Stochastic deep convective parameterization

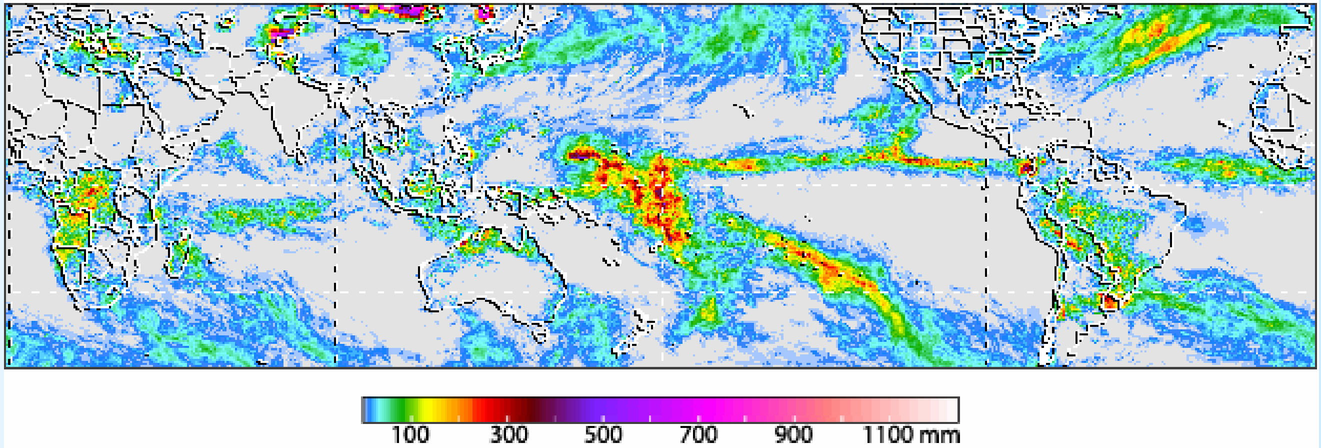
J. David Neelin and Johnny W.-B. Lin*

Dept. of Atmospheric Sciences & Inst. of Geophysics and Planetary Physics, U.C.L.A.
*CIRES, Boulder, CO (now U. Chicago)

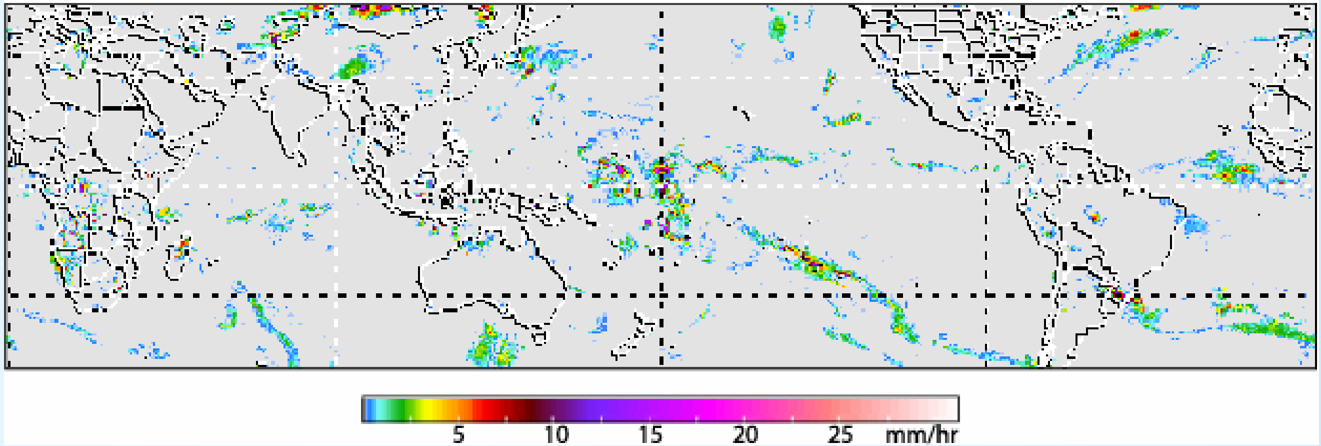
- Moist convective parameterizations represent ensemble mean effects of sub-grid scale motions on Reynolds-average large-scale as deterministic function of the large-scale variables
- For a domain ~(200 km)^2 x (20 minutes) the sample of deep convective elements is not large ➲ variance in average
- Probability 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)

