A Unified Shallow-Deep Mass-Flux Convective Parameterization Using a Stochastic Multicloud Plume Model

IITM Workshop on Prediction Skill of Extreme Precipitation Events and Tropical Cyclones

Nov. 25-27, 2019

Boualem Khouider, University of Victoria

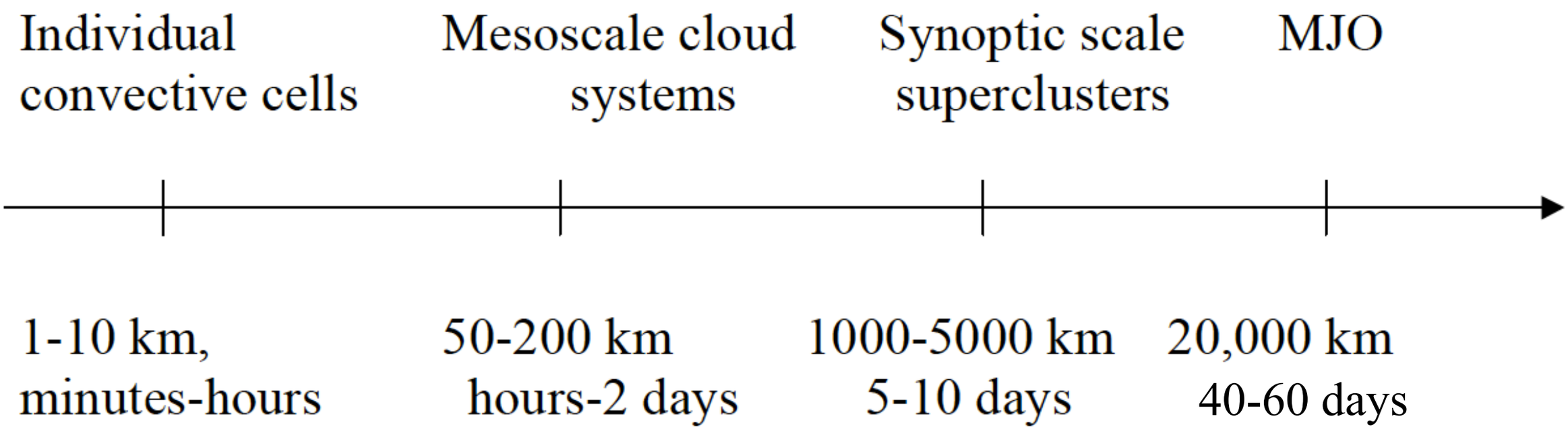
Bityut Goswami, NYU Abu Dhabi (Younsi Univ. S. Korea)

Phani M. Krishan, IITM

Andrew Majda, Courant Institute, NYU

Organized tropical convection

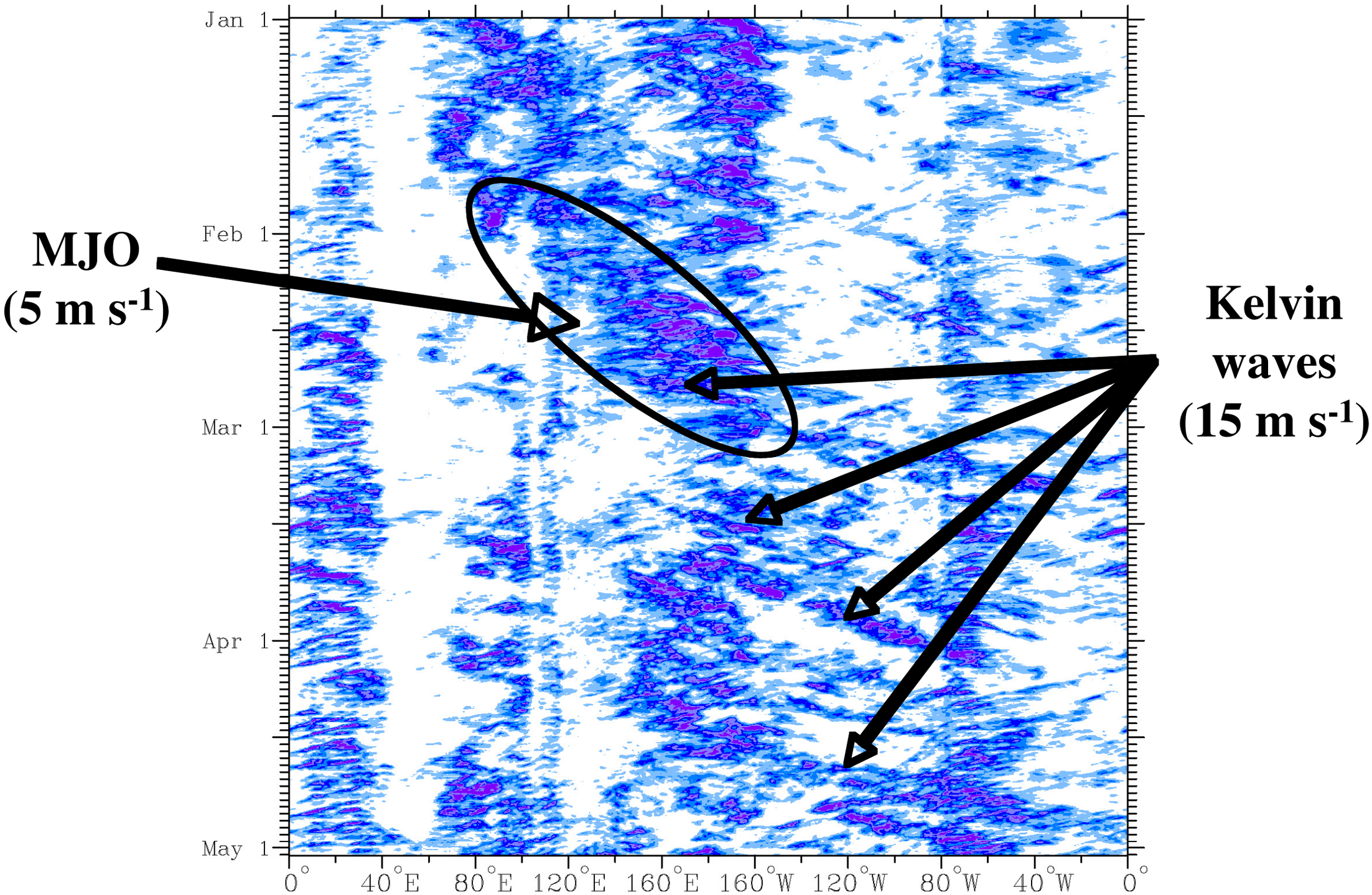
- Tropical variability is dominated by multiscale convective systems
- Involves propagating waves that are embedded in each other
- Impacts topical rainfall as well as climate and weather patterns in both the tropics and extra-tropics



Convectively Coupled Waves: Interaction between Convection and Large Scale (Wave)Dynamics

OBSERVATIONS OF KELVIN WAVES AND THE MJO

Time–longitude diagram of CLAUS Tb (2.5S–7.5N), January–April 1987



Clouds in The Tropics

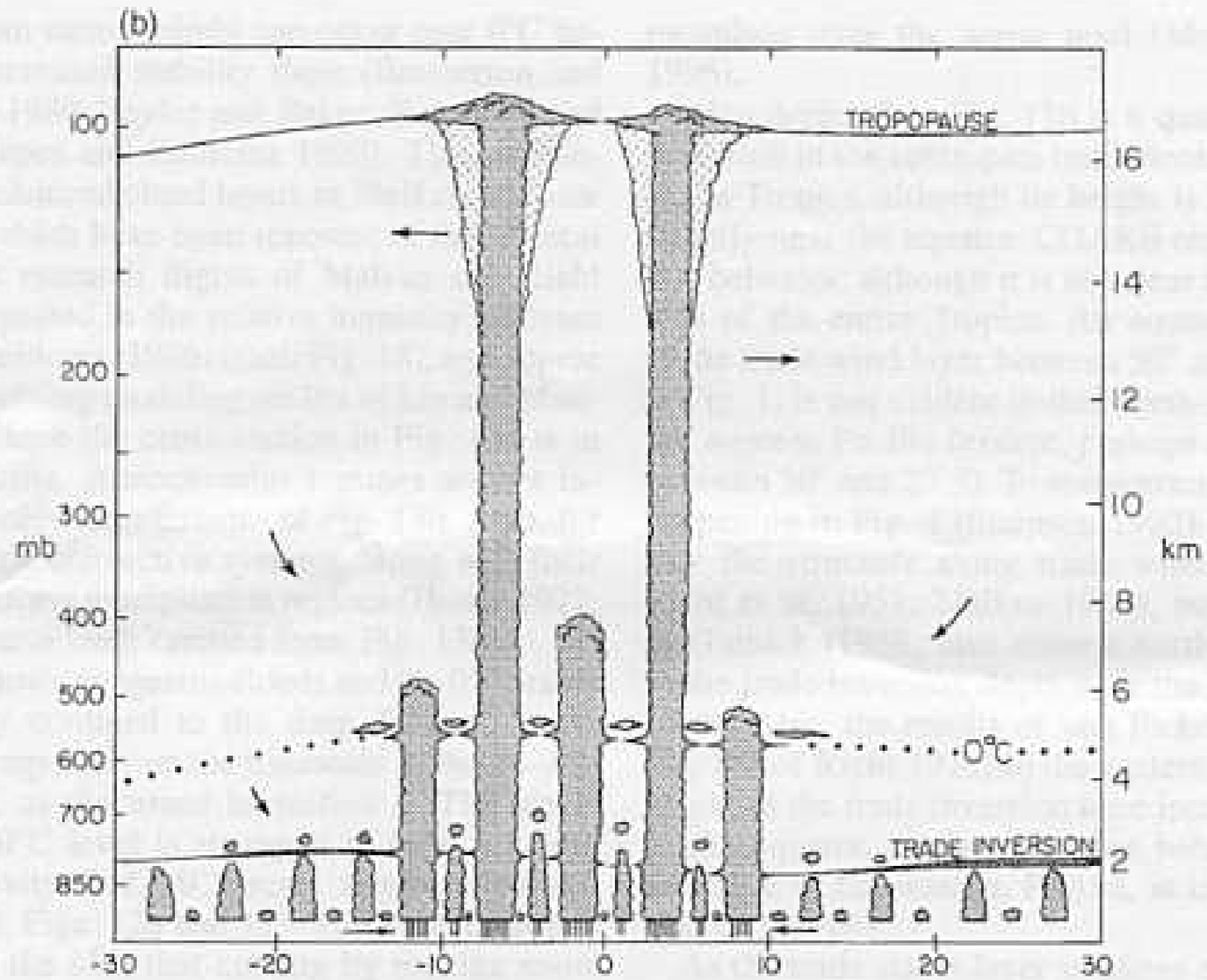
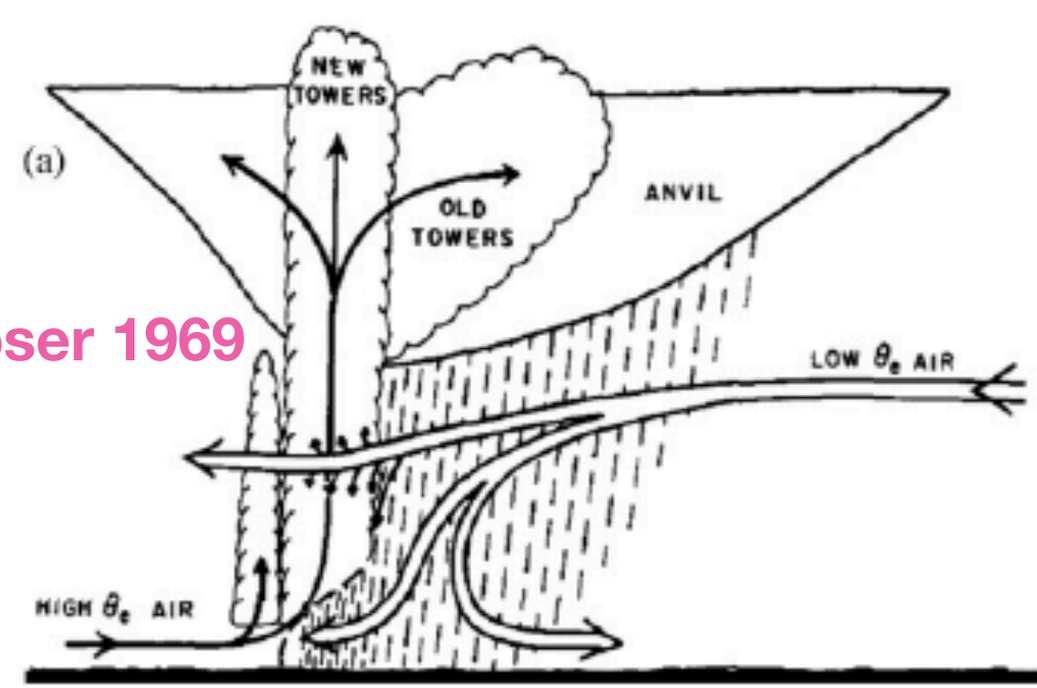


FIG. 13. (*Continued*) cloud types are indicated: shallow cumulus, cumulus congestus, and cumulonimbus. Within the shallow cumulus classification, there are two subdivisions: forced and active cumulus. Three stable layers are indicated: the trade inversion, the 0°C layer, and the tropopause. Shelf clouds and cloud debris near the trade and 0°C stable layers represent detrainment there. Cirrus anvils occur near the tropopause. Considerable overshooting of the trade and 0°C stable layers occurs in the equatorial trough zone. Arrows indicate meridional circulation. Although double ITCZ is indicated, representing IOP-mean, this structure is transient over the warm pool and a single ITCZ often exists.

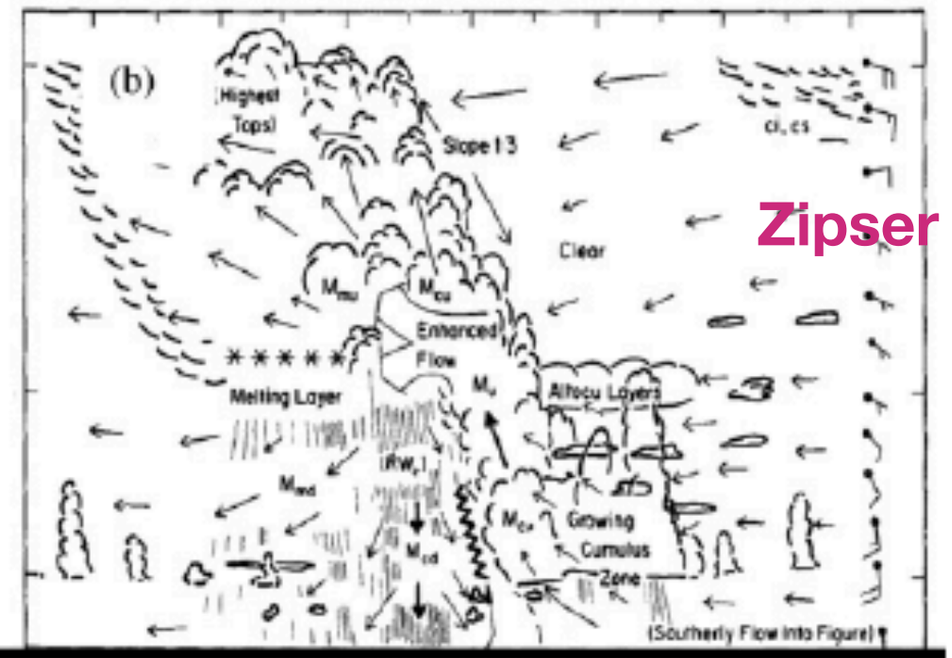
Three main cloud types above trade wind inversion layer: Congestus, Deep, and Stratiform

