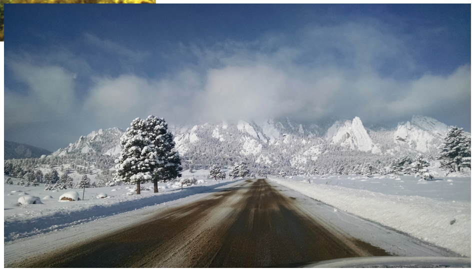
Determining Metrics of Success in Climate Models



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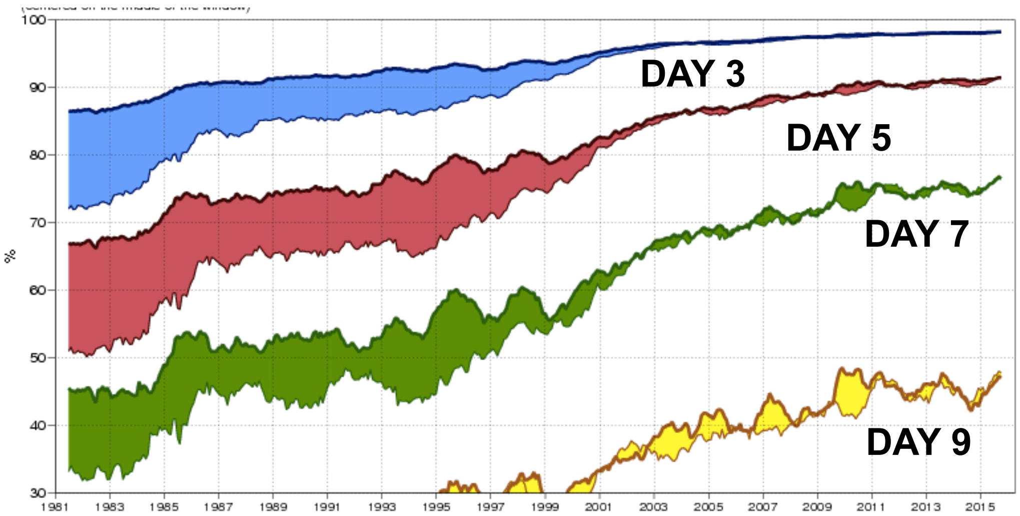
Multiple Thanks: Cecile Hannay, Andrew Gettelman, Pete Bogenschutz, Sungsu Park, Julio Bacmeister, Peter Lauritzen, Mark Taylor, +++

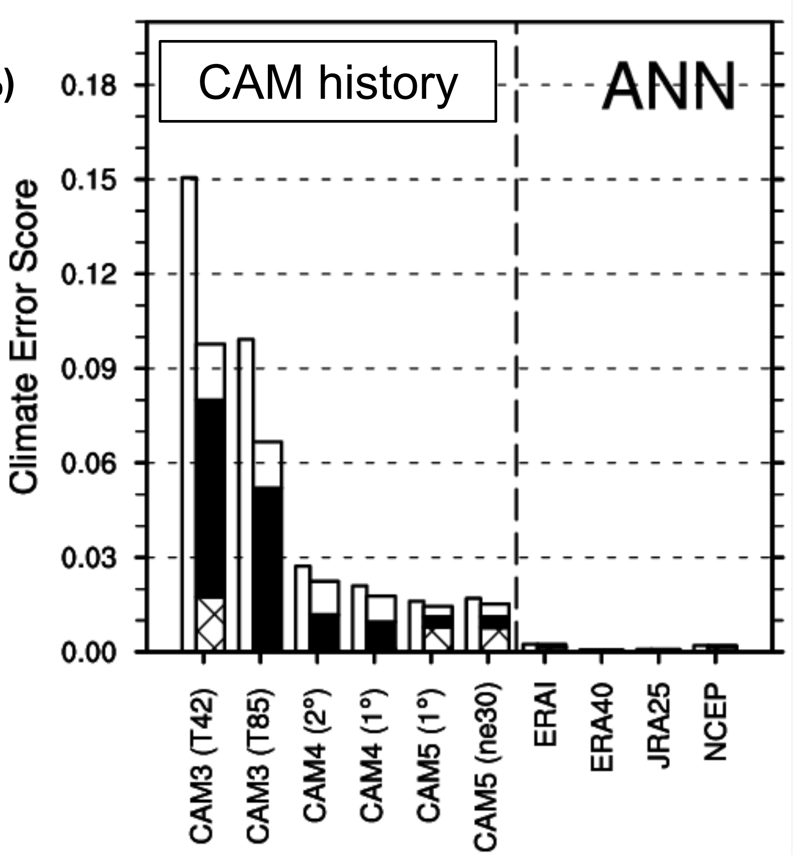
Overview

- How do we determine the success of introducing a change into a comprehensive climate model?
  - A much more difficult problem with physics + dynamics combined (tests)
  - Agreeing on metrics is difficult: Everyone has their favorite
  - Difficult to define: What is the model used for?
  - Consistent response across model hierarchies, resolution, forcings
  - Operating as expected: Process oriented analysis
  - Beyond climate average diagnostics: High-frequency variability

Climate/Forecast Error Scores (500-mb height)

500-mb Geopotential Height – Anom. Corr. Coeff. (ECMWF,%)





Phase errors (a)

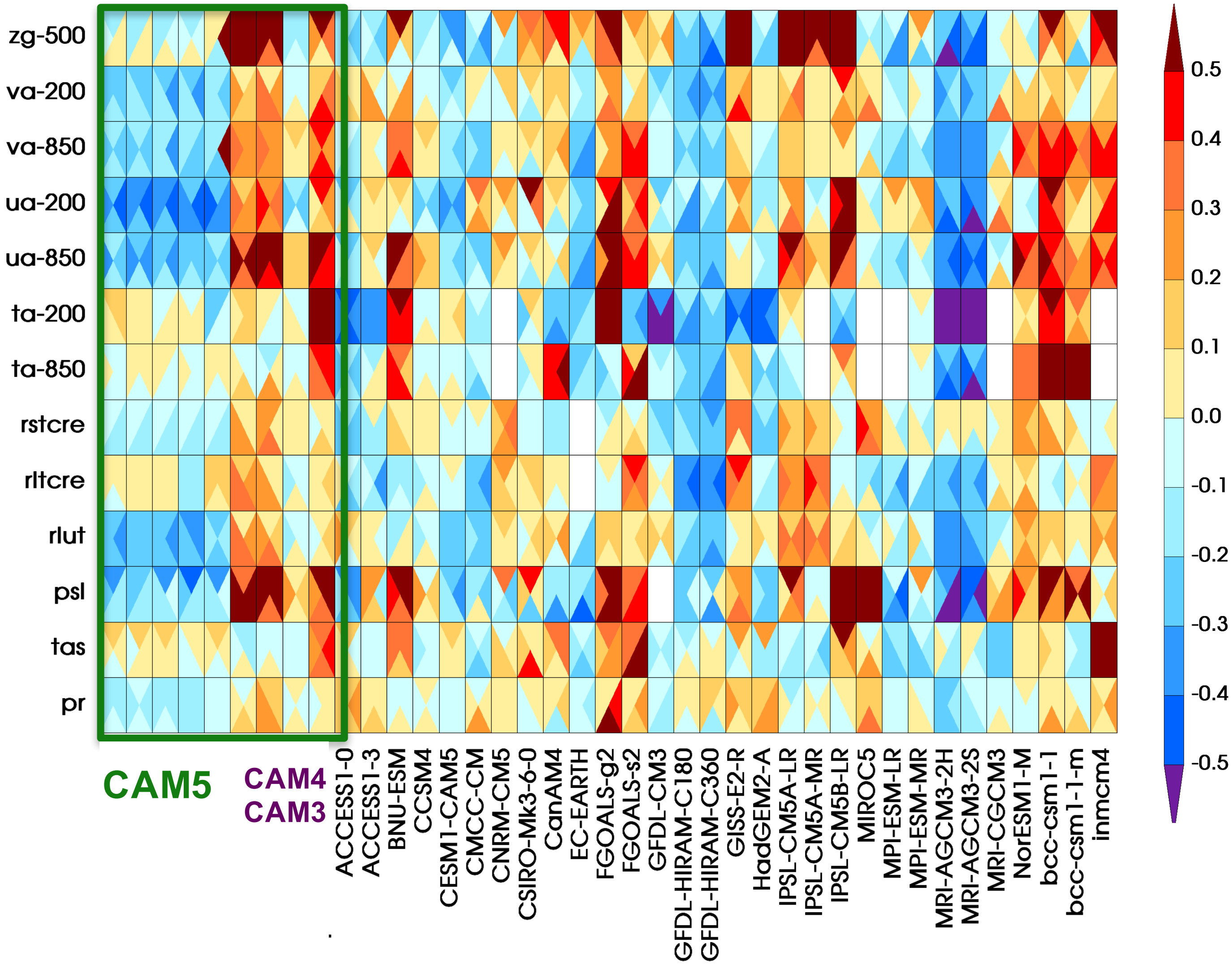
Conditional bias (b)

Unconditional bias (c)

Scaled variance ratio

NMSE = (a)+(b)+(c)

CMIP5: Are we in the middle of the pack?



- **CAM performs well and is improving**
- **No exceptional scores**
- **Good models**
  - **Good physics**
  - **High resolution**
- **Does not give broad indication of performance**
- **Some "red-line" poor performance may be crossed e.g., ENSO**

Example of A Development Pathway

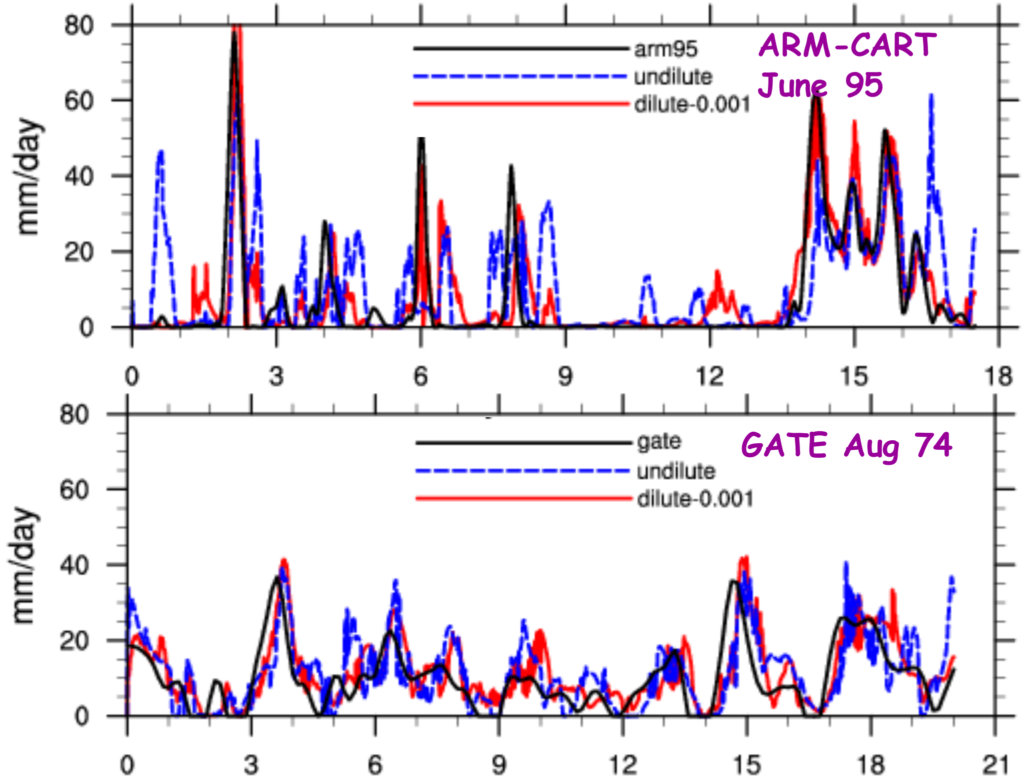
NCAR-DOE Community Earth System Model (CESM)

Community Atmosphere Model (CAM)

CAM3	**2004**
CAM4	**+New convection (2010):** - Deep convection (Neale, Richter)
CAM5	**+New Physics (2011):** - Cloud microphysics (Morrison, Gettelman) - Radiative Transfer (Iacono, Collins, Conley) - PBL and Shallow convection (Bretherton and Park) - Macrophysics (Park, Bretherton, Rasch) - Aerosol formulation (Ghan, Liu, Easter) - Ice clouds (Gettelman, Liu, Park, Mitchell)

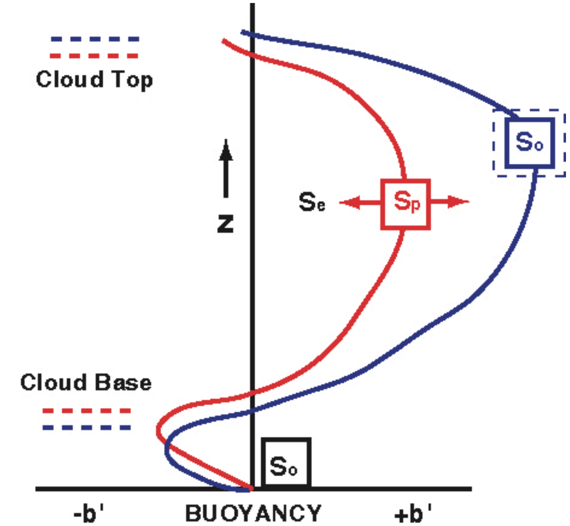
Entrainment: Increasing Moisture Sensitivity

- Bulk mass flux models (A-S, Zhang McFarlane) attempt to include the effects of entrainment with an assumed spectra of plumes/entrainment rates
- Ultimately they are slave to the most **undilute** mode



Single-column experiments

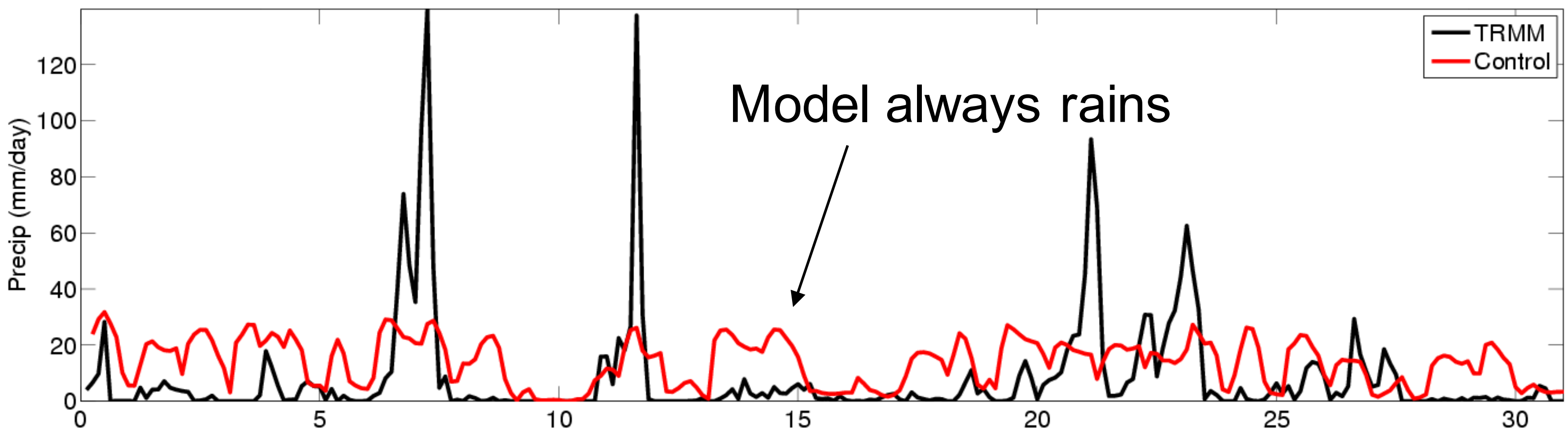
Assume most undilute ascent has some entrainment (dilution)



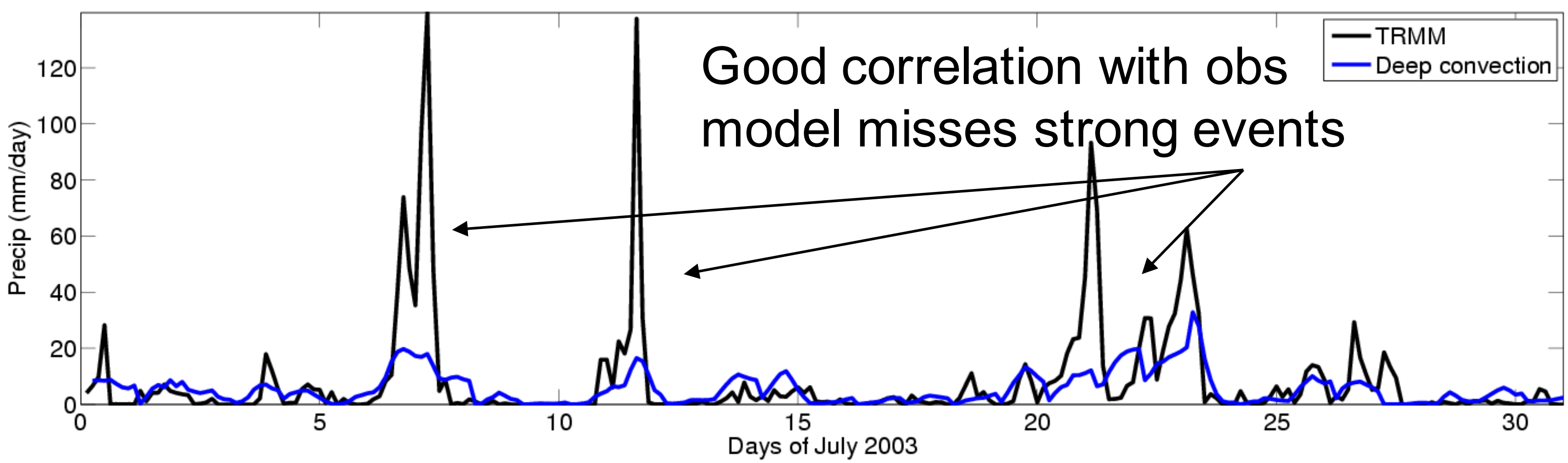
Hindcast Performance

CAPT – 1-day forecasts in the tropical East Pacific

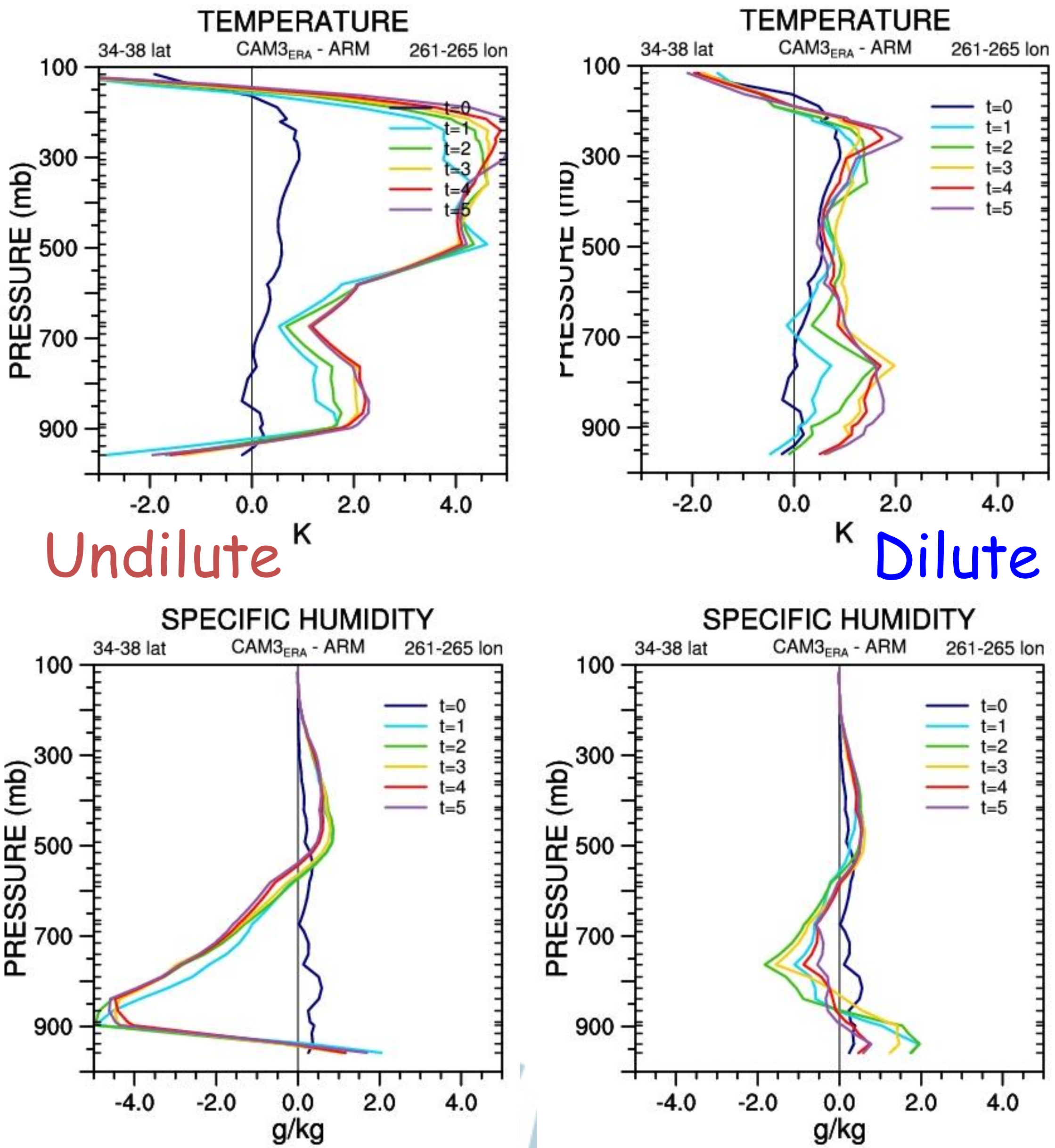
Control (undilute)



