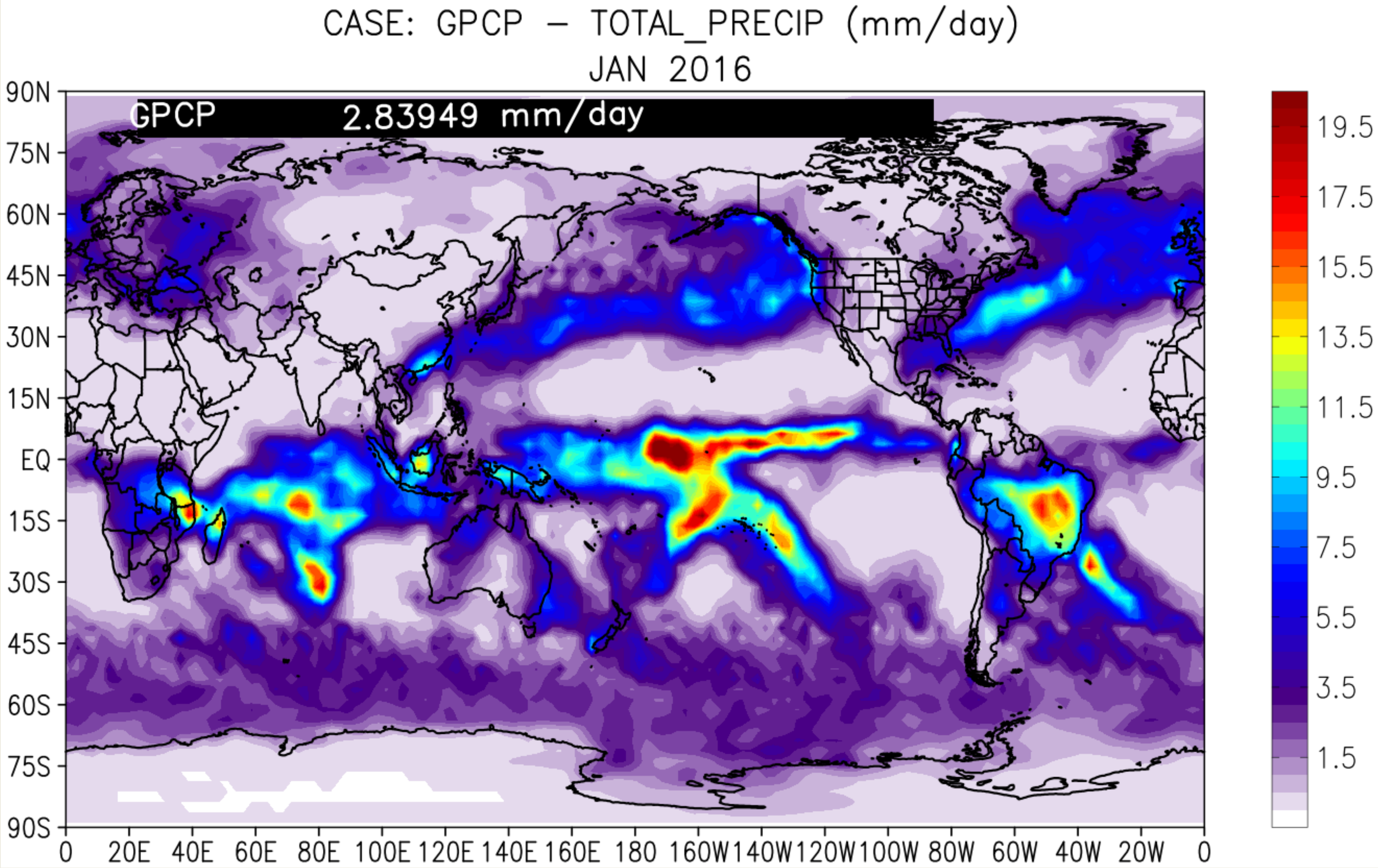
- 3-D simulation on c90 (~ 100 km)
- Area average over the Amazon basin



Initial evaluation for global weather forecast on 12 km with NASA GEOS Global Model

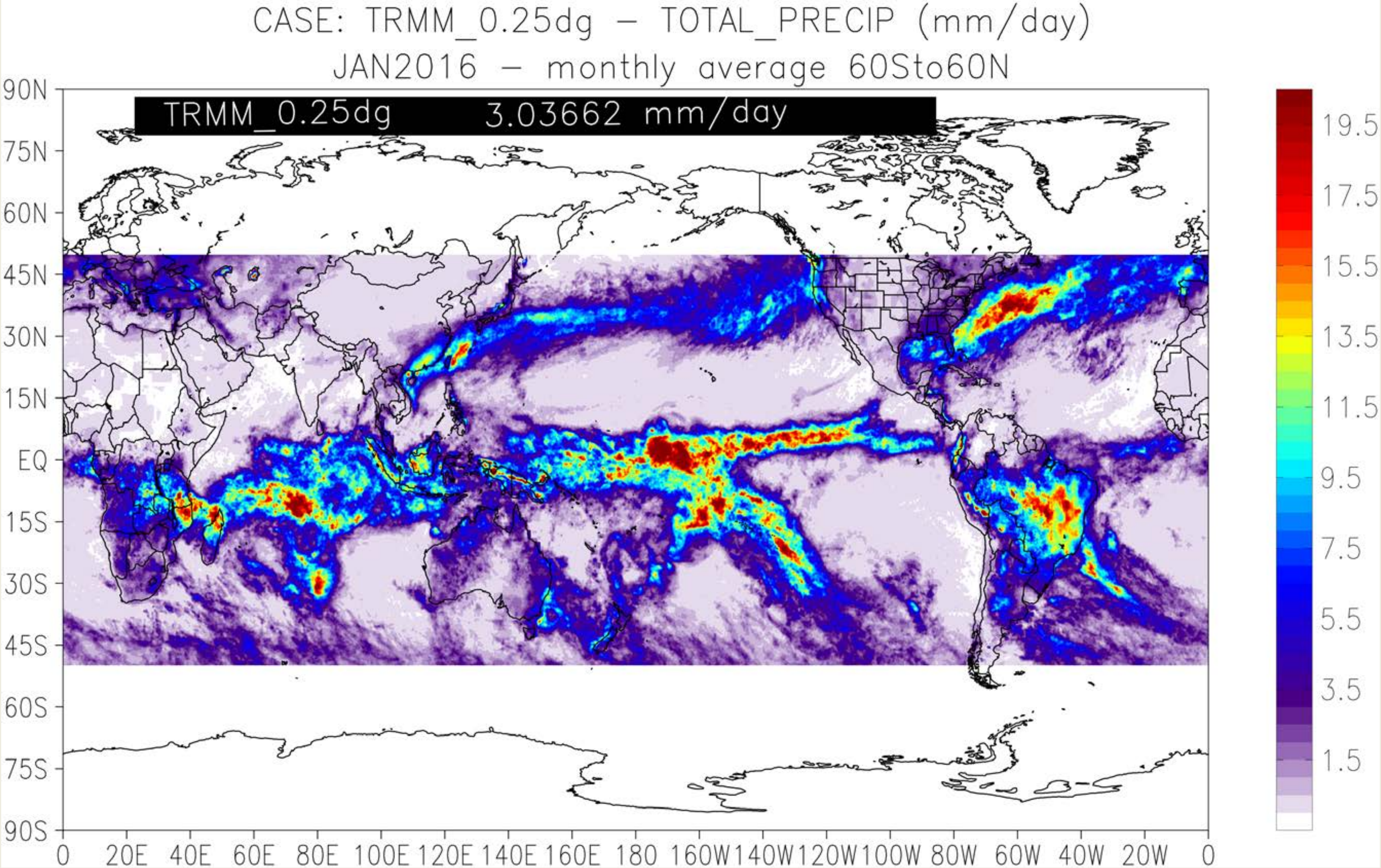
- 5-day forecast
- C360 resolution, 72 vertical levels
- Jan 2016
- Preliminary evaluation

