Multiscale Modeling Framework and Parameterization

Acknowledgments

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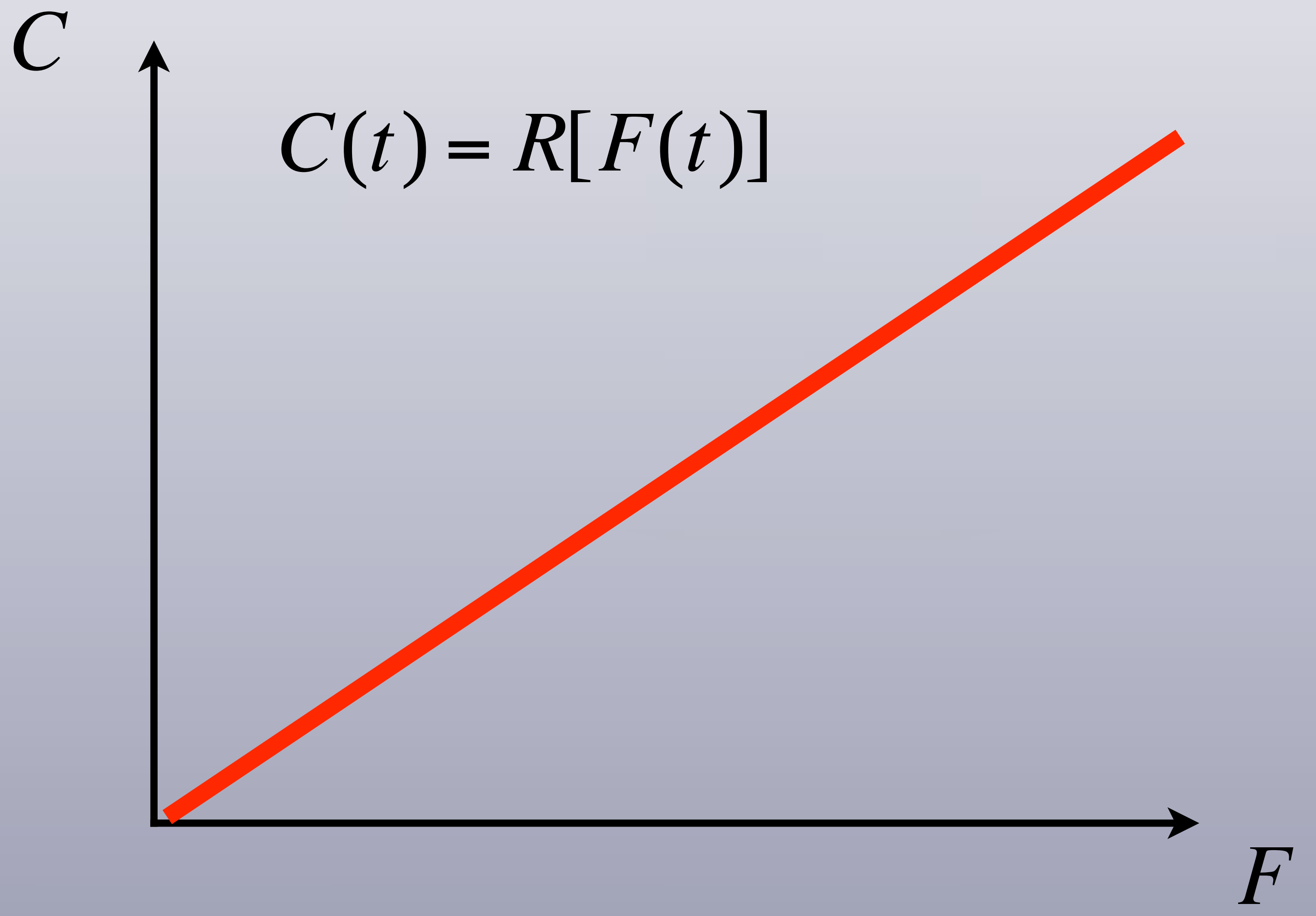
Cloud Parameterizations

Current global models include the effects of cloud processes through "parameterizations," which are (or should be) statistical theories, analogous to thermodynamics but more complicated.

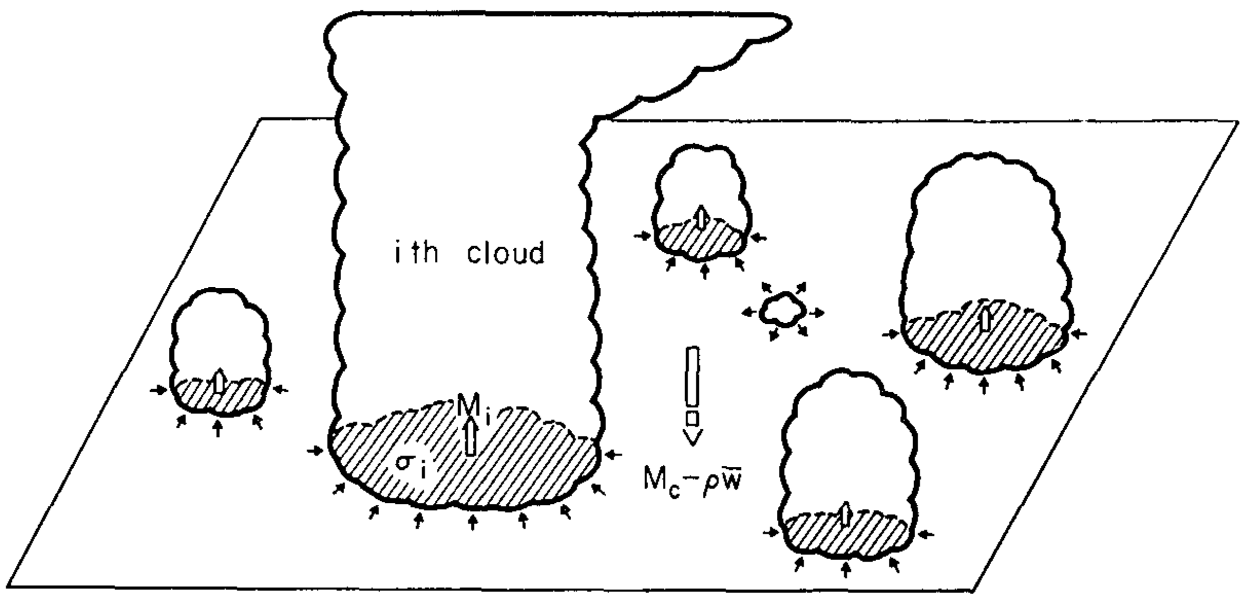
Analogy

	Thermodynamics	*Cloud Parameterization*
Players	**Molecules**	**Clouds**
Volume	**1 cubic cm**	**1 model grid column**
Sample size	**Trillions of molecules**	**Dozens to thousands of clouds**
Simplifying assumptions	**Point-like molecules; Inter-molecular collisions usually negligible**	**Small updraft area; Uniform environment; No direct interactions among clouds**
Nonequilibrium effects	**Brownian motion, etc.**	**TBD, maybe mesoscale organization**

Quasiequilibrium



Sample size



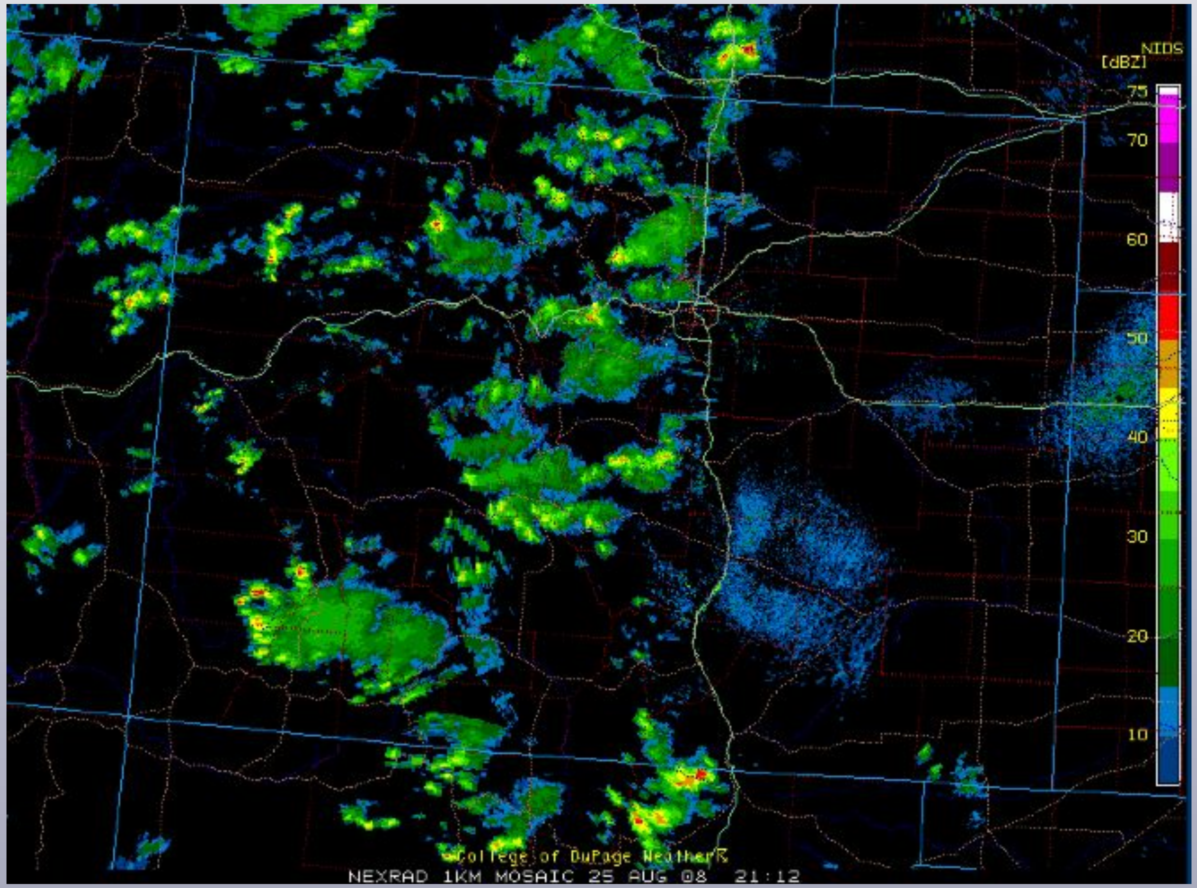
"Consider a horizontal area ... large enough to contain an ensemble of cumulus clouds, but small enough to cover only a fraction of a large-scale disturbance. The existence of such an area is one of the basic assumptions of this paper."

-- AS 74

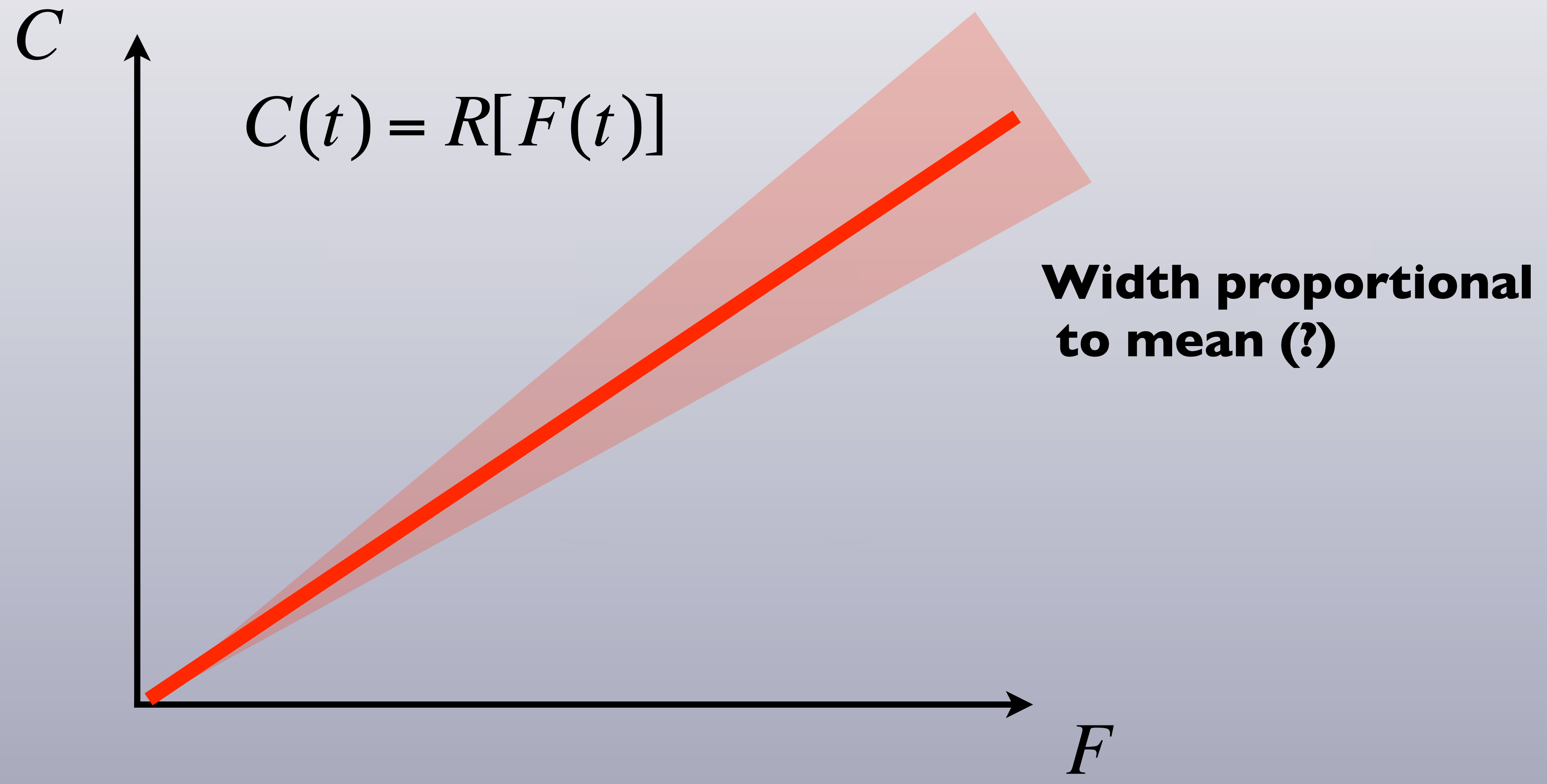
How many thunderstorms fit?

