Improved Tropical Variability in CFS via a Stochastic Multicloud Parameterization

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Introduction

- Despite immense recent progress, coarse resolution GCMs still simulate poorly tropical rainfall

- Instra-seasonal and synoptic variability associated with organized tropical convection are particularly challenging

- Success of cloud permitting and super-parametrization models made it clear that the underlying cumulus parametrization schemes are to blame

- Adequate representation of sub-grid processes associated with organized convection are key in successful simulation of convectively coupled waves, MJO, and monsoon synoptic and ISO variability

- Stochastic parameterizations based on first physical principles can allow a faithful representation of the sub-grid variability associated with organized convection and its interactions across space and time scales

Stochastic Parameterizations

- Quasi-equilibrium hindered deterministic cumulus parameterization to successfully capture tropical variability associated with organized convection
- Stochastic models are used to break the quasi-equilibrium constraint by introducing subgrid variability
- Multiple ways to include stochasticity in models:
  - Statistical dependence: Assume an invariant distribution for small scales which is independent of the large scale state v.s. a distribution of the small scale system continuously changing with the large scale state
  - Scale separation: Does the small scale process reach statistical equilibrium before the large scale state changes or does it not? Are we allowed to take an ensemble of statistically similar plumes during one time step?

Case of Tropical Convection

- Organized tropical convection varies on multiple scales that strongly interact with each other
- Thus, if this is what one is targeting, then the stochastic parameterization must have (1) its distribution continuously changing with the large scales and (2) the small scales do not settle down before the large scale state changes
- No 2 is hard to implement in practice, however Markov Chain Monte Carlo provides and easy way to approximate this behavior by considering the GCM +Stochastic parameterization as one giant single stochastic system

Examples of Stochastic Parameterizations

- Stochastically Perturbed Parameterization Tendencies (Buizza et al. ,2000): Improve ensemble spread in ECMWF Ensemble Prediction System. Imposed invariant distribution.
- Kinetic Energy Back Scatter (Shutts et al.): Cellular automaton for organized variability at small scales; Used to overcome excessive diffusion (dependence on large scales); Not clear whether its implementation assumes scale separation

- Lin and Neelin (~2001): Introduce stochastic noise in CAPE closure of Zhang-McFarlane scheme to break the quasi-equilibrium assumption: Distribution is independent on large scale state

- Plant and Craig (2008): Equilibrium stat-mech to derive equilibrium distribution (Poisson) for cloud base mass flux whose mean depends on large scale predictors (such as CAPE): Assume separation of scales

- Despite the criticism, all these parametrizations have resulted in some success of one form or another

- A decent amount of stochastic noise seems to always help make the underlying parameterization (GCM) move away from its comfort zone!

Trimodality of cloud morphology

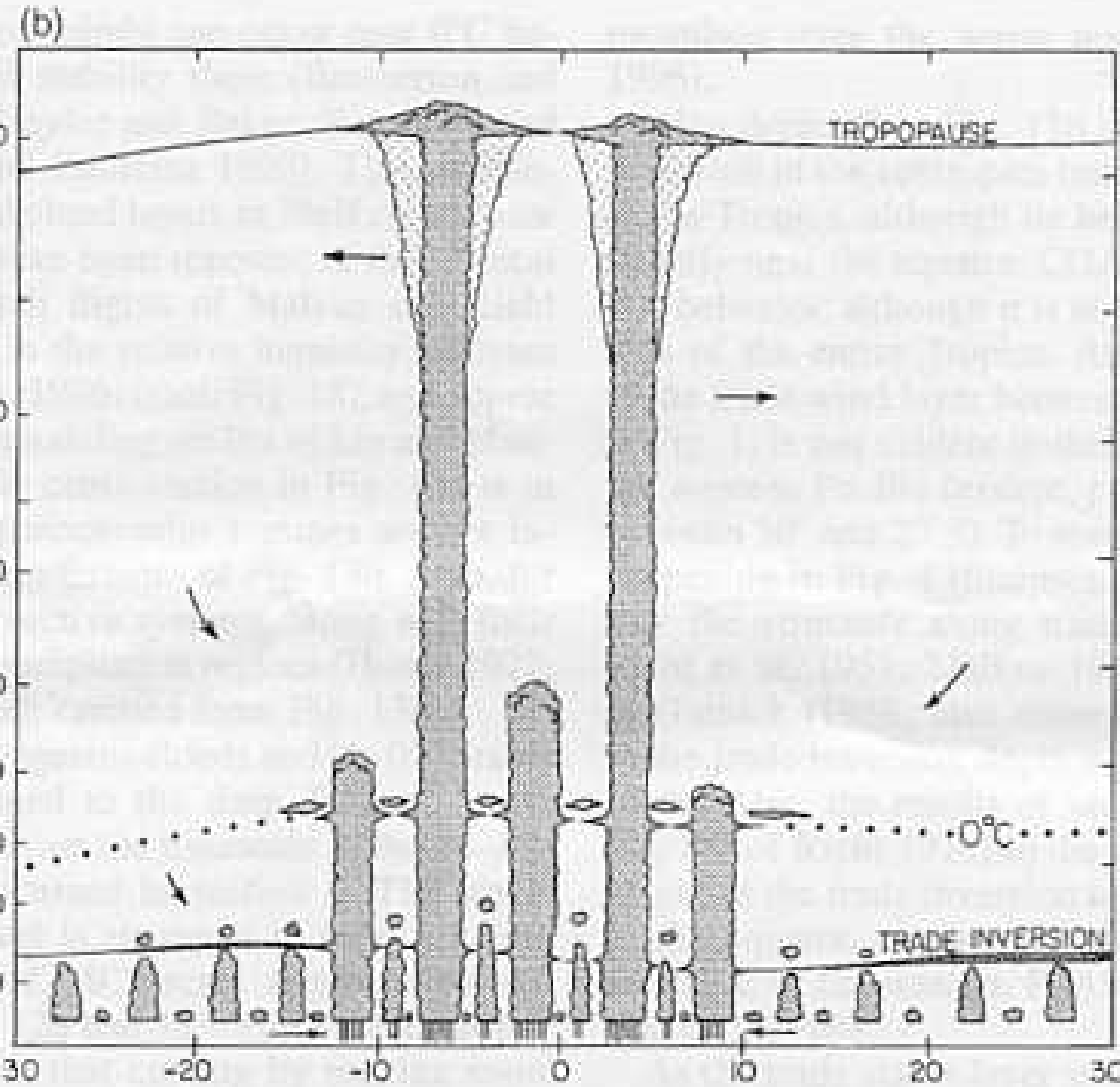


FIG. 13. (*Continued*) cloud types are indicated: shallow cumulus, cumulus congestus, and cumulonimbus. Within the shallow cumulus classification, there are two subdivisions: forced and active cumulus. Three stable layers are indicated: the trade inversion, the 0°C layer, and the tropopause. Shelf clouds 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

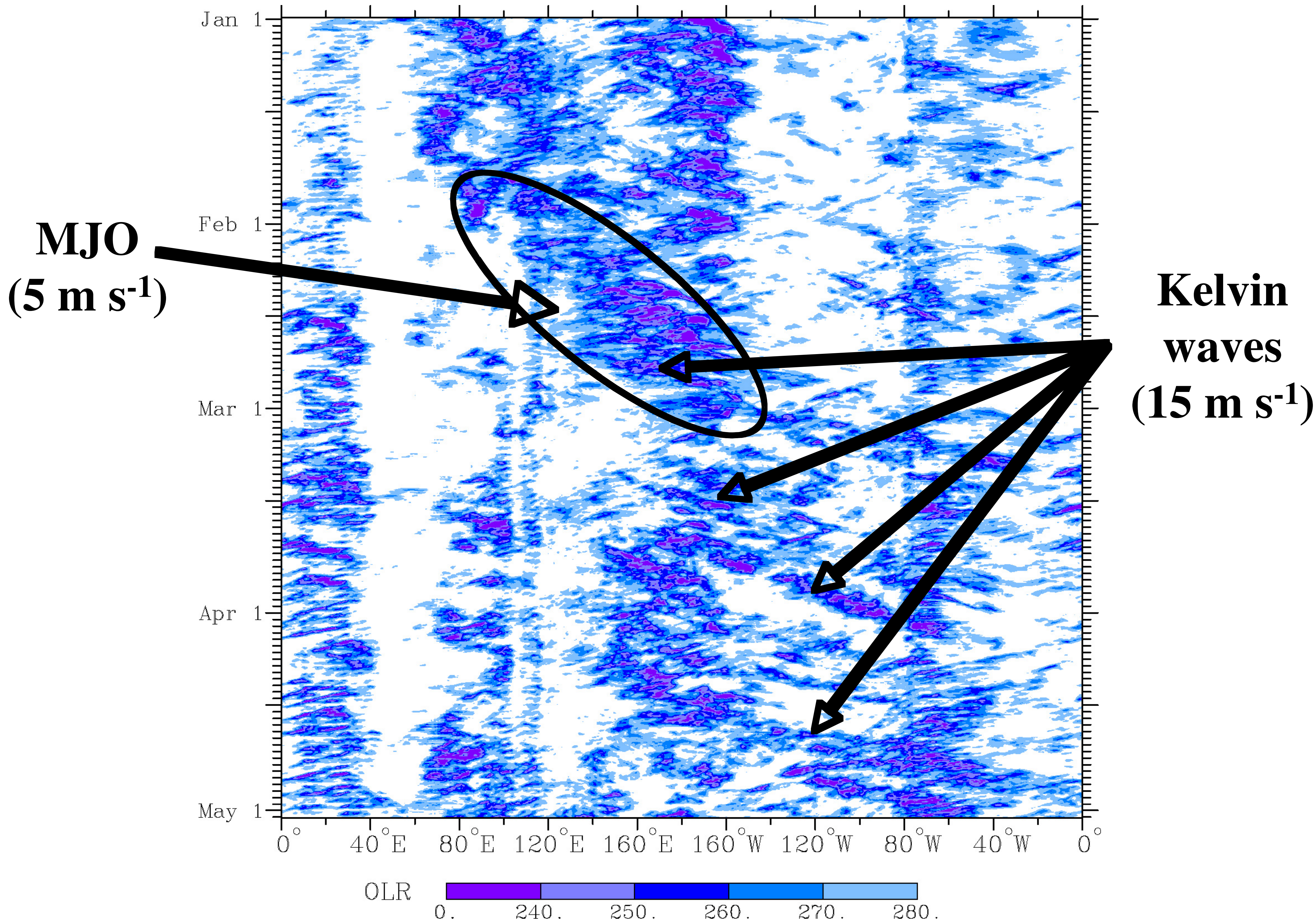
…, which characterize tropical convective systems at multiple scales

Johnson et al. 1999

Hierarchy of Scales

OBSERVATIONS OF KELVIN WAVES AND THE MJO

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

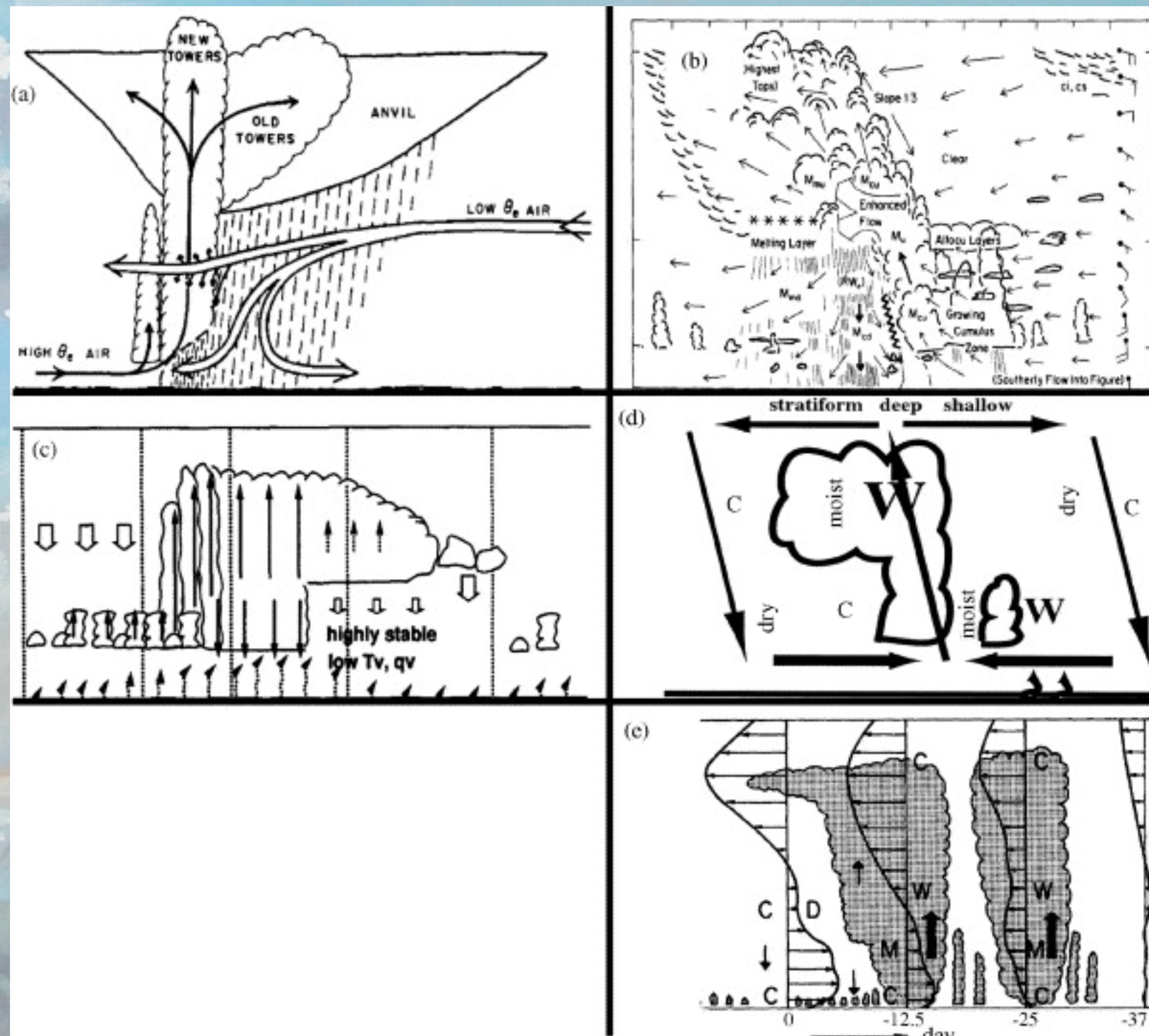


Multiscale self-similar convective systems often embedded in other like Russian dolls.