GPCP



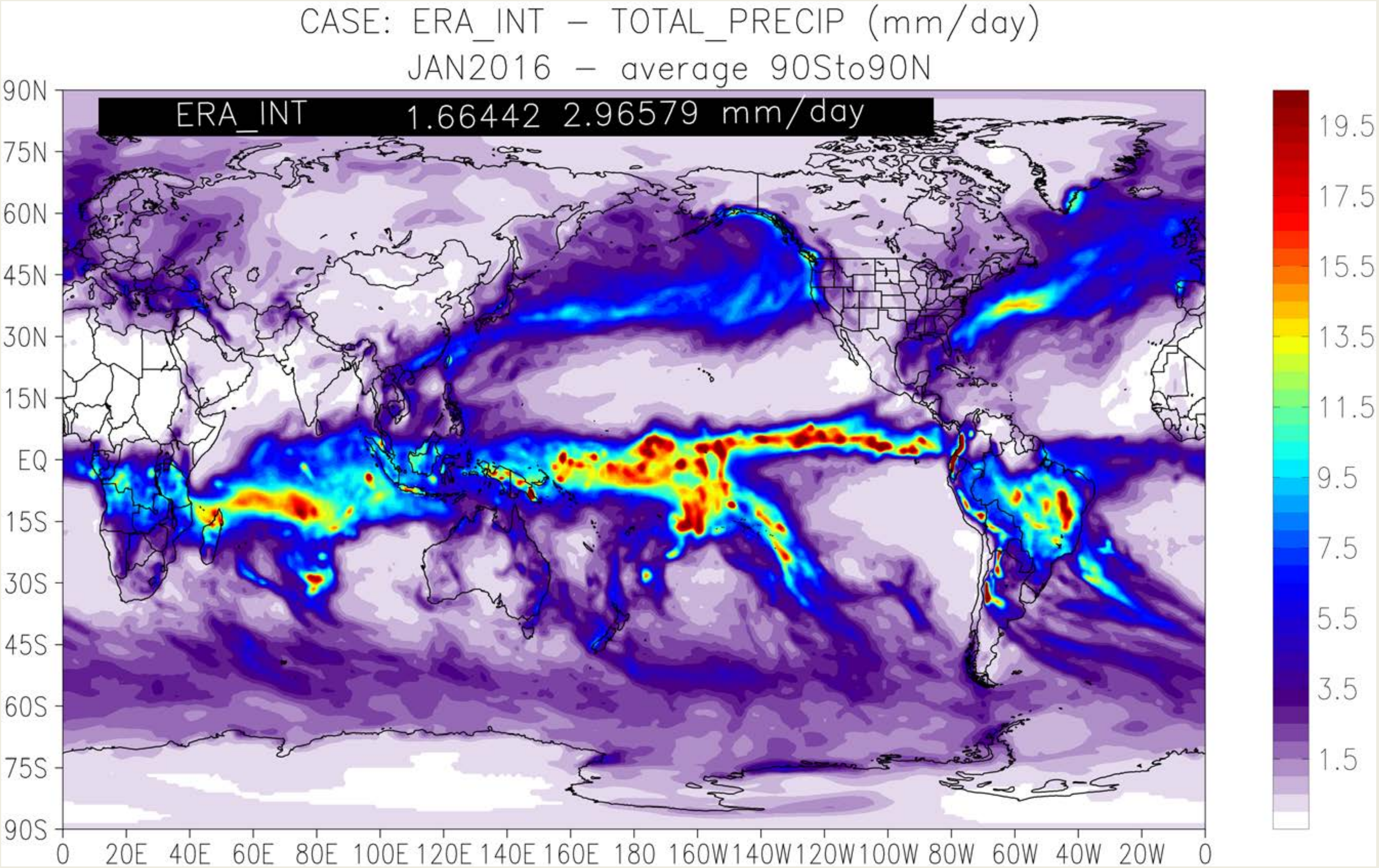
Precipitation: monthly average for JAN 2016

TRMM



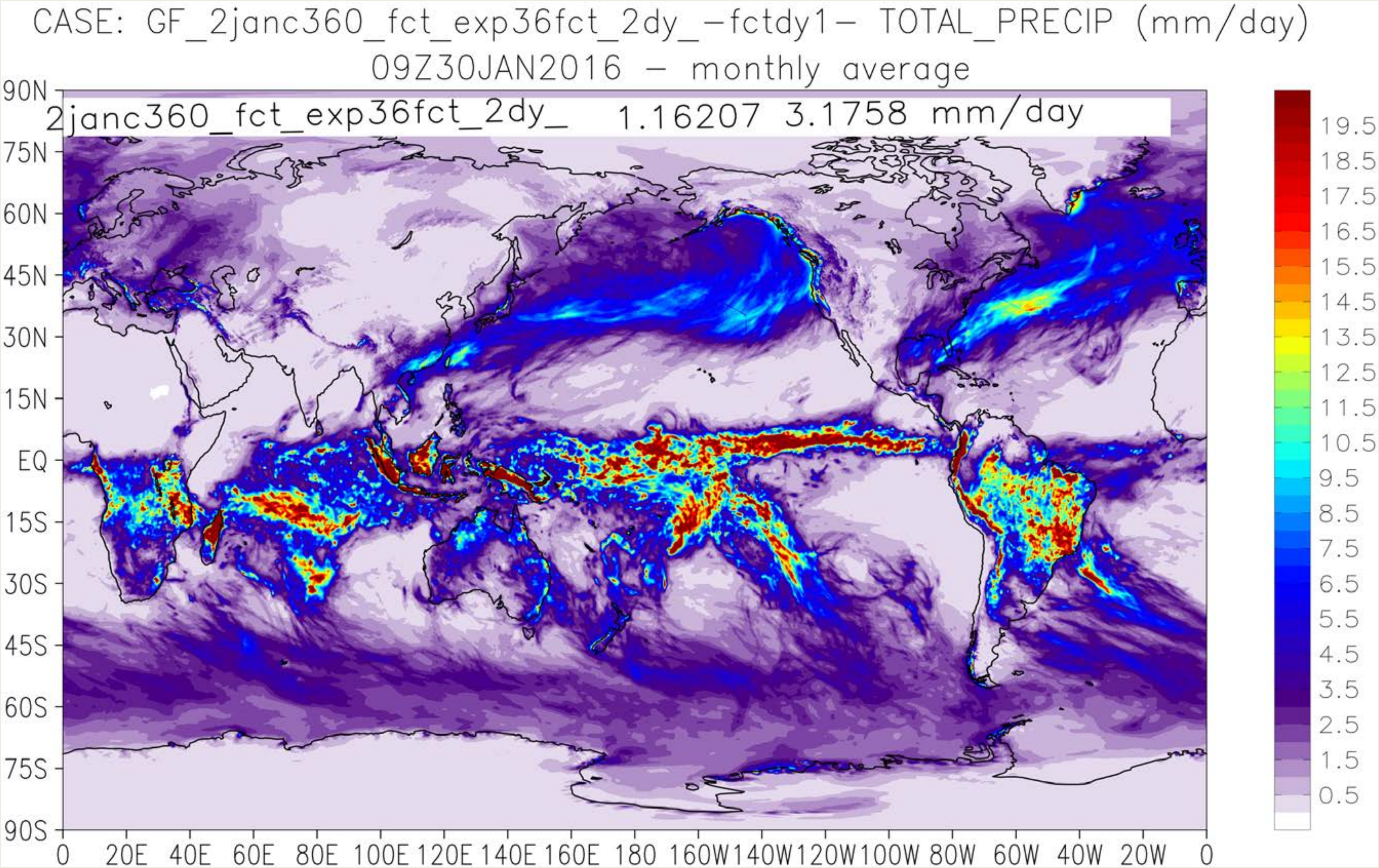
Precipitation: monthly average for JAN 2016

