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

Workshop on multi scale organization of convection

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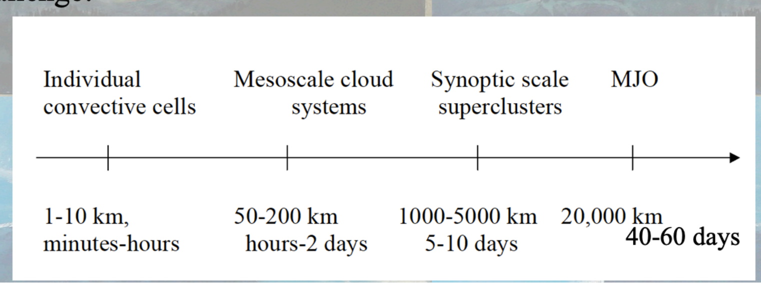
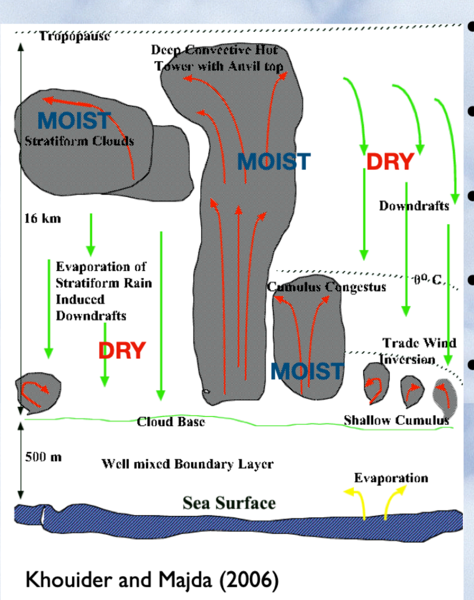
In Memory of Andrew Majda —great collaborator and mentor

Parametrization of 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
- Parameterization of convection and representation of two-way interactions between unresolved processes and large scale waves is a big challenge!