With a grid spacing of 20 km or less, we definitely do not have a statistically meaningful sample of large clouds in each grid column.

Even with a grid spacing of 200 km, the number of large clouds in a grid column is worryingly small.



Sampling a PDF



With a small sample size but slowly changing conditions, we get non-deterministic, non-equilibrium behavior.

Finite adjustment time

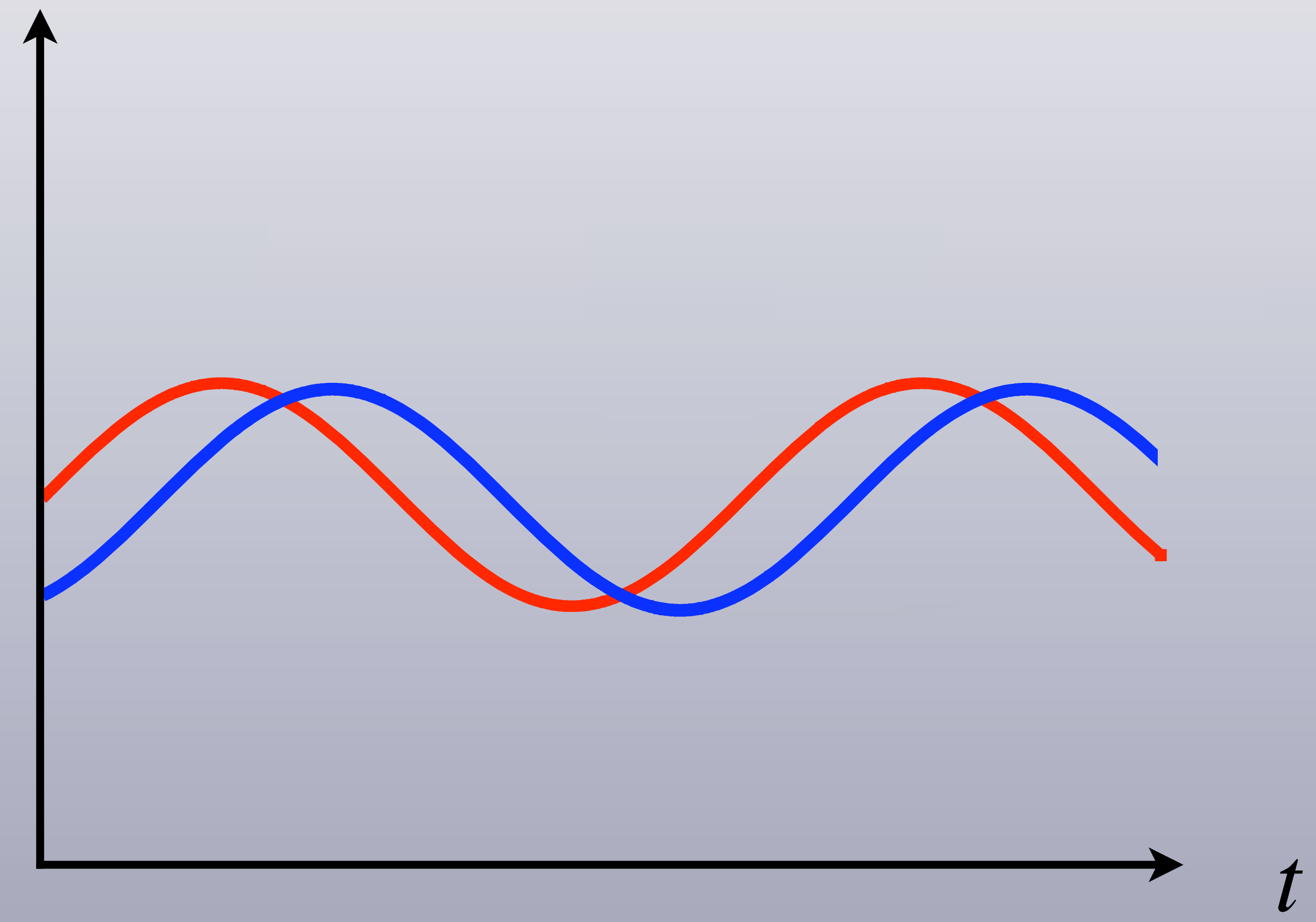
“When the time scale of the large-scale forcing, is sufficiently larger than the [convective] adjustment time, … the cumulus ensemble follows a sequence of quasi-equilibria with the current large-scale forcing. We call this … the quasi-equilibrium assumption.”

“The adjustment … will be toward an equilibrium state … characterized by … balance of the cloud and large-scale terms…”

-- AS 74

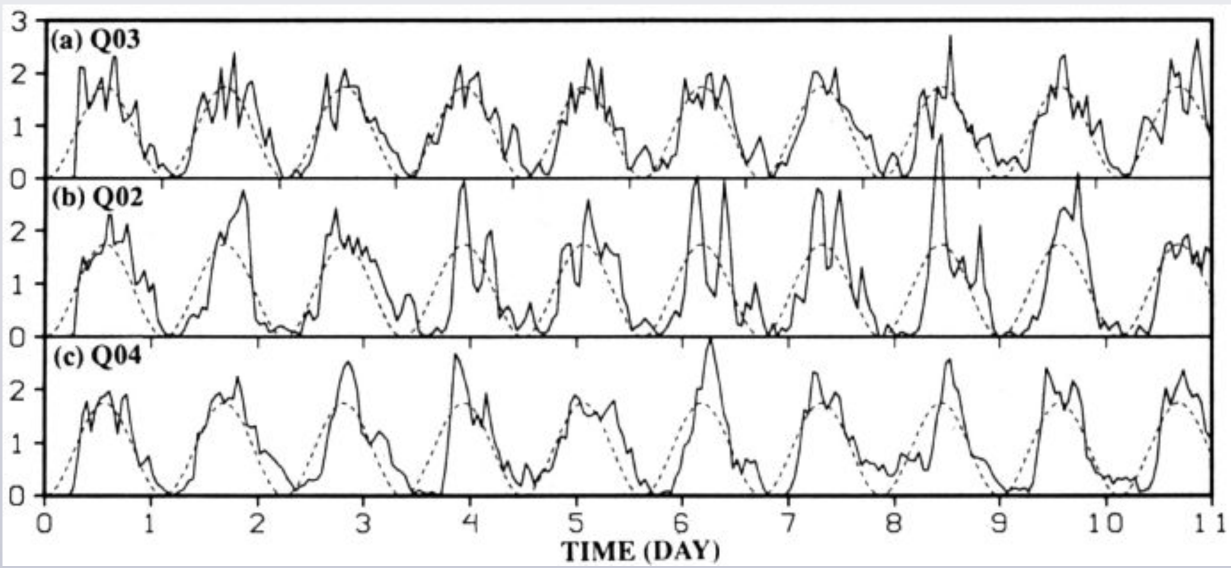
Delayed response

$$C(t) = R[F(t-\tau)]$$

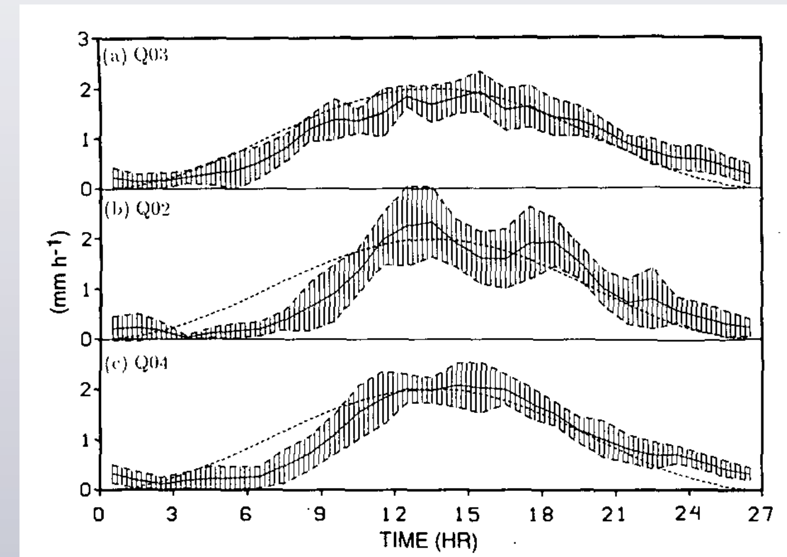


With rapidly changing conditions, equilibrium is not possible (even with a large sample size), but the convection can still be deterministic.

Both problems at once



Composite →

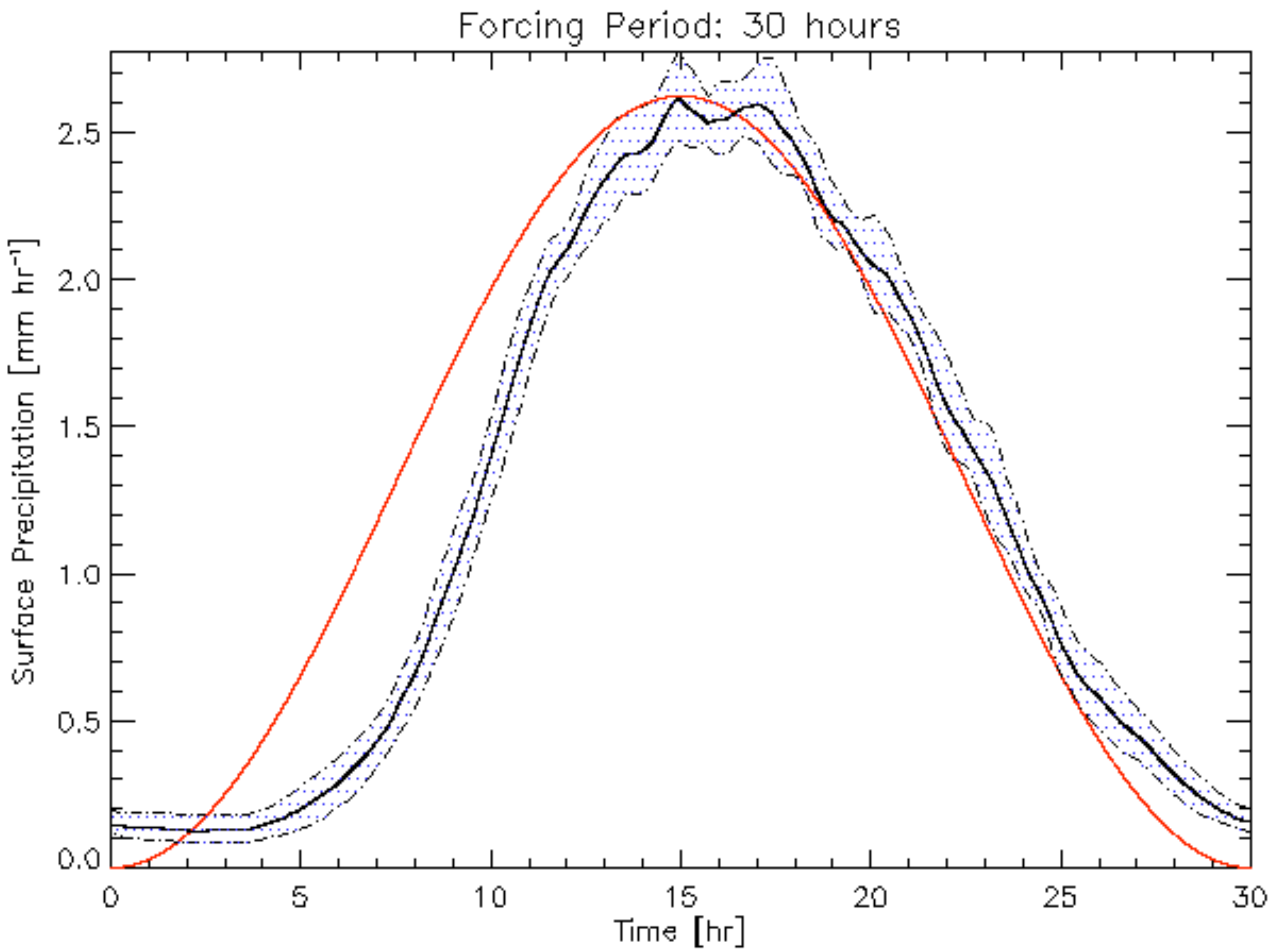


Xu et al. (1992)

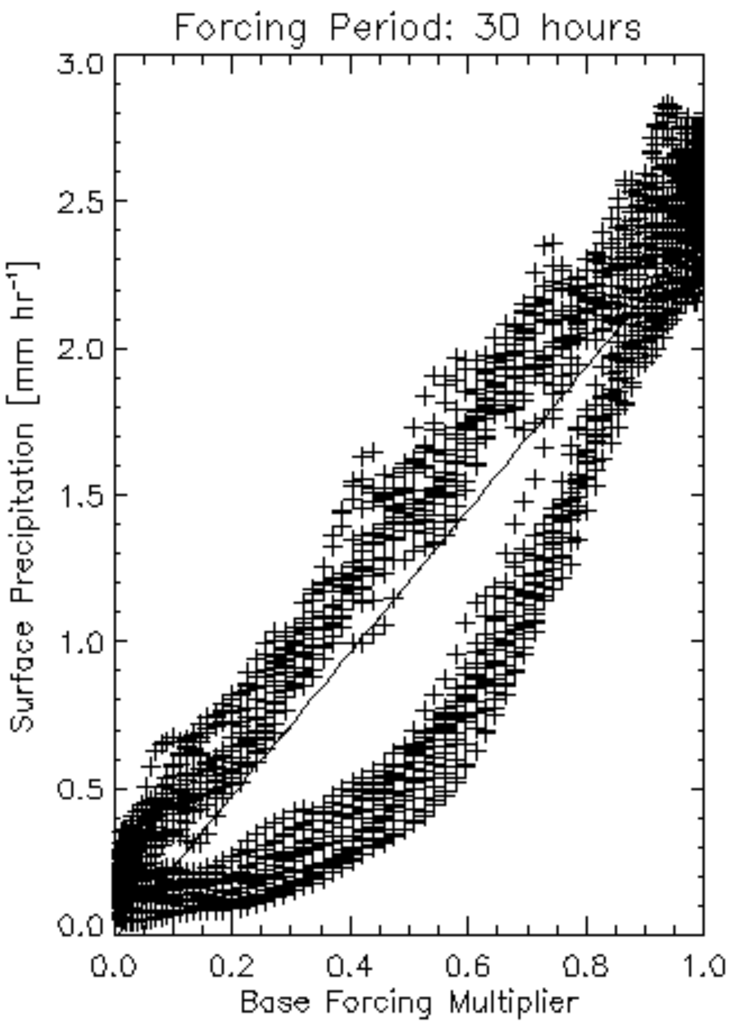
The domain is too small to yield robust statistics, but the forcing repeats exactly, so with a sufficiently large domain the "scatter" in the composite plot would become negligible.