ERA-Interim



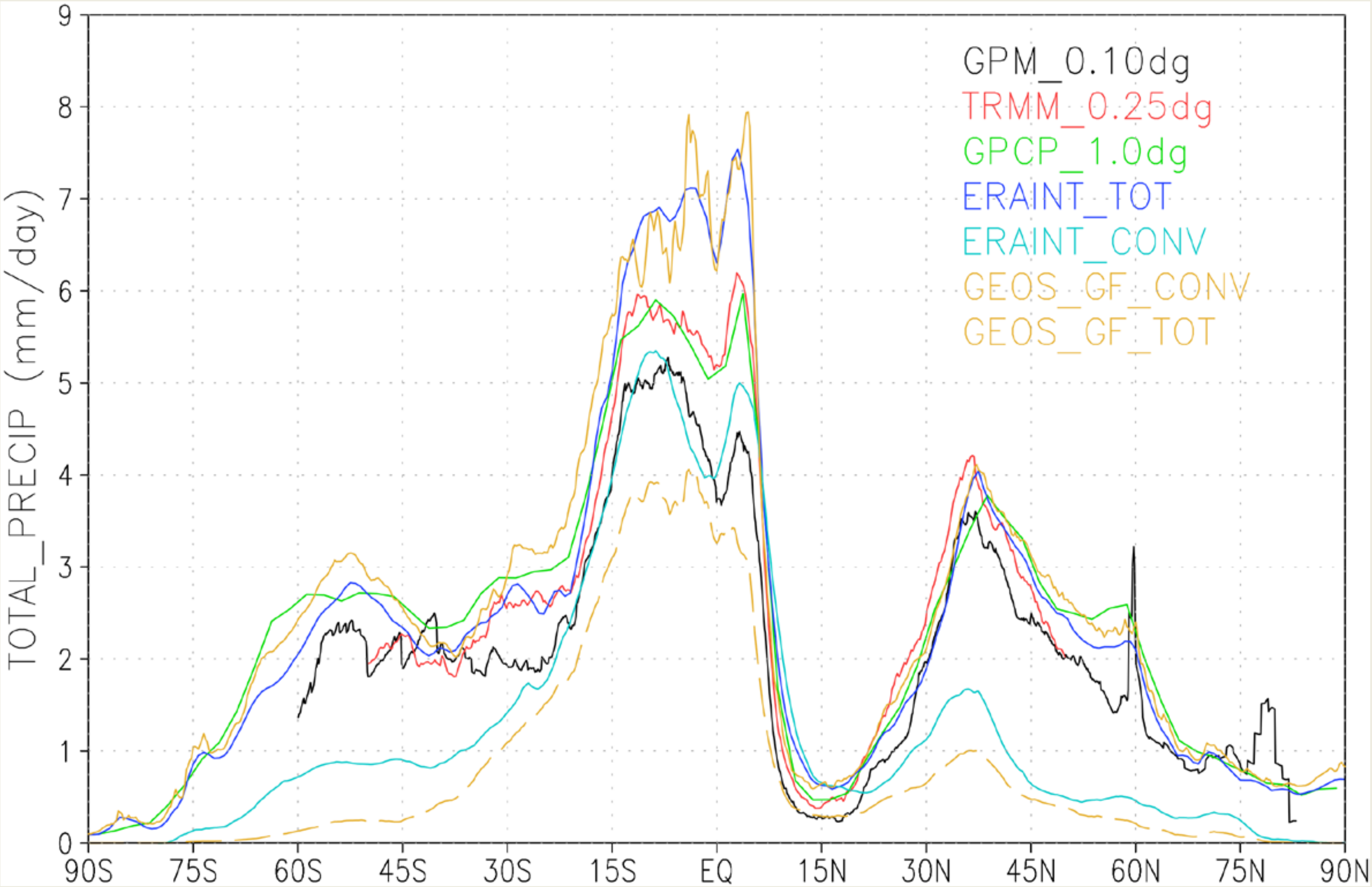
Precipitation: monthly average for JAN 2016

GEOS-5 with FV3 and GF



Precipitation: monthly average for JAN 2016

C360 JAN 2016
Global zonal/monthly average



Discussion

- GF scheme has been applied on regional and global scales with a sort of models (BRAMS, WRF, MPAS, FIM, GEOS) for operational and research purposes.
- The *trimodal* approach with the diurnal cycle closure seems to be a reliable way to address the problem of simulating the transition from shallow to deep convection regimes over the land.
- The scale dependence approach seems to work well on models with uniform or varying grid spacing (see Fowler et al., 2016 with MPAS model).
- The next steps for NASA GEOS model will be a comprehensive quantitative evaluation for operational production on weather (up to 10 days) to seasonal scales.

- Thanks for your attention!

- Backup Slides

A aerosol aware stochastic convectiveparameterization (experimental)

- Parameterization autoconversion from cloud water to rain water is constant: c0=0.002 (Kessler formulation).

