Stochastic ^deep convective parameterization

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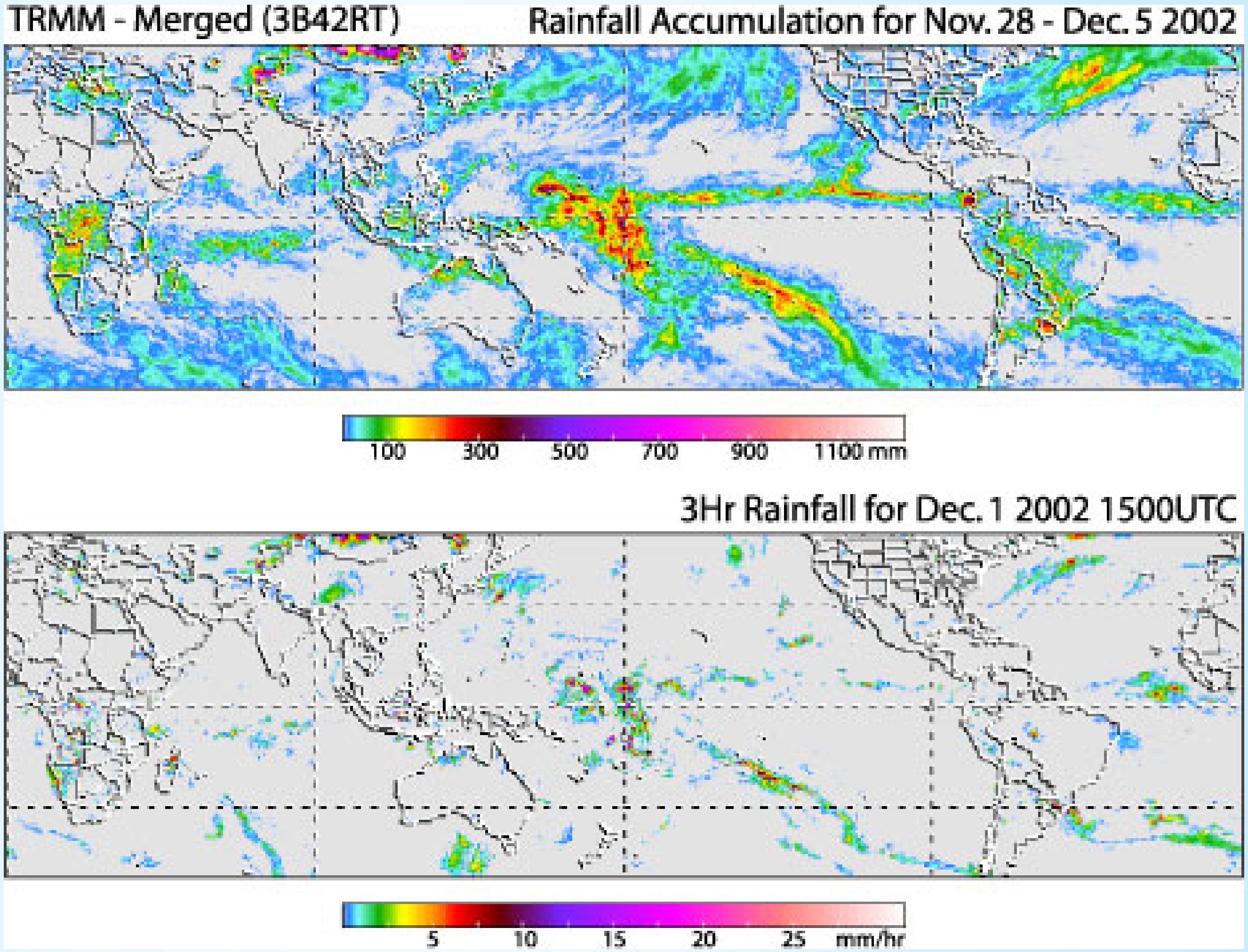
- Moist convective parameterizations represent ensemble mean effects of sub-grid scale motions on Reynolds-average large-scale as deterministic function of the large-scale variables
- For a domain ~(200 km)^2 x (20 minutes) the sample of deep convective elements is not large ➲ variance in average
- Probability distribution of convective heating, etc. at typical grid cell/time step can impact large scales
- Mimic these physical effects by stochastic representation

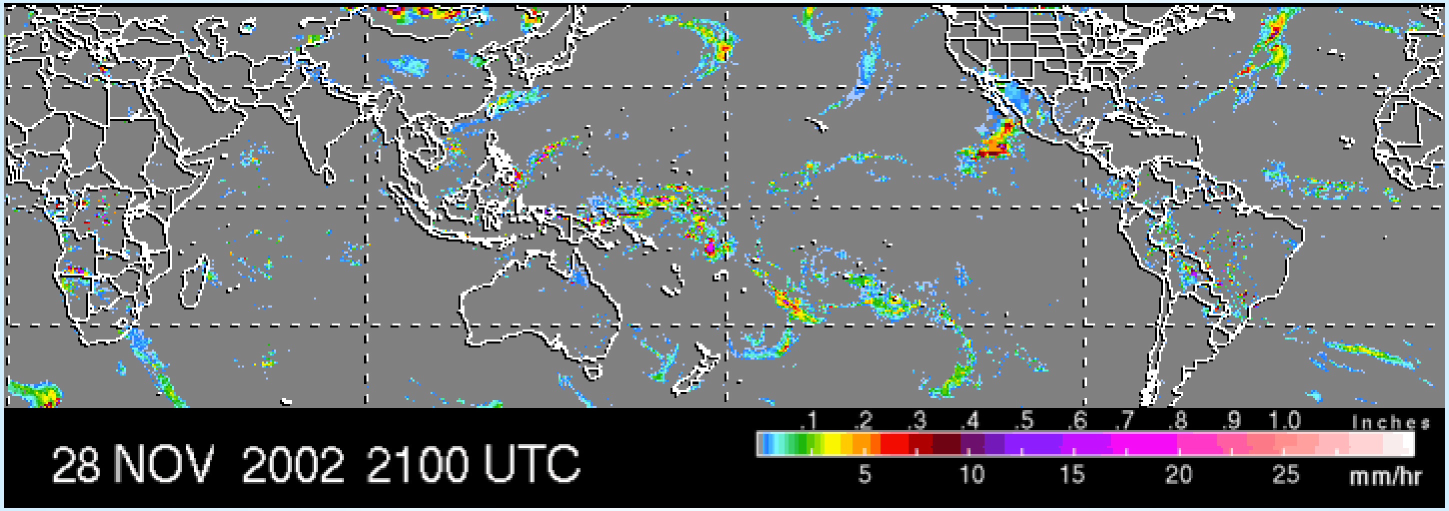
Rainfall from the TRMM-based merged data (3B42RT)

Weekly accumulation

Rain rate from a 3-hourly period within the week shown above



Rainfall animation from the TRMM-based merged data (3B42RT)



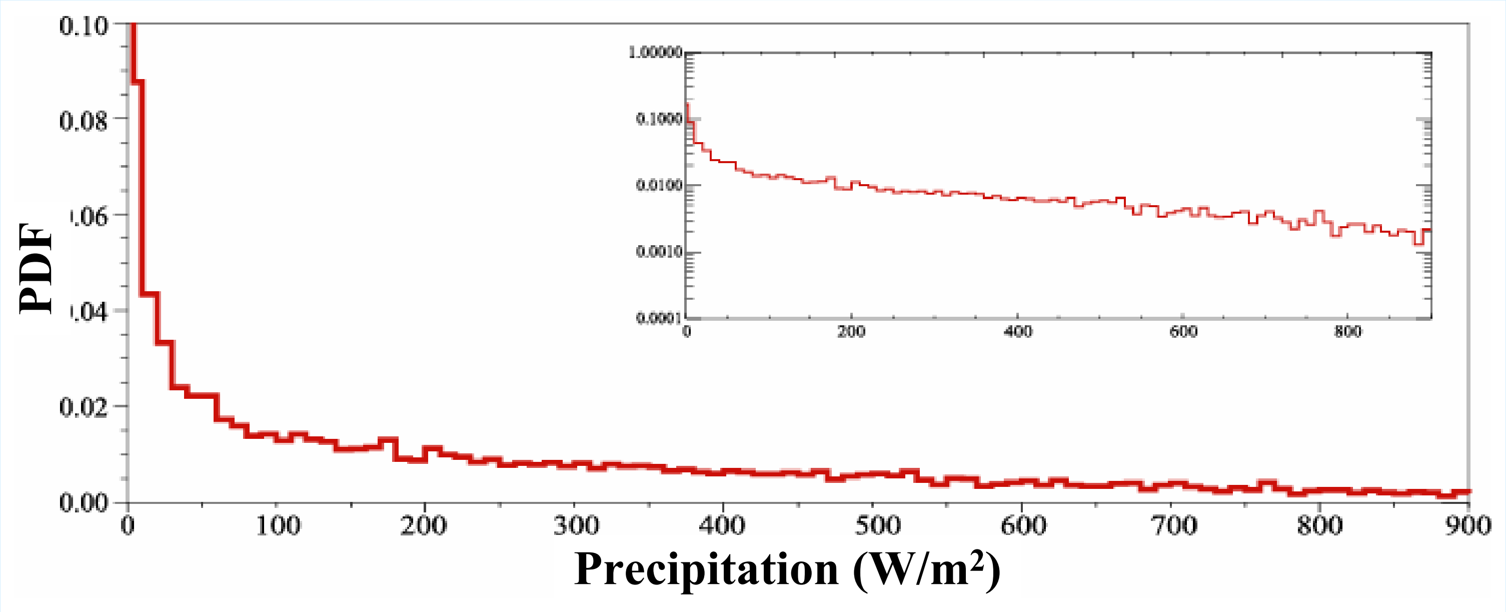
3 hour rainfall over one week (Nov. 28-Dec. 5, 2002)

START

From Goddard Space Flight Center (GSFC), Huffman, 2002.

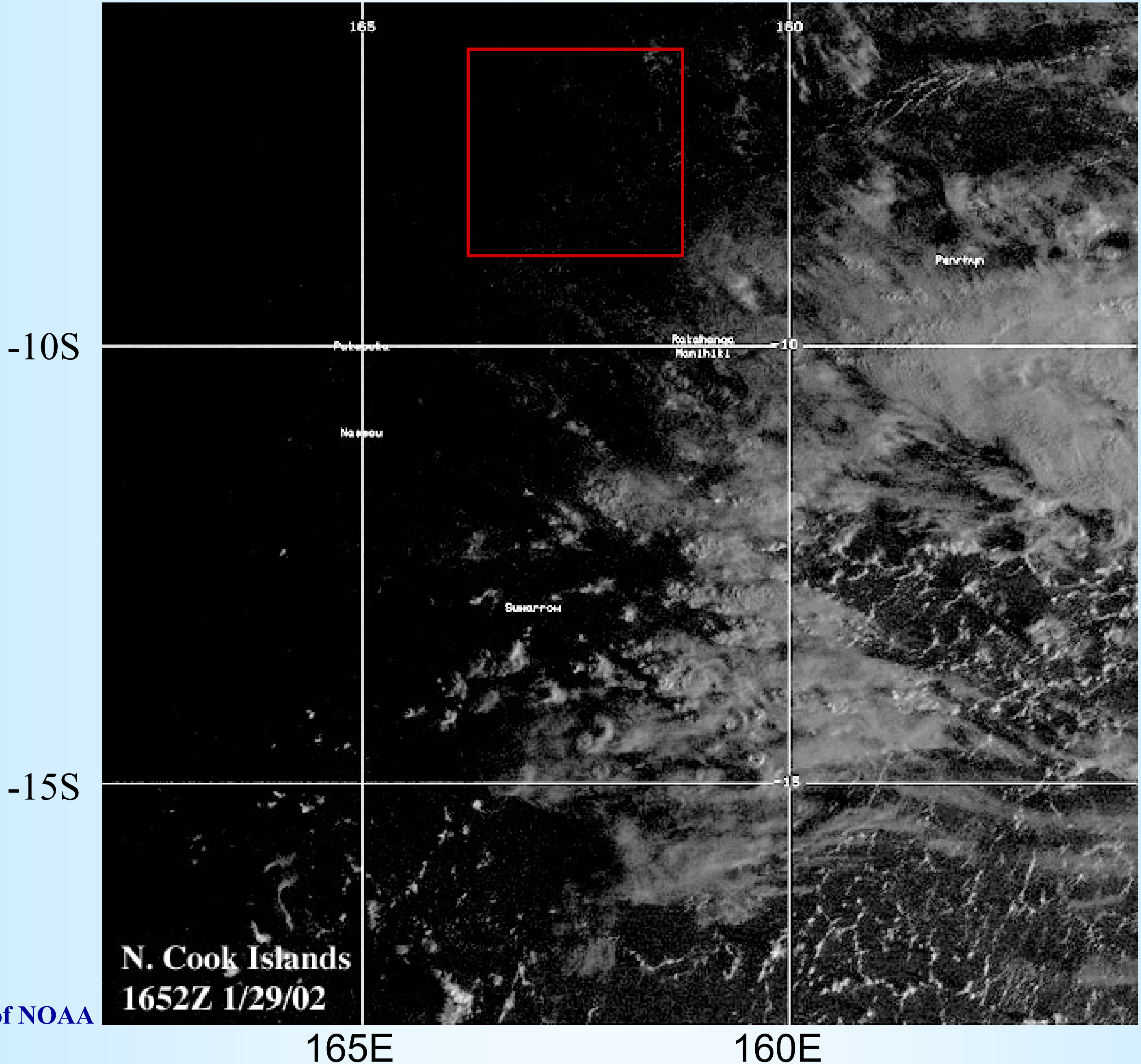
Probability density function of daily precip. in west Pacific warm pool