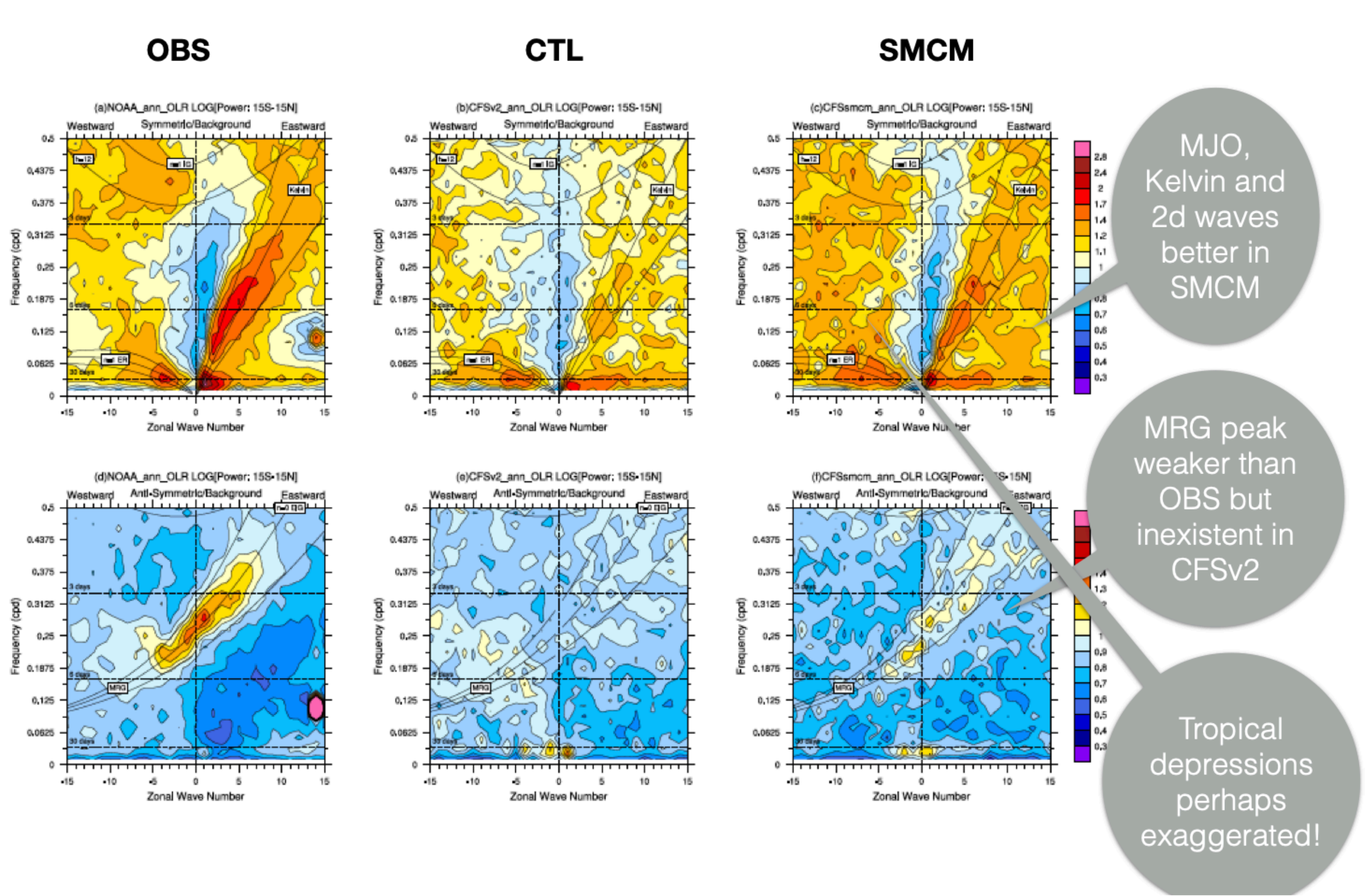
Multicloud—building block model



Khouider and Majda (2006)

- Based on main cloud types of that characterize 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
- Stochastic multicloud models been successfully implemented in both simple and comprehensive GCMs…improved the simulation of convectively coupled waves, MJO, Monsoon variability, and rainfall statistics

Previous Results: SMCM in CFS



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.)

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

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

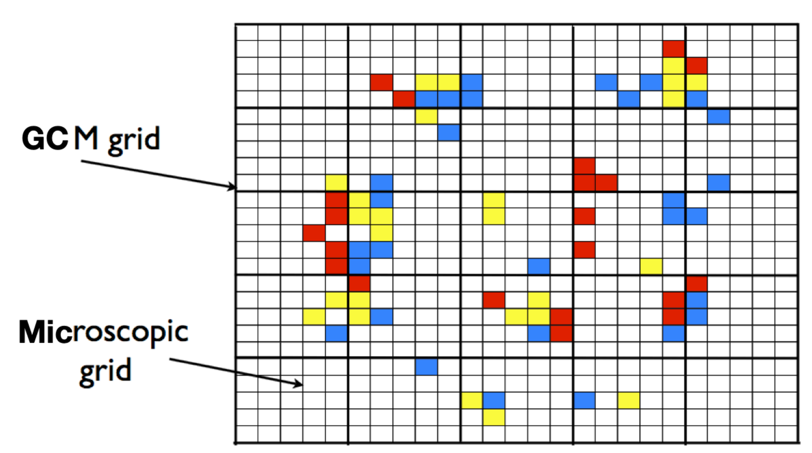
$$m_\lambda(z) = M_b(\lambda) e^{\lambda(z-z_b)}, \quad z_b \le z \le z_\lambda$$

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

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

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

Fine lattice overlaid on GCM Grid

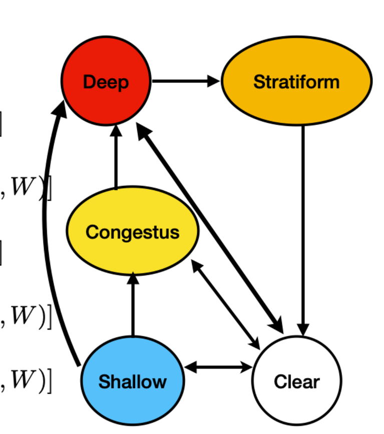


Each lattice site is either occupied by a cloud of certain type or is clear sky…time varying!