Squall lines

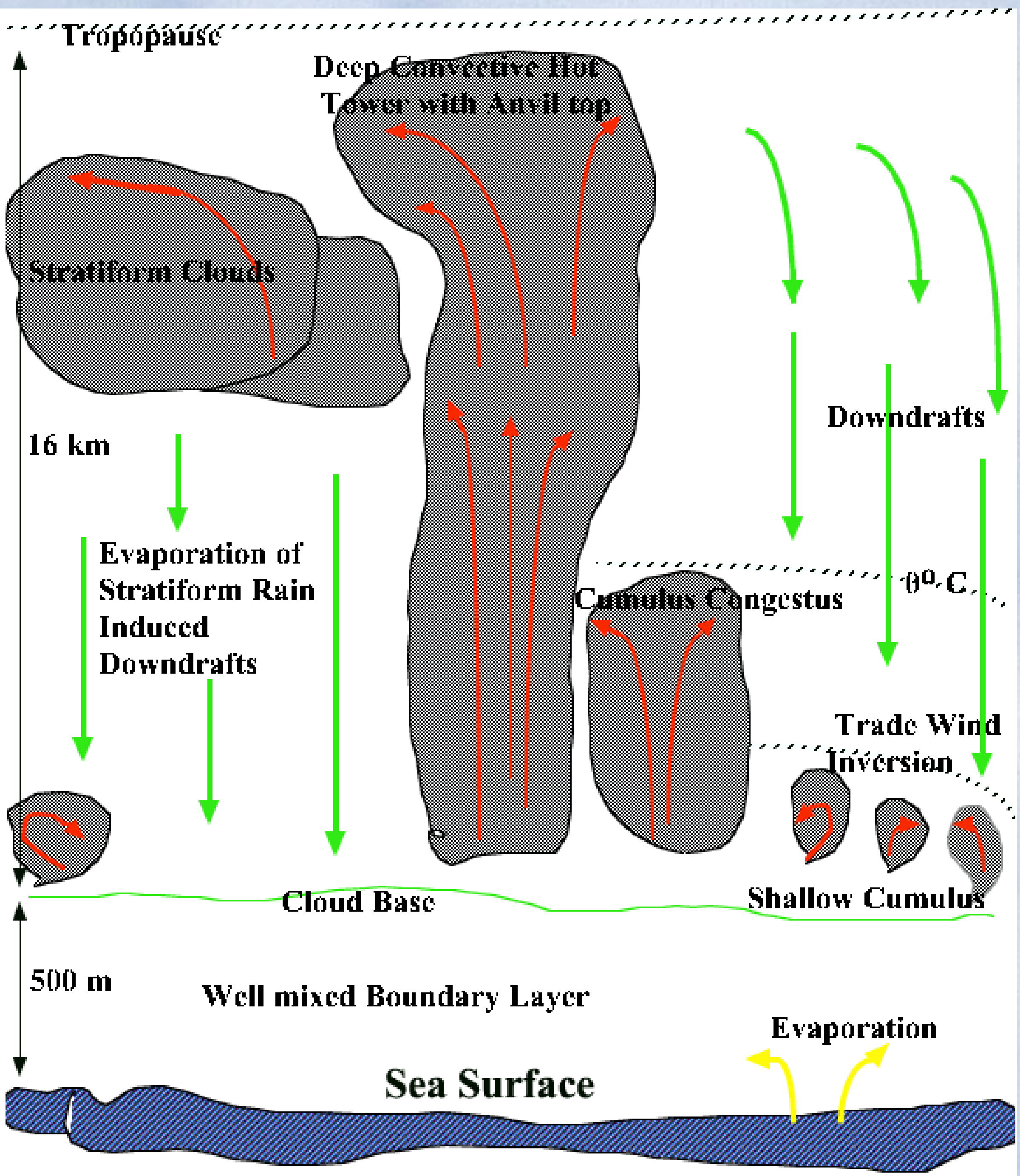
C.C.W.

M.J.O.



Compiled by Mapes et al. DAO. 2006

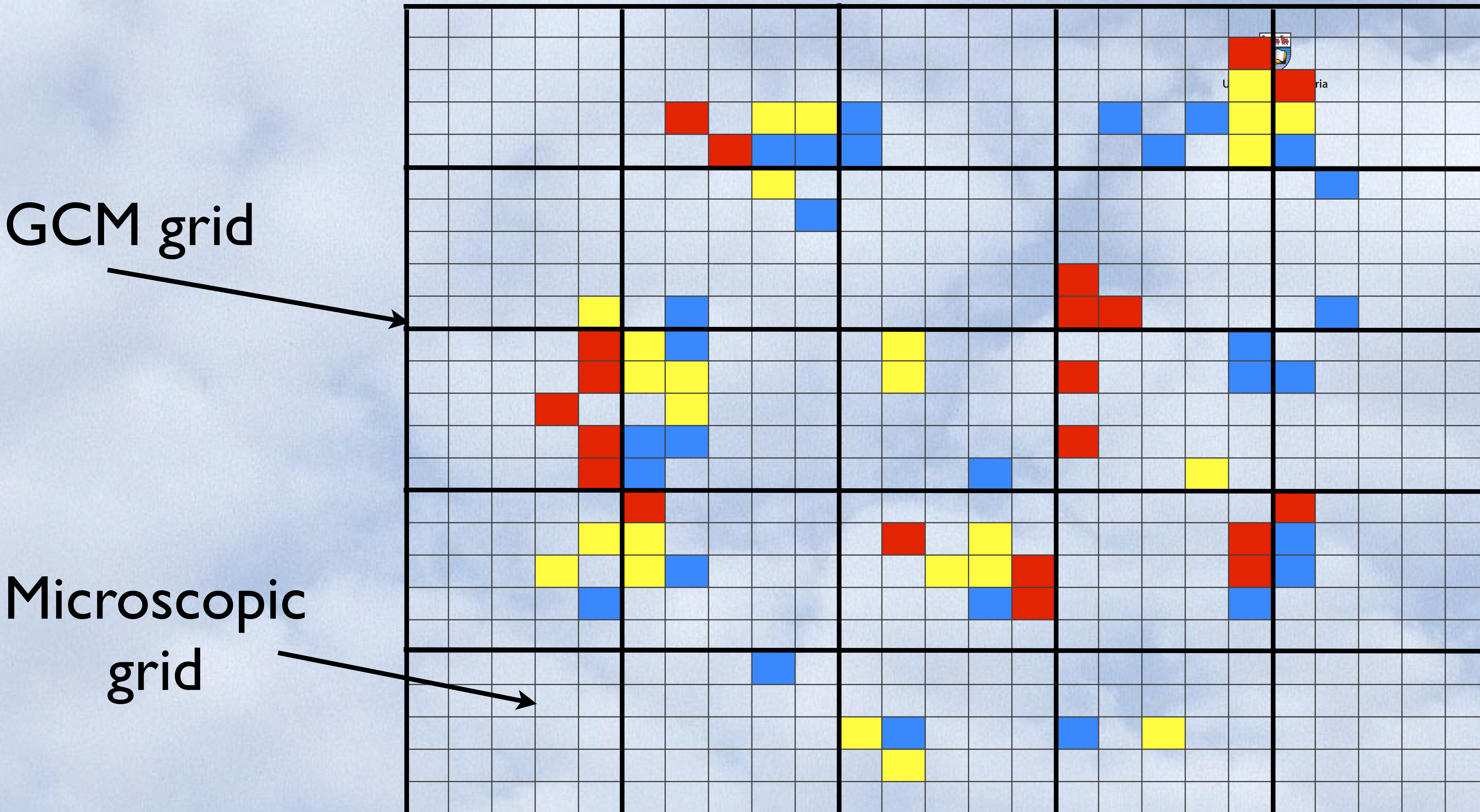
Multicloud model building block



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
- 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)

Lattice Model for Convection



Lattice points 1-10 km apart. Occupied by a certain cloud type (congestus, deep, stratiform)or is a clear sky site.

Transition probabilities depend on large scale predictors

- A clear sky site turns into a congestus site with high probability if CAPE>0 and middle troposphere is dry.
- A congestus or clear sky site turns into a deep site with high probability if CAPE>0 and middle 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

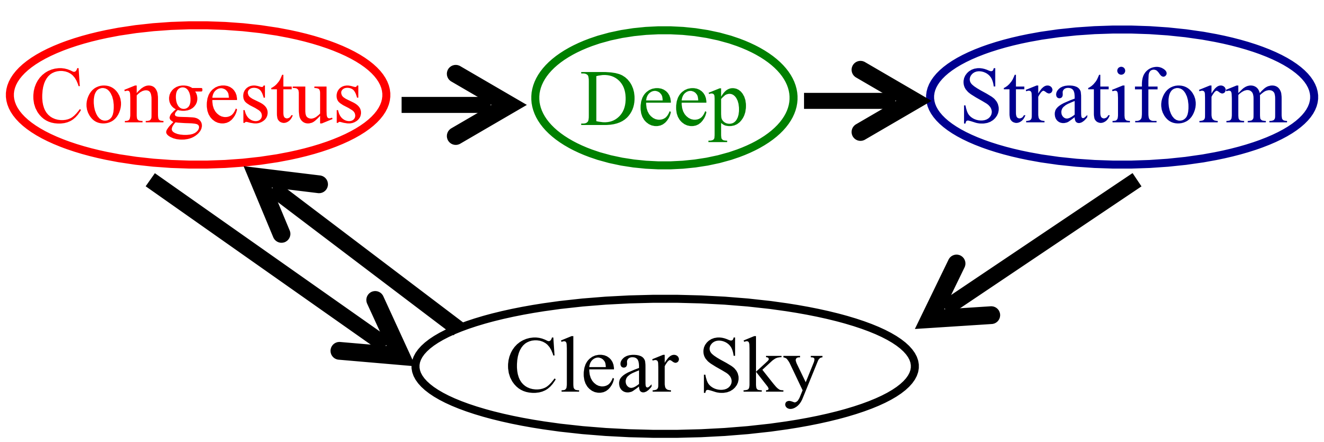
Markov Chain in appearance

- Four state Markov chain at given site

$$\boxed{X_t = \begin{cases} 0 & \text{at clear sky site} \\ 1 & \text{at congestus site} \\ 2 & \text{at deep site} \\ 3 & \text{at statiform site} \end{cases}}$$

- Prob$\{X_{t+\Delta t} = k | X_t = l\}$ = $R_{lk}\Delta t + O(\Delta t^2), l \neq k$

$$R_{kl} = F(Large\, scales)$$



Transition Rates/time scales

Transition	Transition Rate	Time scale (h)
Formation of congestus	$R_{01} = \frac{1}{\tau_{01}}\Gamma(C_l)\Gamma(D)$	$\tau_{01} = 40\tau_{grid}$
Decay of congestus	$R_{10} = \frac{1}{\tau_{10}}\Gamma(D)$	$\tau_{10} = 1\tau_{grid}$
Conversion of congestus to deep	$R_{12} = \frac{1}{\tau_{12}}\Gamma(C)[1-\Gamma(D)]$	$\tau_{12} = 1\tau_{grid}$
Formation of deep	$R_{02} = \frac{1}{\tau_{02}}\Gamma(C)[1-\Gamma(D)]$	$\tau_{02} = 4\tau_{grid}$
Conversion of deep to stratiform	$R_{23} = \frac{1}{\tau_{23}}$	$\tau_{23} = 3\tau_{grid}$
Decay of deep	$R_{20} = \frac{1}{\tau_{20}}[1-\Gamma(C)]$	$\tau_{20} = 3\tau_{grid}$
Decay of stratiform	$R_{30} = \frac{1}{\tau_{30}}$	$\tau_{30} = 2$ or 5 or $10\tau_{grid}$

$$\Gamma(x) = \begin{cases} 1-\exp(-x), & \text{if } x > 0; \\ 0, & \text{otherwise.} \end{cases} \qquad D = (\theta_{eb} - \theta_{em})/T_0$$

$$CAPE_l = \overline{CAPE} + R[\theta_{eb} - \gamma(\theta_1 + \gamma_2'\theta_2)], \quad C_l = CAPE_l/CAPE_0$$

$$CAPE = \overline{CAPE} + R[\theta_{eb} - \gamma(\theta_1 + \gamma_2\theta_2)], \quad C = CAPE/CAPE_0$$