TRMM-based 3B42



- 150-152E, 6.5-8.5S

Visible image – Western Pacific 1652Z



Courtesy of NOAA

START

Approaches to stochastic convective parameterization

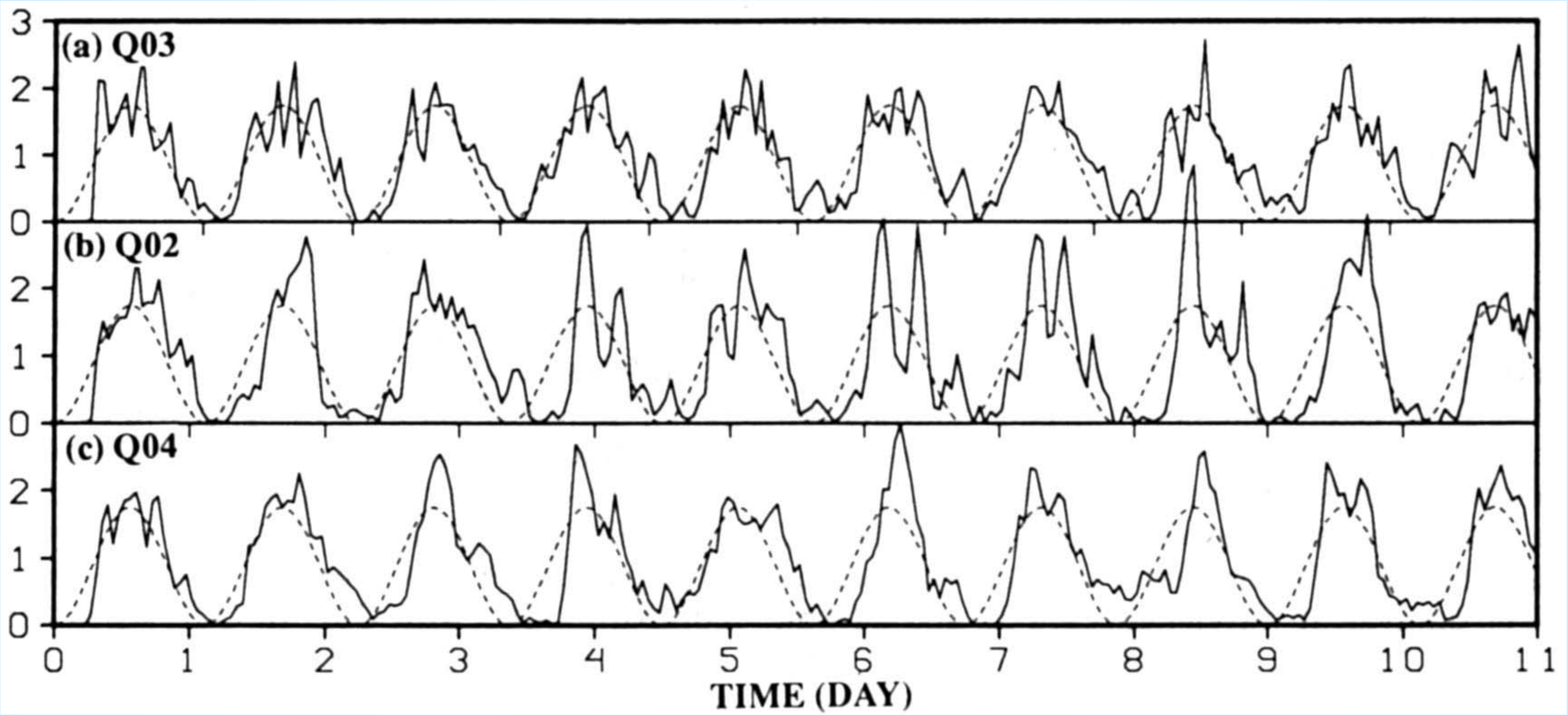
- **Empirical:** Directly control statistics of the overall convective heating; specify distribution as function of model variables, with dependence estimated empirically.
  - Related to hydrology & remote sensing literature but heating/precipitation has strong feedbacks with large-scale flow.
  - Example using "empirical lognormal scheme" in QTCM (Lin & Neelin 2002, JAS).
- **"Physics-Motivated":** Stochastic processes introduced within framework of convective parameterization, informed by physics relevant to unresolved variance.
  - Distribution is a testable outcome of the postulated physics.
  - Example using "CAPE scheme" in QTCM (Lin & Neelin 2000, GRL).
  - Modifications to existing Zhang-McFarlane scheme in CCM3 (Lin & Neelin 2003, GRL).

- Related work: Buizza et al 1999, Khouider and Majda (2001) Mesoscopic CIN; Khairoutdinov and Randall (2001), Grabowski (2001) "Super parameterization"

Xu, Arakawa and Krueger 1992
Cumulus Ensemble Model (2-D)

—— Precipitation rates

- - - - Imposed large-scale forcing (cooling & moistening)



Experiments: Q03 512 km domain, no shear
Q02 512 km domain, shear
Q04 1024 km domain, shear

Temperature T and Moisture q equations

dry static energy $s = T + \phi$

$$(\partial_t + \mathbf{v}\bullet\nabla)T + \omega\partial_p s - \partial_p R + \partial_p S - \partial_p F_{SH} = Q_c$$

convective heating

vertical velocity

Fluxes: longwave radiation(R), solar(S) sensible(SH), latent heat(L)

$$(\partial_t + \mathbf{v}\bullet\nabla)q + \omega\partial_p q - \partial_p F_L = Q_q$$

moisture source/sink

Energy constraint in vertical integral $\langle\ \rangle$

$$\langle Q_c\rangle = -\langle Q_q\rangle$$

⟨Moist static energy equation⟩

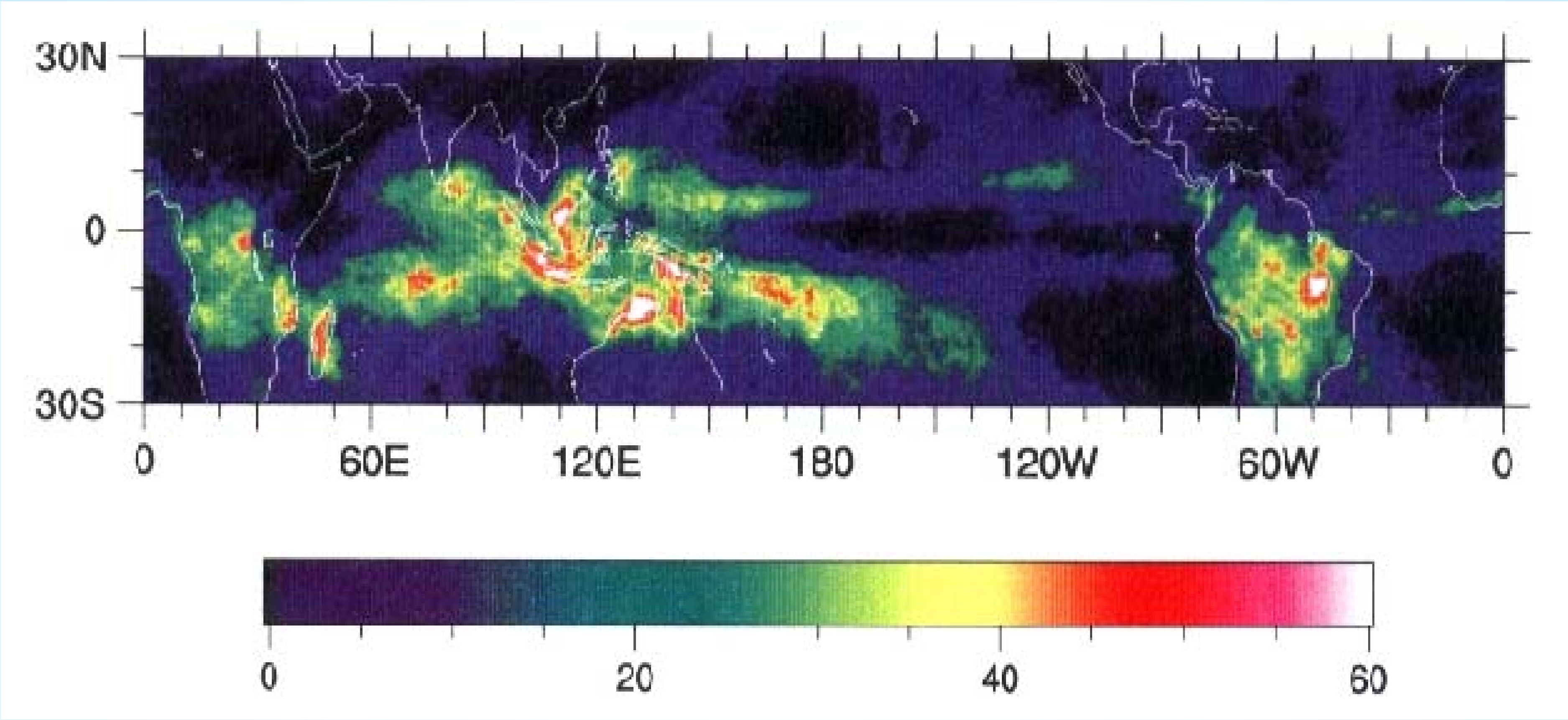
$$\langle(\partial_t + \mathbf{v}\bullet\nabla)(T+q)\rangle + \langle\omega\partial_p h\rangle - F_{net} = 0$$

Transport of moist static energy by divergent flow
≈ (measure of divergence)
x gross moist stability

Moist static energy $h = s + q$

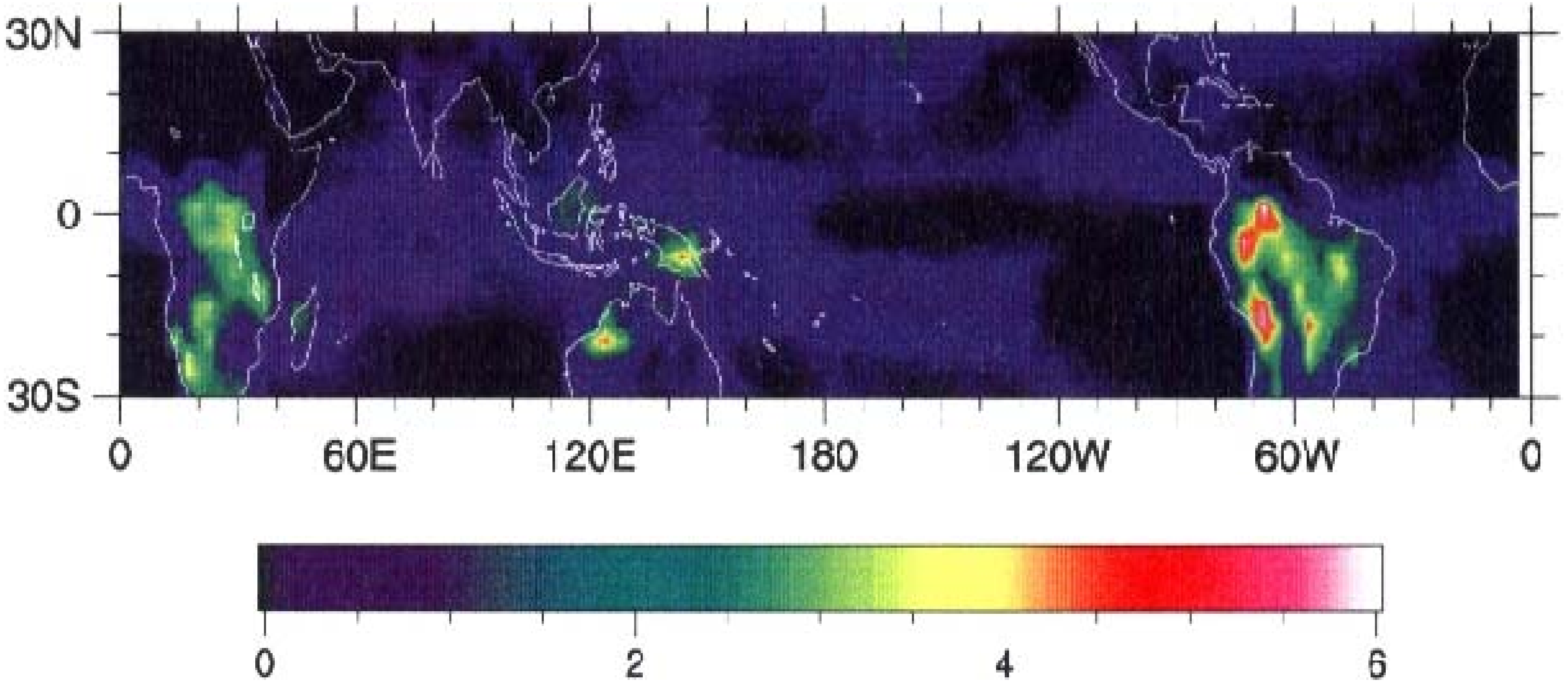
Net energy flux into column

Winter 1984 observed estimate of deep convective heating (DCH) variance [(K/day)^2] (period 6 hours-2 days)