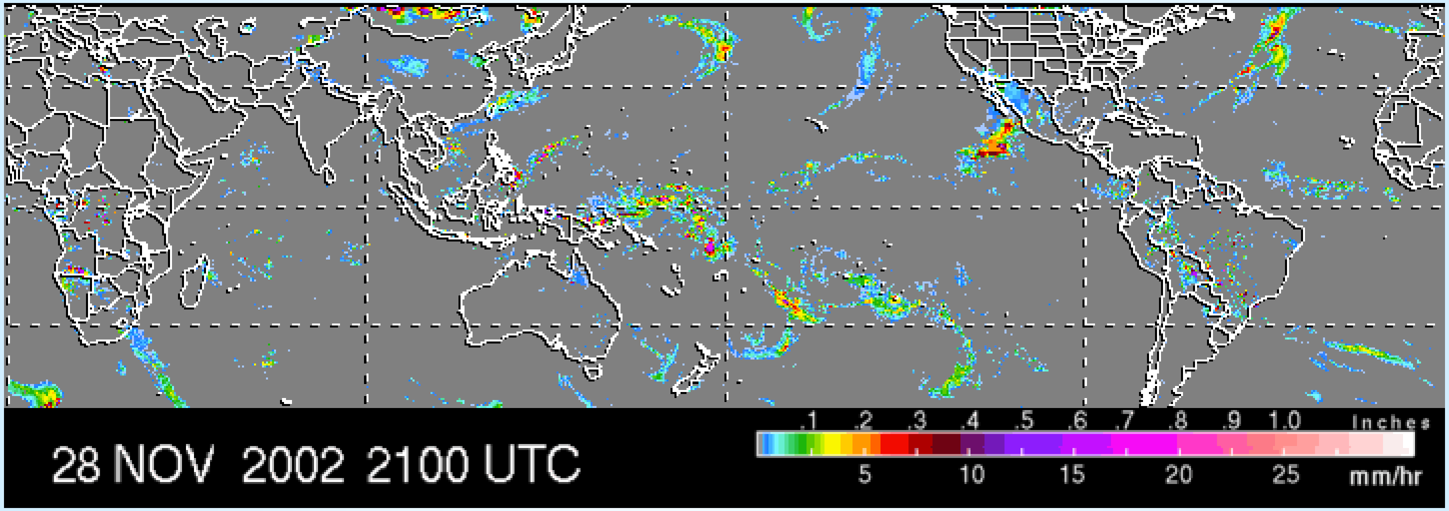
Weekly accumulation


TRMM - Merged (3B42RT) Rainfall Accumulation for Nov. 28 - Dec. 5 2002

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


3Hr Rainfall for Dec. 1 2002 1500UTC

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



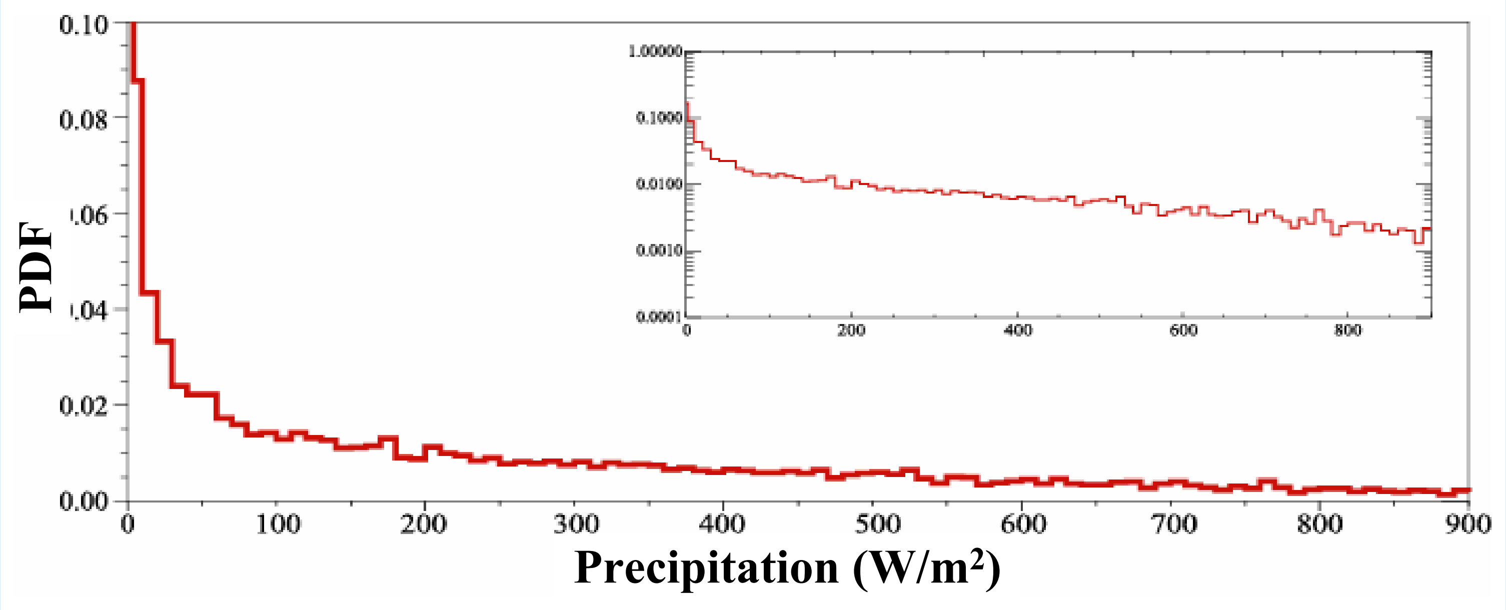
3 hour rainfall over one week (Nov. 28-Dec. 5, 2002)