Because the period of the forcing is short (27 hours) , the forcing noticeably leads the convective response.

Revisiting Xu et al.



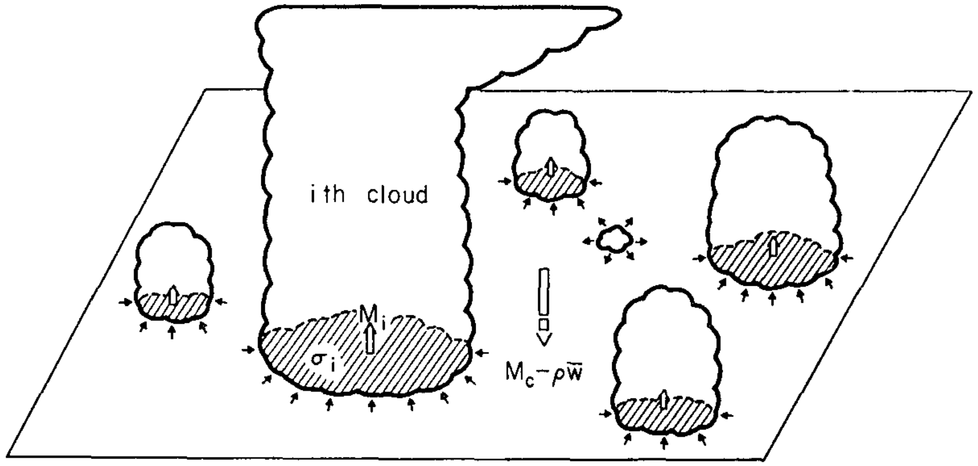
Forcing leads Precip max by: 95 minutes (5.28 % of the forcing period)

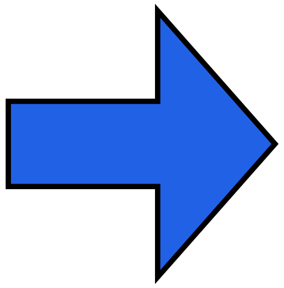


r^2 = 0.875
Slope = 2.437

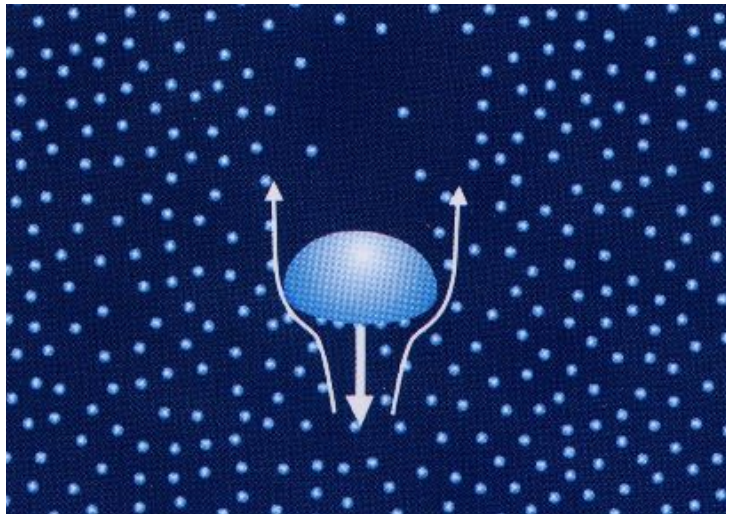
Slide from Todd Jones

Heating and drying on coarse and fine meshes





Increasing resolution



GCM

CRM

Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

Scale-dependence of heating & drying

$$Q_1 \equiv LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H{}'s'}) + Q_R$$

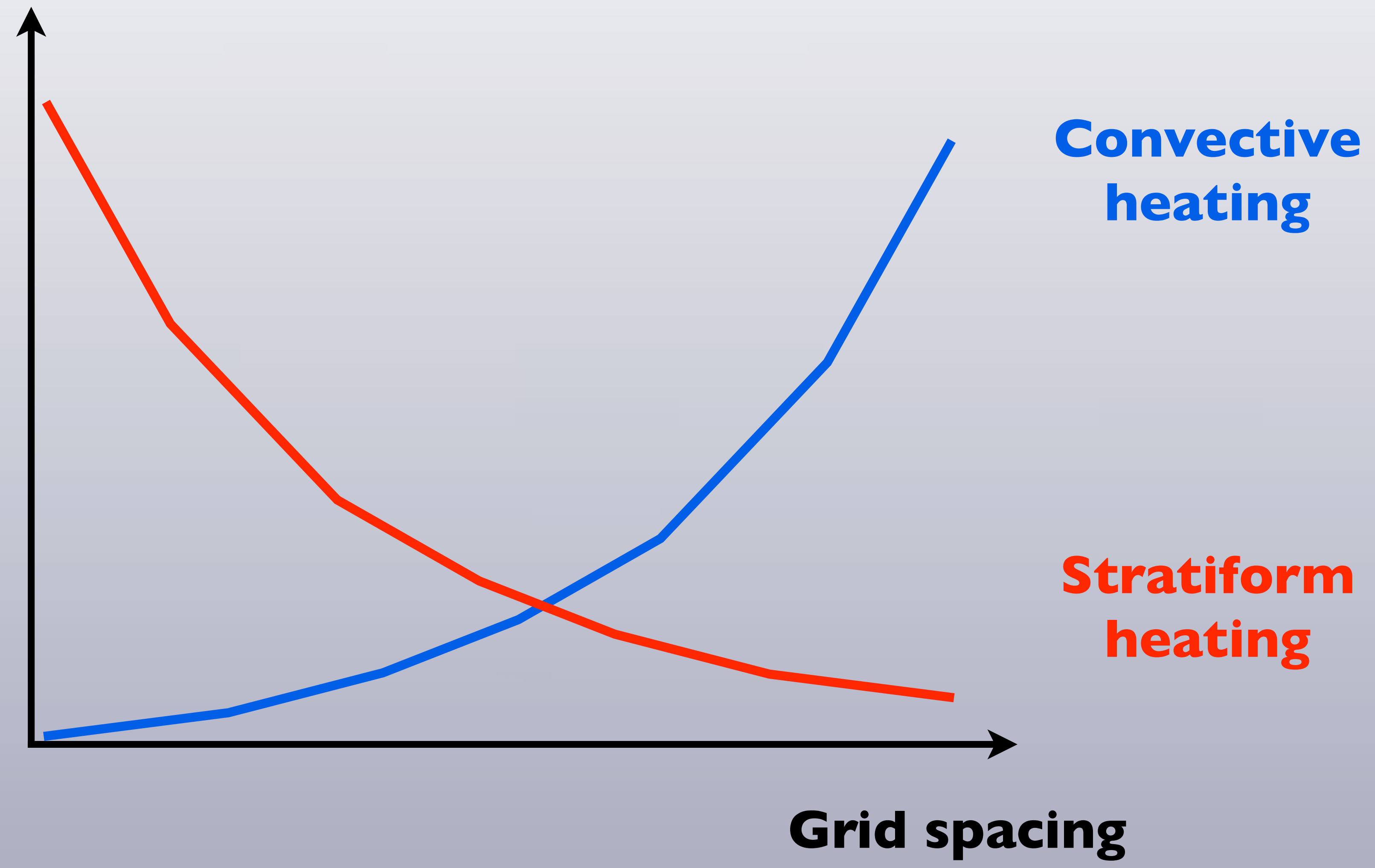
$$Q_2 \equiv LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v{}'}) + \frac{L}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H{}'q_v{}'})$$

These quantities are defined in terms of spatial averages.

As the averaging length becomes smaller:

- **The vertical transport terms become less important. Later horizontal averaging does not change this.**
- **The horizontal transport terms become more important locally. Horizontal averaging kills them, though.**
- **The phase-change terms become dominant.**

Miraculous compensation



A model may do this "automatically."
A model may be formulated so that it is guaranteed to happen.
However, we have no theory to guide us.

Three problems with existing parameterizations at high resolution:

- The sample size is too small.
- The “resolved-scale forcing” varies too quickly.
- Convective transports should give way to microphysics, but we have no quantitative theory for this transition.

Expected values --> Individual realizations

Changing resolution

At very high resolution, a model should grow individual clouds -- *a qualitative difference from current models*.

Therefore, as a model's resolution changes, its formulation should "adjust."

Is there a way to do this?

Dreaming of a global CRM (GCRM)

Model	Grid Spacing	Cost/ Simulated Day
IPCC AR4	200 km	1 unit
ECMWF	20 km	10^3 units
GCRM	2 km	10^6 units

Applications of GCRMs

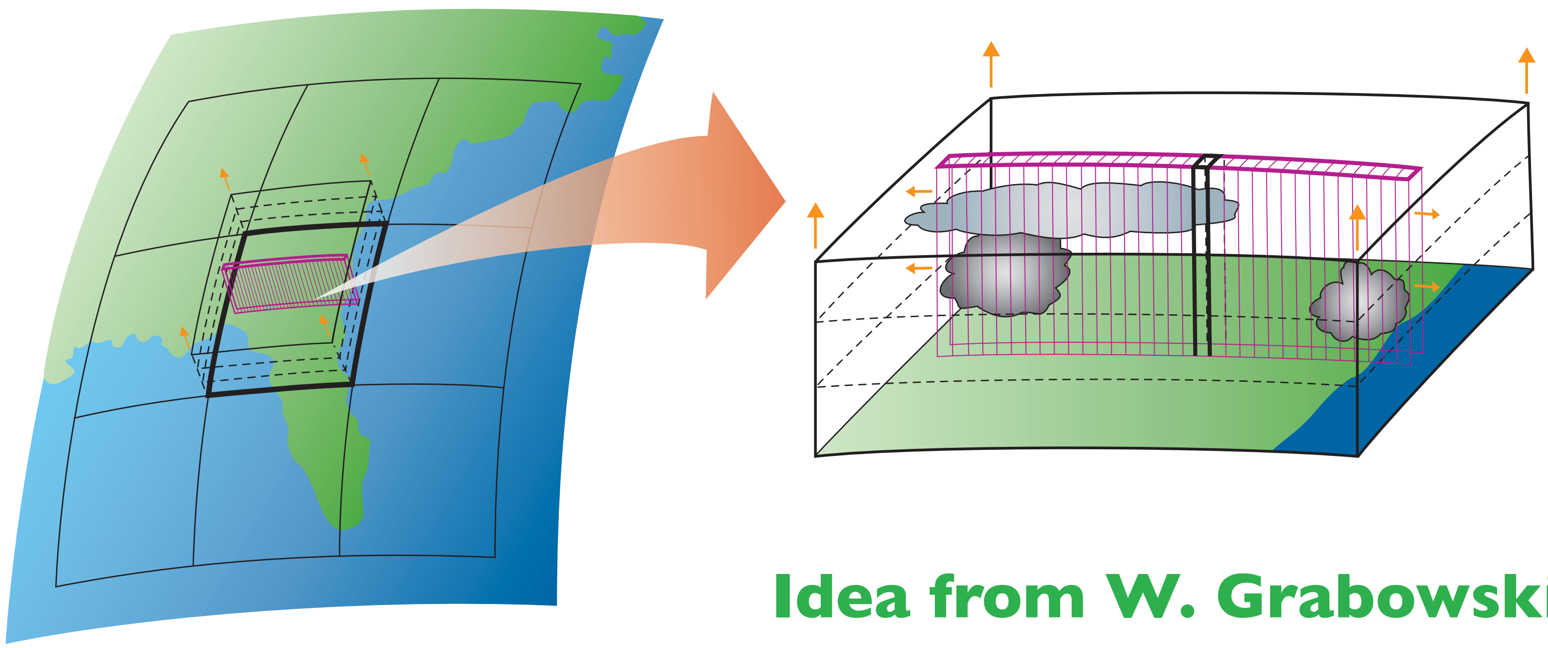
- Parameterization development
  - Interactions from the global scale to the cloud scale
- Numerical weather prediction
- Climate simulation
  - An annual cycle, coupled to the ocean, by 2011
  - Time slices
  - Anthropogenic climate change

