Convection and precipitation in CAM: Sensitivity to new schemes, resolution and dynamical cores

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NESL's Climate & Global Dynamics

U.S. DEPARTMENT OF ENERGY

NSF

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Convection schemes in climate models

Mass flux schemes: How they work. Assumptions made.

What do convection schemes do in AGCMs ? Do we really need them? At which resolutions?

Thermodynamic Equation

$$\partial_t \rho s + \nabla \cdot \rho \mathbf{u} s + \partial_z \rho w s = Q + \ldots$$

Latent heating

Plume/cloud cont. equation

$$\partial_t \rho a + \partial_z \rho a w_c = E - D$$

Cloud areal fraction

Entrainment

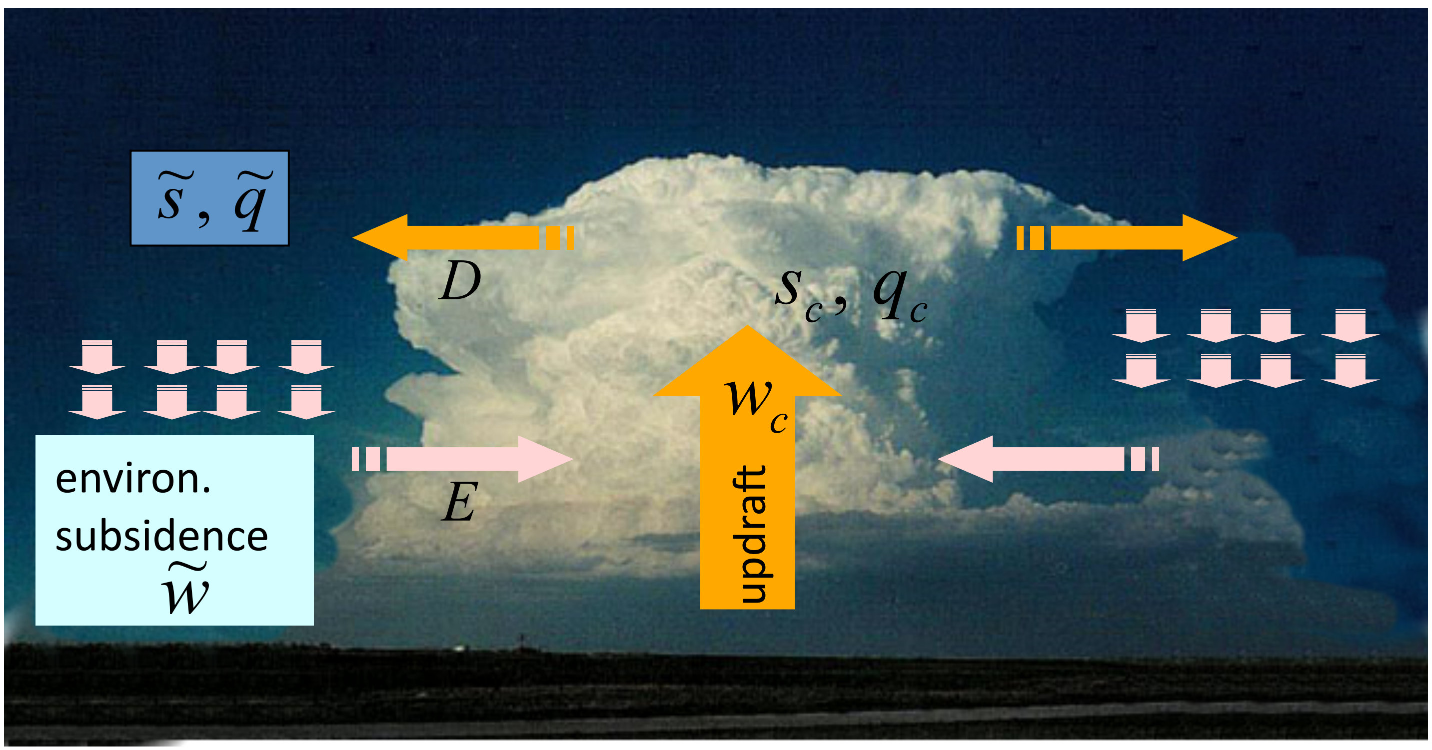
Detrainment

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \overline{Q} - \partial_z \overline{\rho w' s'} + \ldots$$

Plume therm. equation

$$\partial_t \rho a s_c + \partial_z \rho a w_c s_c = E\tilde{s} - D s_c + a Q_c$$



Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \overline{\rho w' s'} + \ldots$$

Sub-grid fluxes re-written

$$\partial_z \overline{\rho w' s'} = \partial_z \rho a w_c s_c + \partial_z \rho (1-a) \tilde{w} \tilde{s}$$

compensating subsidence*

$$\Leftrightarrow \rho a w_c = -\rho (1-a) \tilde{w}$$

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \rho a w_c s_c - \partial_z \rho (1-a) \tilde{w} \tilde{s} + \ldots$$

$$\partial_z \rho a w_c s_c = E \tilde{s} - D s_c + aQ_c - \partial_t \rho a s_c$$

Plume therm. equation

Grid box average therm. equation

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$$\partial_z \rho a w_c s_c = E\widetilde{s} - D s_c + \cancel{aQ_c} - \partial_t \rho a s_c$$

Plume therm. equation

Explicit in-cloud latent heating term drops out

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho}\,\overline{w}\,\overline{s} = -E\widetilde{s} + D s_c + \partial_t \rho a s_c - \partial_z \rho (1-a) \widetilde{w}\widetilde{s} + \ldots$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w s} = -E\tilde{s} + Ds_c + \partial_t \rho a s_c - \partial_z \rho(1-a)\tilde{w}\tilde{s} + \ldots$$

$$-\rho(1-a)\tilde{w} = \rho a w_c \equiv M_c$$

$$a \to 0 \;\; \Leftrightarrow \tilde{s} \to \bar{s}$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w s} = \underbrace{-E\bar{s} + Ds_c + \partial_z M_c \bar{s}} + \ldots$$

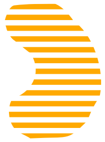
In final form, cumulus forcing is determined entirely by profiles of E, D, and M_c. Key assumptions up to here:

$-\rho(1-a)\tilde{w} = \rho a w_c$ (compensating subsidence);

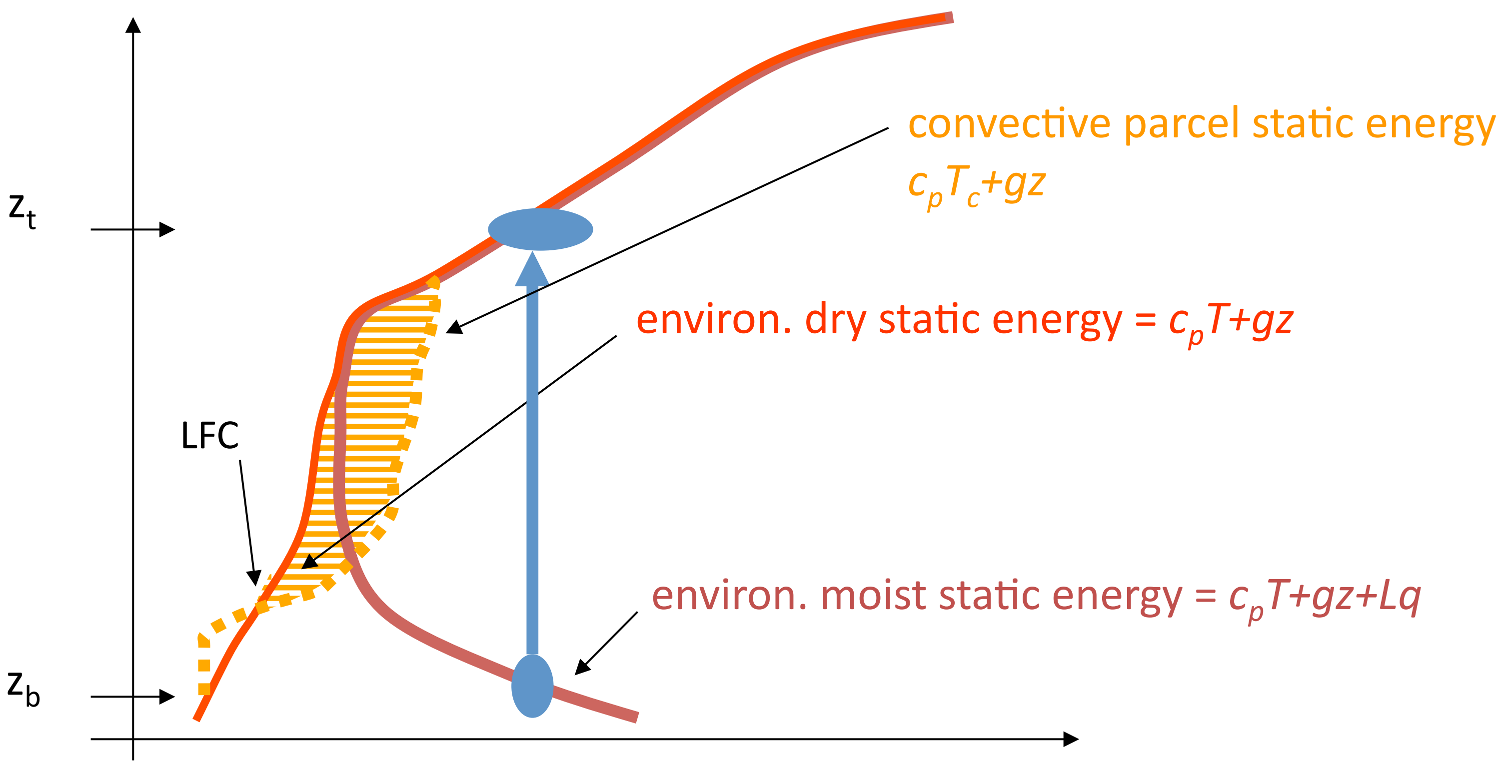
$a \to 0$ (small areal fraction/negligible storage)

Mass-flux convective parameterizations determine profiles E, D, and M_c based on grid mean quantities and ***assumed plume models***.

Convective Available Potential Energy is a common control for parameterized convective mass flux in climate models



$$\sim CAPE = g\int_{z_B}^{z_T} \frac{T_c - T}{T}\,dz \qquad M_c(z_b) \sim f(CAPE, \partial_t CAPE)$$



Climate model problems attributed to convection schemes

Convective "drizzle" falling almost all the time over oceanic convective regions

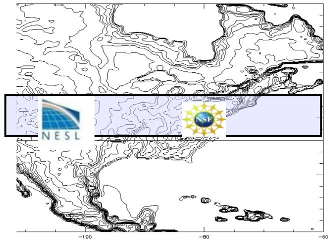
Early diurnal maximum in precipitation over warm land

Overly-regular diurnal cycle of precipitation over warm land

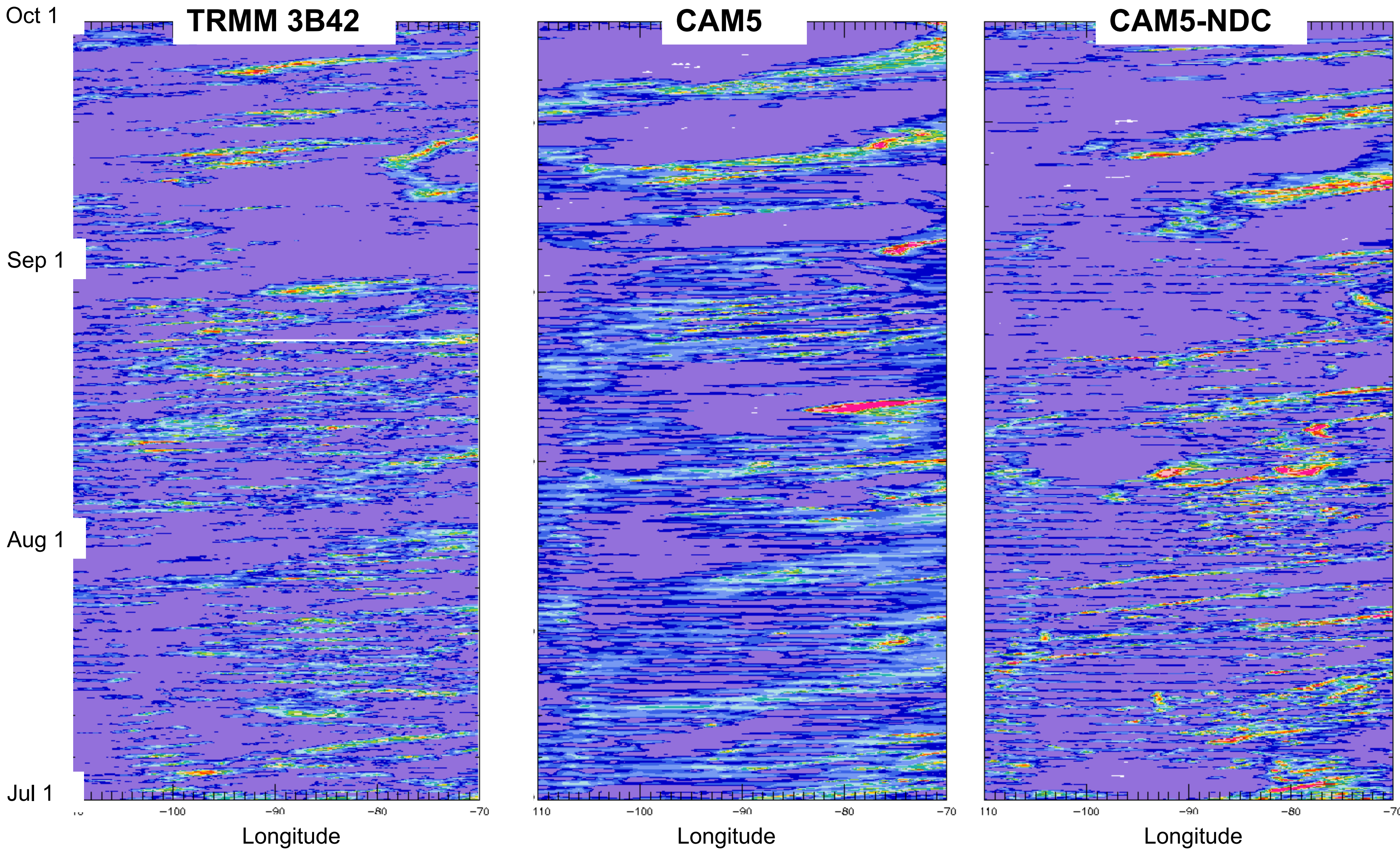
Insufficient tropical cyclogenesis

No MCCs over warm land

No MJOs/weak MJOs



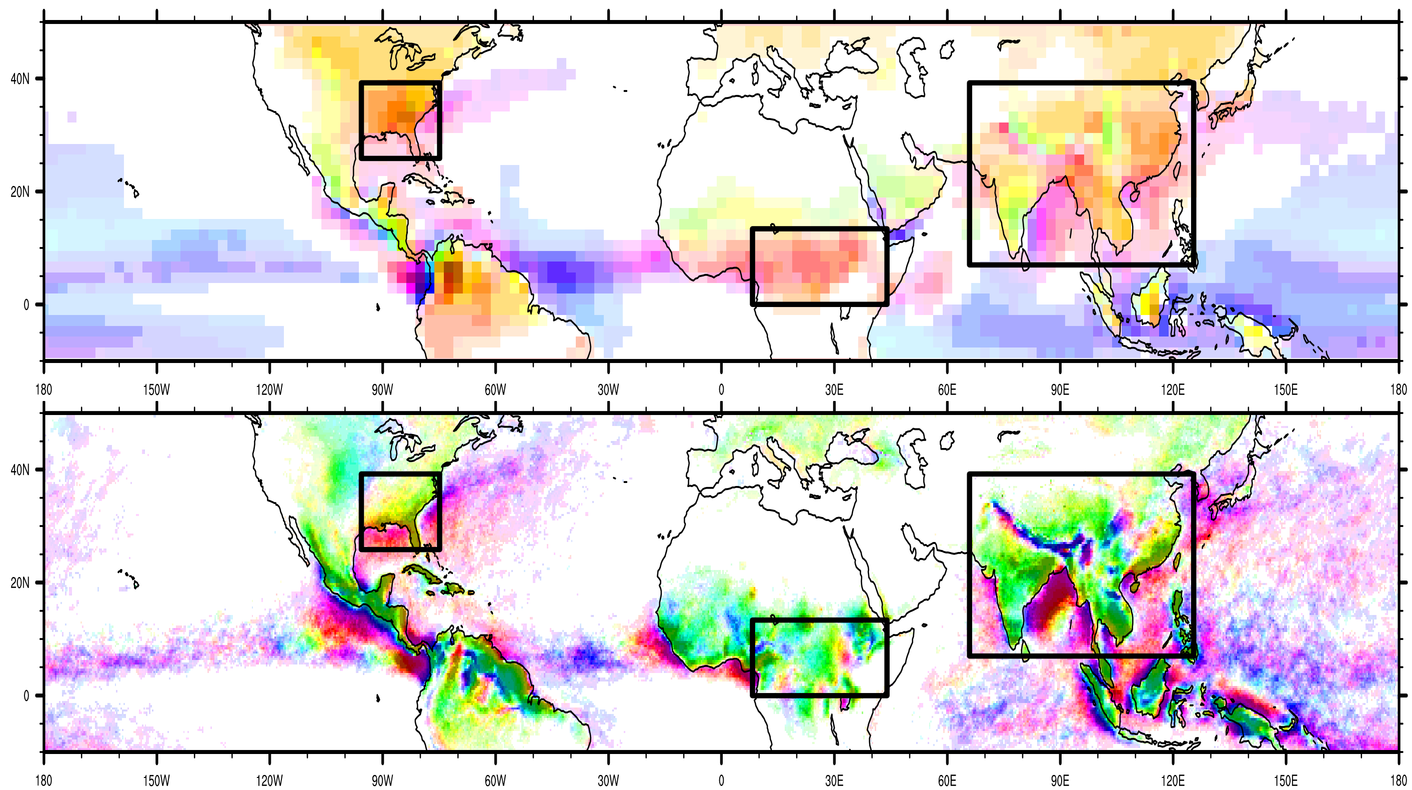
Precipitation Hovmueller diagrams: US Midwest
July 1 to October 1 2005



Diurnal Cycle of Precipitation. JJA.