Cloud area fraction and Equilibrium measure

- When local interactions are ignored, X_t^i, are N independent four state Markov chains with the common equilibrium measure

$$\pi_0 + \pi_1 + \pi_2 + \pi_3 = 1, \pi_1 = \frac{R_{01}}{R_{10} + R_{12}} \pi_0,$$

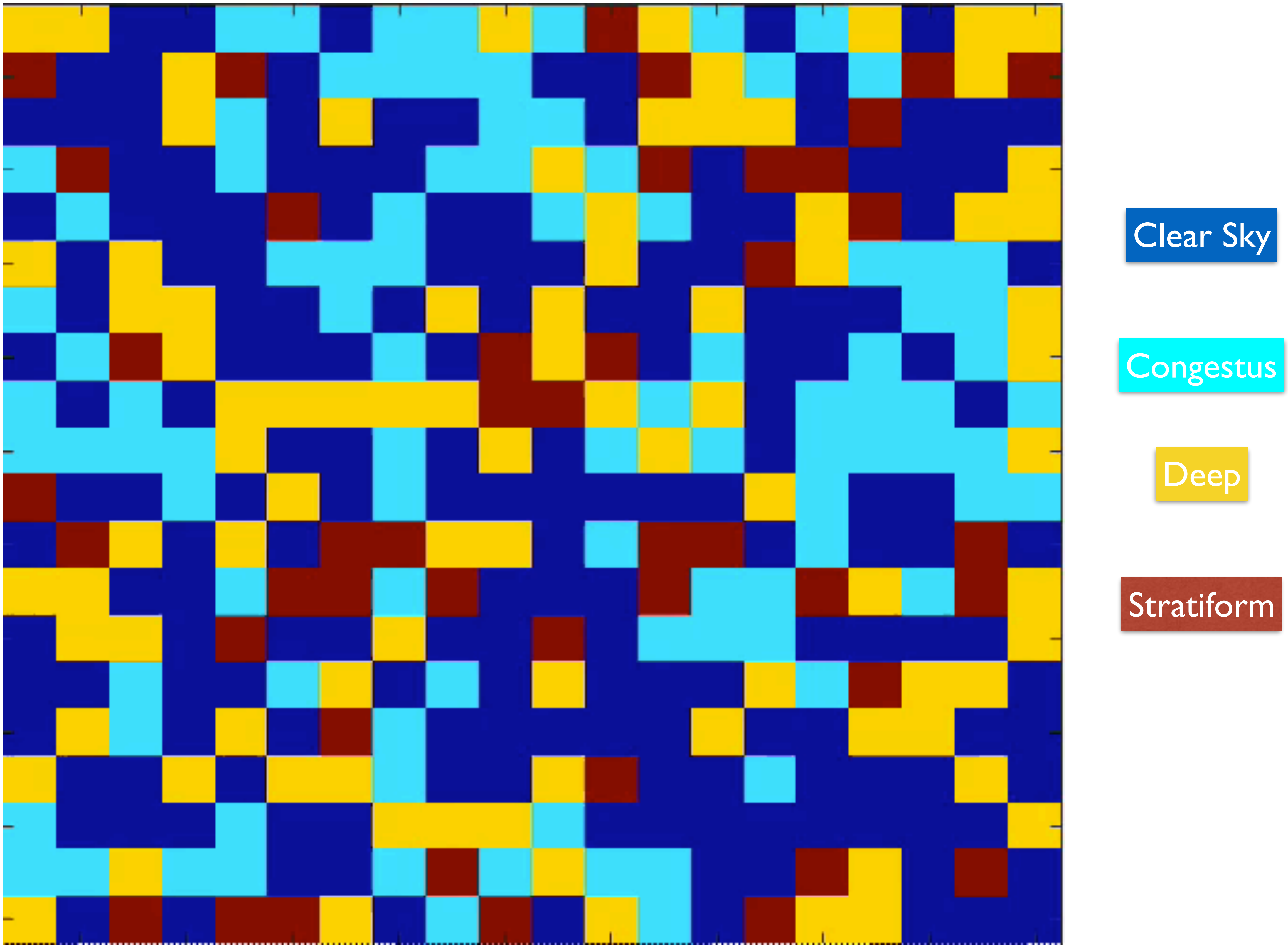
$$\pi_2 = \frac{R_{02}\pi_0 + \pi_1 R_{12}}{R_{20} + R_{23}}, \pi_3 = \frac{R_{23}}{R_{30}} \pi_2$$

- Cloud area fractions on coarse mesh (e.g. congestus)

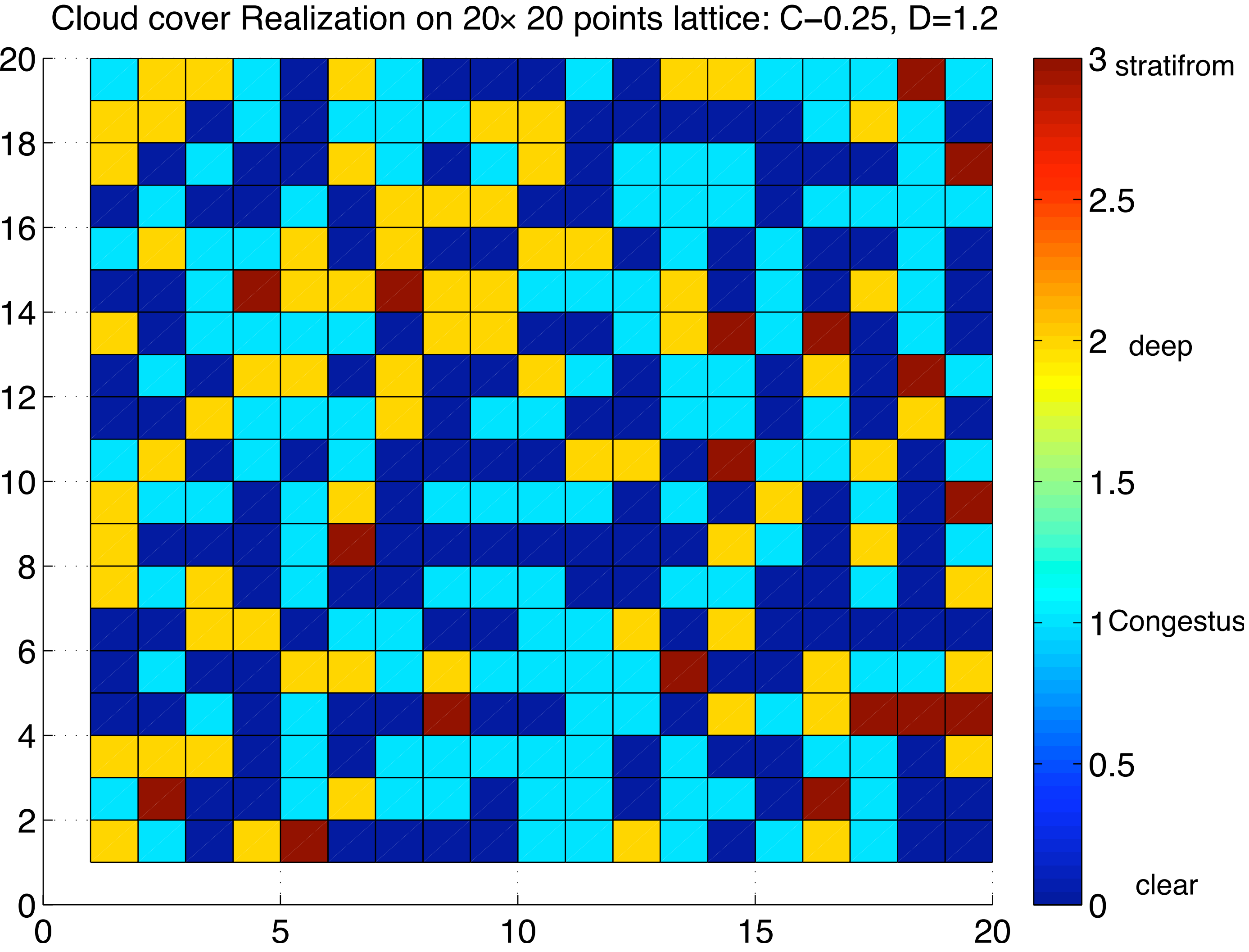
$$N_c^j(t) = \sum_{j \in D_i} \mathbb{I}_{\{X_t^i = 1\}}, \quad \sigma_c^j(t) = \frac{1}{Q} N_c^j(t)$$

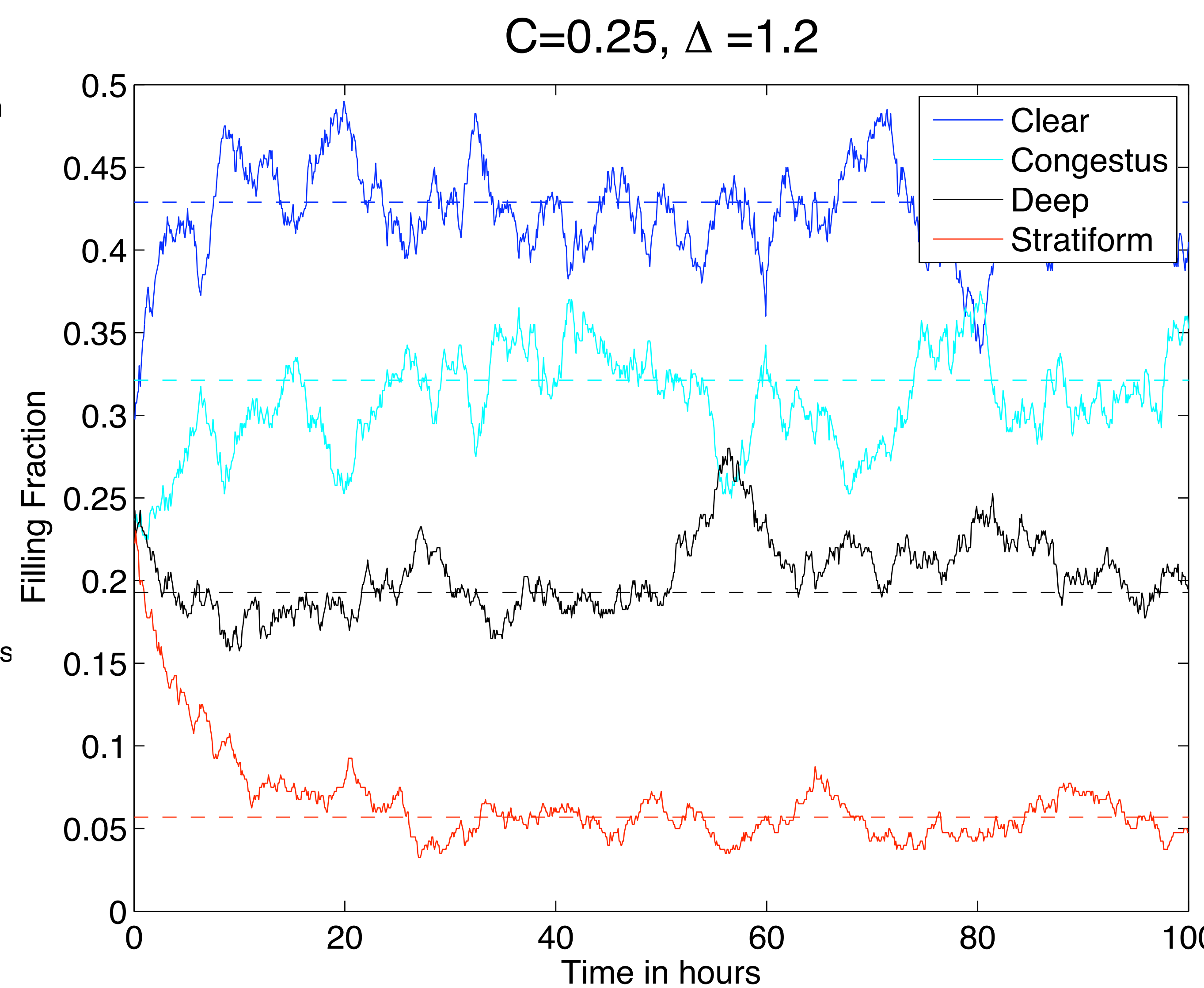
$$0 \le N_c \le Q \qquad E\sigma_c^j(t) = \pi_1(U_j) \text{ at equilibrium}$$