Dilute



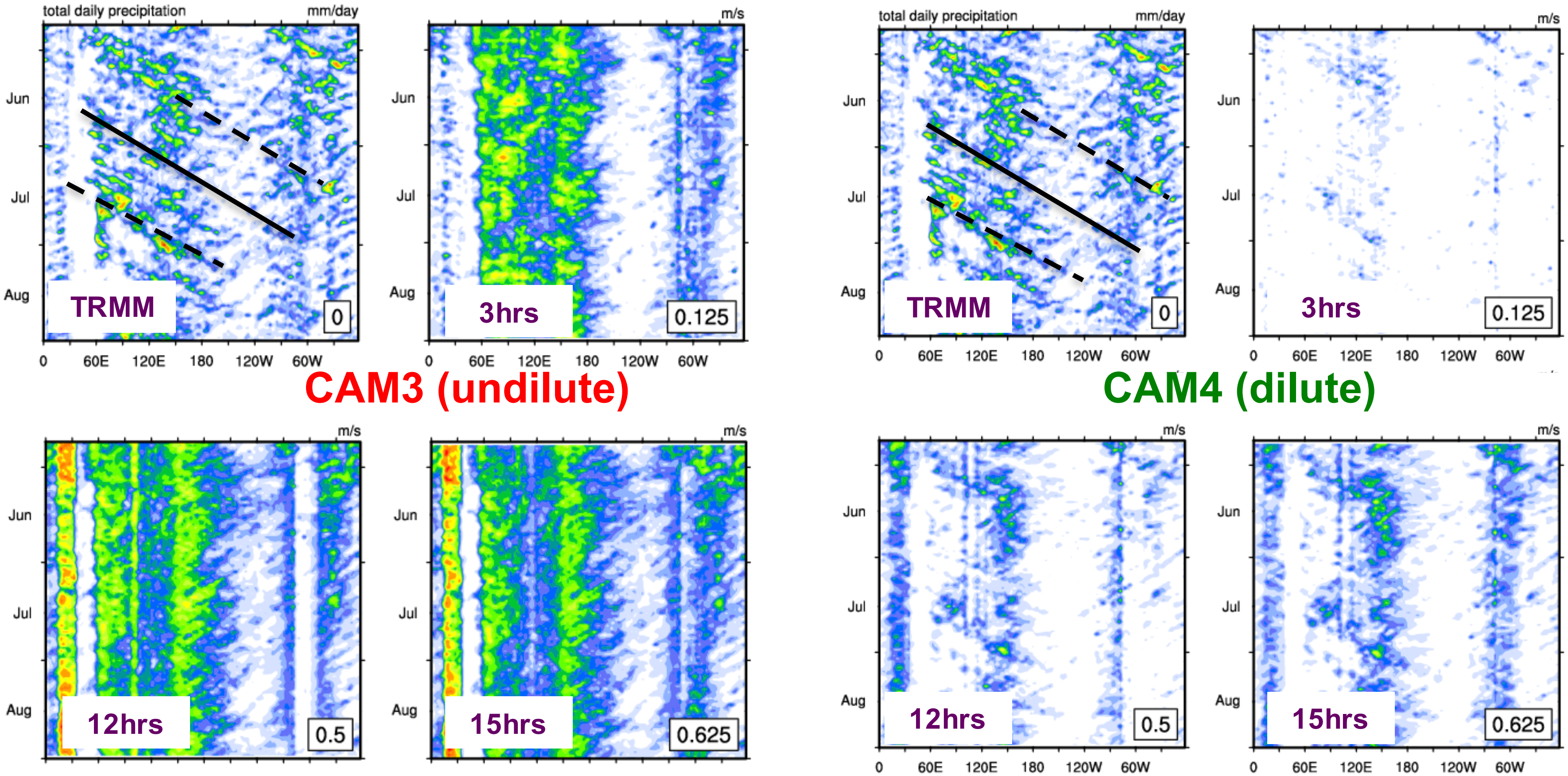
Hindcast Performance



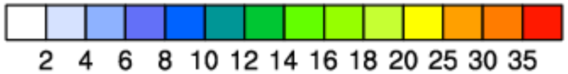
- CAPT simulations
- Southern Great Planes
- Deep convection is the fastest process
- Errors in model state (T,q) response to convection will show first

Hindcast Simulation Spin-up

YOTC hindcasts (Summer 2008) – once daily

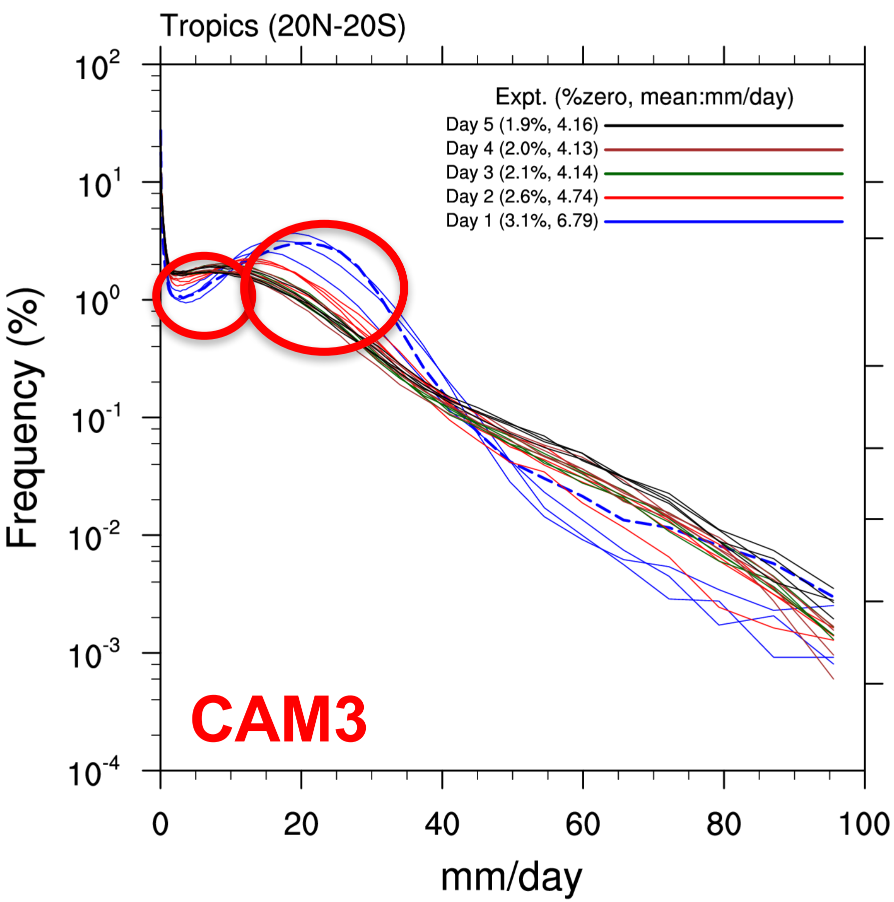


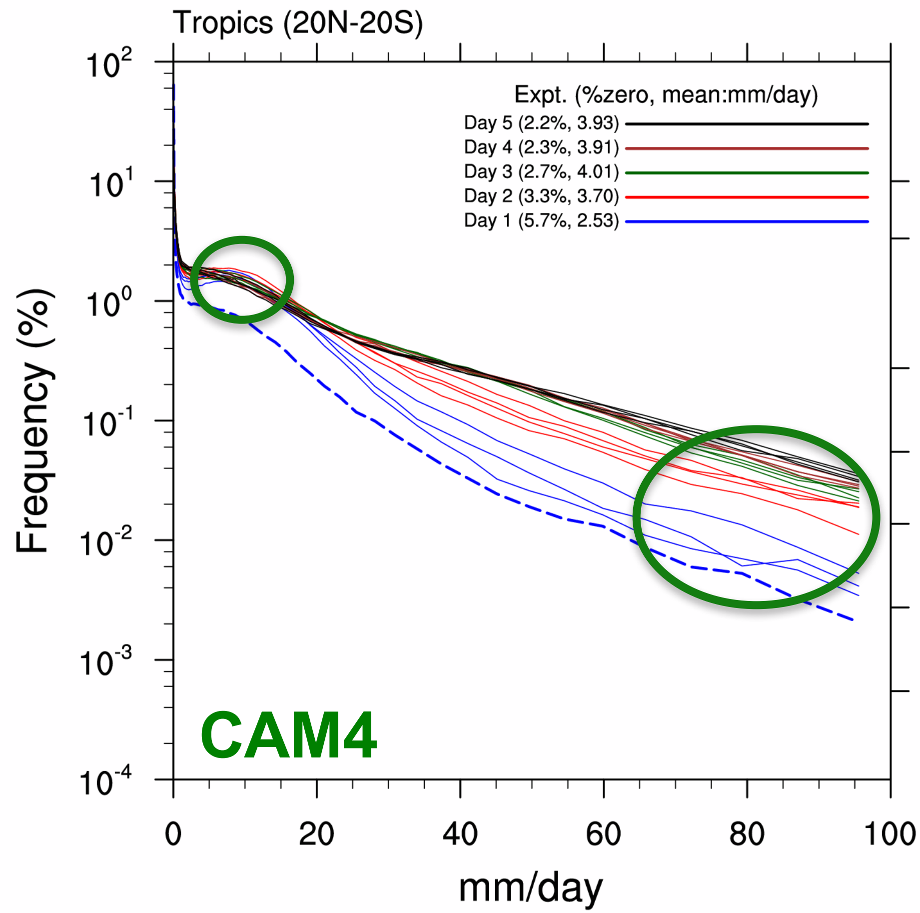
200-mb 20-100 day
band passed
Precipitation (10N-10S , m/s)



Hindcast Spin-up Response

PDF of precip. w/ hindcast length

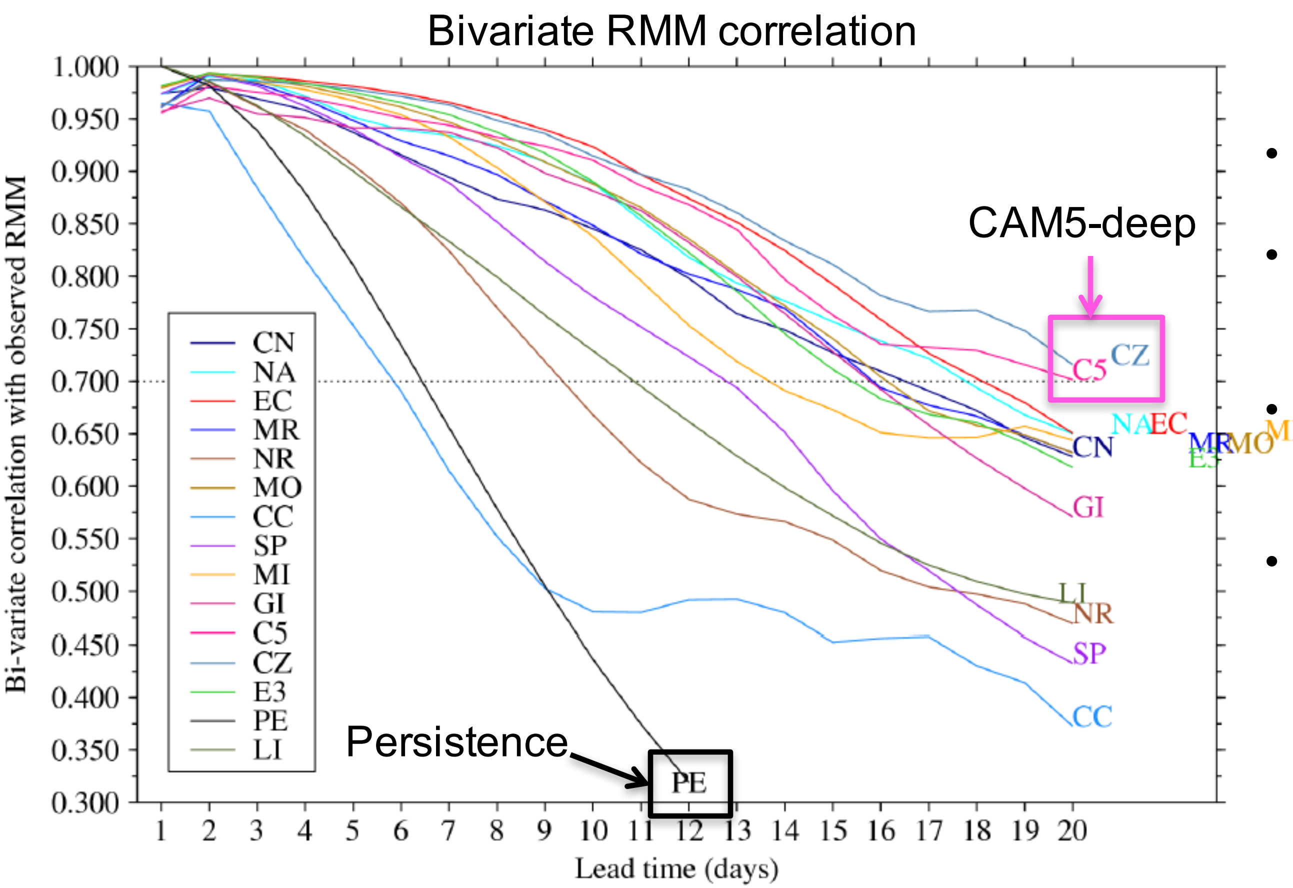




CAM3 overshoots significantly in day 1 then spins down to equilibrium by day 2

CAM5 equilibrates quickly at lower rainfall rates; by day 3 at high rates

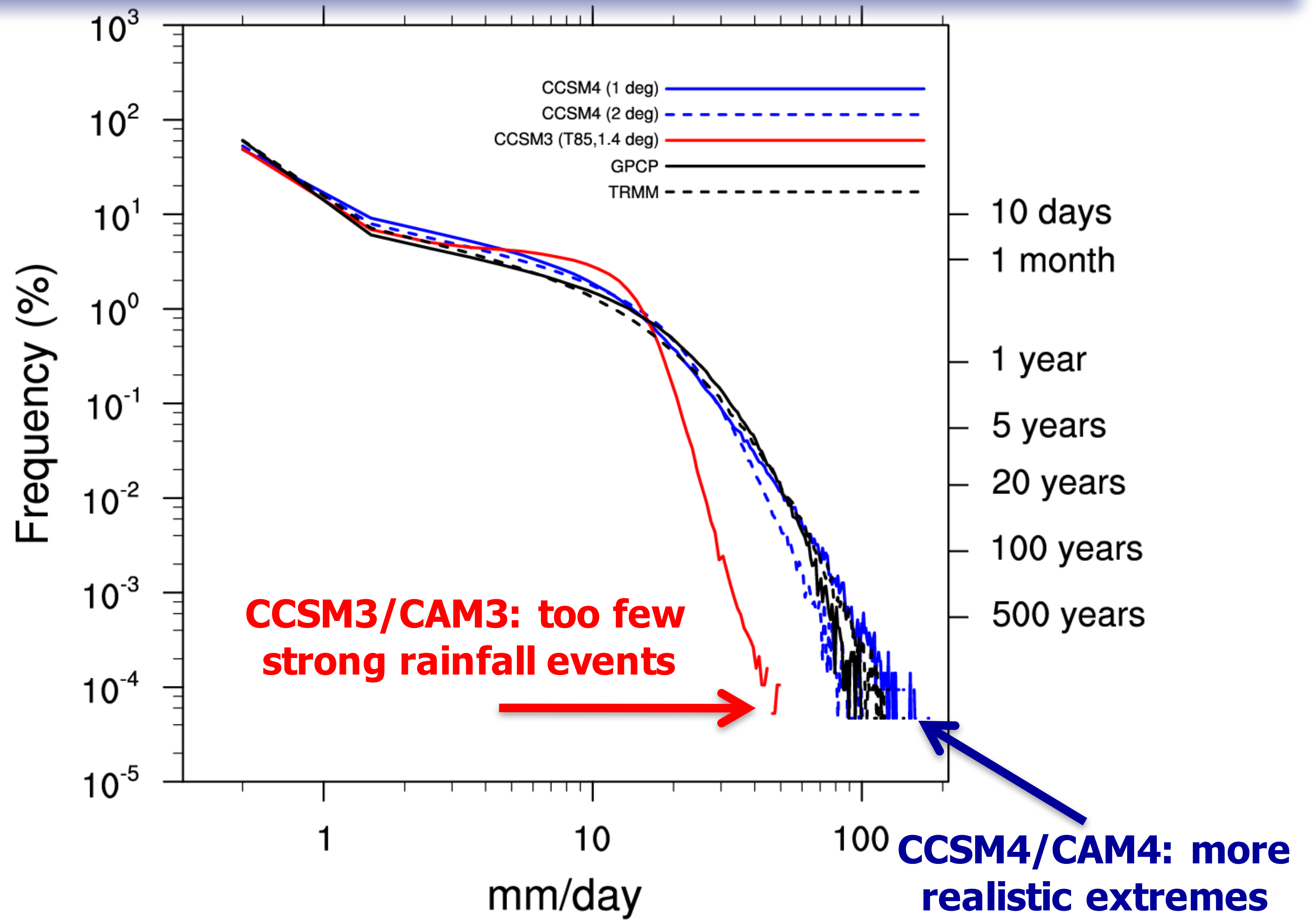
Hindcast Simulation Skill: MJO score (ACC)



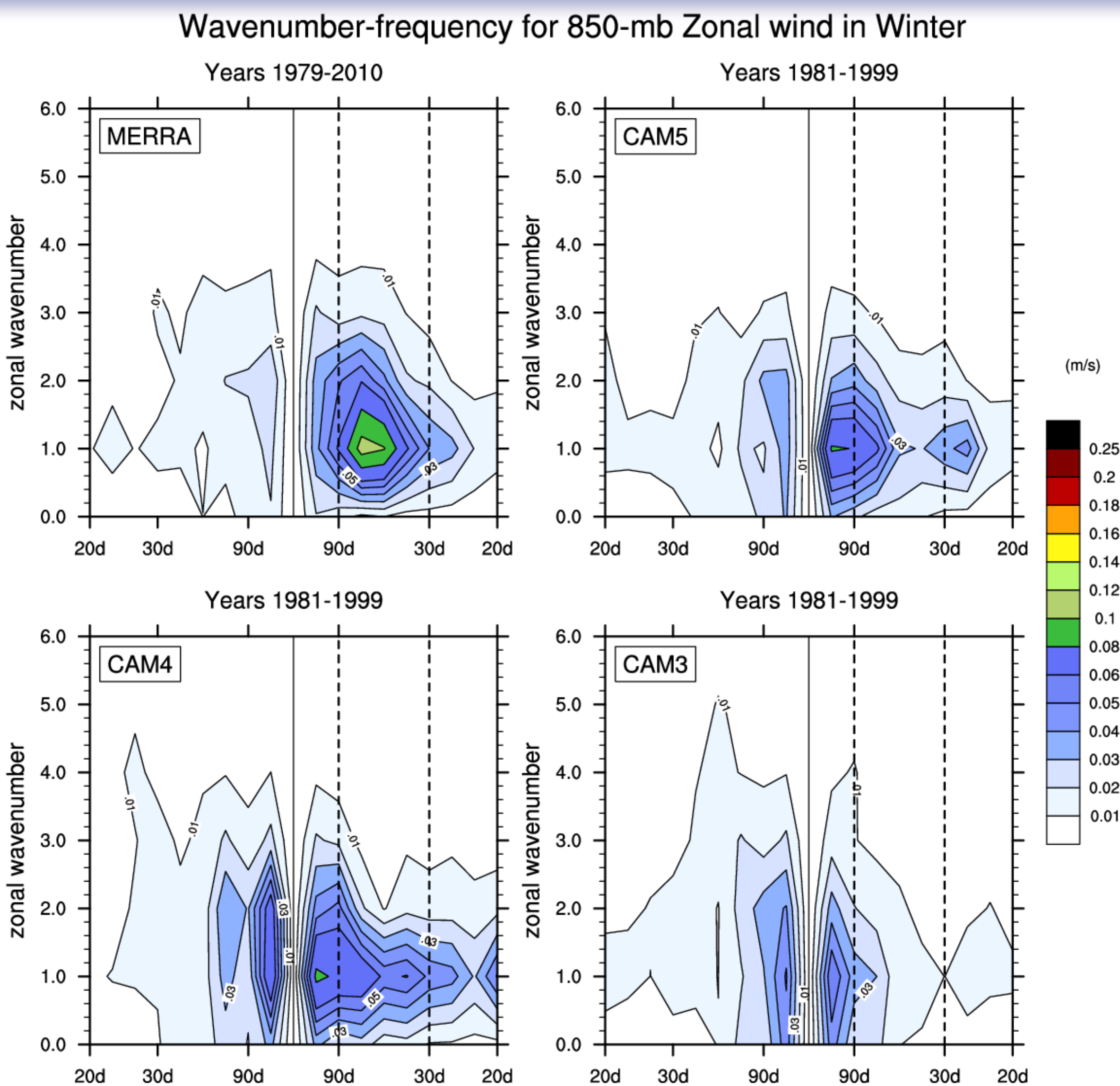
- Initial forecast mode (CAPT)
- During MJO-DYNAMO Campaign
- Combined bivariate mode of MJO variability (RMM)
- CAM5-deep only models to retain skill out to 20 days