Bridges to GCRM climate simulation

Current climate models

GCRM climate

The Multiscale Modeling Framework: A less costly alternative to GCRMs



Periodic boundary conditions

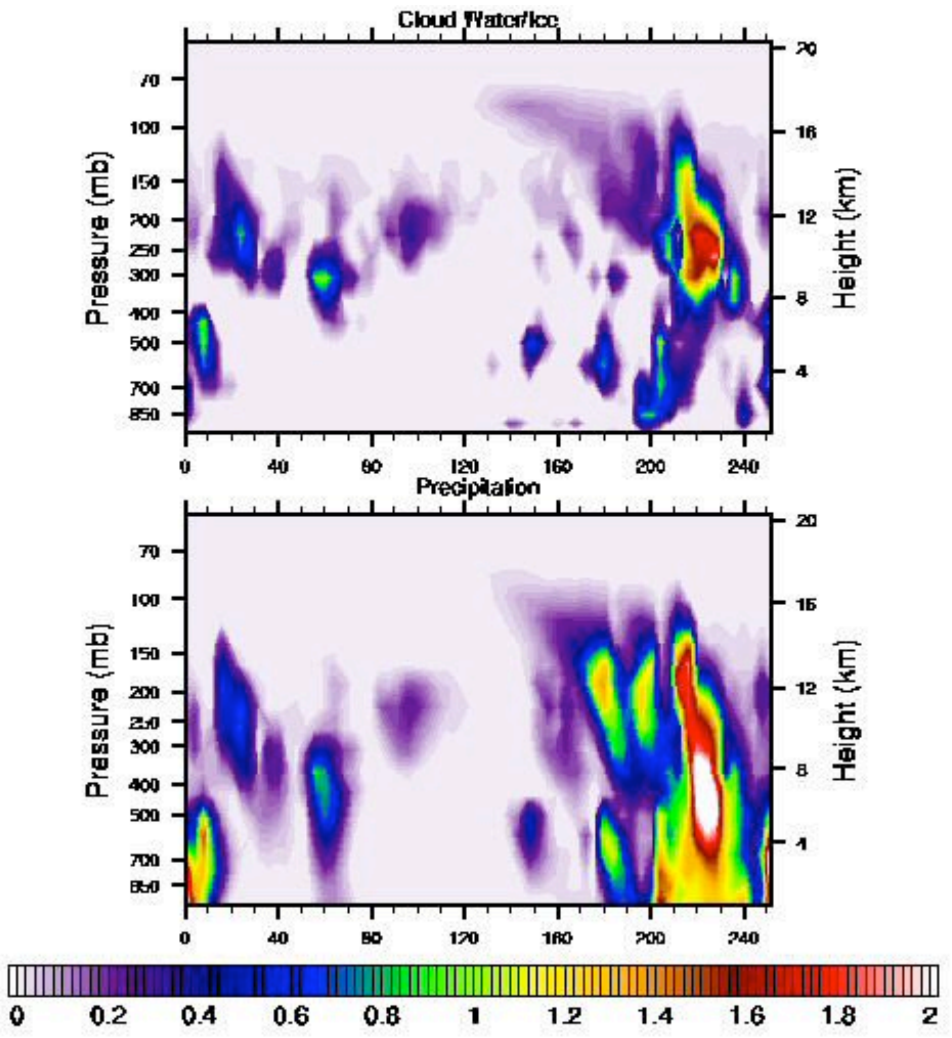
Idea from W. Grabowski

We have demonstrated the potential of this idea using a simple prototype.

There are lots of issues, though.

Compared to what?

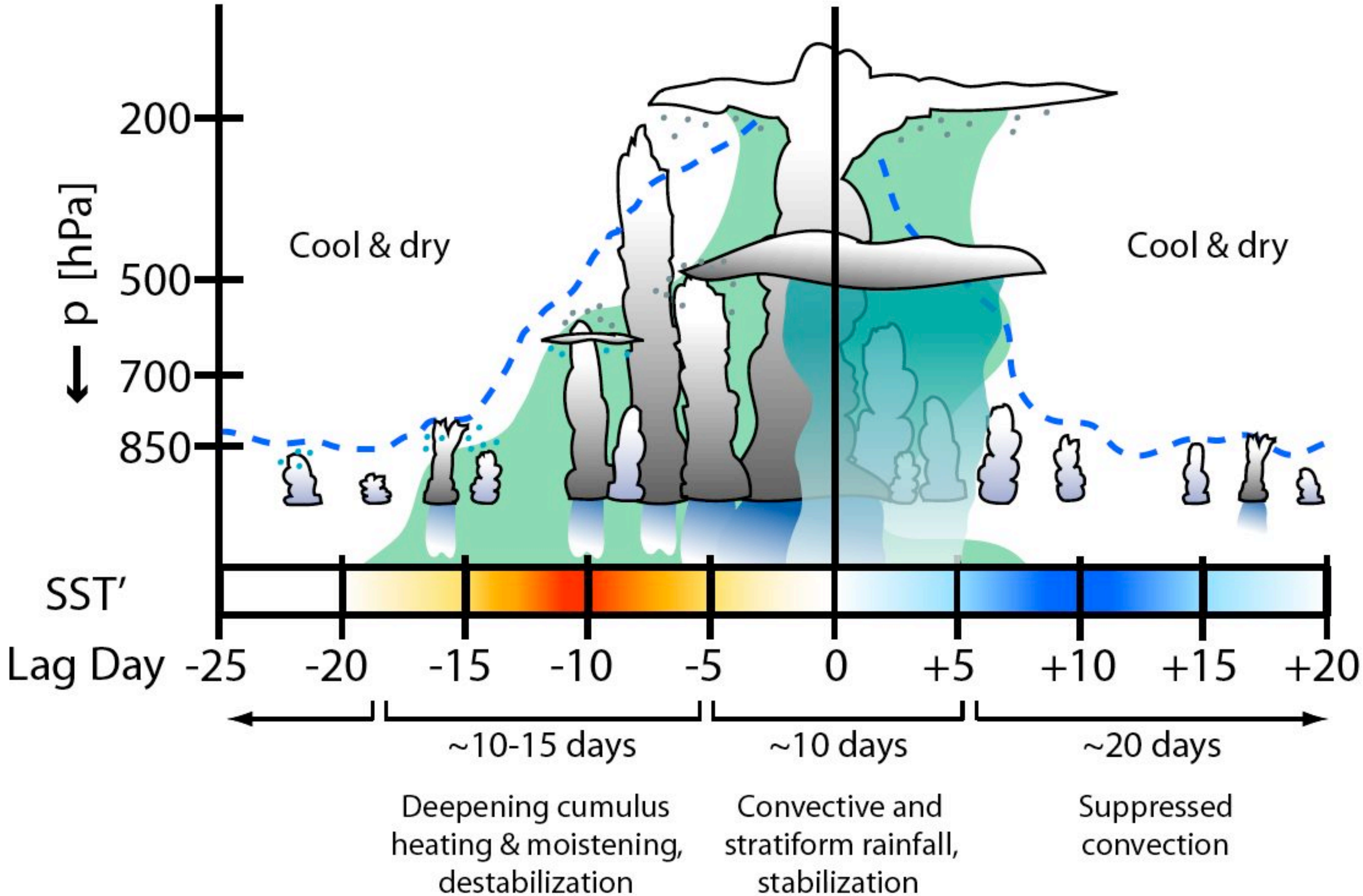
Super-Parameterizations	Conventional Parameterizations
2D	1D
Periodic boundary conditions	Boundary whats?
Shallow convection and turbulence must be parameterized.	Same
Microphysics is simplified but the required input is in pretty good shape.	Microphysics even simpler, and the required input (e.g., local vertical velocity) is not available.
Individual realizations	“Expected values”
200	1



“It’s low-resolution, but at least it uses the right equations.”

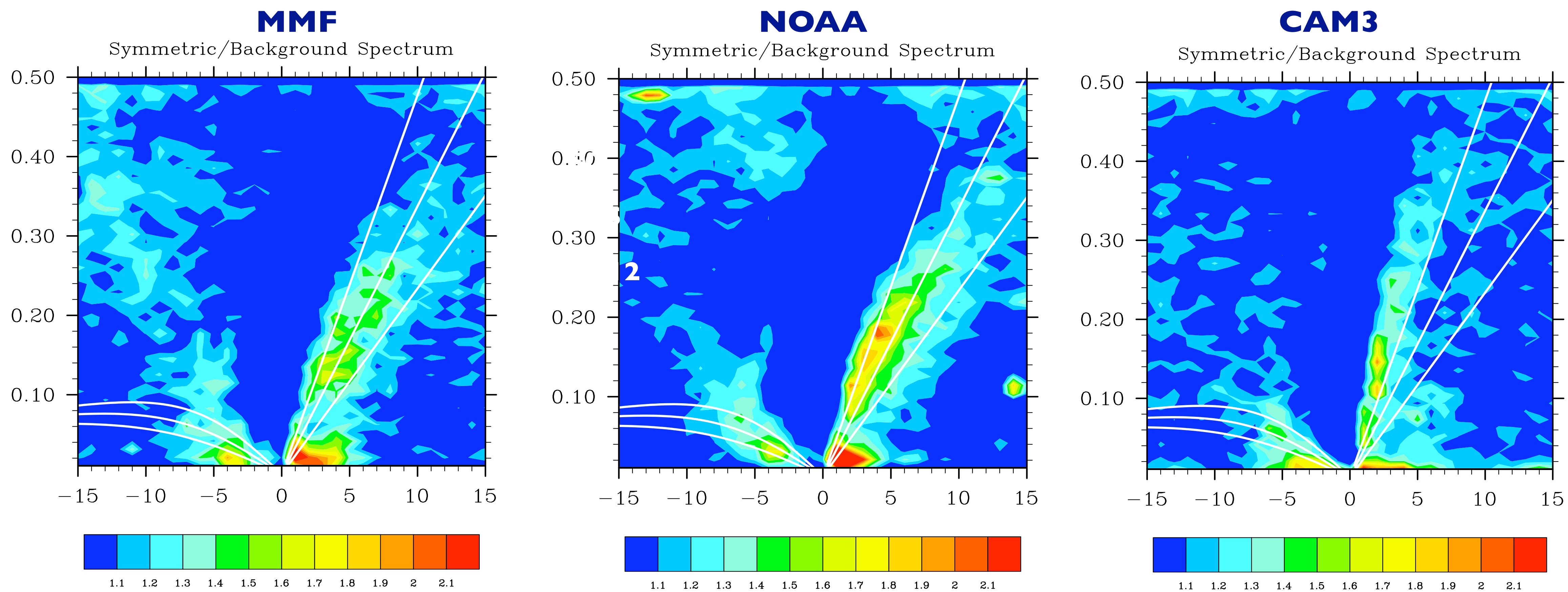
-- Bjorn Stevens

The Madden-Julian Oscillation

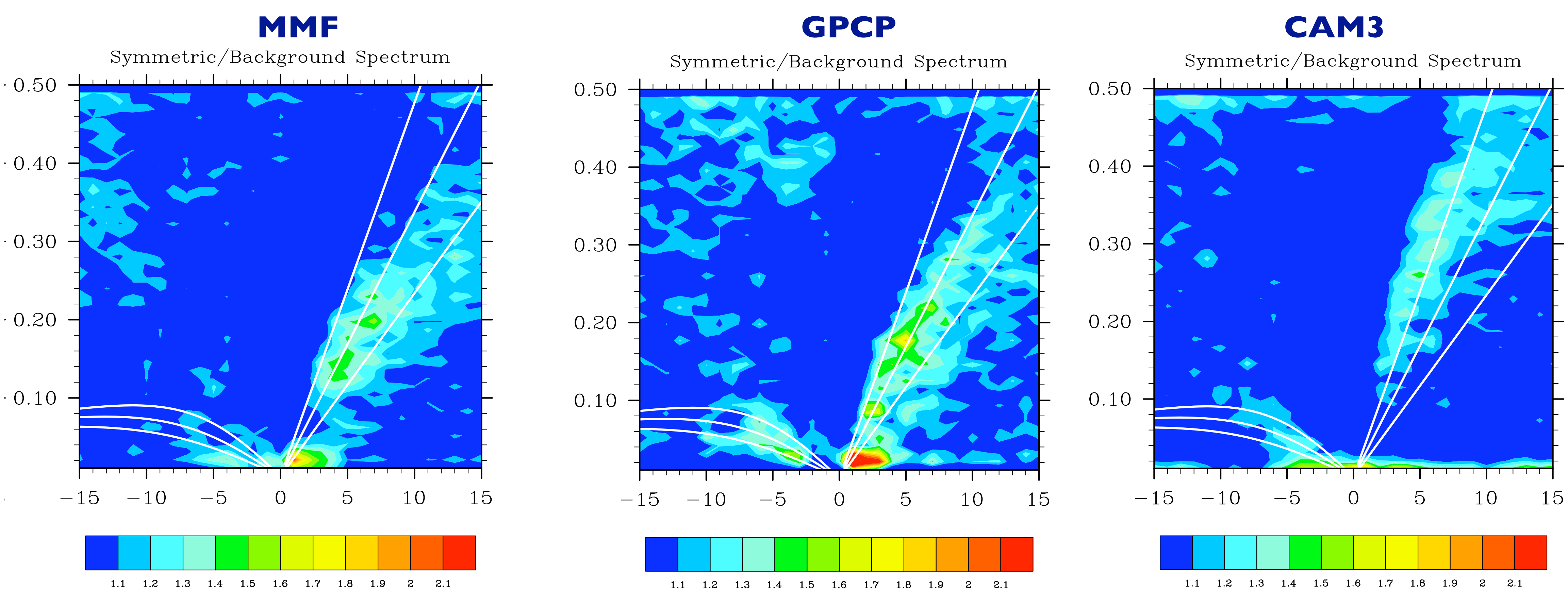


We use the MJO to illustrate that the MMF is useful.