Ricciardulli & Garcia 1999

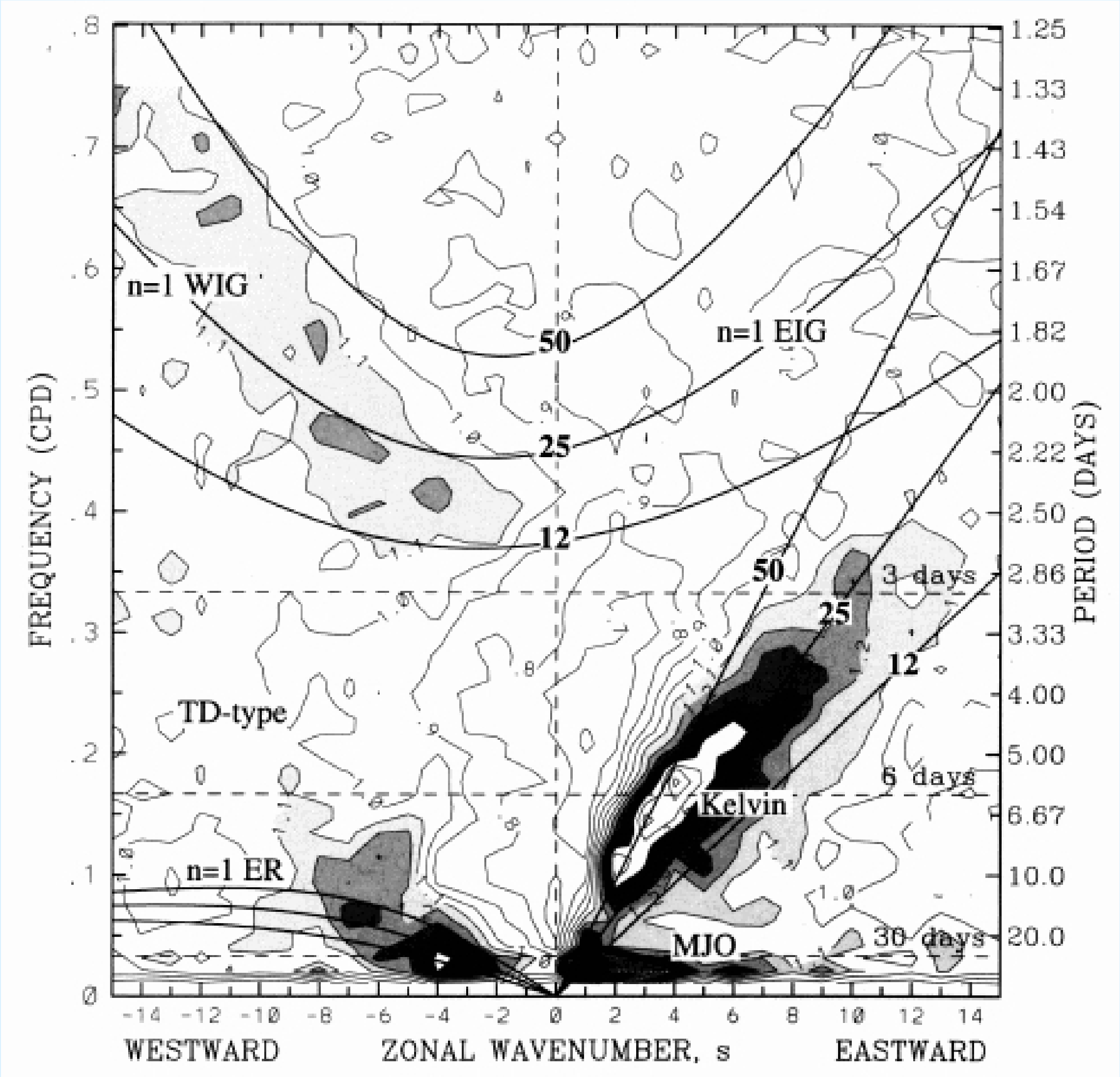
Winter 1984 Modeled DCH Variance [$(K/day)^2$]
(period 6 hrs-2 days)



CCM3 using Zhang-McFarlane convective parameterization

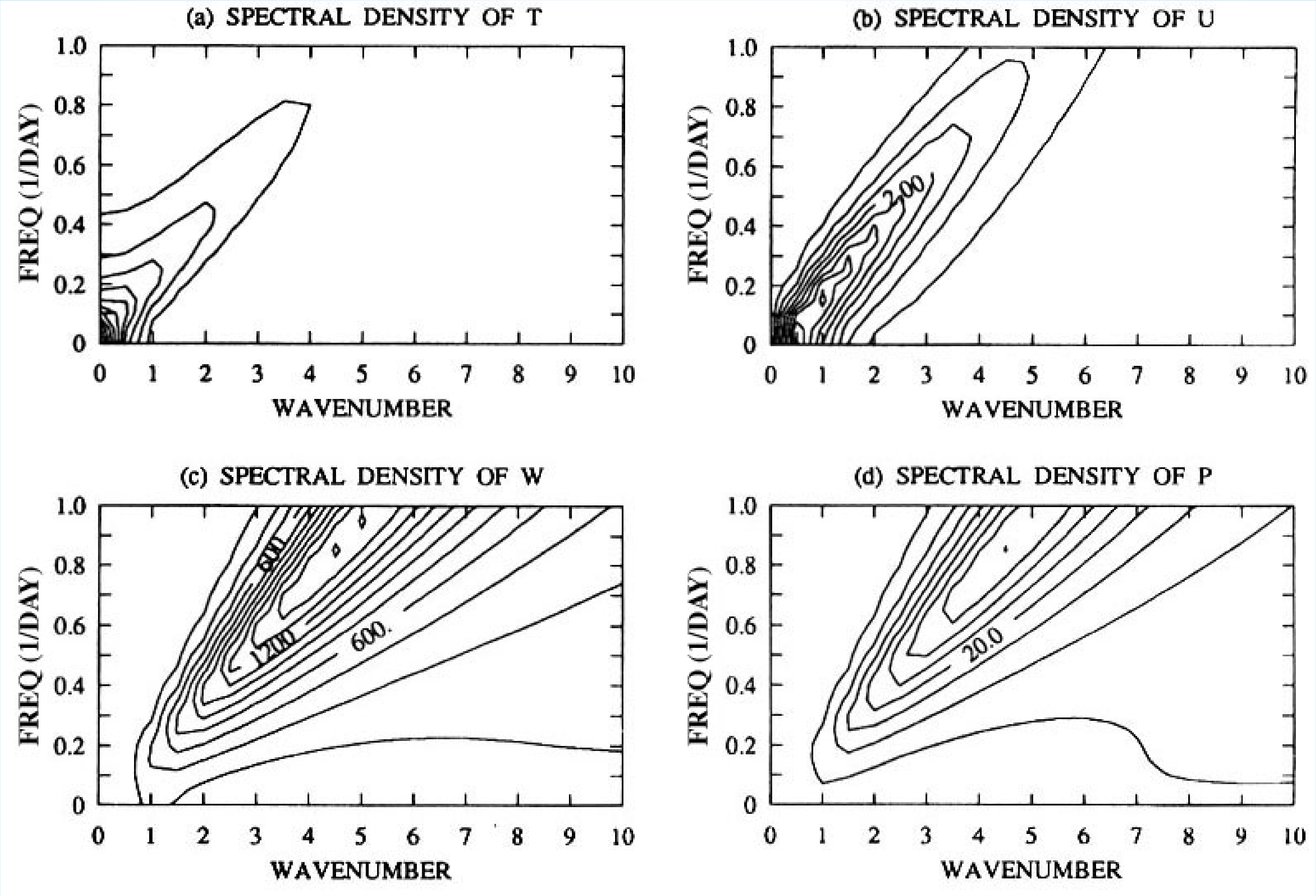
Ricciardulli & Garcia 1999

Tropical OLR Spectral Power ÷ Background (Symmetric)



Wheeler & Kiladis, 1999

Stochastic forcing of intraseasonal variance in linearized P.E. model with Betts-Miller convective scheme



Spatially & temporally white noise in thermodynamic Eqn.

Yu & Neelin, 1994

Quasi-equilibrium Tropical circulation model:

Primitive equations projected onto vertical basis functions from convective quasi-equilibrium analytical solutions

for Betts-Miller (1986) convective scheme, accurate vertical structure in deep convective regions for low vertical resolution

baroclinic instability crudely resolved

1.5min/yr on a Pentium 4 at 5.6x3.75 degree resolution

GCM-like parameters but easier to analyze

Radiation/cloud parameterization:

Longwave and shortwave schemes simplified from GCM schemes (Harshvardhan et al. 1987, Fu and Liou 1993)

deep convective cloud, CsCc fraction param. on precip

Simple land model:

1 soil moisture layer; evapotranspiration with stomatal/root resistance dep. on surface type (e.g., forest, desert, grassland)

low heat capacity; Darnell et al 1992 albedo

Empirical approach stoch. convective param'n.

- **Deterministic Betts-Miller parameterization gives convective heating Q_c as**

$$Q_c^{BM} \propto \tau_c^{-1} R(C_1)$$

  - where $R(x) = x, x > 0; = 0, x \le 0$, τ_c is convective timescale, C_1 a measure of CAPE (Convective Available Potential Energy; depends on moisture and temperature).

- **Calculate Q_c^{BM}, but then choose Q_c as a random number from distribution. Distribution parameterized on Q_c^{BM} (e.g., ensemble mean $\propto Q_c^{BM}$) so changes with time.**

- **Vertically integrated heating = precipitation (in Wm^{-2}) so use precipitation data to estimate.**

- **Issues: probability of zero precip., relation of variance and mean, tail, numerical impacts, estimation from data that includes effects of large-scale, …**

- **Real issue: Feedback from large-scale alters distribution**

"Empirical lognormal" scheme

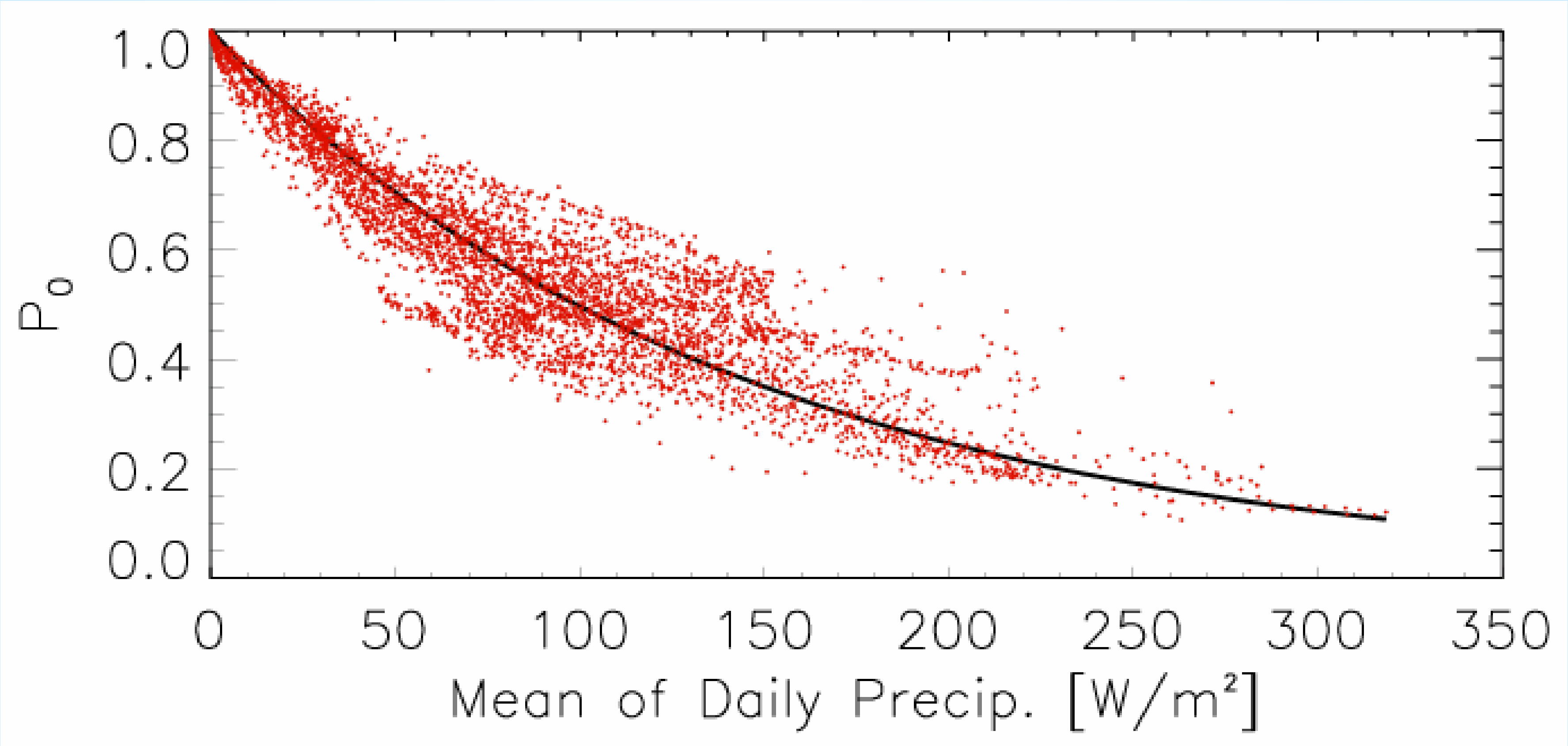
$Q_c = \alpha\xi_t Q_c^{BM}$ with cap on extreme values (50,000 Wm^{-2}!) for numerical reasons. α for sensitivity testing (rescales τ_c^{-1})

$\xi_t = \varepsilon_\xi \xi_{t-1} + (1 - \varepsilon_\xi) y_t$ with ε_ξ chosen such that autocorrelation time $\tau_\xi \approx$ 20 min., 2 hr., 1 day

- ***y*** **from mixed lognormal after Kedem et al (1990)**
- **Cumulative distribution function** $P(y>\acute{y}) = P_o H(\acute{y}) + (1 - P_o) F(\acute{y})$ **P_o probability of zero precip., H Heaviside function**
- $F(\acute{y}, \mu, \sigma)$ **lognormal**
- **Parameterize** $P_o = \exp(-\mu_p Q_c^{BM})$
- **For** $E(y) = 1$, $\mu = \ln(1/(1-P_o)) - \sigma^2/2$, **and set** $\sigma = 4$ **because gives "plausible" variance to mean relation & numerical reasons (Short et al 1993** $\sigma \approx 1$**; higher** σ **gives higher variance for same mean and** P_o**).**

Observed daily precipitation: Fraction of zero precip days P_o vs. mean precip $\overline{Q}_c$

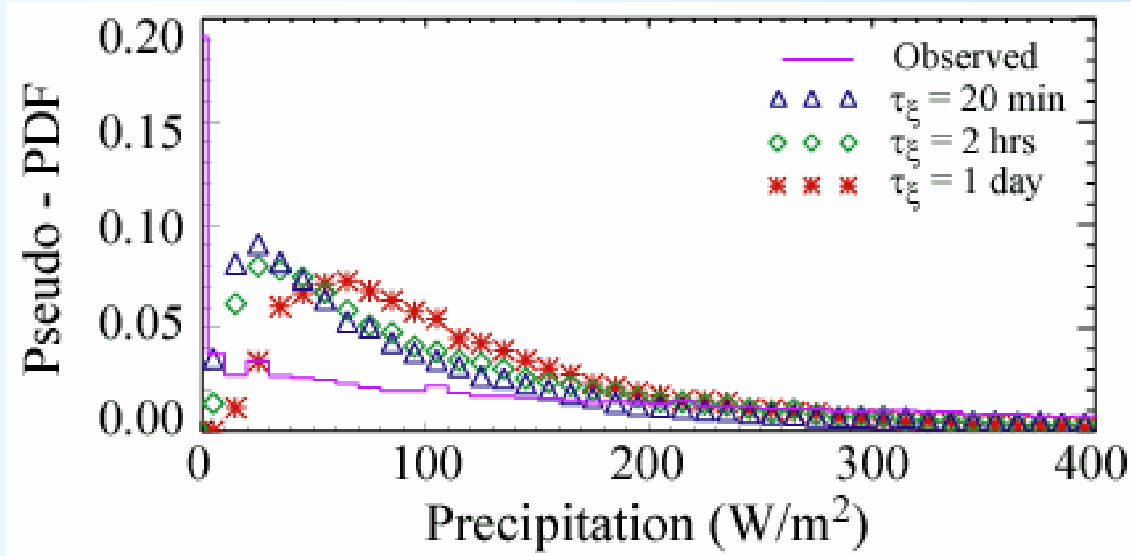
- **Fit: $P_o = \exp(-\mu_p \overline{Q}_c)$**