…, which characterize tropical convective systems at multiple scales

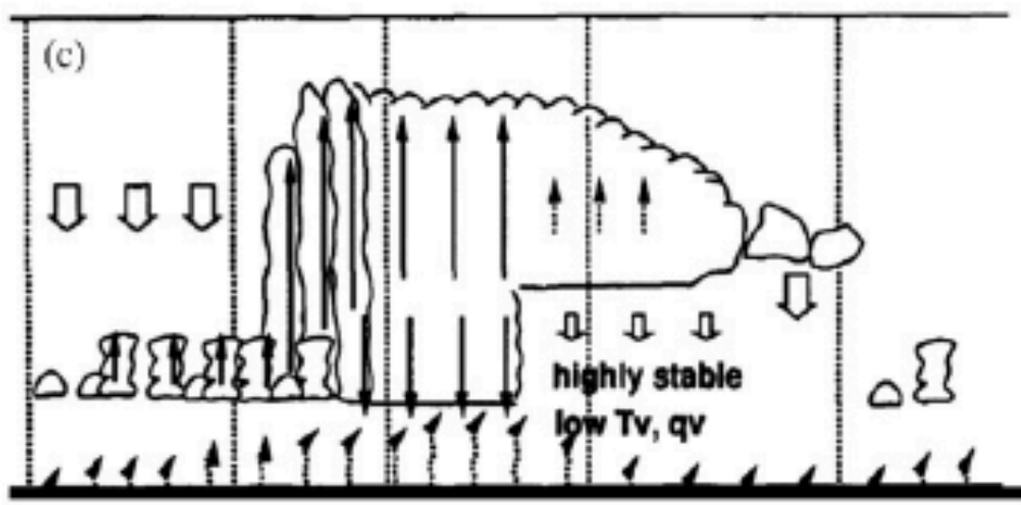
Johnson et al. 1999



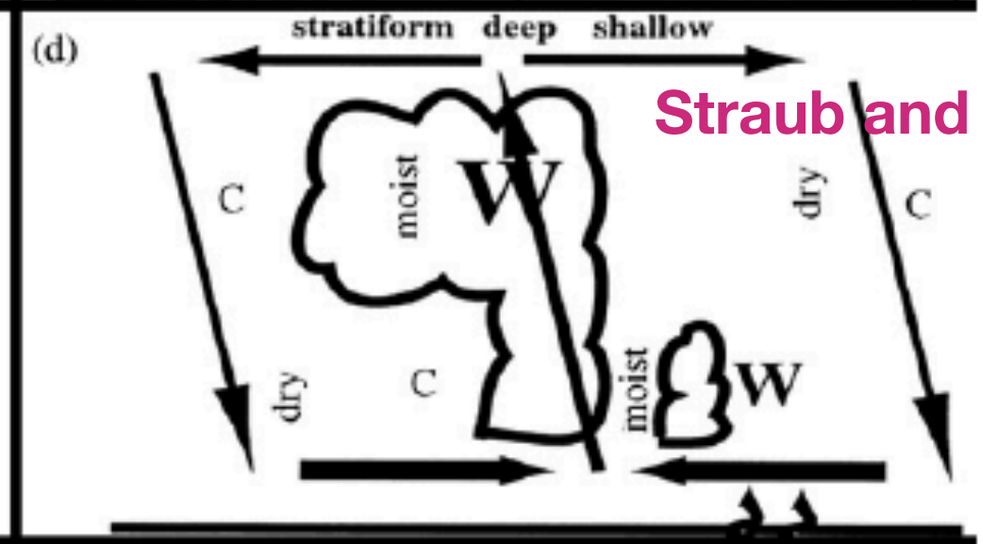
Zipser 1969



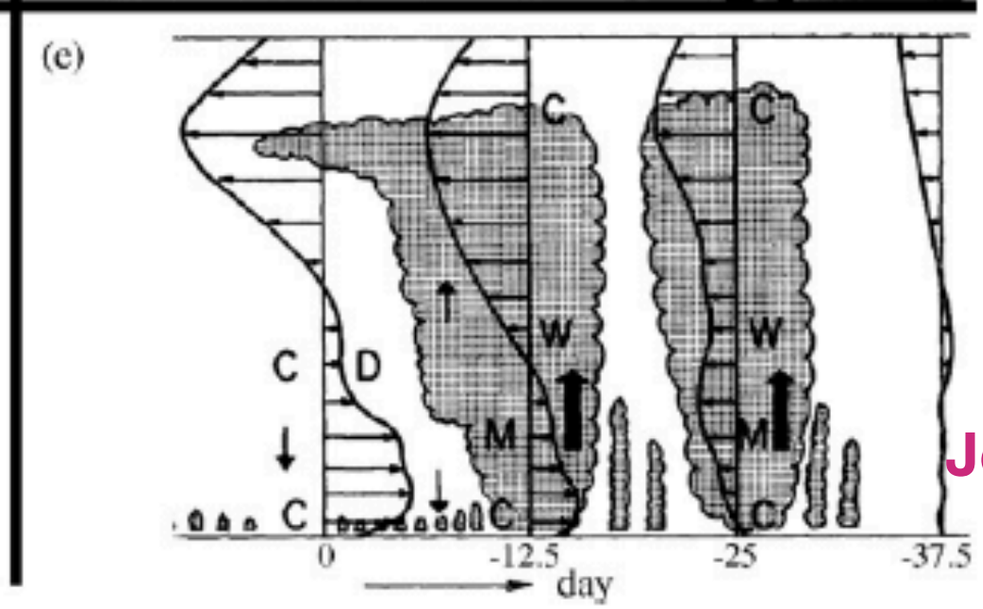
Zipser et al. 1981



Takayabu et al. 1996



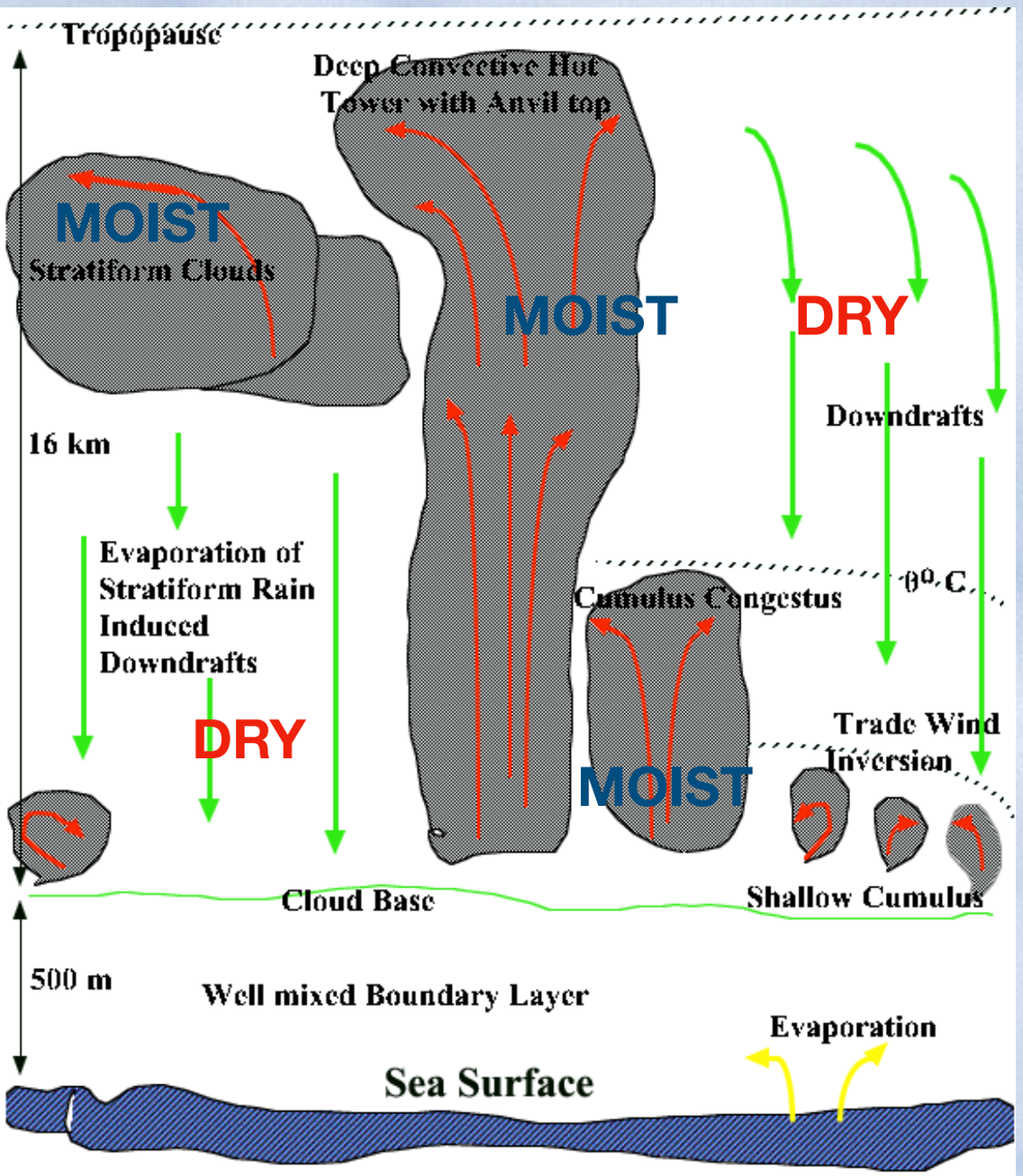
Straub and Kiladis 2002



Lin and Johnson 1996

Compiled by Mapes et al. 2006

Multicloud—building block model



Khouider and Majda (2006)

- Not based on a column model
- Based on observed features of tropical convective systems
- Convection is integrated in equations of motion: direct feedback
- Convection responds to progressive adjustment of environmental variables
- Allows interactions across scales -- between moisture and precipitation
- Successful in representing CCWs and Tropical Intra-seasonal oscillations in both simple models and in aquaplanet HOMME GCM (MJO and monsoon variability)

Mathematics of Planet Earth Series 3

Boualem Khouider

Models for Tropical Climate Dynamics

Waves, Clouds, and Precipitation

This book is a survey of the research work done by the author over the last 15 years, in collaboration with various eminent mathematicians and climate scientists on the subject of tropical convection and convectively coupled waves. In the areas of climate modelling and climate change science, tropical dynamics and tropical rainfall are among the biggest uncertainties of future projections. This not only puts at risk billions of human beings who populate the tropical continents but it is also of central importance for climate predictions on the global scale. This book aims to introduce the non-expert readers in mathematics and theoretical physics to this fascinating topic in order to attract interest into this difficult and exciting research area. The general thyme revolves around the use of new deterministic and stochastic multi-cloud models for tropical convection and convectively coupled waves. It draws modelling ideas from various areas of mathematics and physics and used in conjunction with state-of-the-art satellite and in-situ observations and detailed numerical simulations. After a review of preliminary material on tropical dynamics and moist thermodynamics, including recent discoveries based on satellite observations as well as Markov chains, the book immerses the reader into the area of models for convection and tropical waves. It begins with basic concepts of linear stability analysis and ends with the use of these models to improve the state-of-the-art global climate models. The book also contains a fair amount of exercises that makes it suitable as a textbook complement on the subject.

Mathematics

ISBN 978-3-030-17774-4

9 783030 177744

springer.com

MPE 3 Khouider

Models for Tropical Climate Dynamics

Mathematics of Planet Earth Series 3

Boualem Khouider

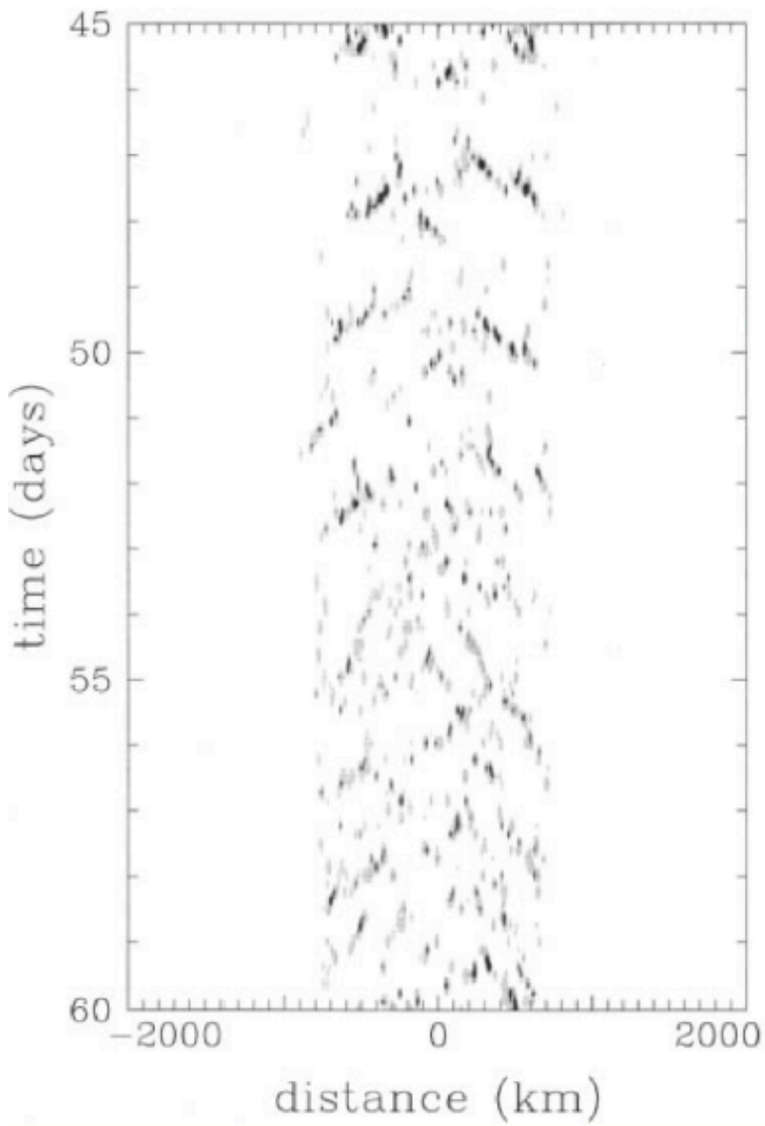
Models for Tropical Climate Dynamics

Waves, Clouds, and Precipitation

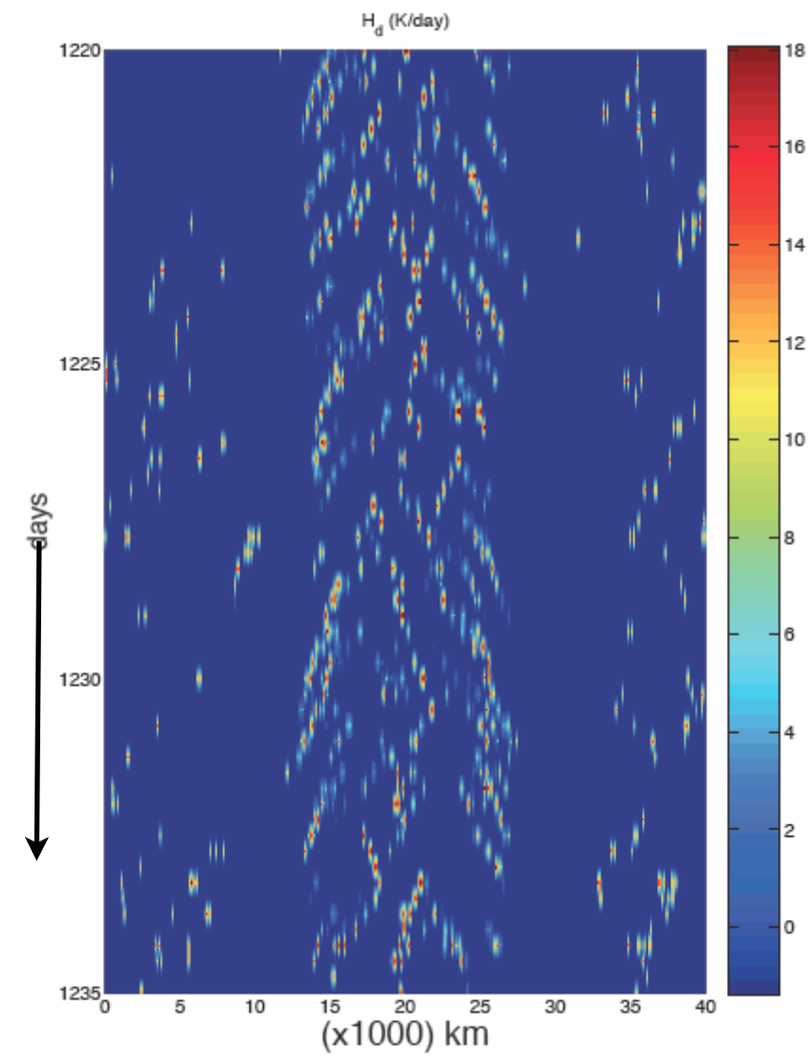
Springer

Warm Pool Simulation using the stochastic MC Model

CRM (Grabowski et al. 2000)



Stochastic MC



Moist Gravity waves!