START

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

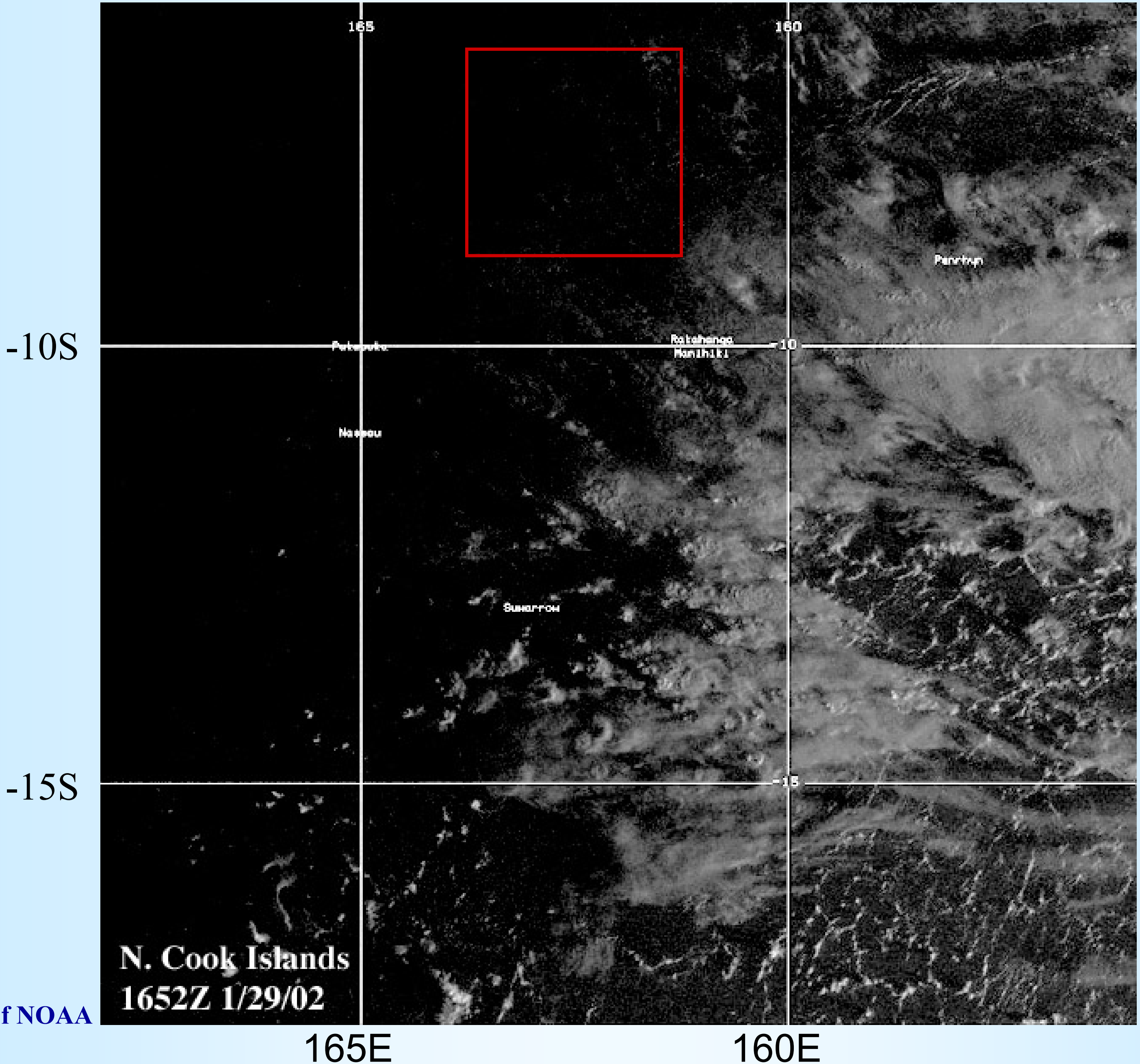
Probability density function of daily precip. in west Pacific warm pool