- Equation for conversion of cloud water to rain water are re-derived

using the Berry formulation:

$$\left(\frac{\partial r_{rain}}{\partial t}\right) = \frac{\left(\rho r_c\right)^2}{60\left(5 + \frac{0.0366\ CCN}{\rho r_c m}\right)}$$

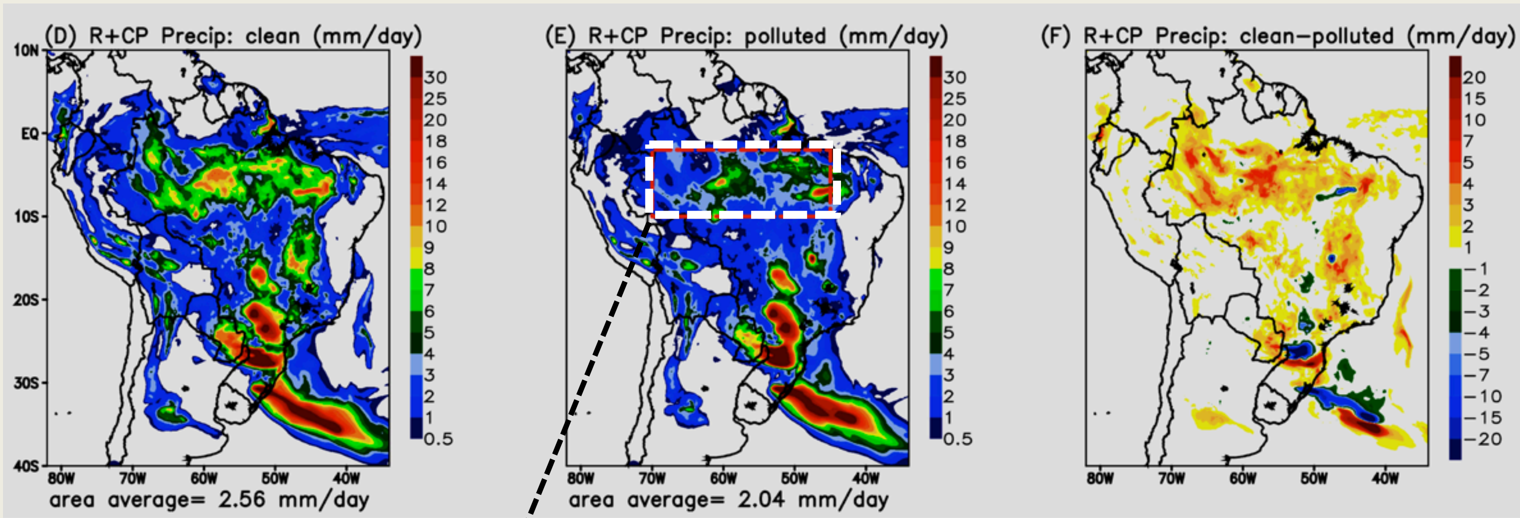
- Based on discussions with Graham Feingold and a paper by Jiang et al (JAS, 2010), making the precipitation efficiency (PE) dependent on CCN:

$$PE \sim (I_1)^{\alpha_s - 1}(CCN)^{\zeta} = C_{pr}(I_1)^{\alpha_s - 1}(CCN)^{\zeta},$$

- Where α_s and ζ are empirical constants and C_{pr} is a constant of proportionality

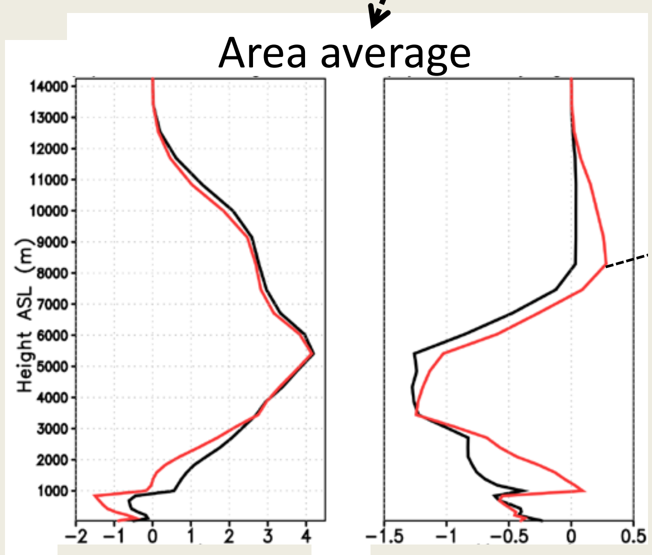
BRAMS simulations for South America
clean / polluted – dx 20 km – 24h accumulated (mm)

total rainfall: clean | **total rainfall: polluted** | **clean - polluted**



Clean:
CCN 150 cm^{-3}

Polluted
CCN 3000 cm^{-3}



Heating rate (K day^{-1}) | Moistening rate (g kg^{-1} day^{-1})