SMCM acts a super-parameterization in representing the statistics of sub grid variability due to organized convection!

Implementation of SMCM in a Coupled Climate Model (NCEP's CFSv2)

B. B. Goswami, K., P. Krishna, P. Mukhopadhyay, A. Majda

(GRL, JAS, JAMES, 2017)

NATIONAL MONSOON MISSION

MoES, India

SMCM parameterized Total heating

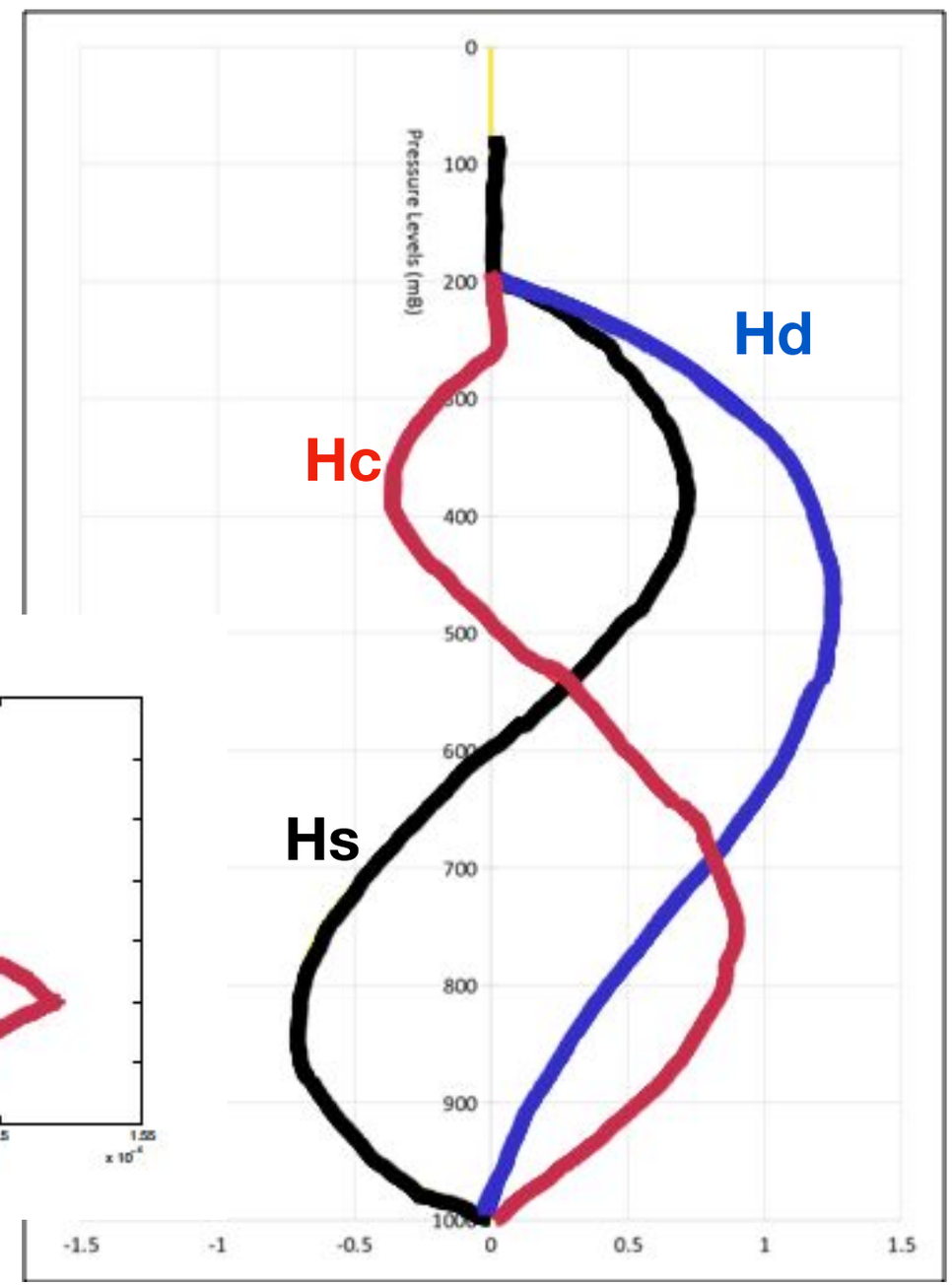
$$Q_{tot}(z) = H_d\,\phi_d(z) + H_c\,\phi_c(z) + H_s\,\phi_s(z)$$

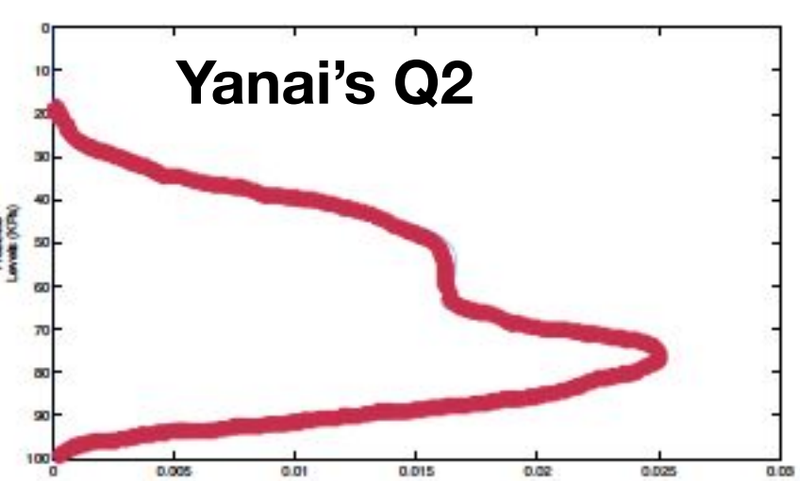
$$H_c = \frac{\sigma_c}{\bar{\sigma}_c}\alpha_c Q_c$$

$$H_d = \frac{\sigma_d}{\bar{\sigma}_d} Q_d$$

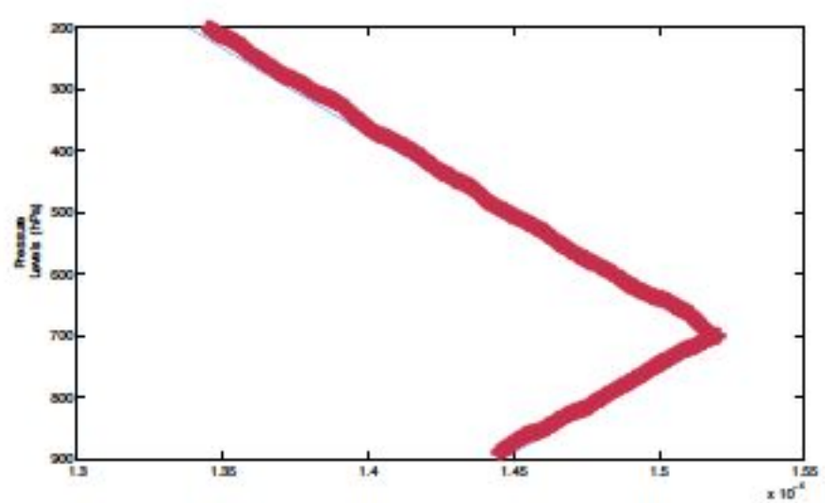
$$\frac{\partial H_s}{\partial t} = \frac{1}{\tau_s}\left(\frac{\alpha_s \sigma_s H_d}{\bar{\sigma}_s} - H_s\right)$$

Empirical Heating And Moisture Sink Profiles





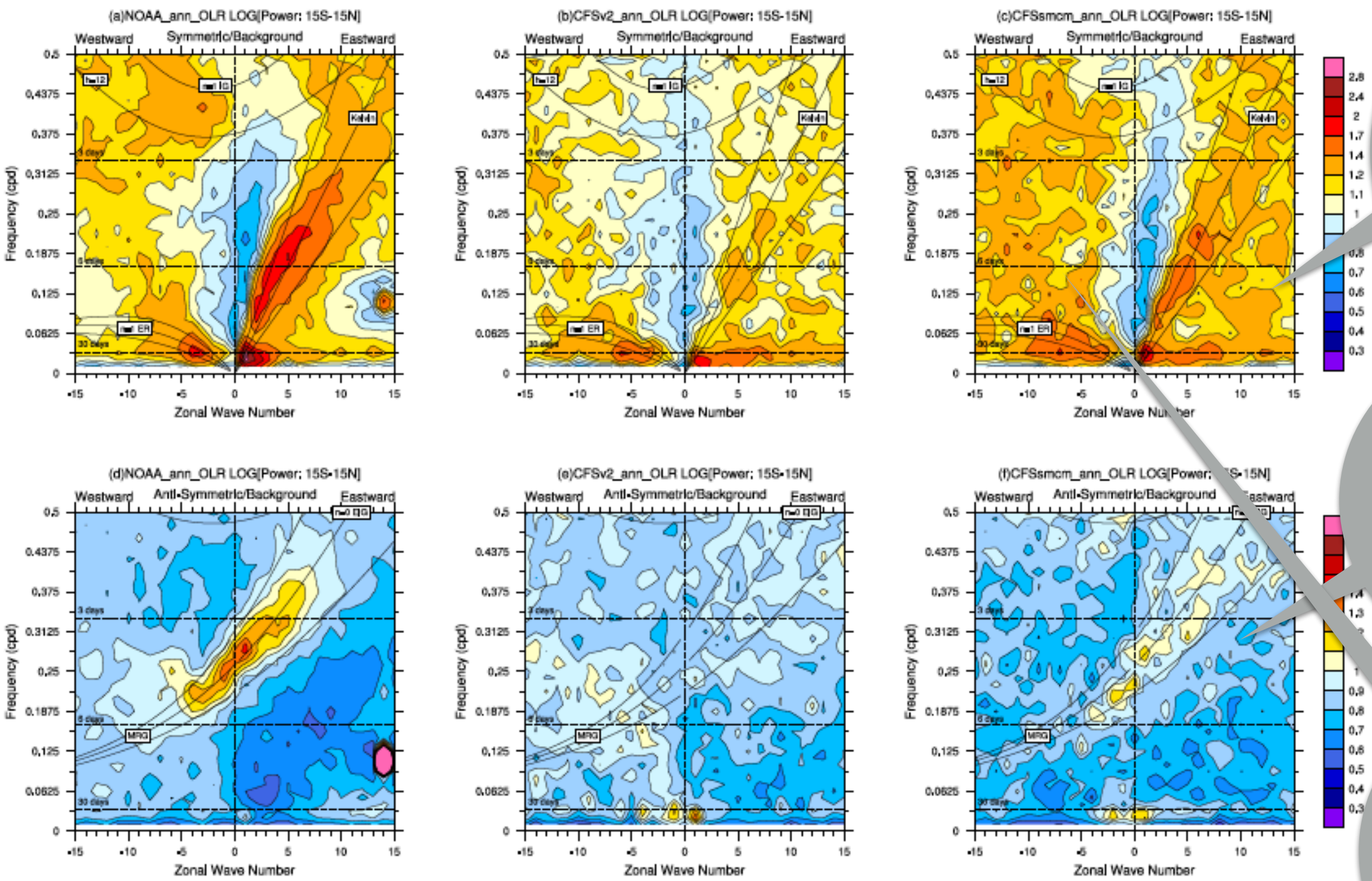
Drying



Moistening

Clear improvements in Wheeler-Kiladis-Takayabu Spectra

OBS **CTL** **SMCM**

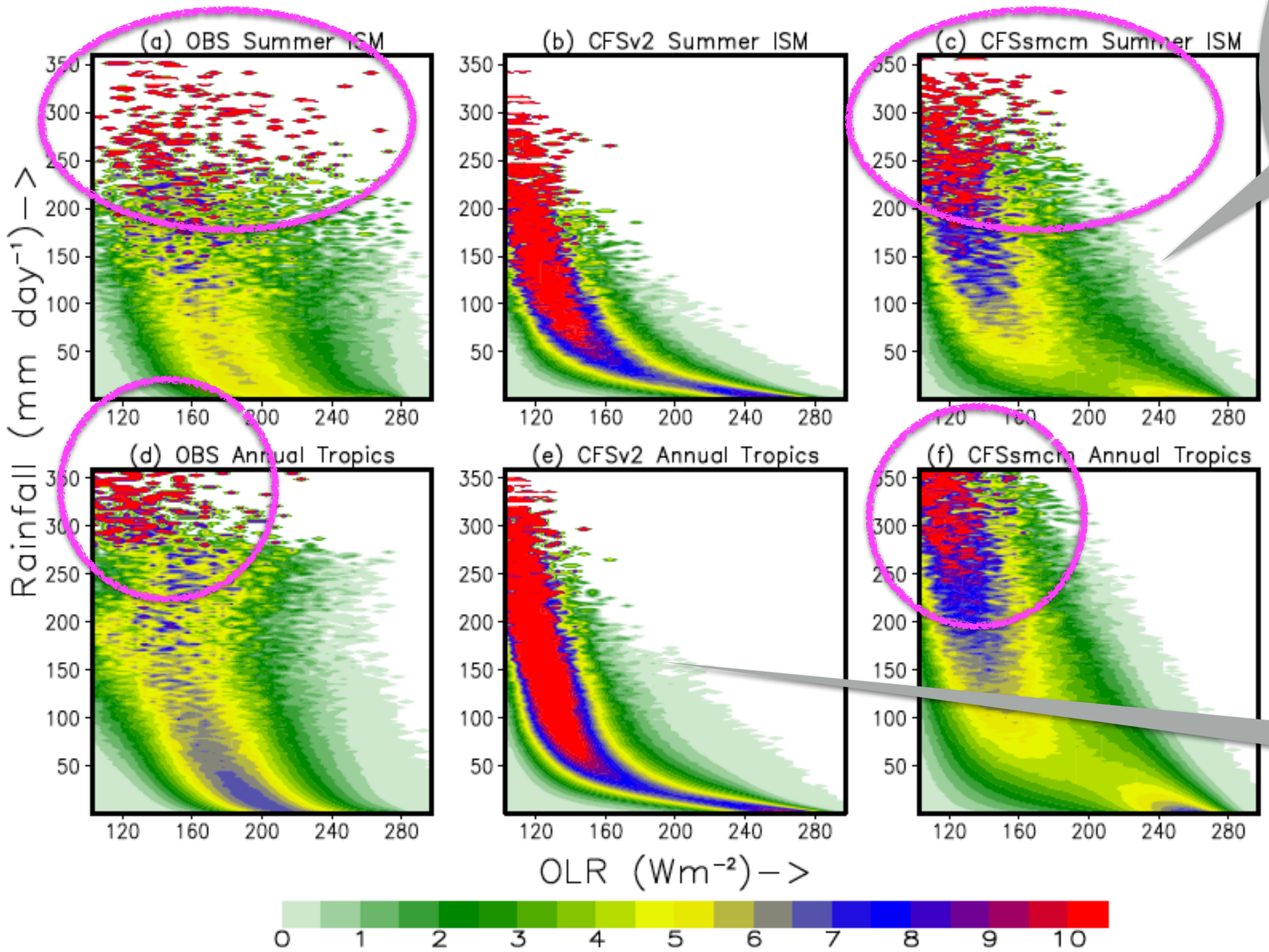


MJO, Kelvin and 2d waves better in SMCM

MRG peak weaker than OBS but inexistent in CFSv2

Tropical depressions perhaps exaggerated!