TRMM-based 3B42



- 150-152E, 6.5-8.5S

Visible image – Western Pacific 1652Z



Courtesy of NOAA

START

Approaches to stochastic convective parameterization

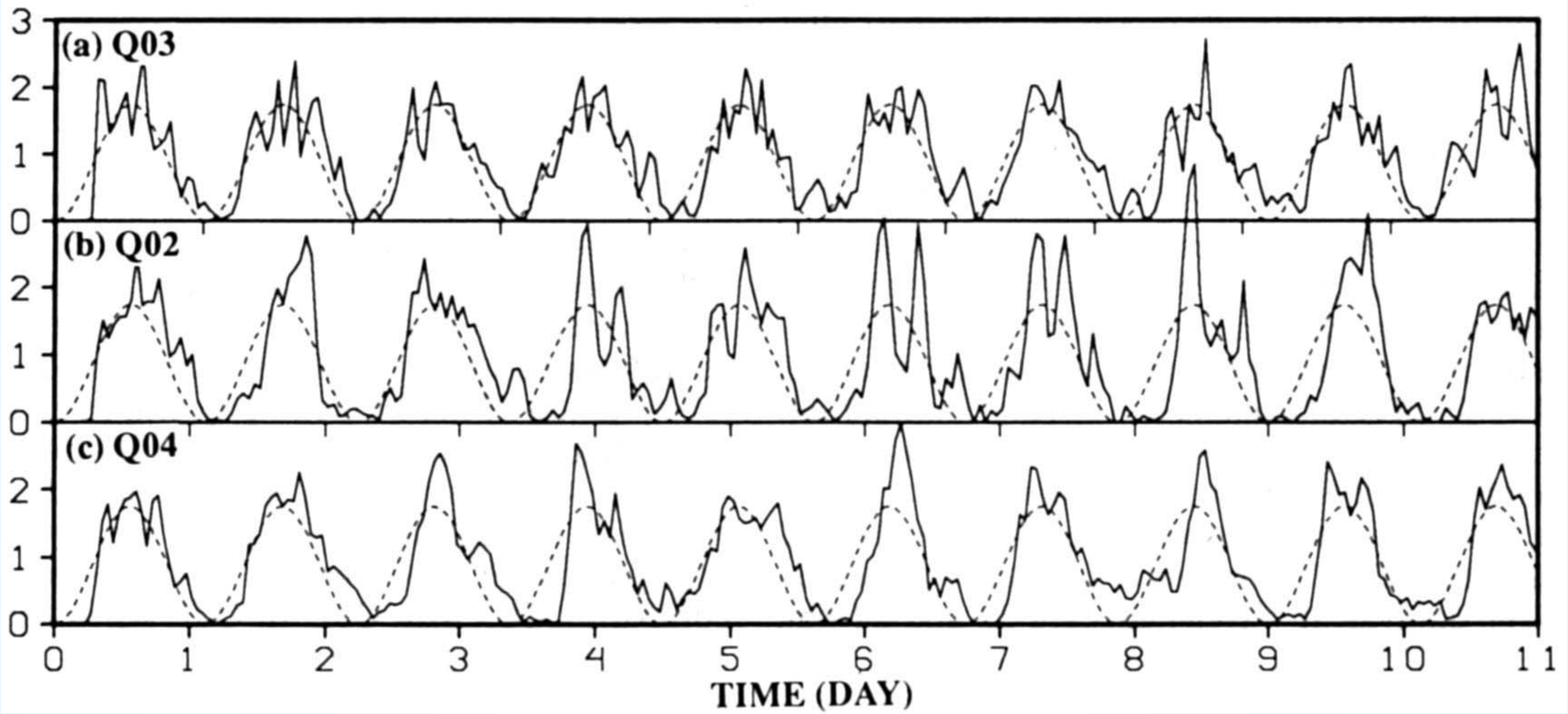
- **Empirical:** Directly control statistics of the overall convective heating; specify distribution as function of model variables, with dependence estimated empirically.
  - Related to hydrology & remote sensing literature but heating/precipitation has strong feedbacks with large-scale flow.
  - Example 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