Cloud types interact stochastically with each other and with the environment

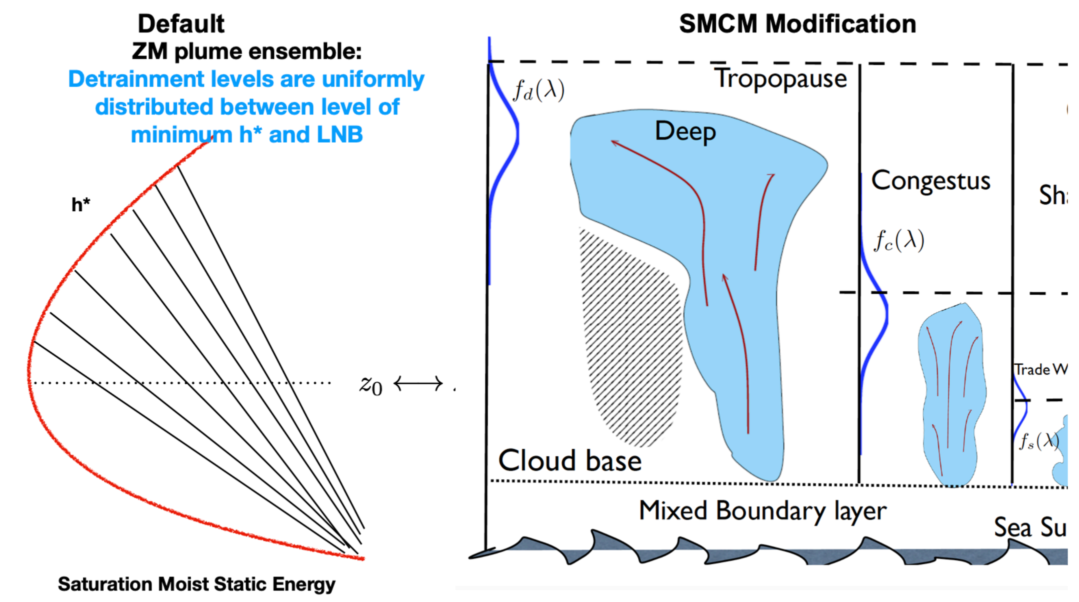
Markovian Model with Transition rates continuously depending on the evolving environment

$$R_{01} = \frac{1}{\tau_{01}} F(C_N, W)$$
$$R_{02} = \frac{1}{\tau_{02}} \Gamma(C_L) * \Gamma(D) * [1 - F(C_N, W)]$$
$$R_{03} = \frac{1}{\tau_{03}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$
$$R_{12} = \frac{1}{\tau_{12}} \Gamma(C_L) * \Gamma(D) * [1 - F(C_N, W)]$$
$$R_{13} = \frac{1}{\tau_{13}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$
$$R_{23} = \frac{1}{\tau_{23}} \Gamma(C) * (1 - \Gamma(D)) * [1 - F(C_N, W)]$$
$$R_{34} = \frac{1}{\tau_{34}}$$



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

Use SMCM to inform detrainment levels in ZM Scheme



Mathematical details

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

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

$\mathrm{Prob}\{P^{\sigma}_{k,n,m} = j | \sigma_{n,m}\}$

$\equiv$ Prob{j plumes of type σ detraining at $z_D \ge z_k$ occur over the site (n, m)}

$=$ Prob{j plumes of type σ detraining at $z_D \ge z_k$ occur over the site (n, m)|d_σ [...]

…. × Prob{$d_\sigma \ge z_k$}.

- Plume number is Poisson distributed (Craig and Cohen, 2006): Mean of each type is set by corresponding cloud ar[...] fraction predicted by SMCM

$$M(z) = \frac{\Lambda M_b}{N_L^2}\int_0^{\lambda_z} e^{\lambda(z-z_b)}\left[N_{sc} f_{sc}(\lambda) + N_c f_c(\lambda) + N_d f_d(\lambda \ldots\right.$$