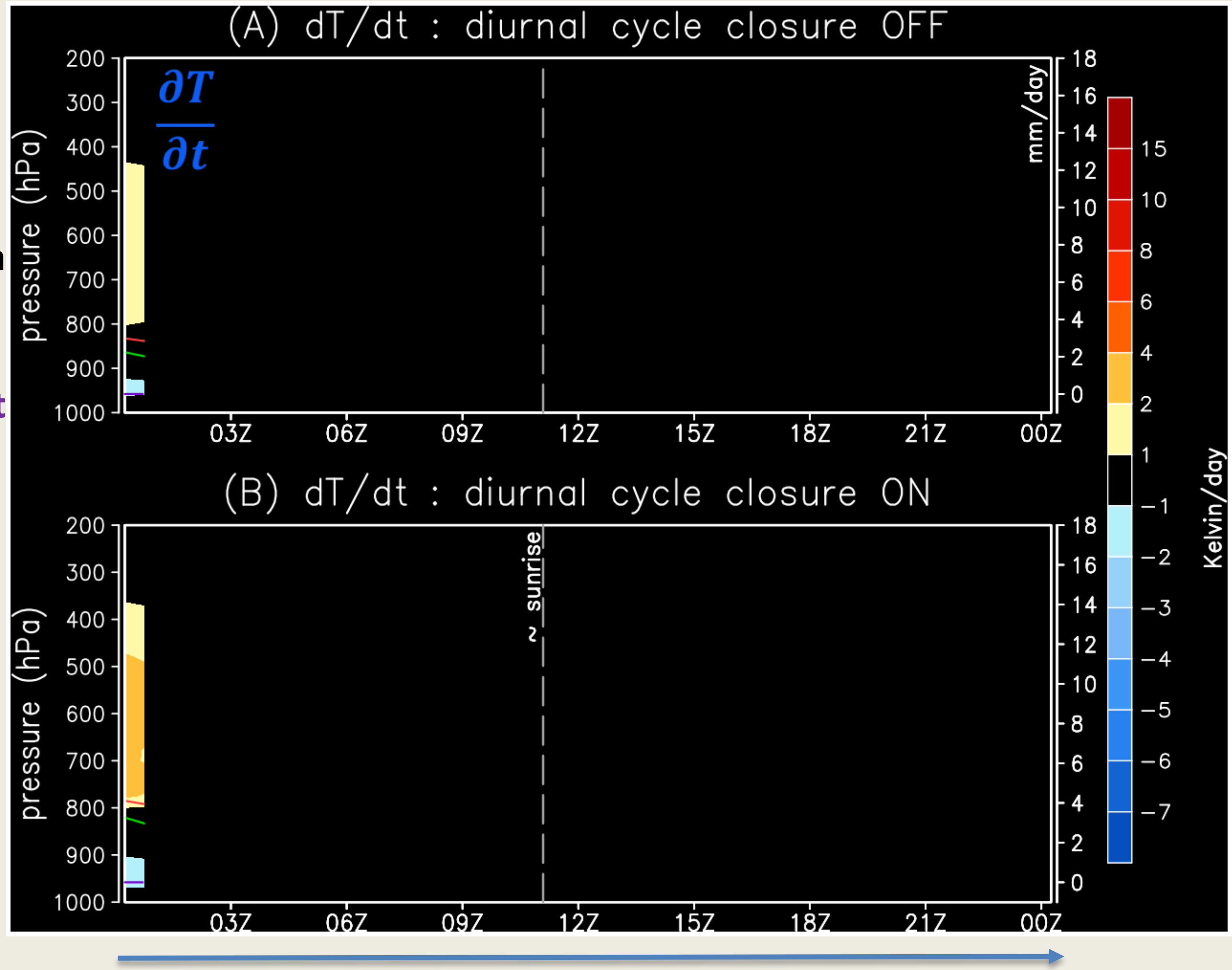
Grell and Freitas, ACP 2014

Diurnal cycle of convection over the Amazon Basin

Convective heating tendency (K day^{-1})

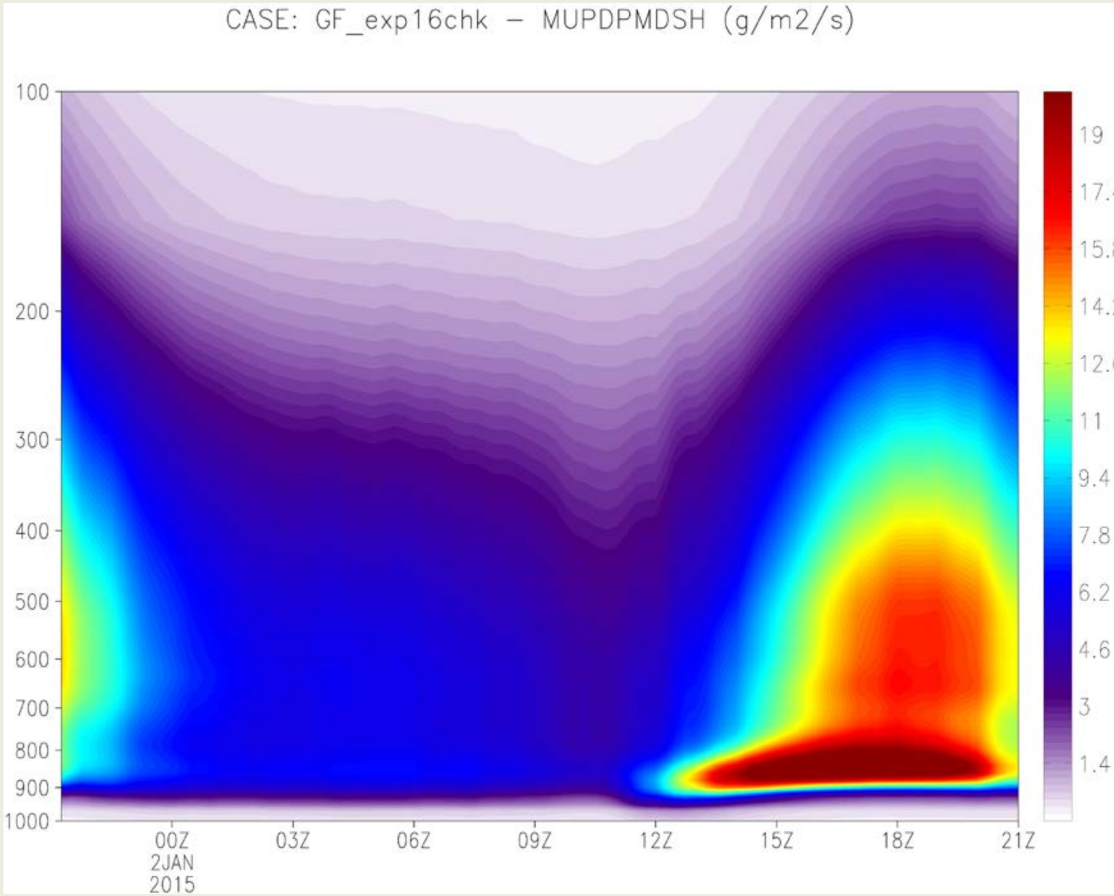
Simulated Rainfall (mm/da
- **Total**
- **Parameterized**
- **Parameterized (congest**

NASA GEOS model with GF
- Single Column model
- Jan-Feb 1999
- IC/BC from MERRA-2 reanalysis



UTC time (LT=UTC-4h)

GEOS-5/GF Diurnal cycle of mass flux of updrafts
Trimodal version (shallow-congestus-deep)