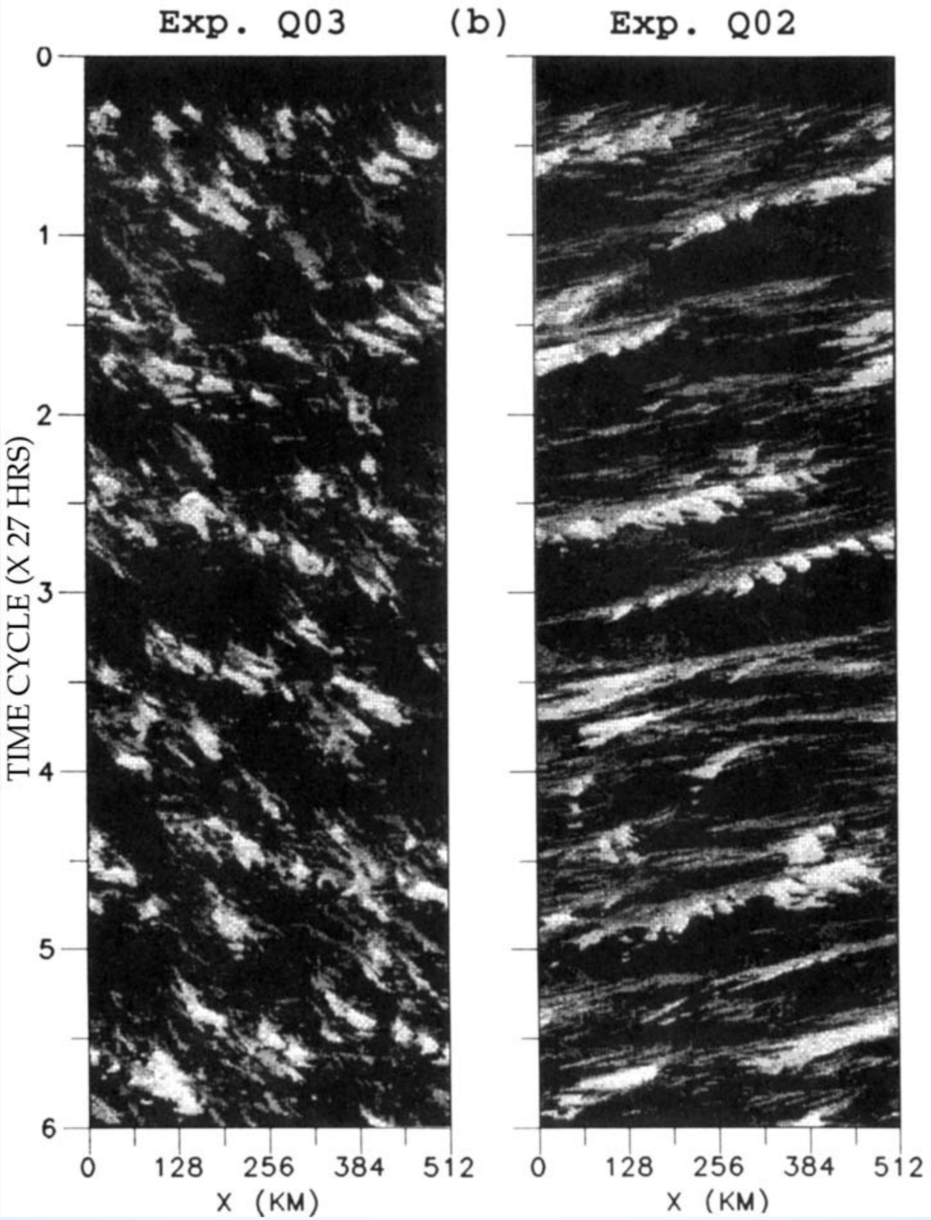
- - - - Imposed large-scale forcing (cooling & moistening)