Time evolution of microscopic system with Fixed Large-Scale State

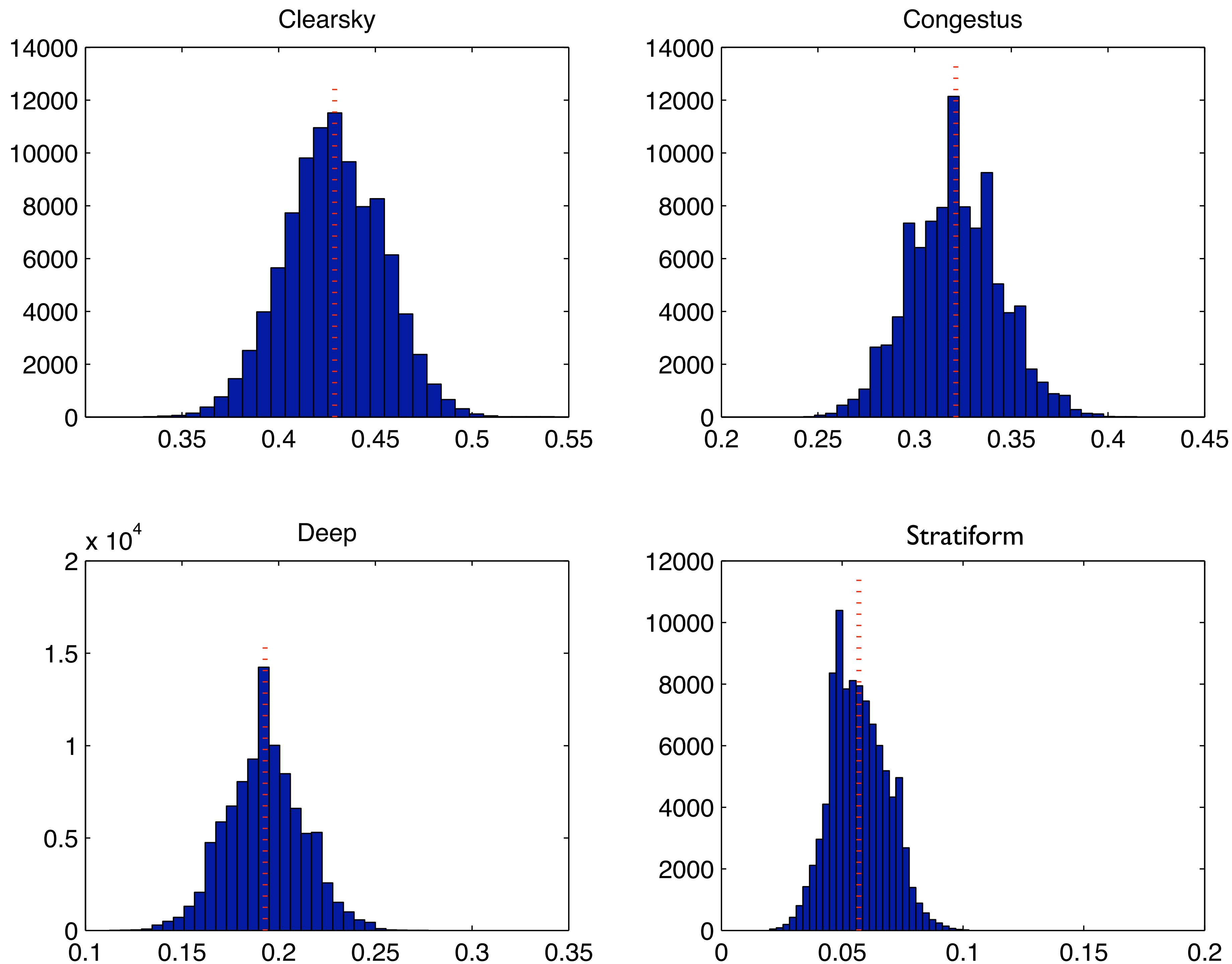


Time evolution and statistics of filling fraction





Bulk Statistics of filling fraction---!!!!!!!!!!!



stoch. mc (uncoupled) CAPE=0.25, Dryness=1.2, dashed==anal. eqilibrium

Proof of Concept: SMCM mimics variability of convection at subgrid-scale

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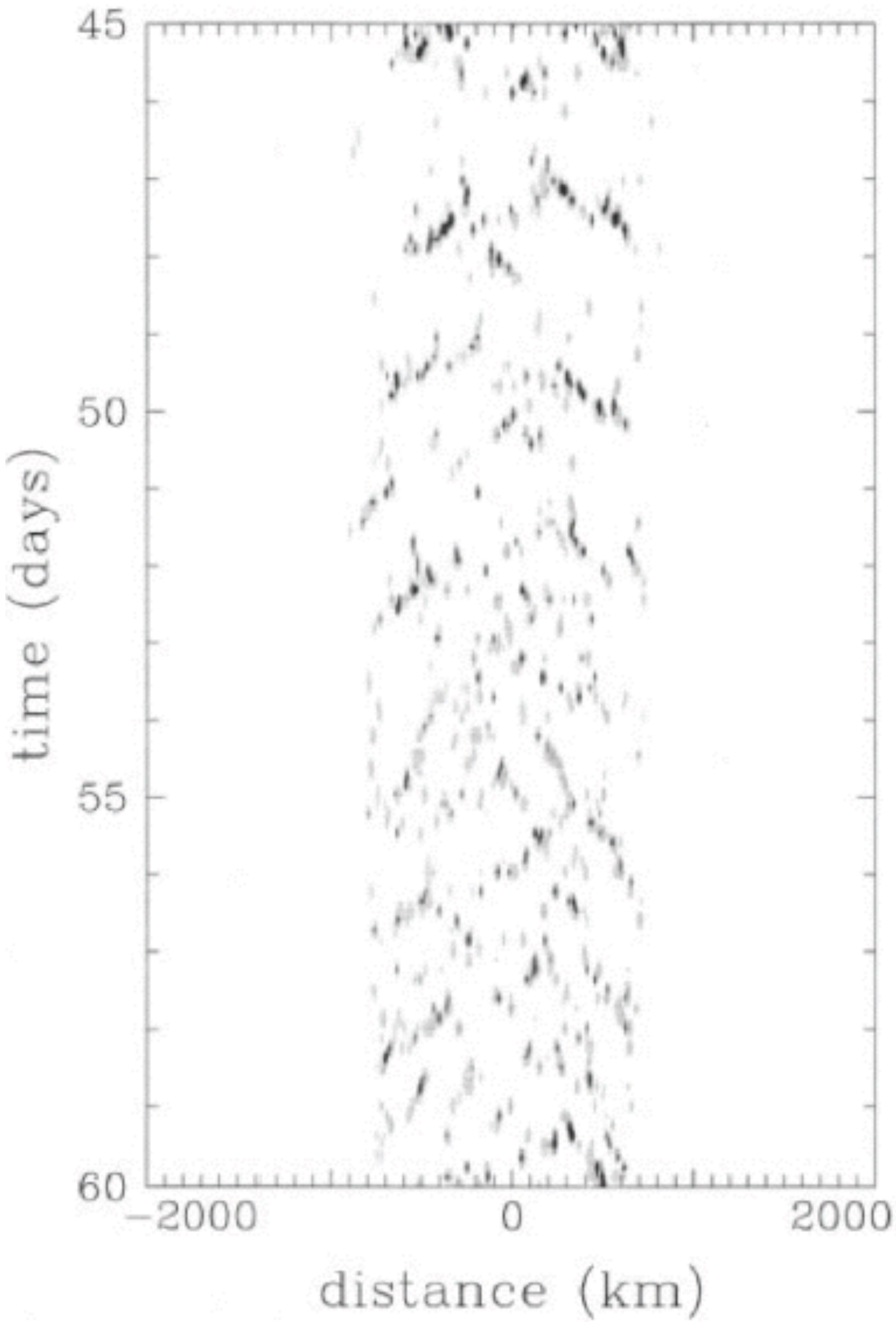
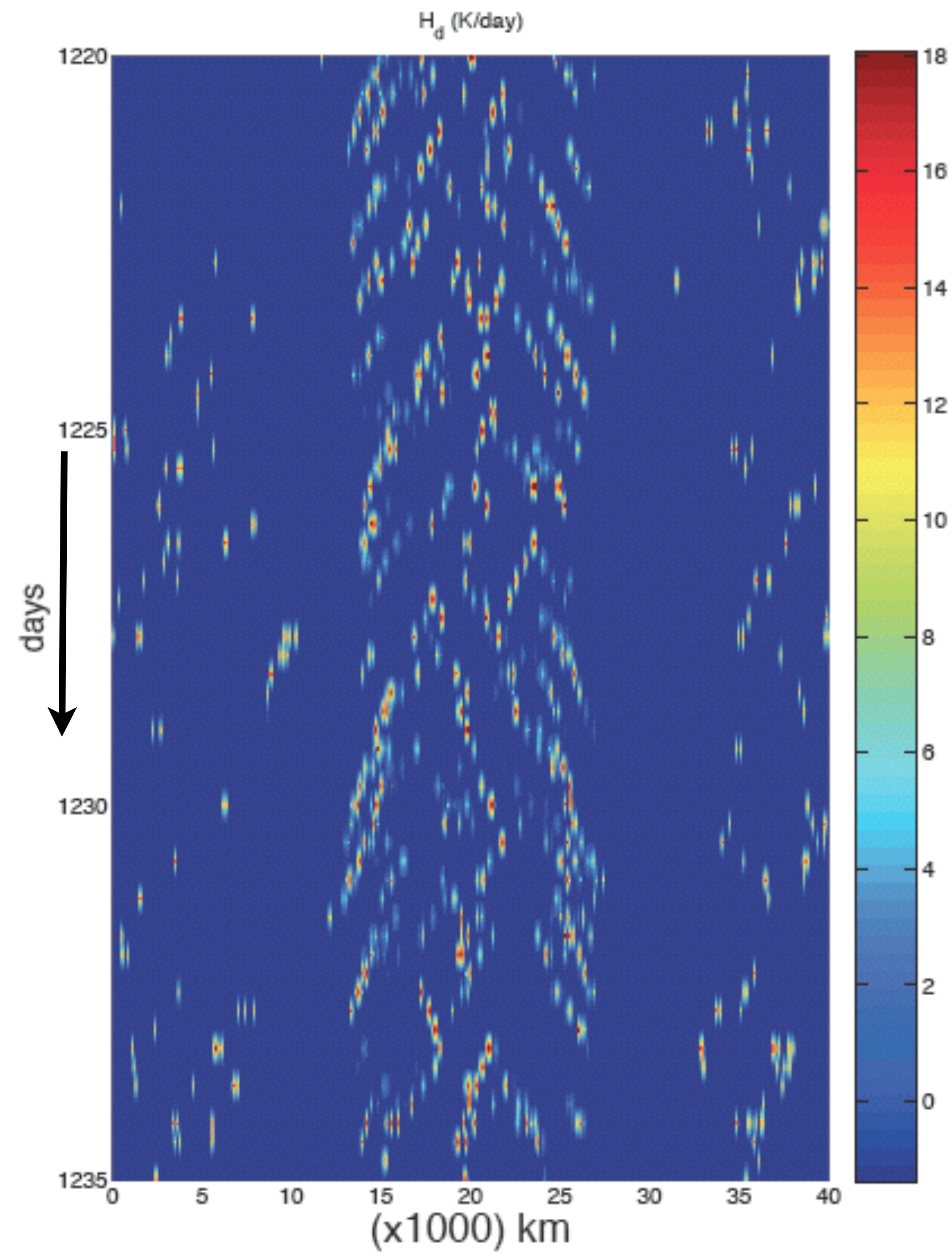
CRM (Grabowski et al. 2000)



Stochastic MC (Frenkel et al., 2012)



SMCM Captures statistics of radar convection

C: ω_{500}
D: RH_{500}

Statistics similar between model vs. observations

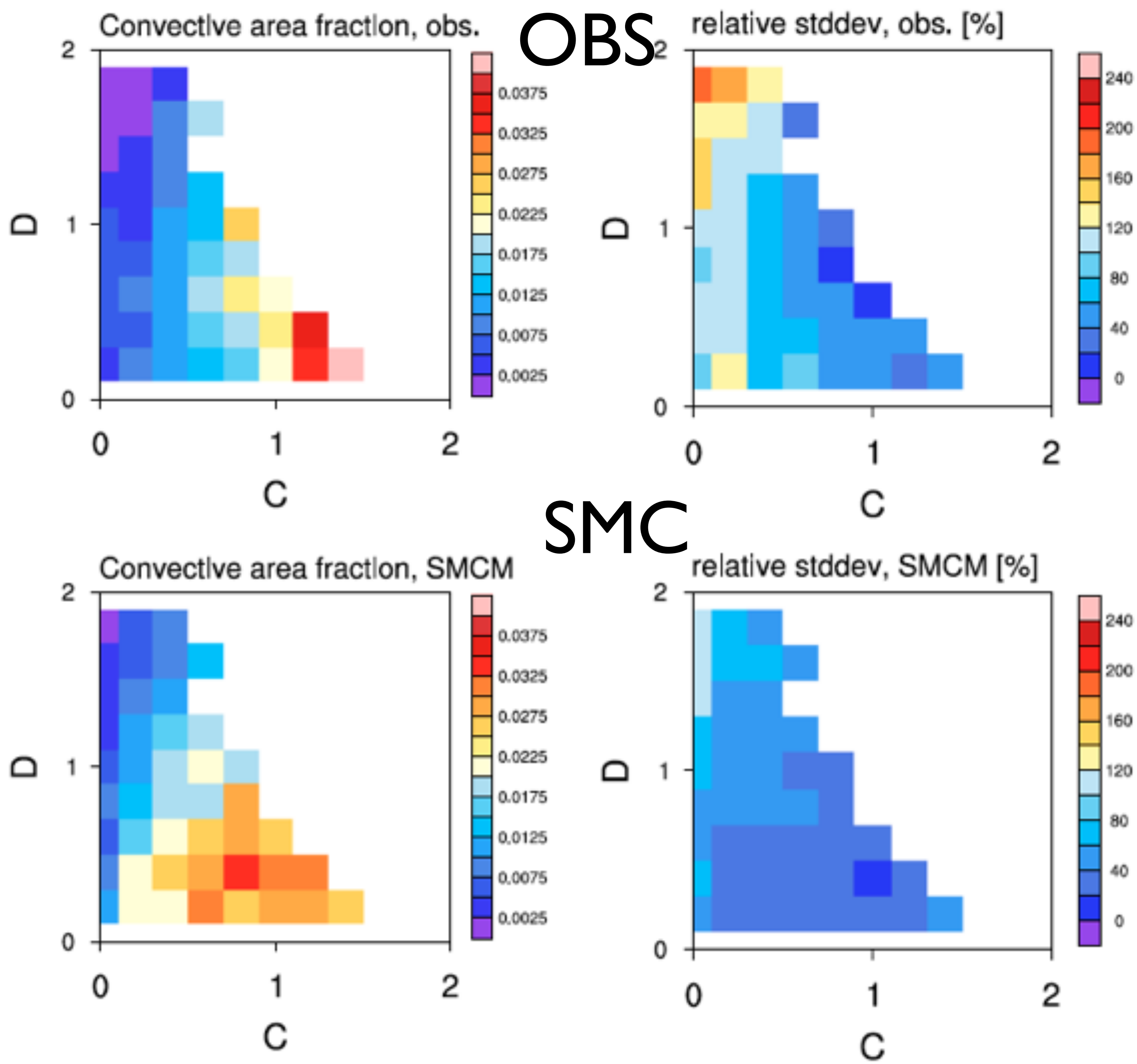
Model “levels” the signal

Peters et al. 2013

✔

OBS

SMC



Distribution of convections does depend on large-scale
Large mean ==> Small Stdv (Deterministic)
Small mean ===> Large Stdv (Random)