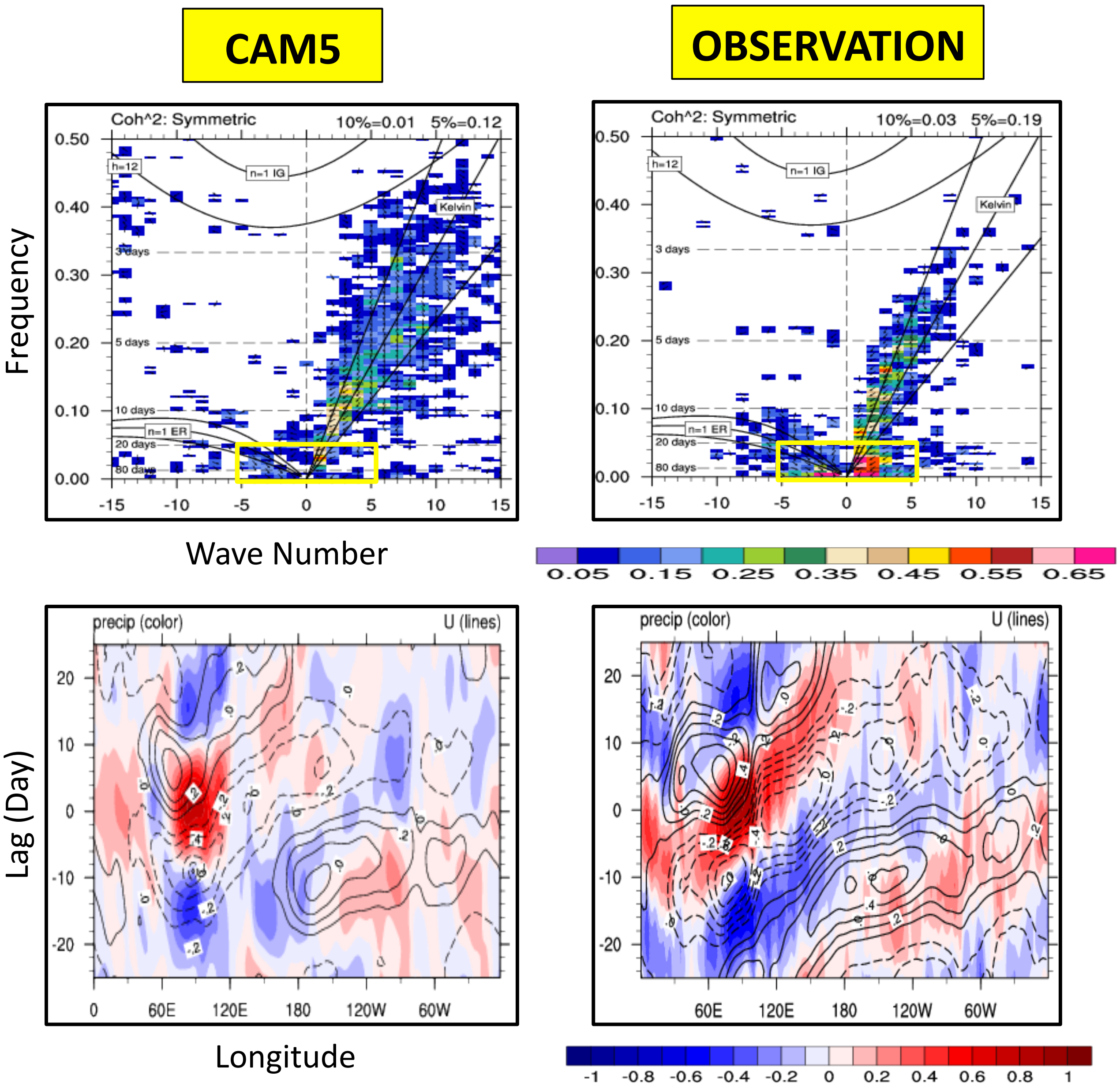
CAM5

OBS

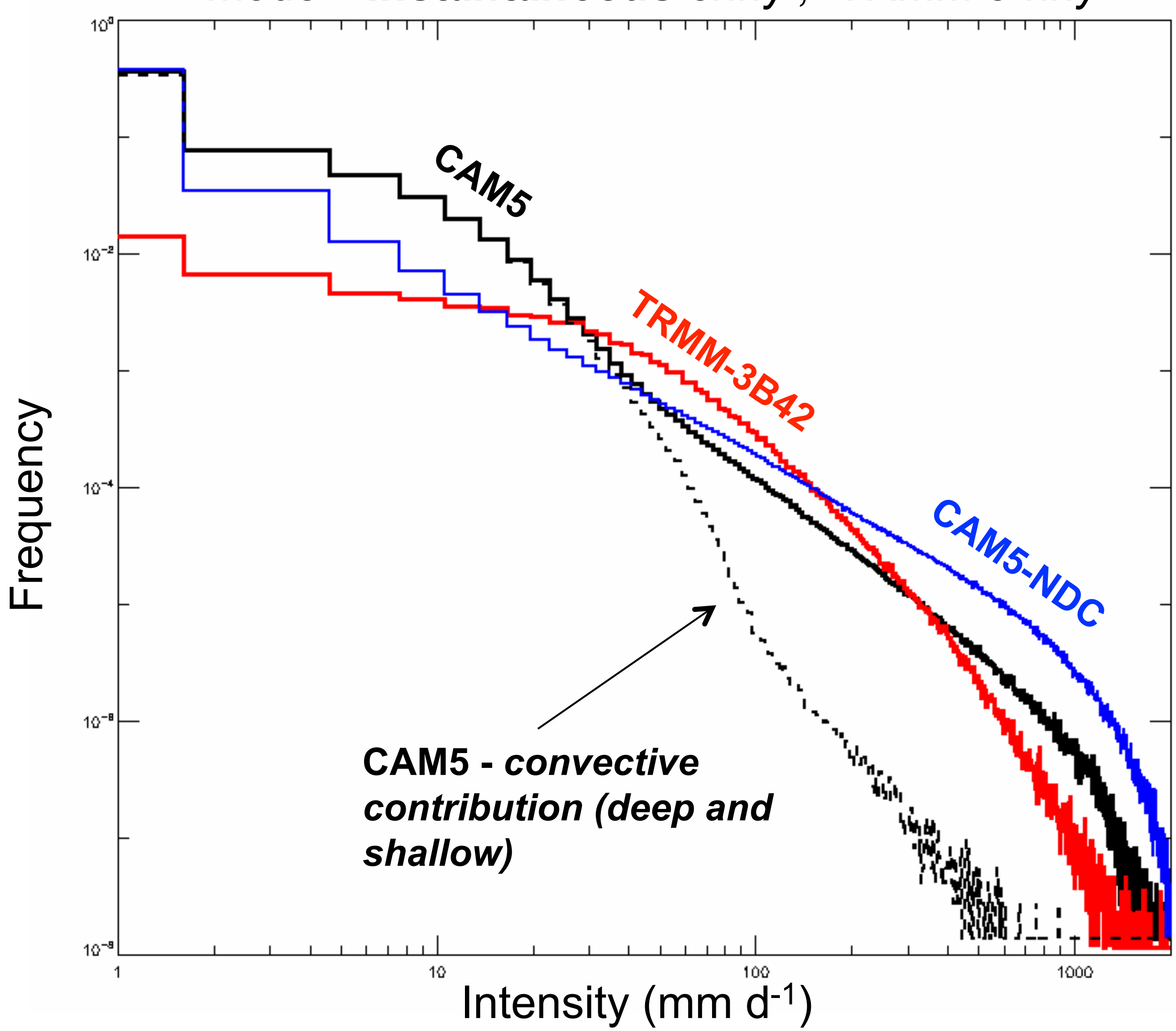


Local Hour of Max Precip

Madden-Julian Oscillation

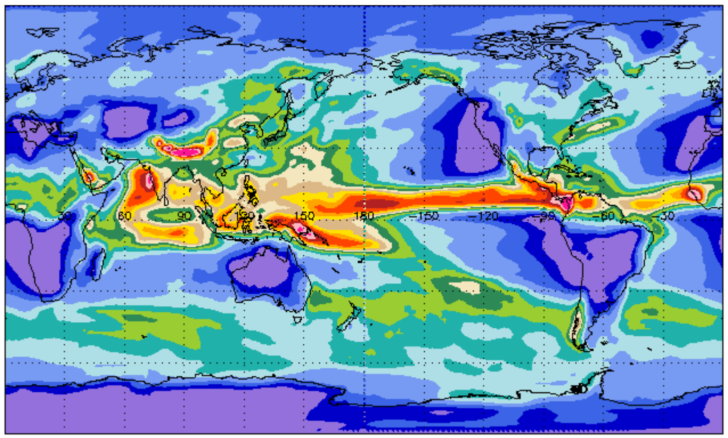


PDFs of tropical precipitation (30S-30N) rates Aug 2005
model –***instantaneous*** *3hrly* , TRMM *3-hrly*

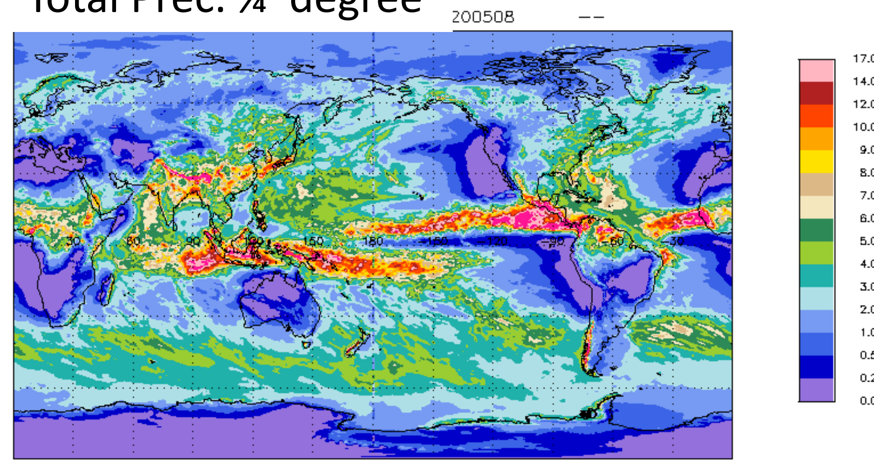


JJA precipitation

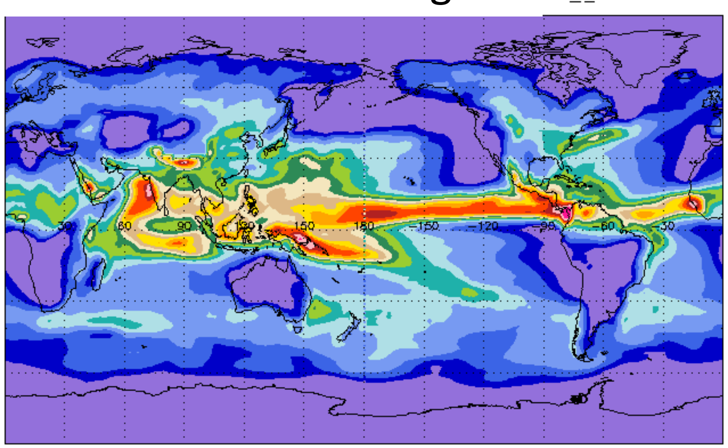
Total Prec. 2 degree



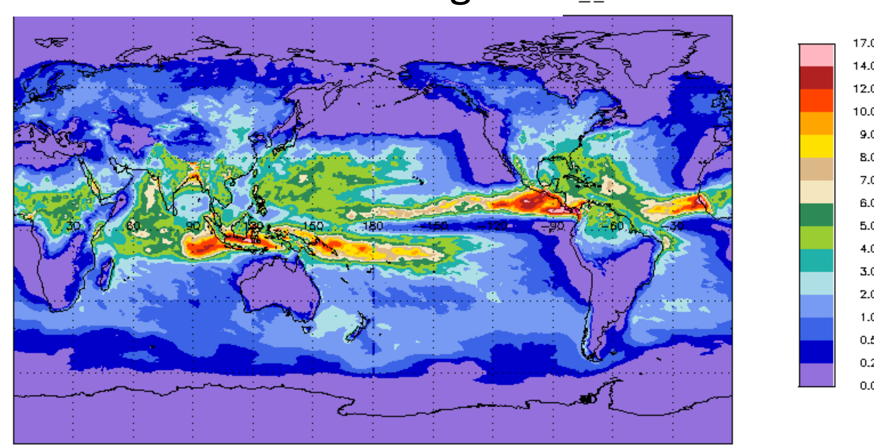
Total Prec. ¼ degree



Convective Prec. 2 degree



Convective Prec. ¼ degree



Climate model precipitation sensitivity to resolution and dynamical cores

Many features do not improve with resolution

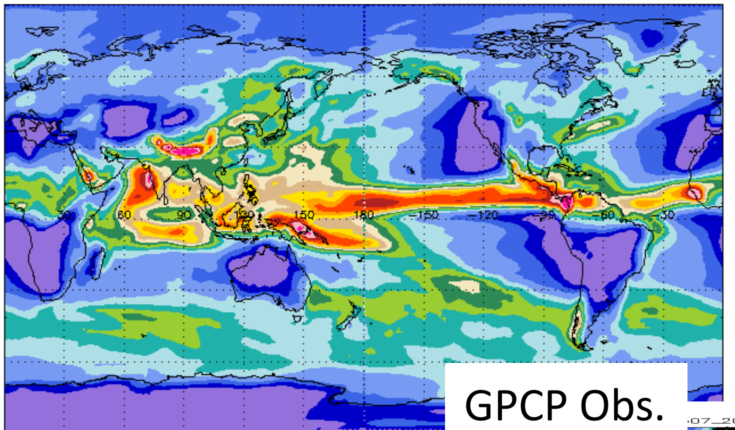
Contribution from convective precipitation drops off with resolution

Apparent trade off between fraction of convective precipitation and “mesoscale organization”

At small-scales and intense rates dynamical core becomes significant

JJA precipitation

Total Prec. 2 degree



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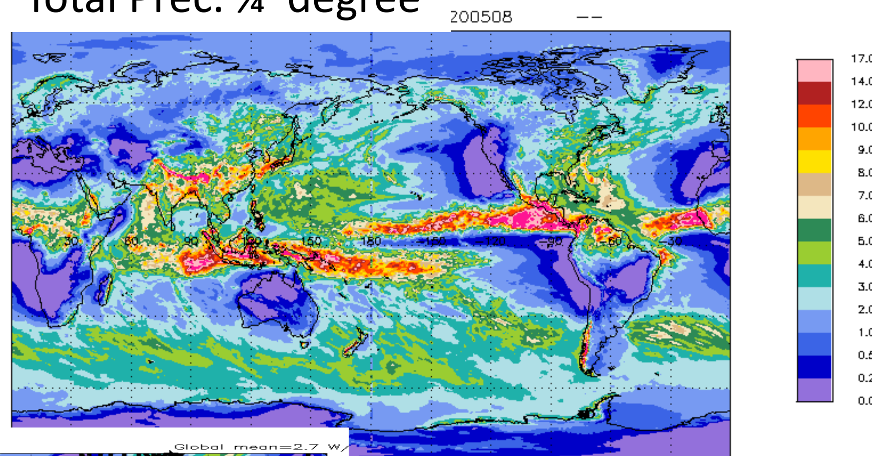
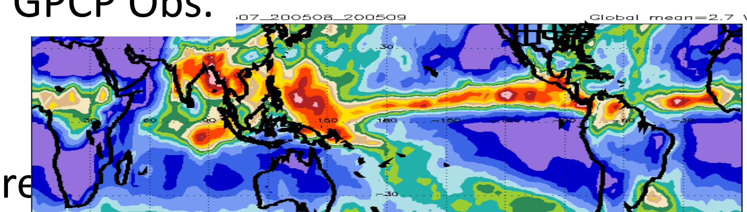
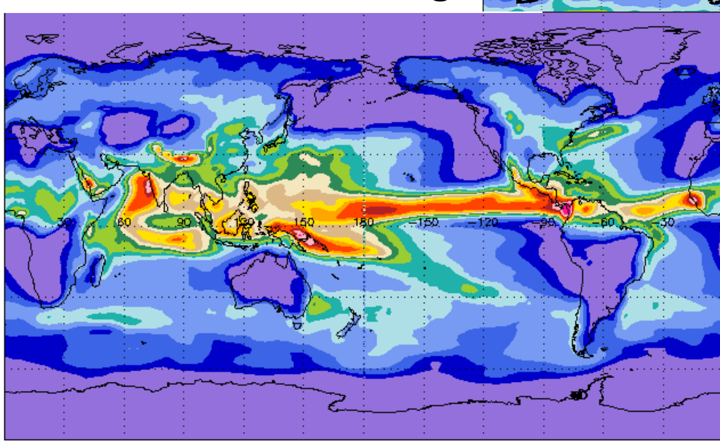


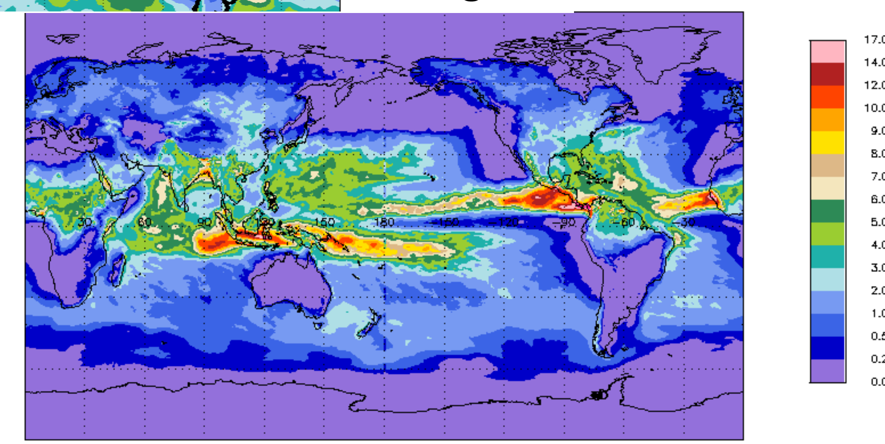
GPCP Obs.