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

Xu et al (1992) Cumulus Ensemble Model
Cloud-top temperatures

No shear



With 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 $\langle\ \rangle$

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

$\langle$Moist static energy equation$\rangle$

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

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

Net energy flux into column

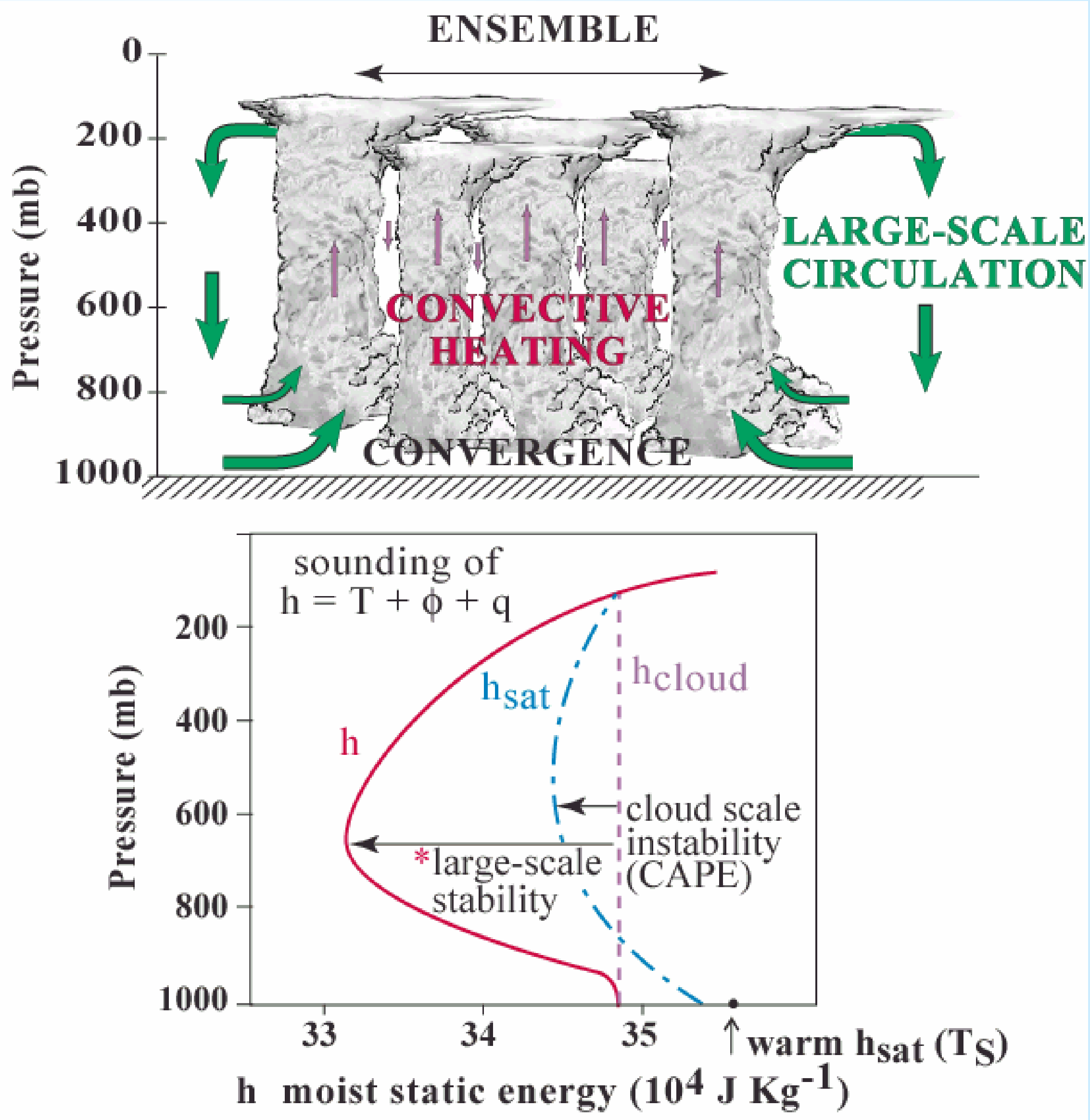
Moist static energy
$h = s + q$

Moist convection interacting with large-scale dynamics

- **Convective Quasi-Equilibrium:**
  Fast convective motions reduce Convective Available Potential Energy (CAPE)
  - ➢ Constrains temperature through deep column
  - ➢ Baroclinic pressure gradients