Outgoing Longwave Radiation



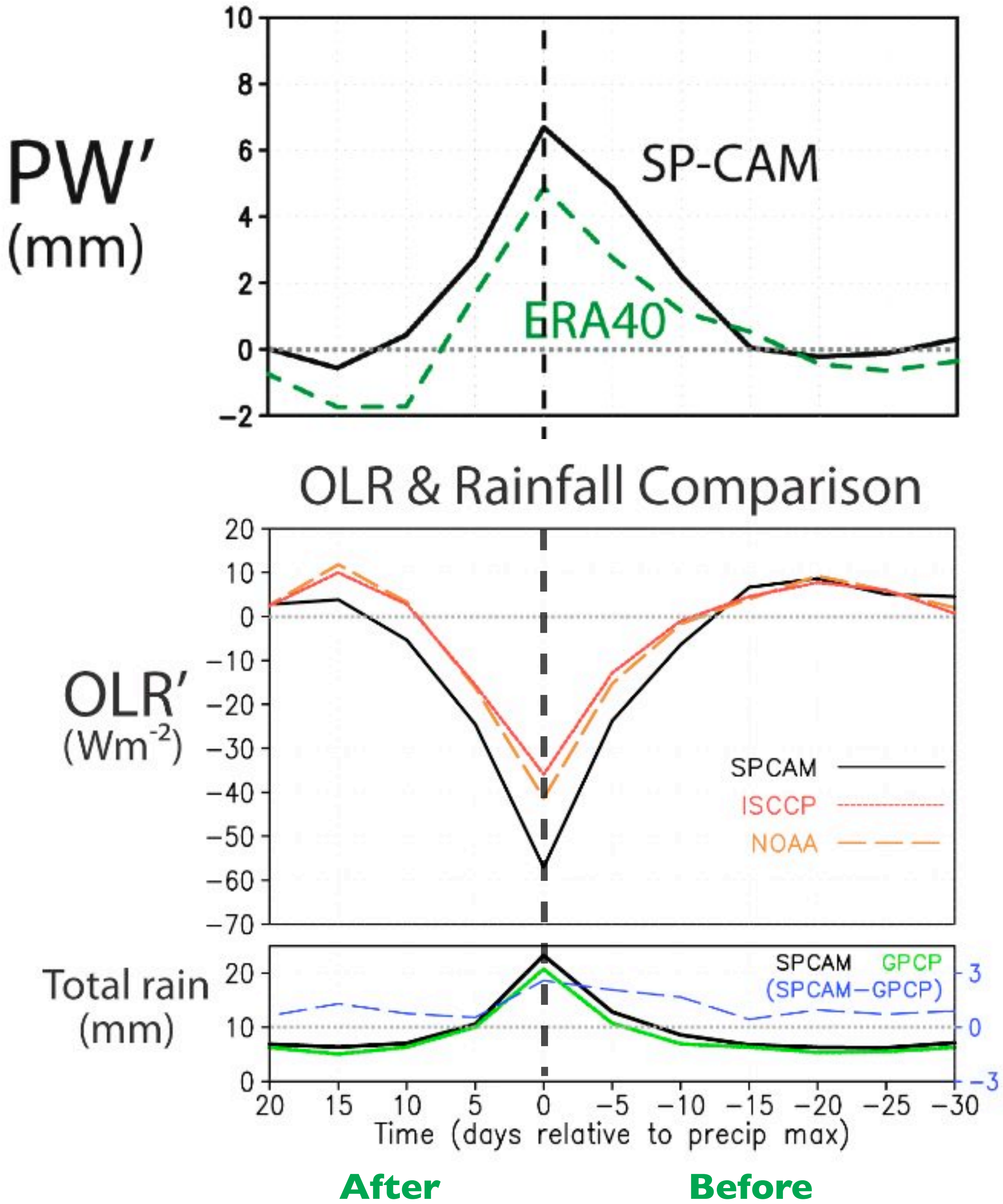
Precipitation




Is the SP-CAM's MJO realistic?

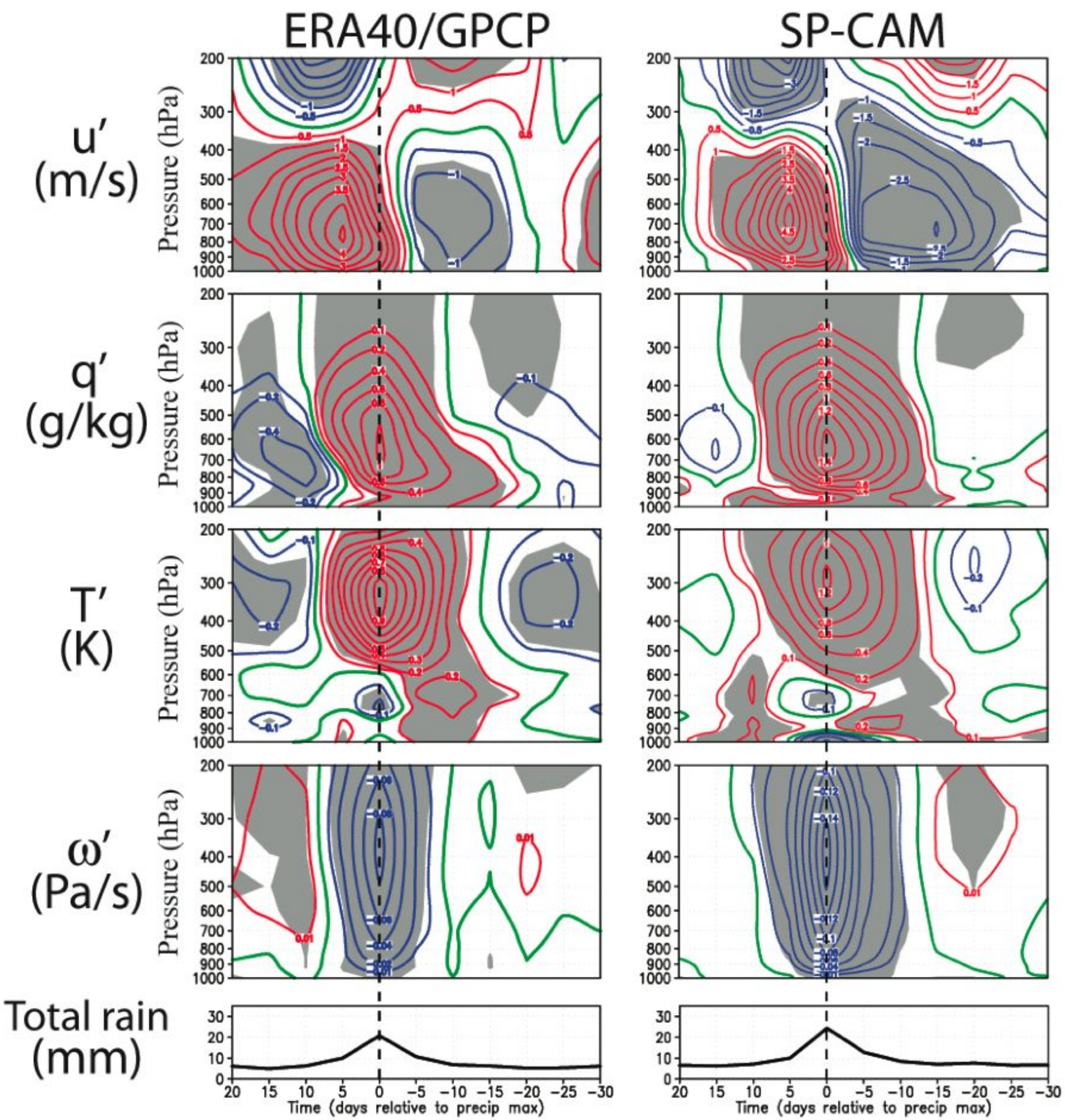
Precipitable water & OLR

Composite of 46 events in GPCP/ERA40 and 46 in SP-CAM



- **Overestimated PW'**
- **Excessively negative OLR'**
- **Exaggerated peak rainfall**

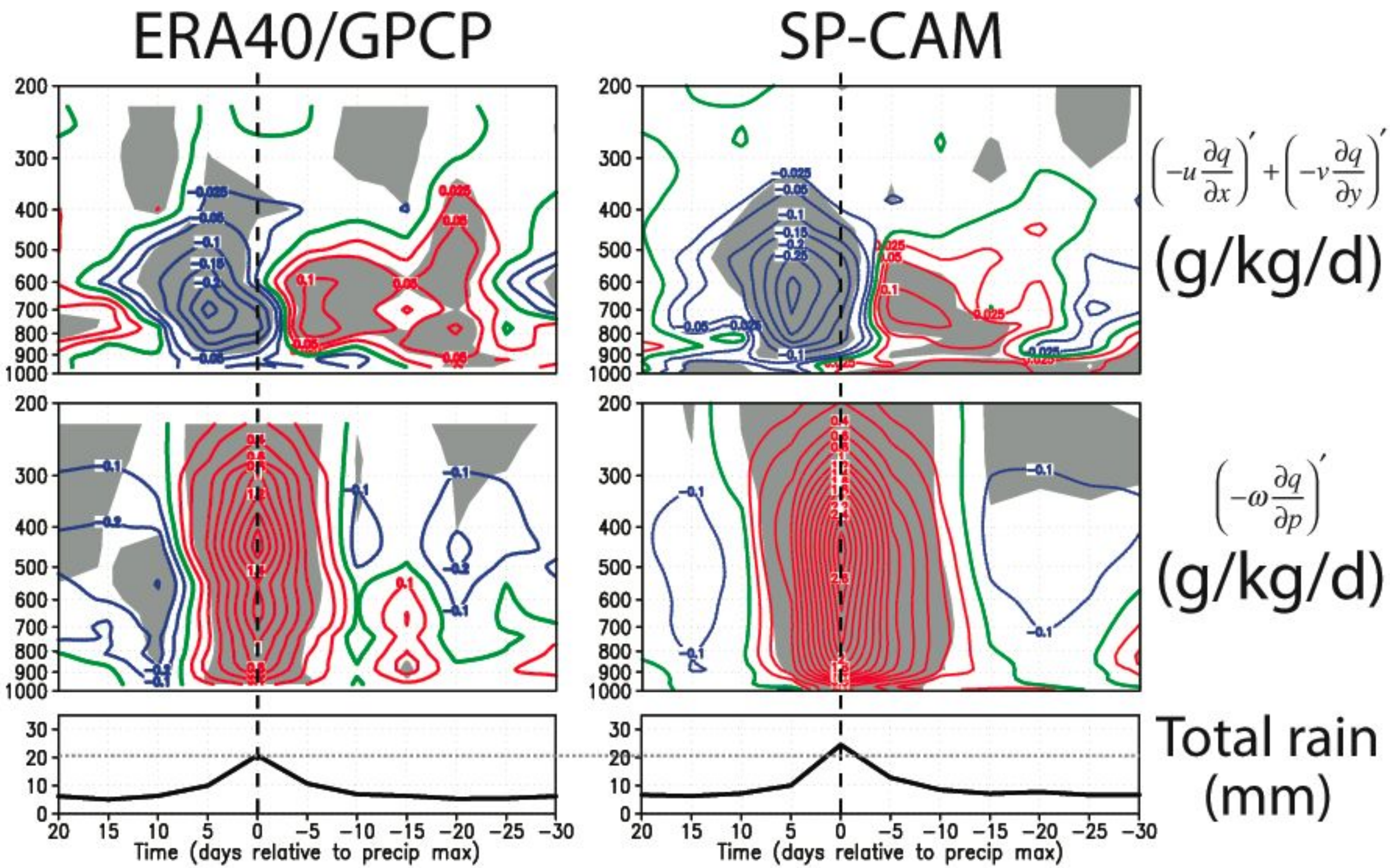
Basics



- **Not bad, but easterlies excessive**
- **Moisture anomaly too strong, less tilt than observed**
- **Leading and trailing cool upper trop. too weak in SP-CAM, warm anoms similar**
- **Upward motion too strong, less tilt than in reanalysis**