Courtesy: Nick Klingaman, U. Reading, UK (MJO task-force)

Free running: Precipitation PDF (ANN, mm/day)



Free Running AMIP Simulations (MJO)



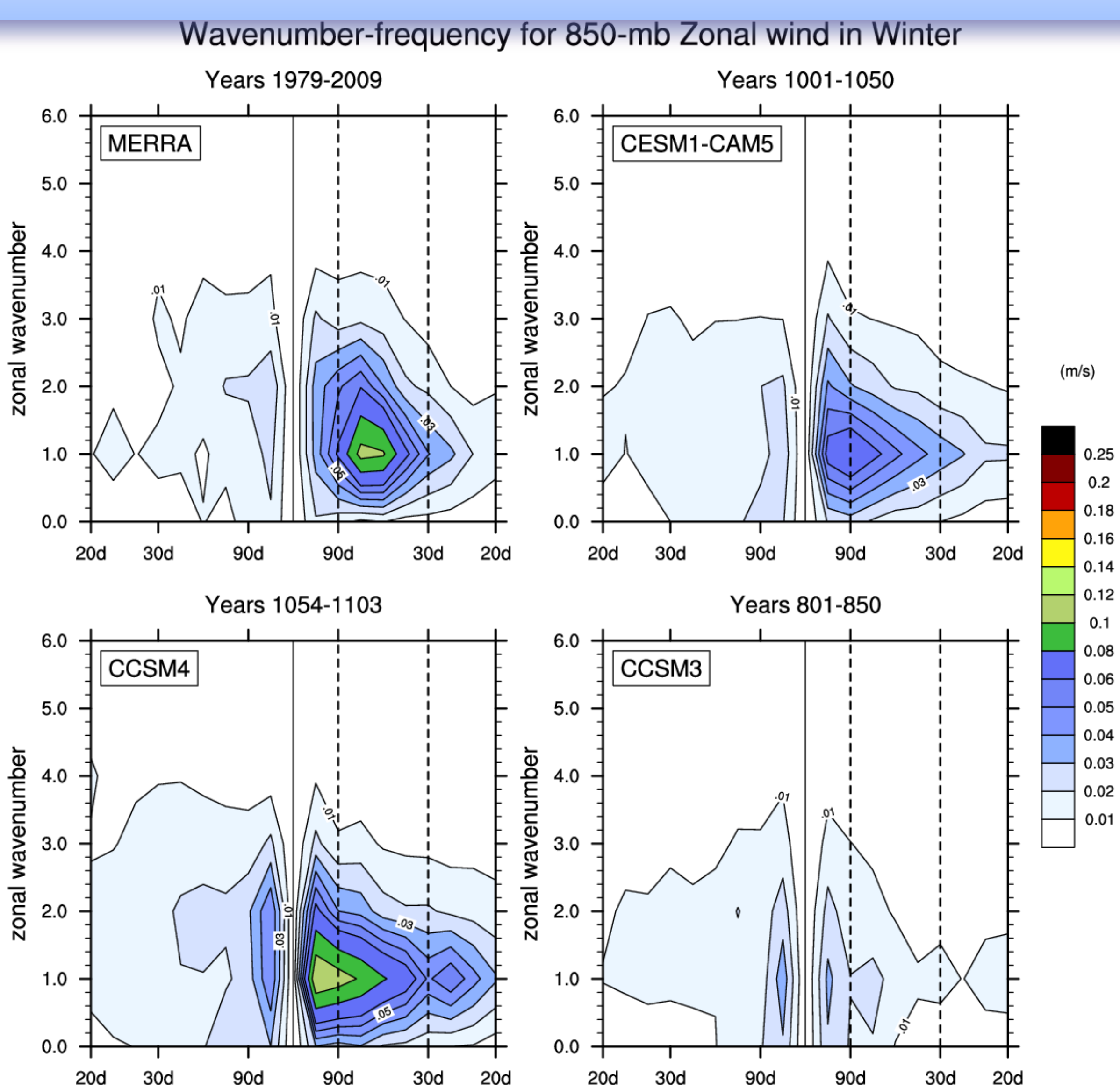
Model Physics

CAM3 poor MJO

CAM4 better MJO (convection changes)

CAM5 degrades MJO a little (non-convective cloud changes)

Free Running Coupled Simulations (MJO)



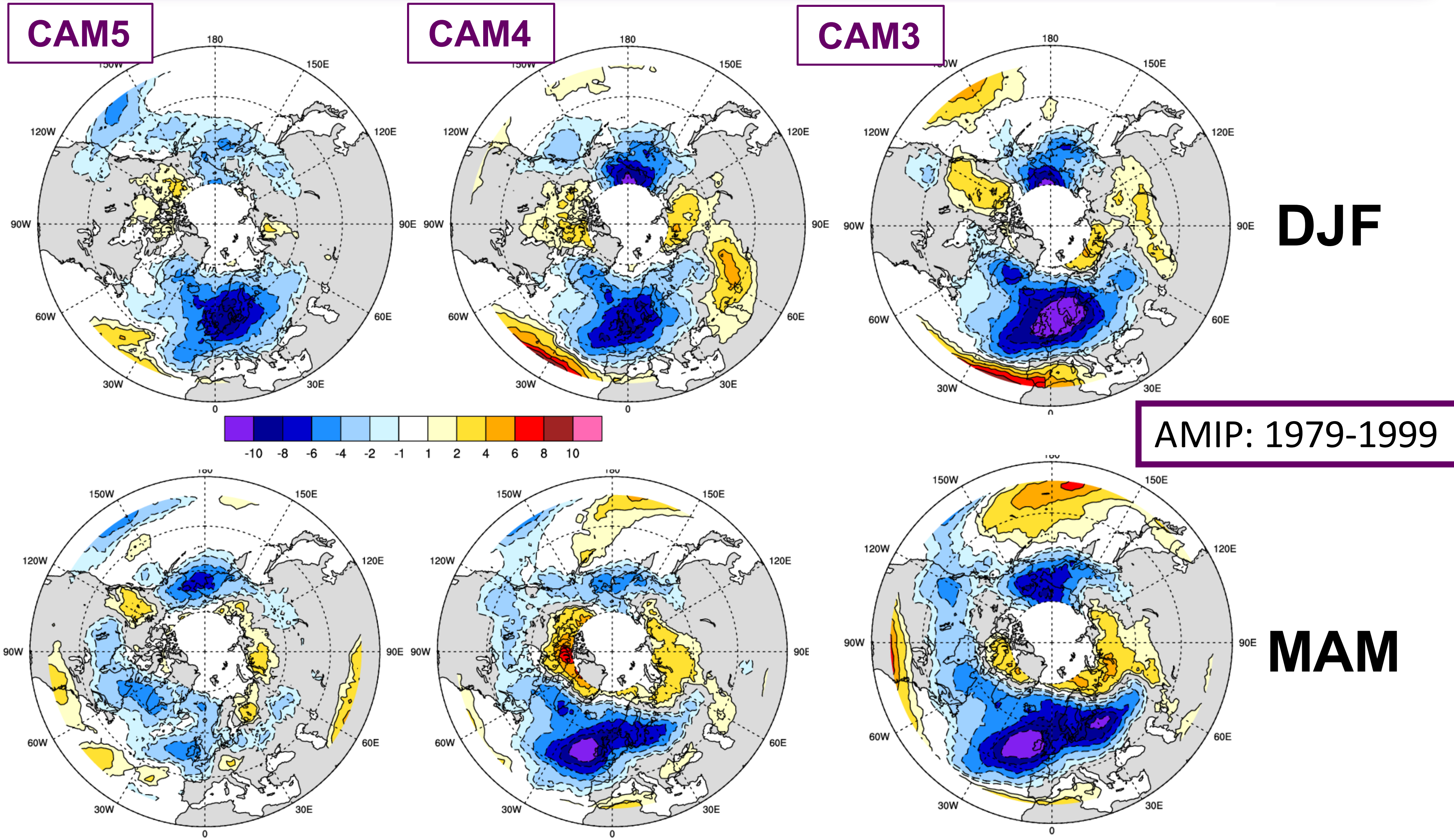
Coupling response

CCSM3 worsens

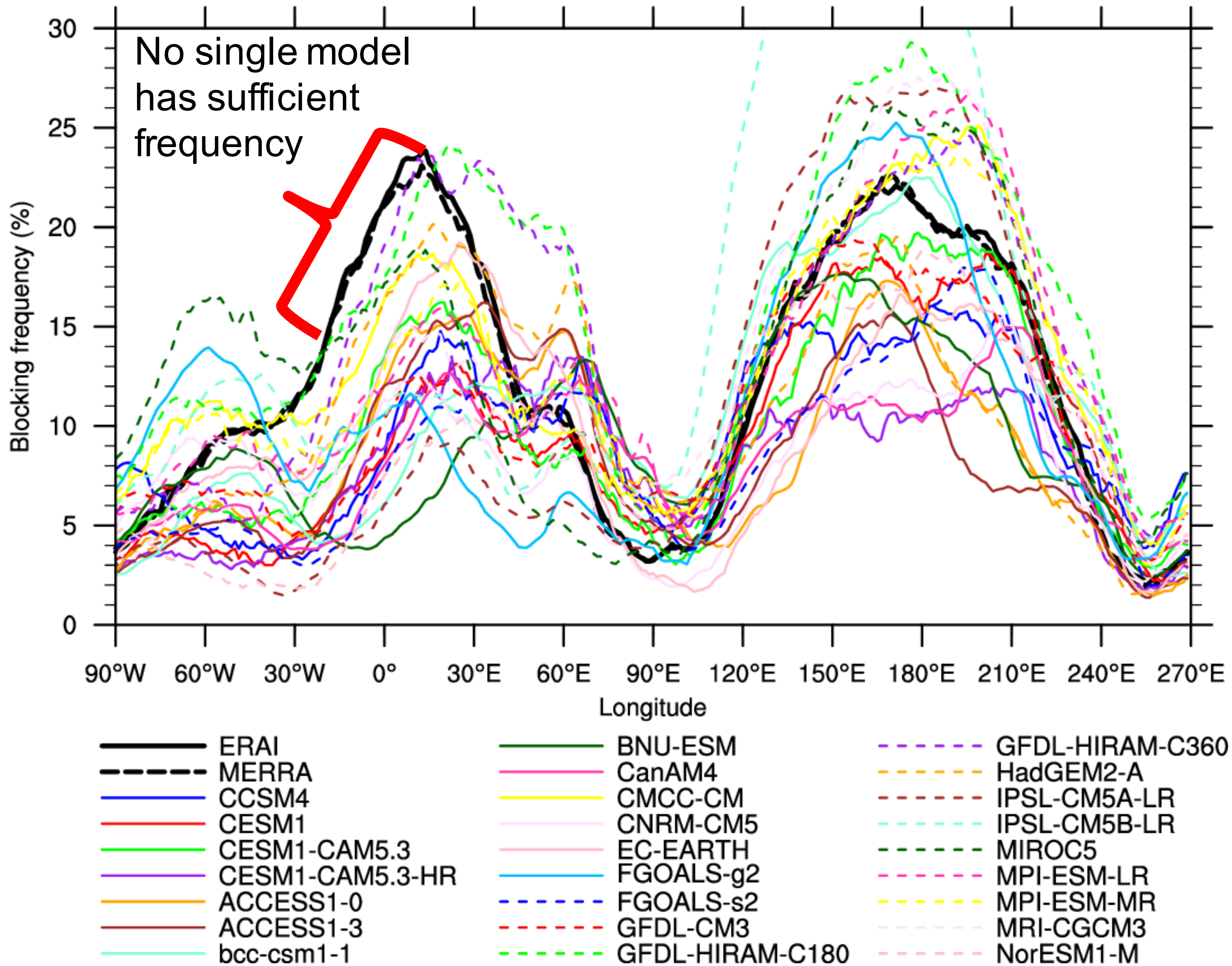
CCSM4/CESM1 improves

Reasons.
-Air-sea interaction?
-Background state shifts?

Evolution of Blocking Simulation in CESM – Physics?

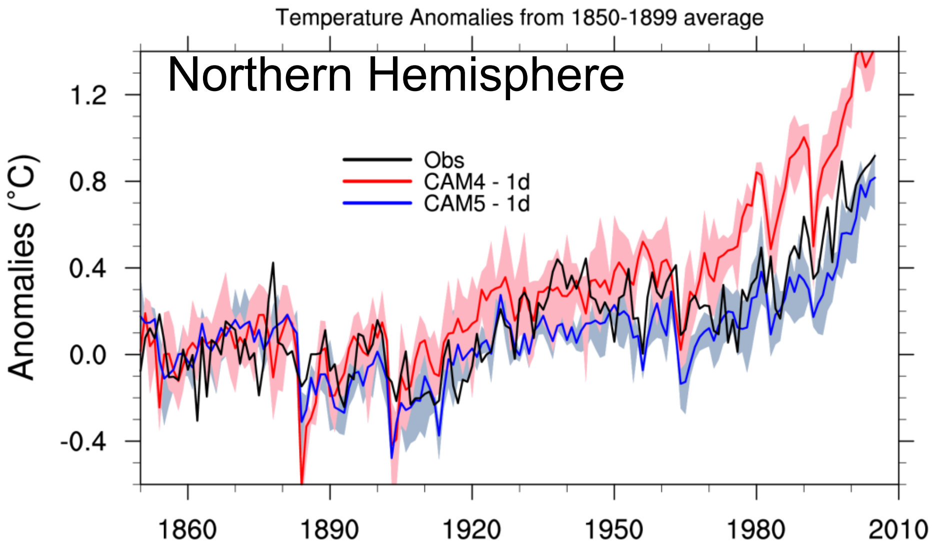


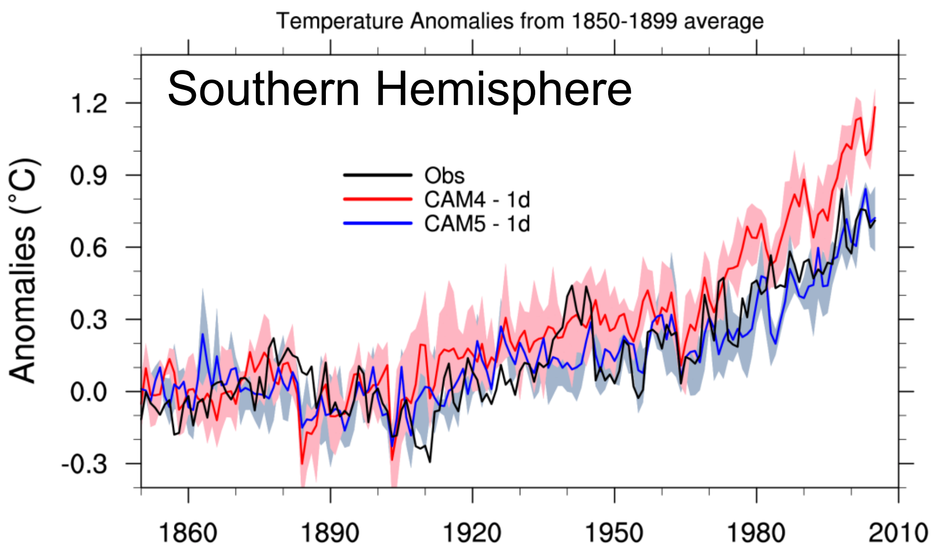
CMIP5 DJF Blocking



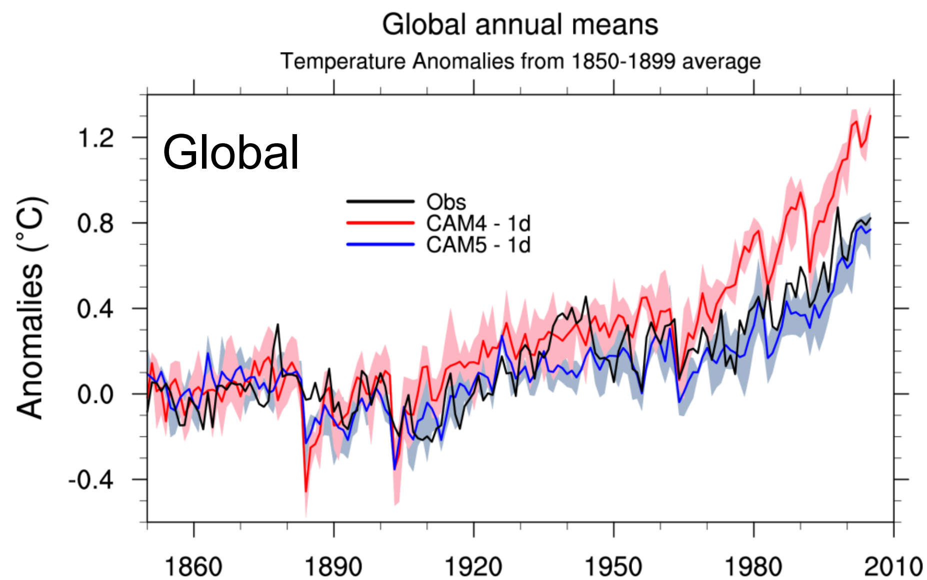
20th Century Climate Change

CESM1(CAM5) CMIP5 version vs. CCSM4(CAM4)



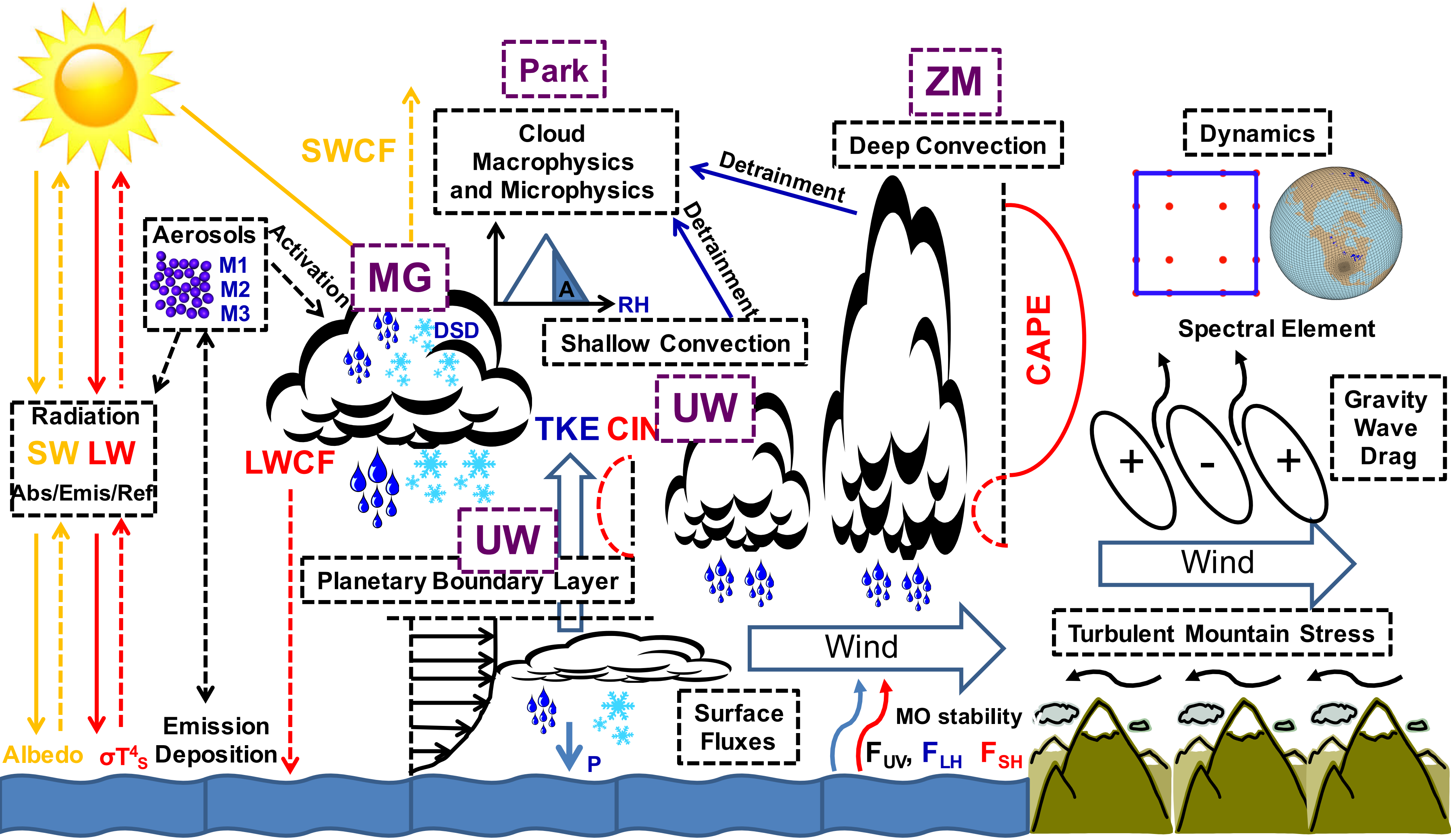


- Climate Sensitivity
  -Feedbacks (clouds, albedo, ocean heat uptake etc.)
- Direct and Indirect (cloud) aerosol effects