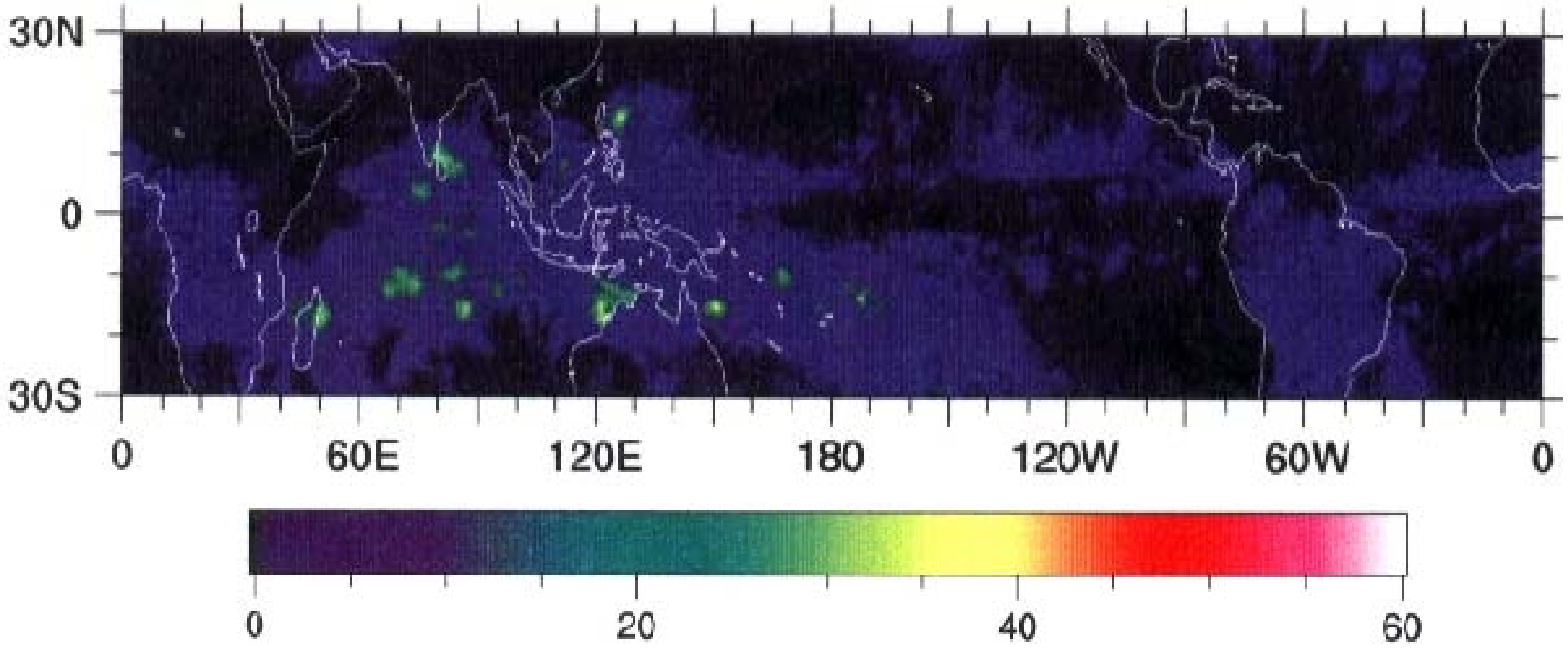
- **Gross moist stability at large scales**

Refs: Arakawa & Schubert 1974; Emanuel et al 1994; Neelin & Yu 1994; Brown & Bretherton 1997; Neelin & Zeng 2000



(After Neelin (1997))

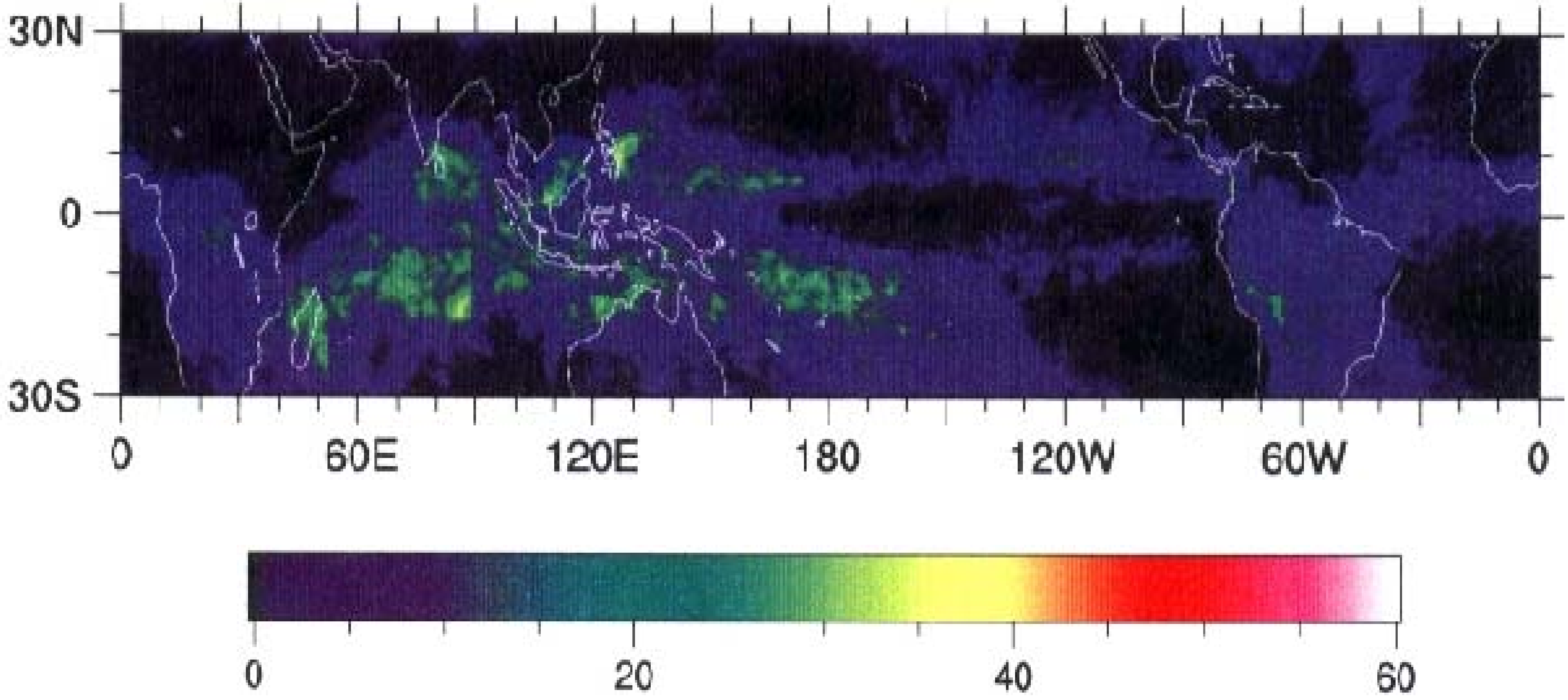
Winter 1984 Observed DCH* Variance [$(K/day)^2$] (period >10 days)