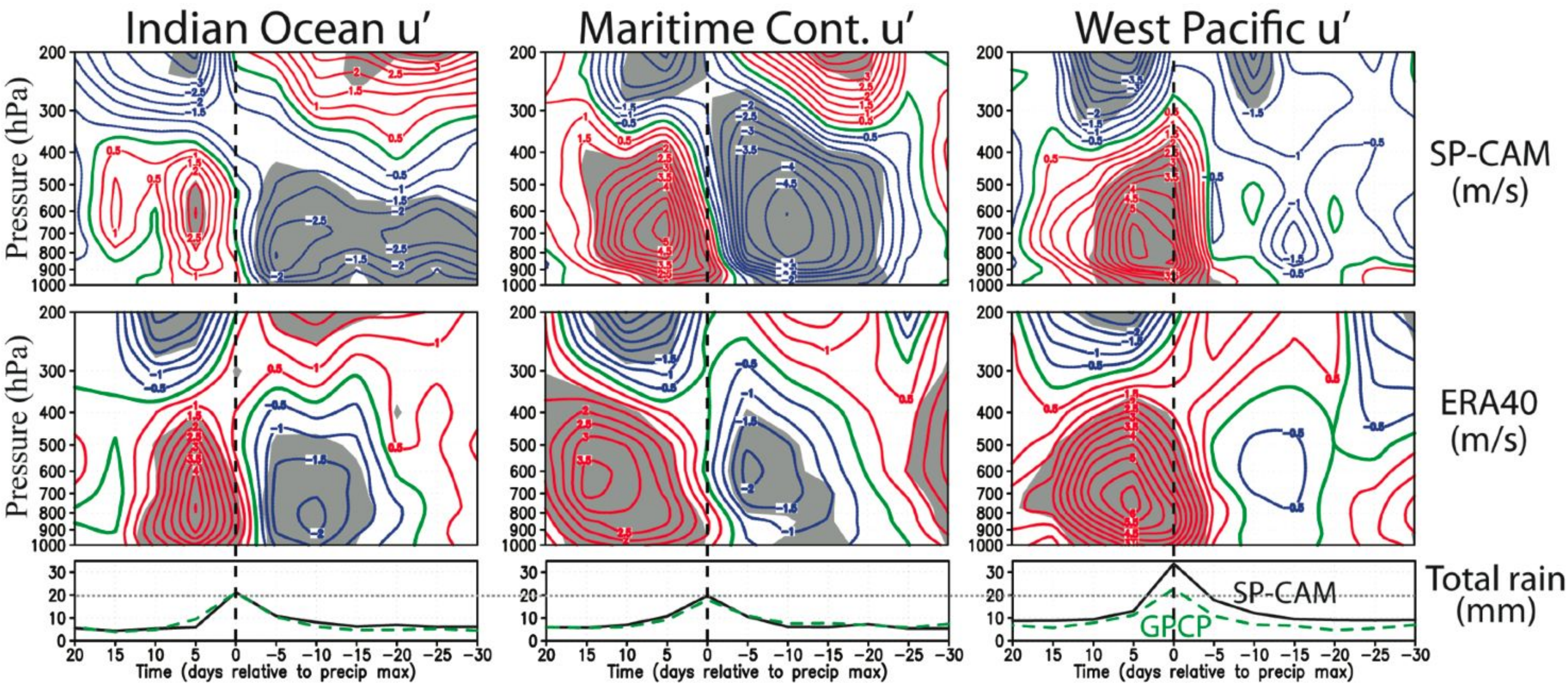
Slide from Jim Benedict

Moisture Advection



Slide from Jim Benedict

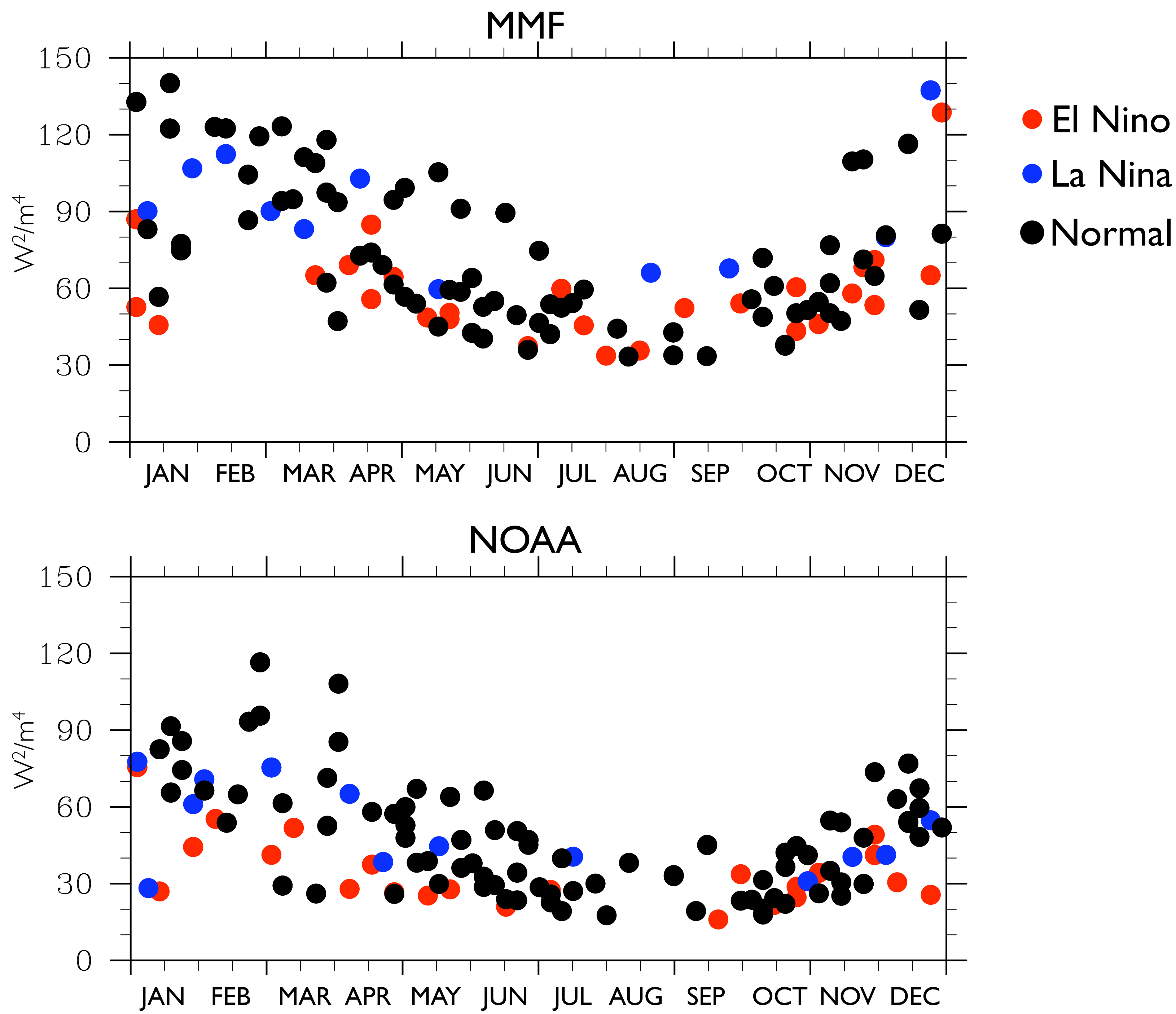
Geographical differences



Westerlies shift eastward relative to precip max
Easterlies weaken

Slide from Jim Benedict

Seasonal Change, 1986-2003



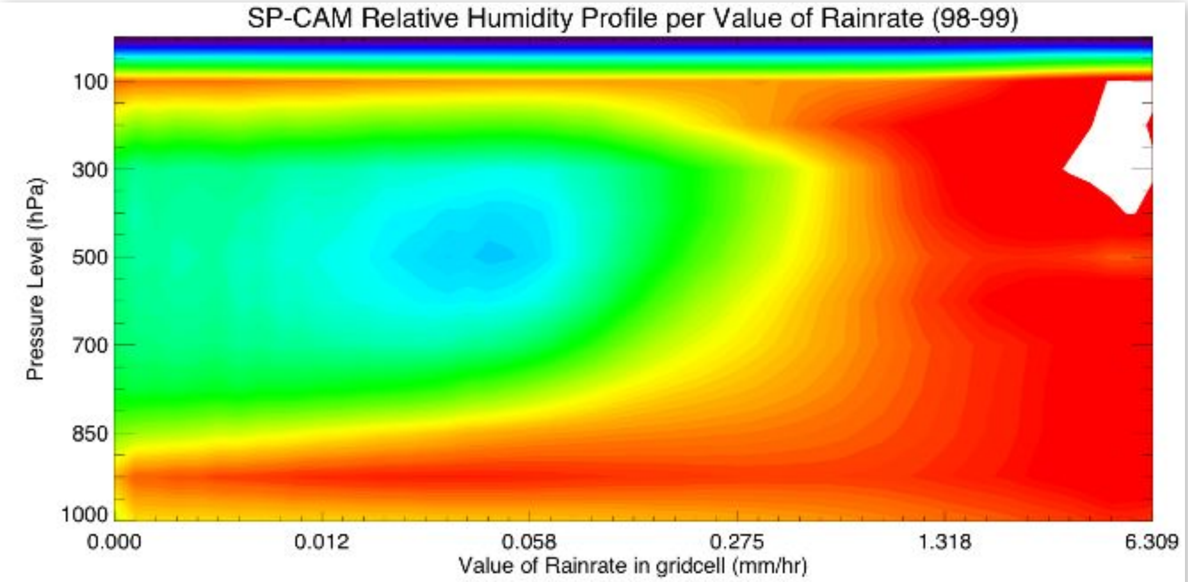
Summary

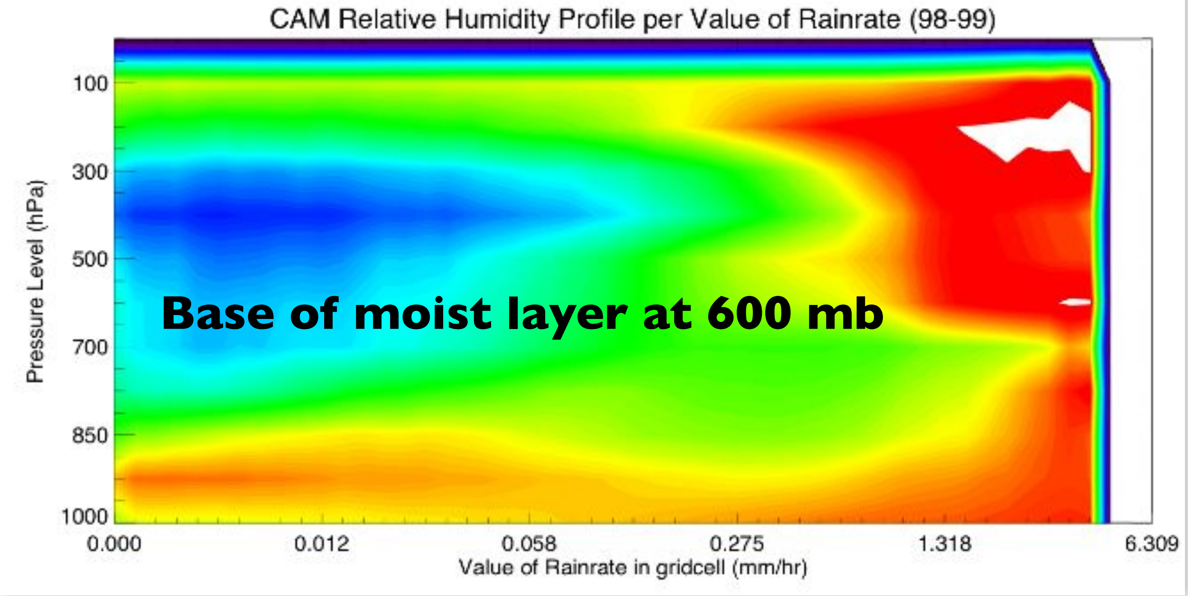
- **The MJO in the SP-CAM is fairly realistic.**
- **Notable deficiencies include excessive pre-event tropospheric easterlies, and *too vigorous day-0 anomalies in many variables*.**
- **Large-scale anomalous moisture advection is well-simulated.**
- **Seasonal cycle is well simulated.**
- **West-to-east evolution of the SP-CAM's zonal wind anomalies qualitatively resembles the reanalysis.**

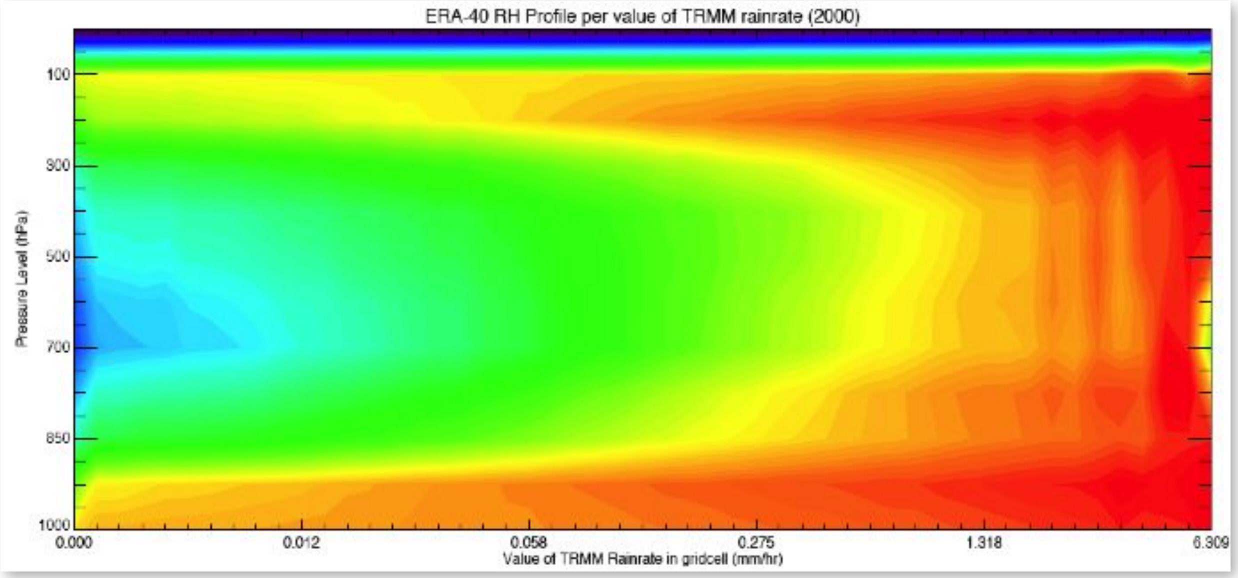
Why is the SP-CAM's MJO realistic?