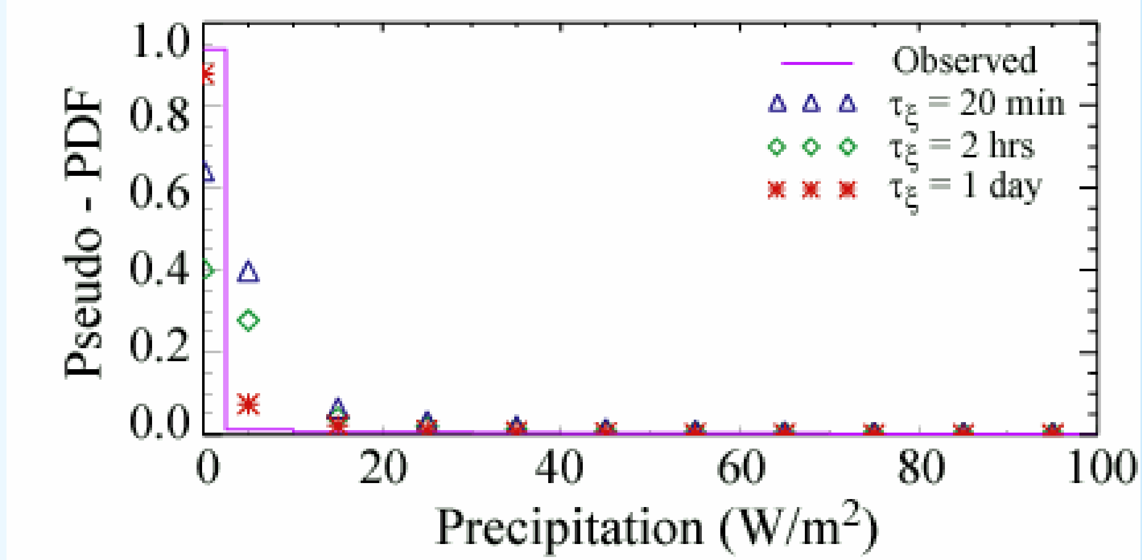
Microwave sounding unit (MSU) ocean region daily data (Jan 1979-Dec 1995). Annual mean used as mean.

PDF of daily precip: Observed vs. QTCM with empirical lognormal stochastic Q_c

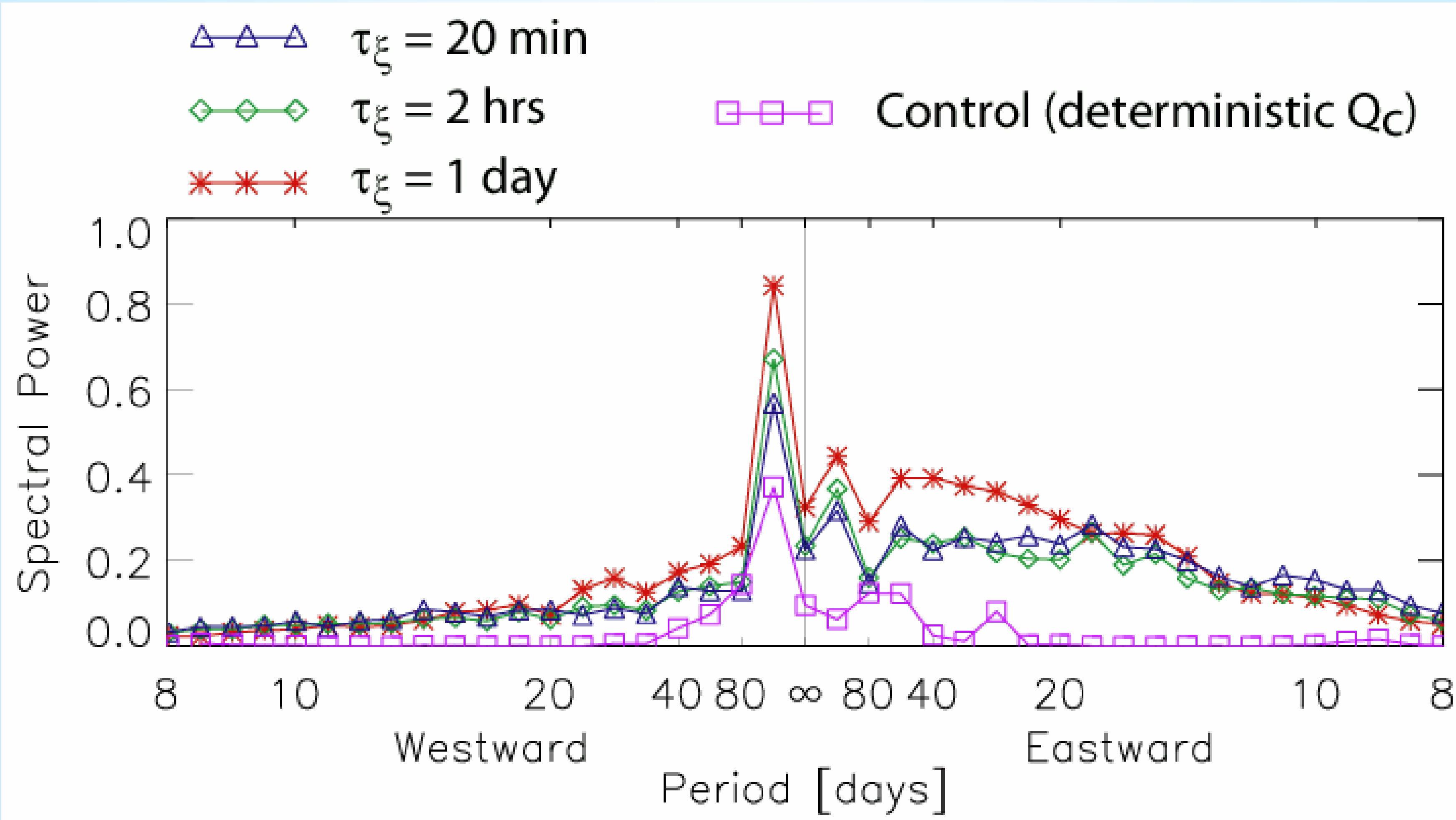
Region of frequent convection (in equatorial Western Pacific)



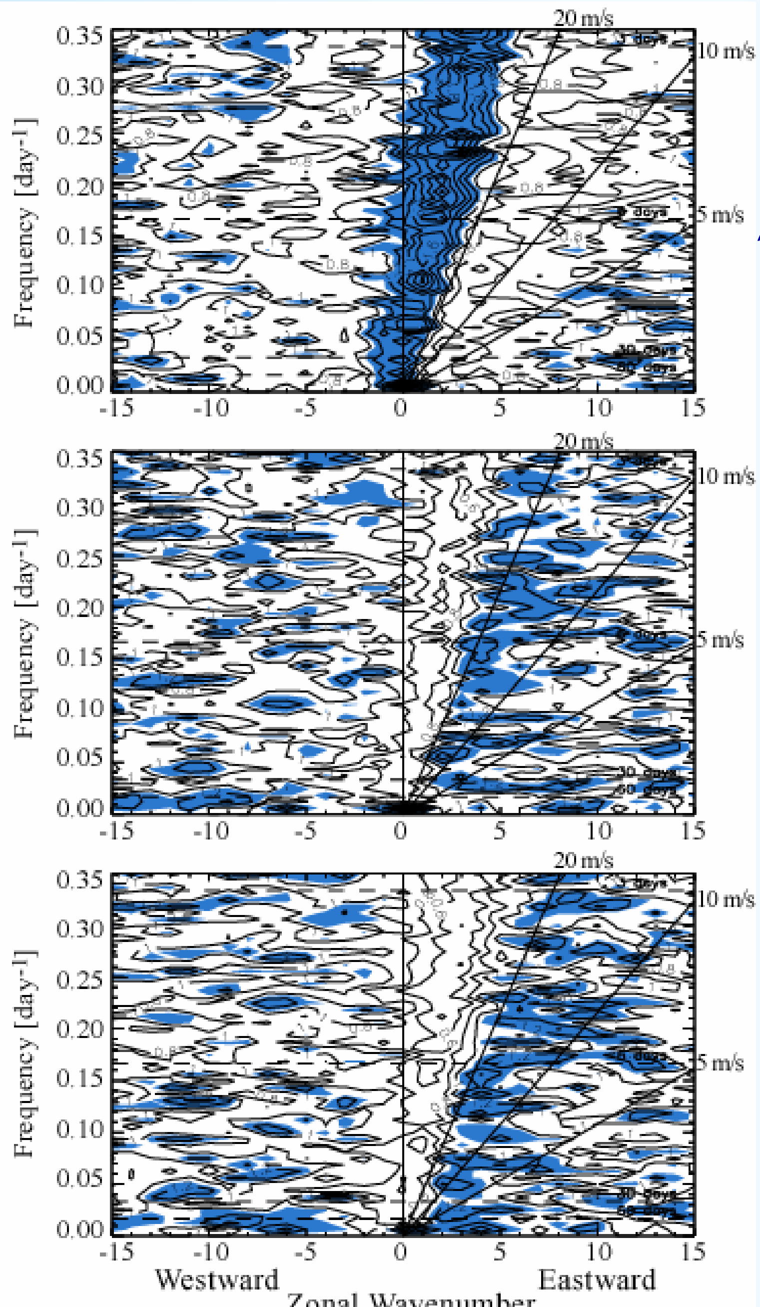
Region of infrequent convection (in tropical Southeastern Pacific)



QTCM with empirical lognormal ($\alpha = 1$) stochastic convective parameterization. Equatorial low-level zonal wind (u_{850}) power spectrum for wave number 1



QTCM OLR PSD ÷ Background (7.5N-7.5S)



Empirical lognormal scheme

τ_ξ = 20 min

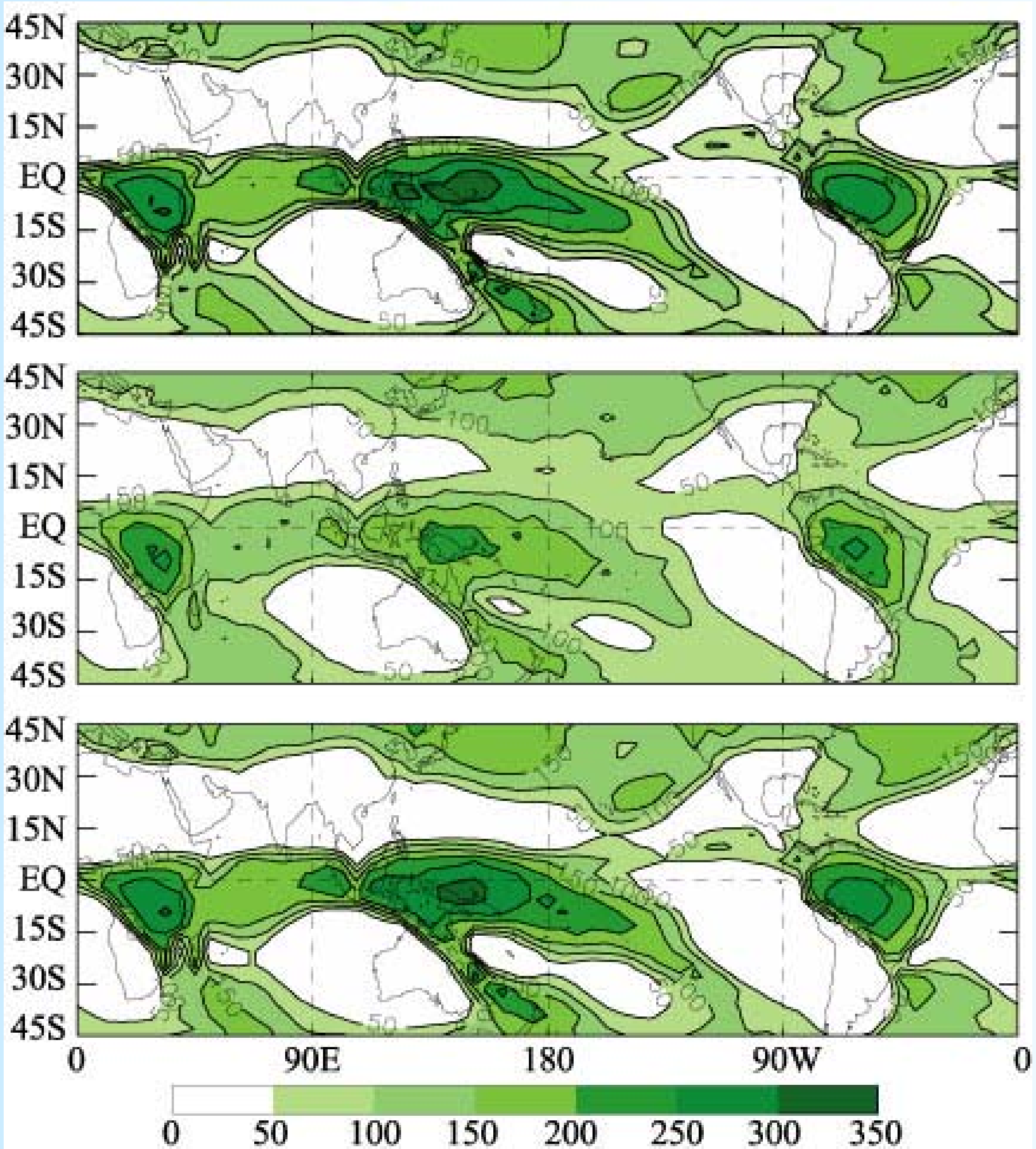
τ_ξ = 2 hrs

τ_ξ = 1 day

Analysis following Wheeler & Kiladis (1999)