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

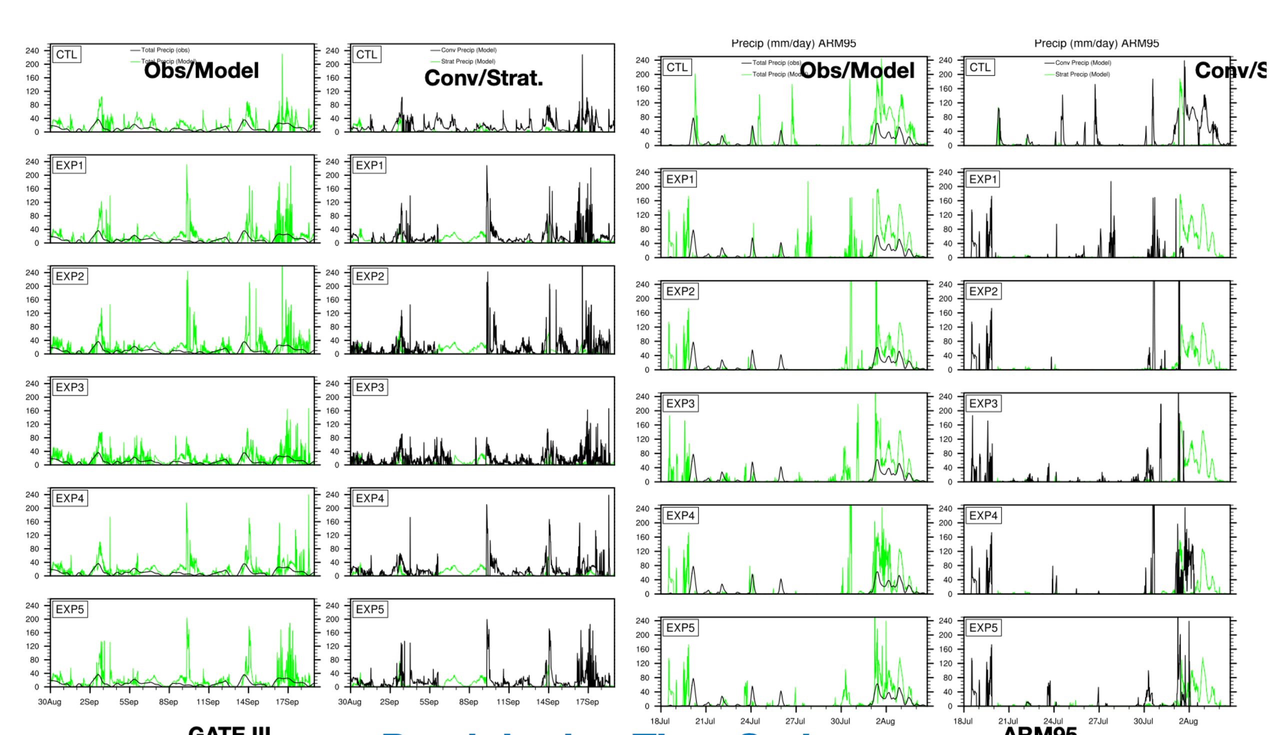
$$= \frac{\Lambda M_b}{M(z)}\int_0^{\lambda_z} \lambda e^{\lambda_z(z-z_b)} f(\lambda) d\lambda + \frac{\Lambda M_b}{M(z)} e^{\lambda_z(z-z_b)} f(\lambda_z)\frac{d\lambda_z}{dz}$$