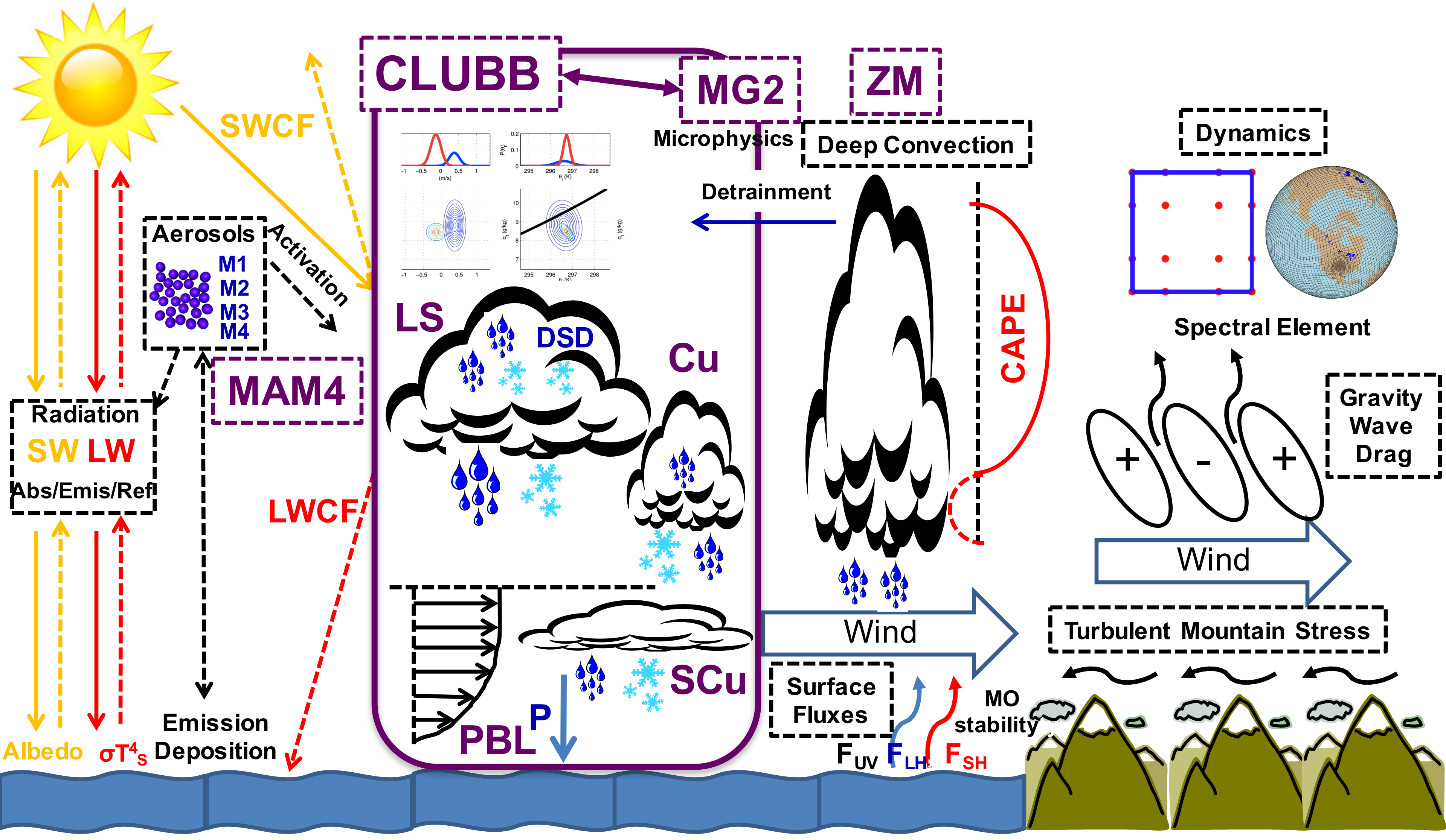


Recent Model Development

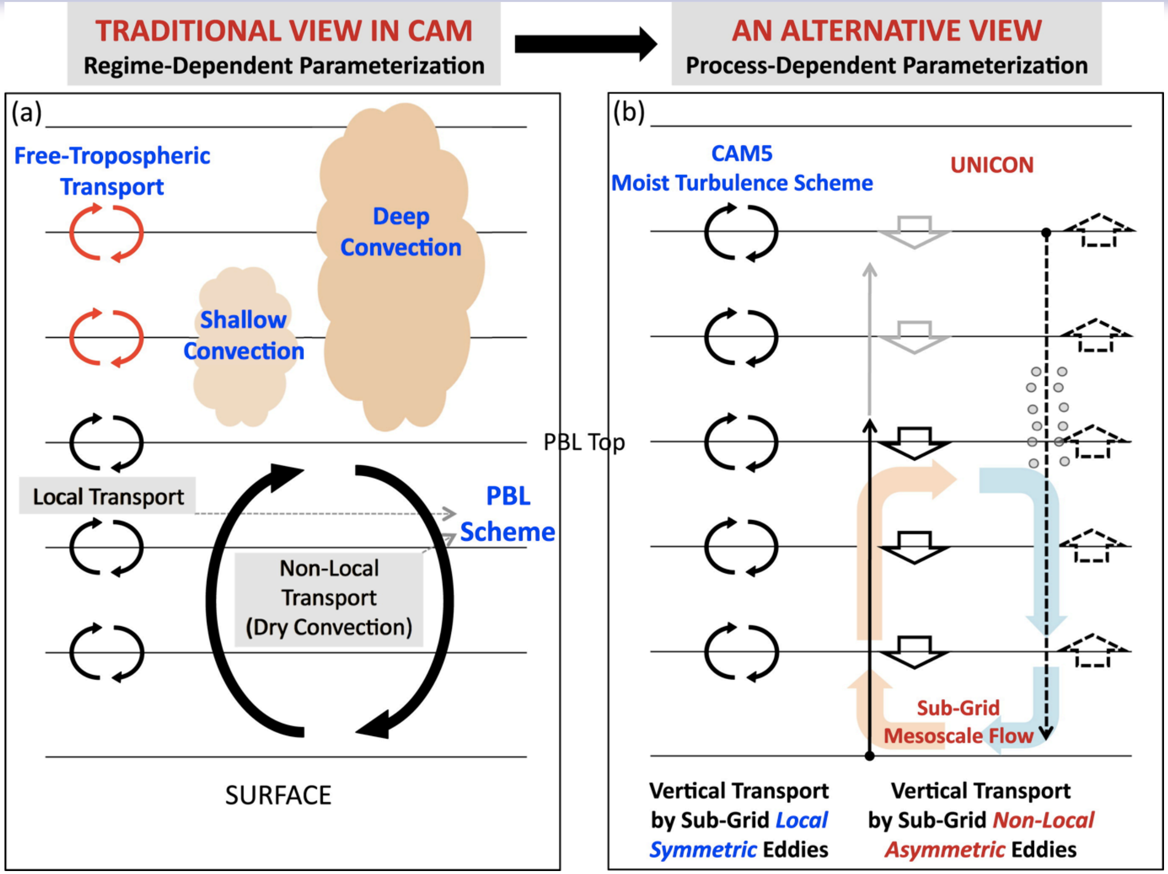
Community Atmosphere Model, version 5 (CAM5)



Community Atmosphere Model, version 6 (CAM6)



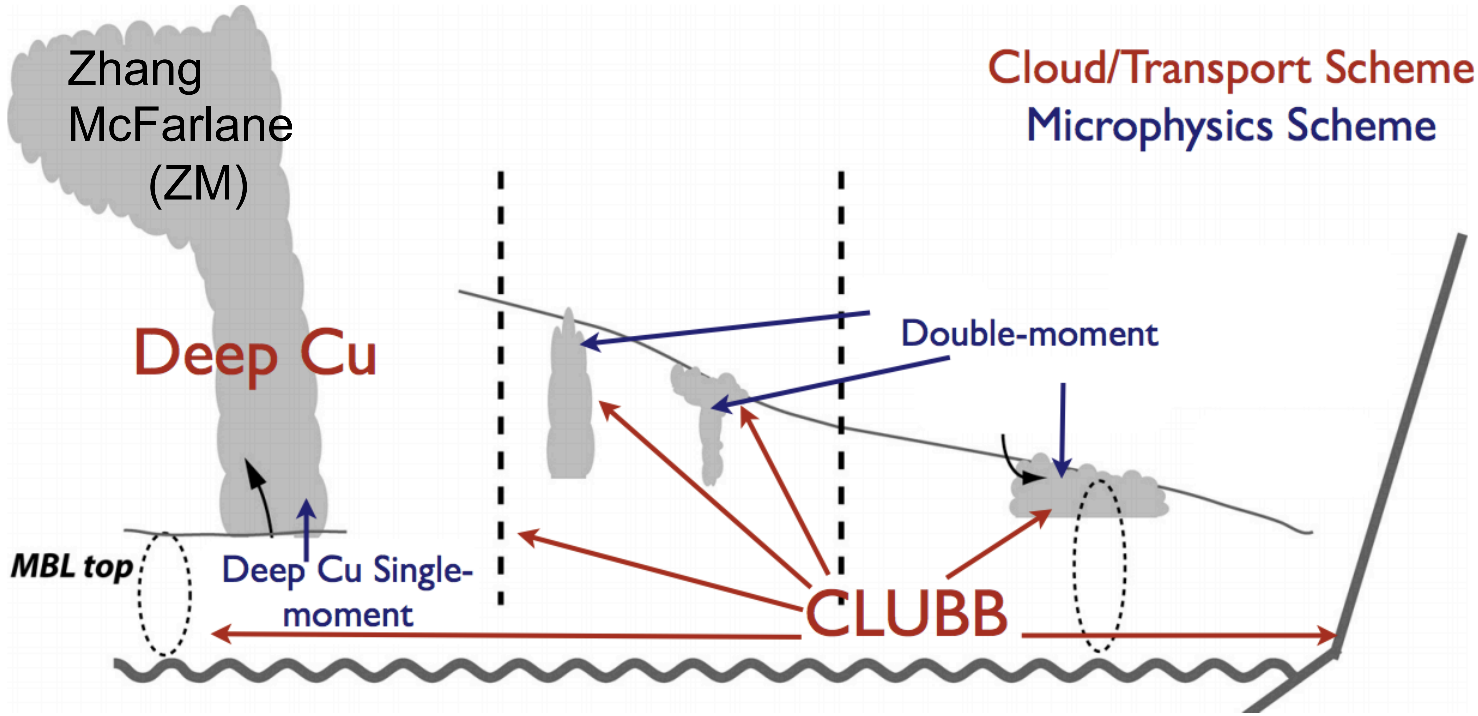
UNICON: Unified Convection Scheme Park 2014a,2014b, *J. Climate*



- Unifies deep and shallow convection schemes
- Generates forced/free/dry shallow convection + deep convection
- Removes quasi-equilibrium and small area approximations
- Accounts for sub-grid mesoscale flows (prognostic)

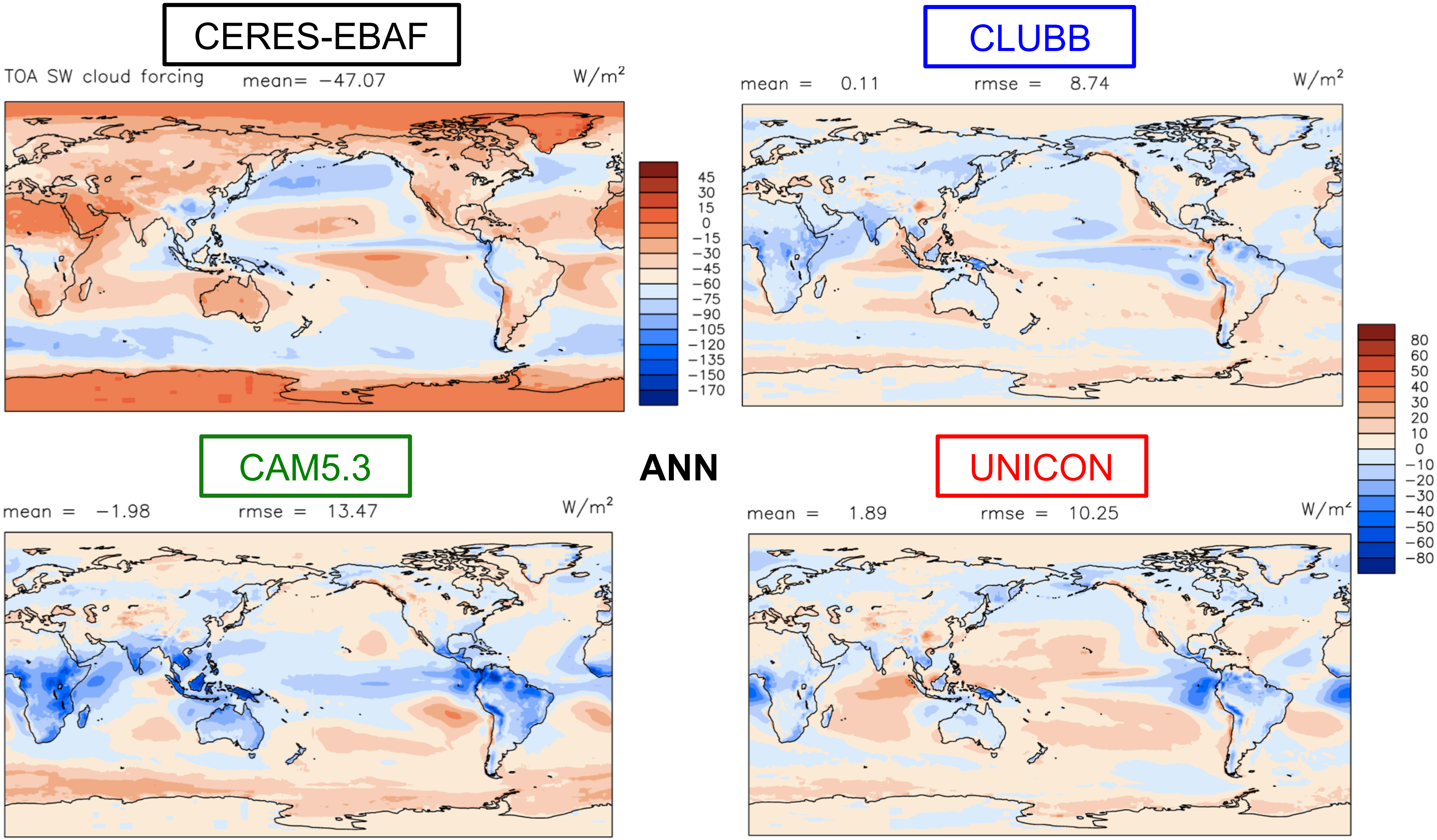
CLUBB: Cloud Layers Unified By Binormals   Golaz 2002b, J. Atmos. Sci.

CAM-CLUBB standard

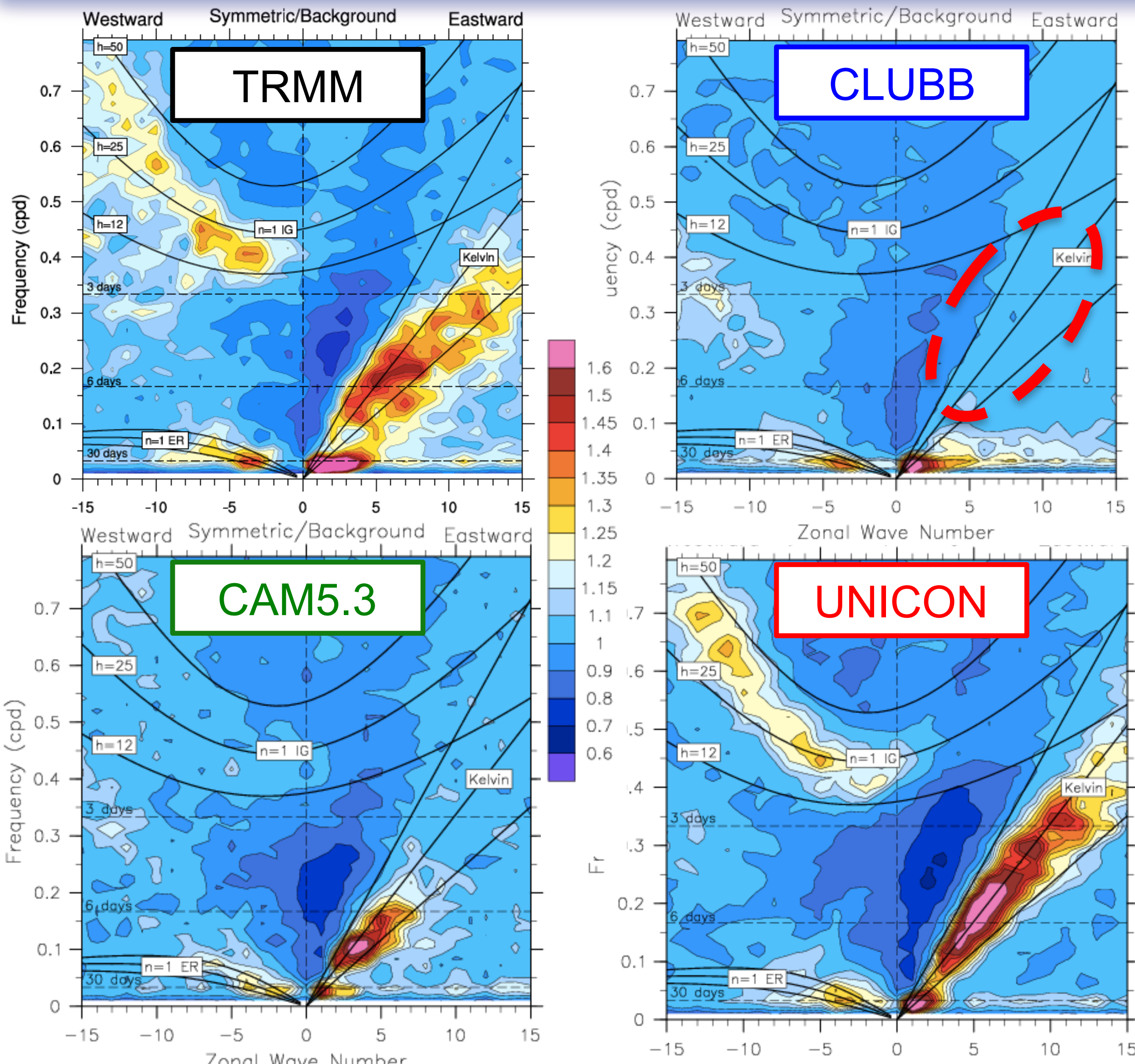


- Unifies moist and dry turbulence (except deep convection)
- Unifies microphysics
- High order closures (1 third order, 9 second order)
- Use two Gaussians to described the sub-grid multivariate PDF: $P=P(w,q_t,\theta_L)$

Clouds: Short-wave cloud forcing (AMIP)