Further Remarks

✓Coarse grained multi-dimentional birth death process for area fractions derived and implemented

✓ Very little to no computational overhead

$$Prob\{N_c^{t+\Delta t} = k+1 / N_c^t = k\} = N_{cs} R_{01} \Delta + o(\Delta t)$$

✓ Can be integrated in parallel with resolved variables by using alternate time marching; scale separation assumption is not needed

$$Prob\{N_c^{t+\Delta t} = k-1 / N_c^t = k\} = N_c (R_{10} + R_{12}) \Delta + o(\Delta t)$$

$$Prob\{N_d^{t+\Delta t} = k+1 / N_d^t = k\} = (N_{cs} R_{01} + N_c R_{12}) \Delta + o(\Delta t)$$

✓ Key parameters systematically and rigorously inferred from data

....

✓ Combine physical intuition and data driving techniques

Model set up

- CFS (coupled model) at T126, 64 levels, 10 min time step, run for 15 years
- Turn off original cumulus scheme (Simplified Arakawa-Schubert) and replace it with SMCM
- Keep shallow convection scheme (as in CFSv2) and large-scale condensation—parameterized cloud radiative forcing turned off
- Large scale fields (q, T, h, w, CIN, CAPE) are inputted into SMCM to compute stochastic transition rates, and heating/cooling and moistening/drying potentials.
- Compare mean climatology and variability against control-CFVv2 model and observation/reanalysis

SMCM parameterized Total heating

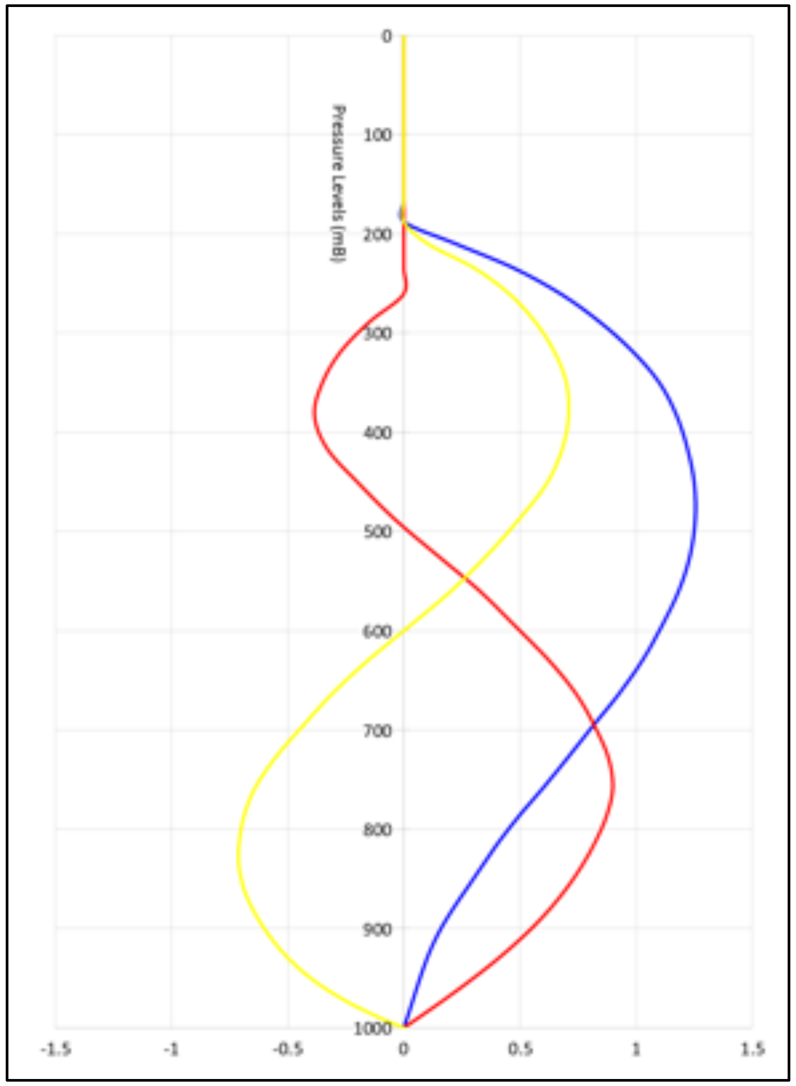
$$Q_{tot}(z) = H_d\,\phi_d(z) + H_c\,\phi_c(z) + H_s\,\phi_s(z)$$

SMCM Closure

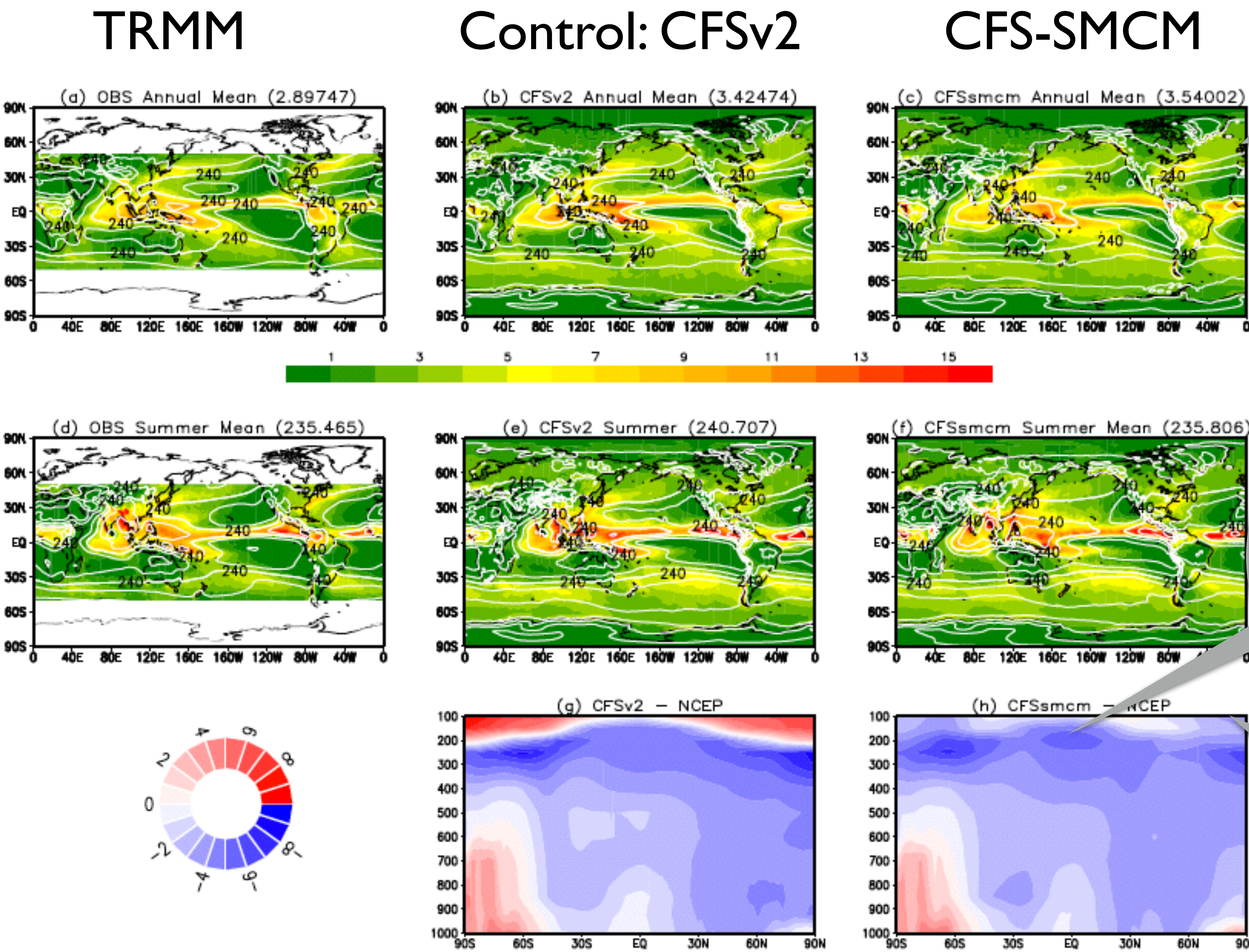
$$H_c = \frac{\sigma_c}{\bar{\sigma}_c}\alpha_c Q_c$$