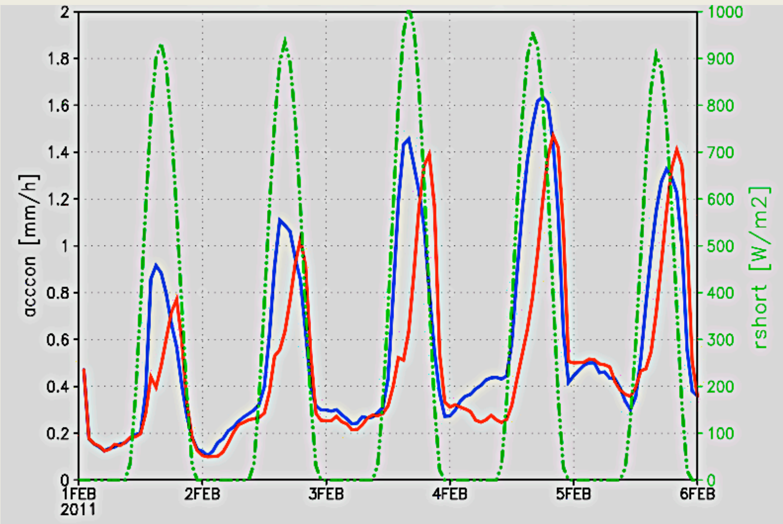


GEOS-5 c90
Average over the Amazon Basin
4-day time average

Local time – UTC-4

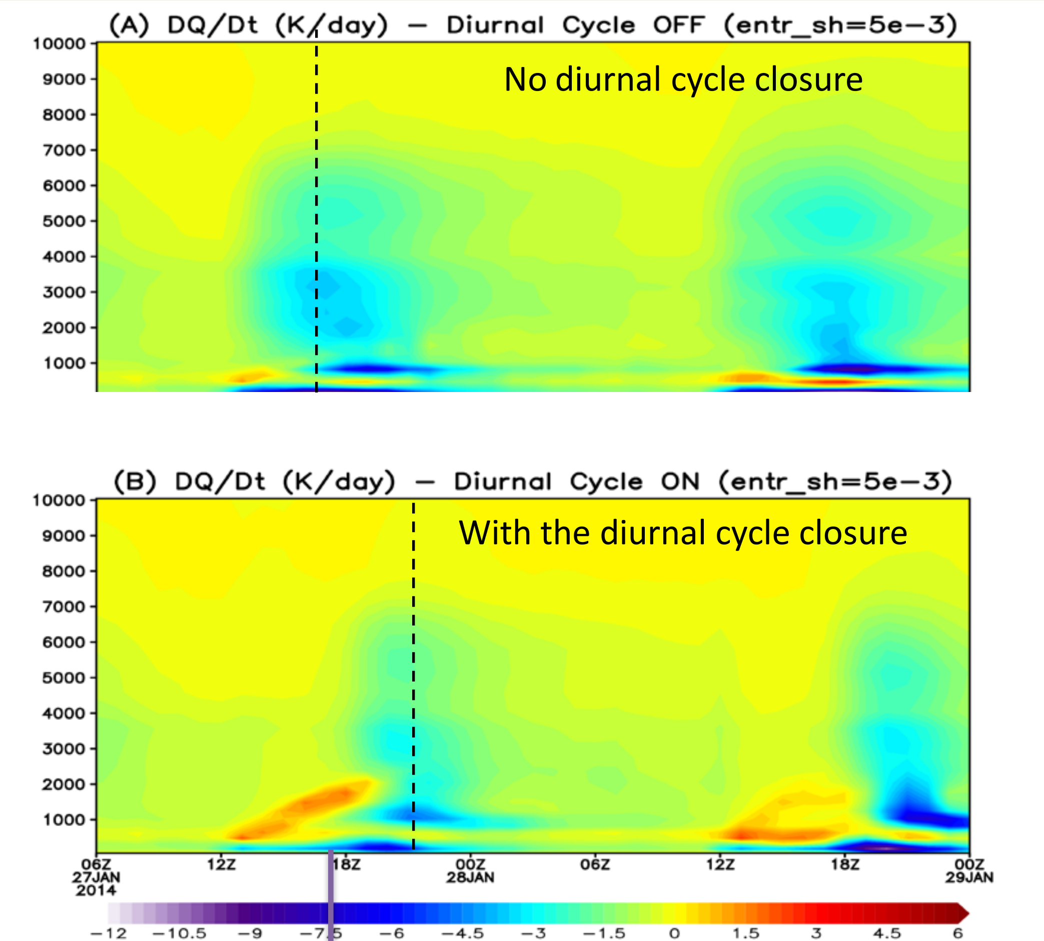
Improved diurnal cycle of deep convection over Amazonia with P. Bechtold and co-authors new closure for non-equilibrium convection

Convective Precipitation (mm/h)



- 5 days forecast of CP precip (mm/h)
- Model grid spacing 27km
- Area average over Amazon Basin
- BLUE = diurnal cycle closure OFF
- RED = diurnal cycle closure ON
- GREEN= surface solar radiation

water vapor tendency (K/day)



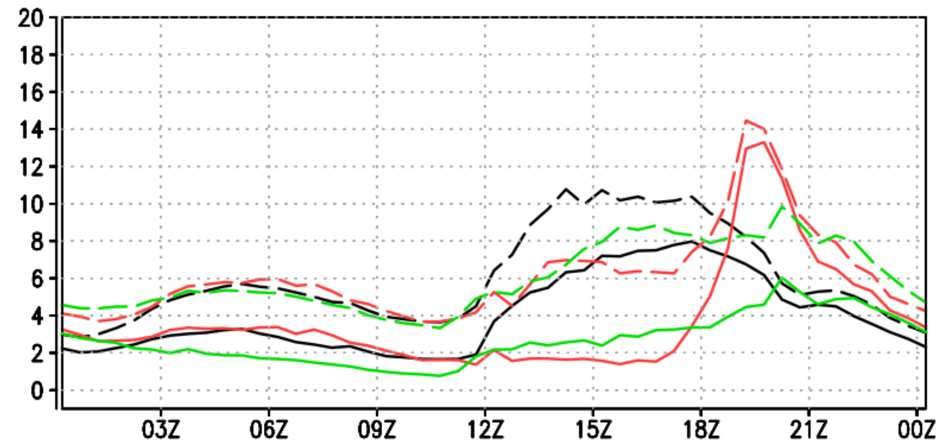
Better transition from shallow to deep convection regimes

Bechtold et al., 2014; Freitas and Grell, in prep.