Entrainment

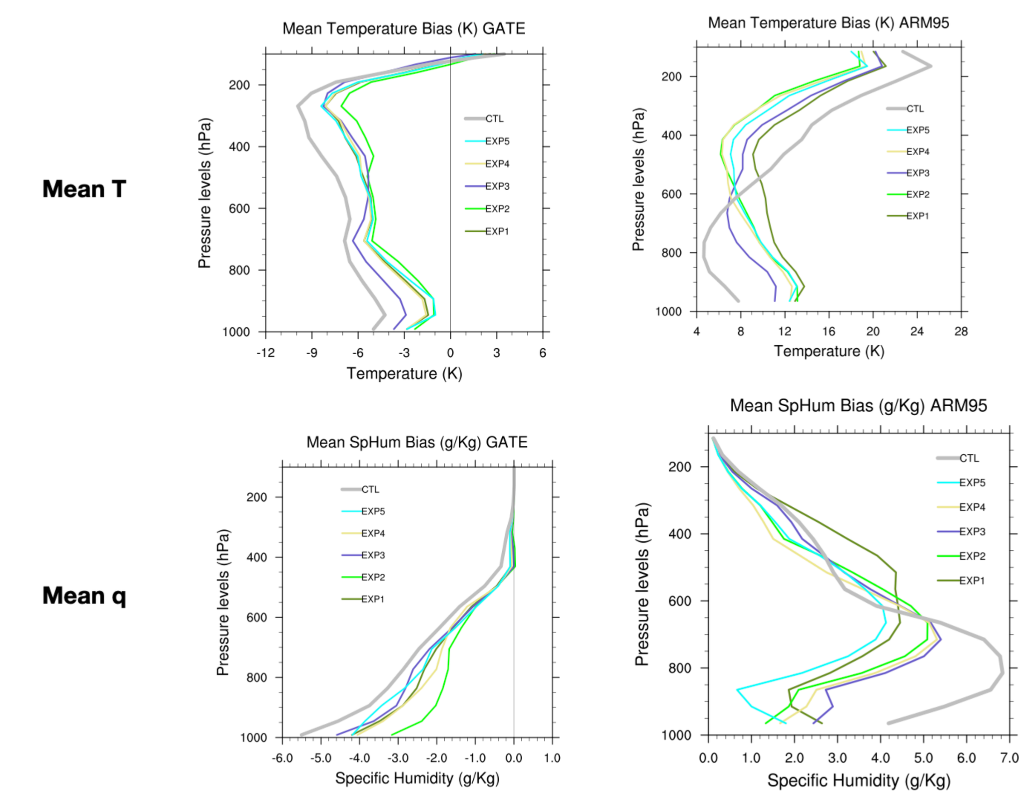
Detrainment

Validation in Single Column

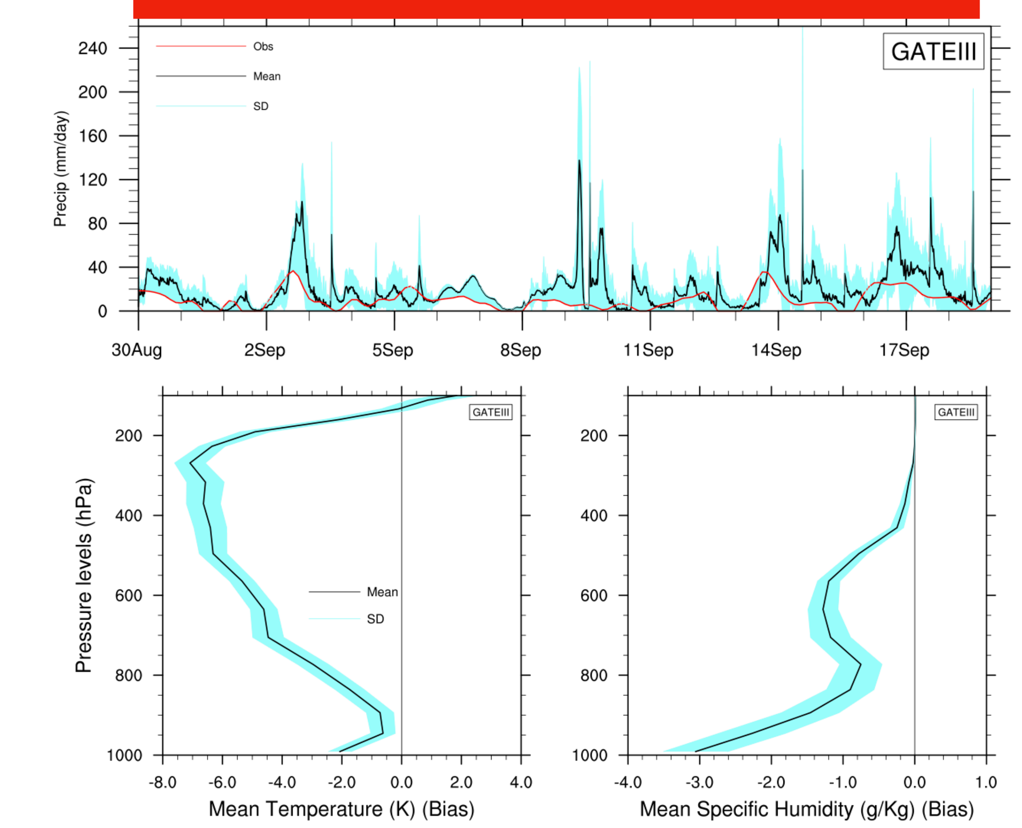
- GATE III: 4 prominent squall lines (Houze & Rappaport, convective envelopes with trailing stratiform decks
- TOGA-COARE II: squall lines and isolated convection (F[...] Rutledge 1998).
- TWP-ICE (2006): Passage of MJO/Monsoon Active & Br[...]
- ARM95: 3 distinct weather regimes of mid-latitude land-[...]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