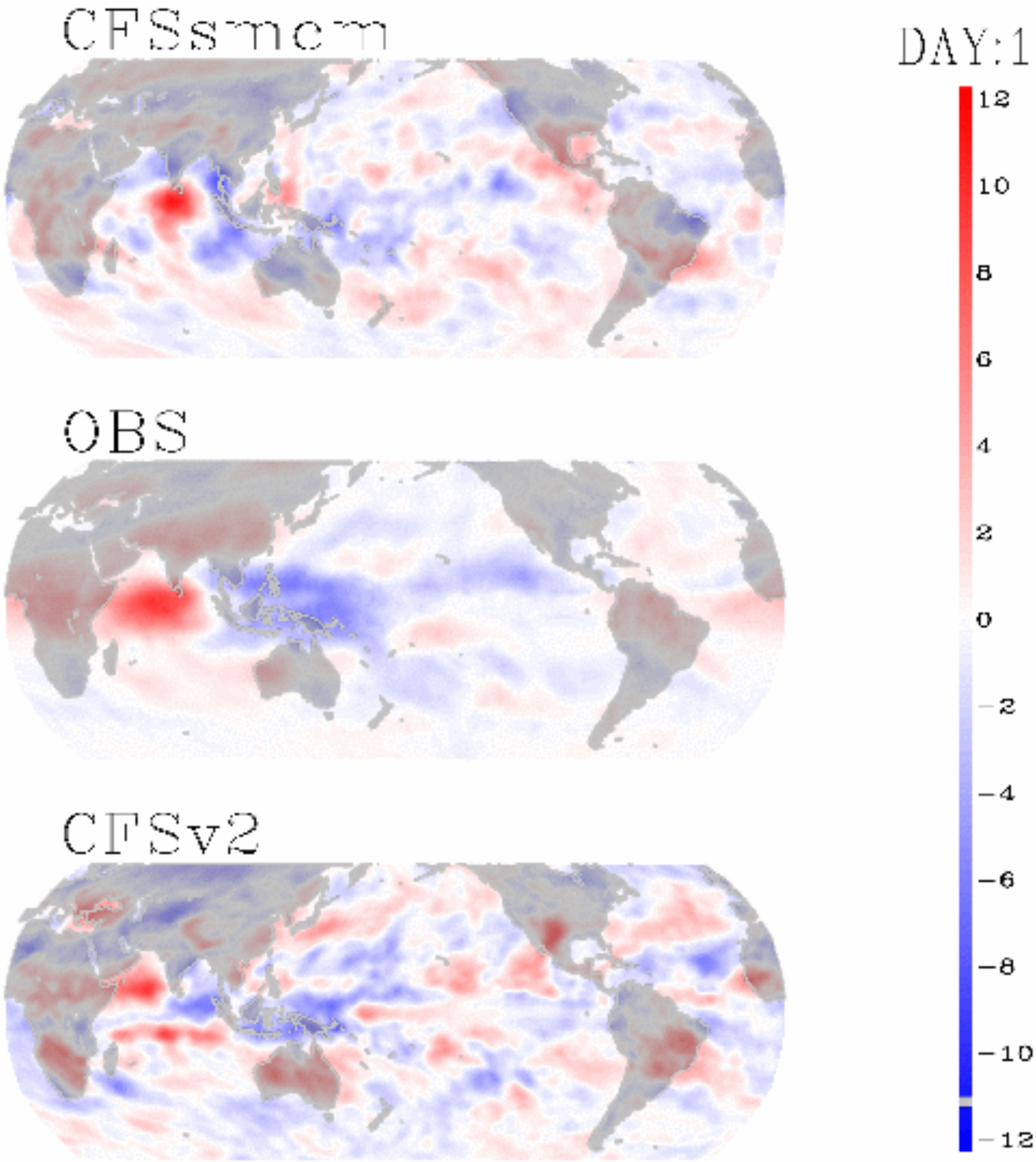
Rainfall-OLR Joint Distribution



Spread of high rainfall events to higher OLR, better captured inSMCM

in CFSv2, precipitation rates are quasi-uniform distributed and locked to low ORL

Figure 4. Joint distribution (in %) of OLR-rainfall over ISM region (15°S-30°N, 50°E-110°E), during boreal



MJO Propagation

Stochastic Multicloud Plume Model — to modify Zhang-McFarlane Scheme

- Extend SMCM to four cloud types: shallow, congests, deep, stratiform
- Use the SMCM CAF to inform detrainment levels
- Modify calculation of bulk mass flux and bulk entrainment and detrainment rates: previous attempts with varying degrees of success in making entrainment parameter moisture dependent (Takoika, Neale and Mapes, …)
- Key idea: Missing physics for ZM scheme to self-reproduce the multicloud-heating profiles?

Mass-Flux Concept Revisited

- Steady state plume model (Arakawa-Schubert, Zhang-McFarlane, etc.)

$$\frac{1}{M(z)}\frac{\partial M}{\partial z} = \epsilon(z) - \delta(z)$$

$$M(z) = \sum_{j,\lambda_j \le \lambda_z} m_j(z) \approx \frac{N_z}{\lambda_z}\int_0^{\lambda_z} M_b(\lambda) e^{\lambda(z-z_b)} d\lambda$$

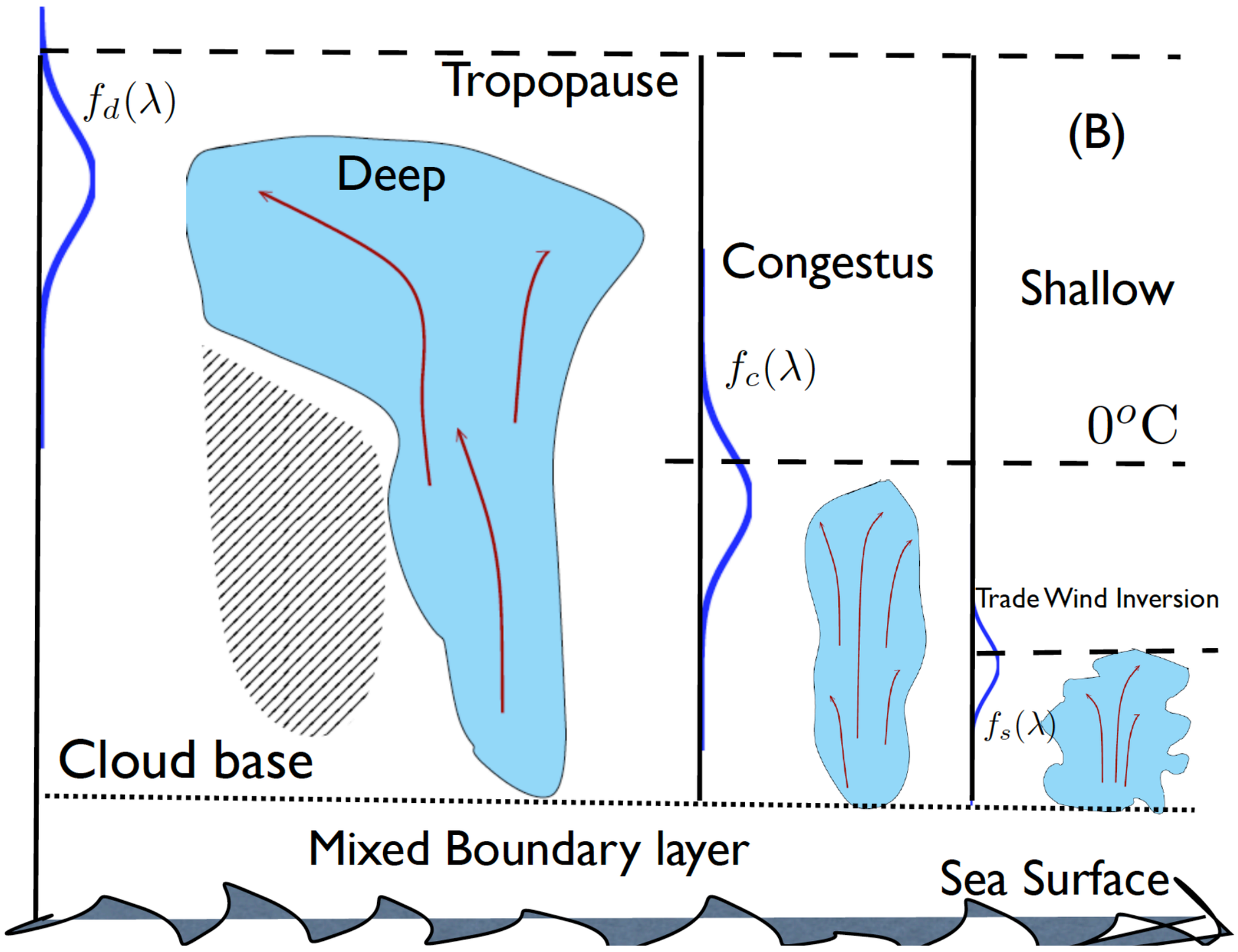
$$m_\lambda(z) = M_b(\lambda) e^{\lambda(z-z_b)}, \quad z_b \le z \le z_\lambda$$

- One-to-one between entrainment rate and detrainment level
- Turbulent closure for convection: $(\phi = S, q, \cdots)$

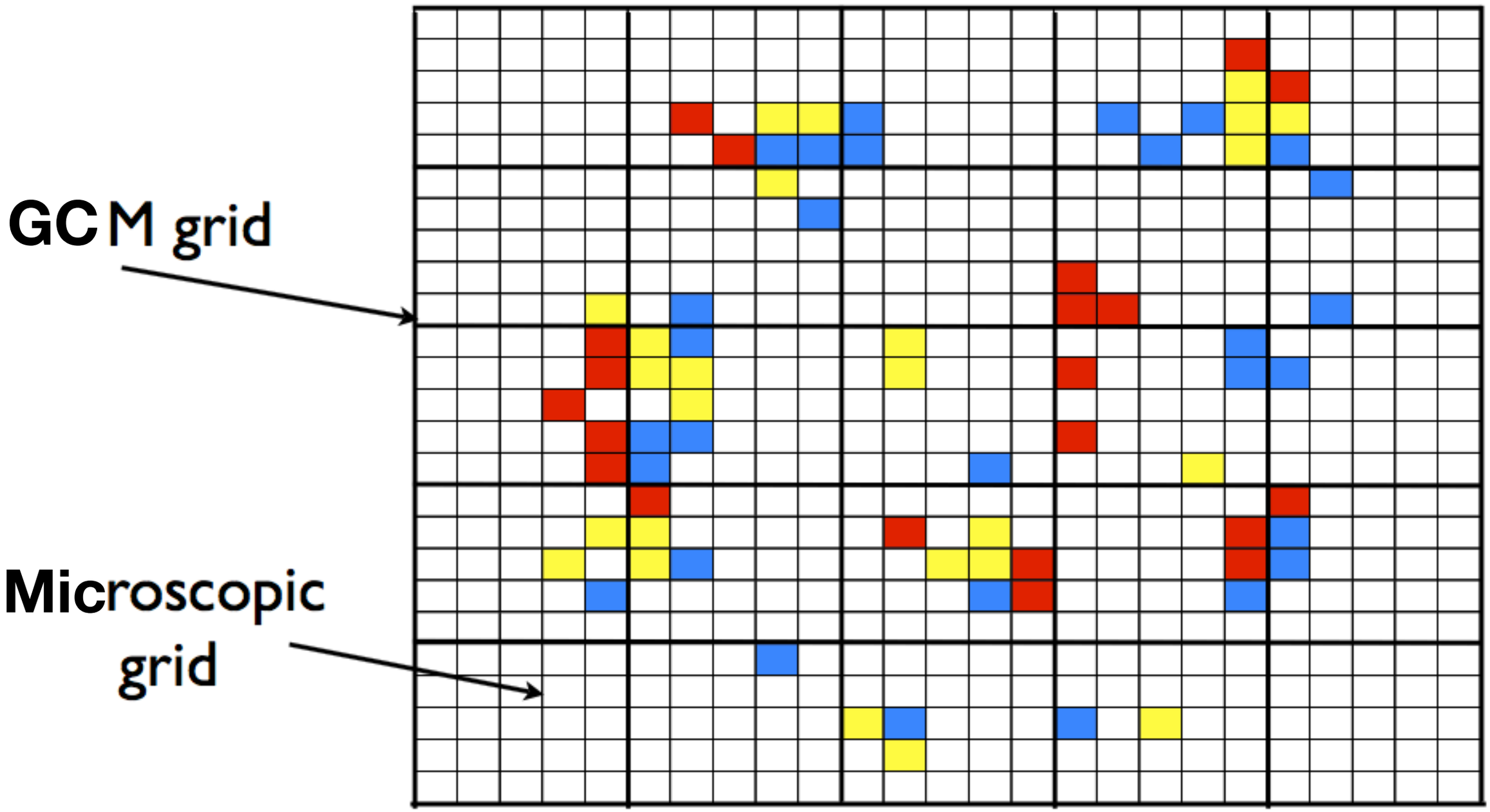
$$\frac{\partial \bar{\phi}}{\partial t} + \bar{\mathbf{V}}\nabla\cdot\nabla\bar{\phi} = -\frac{1}{\rho}\frac{\partial \overline{\rho\phi' w'}}{\partial z} + \cdots$$

$$= -\frac{\partial}{\partial z}\left[M_u(z)(\phi_u - \bar{\phi}) + M_d(\phi_d - \bar{\phi})\right] + \cdots$$

Use SMCM to inform detrainment levels



Fine lattice overlaid on GCM Grid



Each lattice is either occupied by a cloud of certain type or is clear sky…time varying!

4 cloud-type SMCM: Intuitive Probability Rules

- A clear sky turns into a shallow cumulus site with high probability if there is CIN, or strong large-scale Subsidence
- A shallow site turns into congestus with high probability if there is CAPE and mid troposphere is dry
- A shallow site turns into deep with high probability if there is CAPE and mid troposphere is moist
- A clear sky site turns into a congestus site with high probability if CAPE>0 and mid troposphere is dry.
- A congestus or clear sky site turns into a deep site with high probability if CAPE>0 and mid troposphere is moist.
- A deep site turns into a stratiform site with high probability.
- All three cloud types decay naturally according to prescribed decay rates.