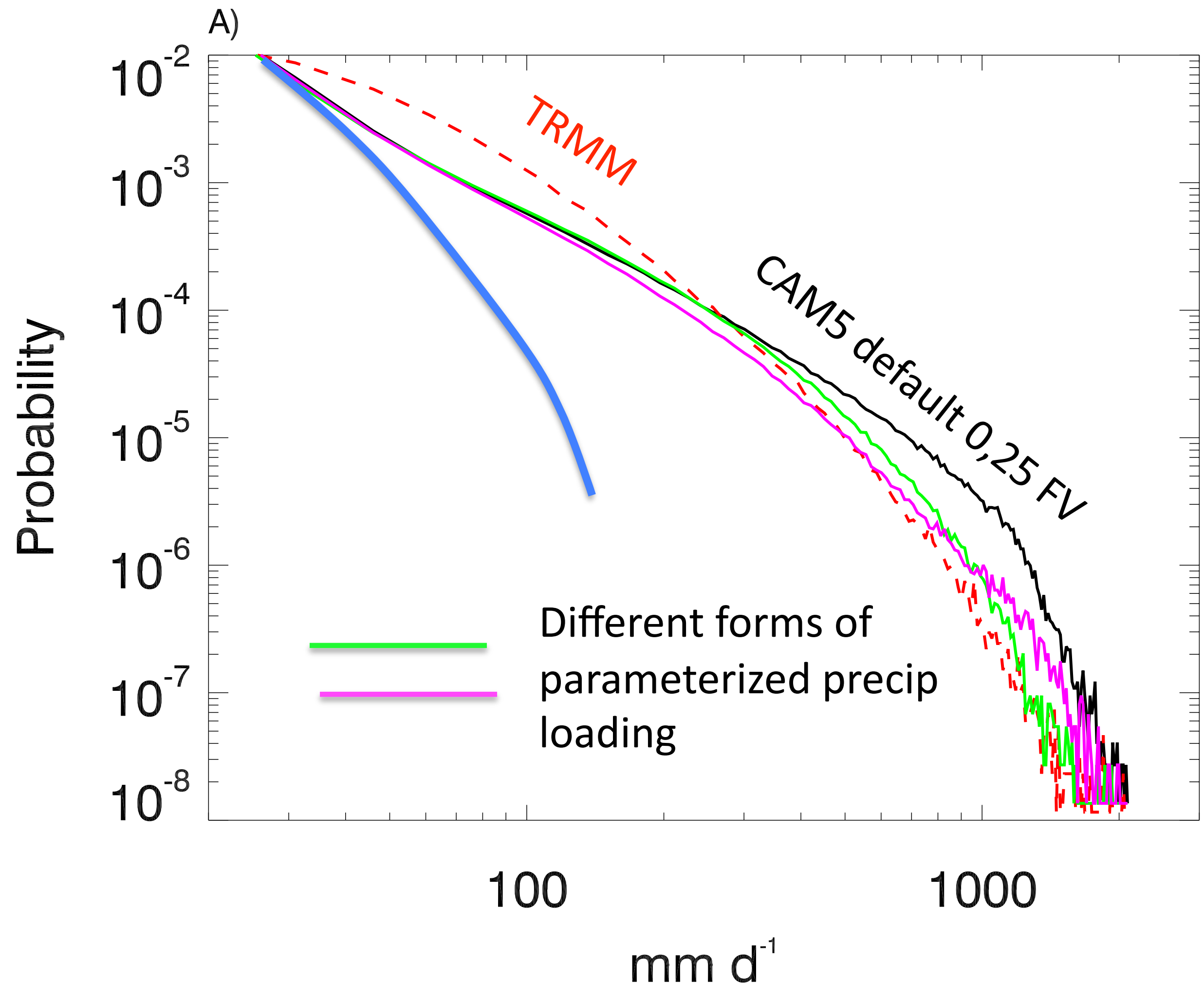
Convective Prec. 2 degre



¼ degree

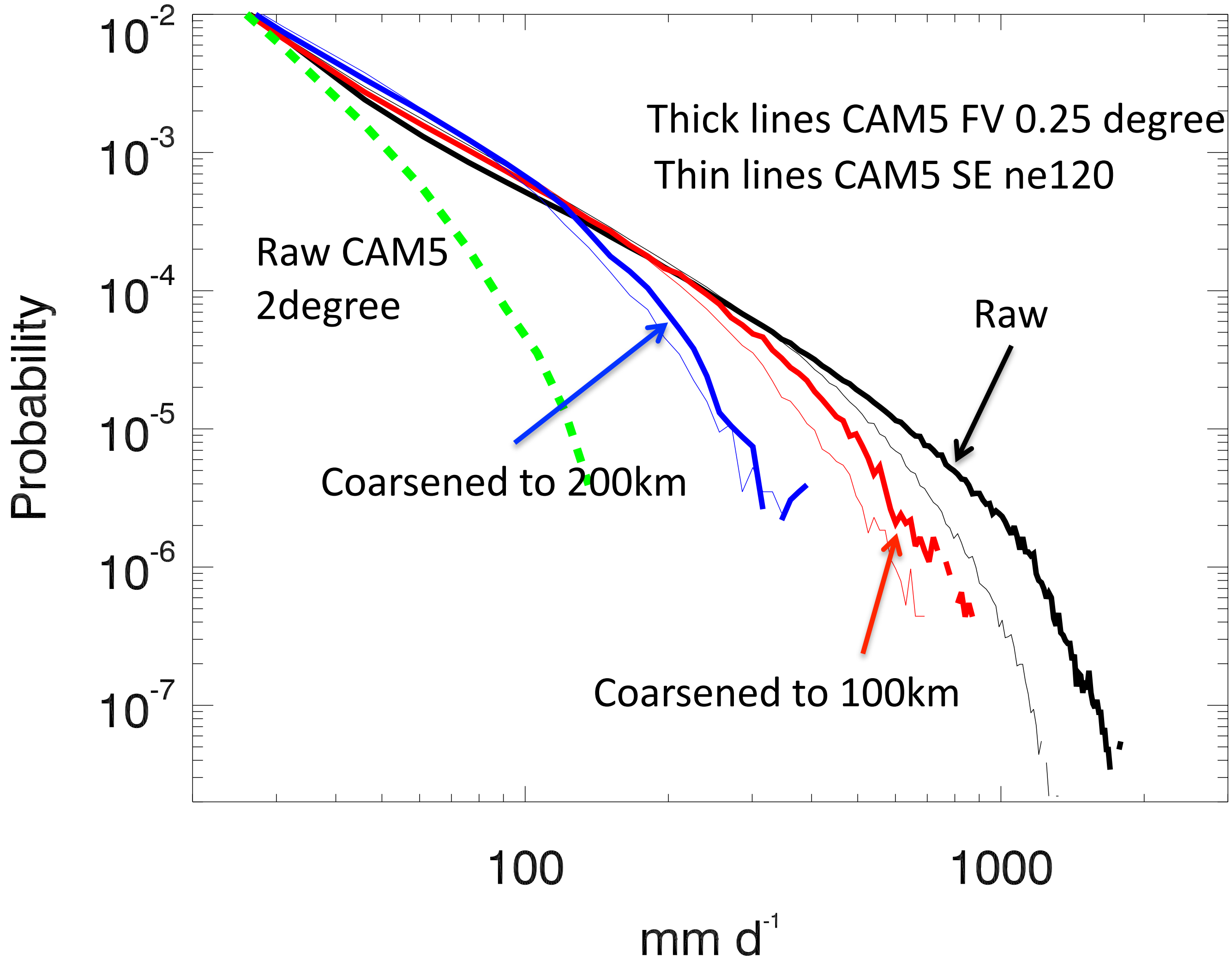


Precipitation Intensity Statistics for August (instantaneous 3hrly data)

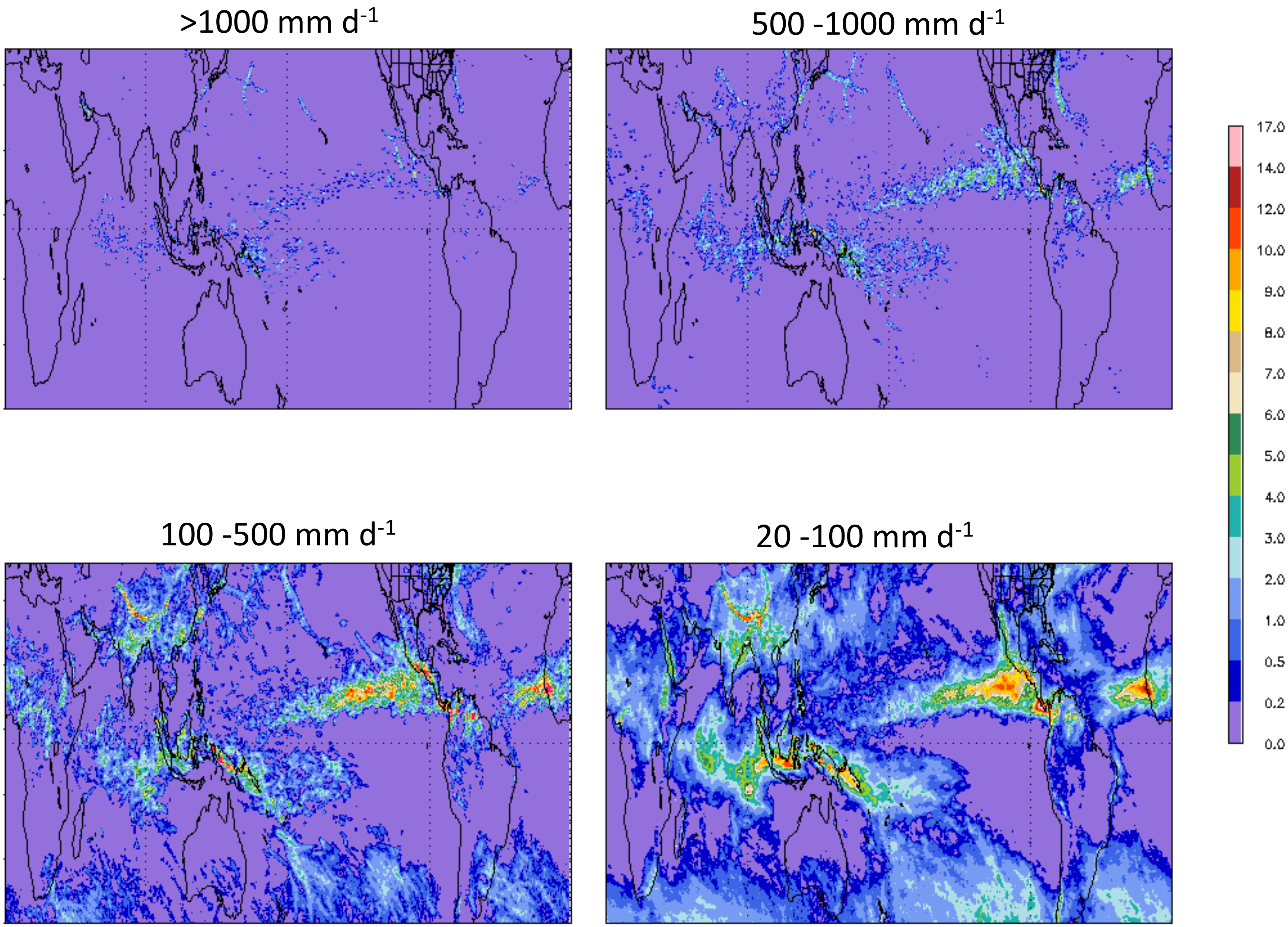


(Bacmeister et al 2012, GRL)

Precipitation Intensity Statistics for JJA (instantaneous 3hrly data)



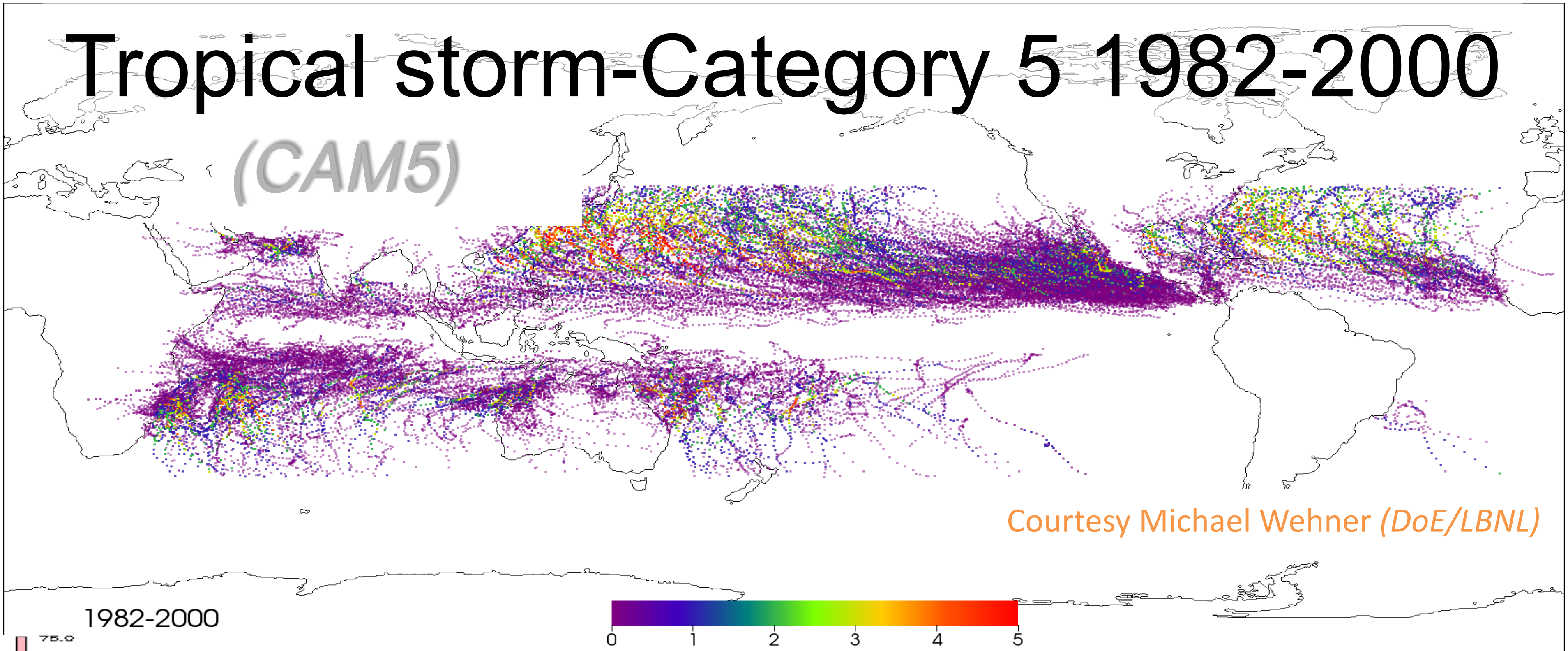
Where do various intensity regimes fall? CAM-FV