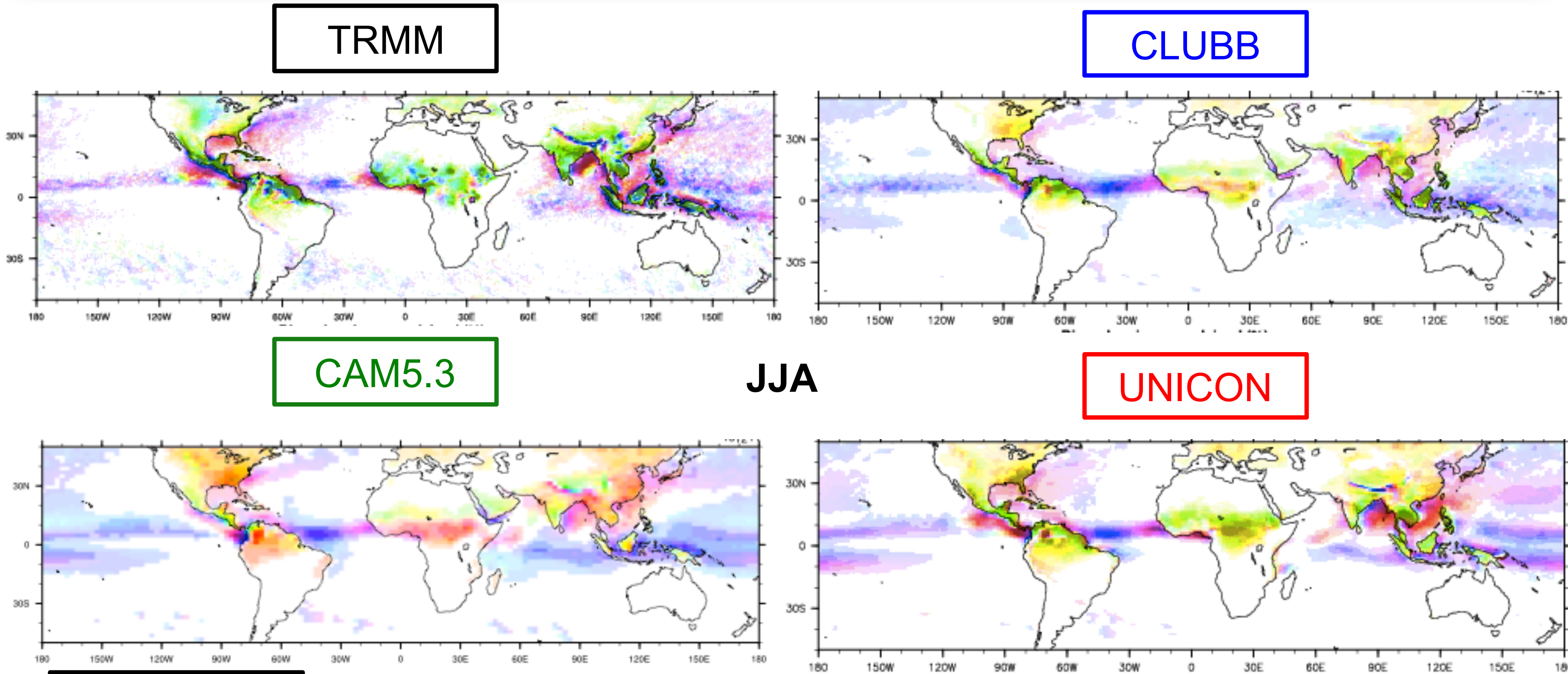


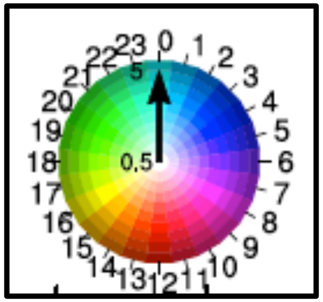
Precipitation: Equatorial waves



- Madden Julian Oscillation peak improved (still too weak)
- Kelvin wave too strong in UNICON
- Kelvin waves very damped in CLUBB rainfall
- UNICON captures westward gravity waves

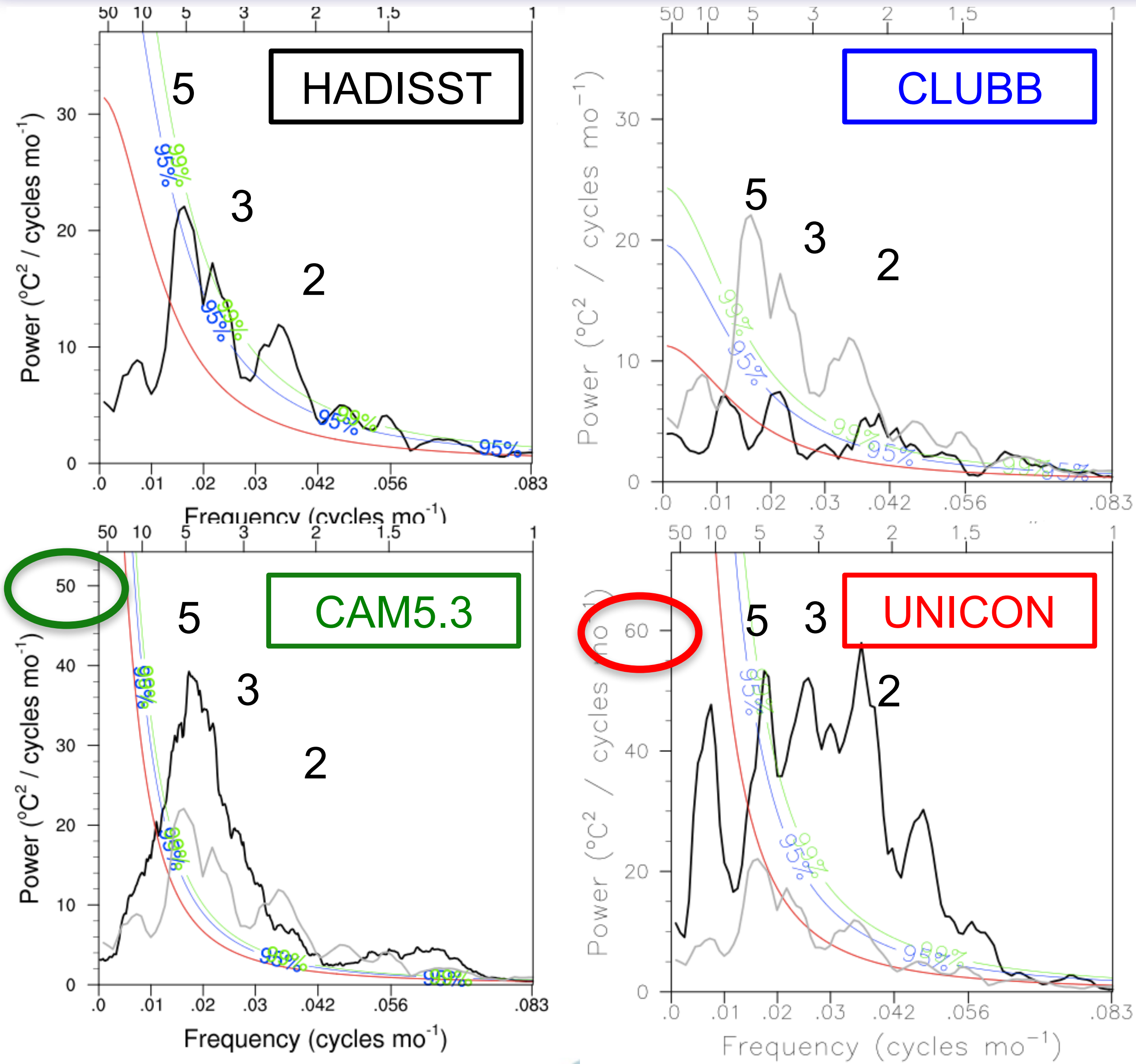
Precipitation Diurnal Cycle: Better Phase





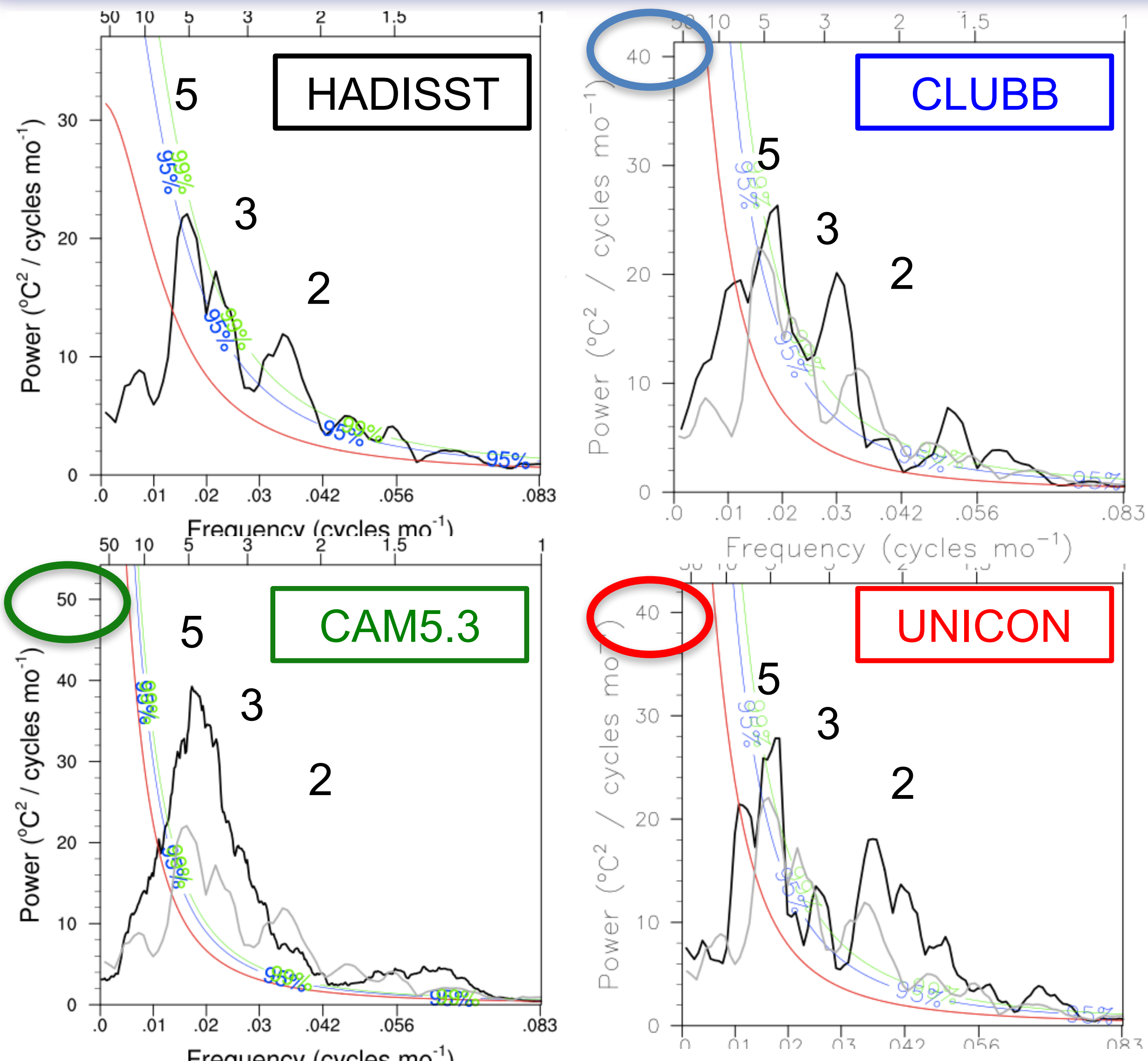
- Diurnal cycle peak remains too early
- Shifts from 12pm to 4pm over land (both)
- Shifts from 2am to 8am over ocean (UNICON better)
- US mid-western rainfall still deficient (at 1°)

ENSO: Cause for concern



- ENSO not well simulated
- UNICON too strong amplitude at two wide a frequency
- CLUBB has very weak amplitude and no preferred frequency

ENSO: Cause for concern: New



- ENSO not well simulated
- UNICON too strong amplitude at two wide a frequency
- CLUBB has very weak amplitude and no preferred frequency

Alternative Techniques

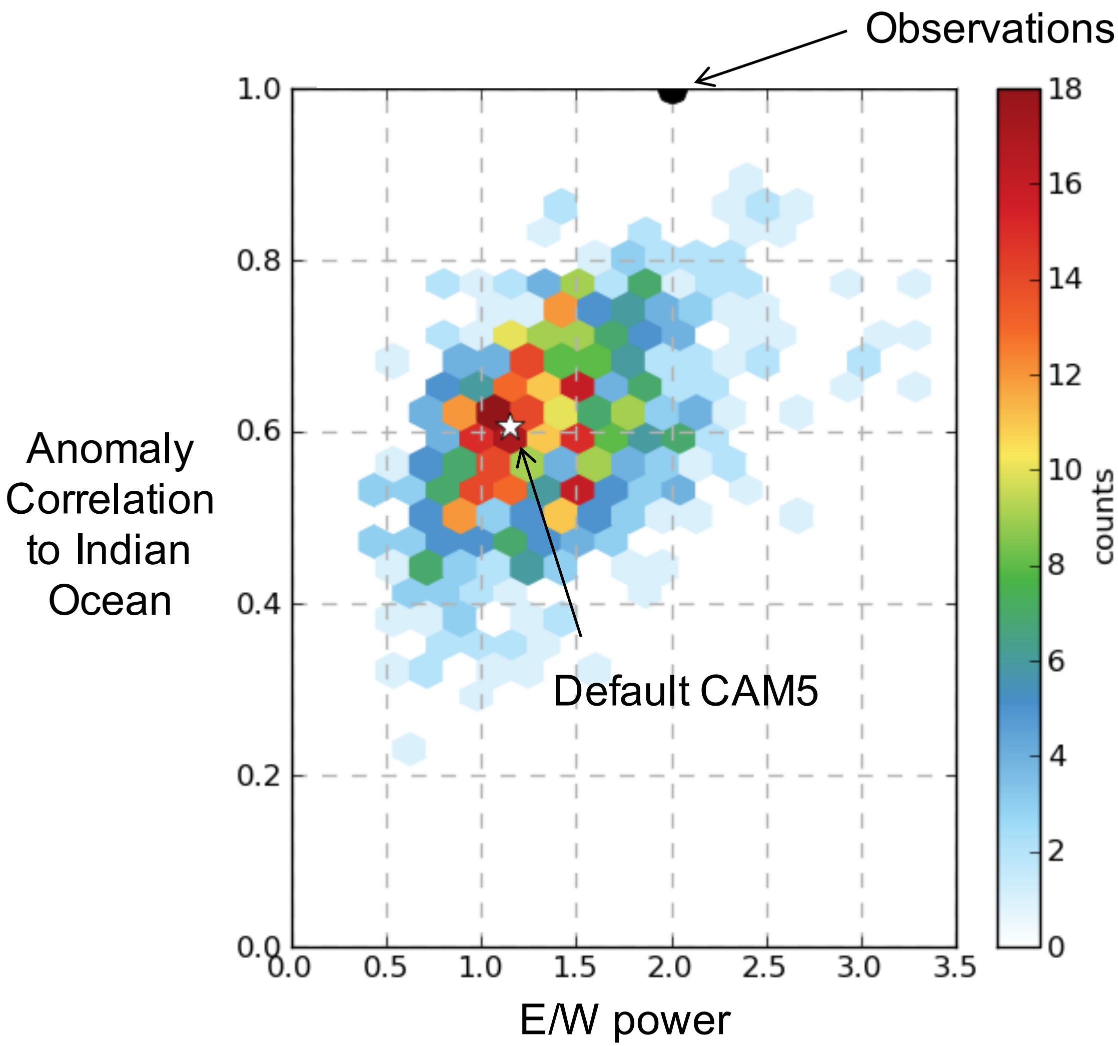
Perturbed Physics Ensembles

CAM5 2^{o}, 22 parameters, 1100 simulations, 5 year AMIP
Latin Hyper-Cube Sampling

	modelSection_modelVariable	variable description	low value	default	high value
Large-Scale Cloud	cldfrc_rhminh	Threshold RH for fraction high stable clouds	0.65	0.8	0.85
	cldfrc_rhminl	Threshold RH for fraction low stable clouds	0.8	0.8875	0.99
	cldwatmi_ai	Fall speed parameter for cloud ice	350	700	1400
	cldwatmi_as	Fall speed parameter for snow	5.86	11.72	23.44
	cldwatmi_cdnl	Cloud droplet number limiter	0	0	1e+06
	cldwatmi_dcs	Autoconversion size threshold for ice to snow	0.0001	0.0004	0.0005
	cldwatmi_eii	Collection efficiency aggregation of ice	0.001	0.1	1
	cldwatmi_qcvar	Inverse relative variance of sub-grid cloud water	0.5	2	5
Aerosol	dust_emis_fact	Dust emission tuning factor	0.21	0.35	0.86
PBL Turb.	eddydiff_a2l	Moist entrainment enhancement parameter	10	30	50
Large-Scale Cloud	micropa_wsubimax	Maximum sub-grid vertical velocity for ice nucleation	0.1	0.2	1
	micropa_wsubmin	Minimum sub-grid vertical velocity for liquid nucleation	0	0.2	1
Shallow Conv.	uwshcu_criqc	Maximum updraft condensate	0.0005	0.0007	0.0015
	uwshcu_kevp	Evaporative efficiency	1e-06	2e-06	2e-05
	uwshcu_rkm	Fractional updraft mixing efficiency	8	14	16
	uwshcu_rpen	Penetrative updraft entrainment efficiency	1	5	10
Deep Conv.	zmconv_alfa	Initial cloud downdraft mass flux	0.05	0.1	0.6
	zmconv_c0_lnd	Deep convection precipitation efficiency over land	0.001	0.0059	0.01
	zmconv_c0_ocn	Deep convection precipitation efficiency over ocean	0.001	0.045	0.1
	zmconv_dmpdz	Parcel fractional mass entrainment rate	0.0002	0.001	0.002
	zmconv_ke	Evaporation efficiency parameter	5e-07	1e-06	1e-05
	zmconv_tau	Convective time scale	1800	3600	28800

Is there any chance of a good MJO?

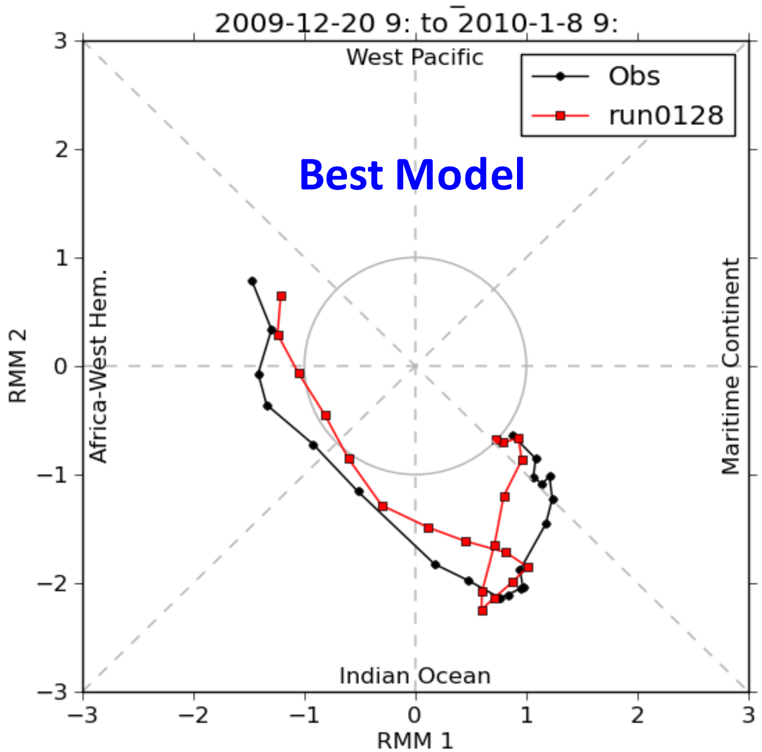
Density Plot of Metrics from PPE Ensemble

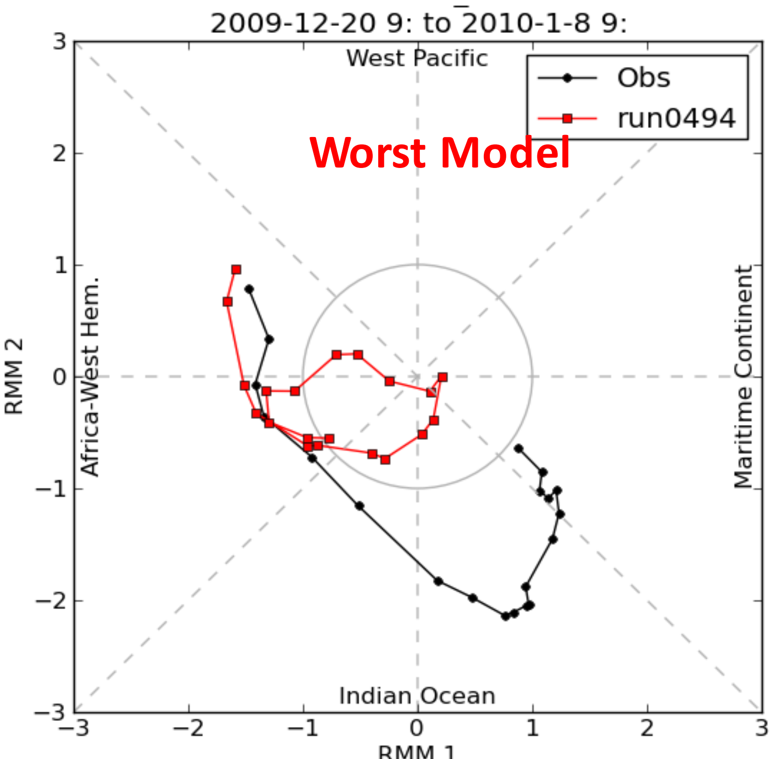


- Default MJO is away from observations (esp. AC)
- No multiple clustering
- Clustering around the default MJO

Is there any chance of a good MJO?