✓Distribution continuously changes with large scale state

Transition Rate Functions

$$R_{01} = \frac{1}{\tau_{01}} F(C_N, W)$$

$$R_{02} = \frac{1}{\tau_{02}} \Gamma(C_L) * \Gamma(D) * [1 - F(C_N, W)]$$

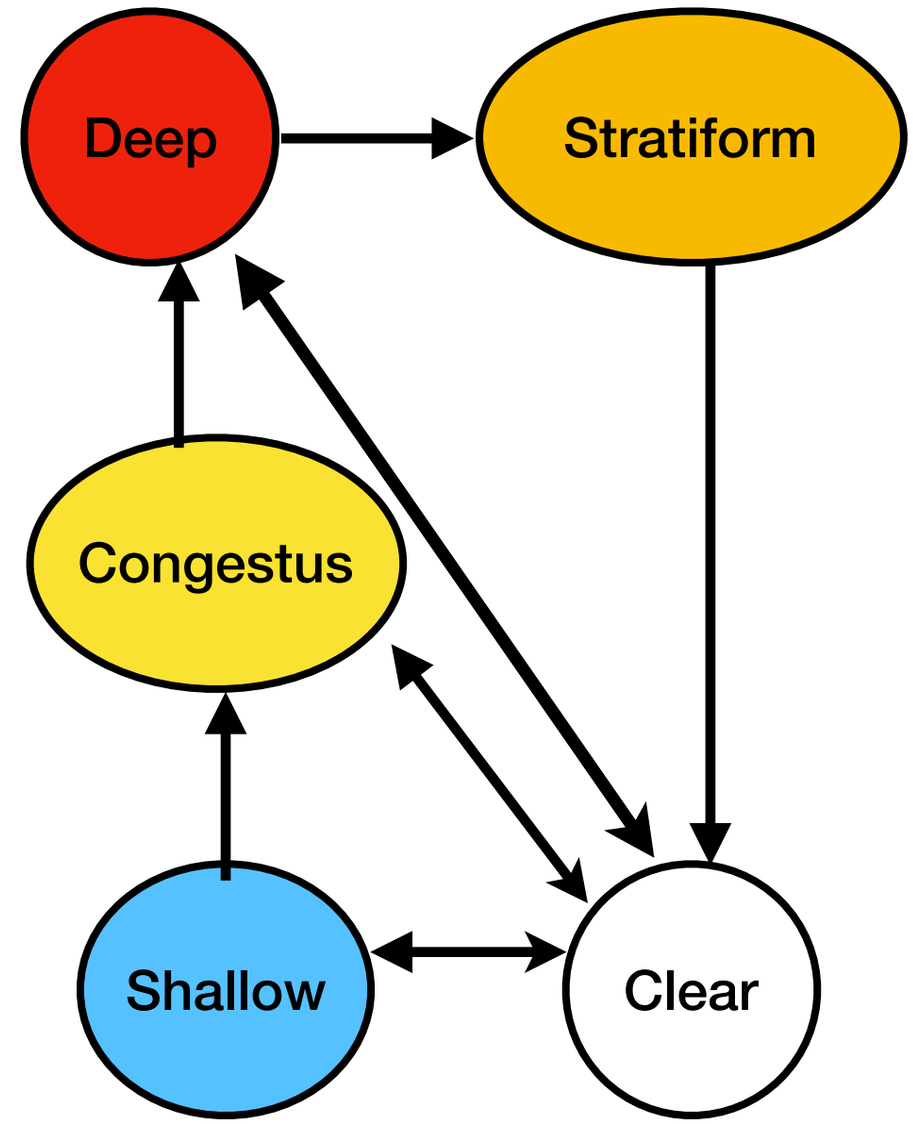
$$R_{03} = \frac{1}{\tau_{03}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$

$$R_{12} = \frac{1}{\tau_{12}} \Gamma(C_L) * \Gamma(D) * [1 - F(C_N, W)]$$

$$R_{13} = \frac{1}{\tau_{13}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$

$$R_{23} = \frac{1}{\tau_{23}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$

$$R_{34} = \frac{1}{\tau_{34}}$$



$$\Gamma(X) = (1 - e^{-X}) \mathbb{1}_{X>0}, \quad F(X, Y) = \Gamma(X) + \Gamma(Y)$$

Horizontal Plume Distribution

- On each site a random number of plumes of certain type is launched

$$\mathrm{Prob}\{P^{\sigma}_{k,n,m} = j|\sigma_{n,m}\}$$
$$\equiv \mathrm{Prob}\{j \text{ plumes of type } \sigma \text{ detraining at } z_D \geq z_k \text{ occur over the site } (n,m)\}$$
$$= \mathrm{Prob}\{j \text{ plumes of type } \sigma \ldots z_k \text{ occur over the site } (n,m)|d_\sigma \geq z_k\}$$
$$\ldots \times \mathrm{Prob}\{d_\sigma \geq z_k\}$$

- Plume numb … hen, 2006): Me … d area frac …

Mb is computed using a CAPE-TKE weighted closure according to SMCM CAF predictions.

$$M(z) = \ldots \lambda) + N_d f_d(\lambda)]\, d\lambda$$

$$\epsilon(z) - \delta(z) \ldots \frac{\ldots}{M(z)} \ldots$$

Detrainment

$$= \frac{\Lambda M_b}{M(z)} \int_0^{\lambda_z} \lambda e^{\lambda_z (z - z_b)} f(\lambda) d\lambda + \frac{\Lambda M_b}{M(z)} e^{\lambda_z (z - z_b)} f(\lambda_z) \frac{d\lambda_z}{dz}$$

Transition times Scales are Uncertain Parameters

- Bayesian Inference to learn transition time scales from data
- De La Chevrotiere et al.: Giga-LES, Kharoutidnov et al. (GATE III) (1 day simulation)
- Cardosso-Bihlo et al.: Dynamo, MJO 1 (1 day suppressed, 2 days initiation, ~4days active phase)
- Applying the inference method to long-period data set has been a challenge
- Undergraduate Student Isobel Glover has been working on optimizing the code…
- Replace MCMC with Variational Inference ….

Validation in Single Column CAM

Validation test cases

- GATE III: 4 prominent squall lines (Houze & Rappaport, 1984), convective envelopes with trailing stratiform decks
- TOGA-COARE II: squall lines and isolated convection (Rickenbach & Rutledge 1998).
- TWP-ICE (2006): Passage of MJO/Monsoon Active & Break Phases
- ARM95: 3 distinct weather regimes of mid-latitude land-convection: variable cloudiness, clear sky, high cloudiness: meso-scale systems (Xu and Randall, 2000)
- ARM97: 3 weather periods (heavy precipitation, clear sky, moderate precipitation) (Xu et al., 2002)
- MPACE: various weather regimes including boundary layer stratocumulus, cirrus clouds, multilayer stratus (Wang et al. 2016)

EXP1: Dynamo MJO, Active

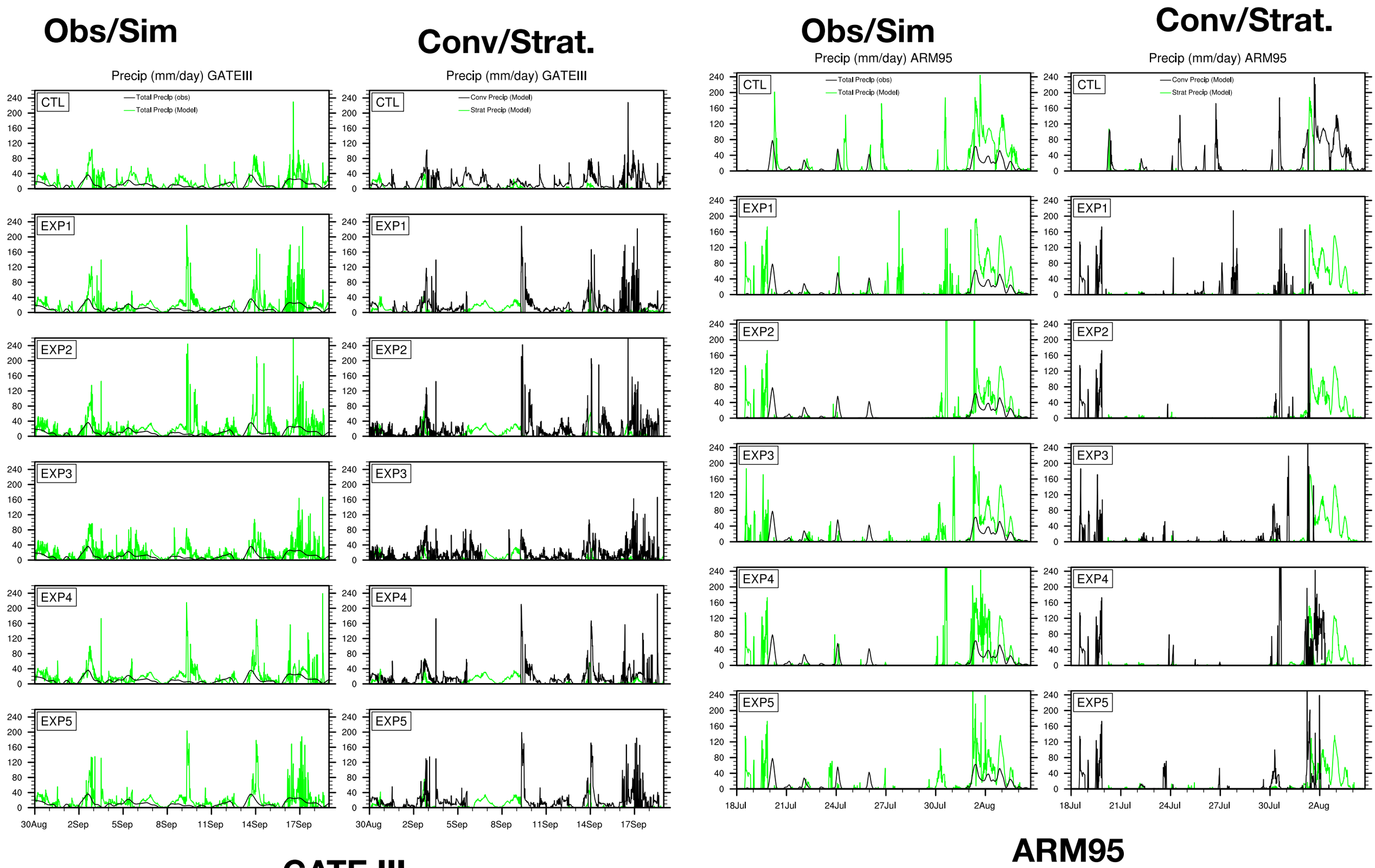
EXP2: GATEIII

EXP3: Modif. GATEIII

EXP4: Variational, Mean CAF Dynamo

EXP5: Guess

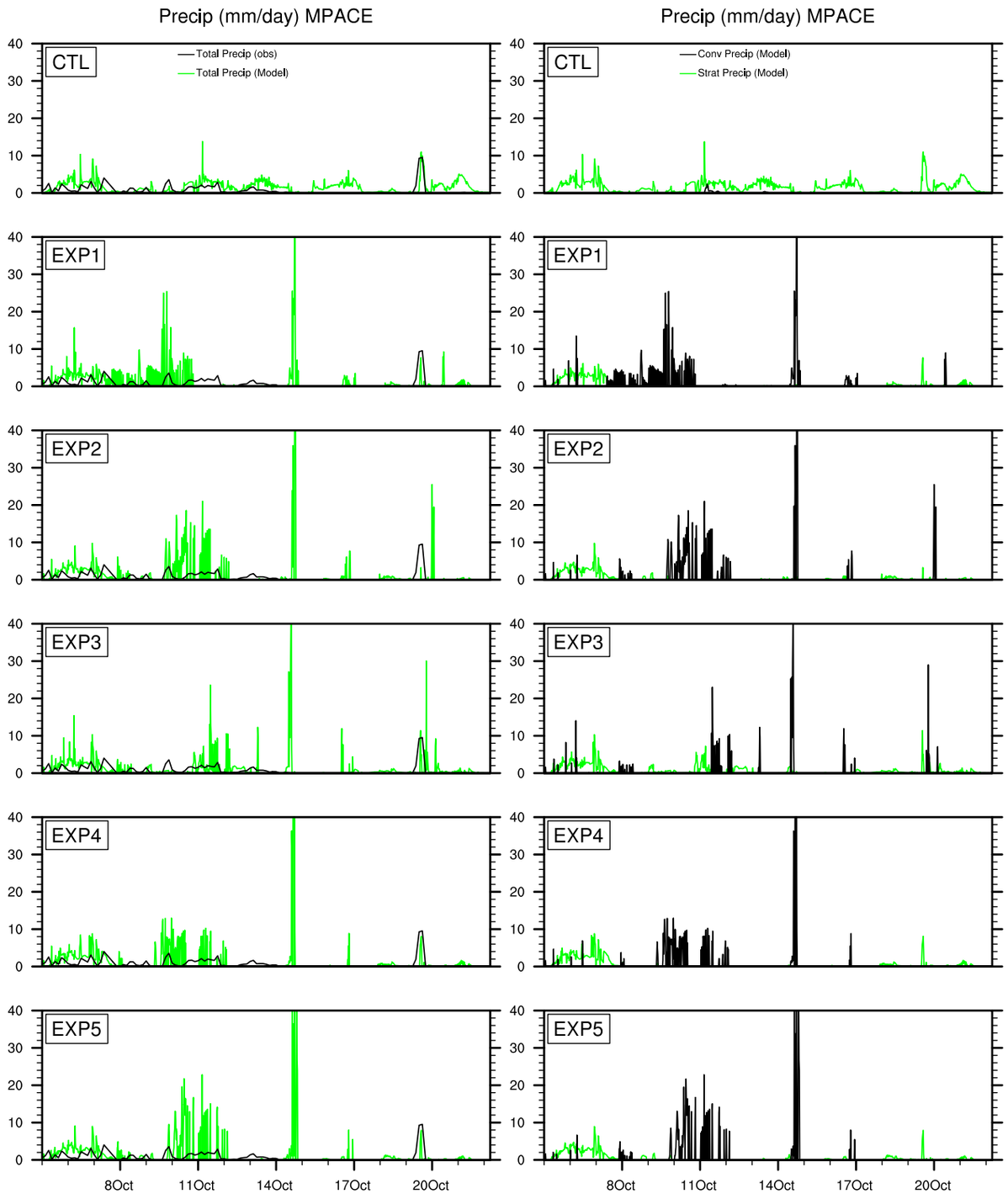
Description	Parameter	Value				
		Exp1	Exp2	Exp3	Exp4	Exp5
Clear sky to shallow cumulus	τ_{01}	1	1	9	0.035	2
Clear sky to congestus	τ_{02}	5.6	32	32	0.008	2
Clear sky to deep	τ_{03}	0.1	12	12	0.085	0.75
Shallow cumulus to congestus	τ_{12}	3	1	12	4.13	2
Shallow cumulus to deep	τ_{13}	0.14	1	1	0.00045	1
Congestus to deep	τ_{23}	0.31	0.25	0.25	0.00018	1.5
Deep to stratiform	τ_{34}	2	0.25	0.25	0.0026	1
Shallow cumulus to clear sky	τ_{10}	5	2	20	6.667	5
Congestus to clear sky	τ_{20}	7	2	2	0.0001	7
Deep to clear sky	τ_{30}	14.3	9.5	9.5	6.2	10
Stratiform to clear sky	τ_{40}	30	1	1	0.018	20



Precipitation Time Series

Obs/Sim

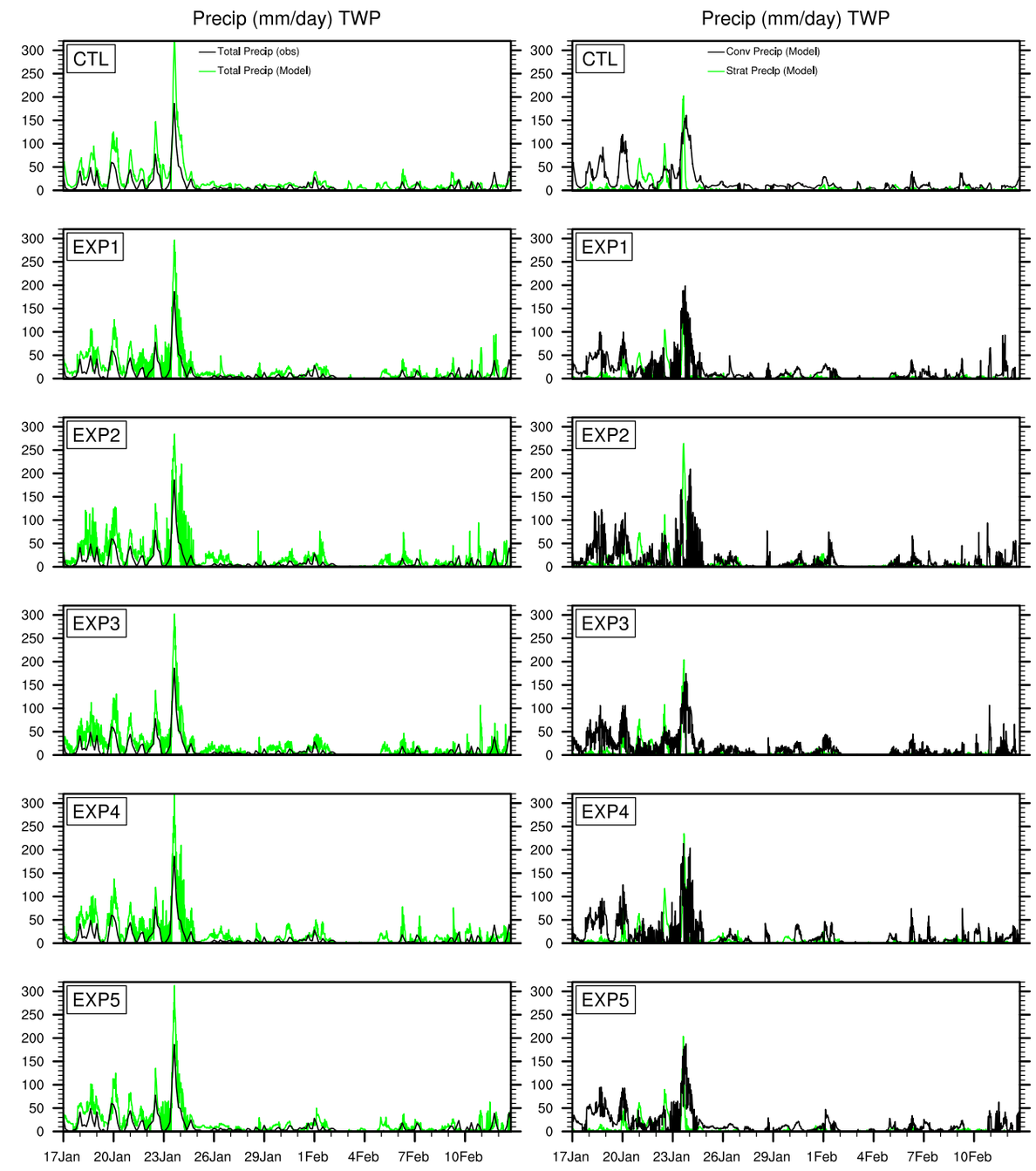
Conv/Strat.