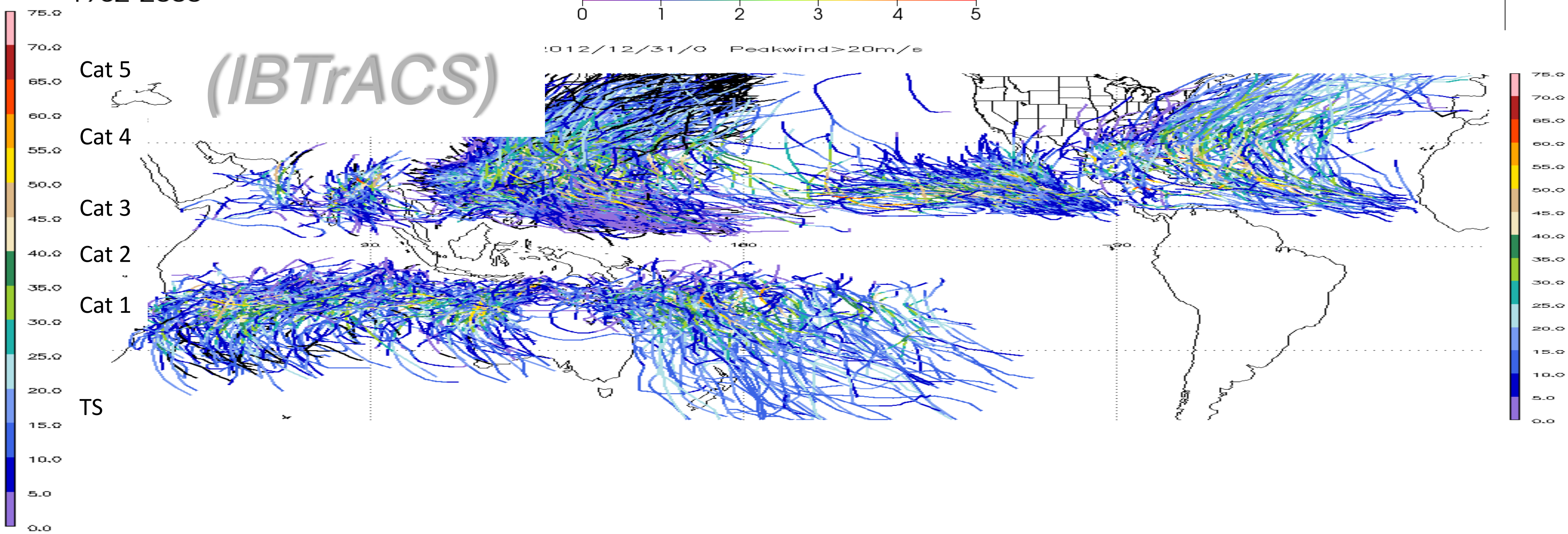


Mesoscale organization in climate models

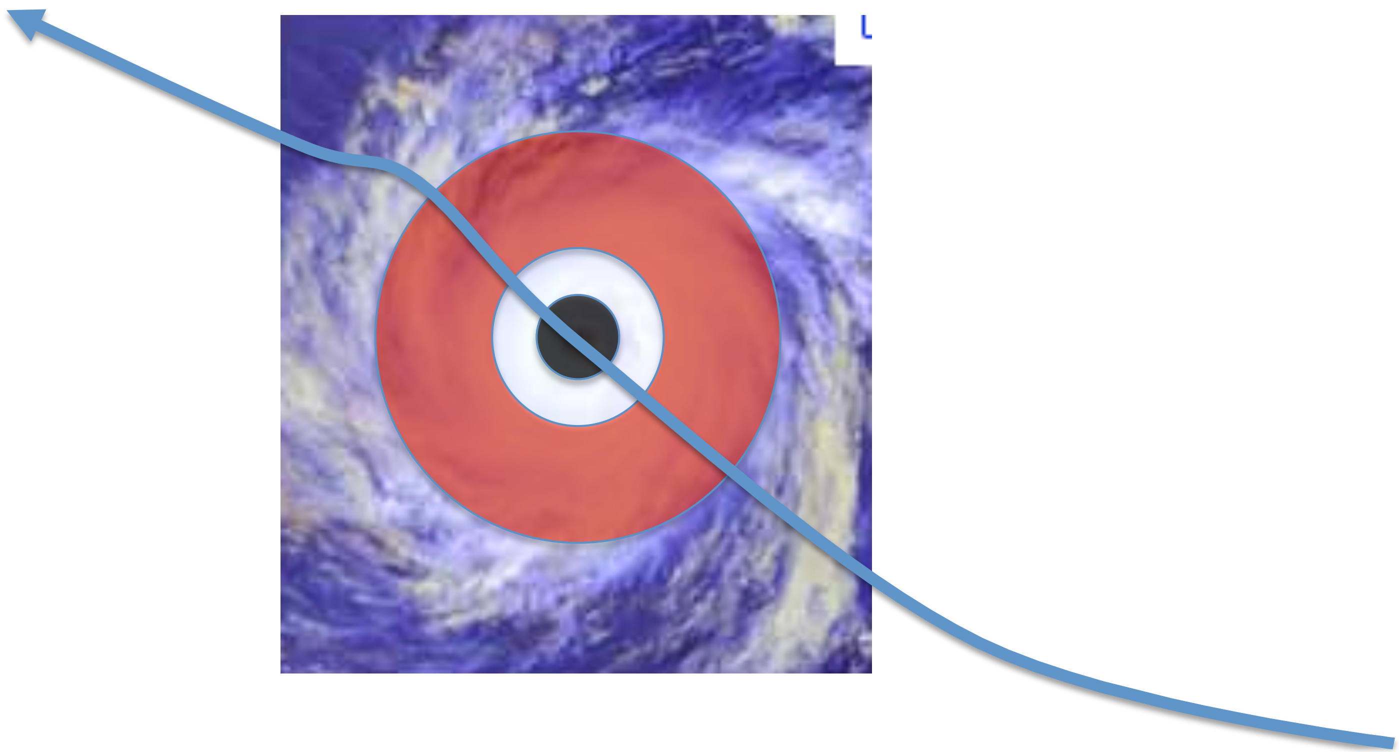
3 US climate modeling groups (GFDL, NCAR, NASA/GMAO) note improvements in mesoscale aspects of climate associated with reduced activity in parameterized convection

Tropical storm-Category 5 1982-2000





Time series of precipitation following storms in CAM5;
core r<50km (black) and ***storm exterior*** 500km>r>250km

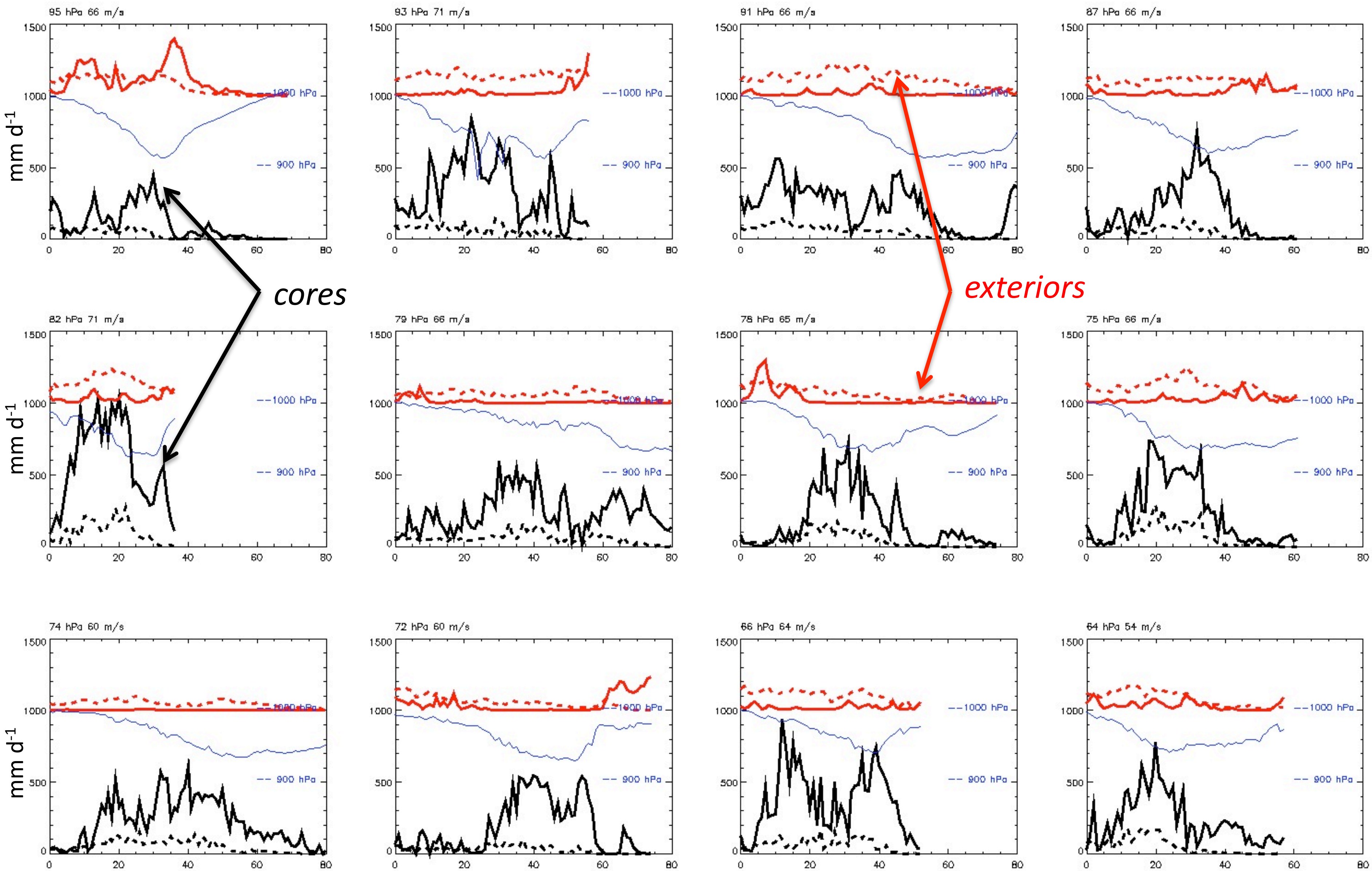


Convective and large-scale precipitation separated

Precipitation time series in ***storm cores*** ***(black)***, ***storm exteriors*** ***(red)***.

Convective precip (dashed), Large-scale precip (solid).

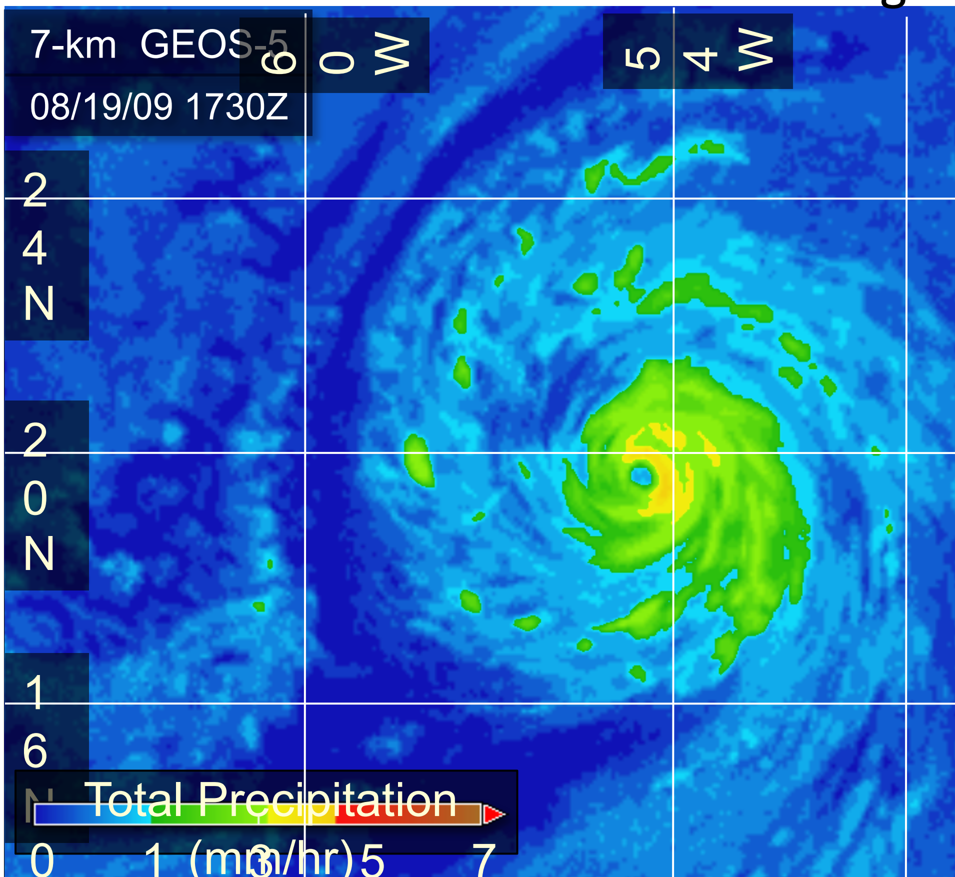
Thin ***blue*** *lines show surface pressure.* ***Note overwhelming dominance of LS in cores***

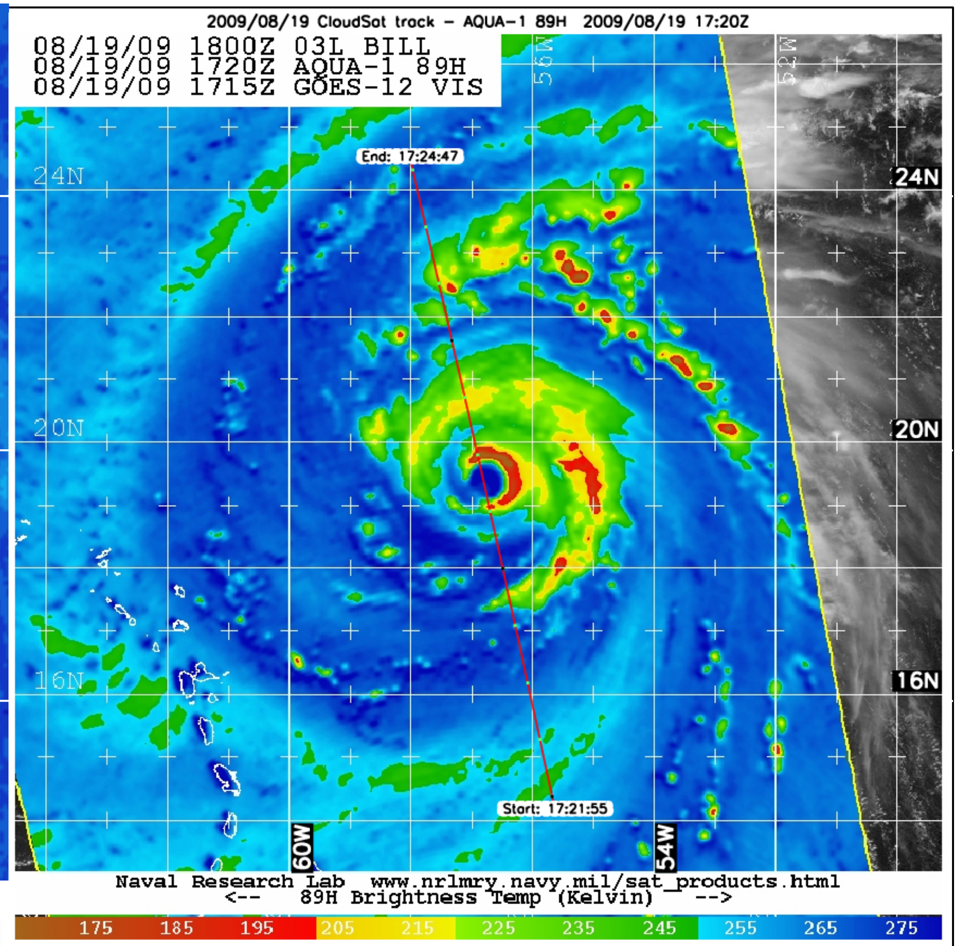


Hurricane Bill

August 2009

69-hr forecast Initialized 2009-08-16 21z





The strong influence of RAS, and a 15 minute time-step for the moist physics leads to problems within the circulation of Hurricane Bill at 7-km resolution:

- a lack of deep convective (heavy) precipitation
- an excess of shallow precipitation
- a very small eye, filled with drizzle