MJO Phase Plots (RMM)





Using CAM5, 20-day hindcast can capture YOTC MJO event with **'best'** free running model configuration

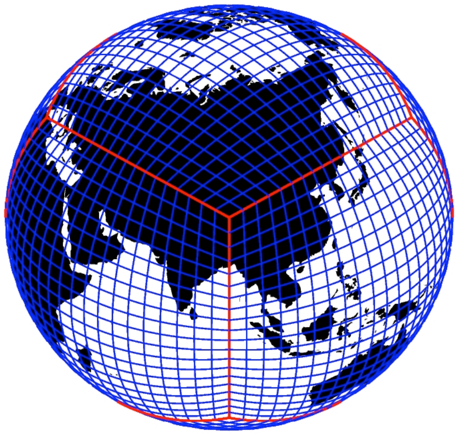
'Worst' free running configuration damps it very quickly

S. A. Klein, J. Boyle, J. Tannahill, D. Lucas, S. Xie, K. Sperber, and R. Neale, 2012: Perturbed parameter hindcasts of the MJO with CAM5. *J. Climate*

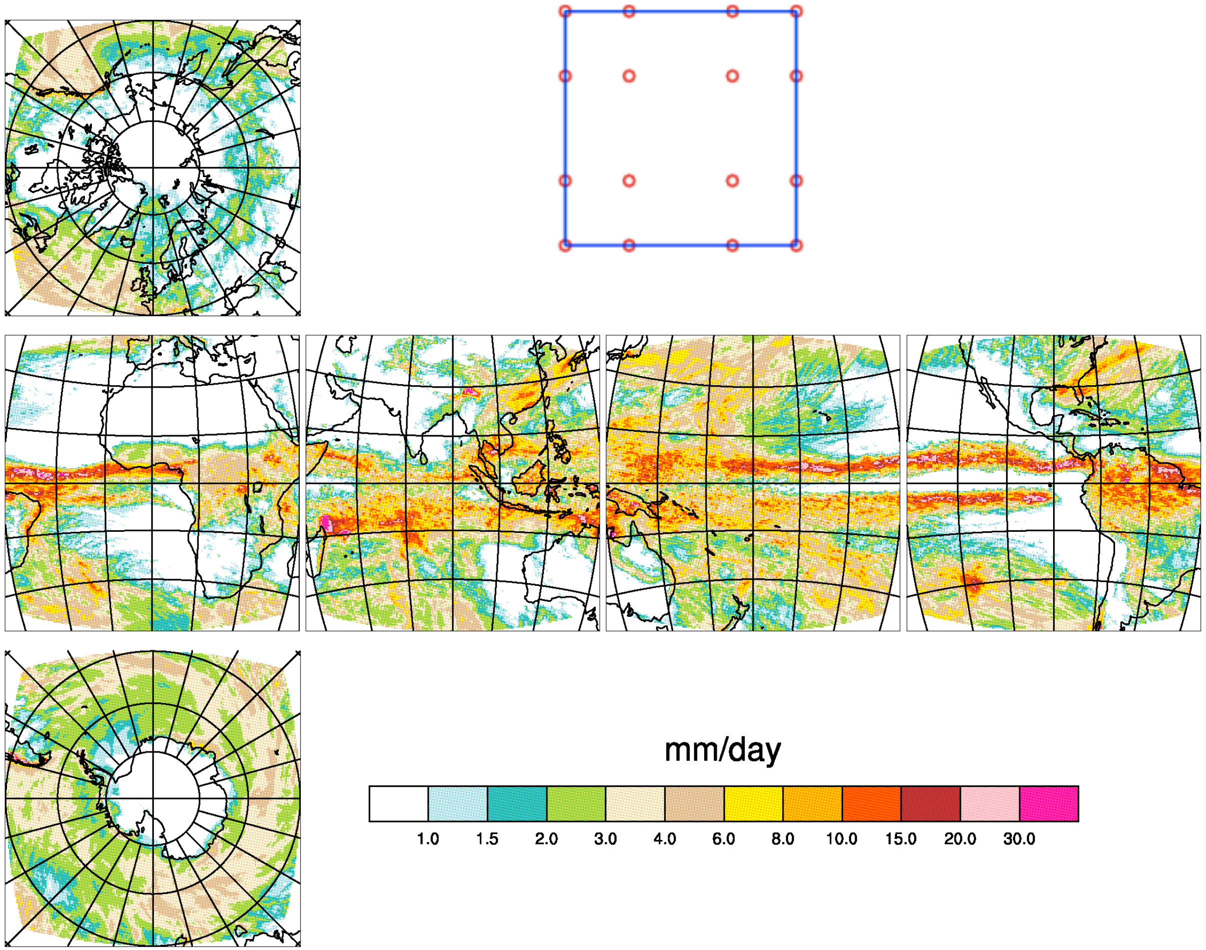
Resolution Sensitivity

Dynamical Core for high-res: Spectral element

Cubed Sphere



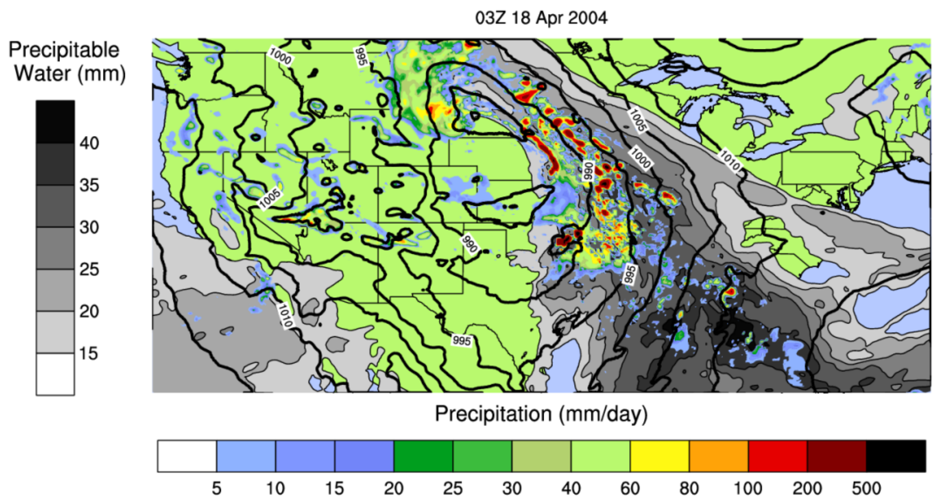
Regular lat-lon



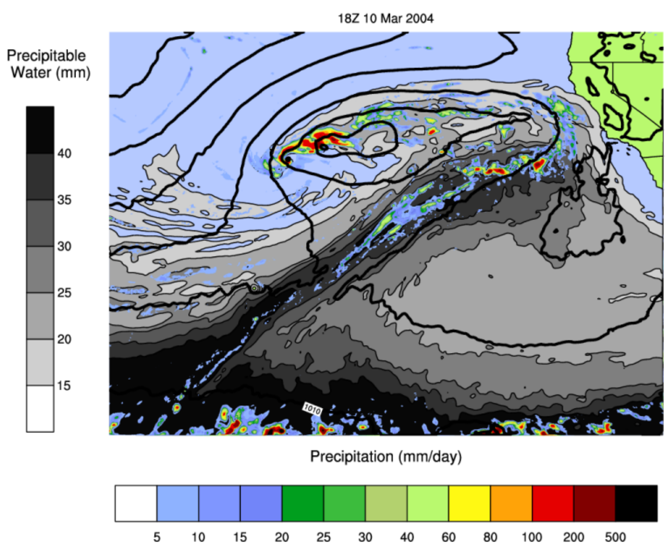
High-Impact Phenomena

12-km CAM5-SE AMIP Simulation Snapshots

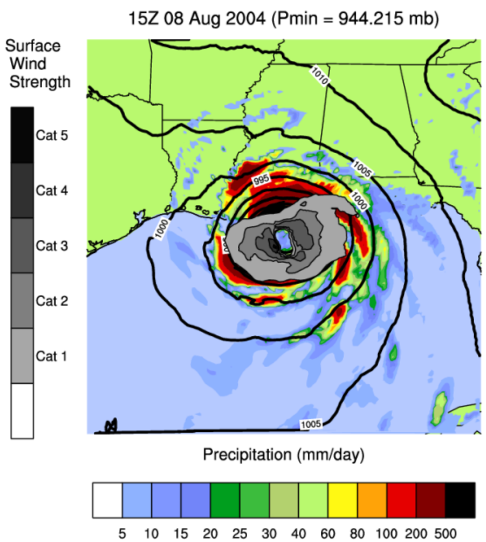
Mid-west Spring time systems



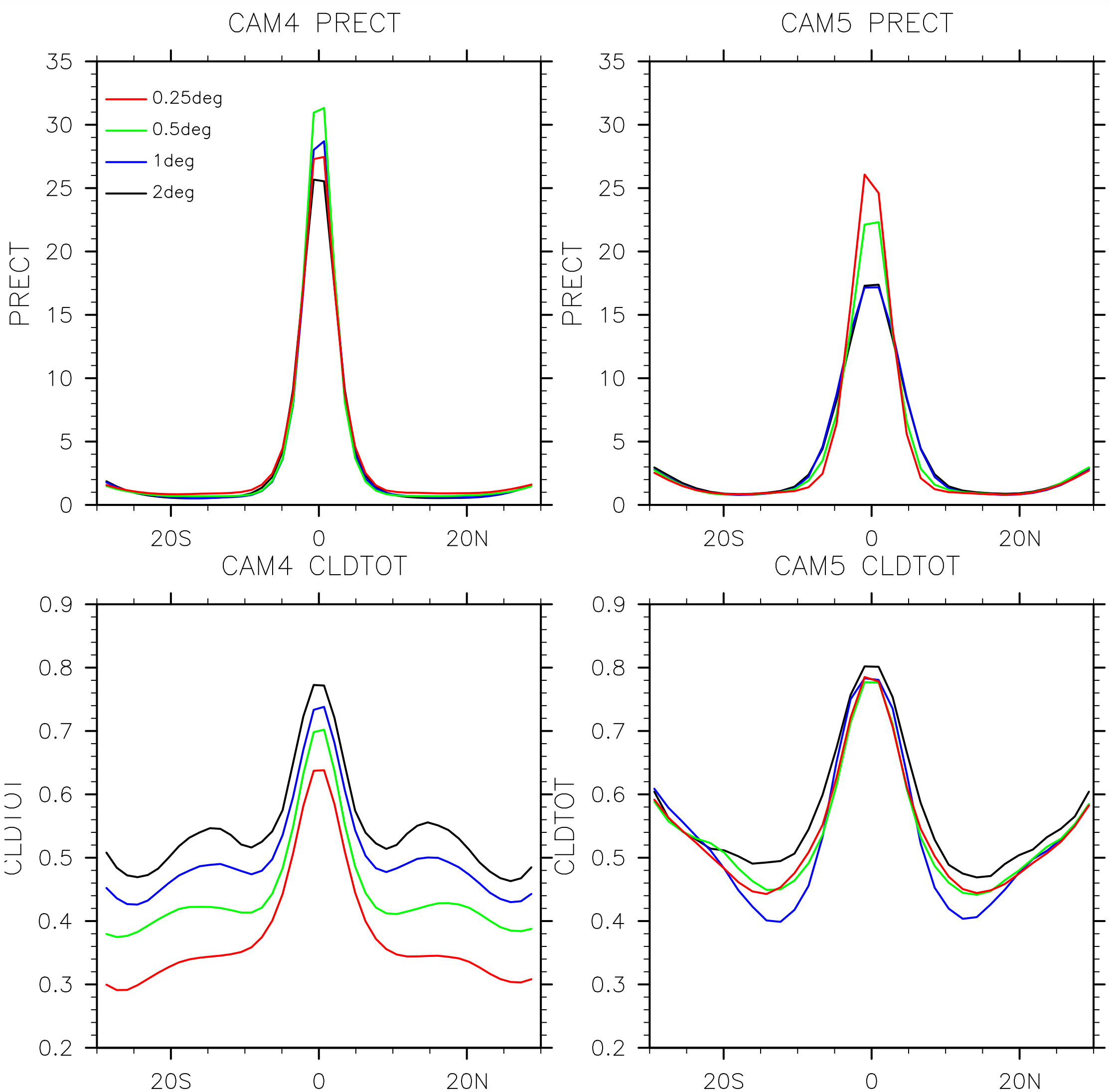
Atmospheric Rivers



Tropical Cyclones

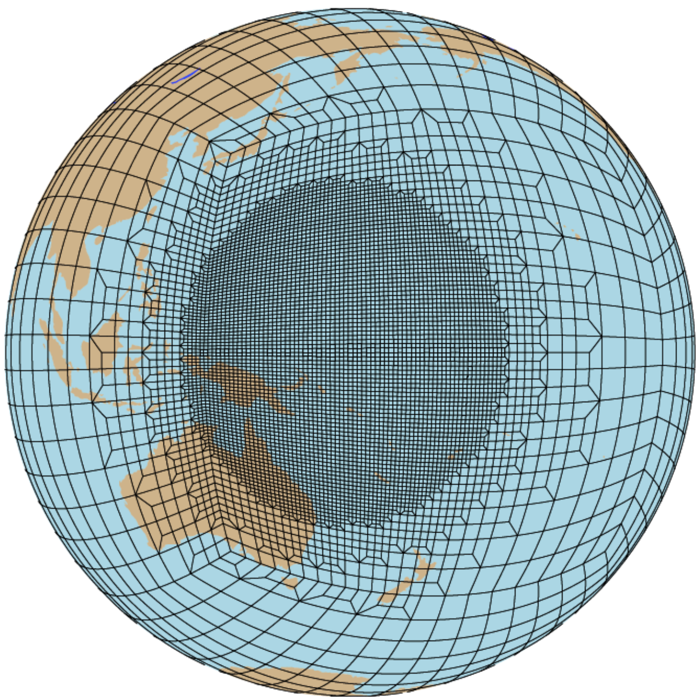


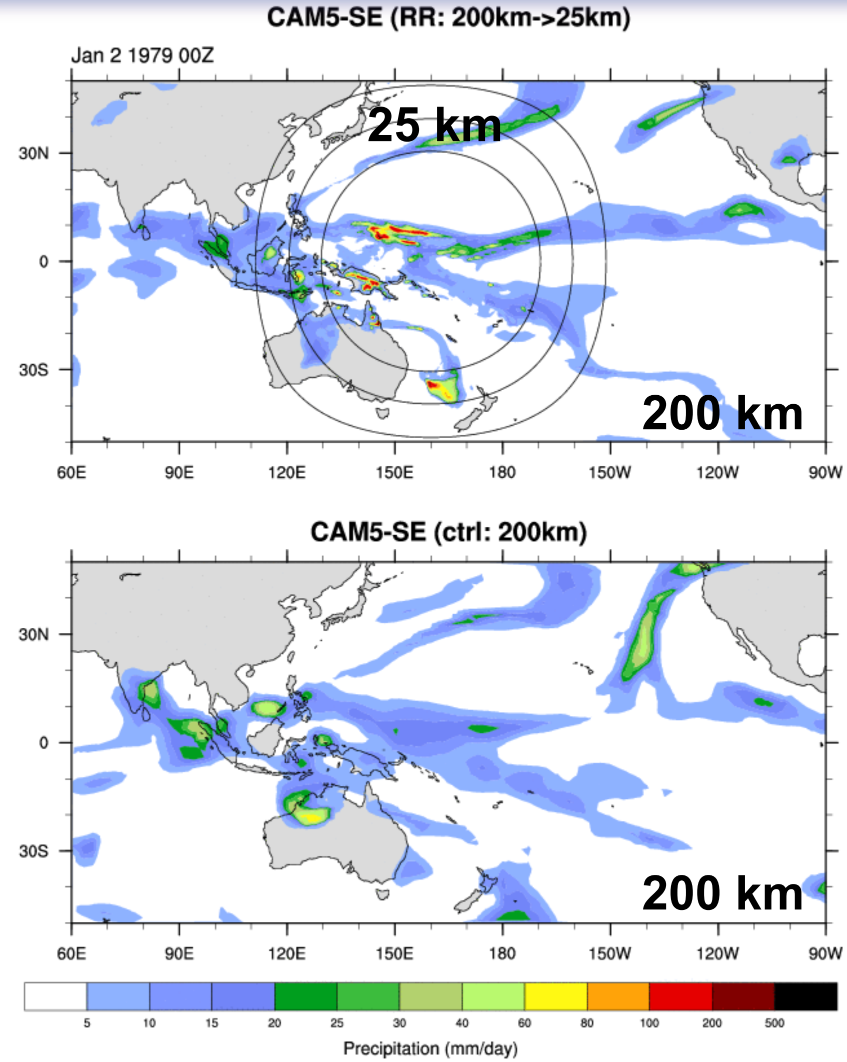
Resolution Dependence: Complex behavior (aqua-planet)



Regional refinement: Mean Climate

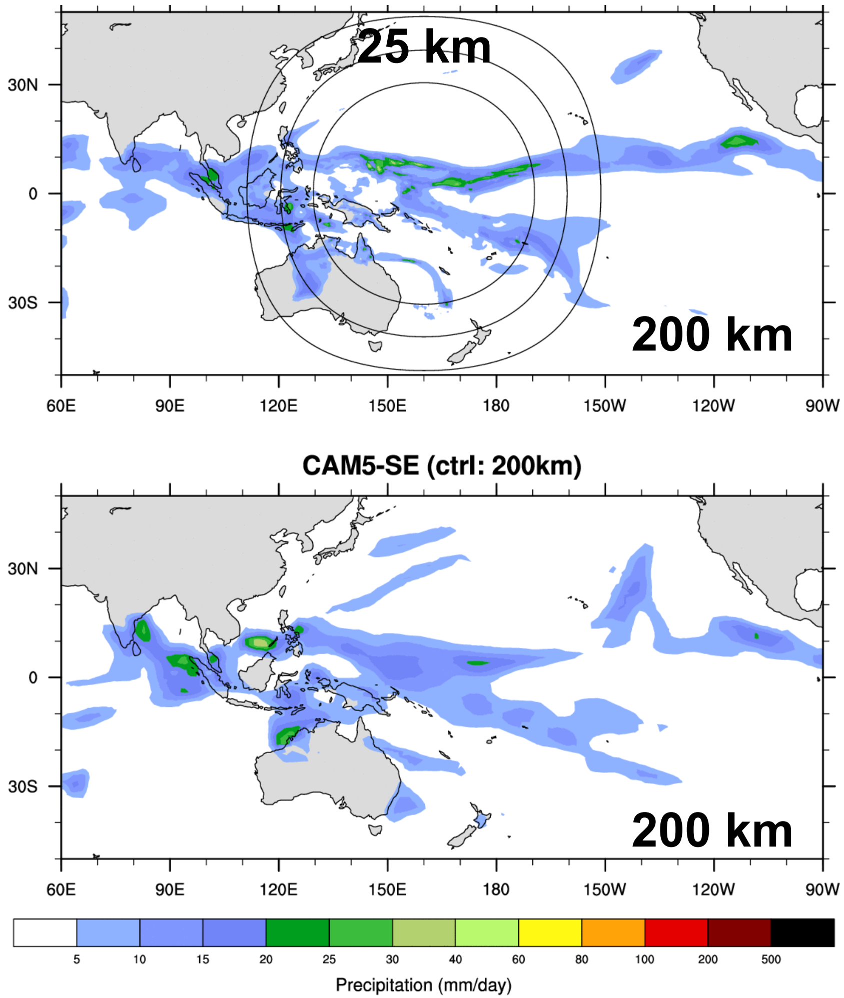
- Target regions of interest
- If 5% of globe 25km within 200km: 3x (25km uniform = 32x)