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

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



Mean Precipitation and Mean Temperature Bias



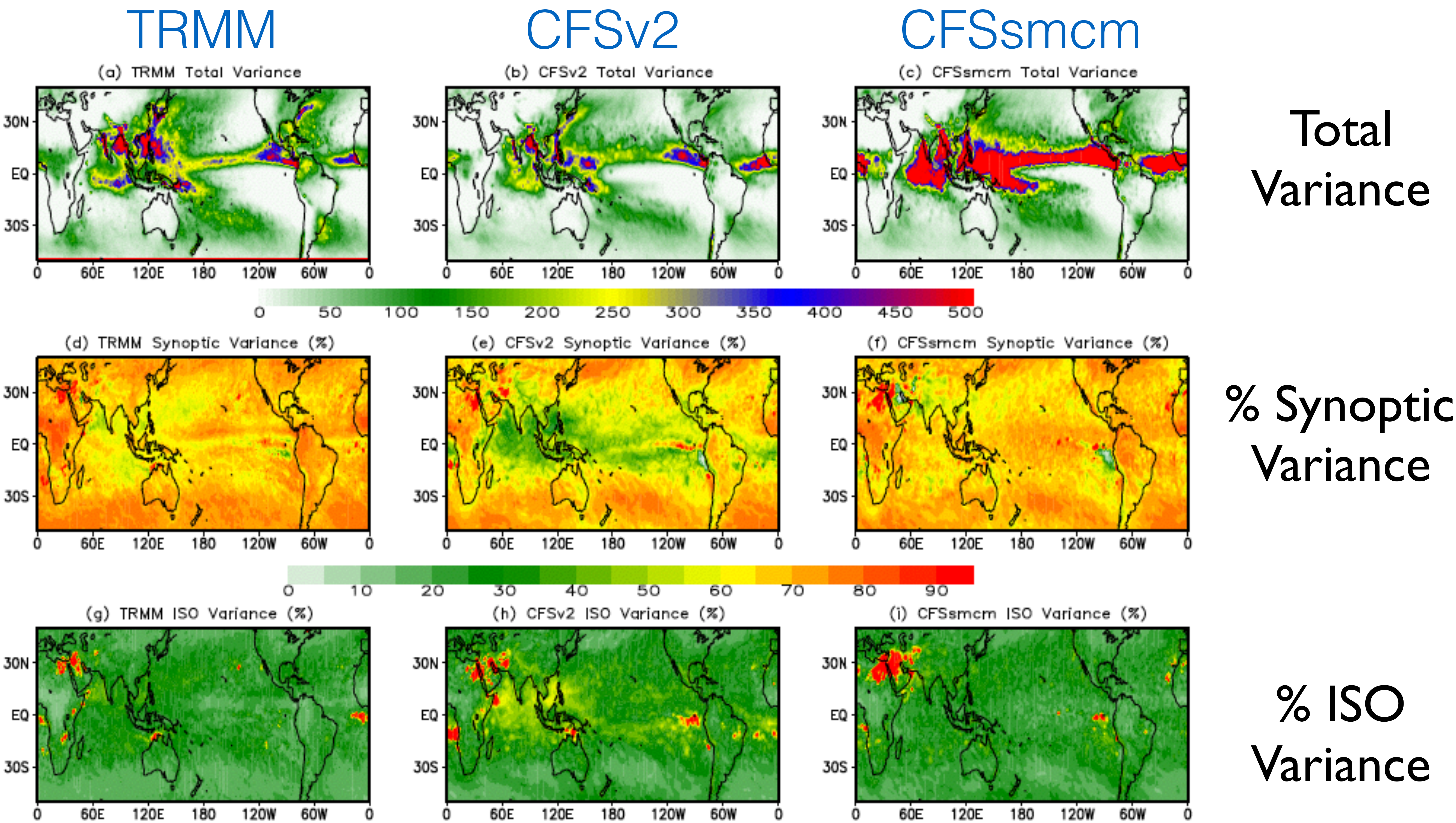
Excessive rain in warm pool reduced

Reduced dry bias over India

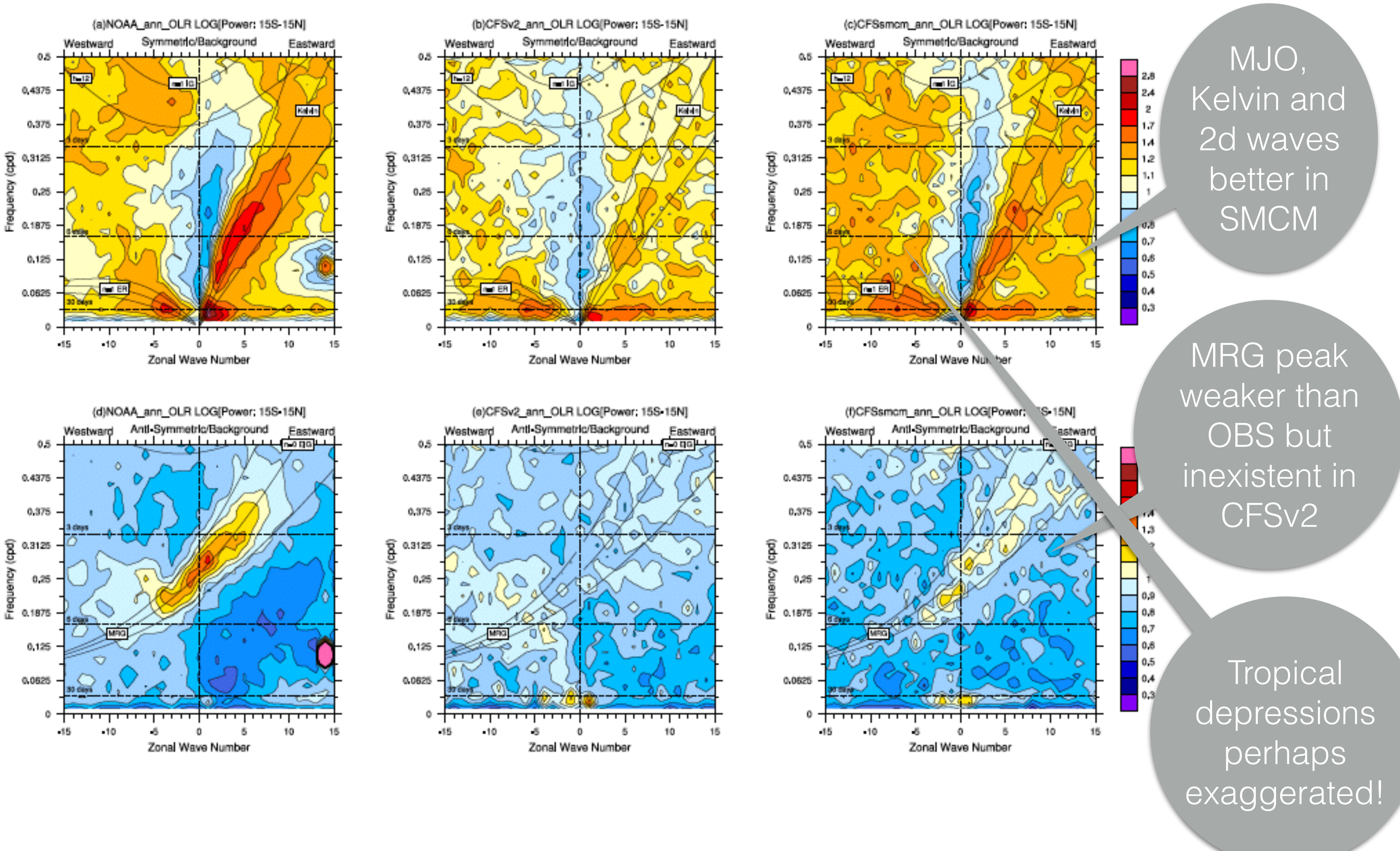
TOT Cold bias slightly reduced & became more evenly distributed

TOP Warm bias eliminated

- SMCM captures balanced synoptic v.s Intra-seasonal variance
- Total variance exaggerated—under-estimated in CFSv2



Clear improvements in Wheeler-Kiladis-Takayabu Spectra



Rainfall-OLR Joint Distribution

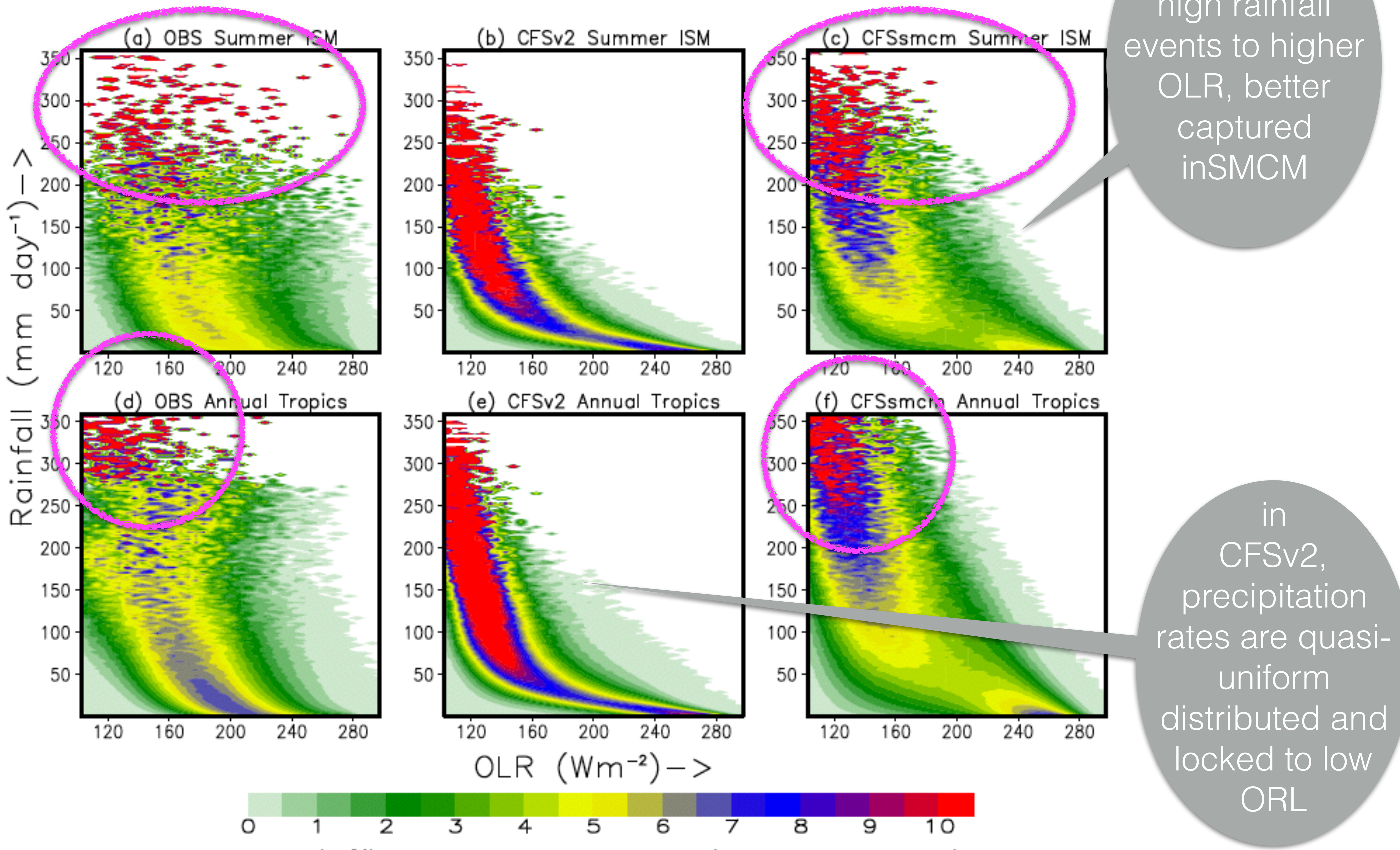
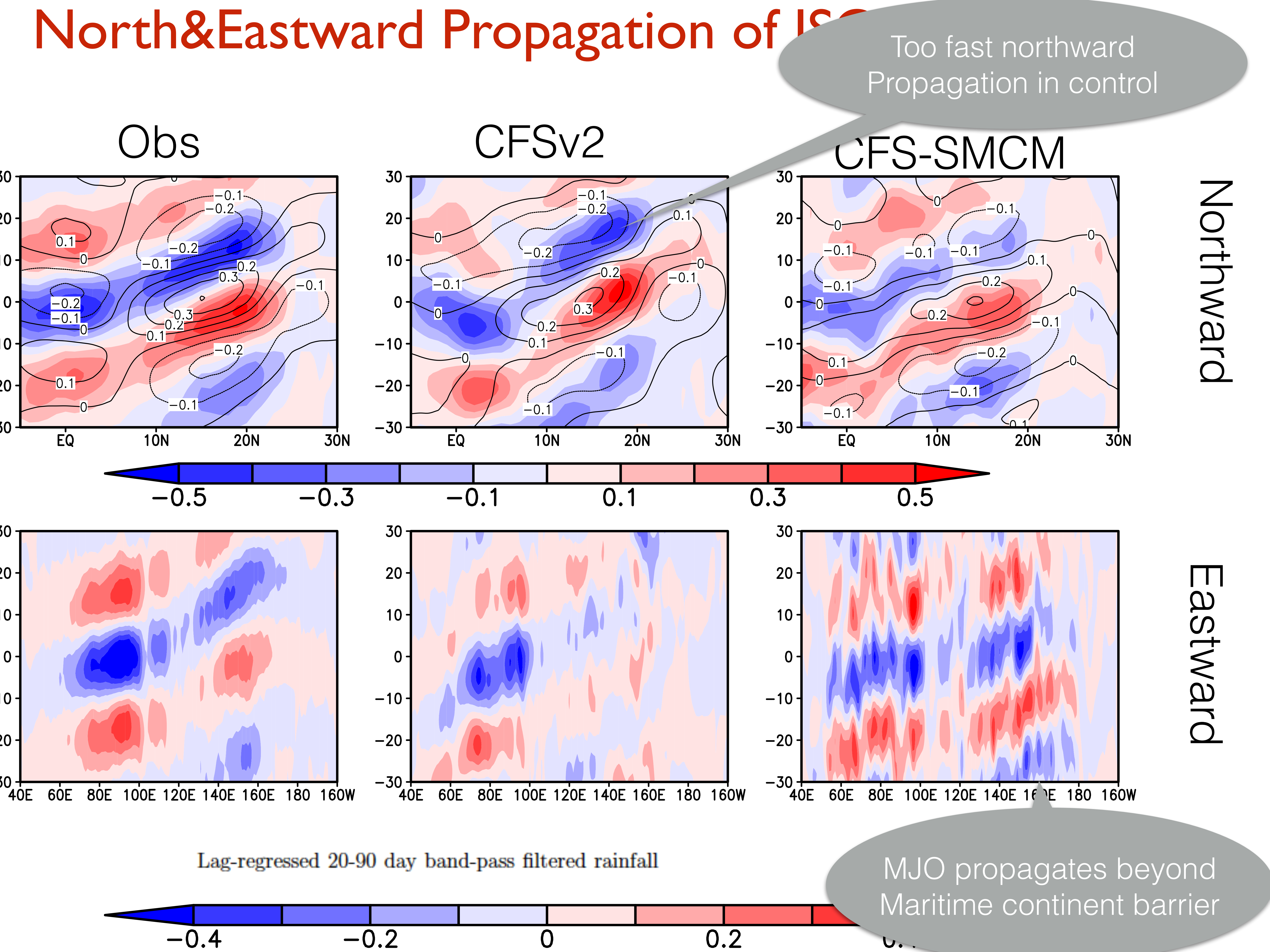


Figure 4. Joint distribution (in %) of OLR-rainfall over ISM region (15°S-30°N, 50°E-110°E), during boreal