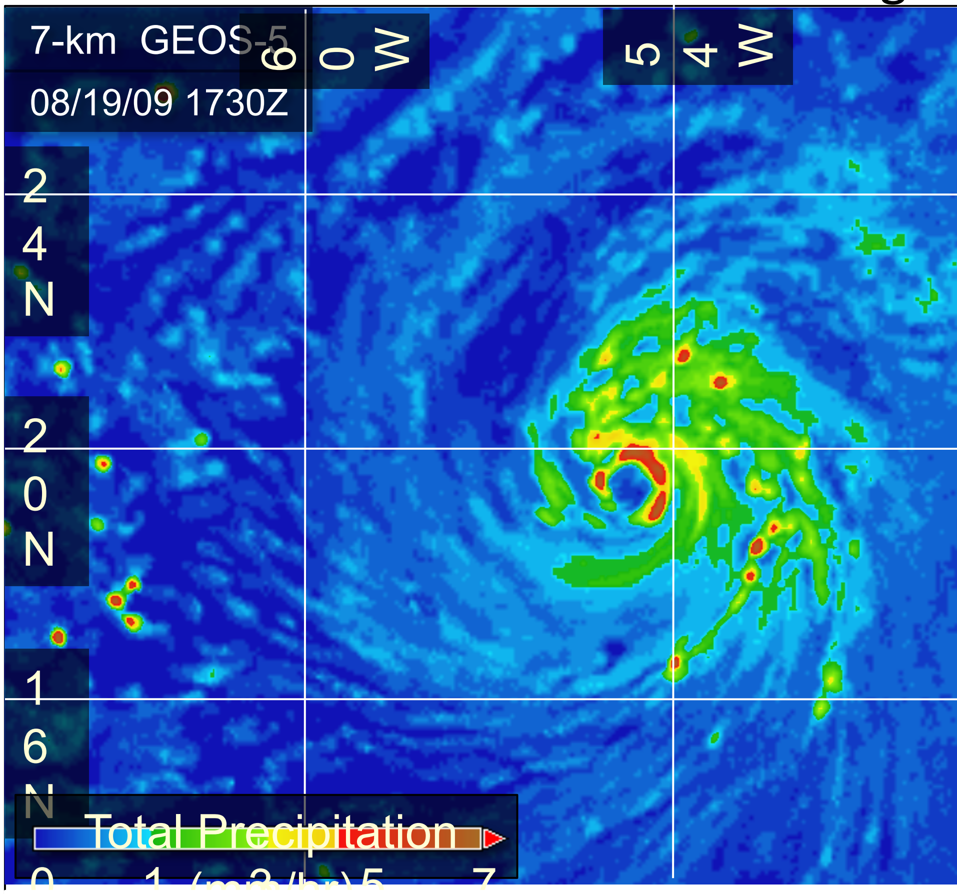
18N 19N 20N 21N

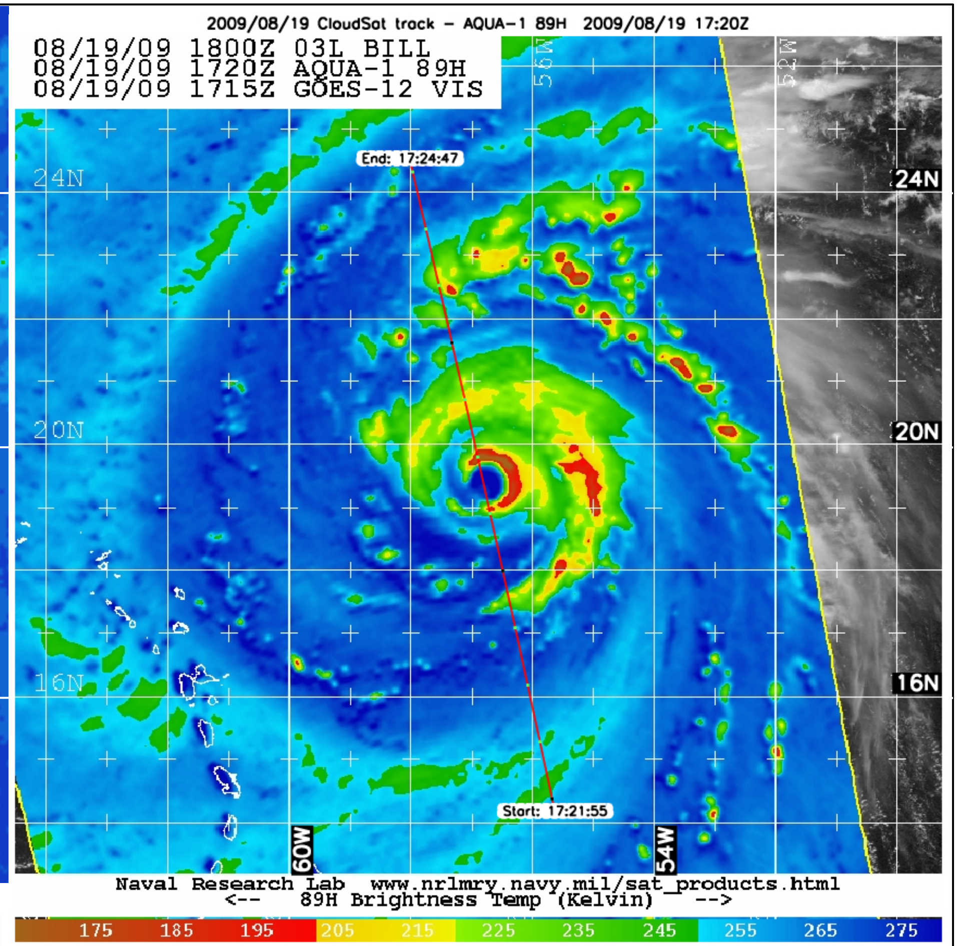
22N 23N 24N

Hurricane Bill

August 2009

69-hr forecast Initialized
2009-08-16 21z



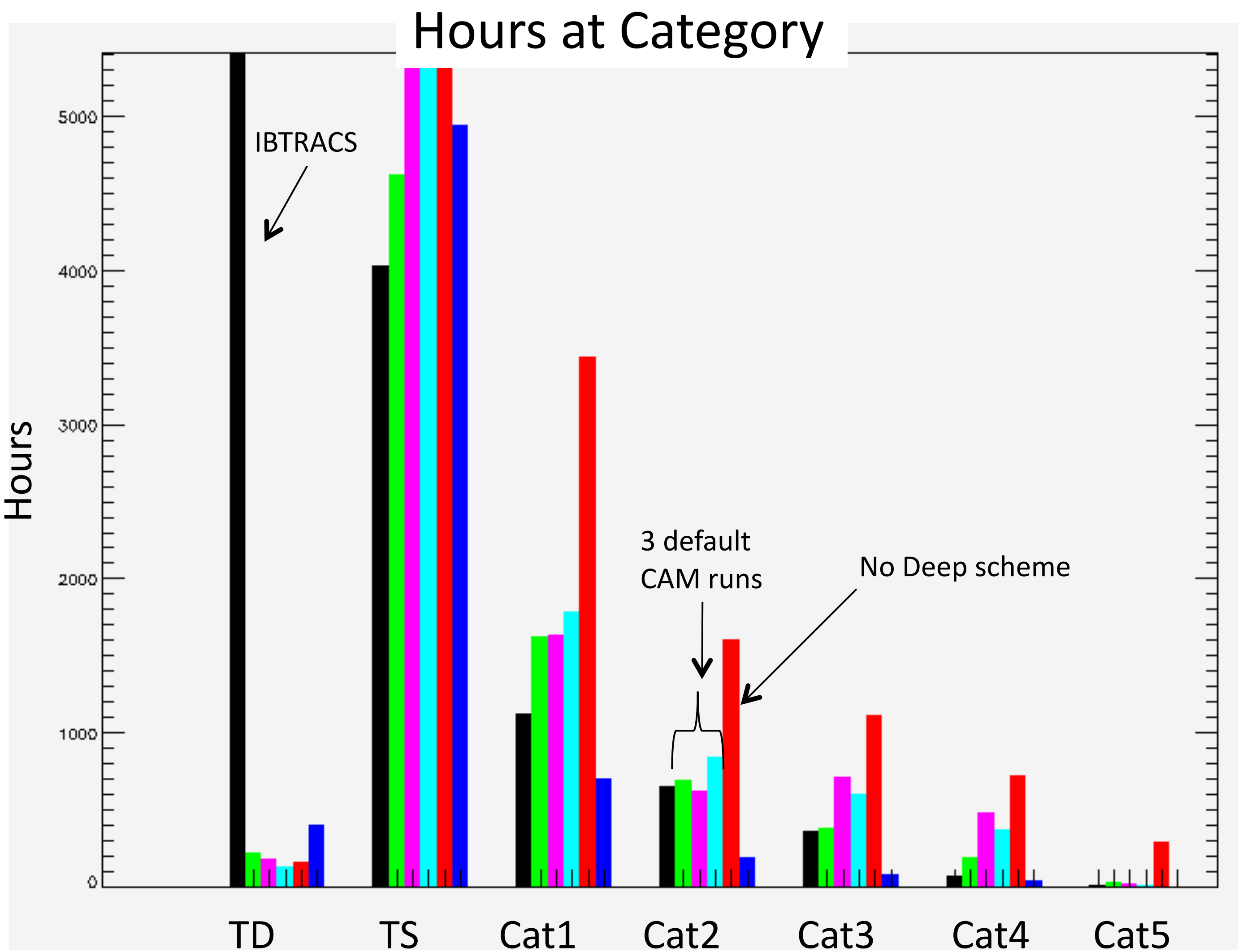


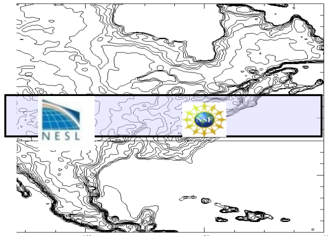
Using Tokioka limiter to reduce RAS, and a 120 second time-step for the moist physics improves the convection within Hurricane Bill:

- deep convective precipitation within the eye wall
- Banded structure with embedded convection
- Realistic eye diameter, clear of precipitation

18N 19N 20N 21N
22N 23N 24N

Time spent by tropical cyclones/storms in each intensity category- Global 2005





Precipitation Hovmueller diagrams: US Midwest
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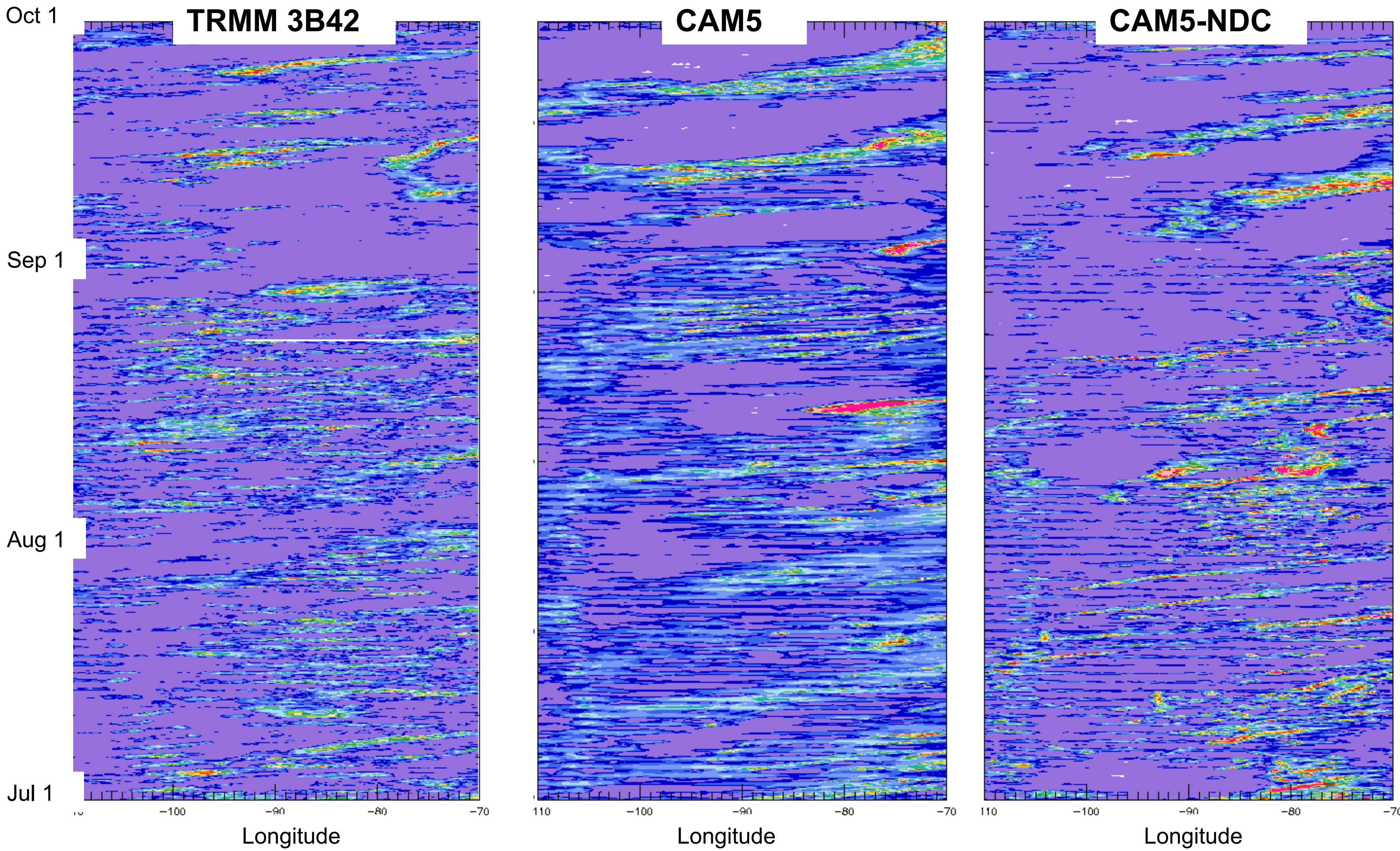


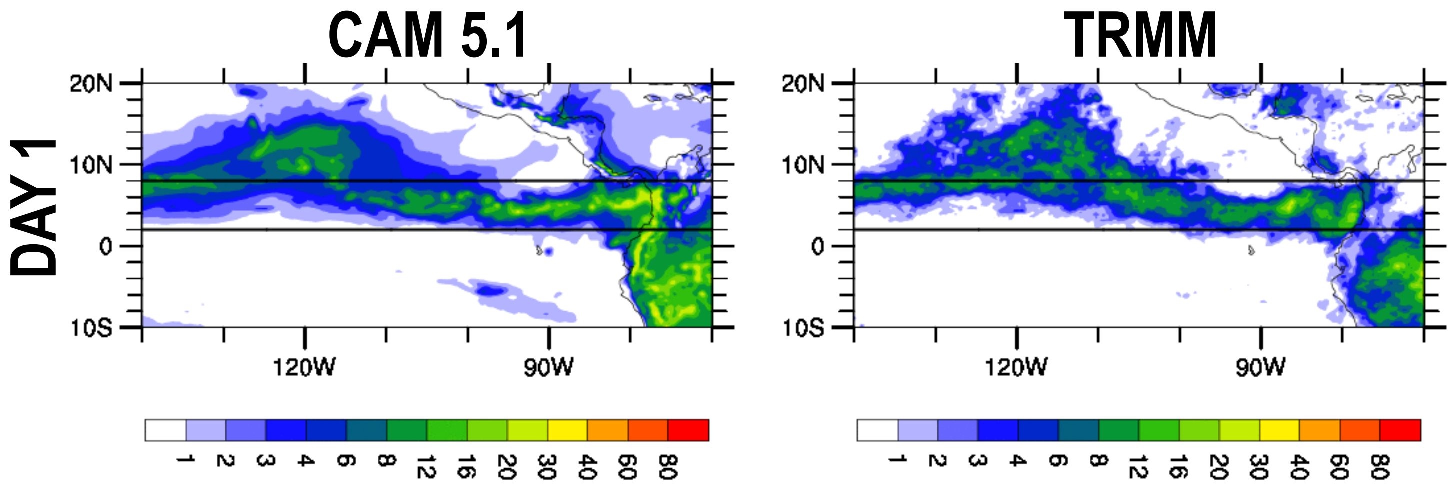
Mesoscale organization in climate models
Too much of a good thing?

Forecast runs using CAM5-FV at 0.25 resolution – using default model with 1800 sec *convective relaxation time* and then 300 sec relaxation time

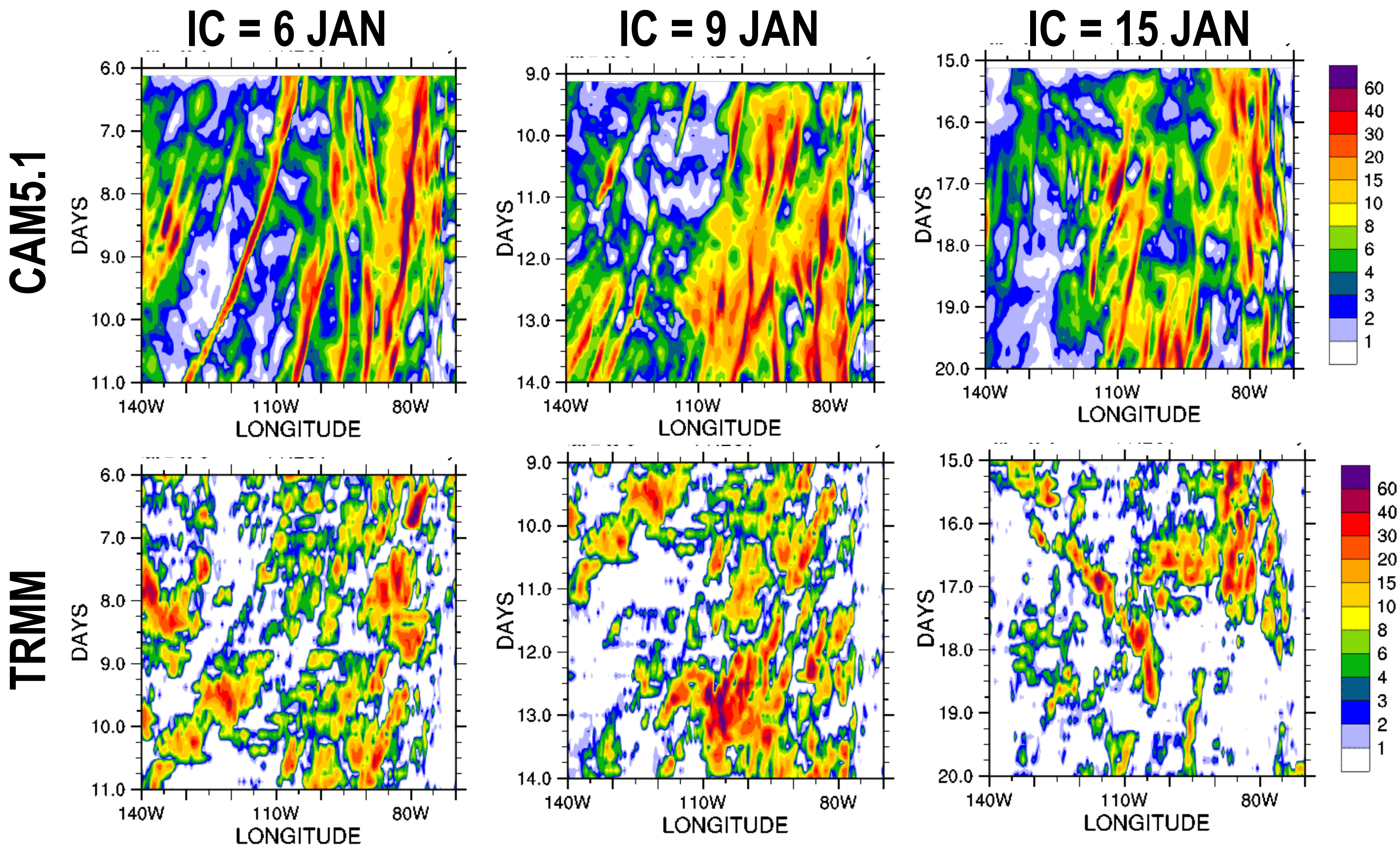
North East Pacific ITCZ – note excessively long lived storms in default model

Courtesy: Dave Williamson (CGD/AMP)