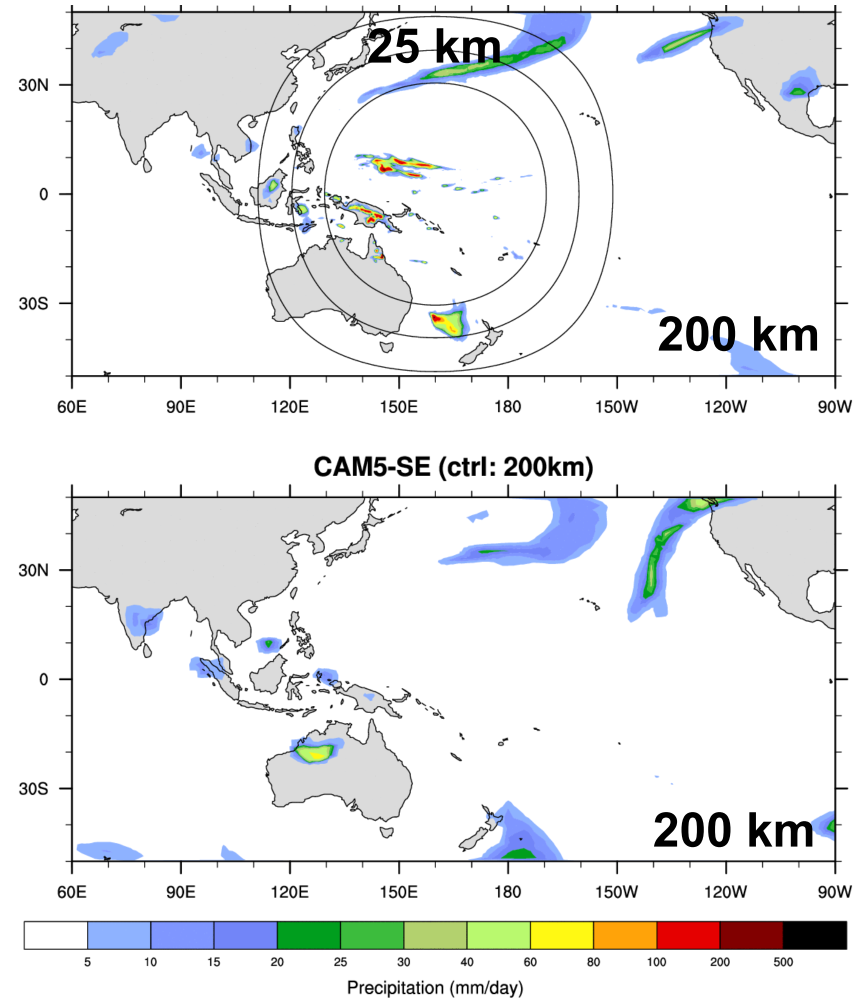


Regional refinement: Precipitation

Convective Precipitation



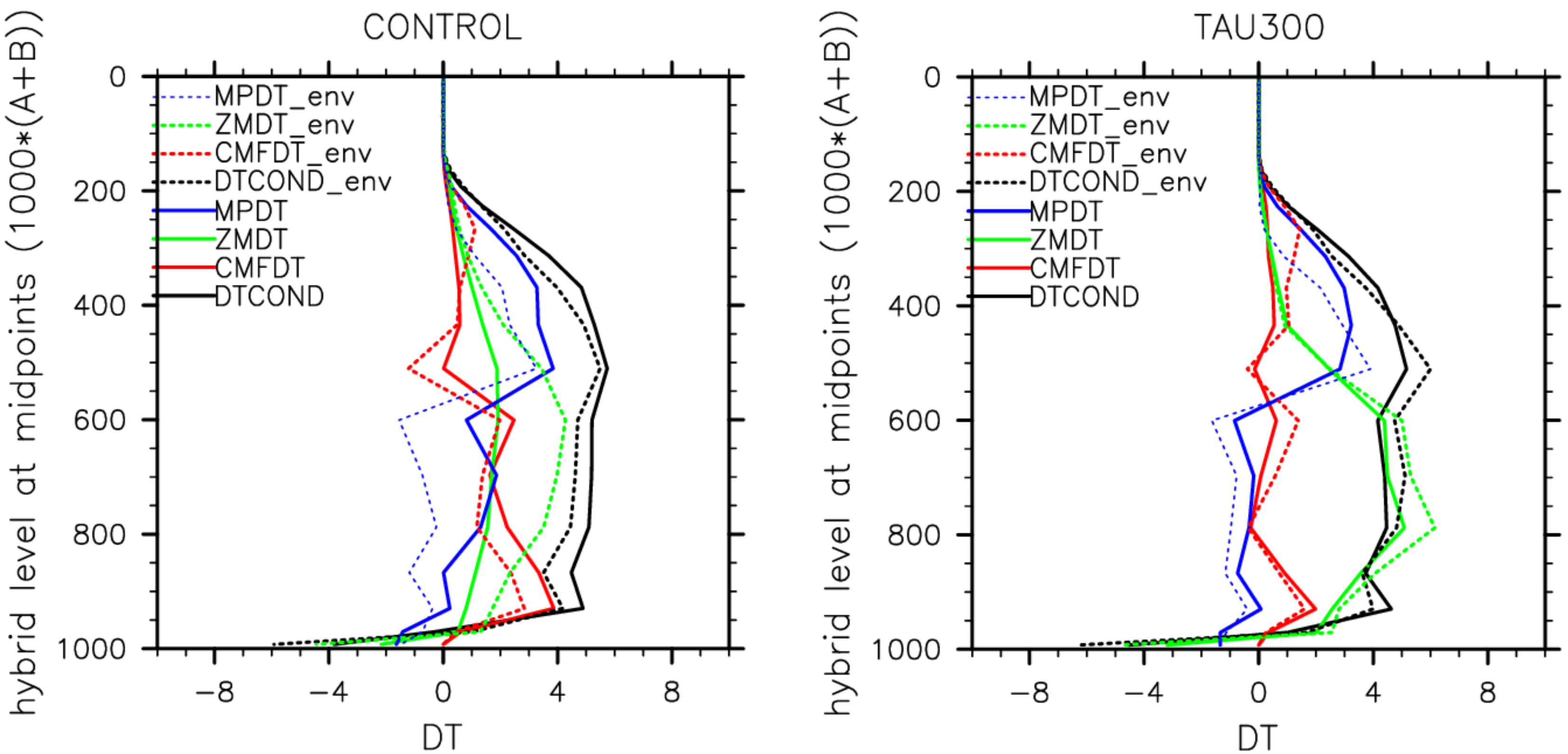
Large-Scale/Resolved Precipitation



Process Oriented Diagnostics

Resolution Sensitivity

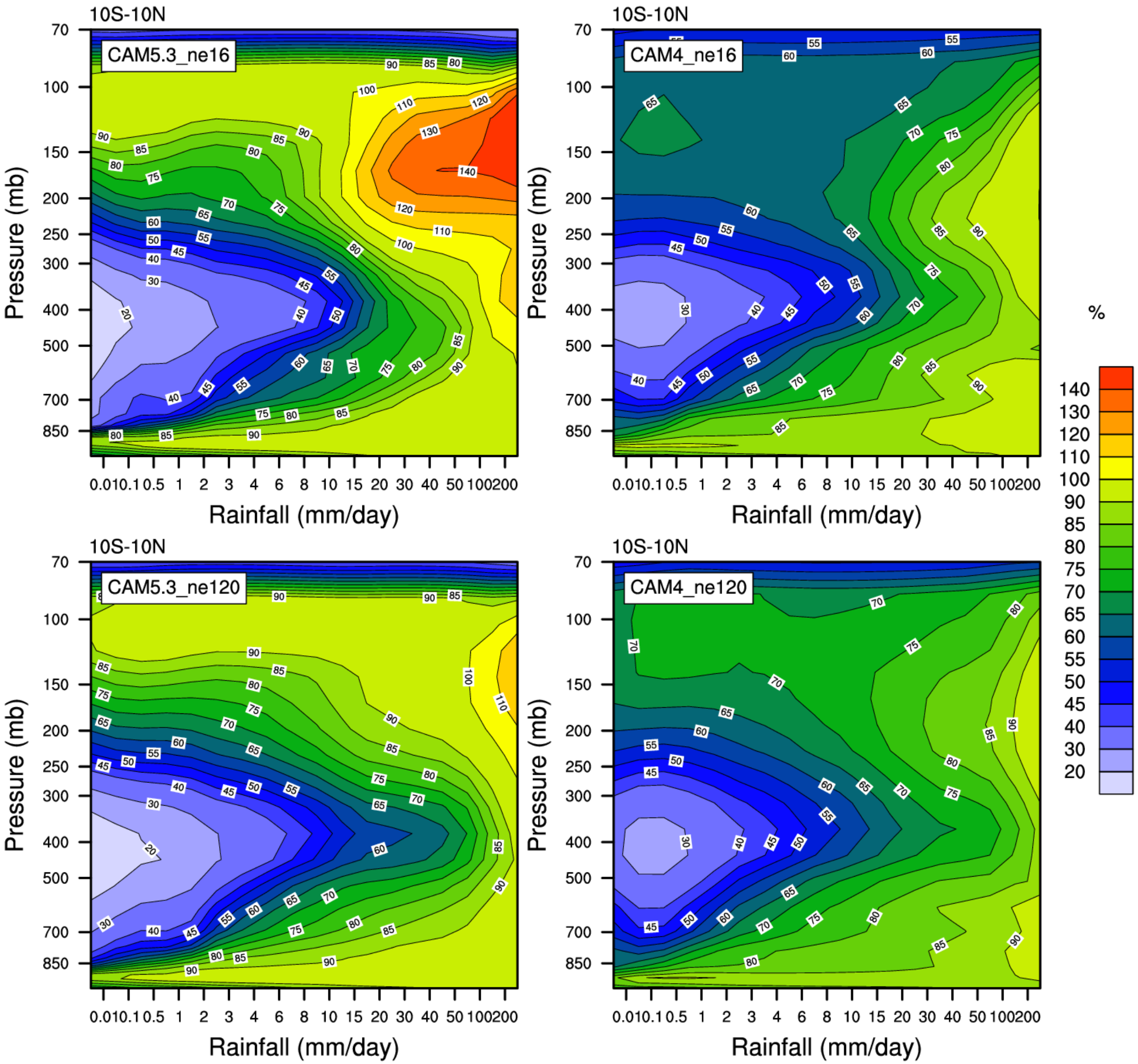
Temperature tendency budget (K/day) – CAM4



Tendencies within and outside (_env) regional refinement region.

- -MPDT: Cloud fraction and microphysics
- -ZMDT: Deep convection
- -CMFDT: Shallow convection
- -DTCOND: Total moist processes

CAM5 (1°) CAM4 (1°)



CAM5 (0.25°) CAM4 (0.25°)

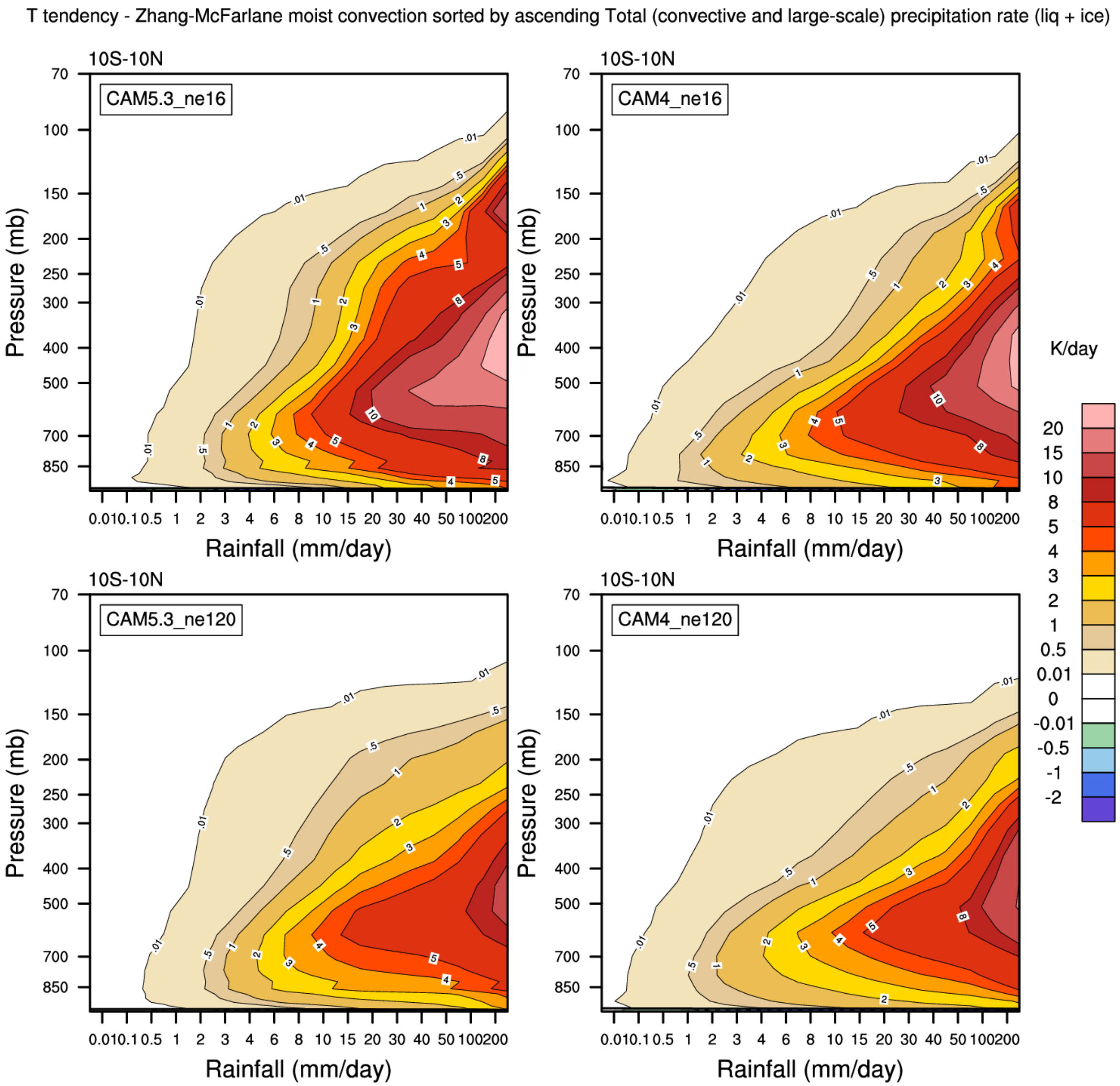
Relative Humidity

- PBL moistening deepening
- CAM5 > 100%
- CAM5 greater U. trop RH
- High-res dryer

Rainfall-vertical profile plots

- Daily averaged data
- ~1 year period
- From native SE grid
- 10N-10S ave
- Anom. plots remove rainfall=0 profile

CAM5 (1°) CAM4 (1°)

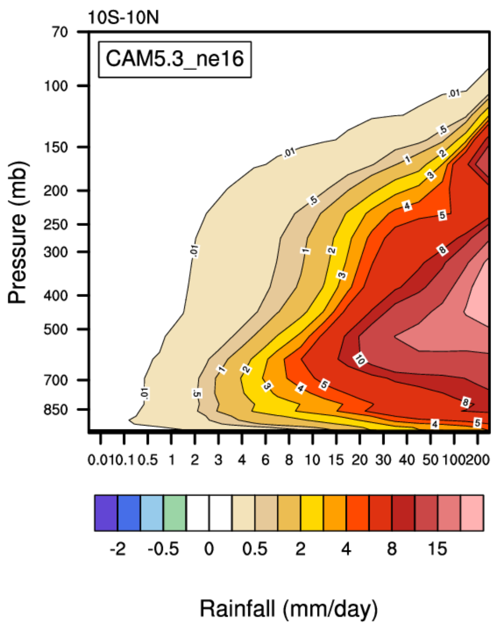


CAM5 (0.25°) CAM4 (0.25°)

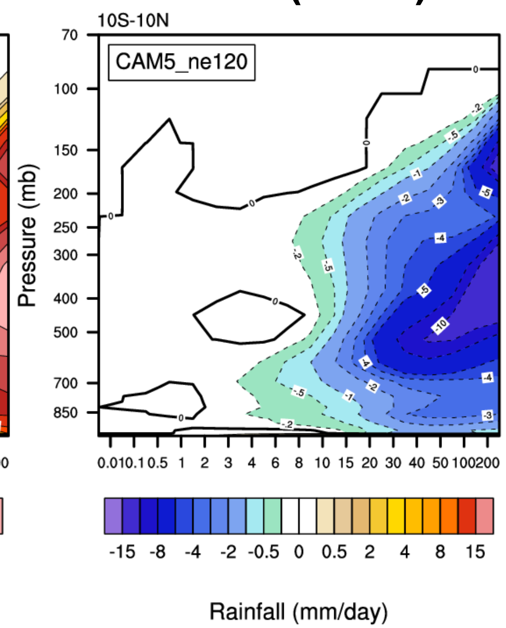
DT deep convection

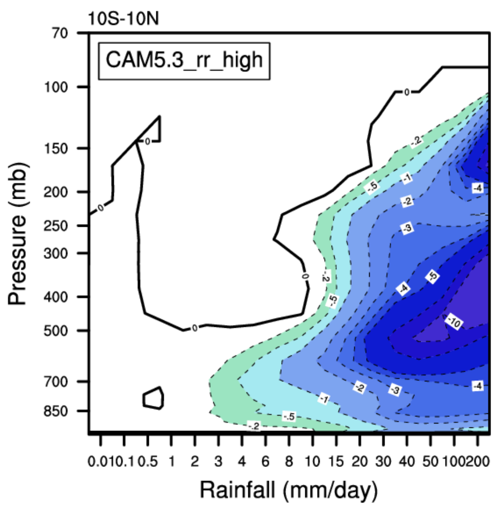
- Dominant heat source for high rainfall rates
- CAM5 more top heavy.
- Stronger low level heating at low rainfall rates in CAM4

CAM5 (1°)

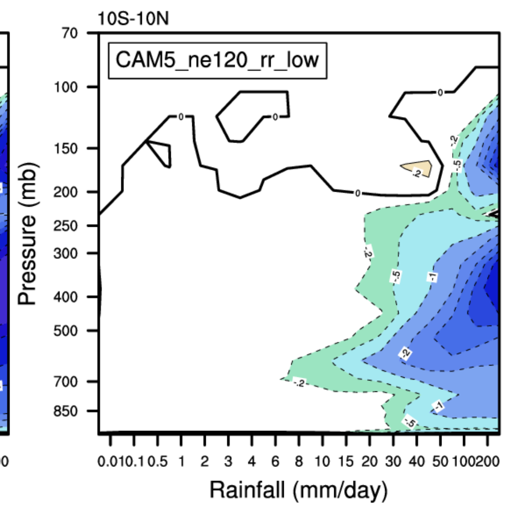


CAM5 (0.25°)





CAM5 (RR 0.25°)



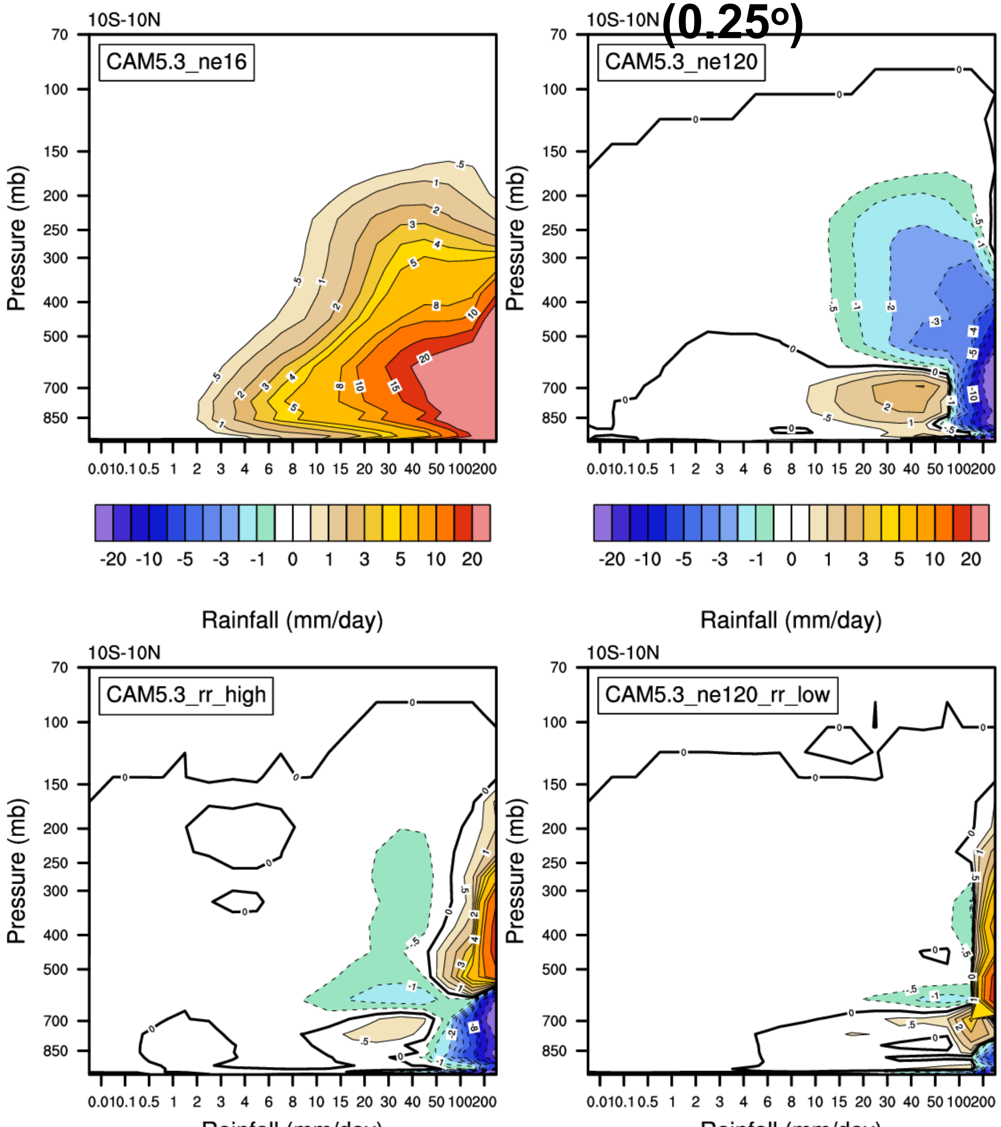
CAM5 (RR 1°)