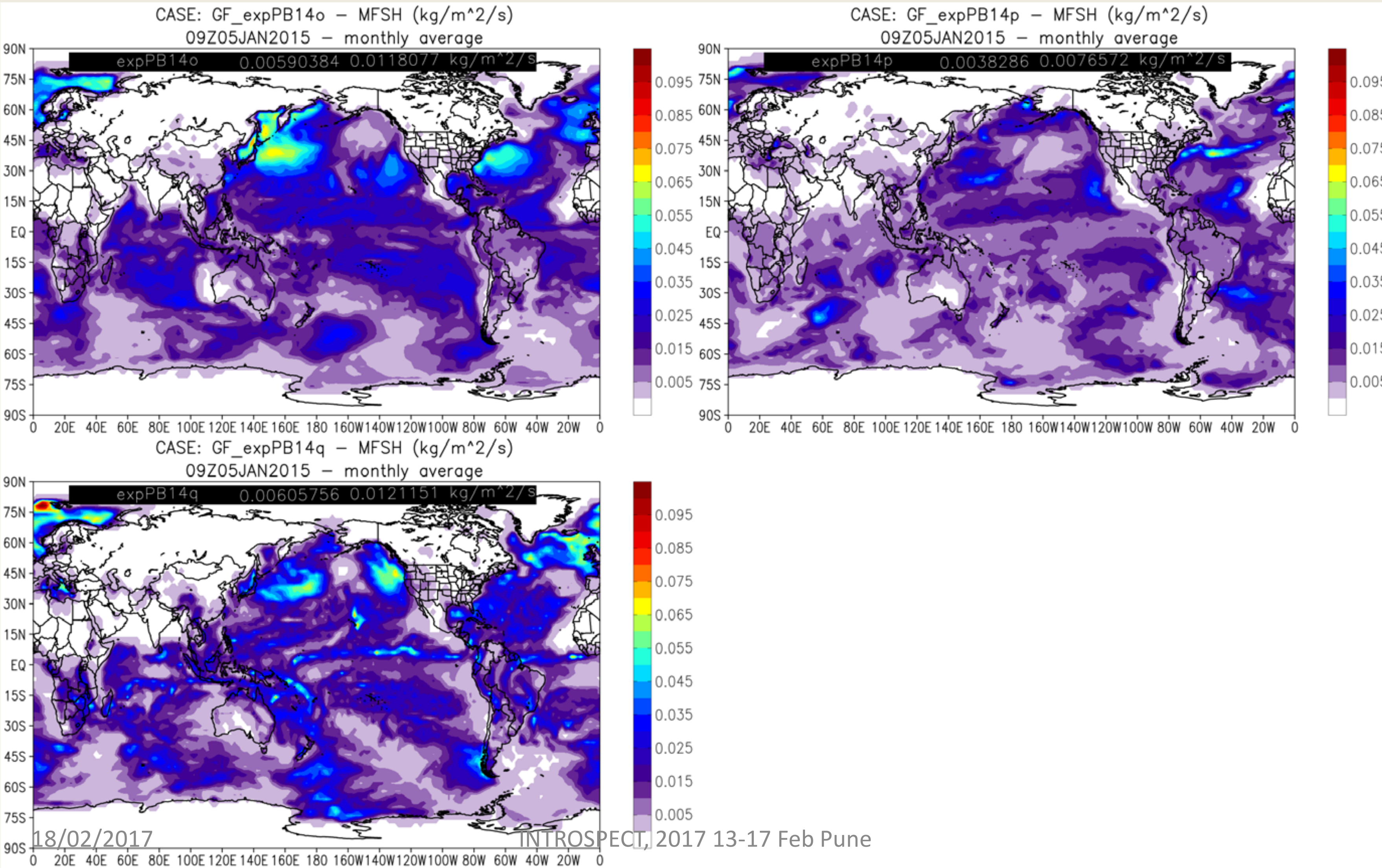
TRMM LBA

Simulated Rainfall (mm/day)
- **Total ---**
- **Parameterized ___**
- **Green RAS**
- **BLACK GF no dicycle**
- **RED GF with dicycle**

NASA GEOS model
- Single Column model
- Jan-Feb 1999
- IC/BC from MERRA-2 reanalysis