Large-scale dynamics reduces sensitivity of clim.

$$Q_c = \alpha\xi Q_c^{BM}$$



Control

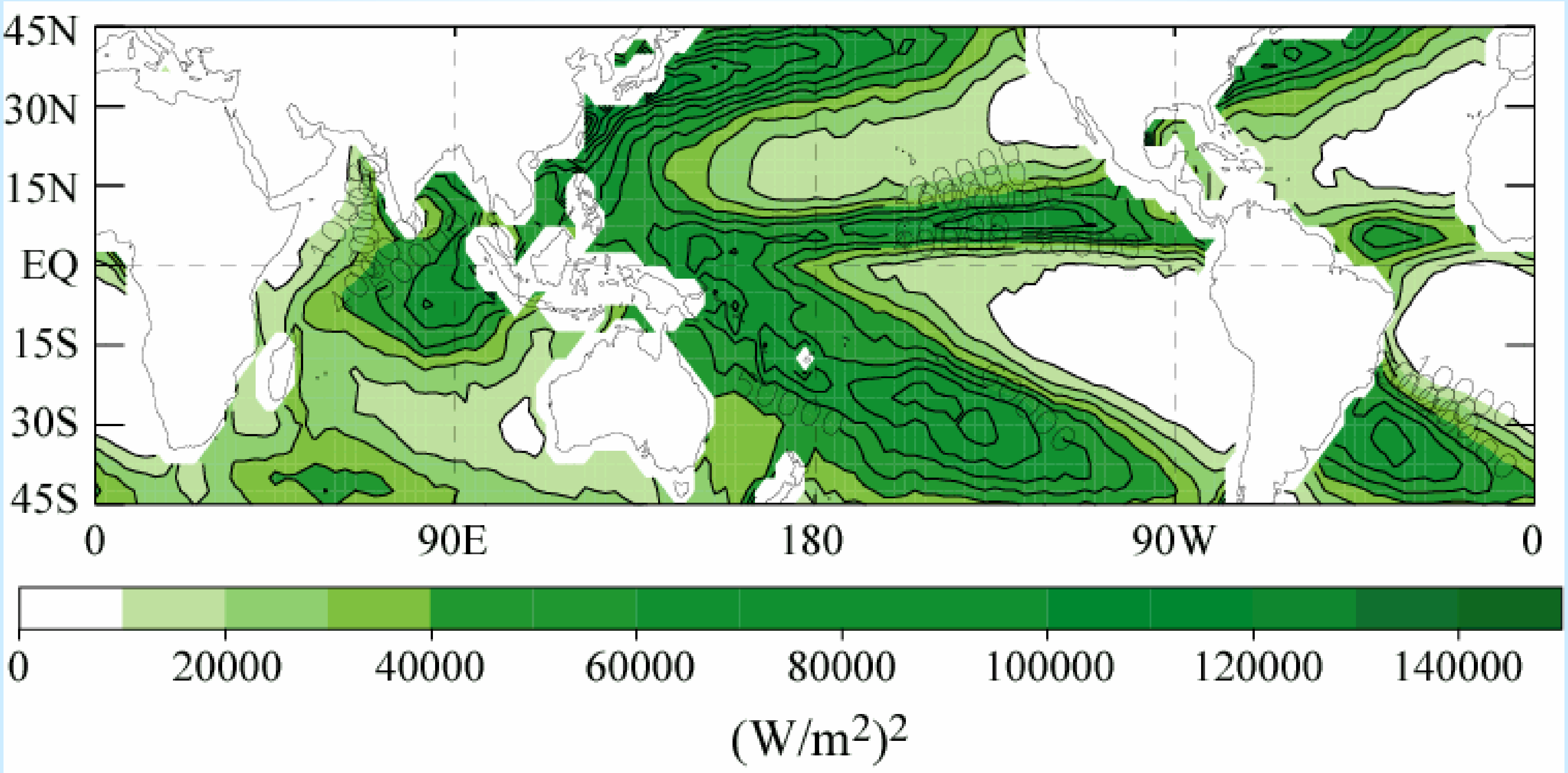
$\alpha = 1$ (Similar to deterministic case with τ_c=2*11)

$\alpha = 11$ (Not a factor of 11 different)

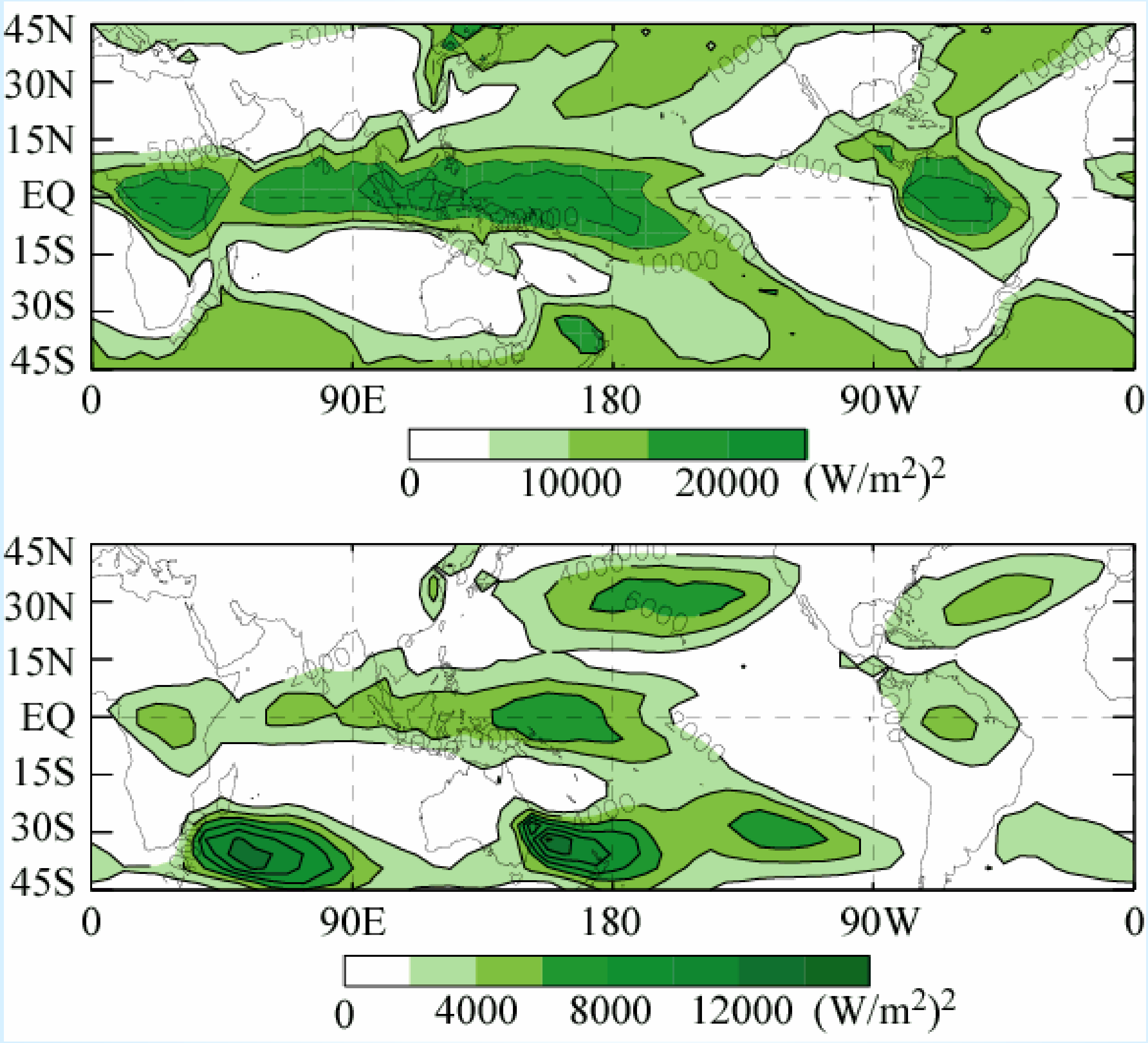
January Precipitation

LN02

Variance of daily mean precipitation from observations (MSU)



Model dynamics can increase or decrease precip. variance relative to "no dynamics" case (Q_c^{BM} from clim. input to stoch. scheme)



No dynamics case

$\alpha = 11$
$\tau_\xi = 1$ day

$\alpha = 11$
$\tau_\xi = 1$ day

Physics-motivated approach, example in QTCM Stochastic "CAPE scheme"

- **Betts–Miller**

$$Q_c \propto \tau_c^{-1} \mathrm{R}(C_1)$$

– Q_c convective heating, τ_c time scale

– C_1 a measure of CAPE, $\mathrm{R}(x) = x, x > 0; = 0, x \leq 0$

- **Retain physical postulates but assume CAPE Gaussian about mean**

$$Q_c \propto \tau_c^{-1} \mathrm{R}\,(C_1 + \xi)$$

– $\xi_t = \varepsilon_\xi \xi_{t-1} + z_t$

- **Choose ε_ξ such that autocorrelation time of CAPE random process τ_ξ = 20 min, 2 hr, 1 day.**

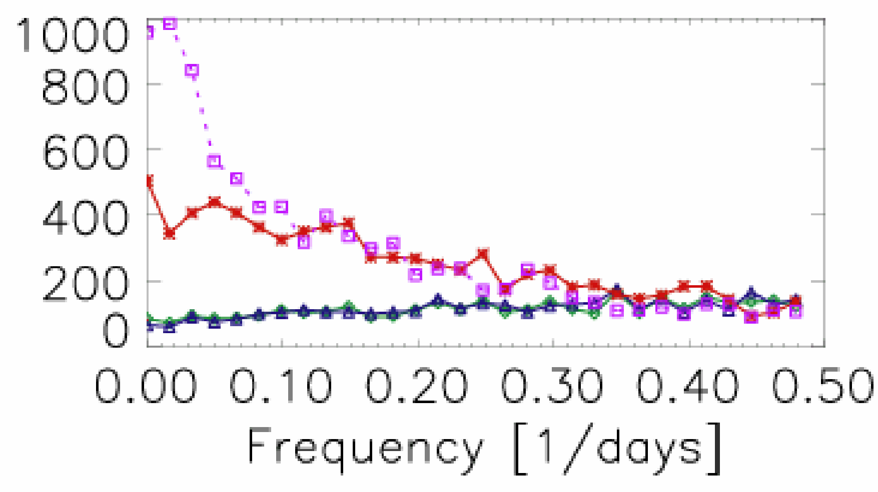
– Sensitivity test and corresponds to different physics (convective cells to longer lived mesoscale systems)

- **z_t Gaussian, zero mean, s. dev. σ_z.**

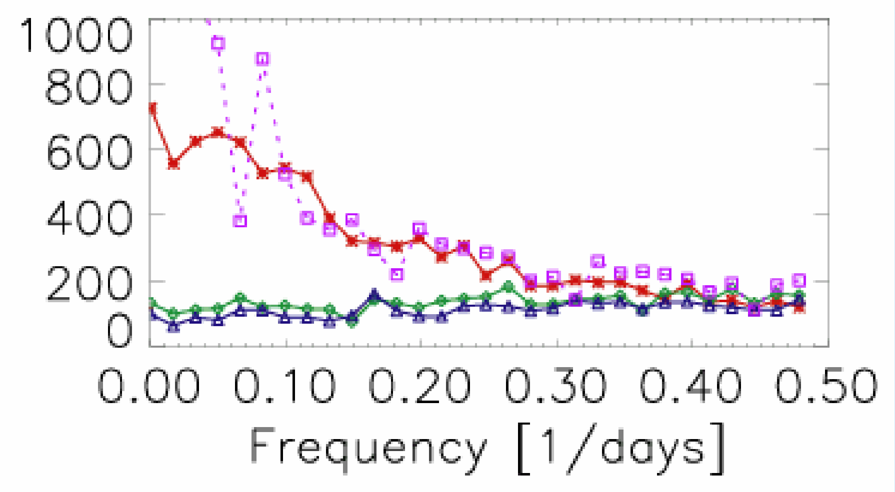
– set σ_z such that model matches observations in freq band (0.4, 0.5 day^{-1})

Observed and model power spectrum of precip at 60E and 180E on the equator

Mid-Indian Ocean



Mid-Pacific Ocean



Observed MSU - - - - - - - -

Model with stochastic precip parameterization:

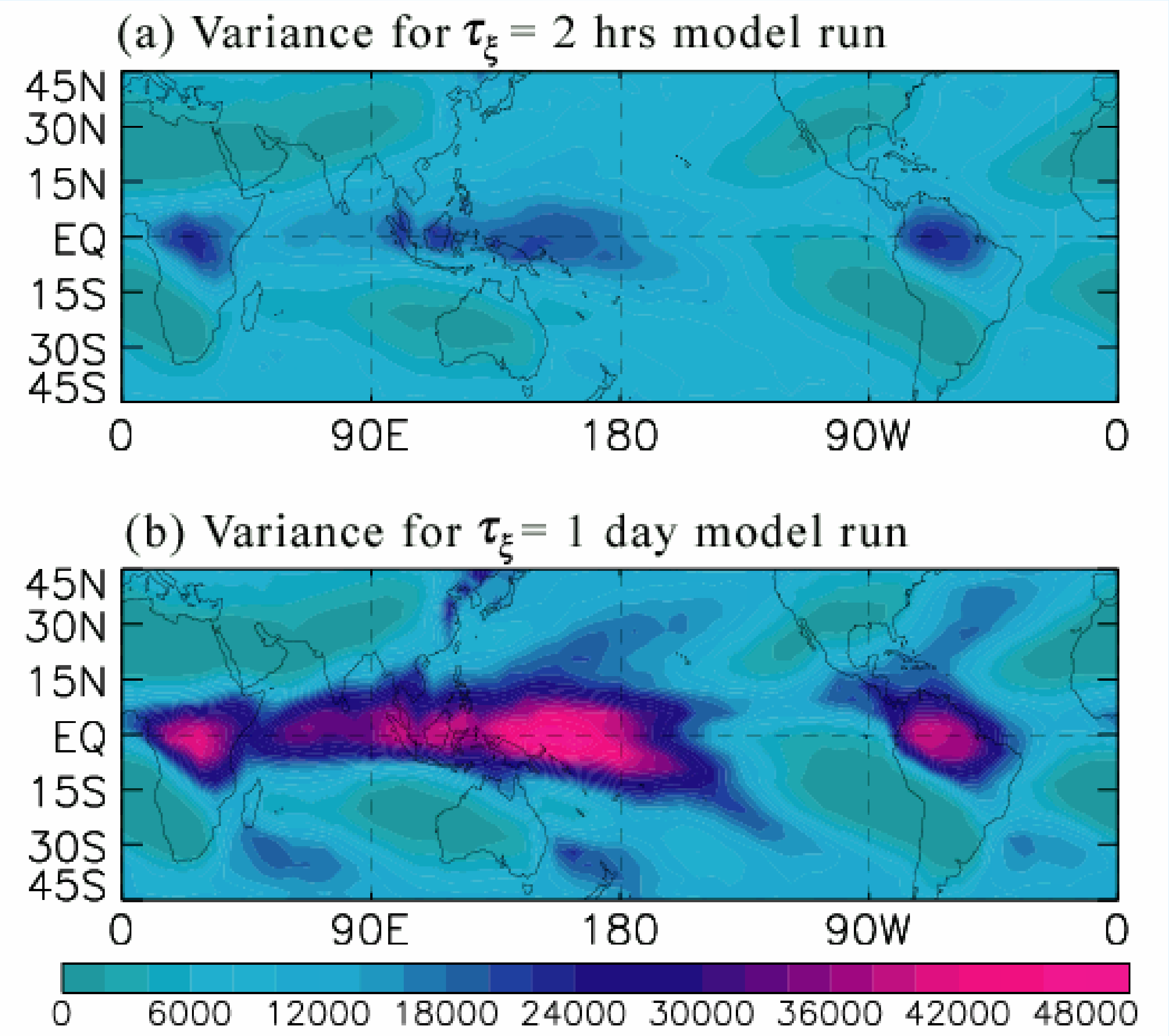
τ_ξ = 20 min ————————

τ_ξ = 2 hrs ————————

τ_ξ = 1 day ————————

LN00

Variance of QTCM with stochastic CAPE scheme for two values of τ_ξ

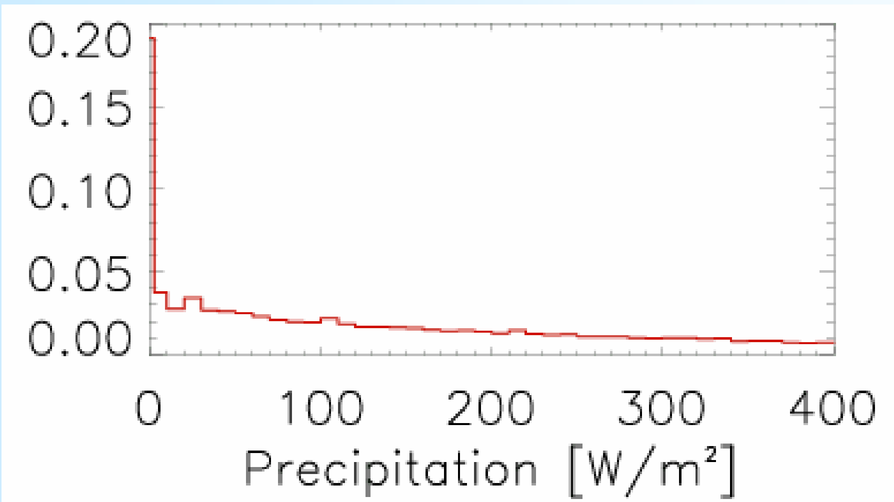


σ_z=0.8K

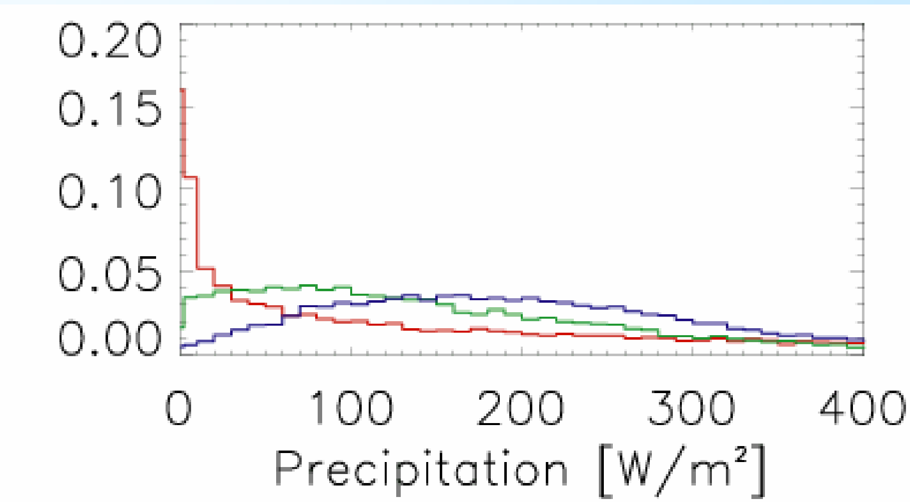
σ_z=0.1K

Probability density function of daily precip (in west Pacific, 5N)

MSU Observations



Model runs



QTCM with CAPE stochastic precip. parameterization:

τ_ξ = 20 min

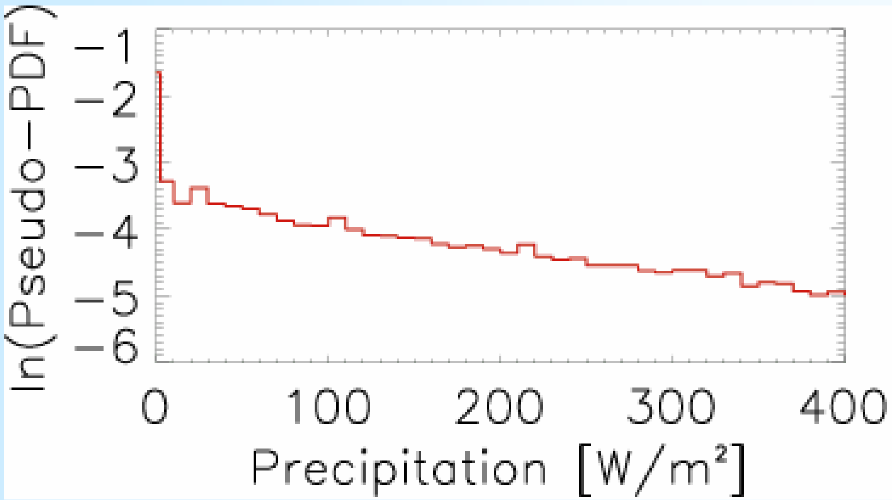
τ_ξ = 2 hrs

τ_ξ = 1 day

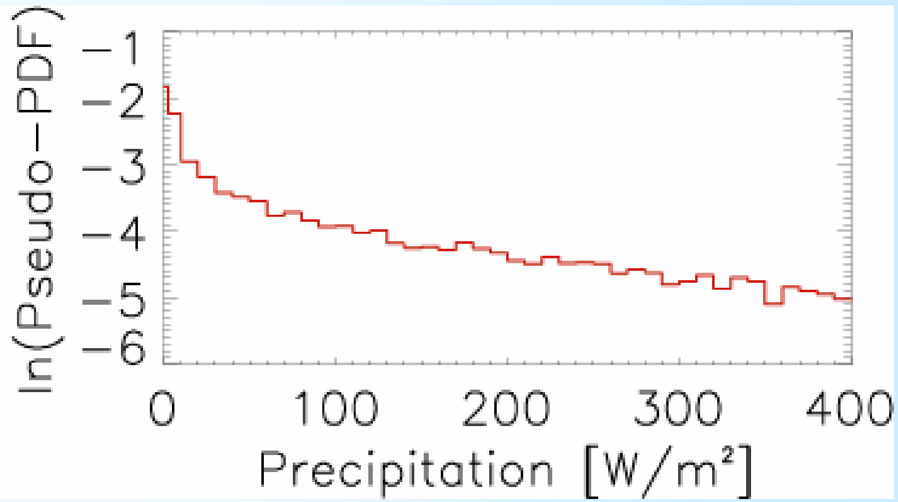
Probability density function of daily precip (in west Pacific, 5N)

- Log-linear

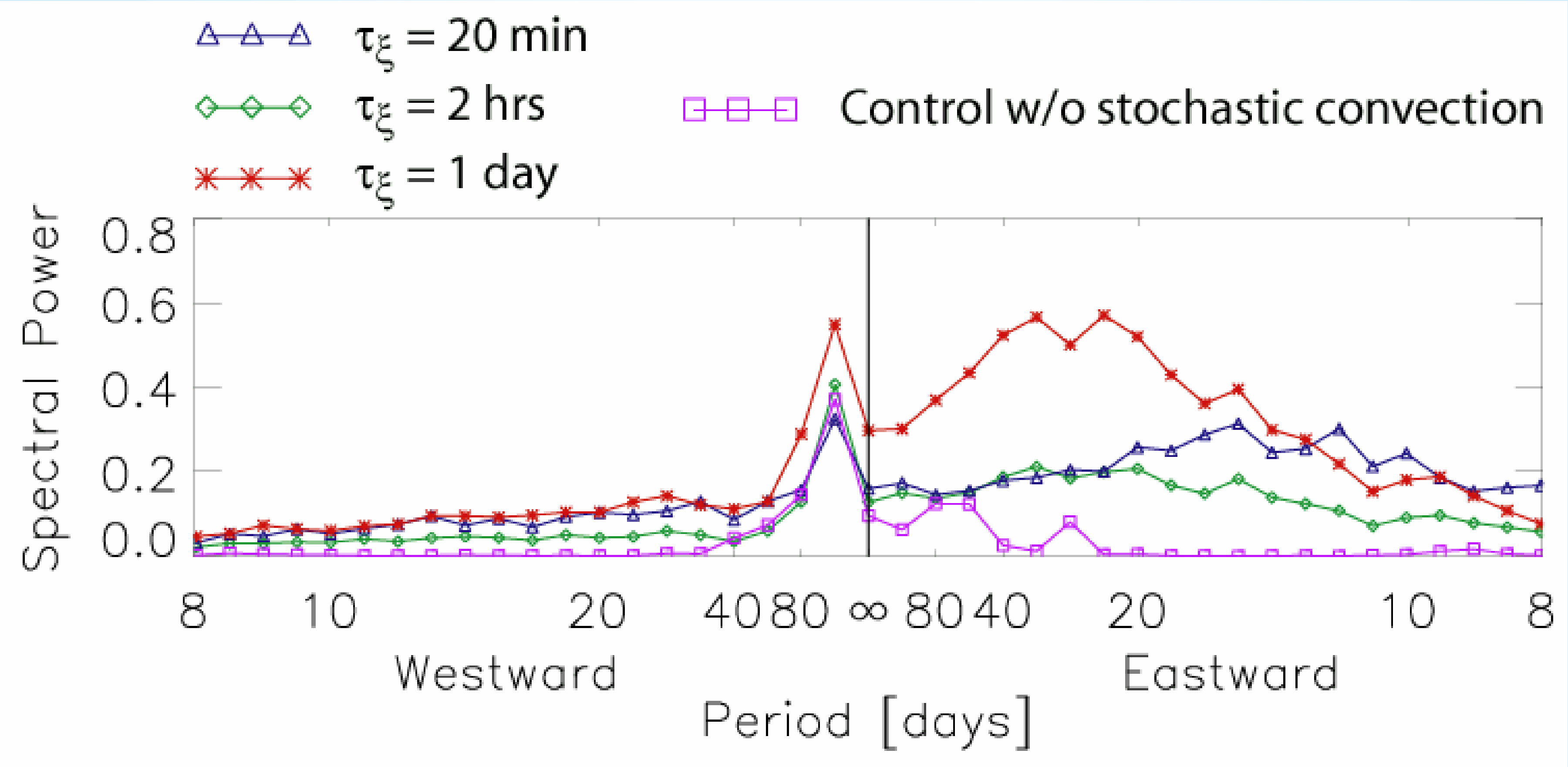
MSU Observations



QTCM with stochastic CAPE scheme, τ_ξ = 1 day



Impact of CAPE stochastic convective parameterization on tropical intraseasonal variability