MPACE

Obs/Sim

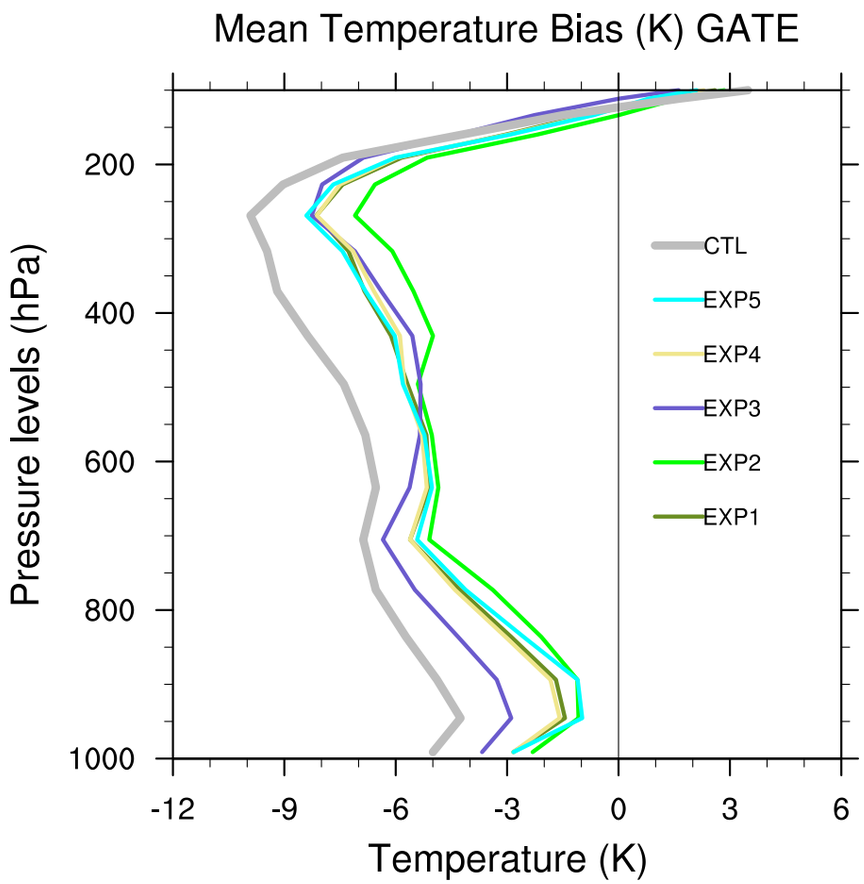
Conv/Strat.

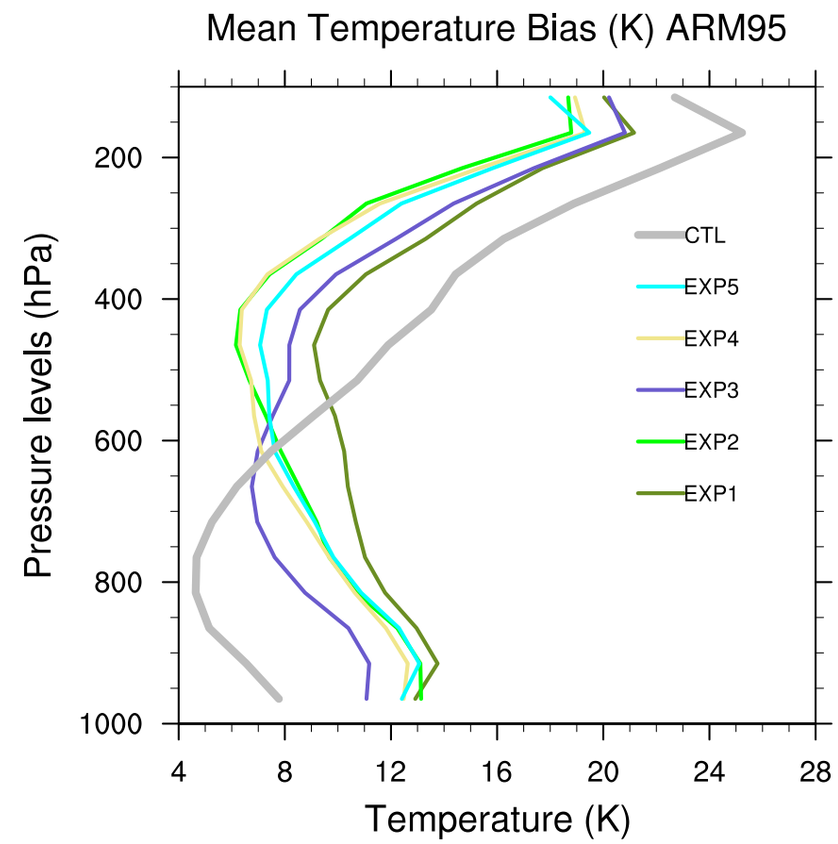


TWP-ICE 2006

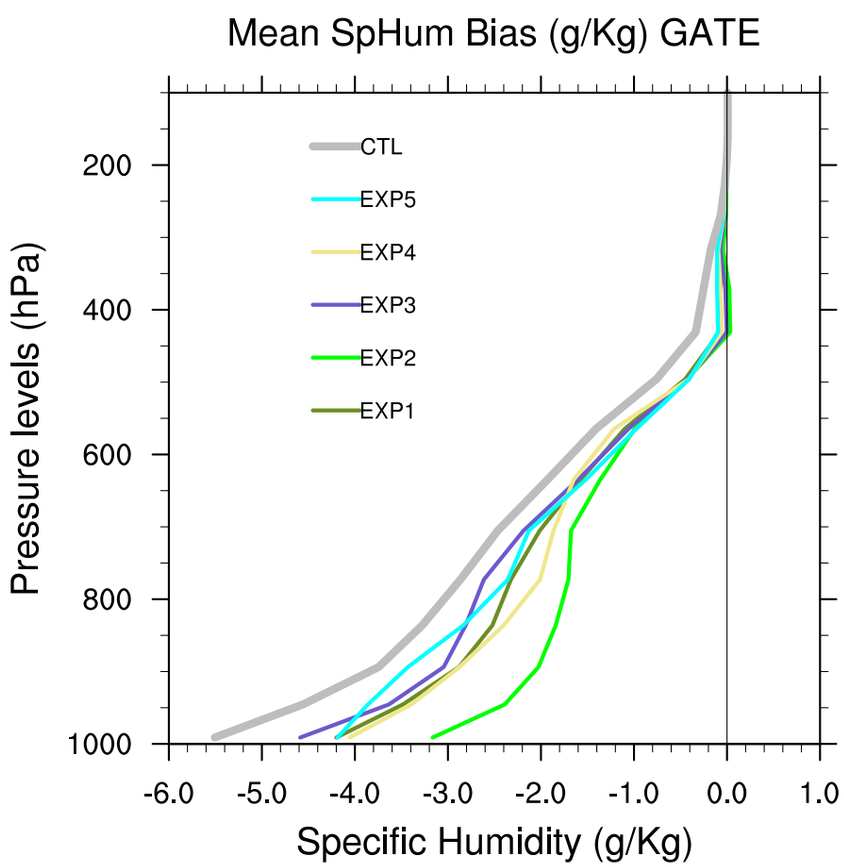
Precipitation Time Series

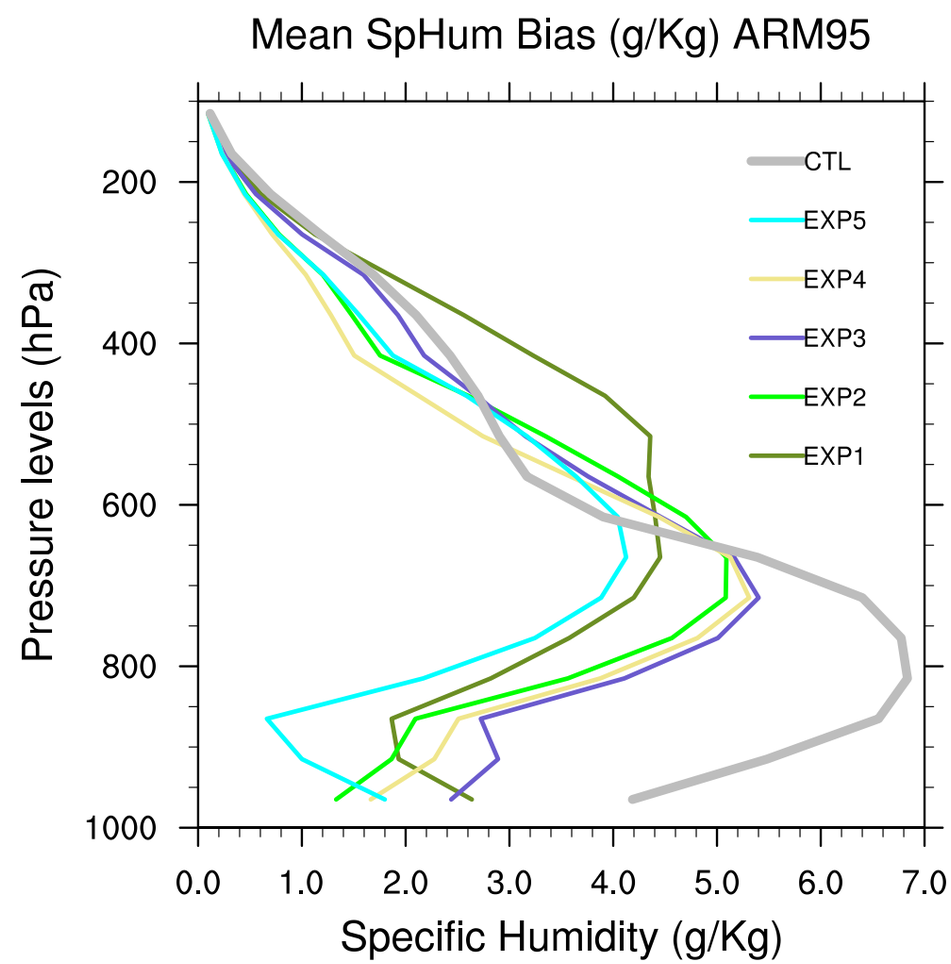
Mean T


Mean Temperature Bias (K) GATE
Pressure levels (hPa)
200
400
600
800
1000
-12
-9
-6
-3
0
3
6
Temperature (K)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

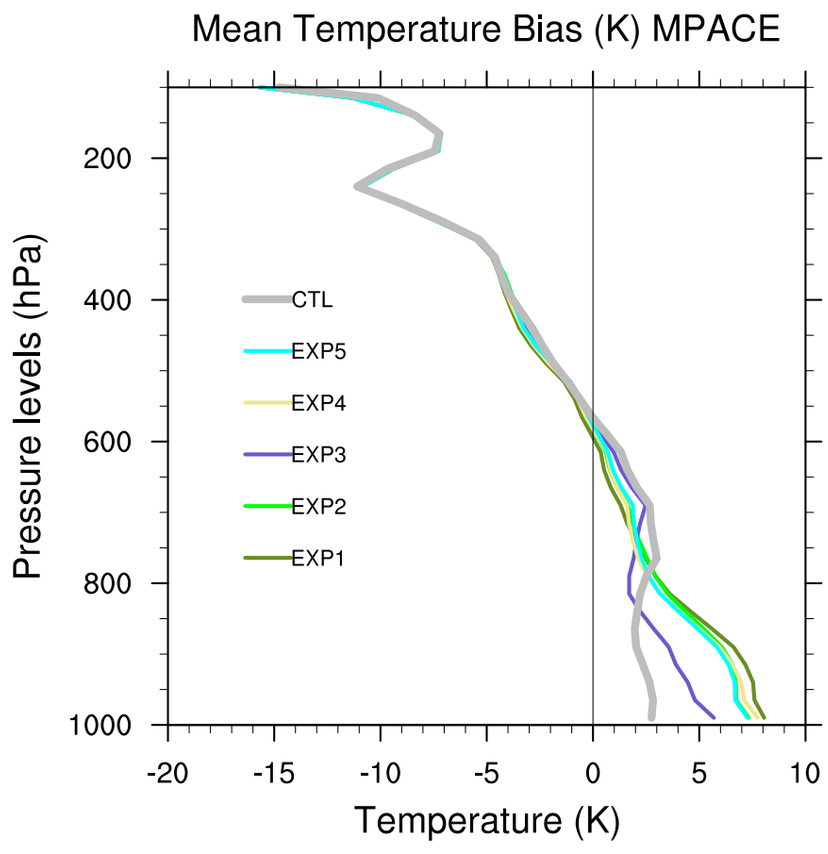

Mean Temperature Bias (K) ARM95
Pressure levels (hPa)
200
400
600
800
1000
4
8
12
16
20
24
28
Temperature (K)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

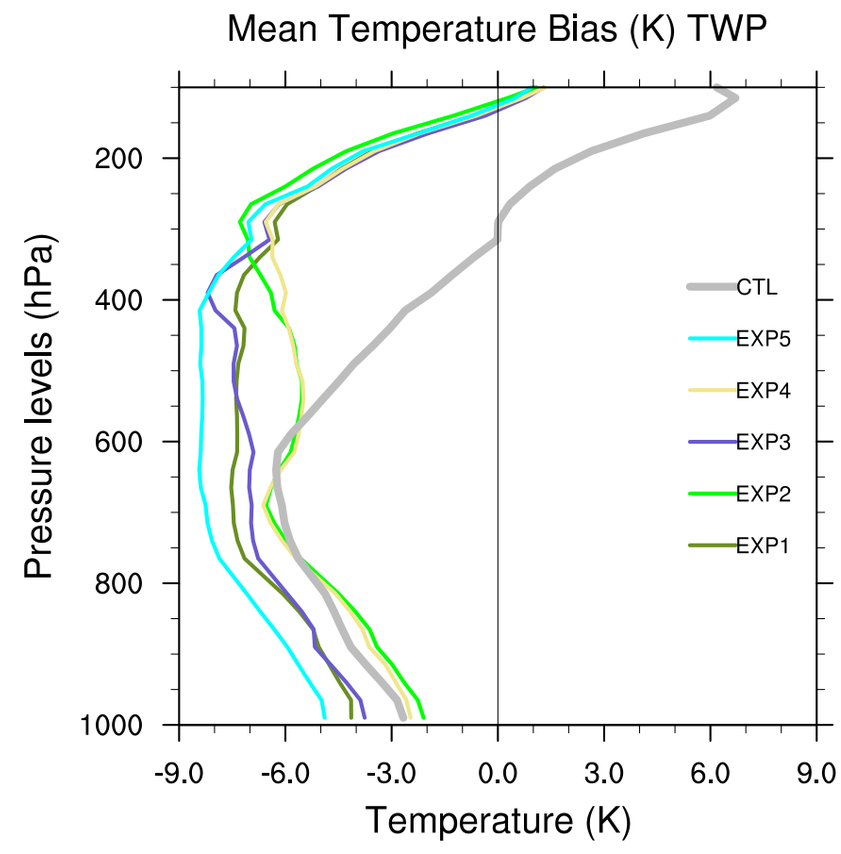
Mean q


Mean SpHum Bias (g/Kg) GATE
Pressure levels (hPa)
200
400
600
800
1000
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
Specific Humidity (g/Kg)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