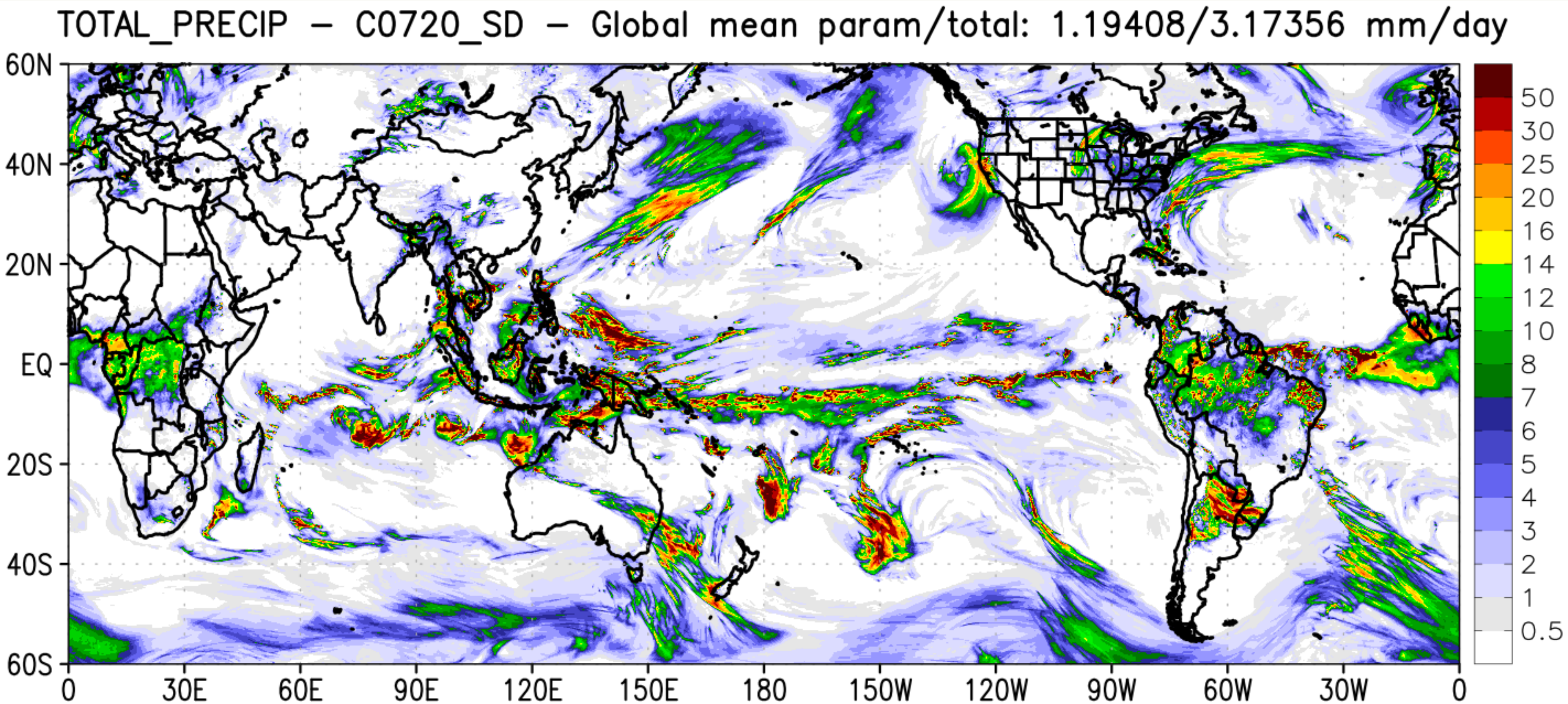


Shallow convection three closures



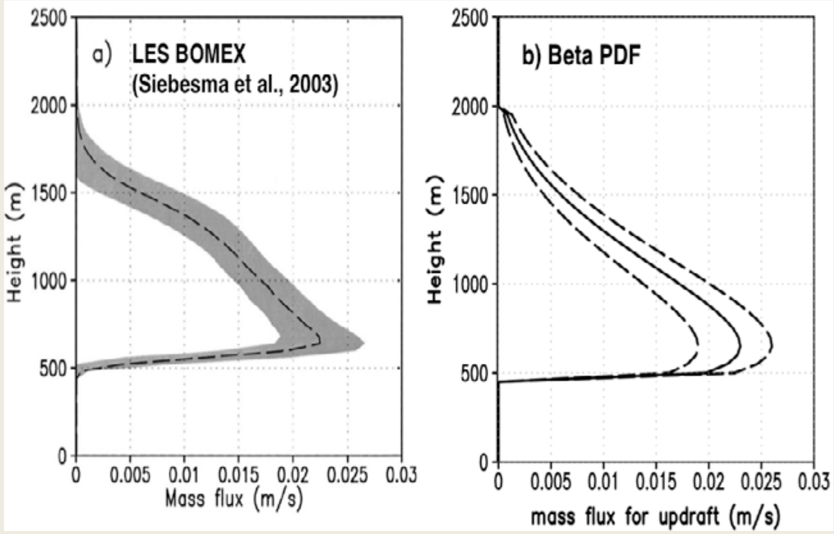
Results with NASA GEOS Global Model

Comparison with TRMM rainfall estimation

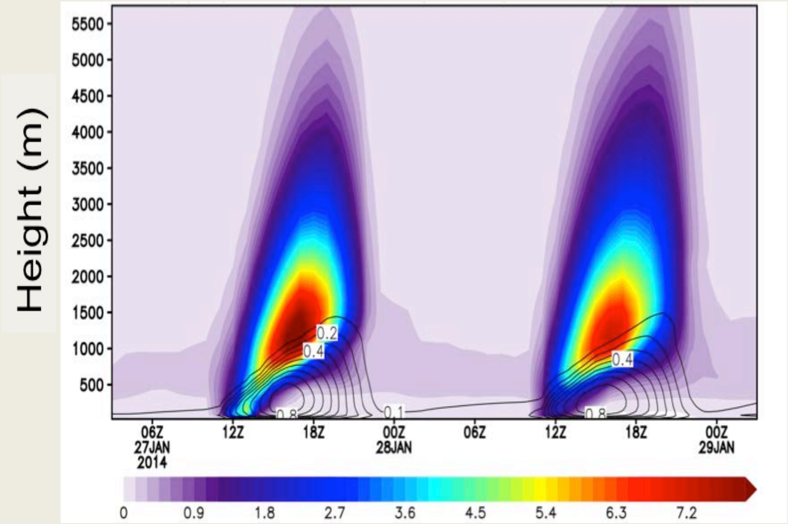


Shallow Convection Plume

- Non-precipitating
- Initial entrainment rate ~ 10^{-3} m^{-1}, Z^{-1} functional relationship
- Mass flux profile given by a Beta PDF
- Three closures – BLQE (Raymond, 1995), W^*(Grant, 2001) and, convection as natural heat engine (Rennó and Ingersoll, 1996)
- Cloud top constrained at 1st inversion layer above PBL height



On the left, mass flux profile of shallow convection simulated by a large eddies resolving model. On the right, a representation of the mass flux profile within the GF parameterization scheme using beta pdf

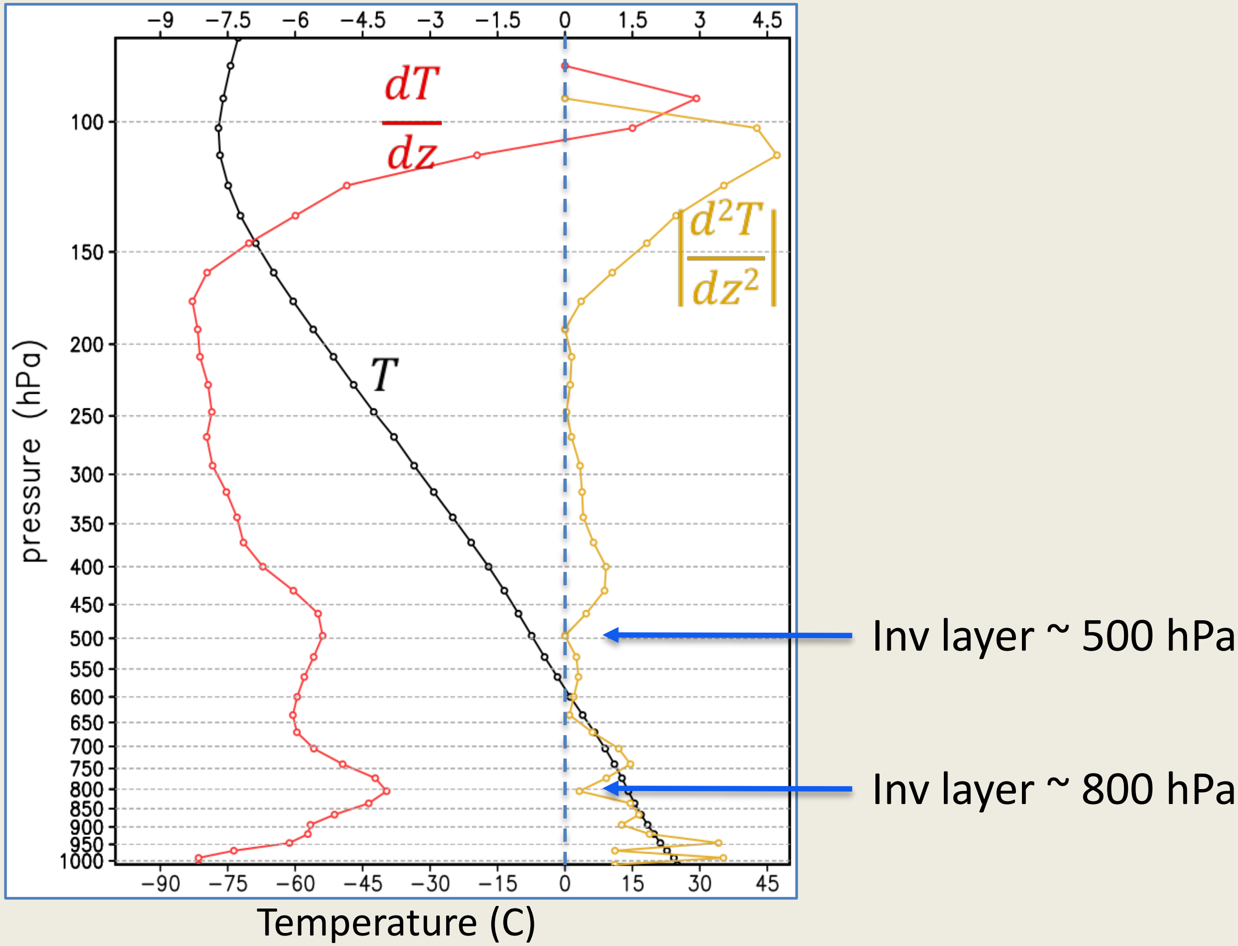


Diurnal cycle of the PBL and of shallow convective plume. The PBL is shown by the turbulent kinetic energy (m^2 s^{-2}, black contours), while the convective plume with saturated air is represented by the mass flux (10 kg m^{-2} s^{-2}, shaded colors).

A simple and efficient algorithm to determine atmospheric inversion layers

$$\frac{d^2T}{dz^2} \approx 0$$

$\frac{dT}{dz}$ local maximum



A scale aware stochastic convective parameterization

Arakawa et al (2011) propose the following equation for the vertical eddy transport that includes the scale dependence trough σ parameter:

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

Eddy transport

Fractional area covered by active cloud drafts.

Eddy transport given by a conventional CP for a full adjustment to a quasi-equilibrium state.

where σ and $\left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$ must be determined to close the unified parameterization.

$\left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$ $\begin{cases} \text{eddy transport for a full adjustment to a quasi-equilibrium state} \\ \text{can be calculated from a conventional cumulus parameterization.} \end{cases}$

σ is the fraction of the area covered by active updraft and downdraft plumes.

In the proposed scheme, σ is initially calculated by the entrainment (ε) rate and the grid-cell area:

$\varepsilon = \dfrac{b}{R}$, where R is the radius of the convective plumes (up and downdraft), $b = 0.2$

The initial entrainment is defined as $7\ 10^{-5}$.

$$\therefore \sigma = \begin{cases} \dfrac{\pi R^2}{\Delta x \Delta y}, \text{ if } < 0.7 \\ 0.7 \text{ and } \begin{cases} R = \sqrt{0.7 \Delta x \Delta y / \pi} \\ \varepsilon = \dfrac{b}{R} \end{cases} \end{cases}$$