Rainfall-humidity composites

SP-CAM







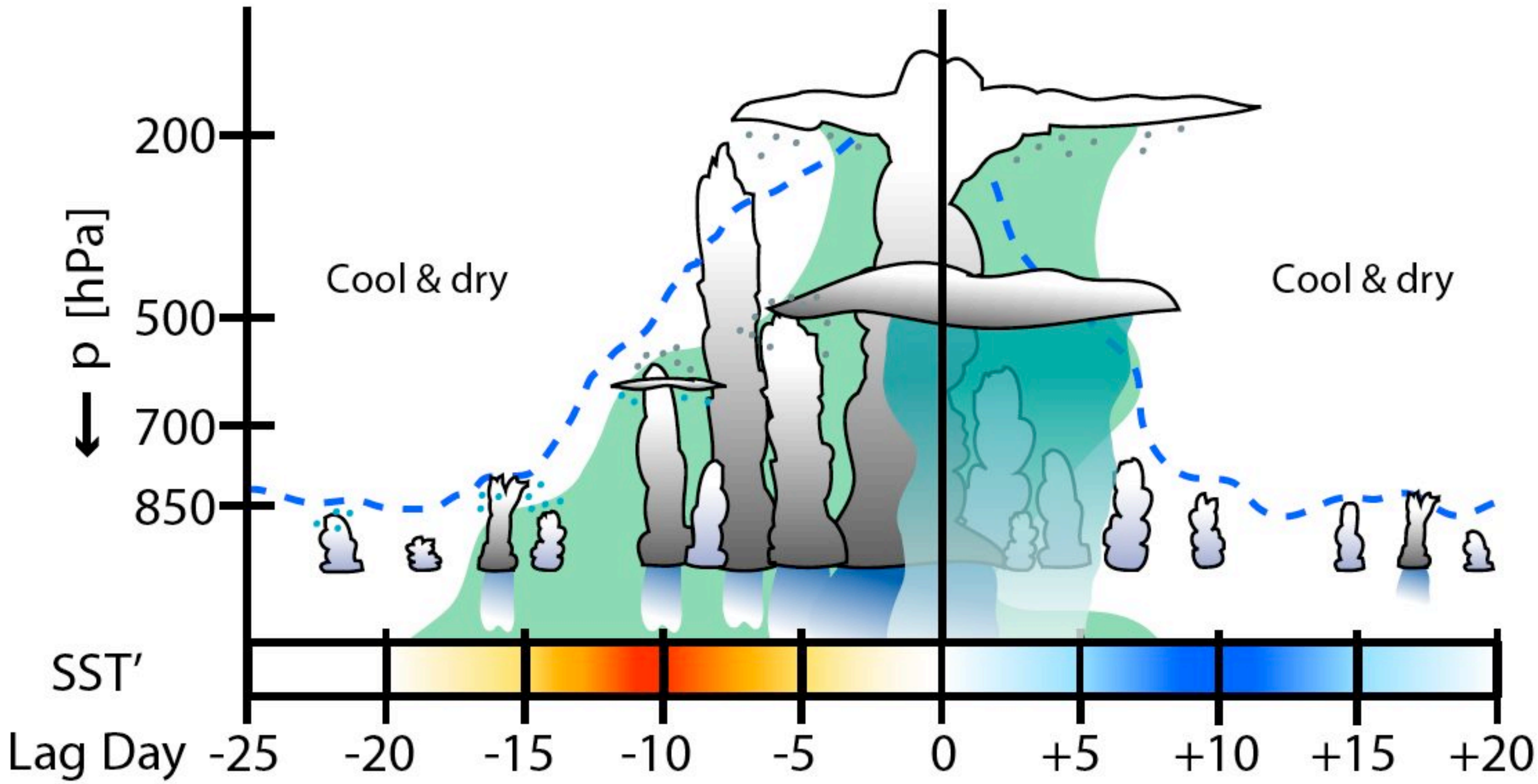
CAM

ERA-40 and TRMM

Slide from Kate Thayer-Calder

Why very wet matters

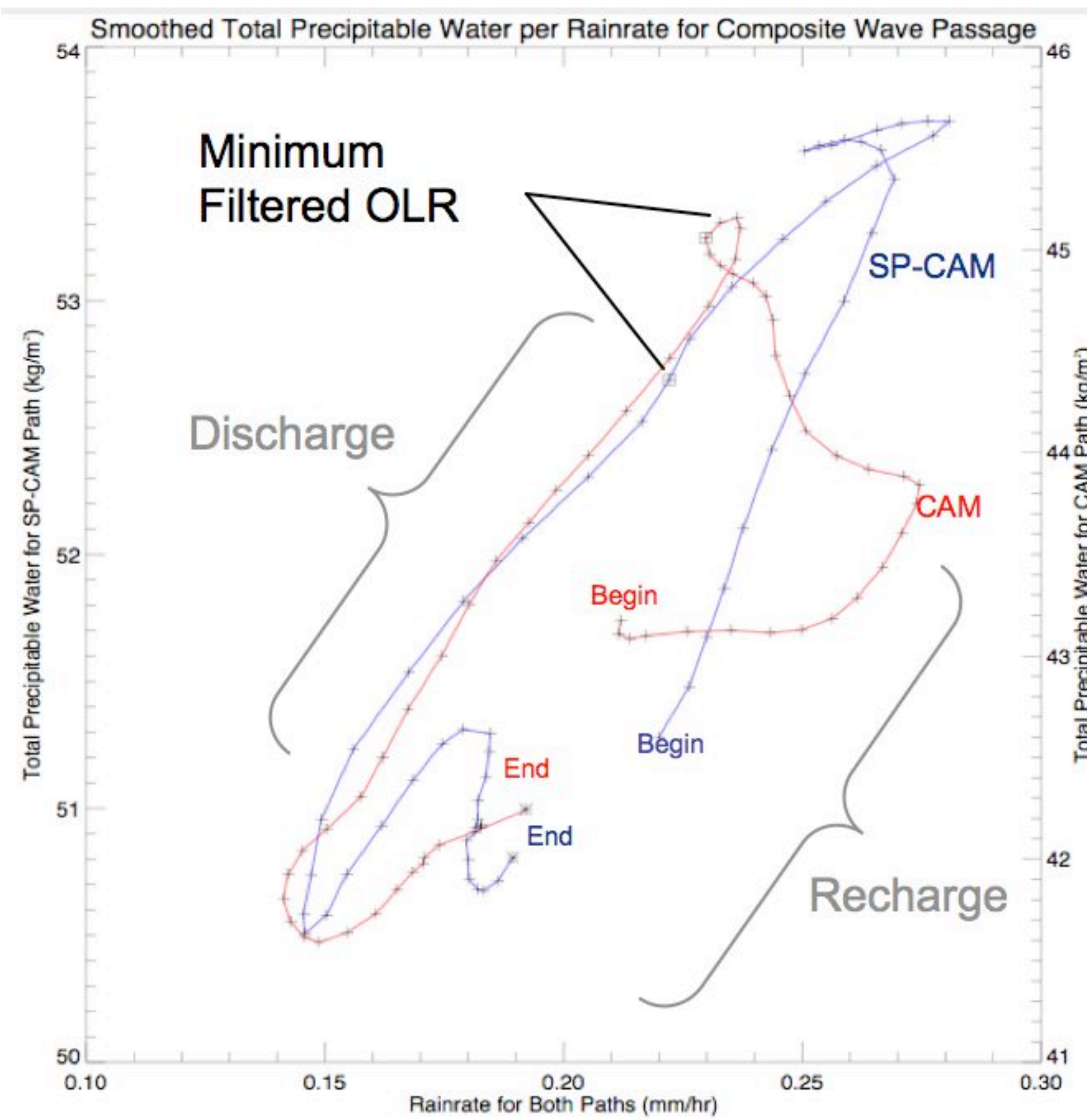
(Ref Emanuel 1989, Bony & Emanuel 2005)