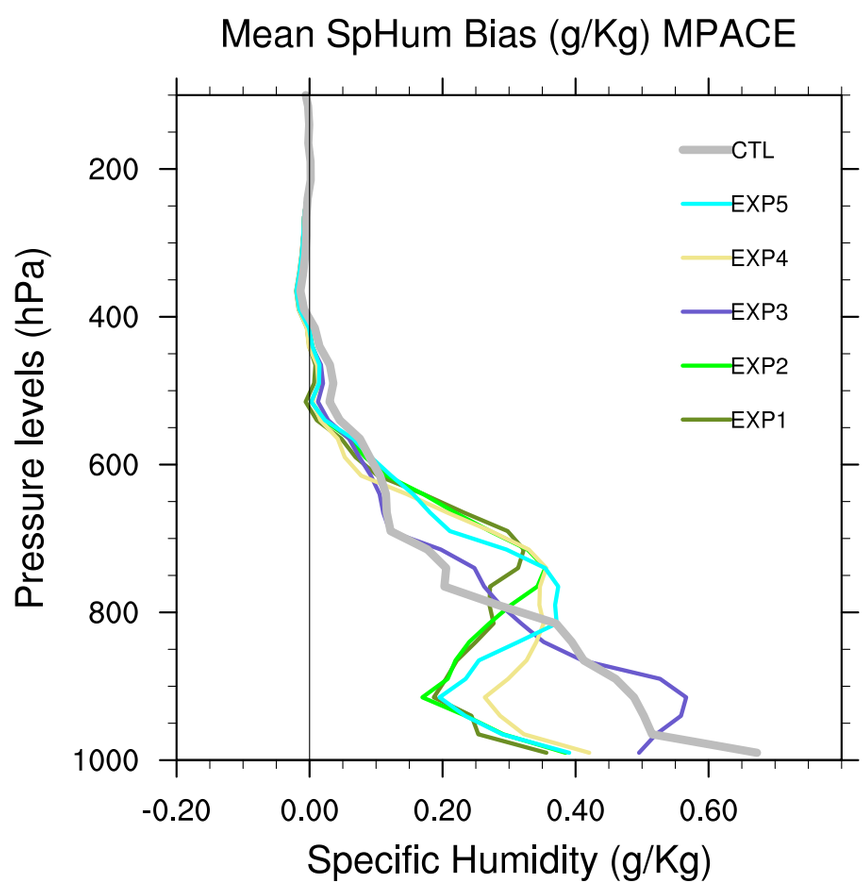

Mean SpHum Bias (g/Kg) ARM95
Pressure levels (hPa)
200
400
600
800
1000
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Specific Humidity (g/Kg)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

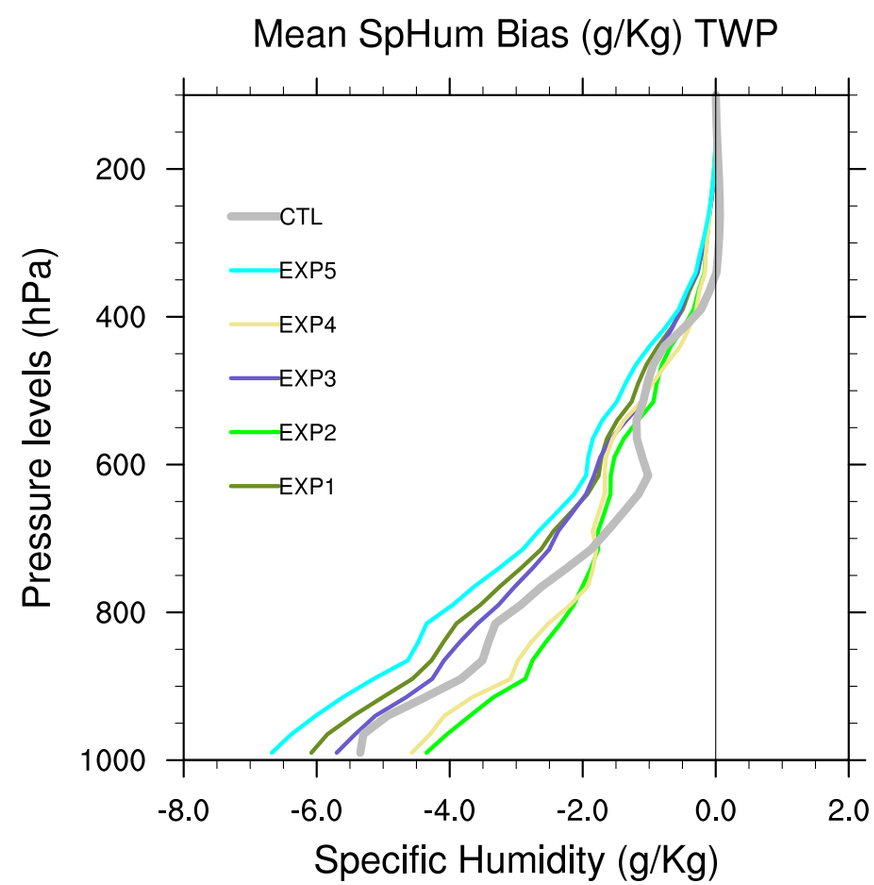
Mean T


Mean Temperature Bias (K) MPACE
Pressure levels (hPa)
200
400
600
800
1000
-20
-15
-10
-5
0
5
10
Temperature (K)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

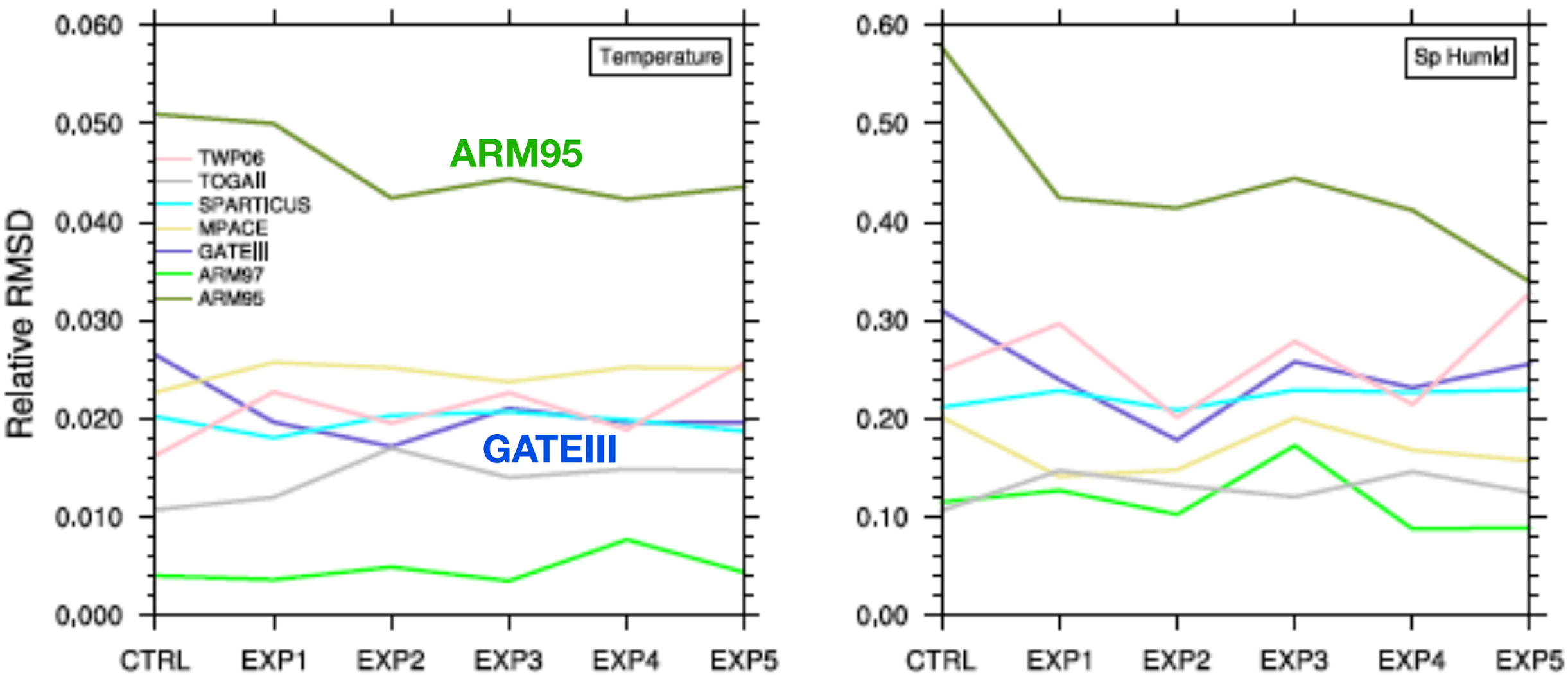

Mean Temperature Bias (K) TWP
Pressure levels (hPa)
200
400
600
800
1000
-9.0
-6.0
-3.0
0.0
3.0
6.0
9.0
Temperature (K)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

Mean q

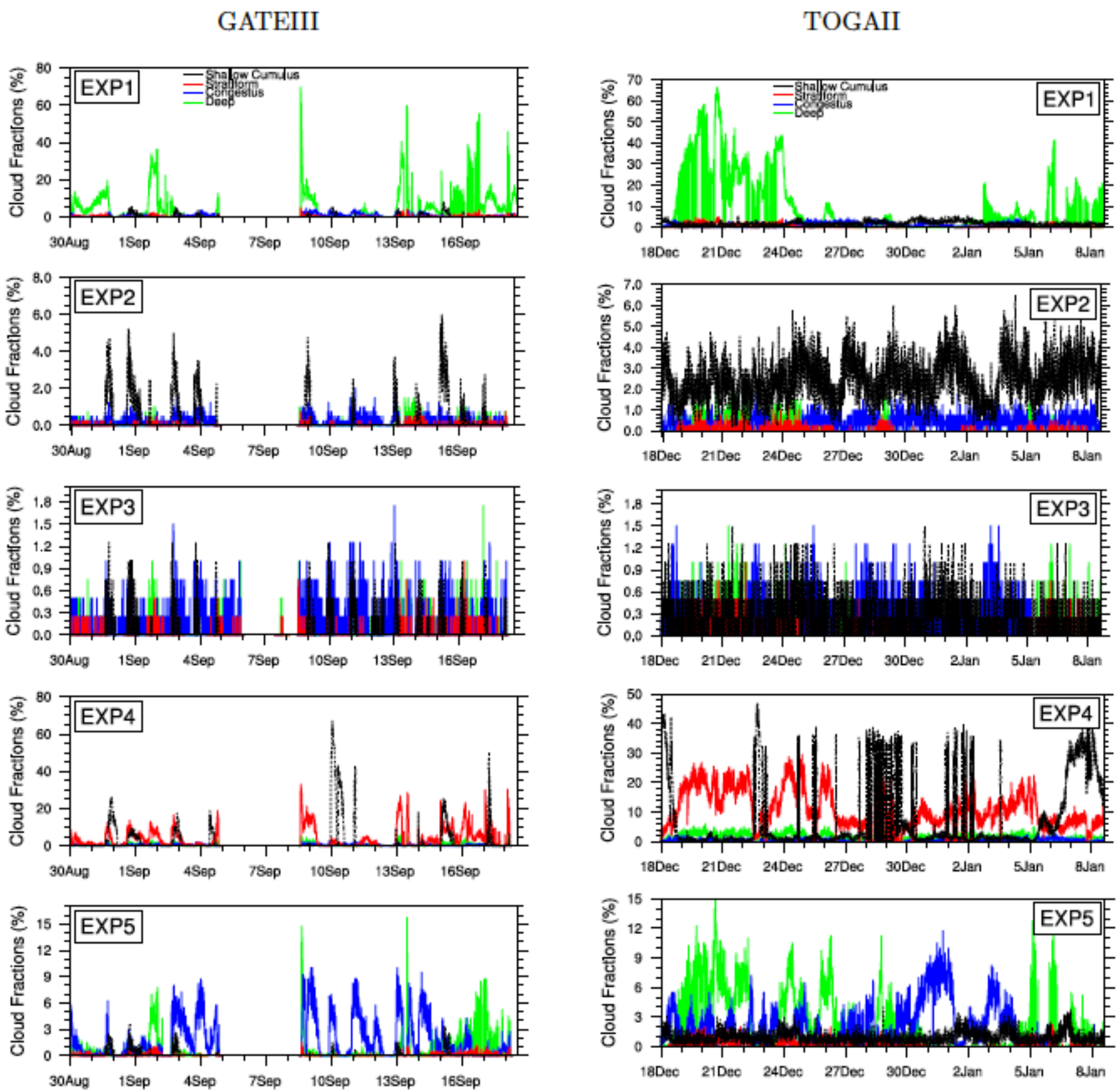

Mean SpHum Bias (g/Kg) MPACE
Pressure levels (hPa)
200
400
600
800
1000
-0.20
0.00
0.20
0.40
0.60
Specific Humidity (g/Kg)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1


Mean SpHum Bias (g/Kg) TWP
Pressure levels (hPa)
200
400
600
800
1000
-8.0
-6.0
-4.0
-2.0
0.0
2.0
Specific Humidity (g/Kg)
CTL
EXP5
EXP4
EXP3
EXP2
EXP1