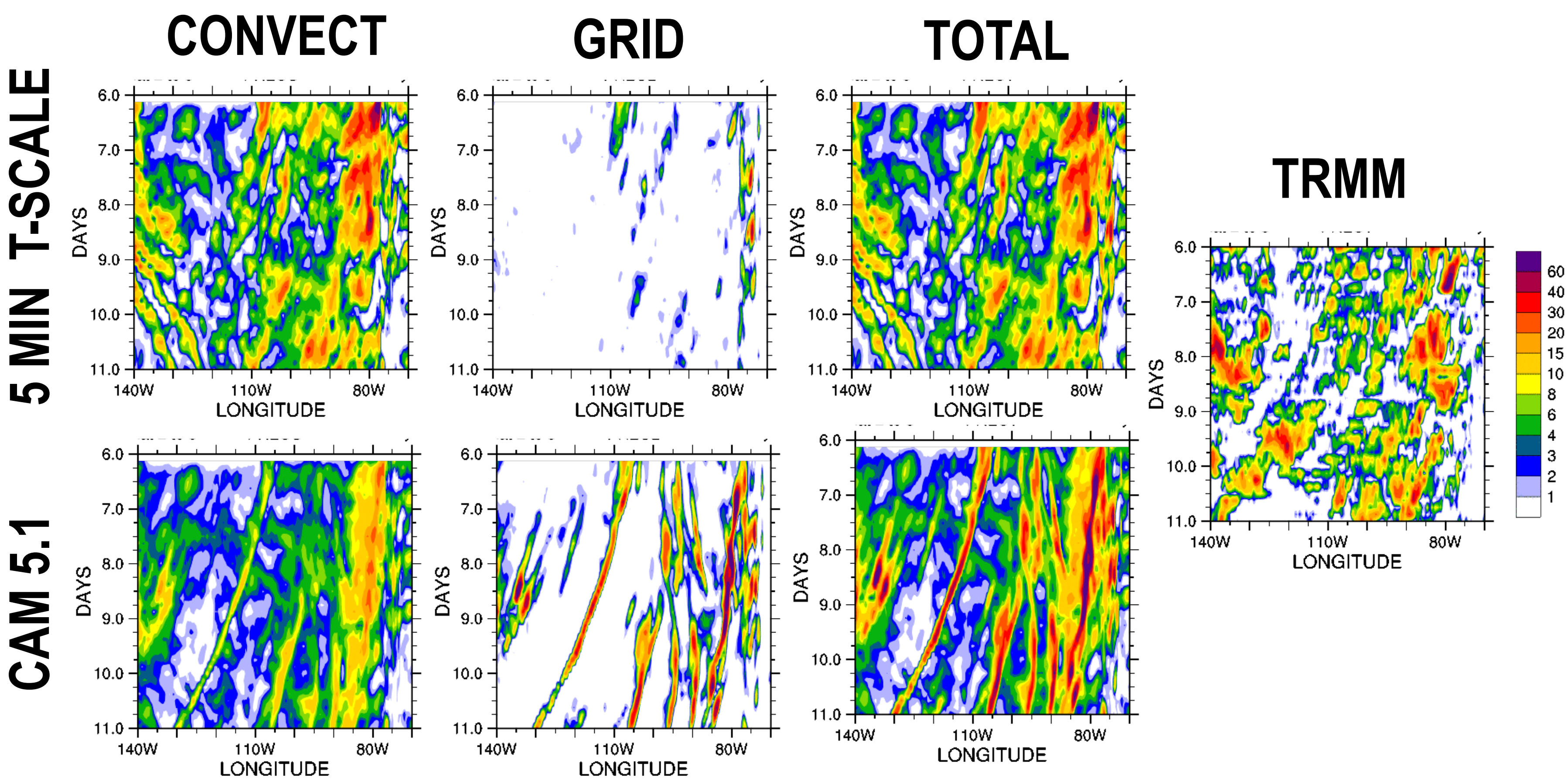
FORECAST ENSEMBLE 24-HR PRECPITATION



INDIVIDUAL FORECASTS 3-HR PRECIPITATION
3 HOUR AVERAGES 2 to 8 DEGREES

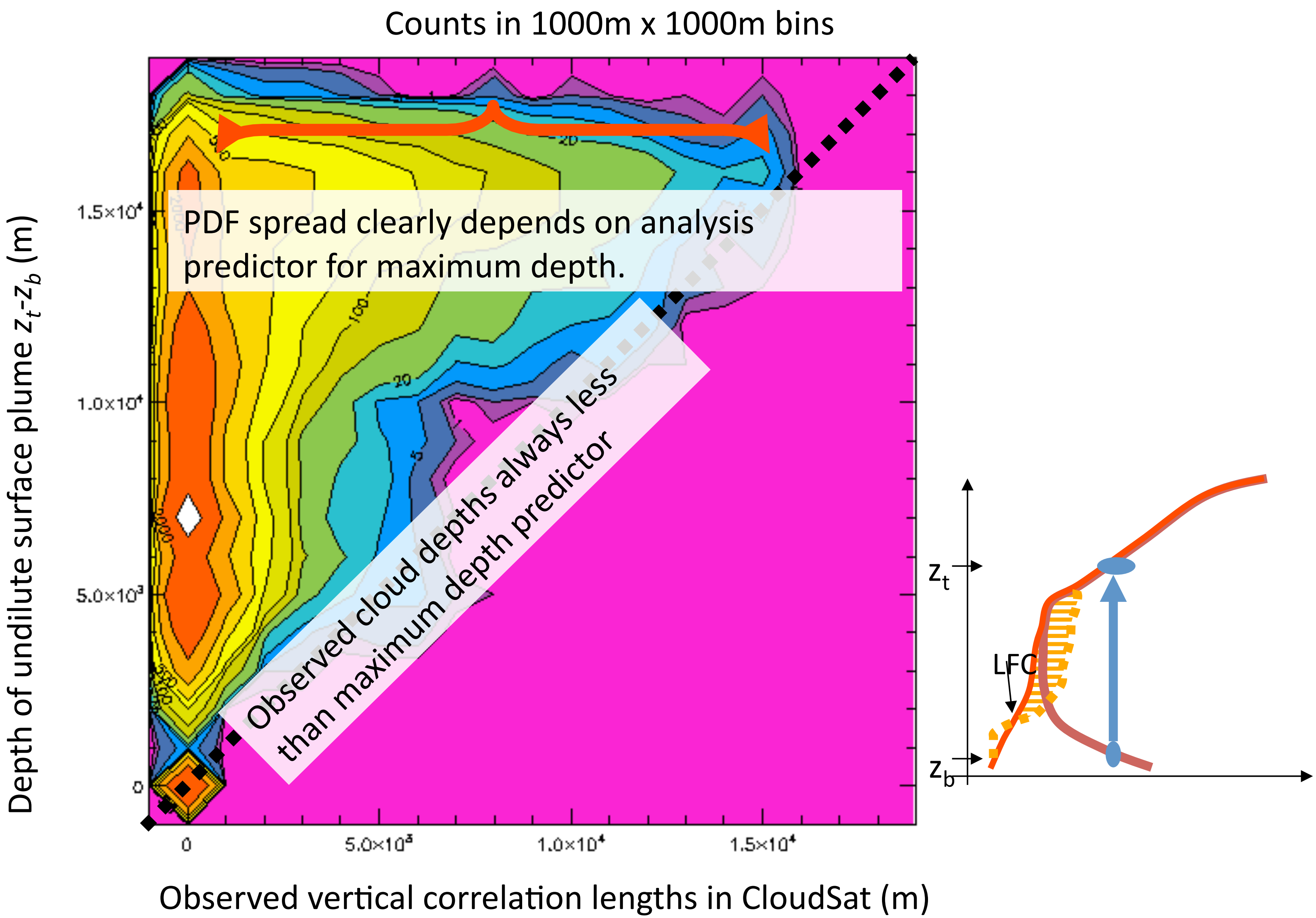


INDIVIDUAL FORECAST IC = 6 JAN



Are deep schemes too confident in their prediction of convective activity?

Joint PDF of *observed* CloudSat vertical correlation scales vs *predicted* maximum cloud heights in GEOS-5 reanalysis. **Tropical Oceans**, July 2006.



New approaches seek to include other "ingredients" in their prediction of convective activity

Overview of UNICON *(Sungsu Park)*

I. A completely new sub-grid vertical transport scheme by non-local asymmetric turbulent eddies :

- Developing a conceptual framework : July. 2006 ~ Jan. 2009.
- Mathematical formulation and coding : Jan.2009 ~ Nov. 2009.
- Intensive debugging, refinement and test : Nov. 2009 ~ Present.
- Code : ~ 20,000 Lines, Computation time : ~ CAM5 shallow convection scheme when n=1.

II. Some of unique aspects of UNICON are

- Consistent closure for all scalars (q_t, θ_c, u, v, w, A_m, $A_{\#}$, R)
- Updraft plume mixing rate as a function of plume radius R
- Launch correlated multiple plumes with different thermodynamic properties and R
- Generic treatments of 'convective downdraft' and 'detrainment'
- Treatment of 'vertical tilting of updraft plume'
- Parameterization of sub-grid 'meso-scale organized flows'
- Unified treatment of 'shallow/deep', 'dry/moist', and 'forced/free' convections
- No CIN/CAPE closures : 'fully dynamic plume model' without any equilibrium assumptions
- Well-harmonized with CAM5 local symmetric turbulence scheme (i.e., moist PBL scheme)
- Scale-aware parameterization – minimal sensitivity to $\Delta x \bullet \Delta y$, Δz, Δt

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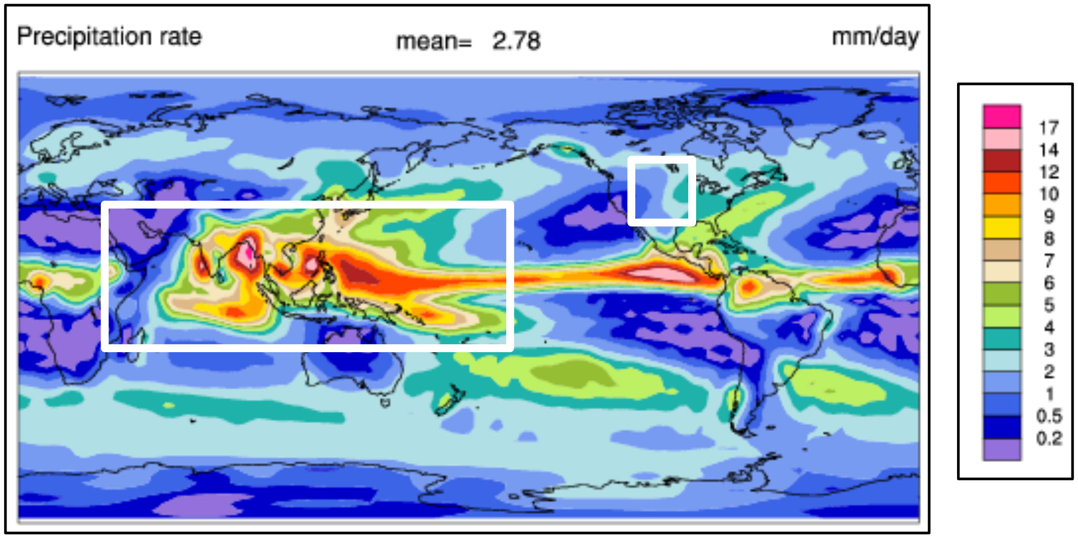
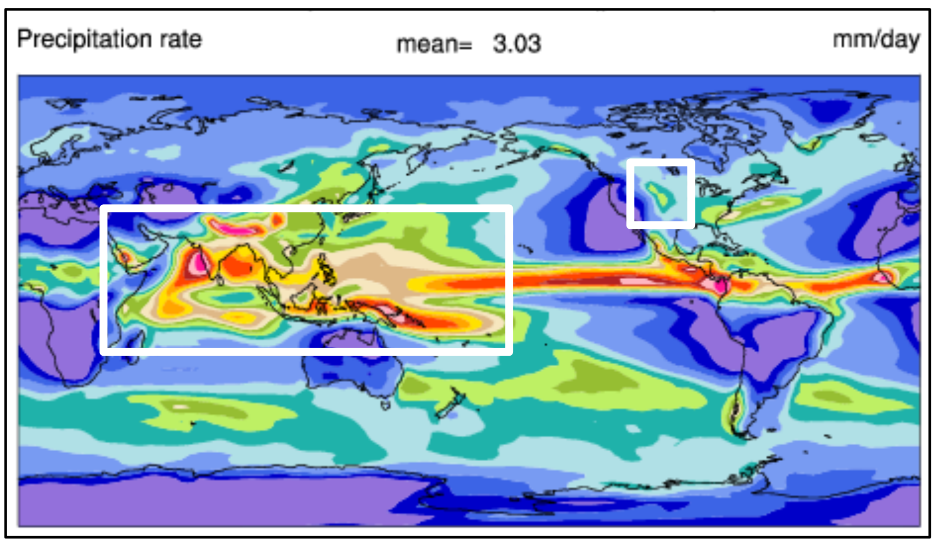
Precipitation Climatology. JJA.

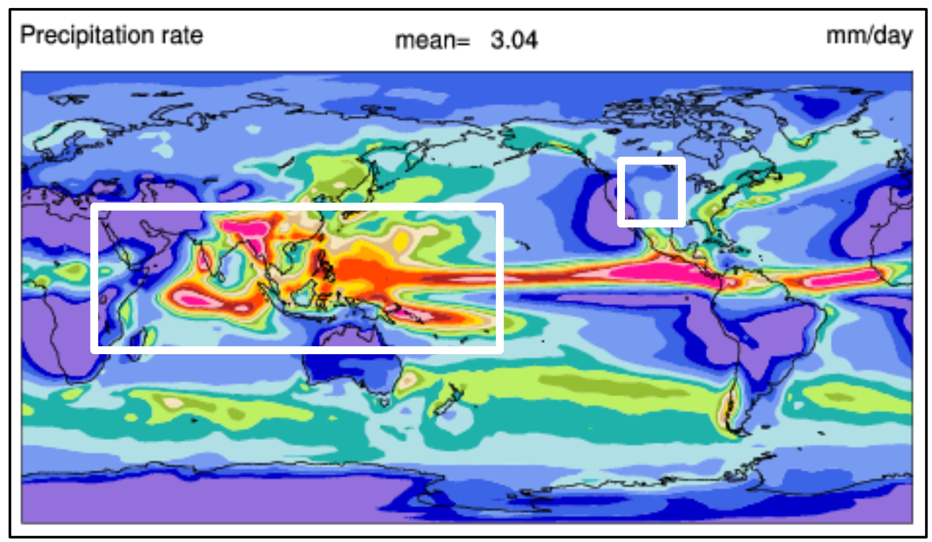
OBSERVATION



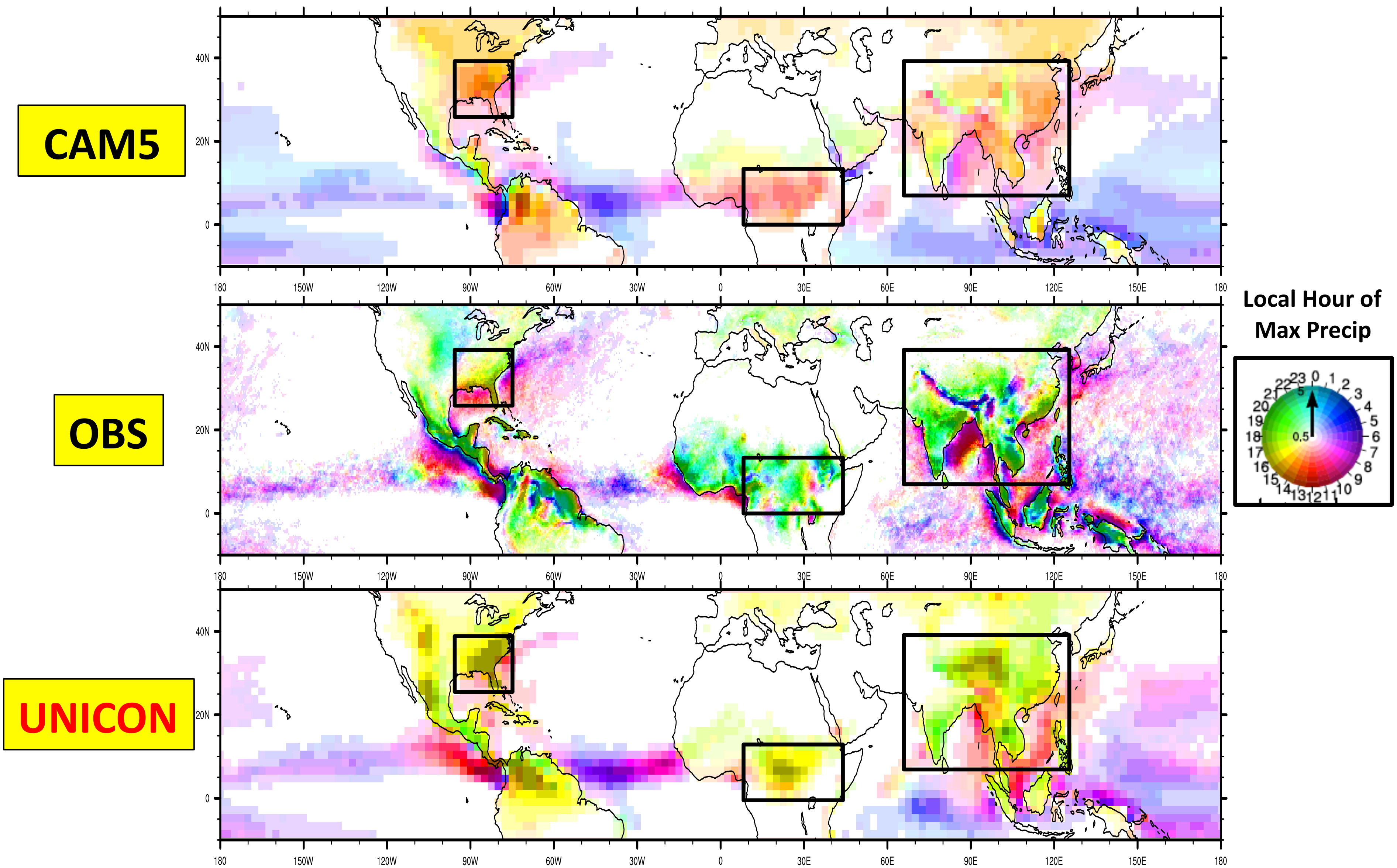
CAM5



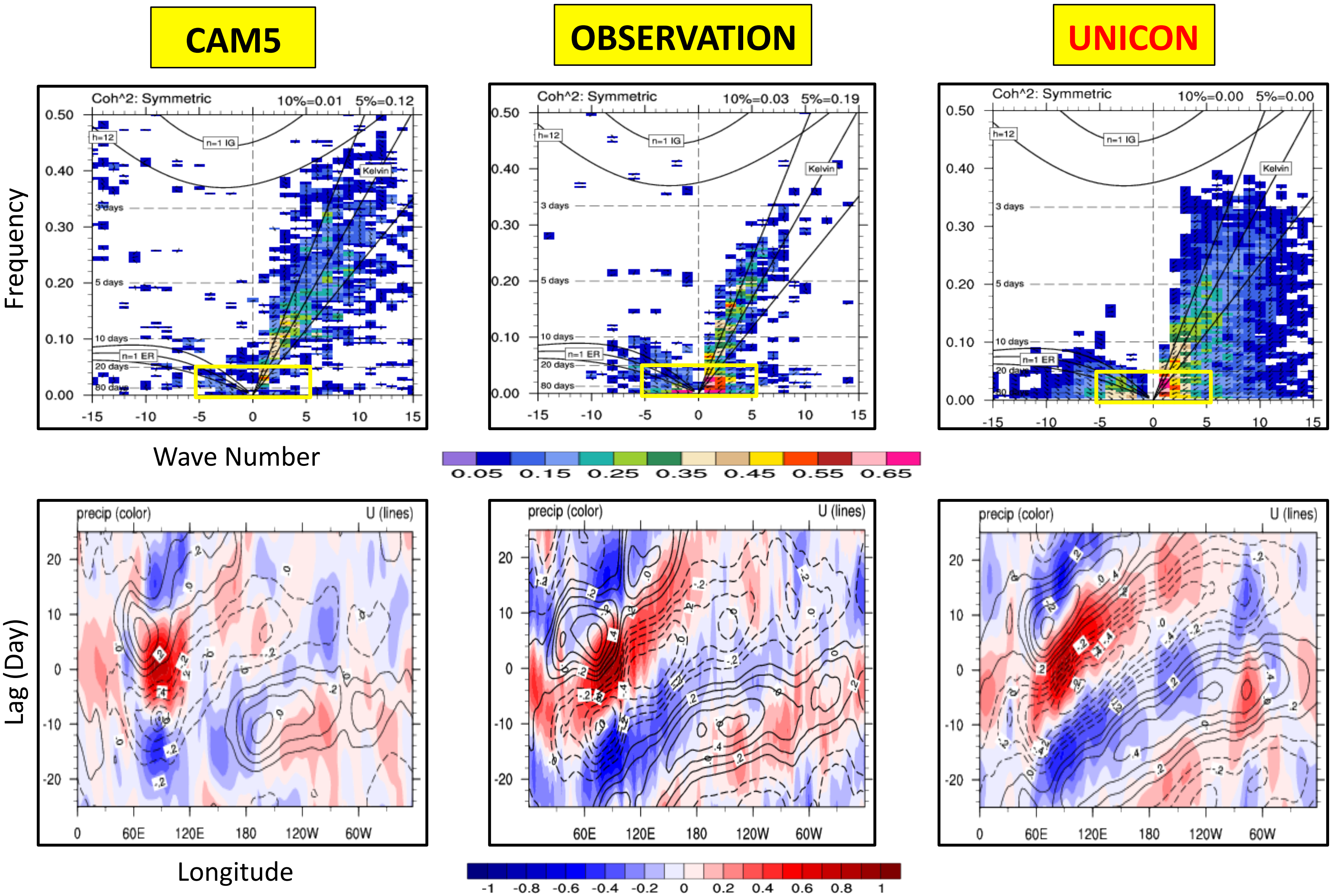
UNICON



Diurnal Cycle of Precipitation. JJA.