Physics-motivated approach example in CCM3
Stochastic "CAPE-M_b" scheme

Modify mass flux closure in Zhang - McFarlane (1995) scheme

Evolution of CAPE, A, due to large-scale forcing, F

$$\partial_t A\,_c = -M_b F$$

Closure

$$\partial_t A\,_c = -\tau^{-1} A$$

$$\Rightarrow \quad M_b = A(\tau F)^{-1} \quad (\text{for } M_b > 0)$$

Stochastic modification

$$M_b = (A + \xi)(\tau F)^{-1}$$

$$\Rightarrow \quad \partial_t A\,_c = -\tau^{-1}(A + \xi)$$

i.e., same as adding stochastic component to CAPE

But posited as stochastic effect in cloud base mass flux M_b

ξ Gaussian, autocorrelation time 1day

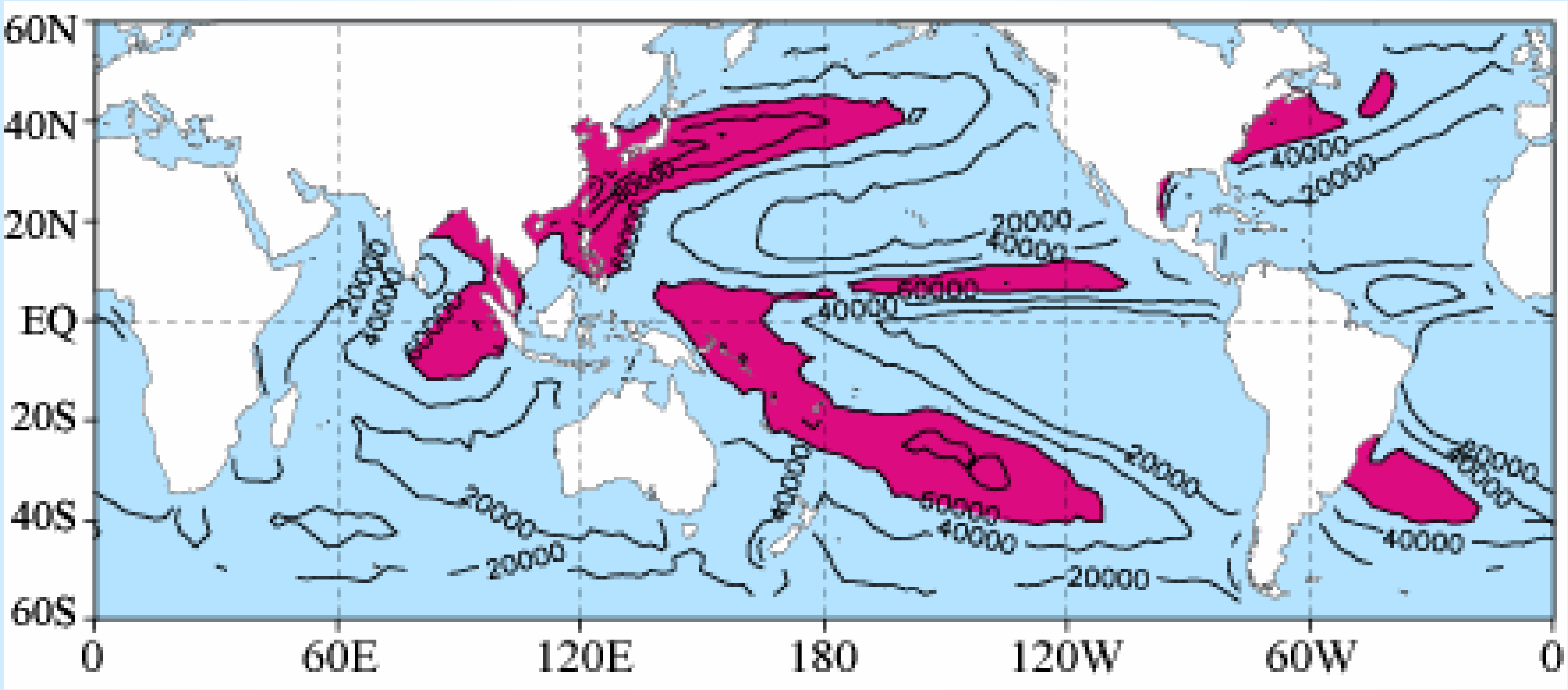
CCM3 Test scheme for stochastic effects in vertical structure of heating (VSH scheme)

$$Q_c(p) = Q_c^{ZM} + (\xi_t - < \xi_t >)/\Delta t$$

- ξ_t Gaussian, autocorrelation time $\tau_\xi = 1$ day
- White in vertical except zero vertical mean
- Convective heating only

- Simple test for potential impacts of variations in vertical structure
- Contrasts with CAPE-M_b scheme which has no direct alteration of vertical structure from ZM scheme

Variance daily precipitation (Microwave Sounder Unit product)