DT deep convection (Control)

- Less heating at high rainfall rates
- Large-scale/shallow convection taking over

CAM5 (1°)

CAM5 (0.25°)



CAM5 (RR 0.25°)

CAM5 (RR 1°)

DT deep convection (tau300)

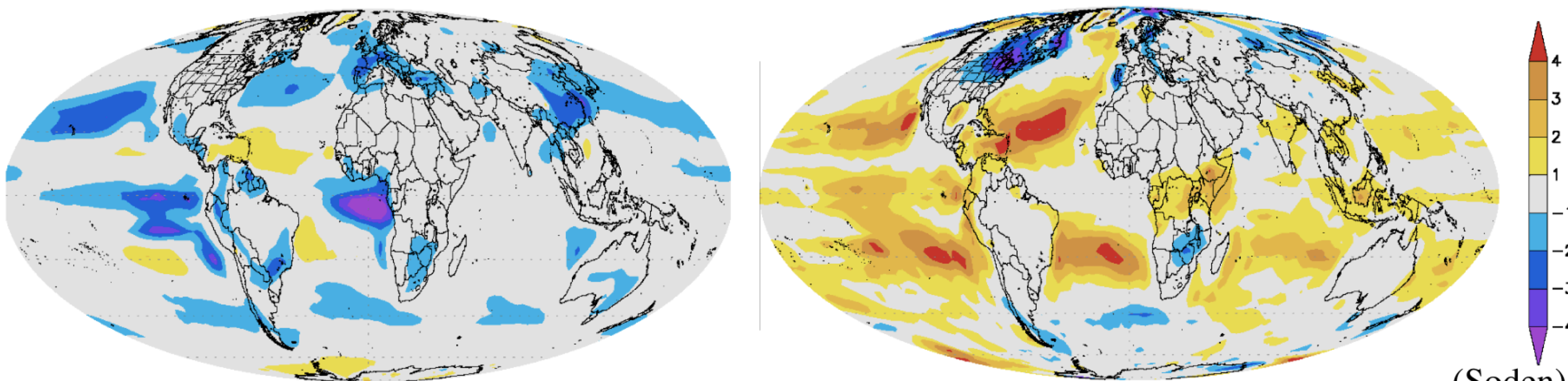
- Less heating at high rainfall rates for all regions
- Less sensitivity to higher resolution at moderate rainfall rates
- At the highest rainfall rates high resolution sensitivity is different between uniform and RR regions

Consequences?

Emergent Phenomena: Climate Sensitivity

What happens to clouds when we double CO_2?

GFDL Model **+4.2K** NCAR Model **+1.8K**



(Soden)

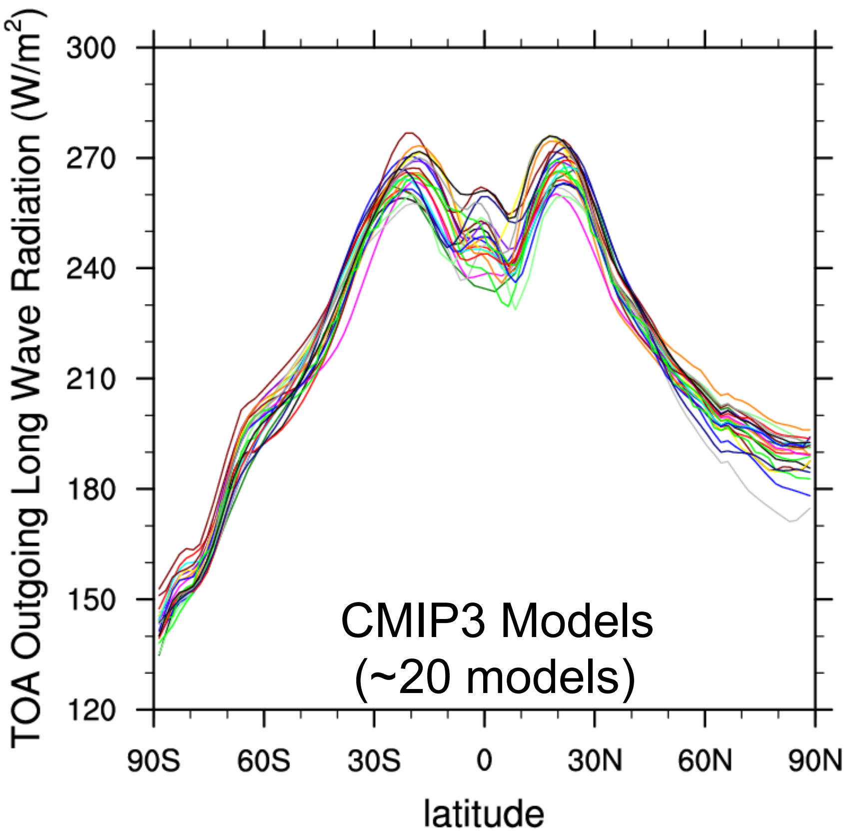
Change in low cloud amount (%)

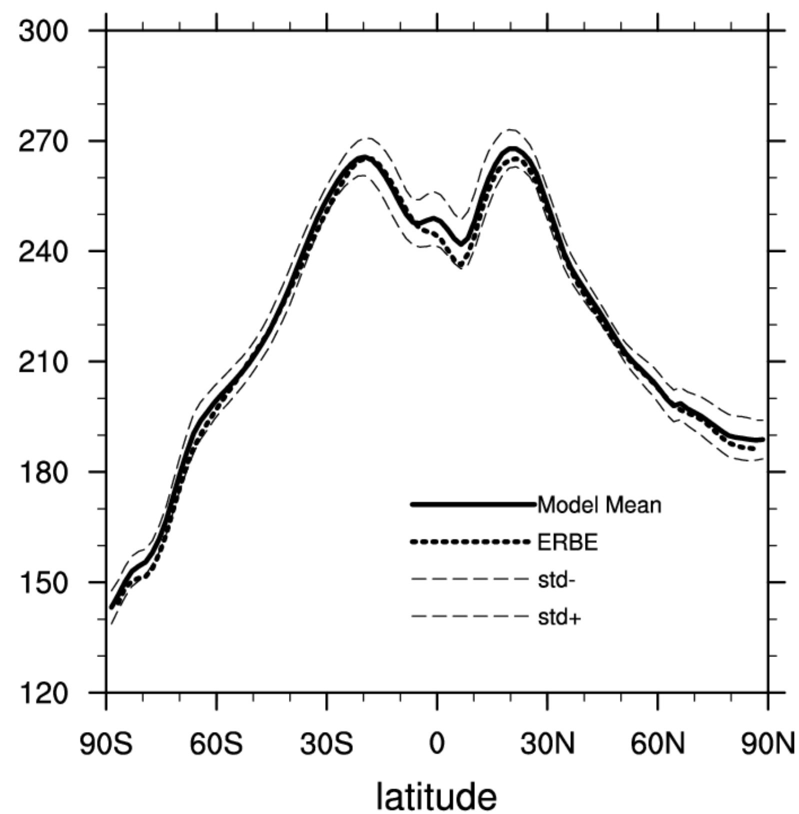
- Significant range in **low-cloud sensitivity** (low and high end of models)
- Cloud regimens are largely **oceanic stratocumulus** (difficult to model)
- Implied temperatures change is due to (higher/lower) solar radiation reaching the ground because of **clouds feedbacks.**

Emergent Phenomena: Cloud processes in GCMs

State of the Art from CMIP3

Outgoing Long-wave Radiation
(Annual, 1990-1999)

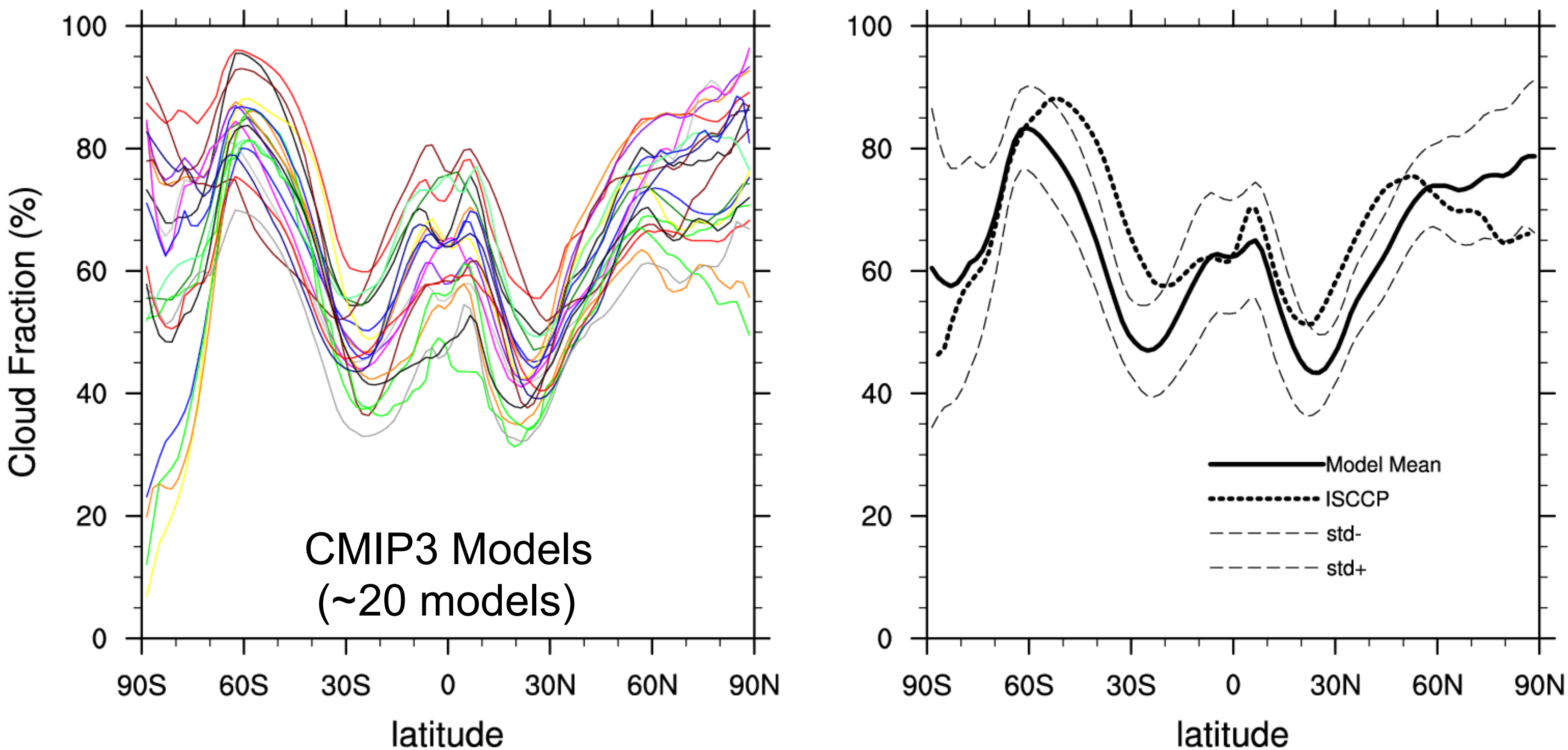




Emergent Phenomena: Cloud processes in GCMs

State of the Art from CMIP3

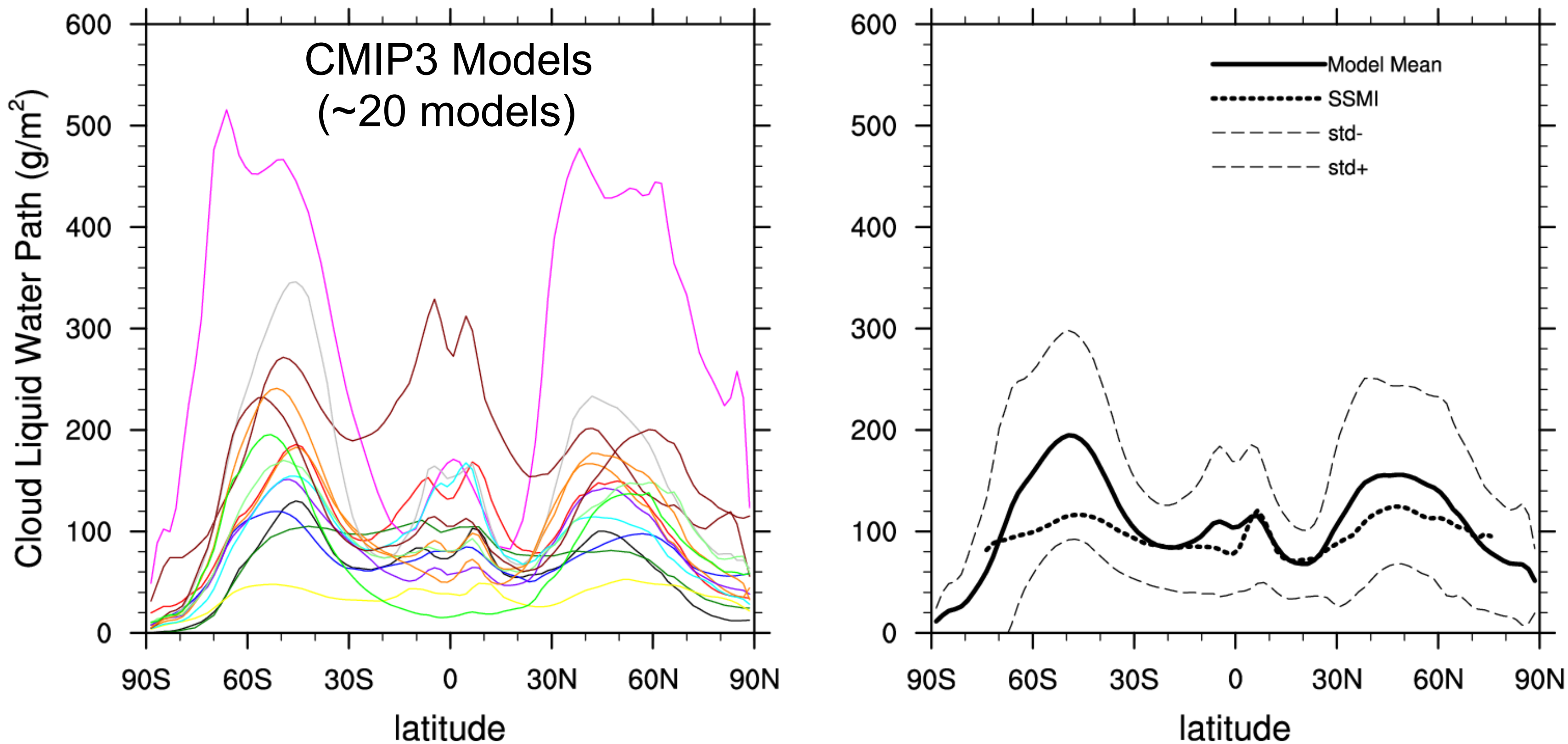
Total Cloud Fraction
(Annual, 1990-1999)



Emergent Phenomena: Cloud processes in GCMs

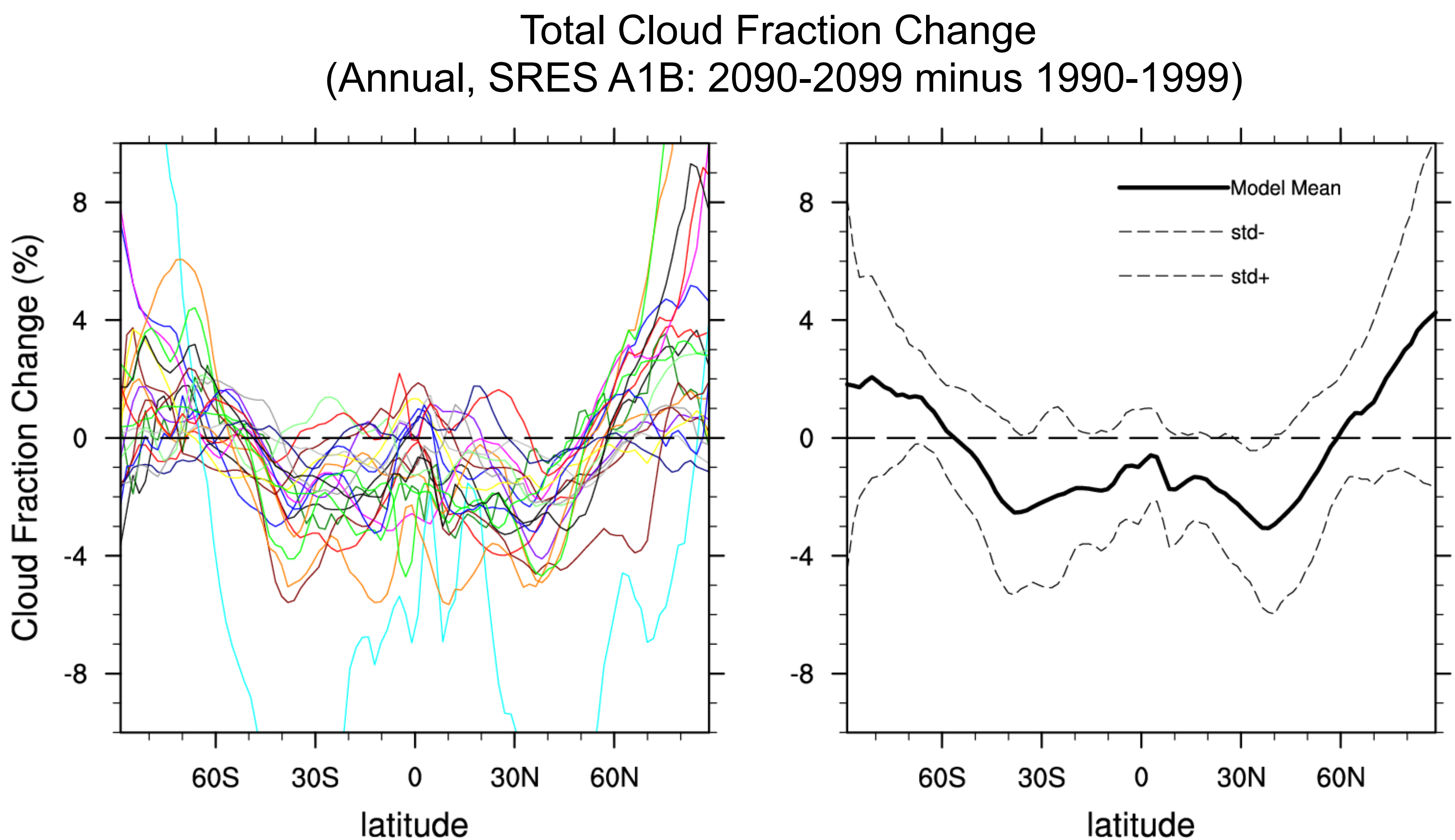
State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)



Emergent Phenomena: Cloud processes in GCMs

State of the Art from CMIP3 – response to climate change



Summary

- **<u>How do we define success?</u>**
- Metrics are hard, diagnostics are too many
- Hierarchy of approaches for validation
- Examine variability and process oriented diags.
- “Red-line” diagnostics (ENSO, 20^{th} C, sea-ice)
- Model complexity -> more ways to ‘fail’
- The better things get the easier it is to make things worse