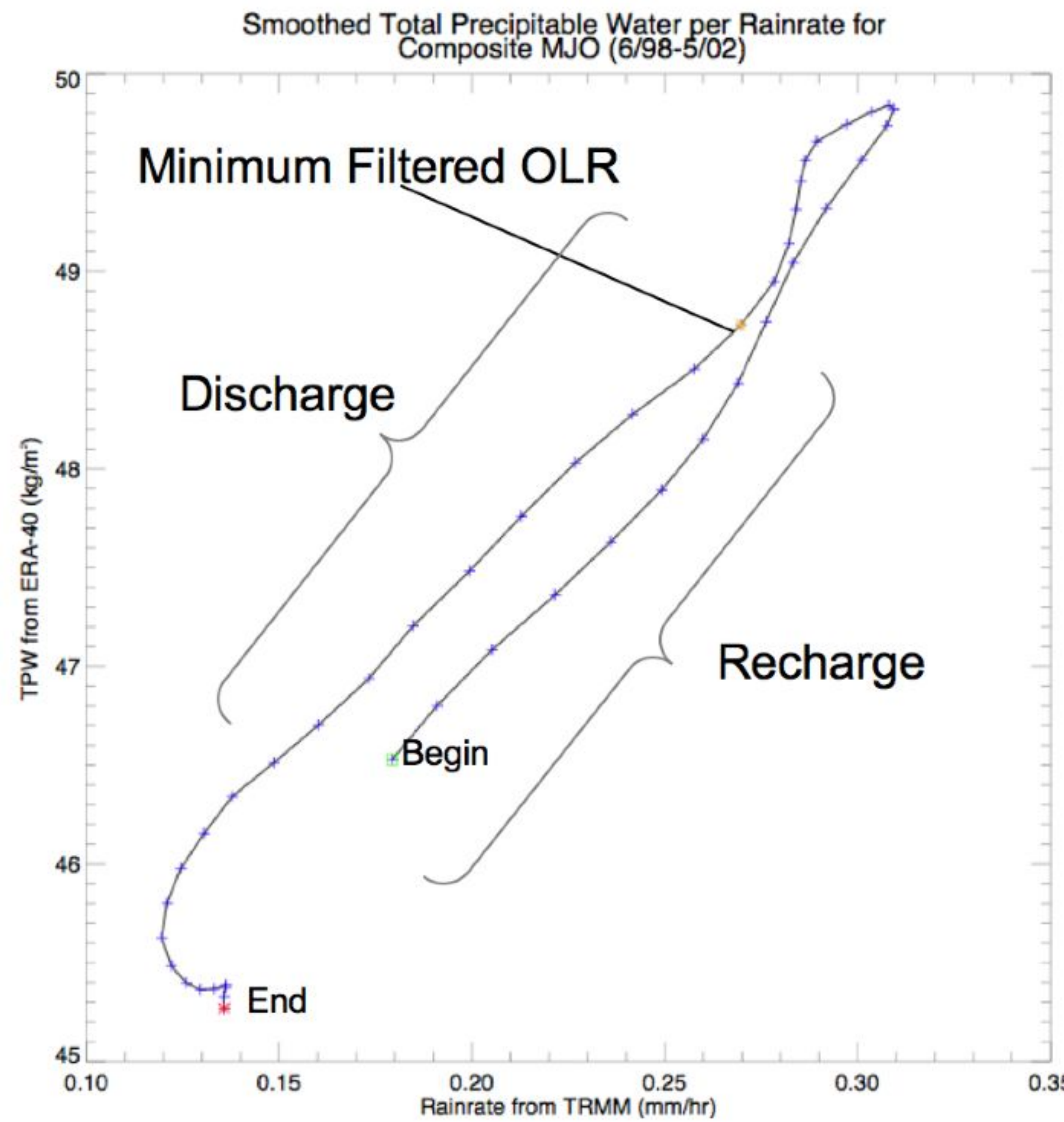


Downdrafts stabilize BL

Downdrafts ineffective

Discharge and Recharge





Models

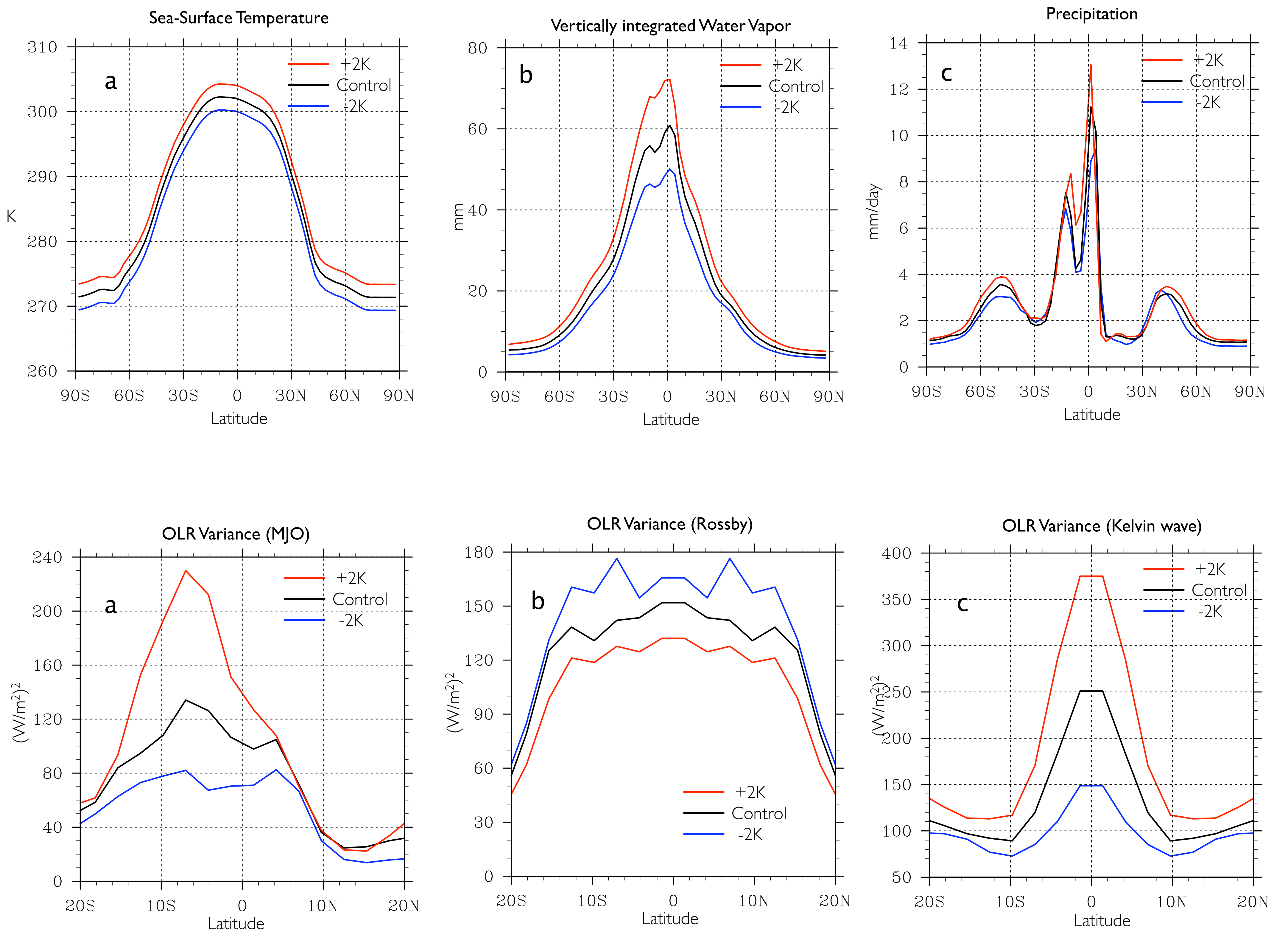
ERA-40 & TRMM

Slide from Kate Thayer-Calder

What I think is going on

- During the “recharge” phase, convective stabilization occurs mainly through the effects of downdrafts on the PBL moist static energy (Raymond’s BL QE).
- When the troposphere becomes very moist, this mechanism does not work well. The brakes fail.
- Convection then intensifies, exciting a large-scale disturbance.
- The disturbance produces warming aloft and strong dry advection west of the heating, which shut off the deep convection.
- Recharge resumes.
- This is generally consistent with the model of Bony and Emanuel (JAS, 2005), who discussed a “moisture-convection feedback.”
- For this mechanism to work, a model needs:
  - Downdrafts that stabilize the PBL
  - A tendency to moisten a deep layer as the rainfall rate increases

MJO on a Warm Aquaplanet



Slide from Marat Khairoutdinov

Problems with the first-generation MMF

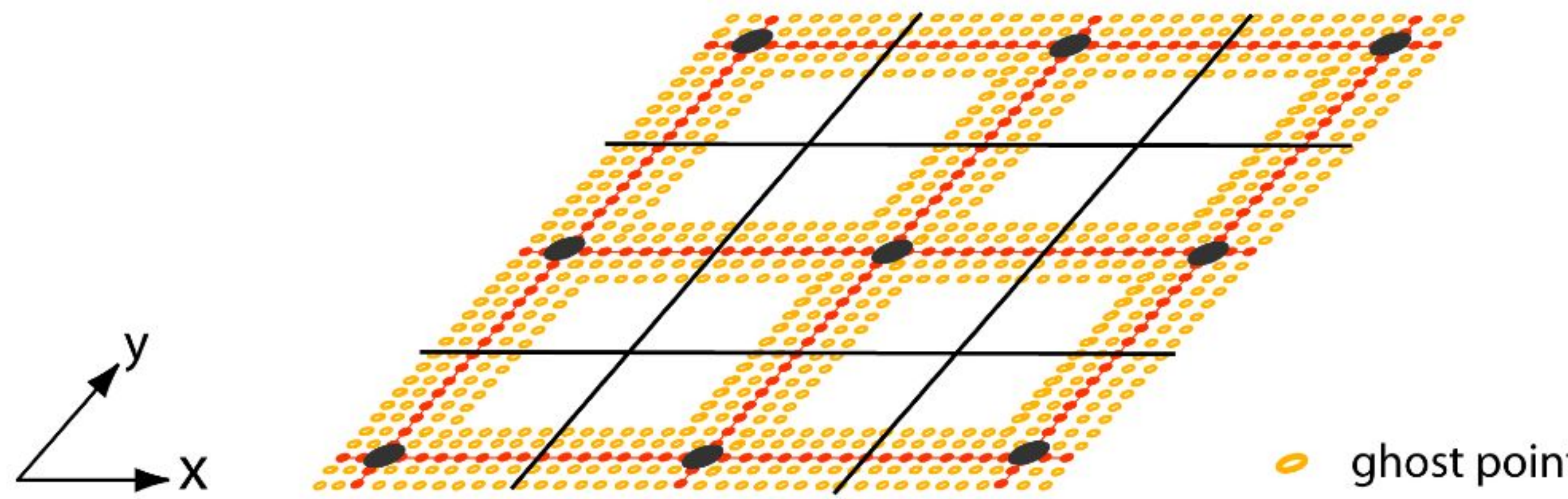
- Two-dimensionality
  - The dynamics is wrong.
  - Can’t include momentum transport.
- Periodic boundary conditions
- Need for a better turbulence parameterization
- Ambiguous relationship between the fine and coarse meshes
  - How “big” should the CRM be?
  - What happens as the outer mesh is refined?

Plans for a second-generation MMF

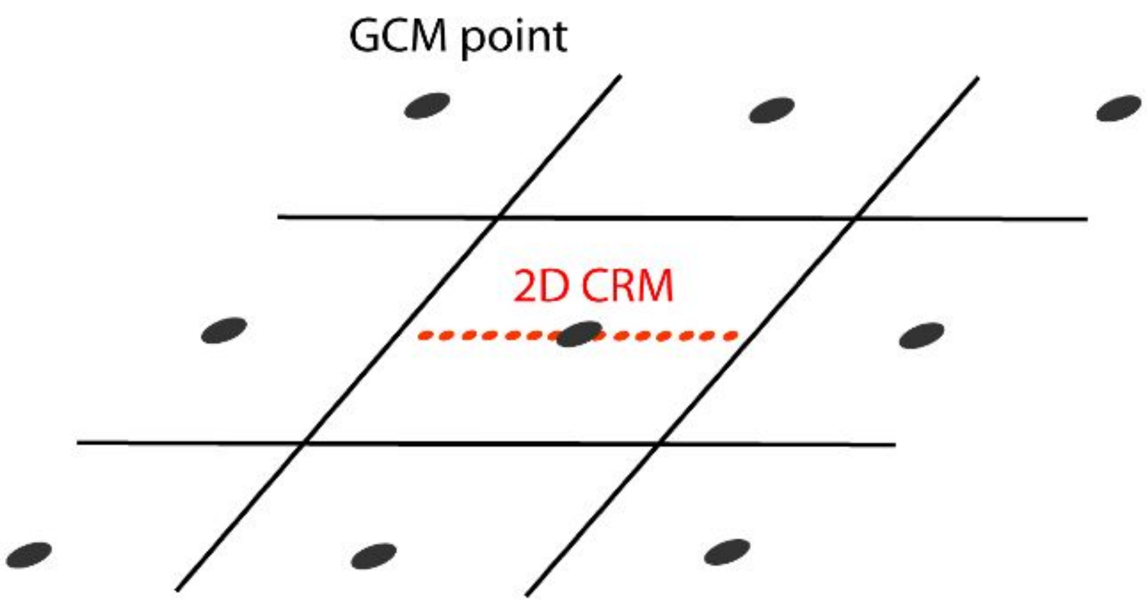
(Arakawa & Jung)

- **Quasi-three-dimensional**
  - **3D uniform coarse grid, or "net"**
  - ***3D global cloud-scale mesh with gaps***
  - **3D equations everywhere on the cloud mesh, using "ghost points"**
- **Well-defined relationship between the fine and coarse meshes**
- **The coarse grid nudges the fine grid, and the fine-grid statistics feed back on the coarse grid.**

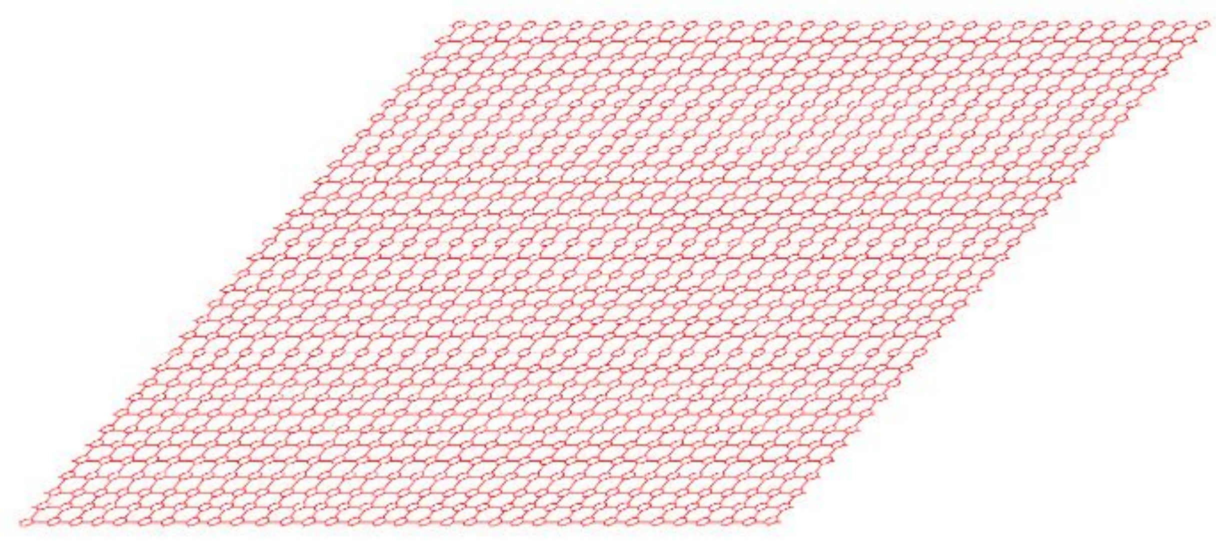
Q3D MMF



PROTOTYPE MMF

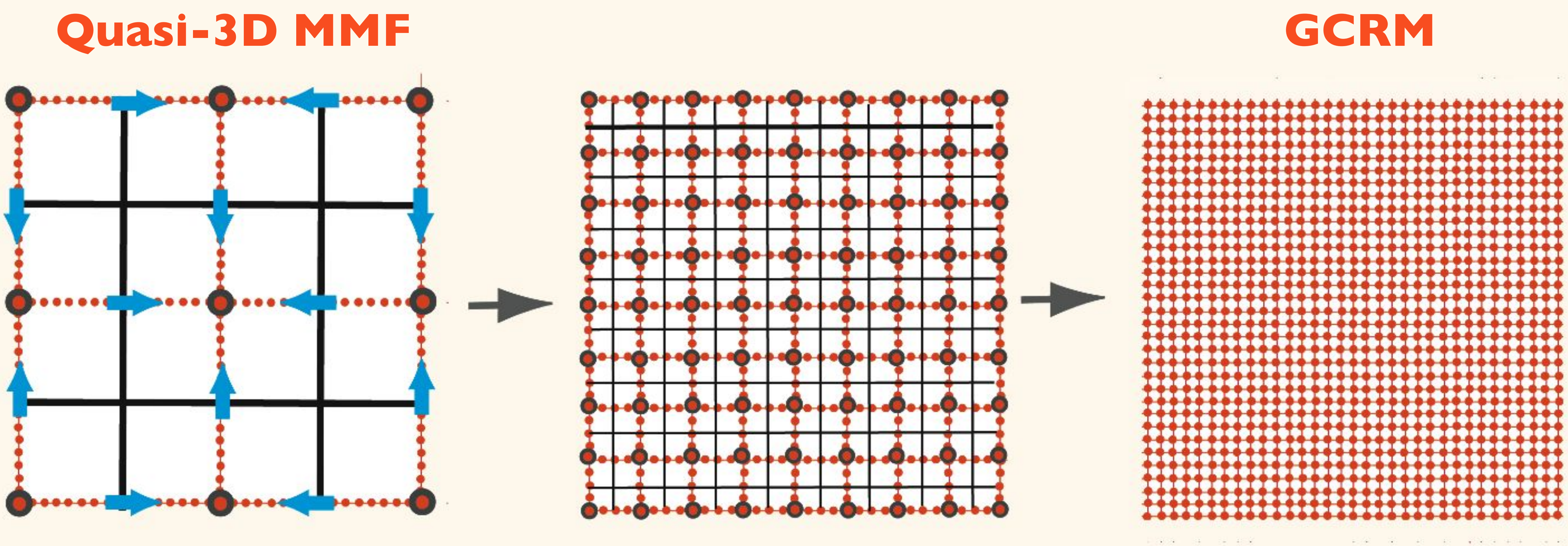


3D CRM



Slide from Akio Arakawa

Second-generation MMF



Convergence (in the mathematical sense):
Same equations, same code
Q3D MMF --> GCRM

Slide from Akio Arakawa

Changing resolution

At very high resolution, a model should grow individual clouds -- *a qualitative difference from current models*.

Therefore, as a model's resolution changes, its formulation should "adjust."

The 2nd-generation MMF is designed to do this.

Summary

- As grid spacings decrease, conventional cloud/convection parameterizations suffer from three problems:
  - Sampling error increases.
  - Adjustment is too slow.
  - Convective transports give way to microphysics.
- GCRMs avoid these issues, but are too expensive at present.
- MMFs also avoid these issues.
- The first-generation MMF gives some insight into the MJO, but has several deficiencies.
- A second-generation MMF is under development.