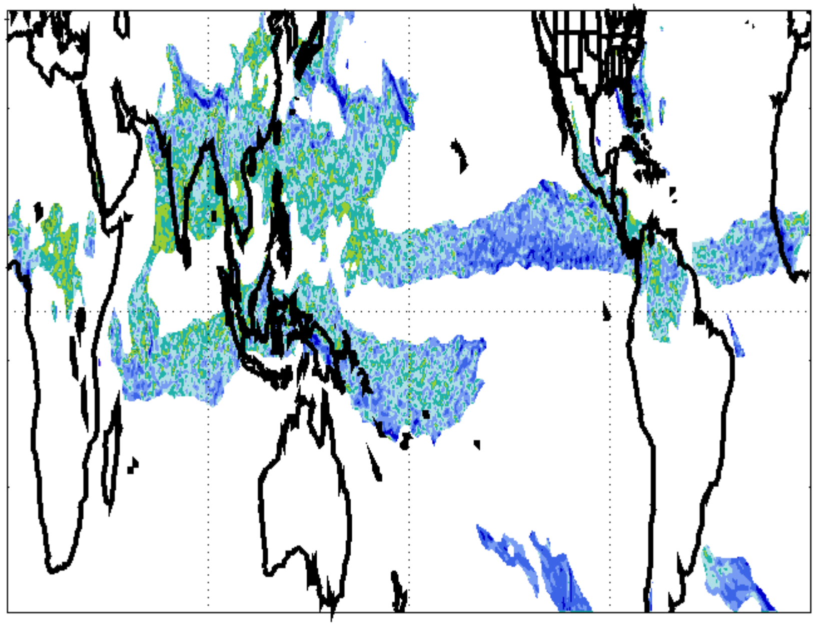


Madden-Julian Oscillation

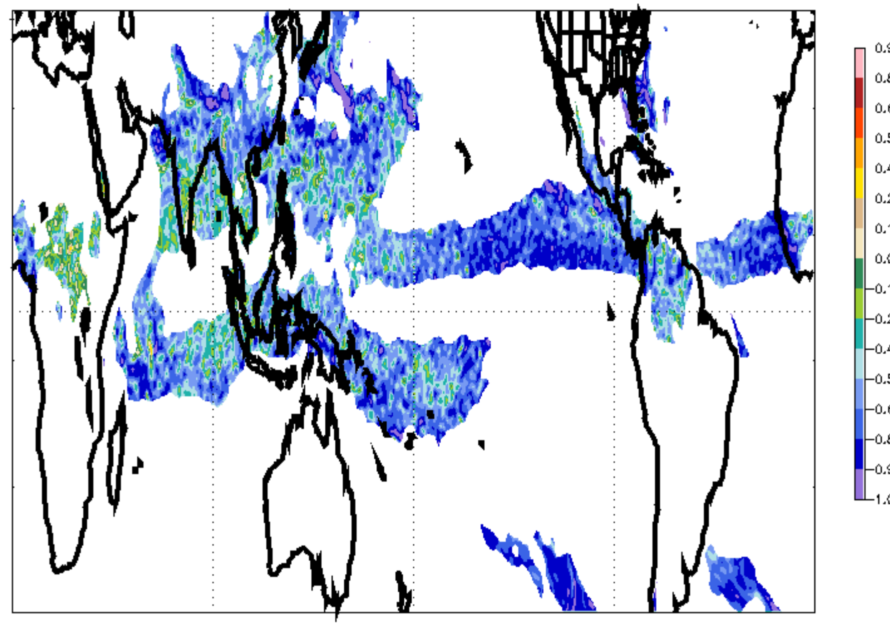


Multivariate precipitation statistics at high-resolution

Attempt to find dynamical relationships, perhaps new quantities for validation

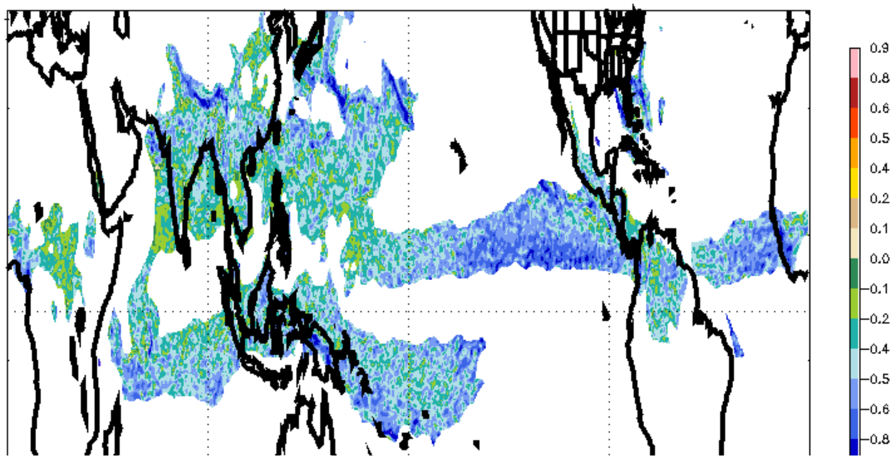


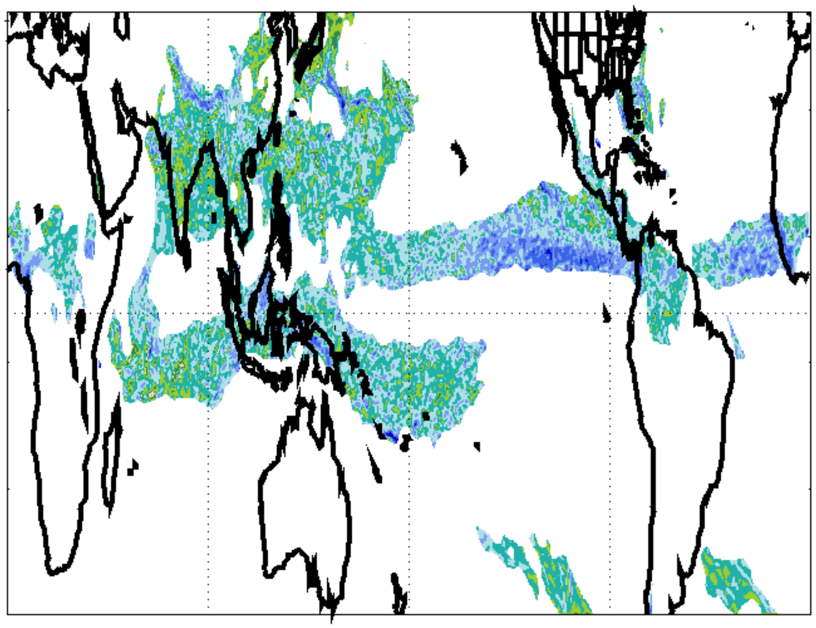
Raw 3-hrly 0.25 degree



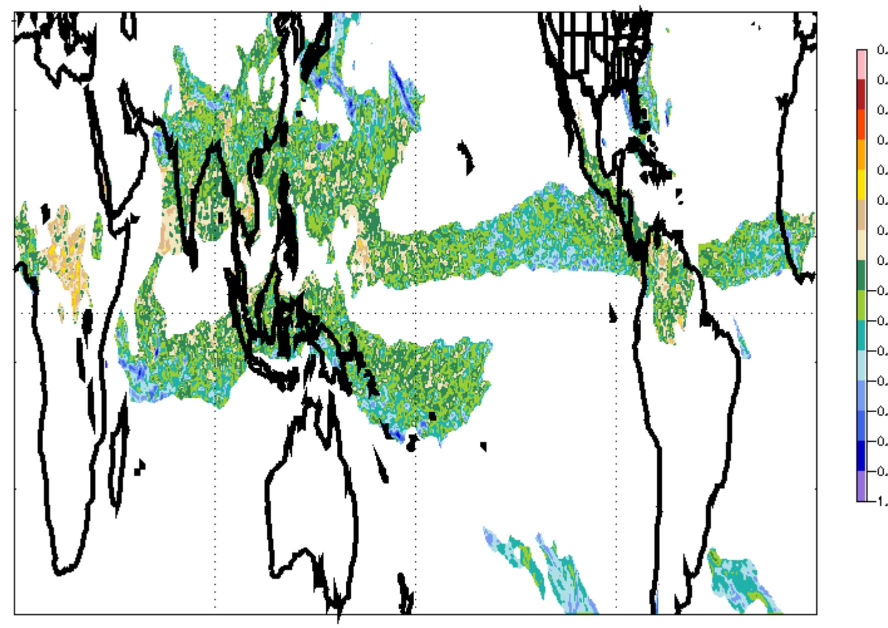
Binned to daily 1 degree

Correlation of 90-day precipitation and w_{850} time-series





Precipitation lags w_{850} by 3hours



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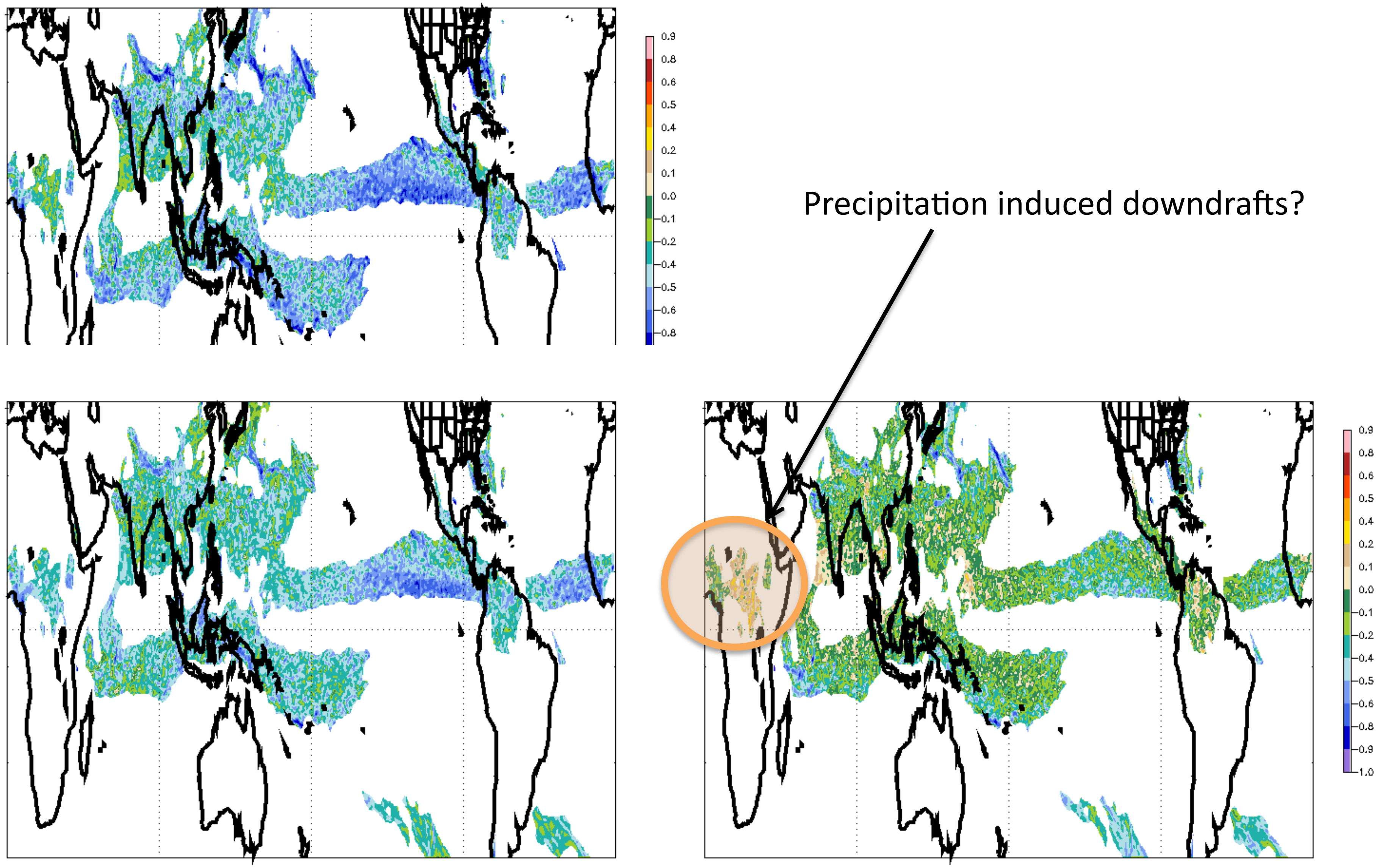


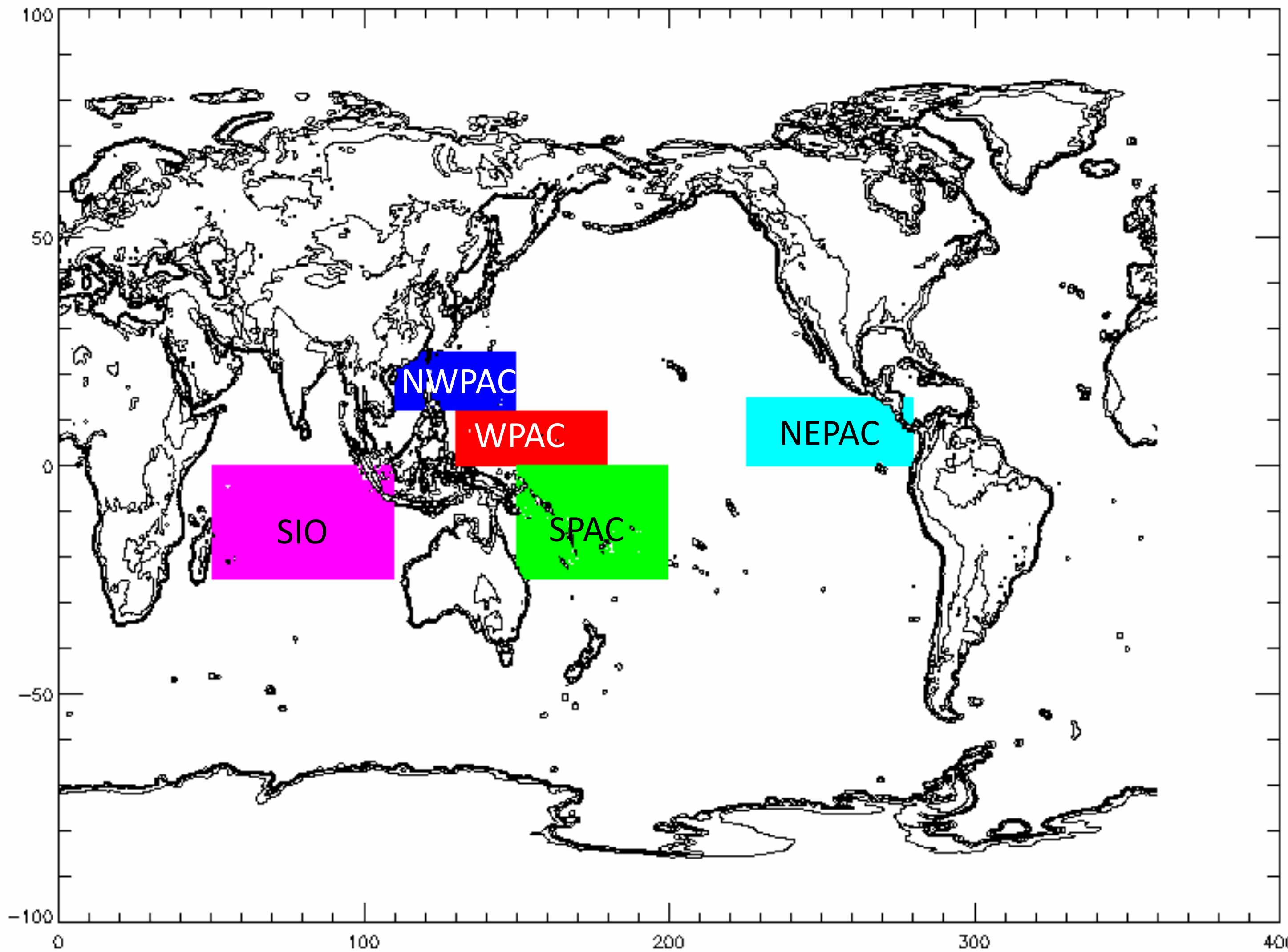
Precipitation lags w_{850} by 3hours

Precipitation leads w_{850} by 3hours

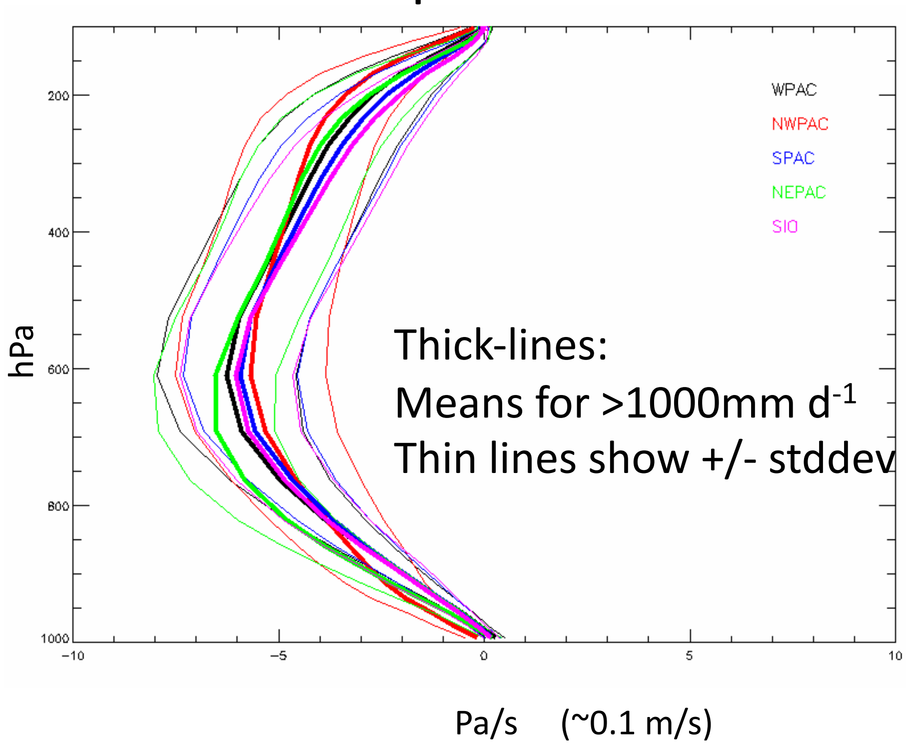
Composites conditioned on precipitation rates