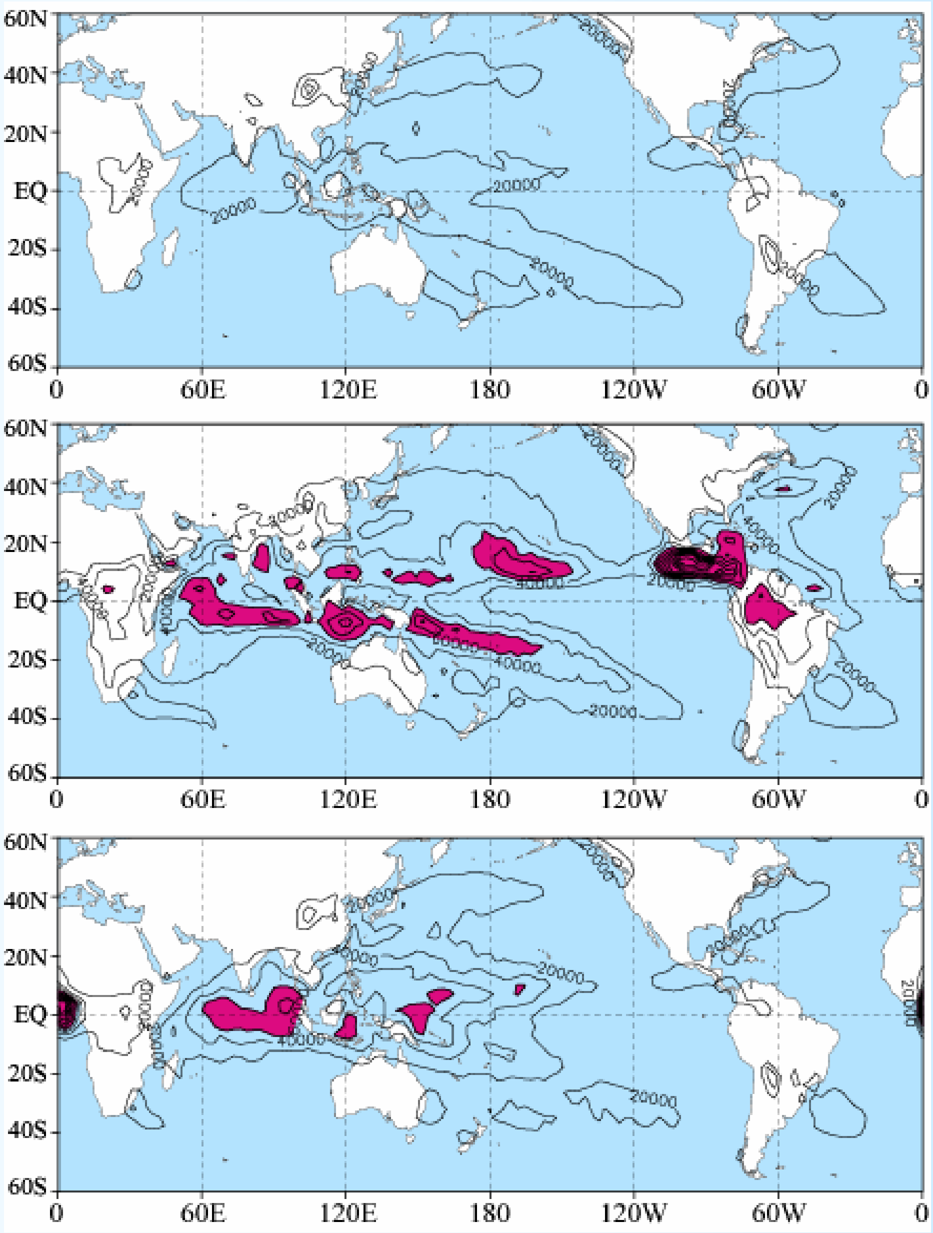


CCM3 variance of daily precipitation

Control run

CAPE-M_b scheme

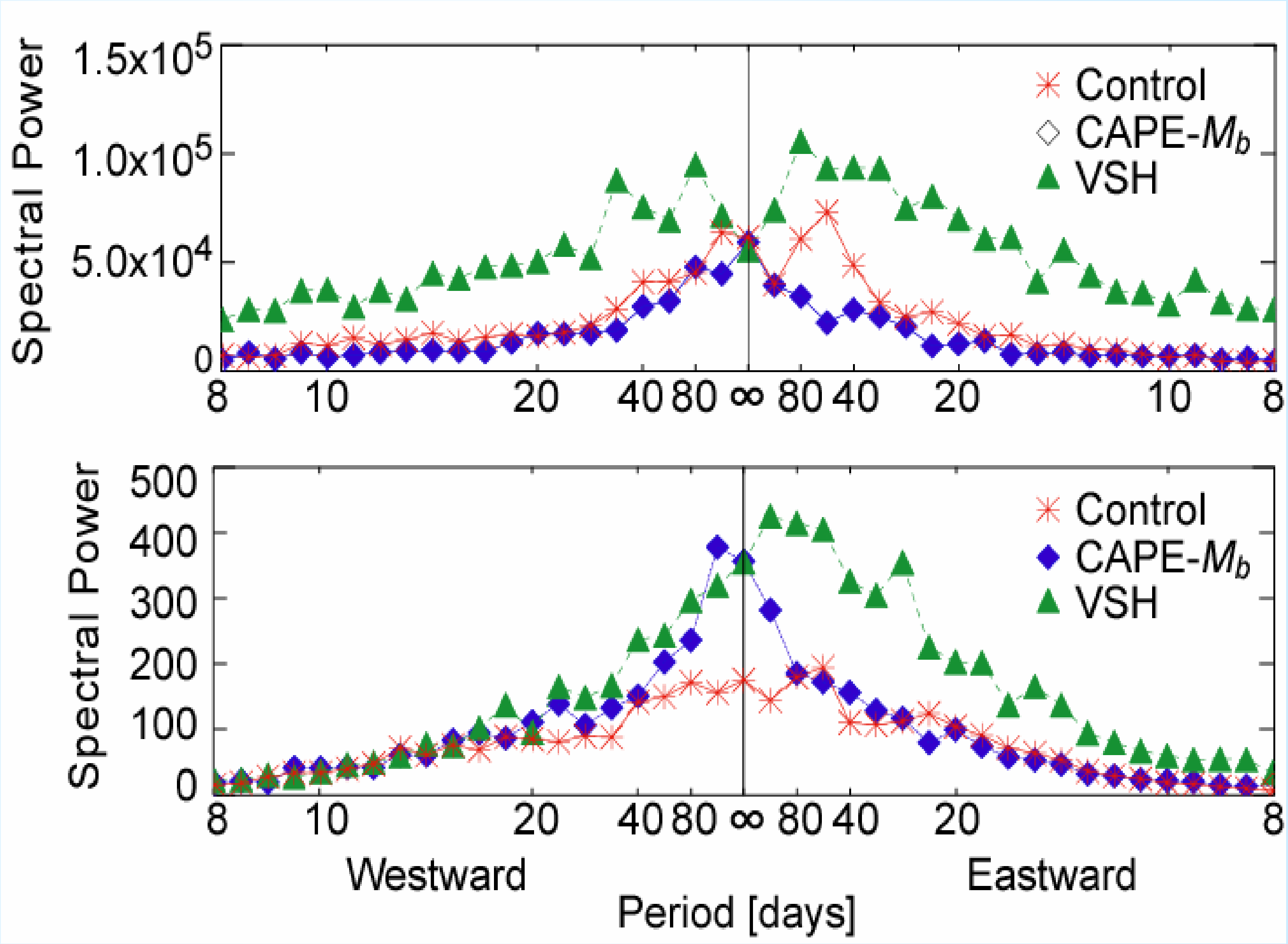
VSH scheme



CCM3 Equatorial wavenumber one spectral power: precipitation and-low level winds

Precipitation anomalies

850 hPa zonal wind anomalies

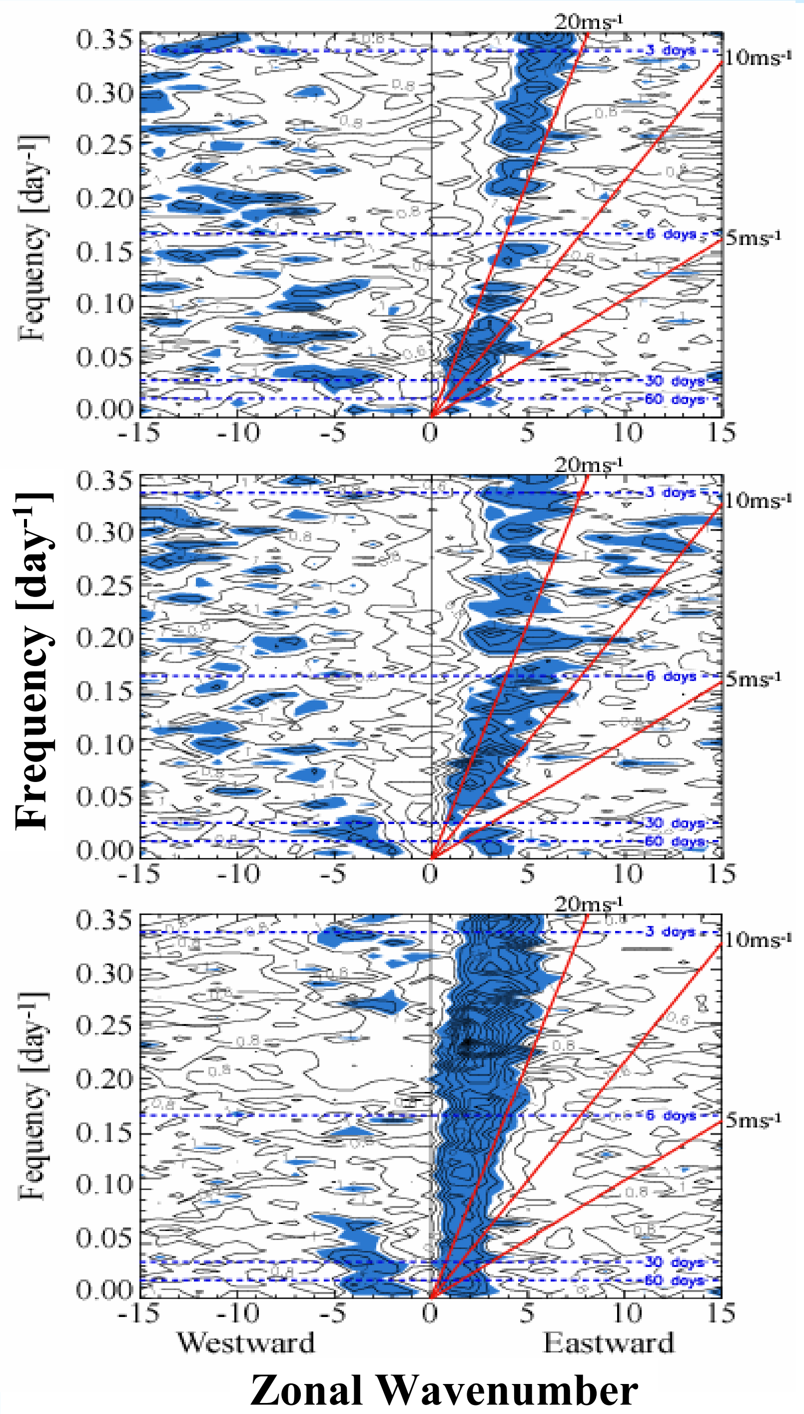


CCM3 OLR (7.5N-7.5S) Power spectral density ÷ Background

Control run

CAPE-M_b scheme

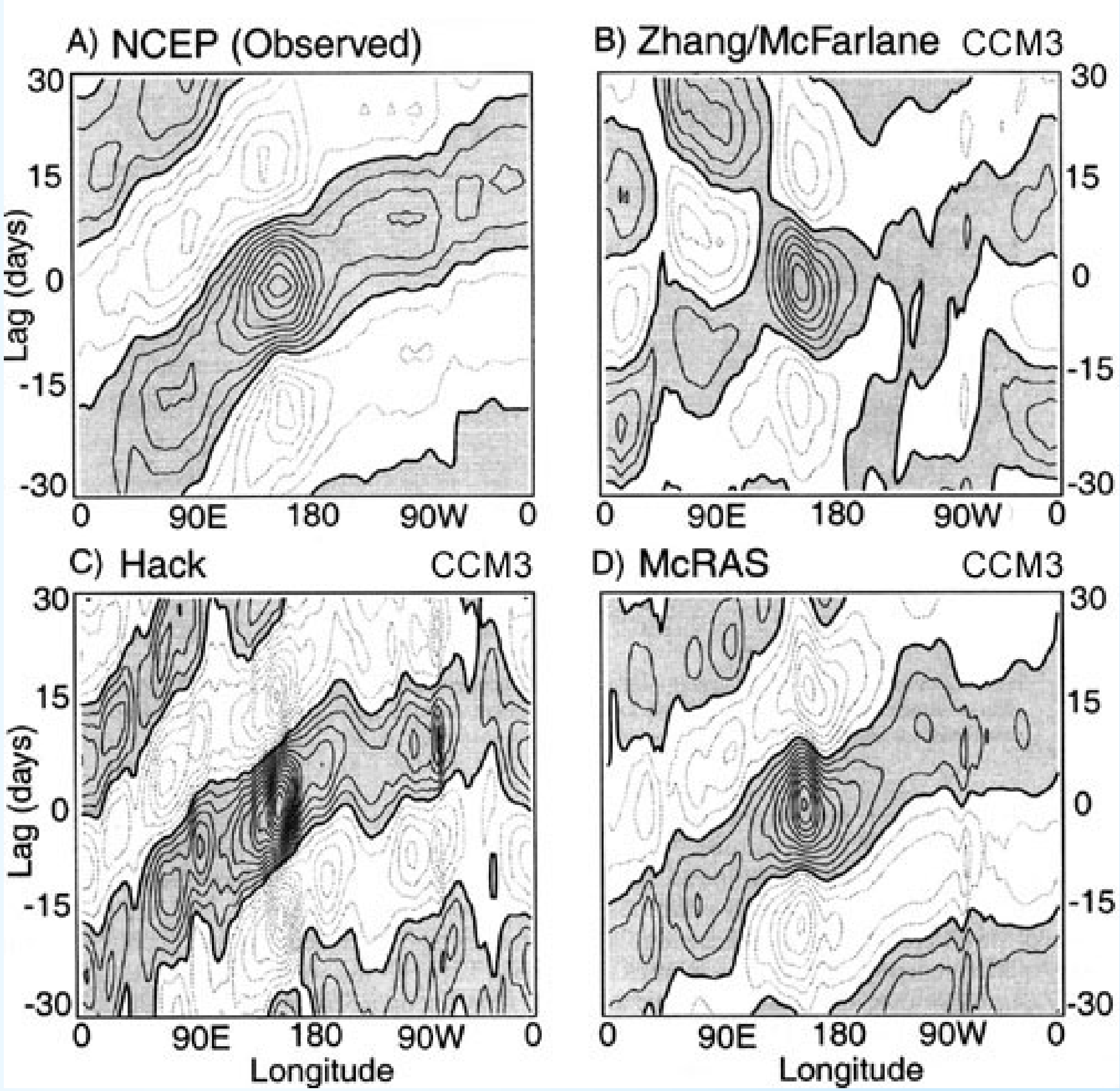
VSH scheme



Analysis following Wheeler & Kiladis (1999)

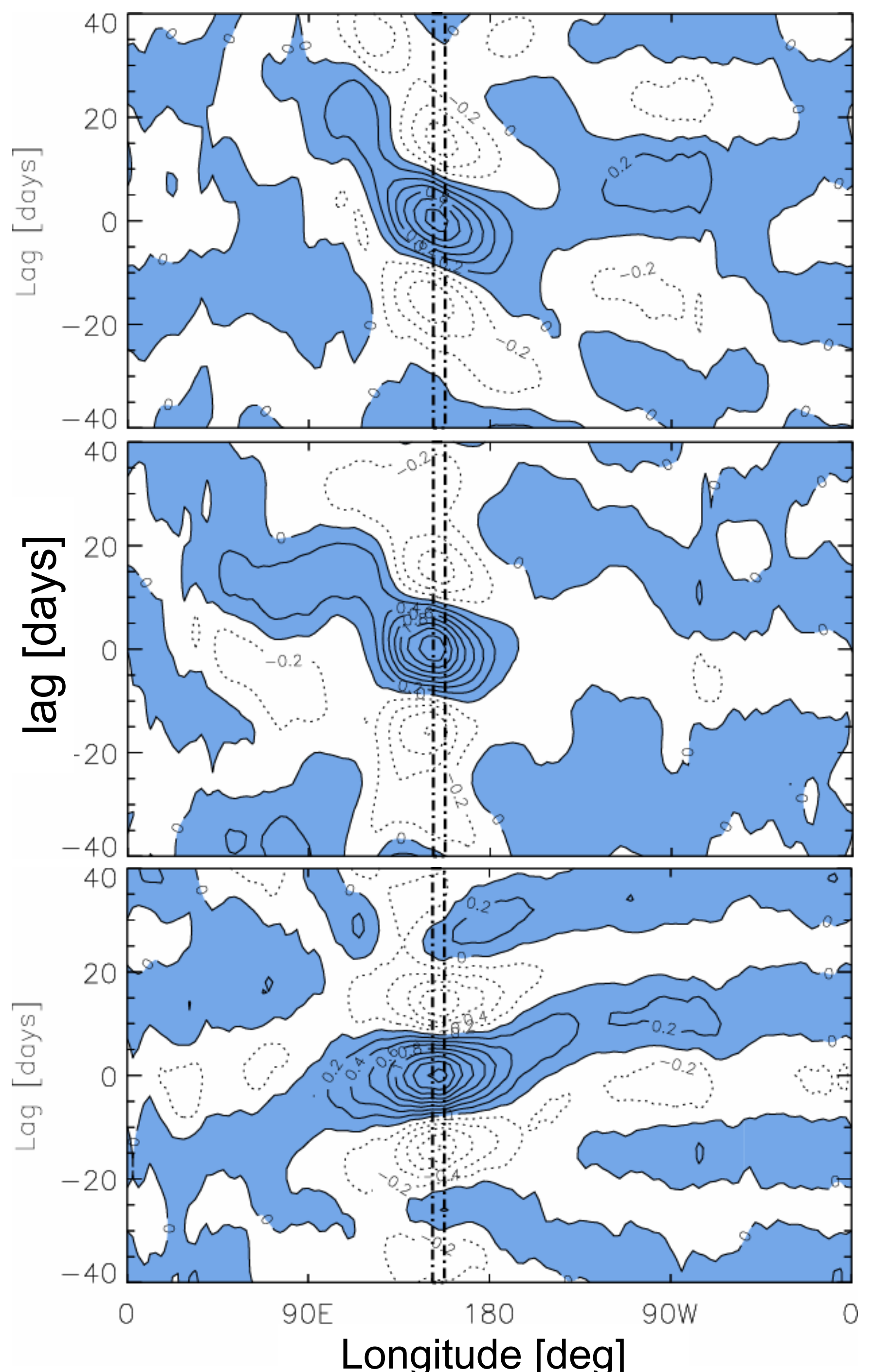
Equatorial zonal wind at 850mb (u_{850}) regressed on u_{850} avg. near 155E (10S-10N)

NCEP (Dec-May) vs. CCM3 with three deep convective parameterizations (perpetual March)



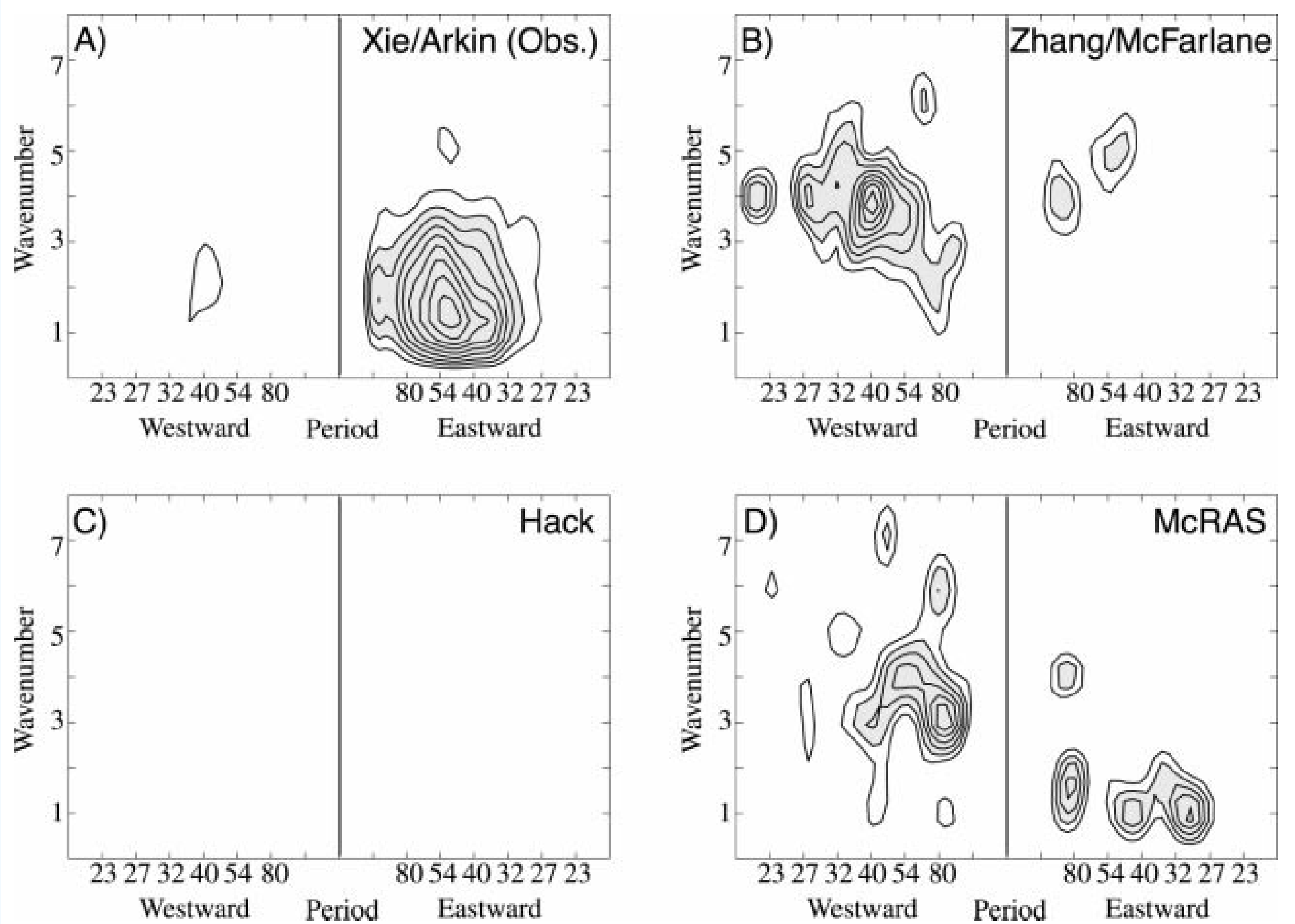
Maloney and Hartmann, 2001

CCM3 Equatorial zonal wind at 850mb (u_{850}) regressed on u_{850} avg. near 155E (10S-10N)



Power spectral density CCM3 vs. obs.

Three convective parameterizations



Maloney and Hartmann, 2001

Summary: Empirical approach

- **Heating strongly interacts with the large-scale.**
  - e.g., dynamics reduces variance relative to "no-dynamics" calculation in some cases and increases it in others
  - **can't estimate heating probability distribution from data and calibrate scheme offline since dynamics so strongly changes properties (favors physics-motivated approach).**
- Large-scale dynamics tends to adjust mean toward a climatology intrinsic to the model ➲ reduced sensitivity to stochastic component; preservation of mean of deterministic scheme not an important property of stochastic scheme.
- **Intraseasonal variability can be strongly impacted by inclusion of stochastic component, but there is parameter sensitivity.**

Summary: Physics-motivated approach

- **Even simple version, e.g., CAPE scheme, can yield encouraging results (incl. probability distribution of heating)--but there is parameter sensitivity.**
- **Autocorrelation time of the stochastic processes matters.**
  - Longer autocorrelation time, on the order of a day, yields more impact and better results for the CAPE scheme example in the QTCM. Suggests importance of mesoscale processes?
- **Stoch. forcing arising physically from small-scales can be a significant source of intraseasonal variability--but nature depends strongly on interaction with large-scale**
- **Variations in vertical structure yield signature more suggestive of dry wave types with precip. by-product**

Where to go….

- modify Relaxed Arakawa-Schubert but including updraft history--will this give physical basis to time autocorrelation and vertical variation of heating?
- evaluate buoyancy decay closure vs. "goes 'til it can't"
- impacts on transports, strat-trop, chemistry,…?
- "convective entities": e.g., randomly initiated simplified model of mesoscale system within grid cell?

Percent of TRMM precip. from mesoscale convective systems

Nesbitt et al., 2002