North&Eastward Propagation of ISO



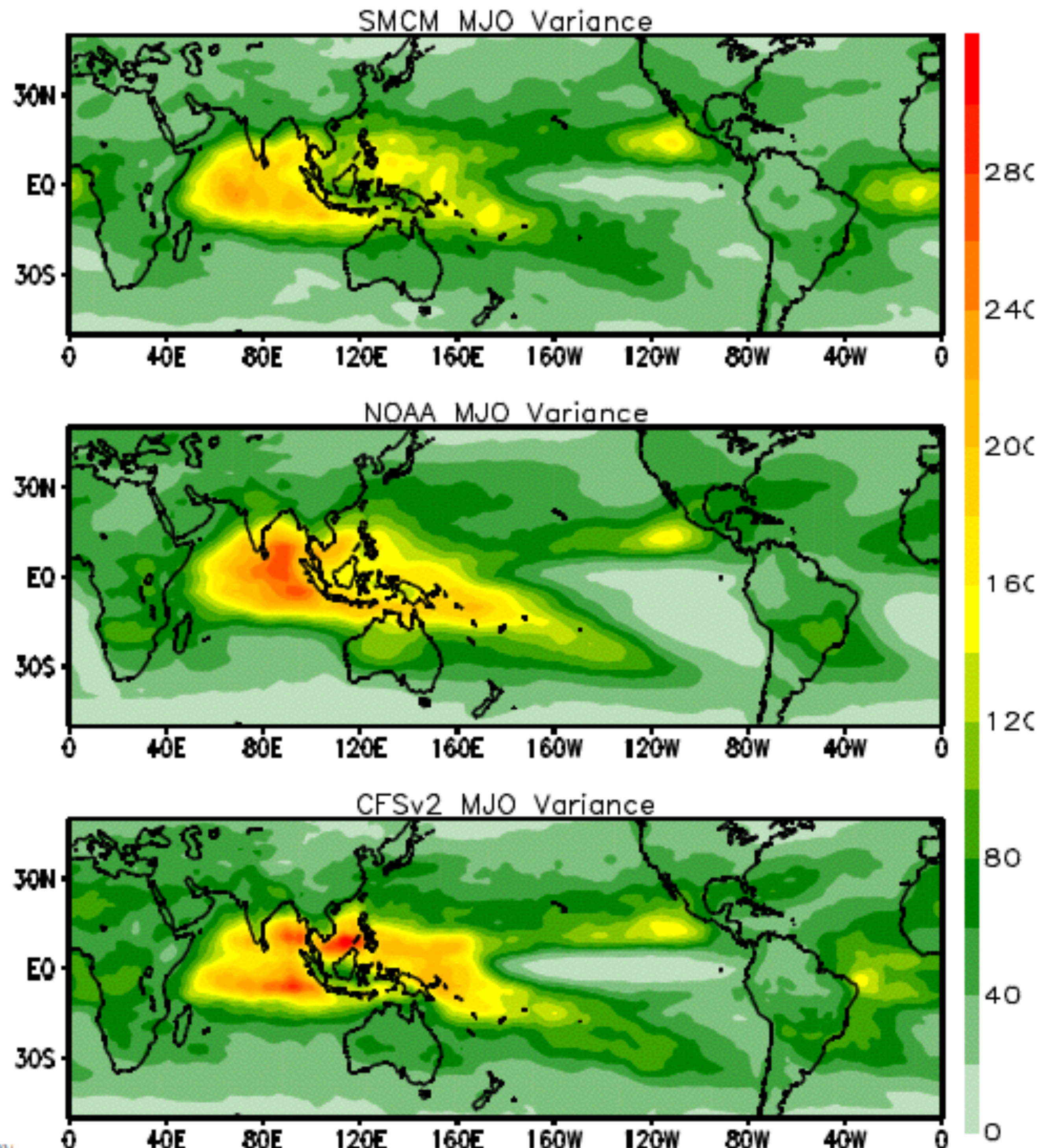
Lag-regressed 20-90 day band-pass filtered rainfall

Physical and Dynamical Features of Main modes of tropical variability

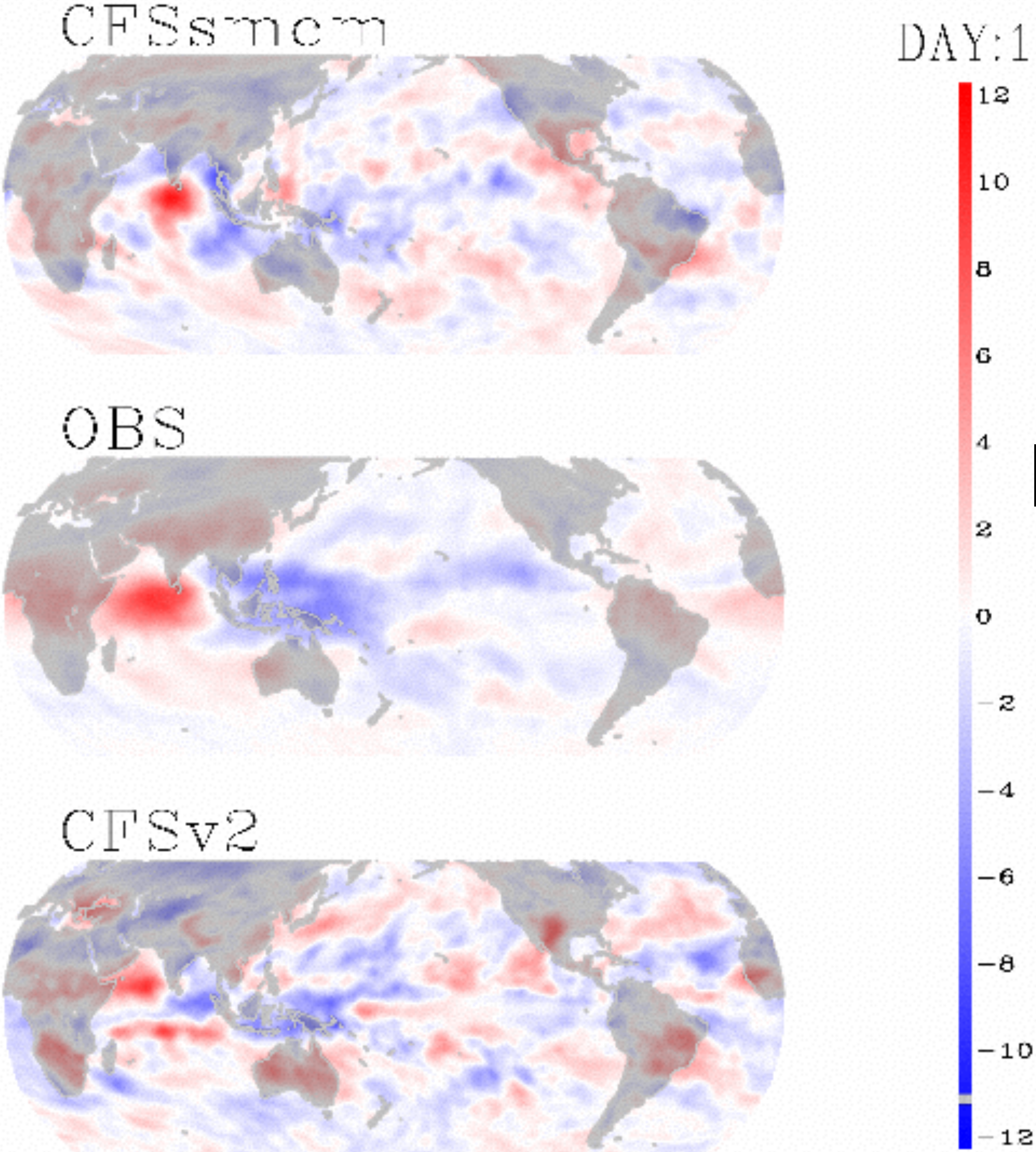
- MJO
- CCWs: Kelvin, Equatorial Rossby, MRG, WIG, EIG
- Monson Intra-seasonal Oscillation (MISO)

MJO Filtere OLR Variance

MJO Variance (MJO filtered anomalies)

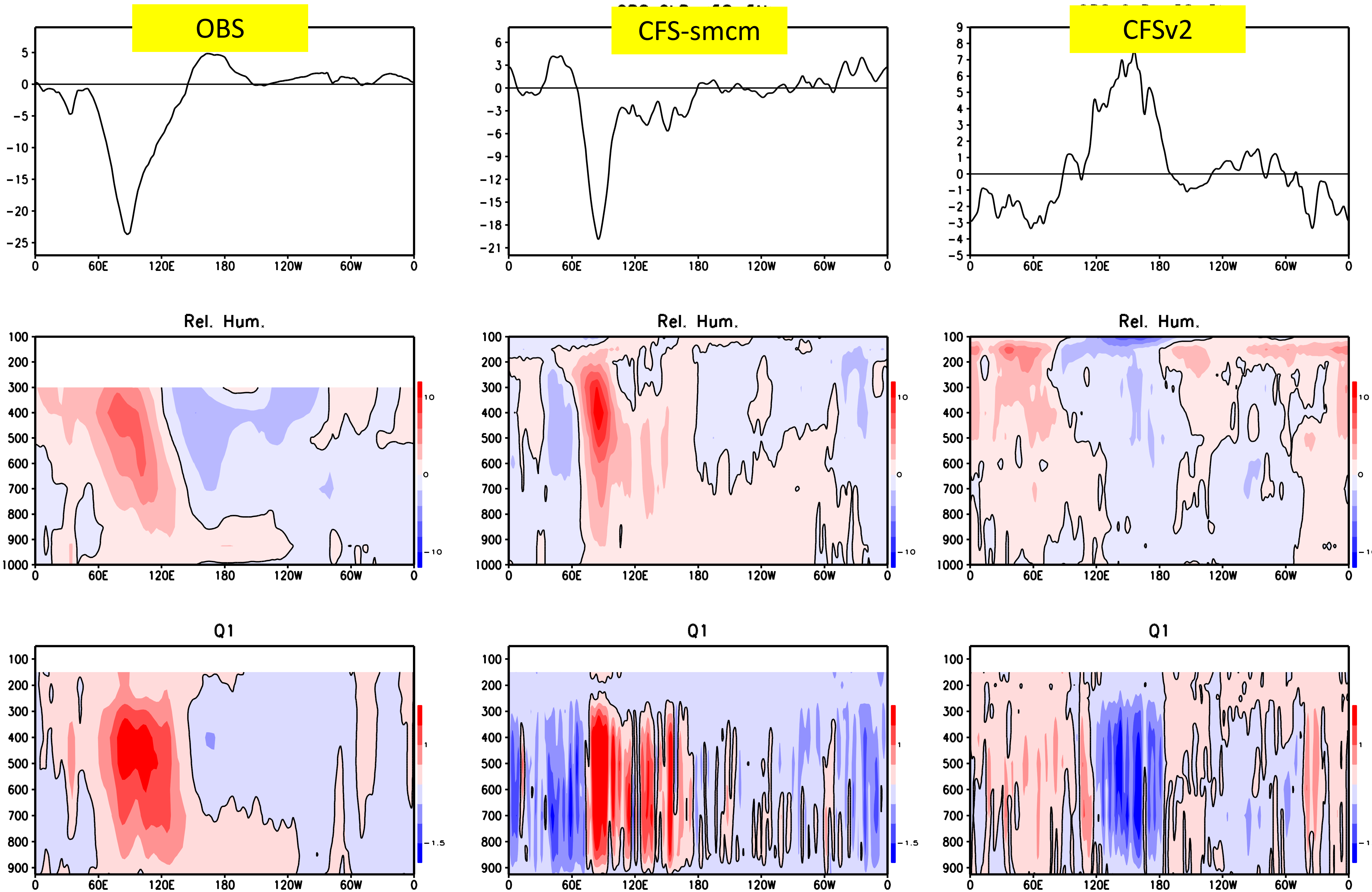


Amplitude and location of **MJO variance is captured well by CFSsmcm**, although slightly shifted **westwards** and **underestimated** over the oceanic ITCZ region. CFSv2 shows a double peaked unrealistic distribution of the MJO variance.