e.g., *Sahany, Neelin and co-workers*

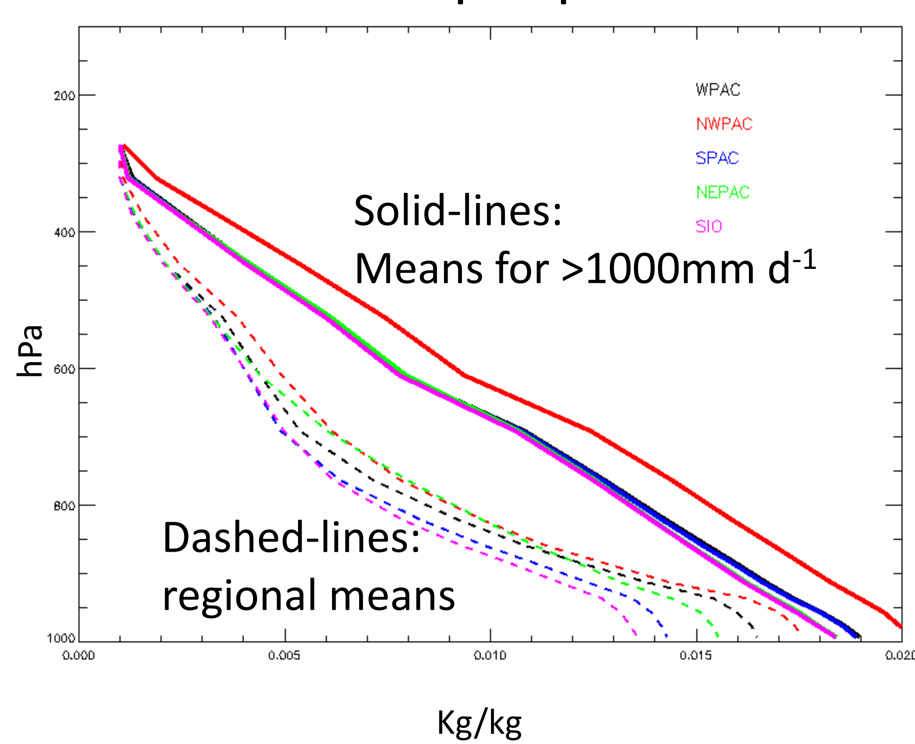
Domains for composite analysis



w profiles



water vapor profiles



Summary

Climate model precipitation does not improve with resolution

Climate model convective schemes tend to (or are forced to) "take a back seat" at high-resolution

Bad thing for long term means of precipation?

Good for capturing mesoscale organization. Too good?

New approaches to climate model convective parameterization seek to include more ingredients in predictions of mass flux, e.g., organization and plume-size, stochastic triggers …

Thank you

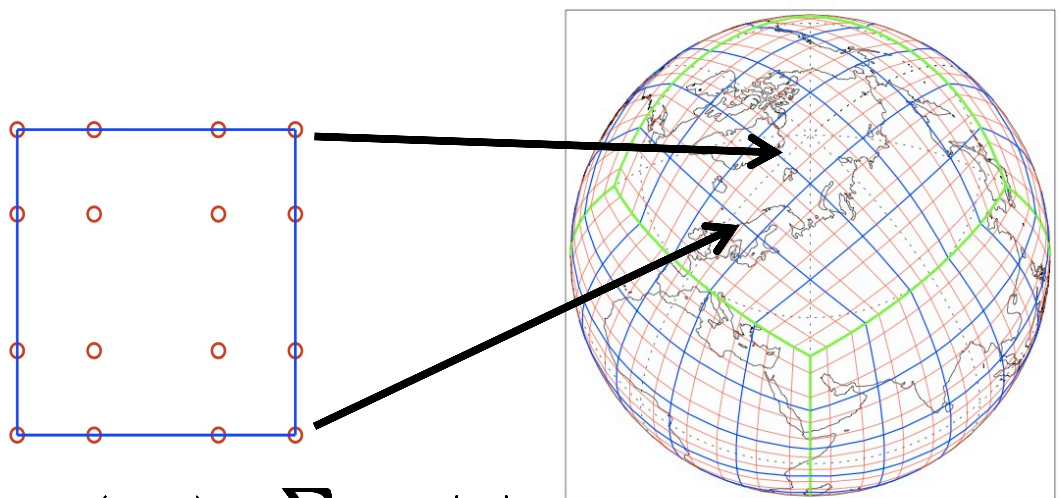
CAM-FV (Finite volume) dynamical core

Lat-lon grid ➔ poor scaling due to pole problems

CAM-MPAS dynamical core

CAM-SE (spectral element) dynamical core

(M. Taylor, DoE Sandia Lab)



$$\Psi_k(x,y) = \sum_{i+j\leq 3} c_{i,j} x^i y^j$$

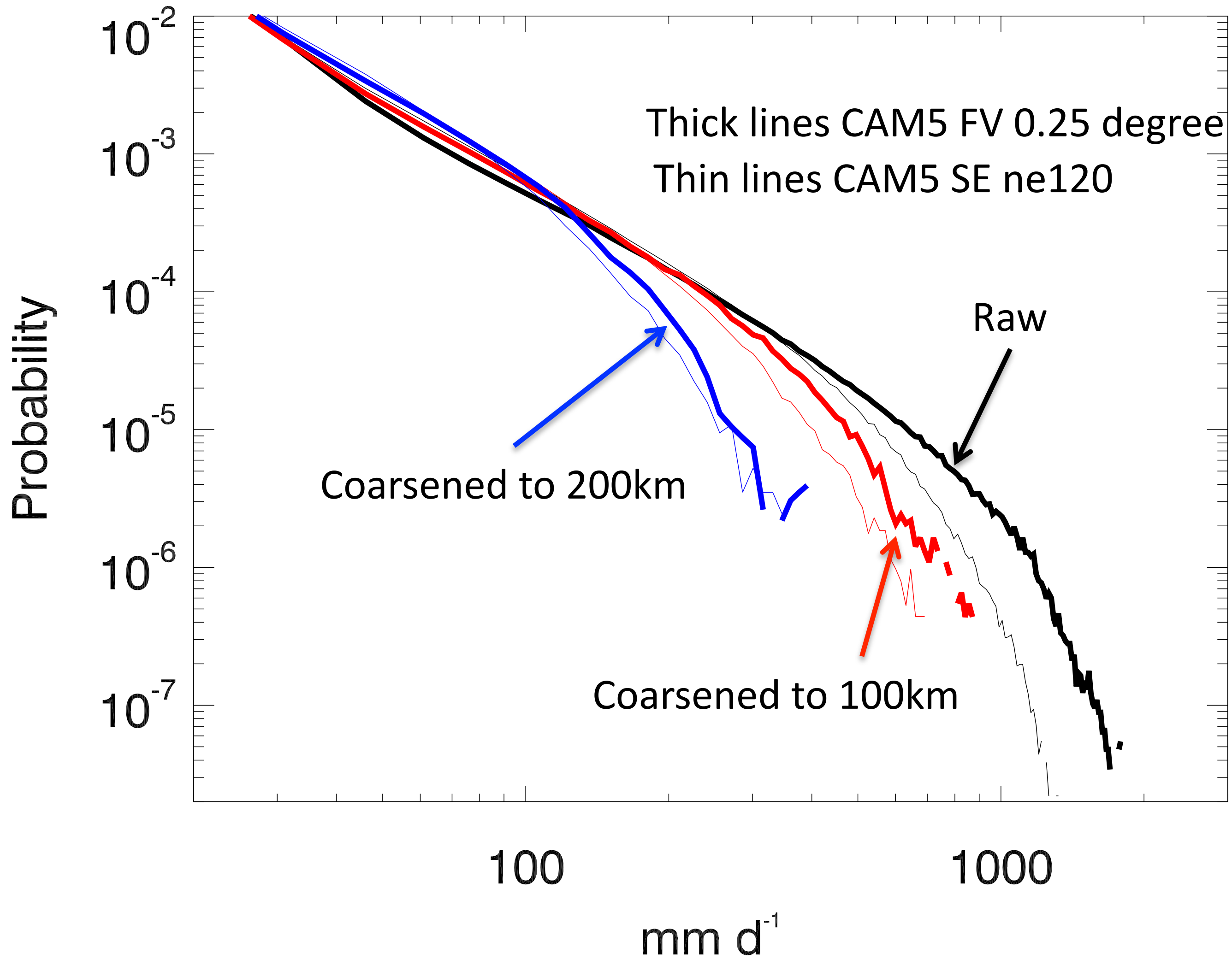
Continuous Galerkin spectral finite elements, explicit RK time-stepping
Energy conservation at element level
Mesh refinement capability exists

Sensitivity to use of Deep Convection Scheme

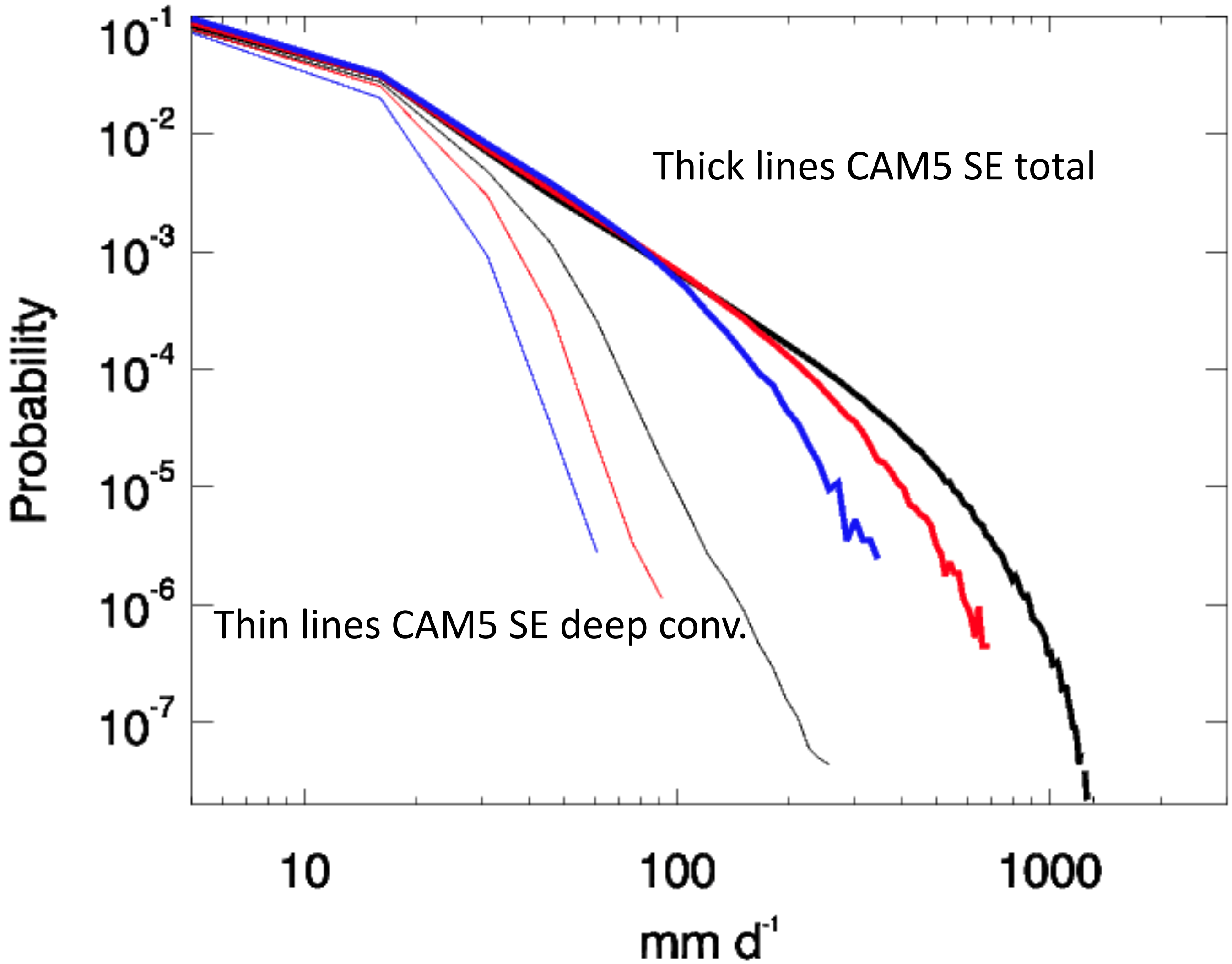
GEOS-5 attempts to hobble deep convection scheme via entrainment limits. GFDL eliminates deep scheme (with tuned shallow scheme). CAM5 precip in TC cores dominated by large-scale.

What happens if deep scheme is removed from CAM?

Precipitation Intensity Statistics for JJA (instantaneous 3hrly data)

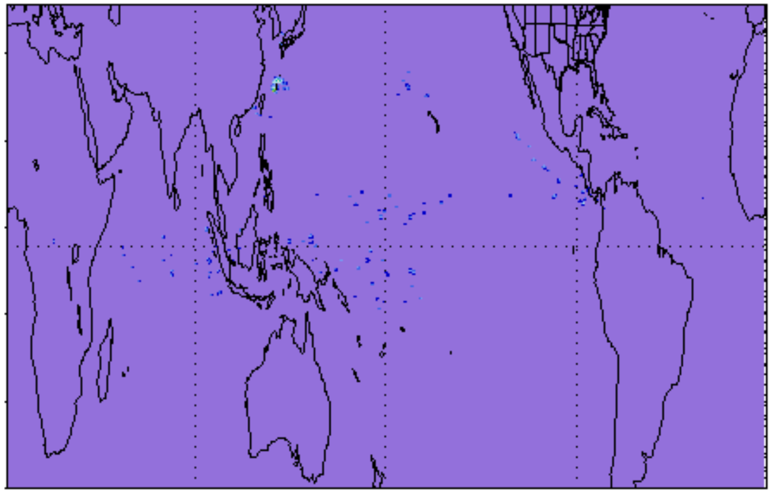


Convective versus total precipitation statistics

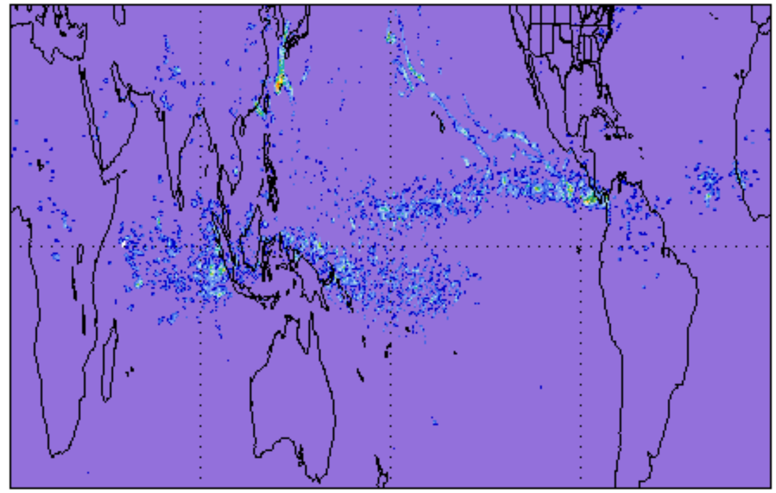


Where do various intensity regimes fall? CAM-SE

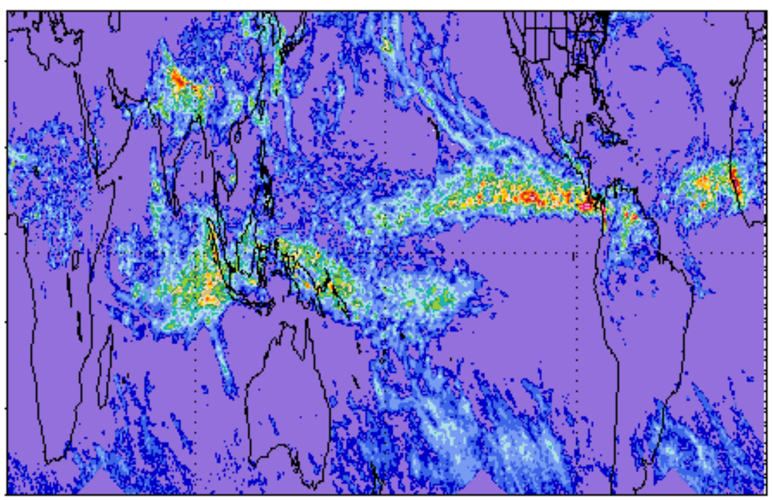
>1000 mm d^{-1}



500 -1000 mm d^{-1}



100 -500 mm d^{-1}



20 -100 mm d^{-1}