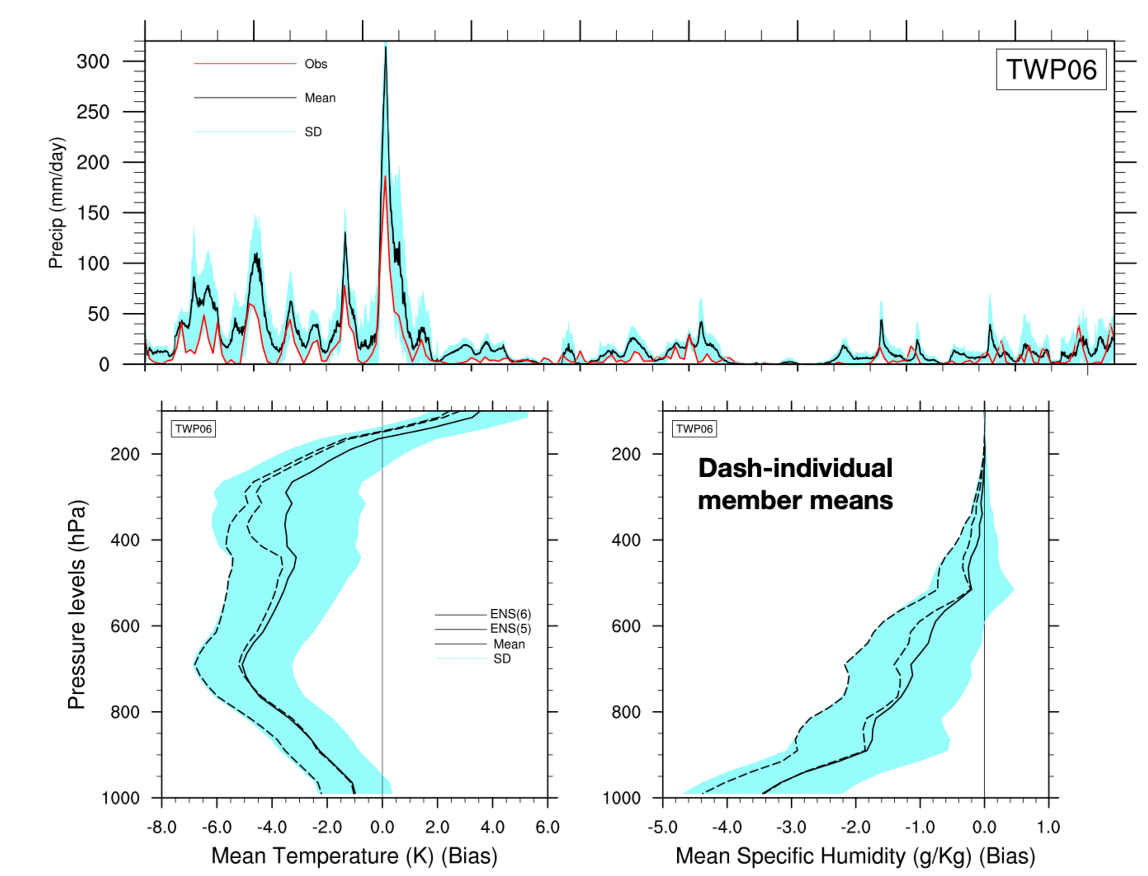


Precipitation Time Series



Ensemble runs; Changing Seed in Random number generator





Conclusion

- SMCM mimics organized tropical convection
- Represents missing subgrid variability in GCMs through stochasticity
- 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 for ensemble runs to take into account model error uncertainty