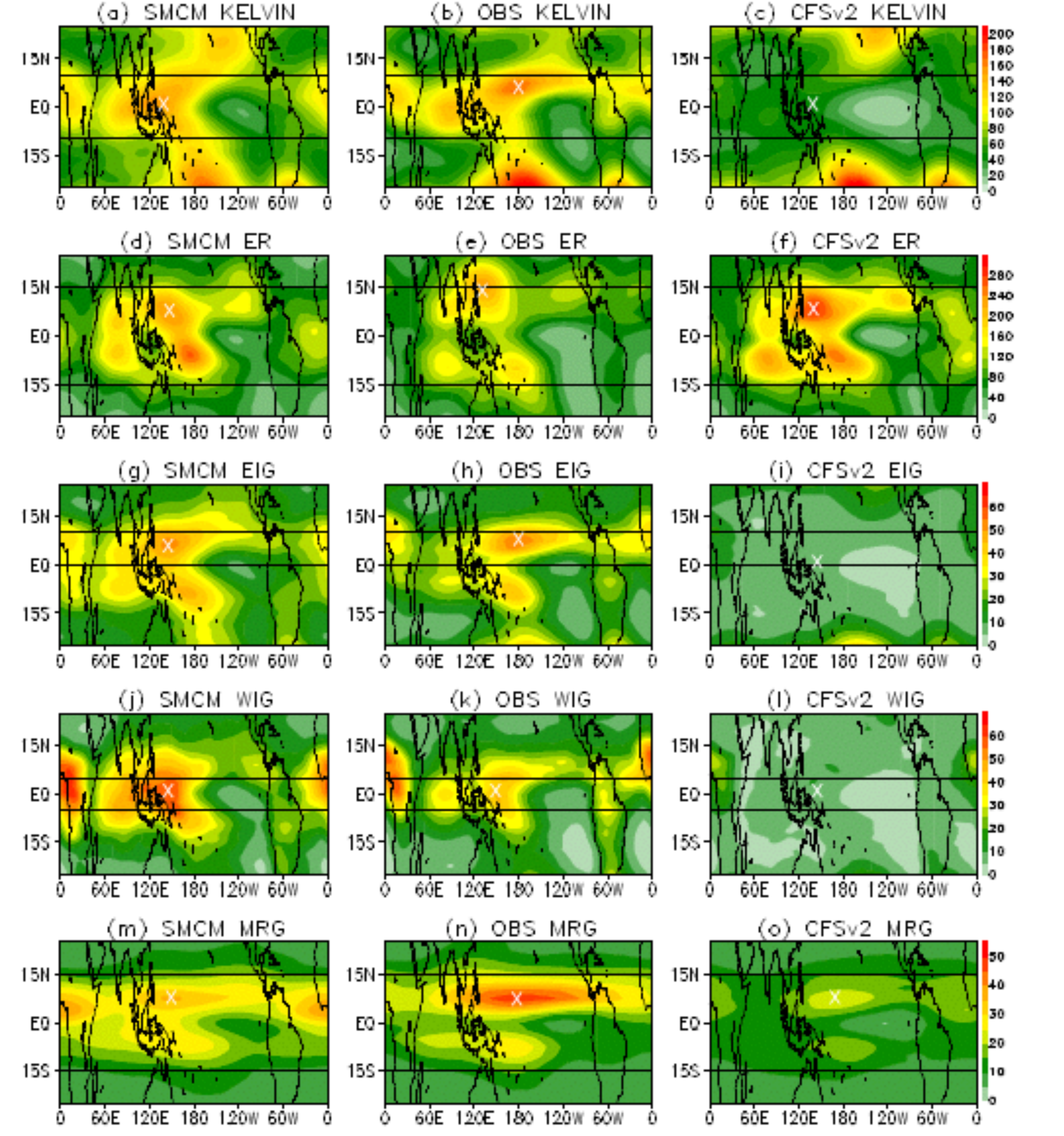


MJO Propagation

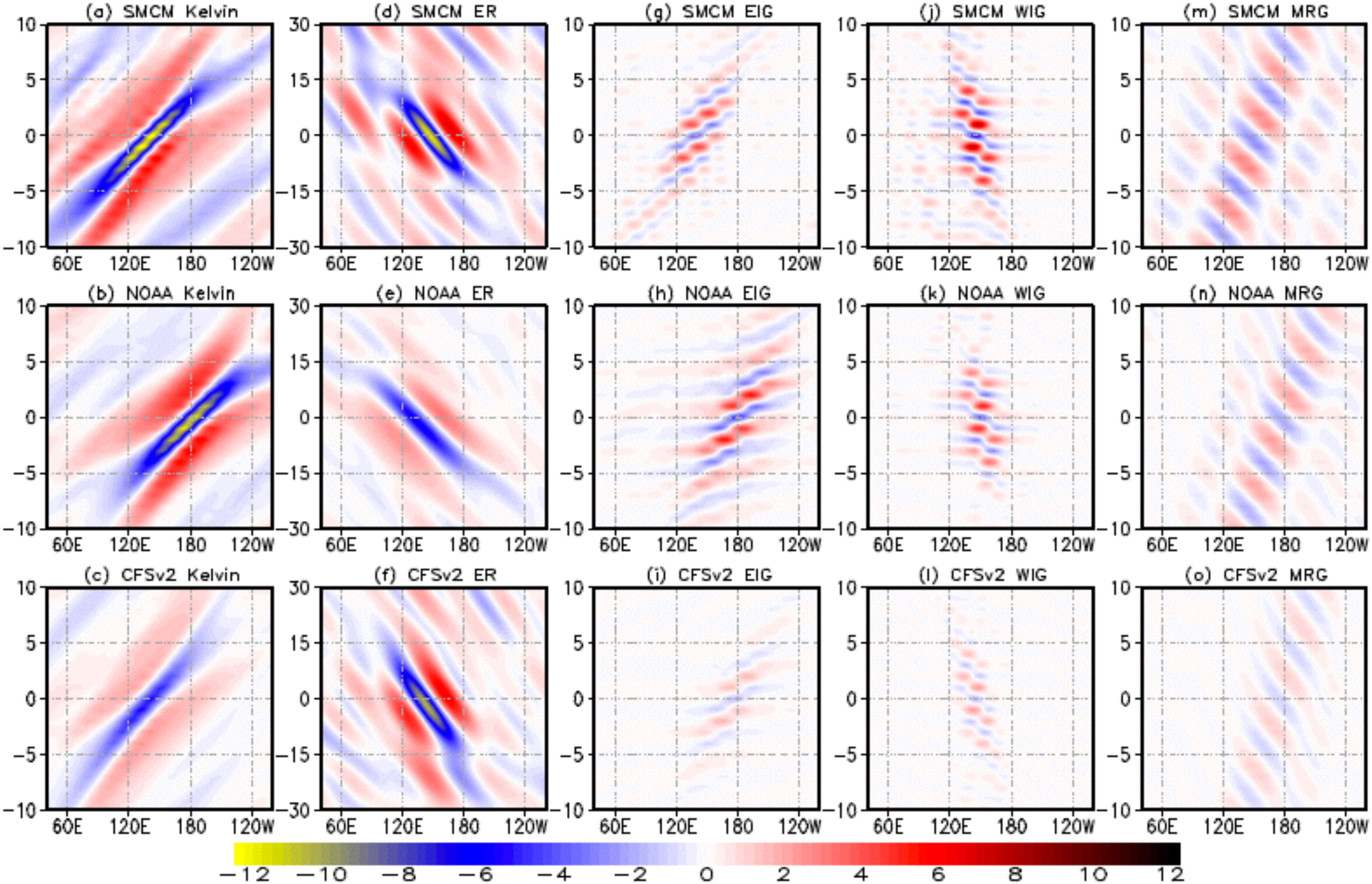
Low-level moistening during suppressed phase: congestus clouds



CCWs Variance

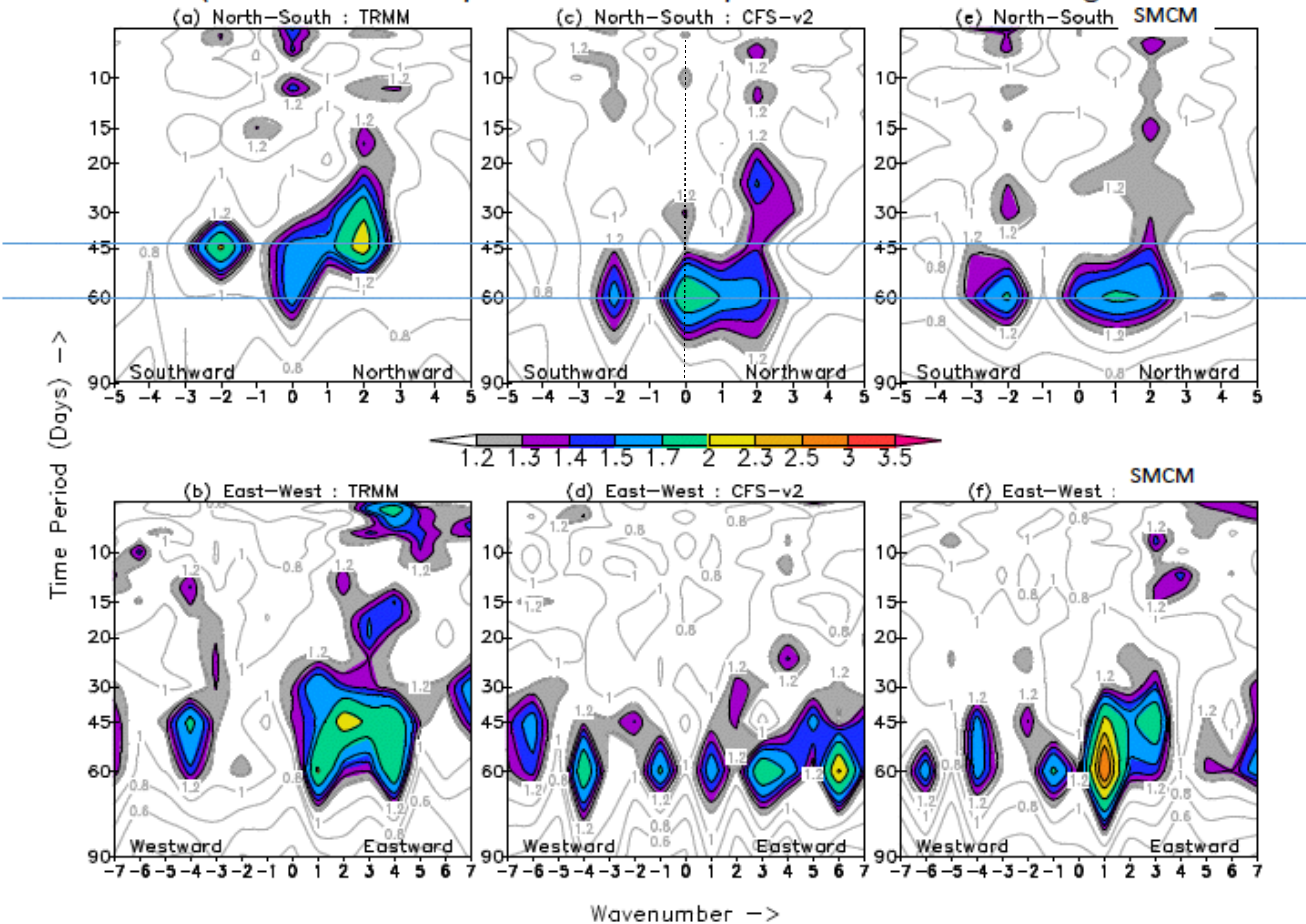


Propagation … Composite Hovmoller



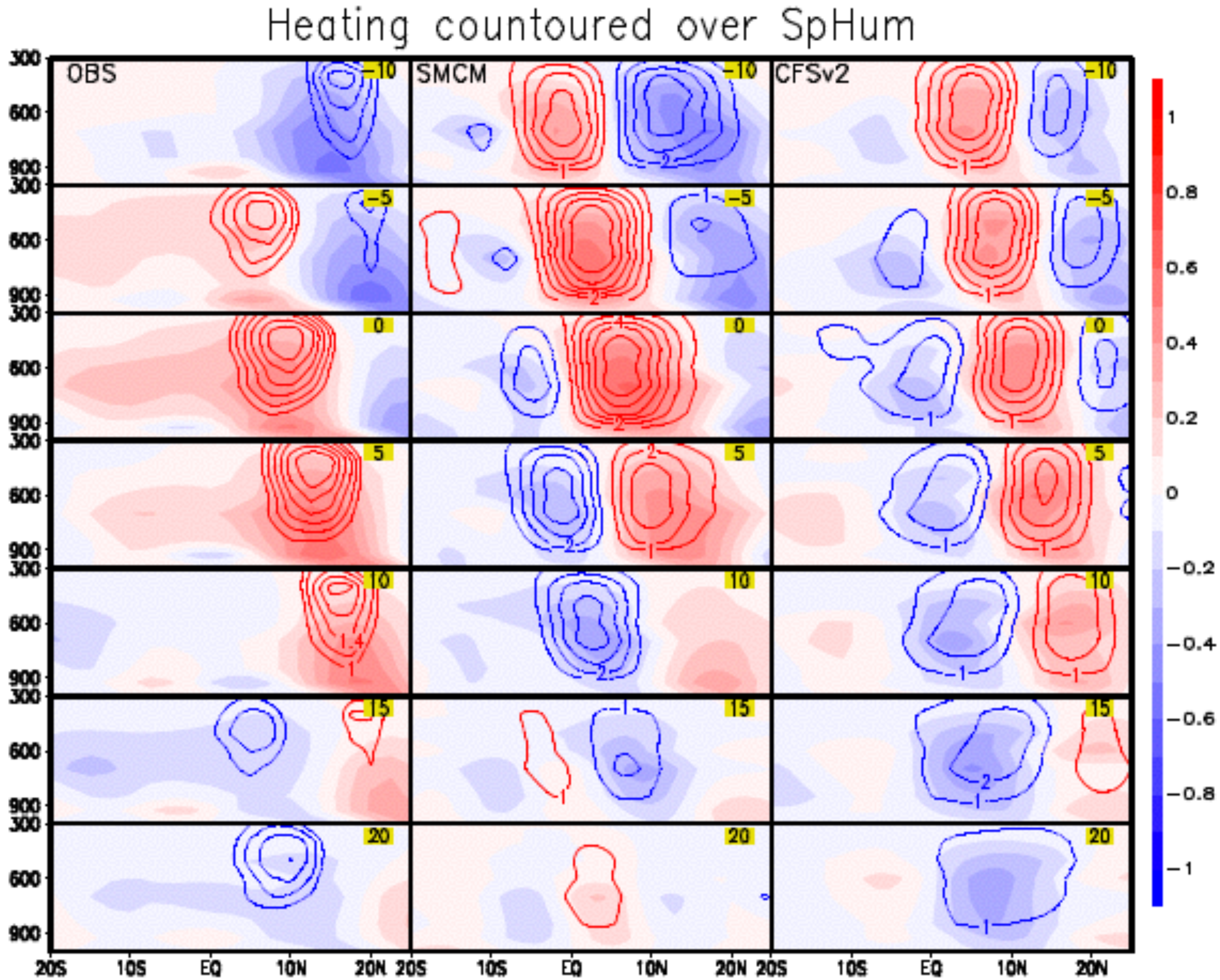
Boreal summer ST spectra

(For north-south spectra: k=1 corresponds to 20S-27N=48 degrees)



MISO Phase propagation

The shear-vorticity-moisture mechanism



Conclusions—CFSsmcm

- SMCM, based on a stochastic lattice model, mimics sub-grid variability of organized convection: "cheap version of super-parameterization"
- Considerable improvements in synoptic and intra-seasonal variability without deterioration of mean climate
- Improvement in Wheeler-Kiladis-Takayabu spectra, especially Kelvin, MRG, and 2day waves
- Improved northward propagation of ISO rainfall, MJO propagation beyond maritime continent in SMCM
- Key improvements in detailed dynamical structure of MJO, MISO, and CCWs—realistic physical features such as titled heating, leading low-level moistening, MJO quadruple vortex structure—completely absent in control CFSv2—Physics of Northward propagation in CFSv2 ???
- Further demonstration that tropical convective variability is both multi scale and self-similar in nature
- Complex interactions of the three key cloud types, congestus, deep, and stratiform, with the dynamical and moisture fields, Shaping up the vertical structure of the diabatic heating, on multiple scale scales