RMSE over levels



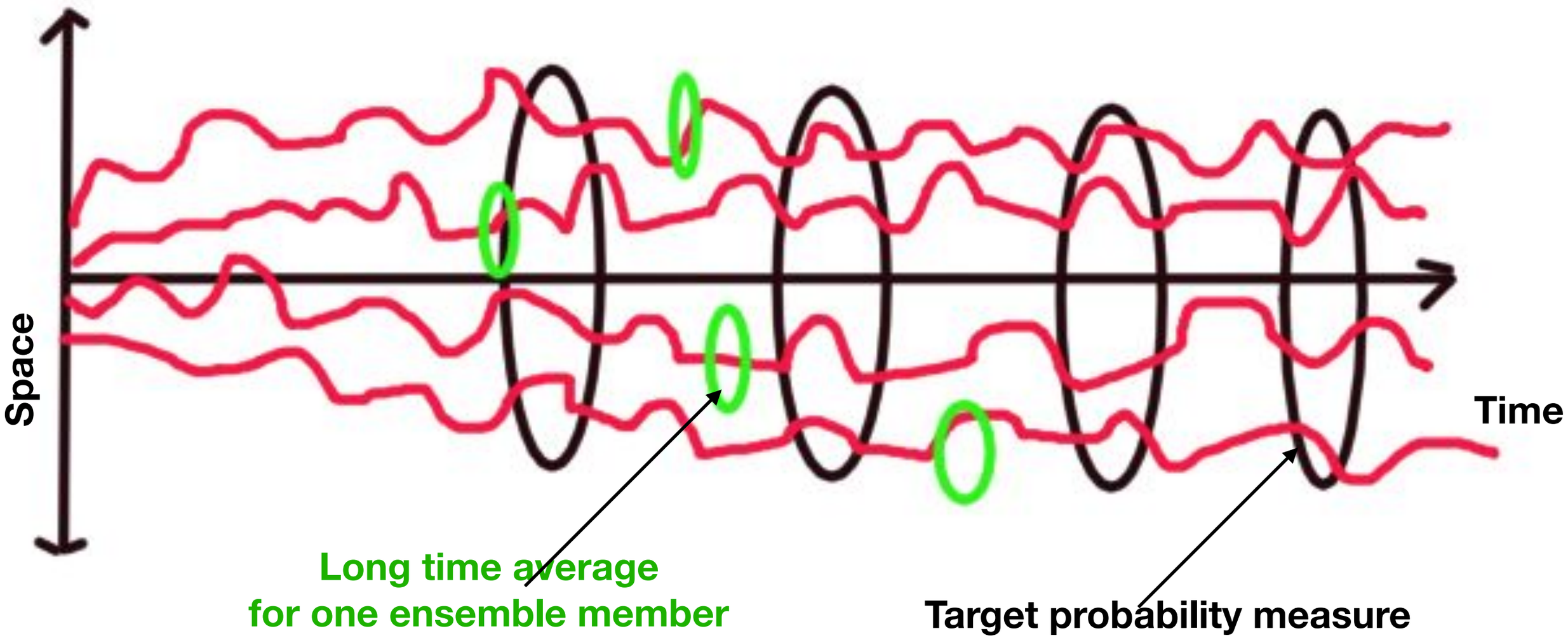
Stochasticity and Model Error



Ensemble simulation with 100 members

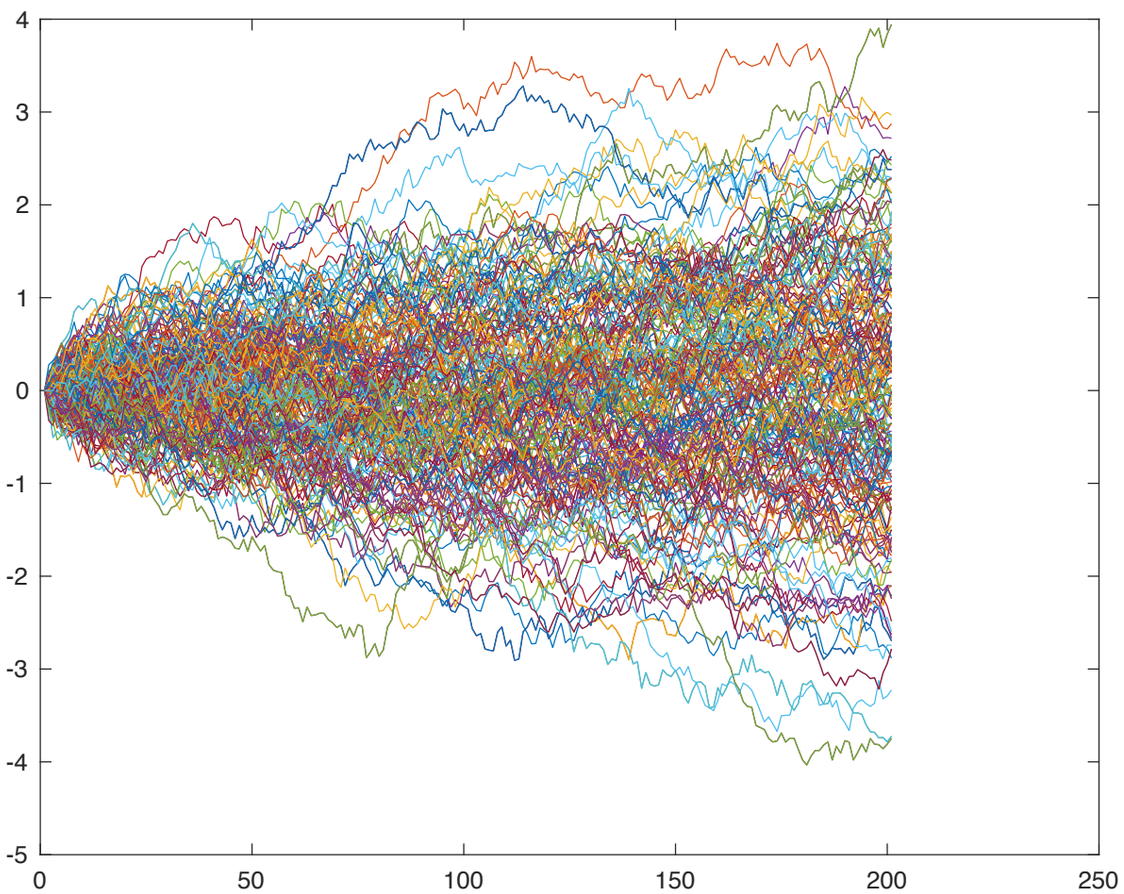
(Change Seed of Random Number generator)

Stochasticity to account for model error in high dimensional systems

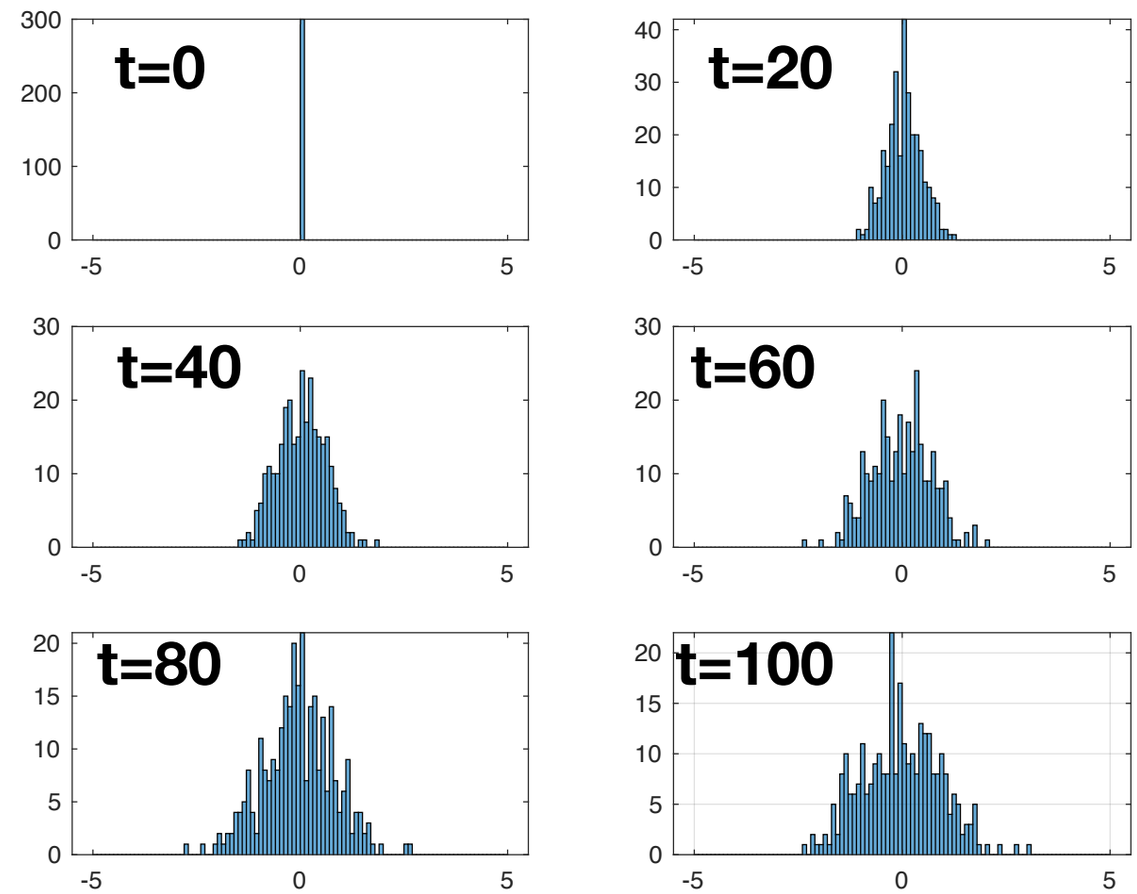


- **Ergodicity valid only for Stationary Distribution Systems**
- **Especially true for Markov process will no or weak mixing!**

Stochastic Representation of Model Error: Brownian Motion

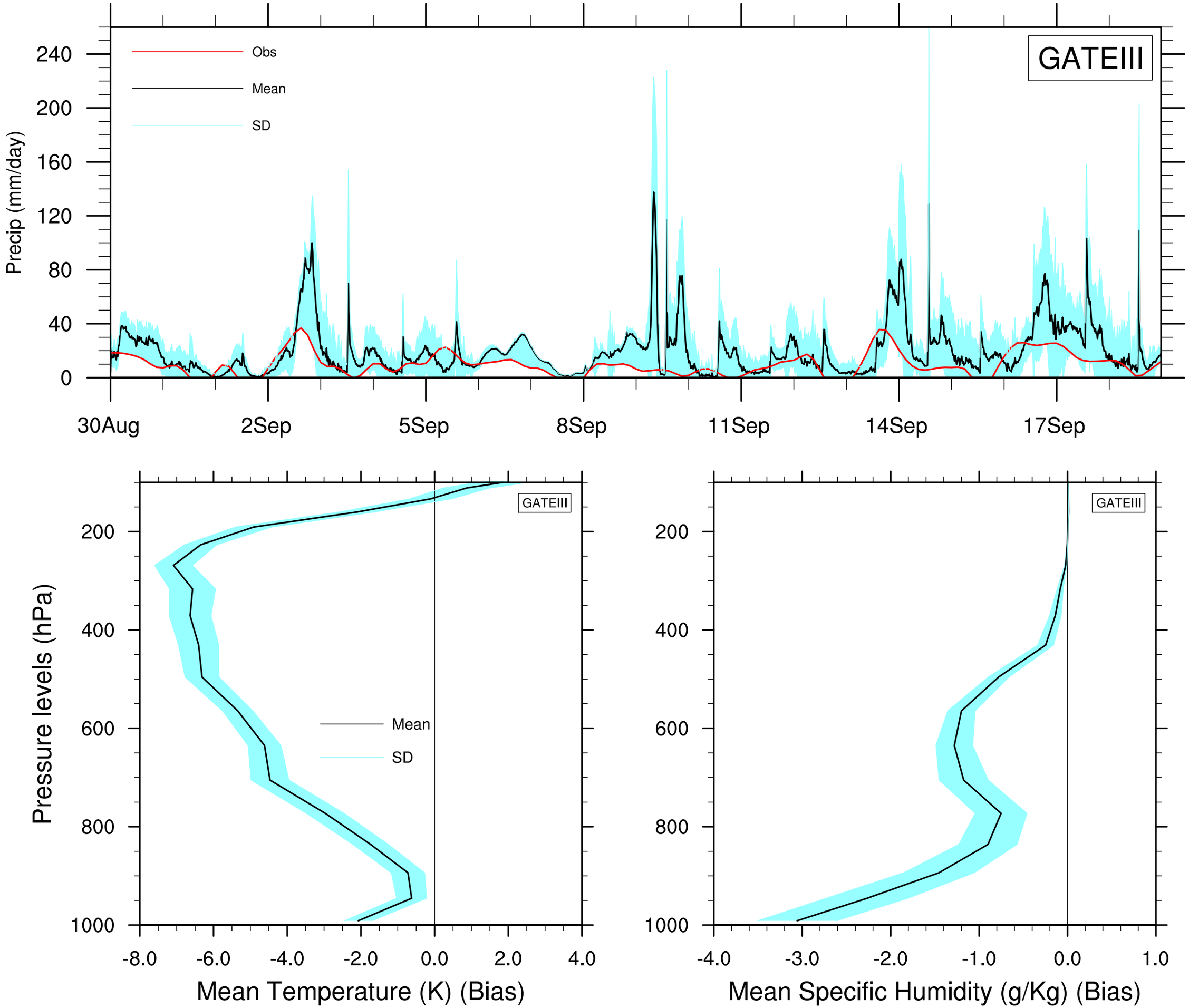


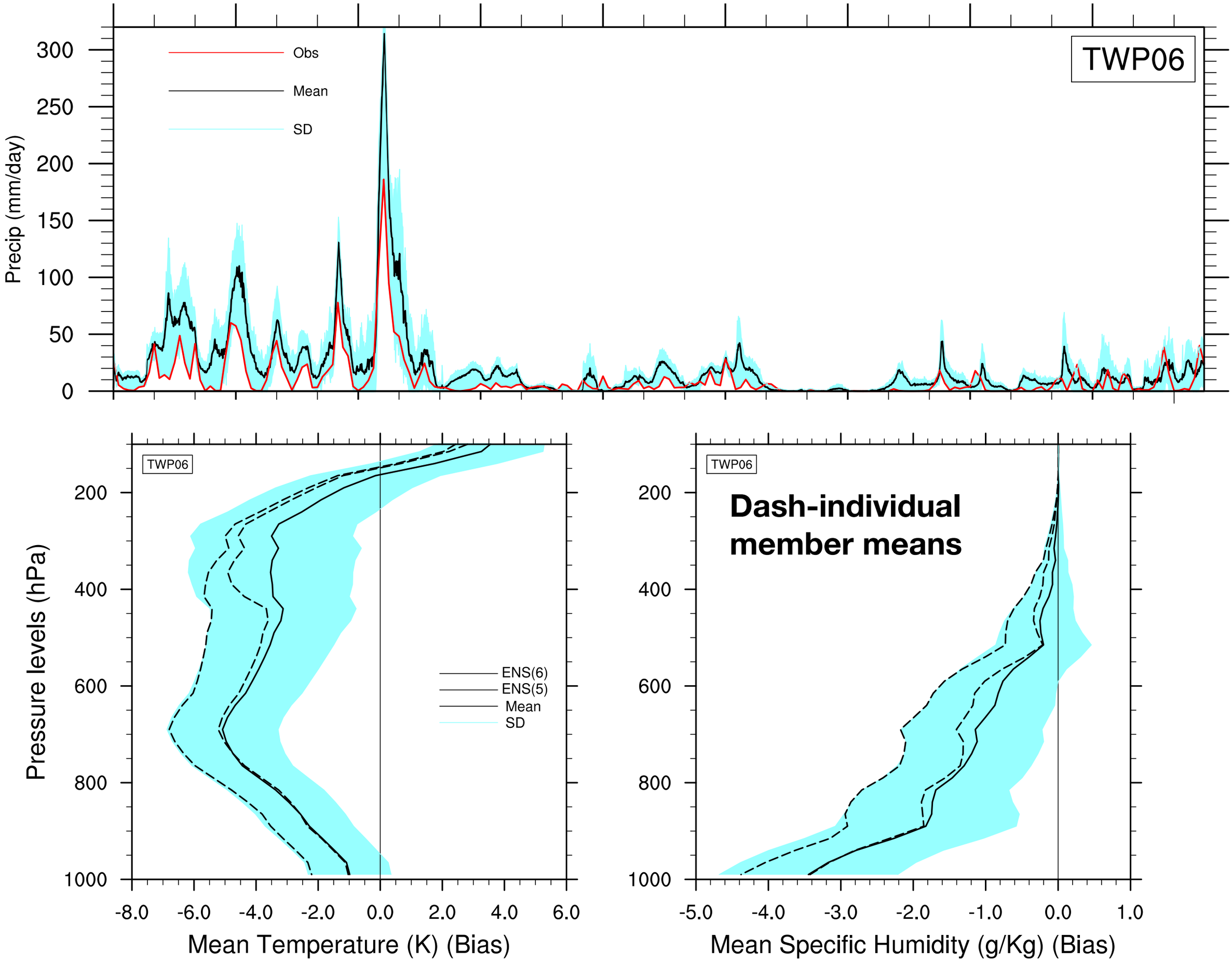
Ensemble of Brownian motion Paths



Evolving Distribution Histograms

Imagine we made only one realization of the Brownian motion?


GATEIII
Obs
Mean
SD
Precip (mm/day)
240
200
160
120
80
40
0
30Aug
2Sep
5Sep
8Sep
11Sep
14Sep
17Sep
GATEIII
Mean
SD
Pressure levels (hPa)
200
400
600
800
1000
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
Mean Temperature (K) (Bias)
GATEIII
200
400
600
800
1000
-4.0
-3.0
-2.0
-1.0
0.0
1.0
Mean Specific Humidity (g/Kg) (Bias)


TWP06
Obs
Mean
SD
Precip (mm/day)
300
250
200
150
100
50
0
TWP06
ENS(6)
ENS(5)
Mean
SD
Pressure levels (hPa)
200
400
600
800
1000
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
Mean Temperature (K) (Bias)
TWP06
Dash-individual
member means
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
Mean Specific Humidity (g/Kg) (Bias)

Conclusion

- SMCM mimics organized tropical convection
- Represents missing subgrid variability in GCMs
- Preliminary implementation of SMCM in CFS is very successful in representing tropical modes of variability: MJO, CCWs, Monsoon variability, LPS's …
- Extended to four cloud types and used to build unified mass-flux scheme: stochastic multicloud plume model (SMPM)
- Validated in Single Column CAM on various test cases of tropical and non-tropical convection: Often beats default ZM control
- Ensemble runs used to demonstrate how stochastic model can be used to take into account model error uncertainty

ZM plume ensemble:

Detrainment levels are uniformly distributed between level of minimum h* and LNB