*DCH = deep convective heating

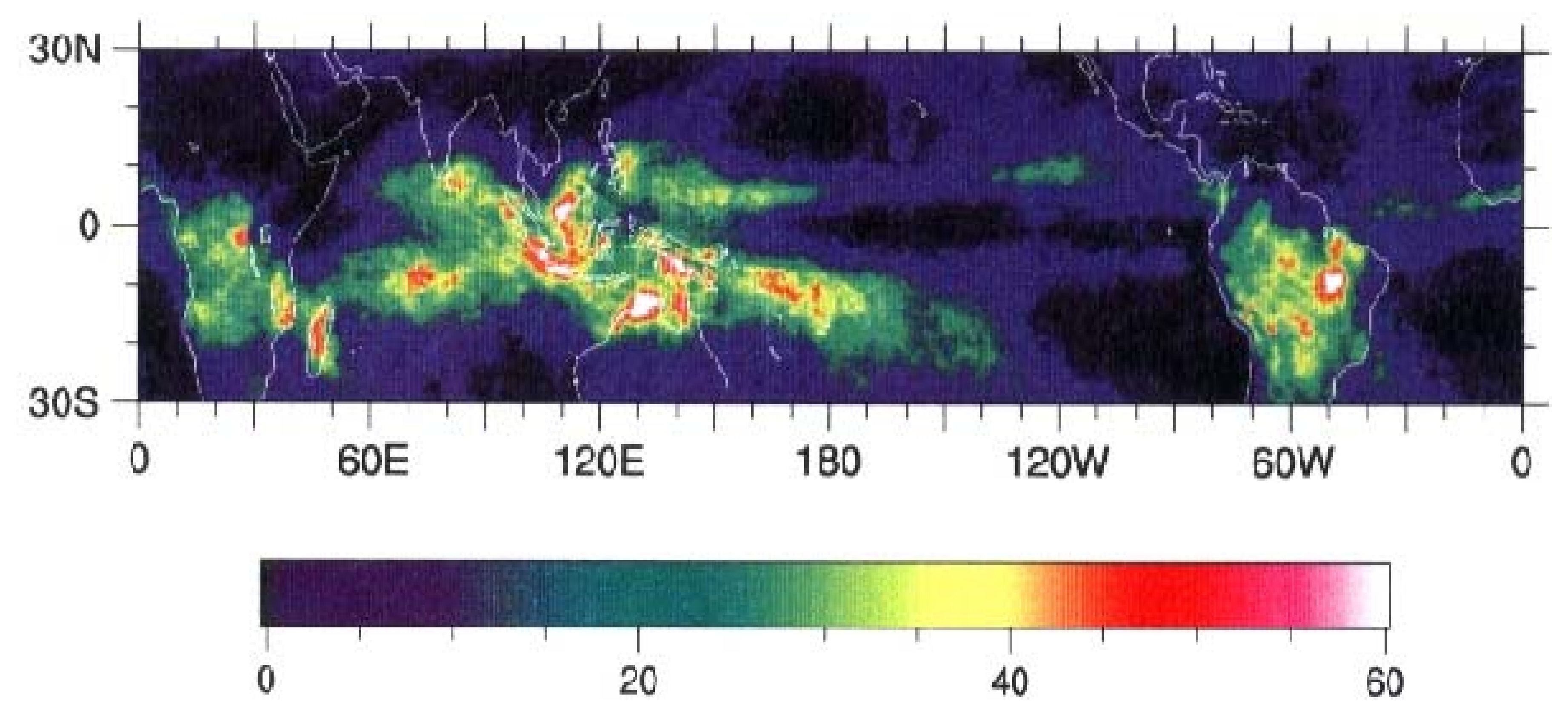
Ricciardulli & Garcia 1999

Winter 1984 Observed DCH Variance [$(K/day)^2$] (period 2-10 days)



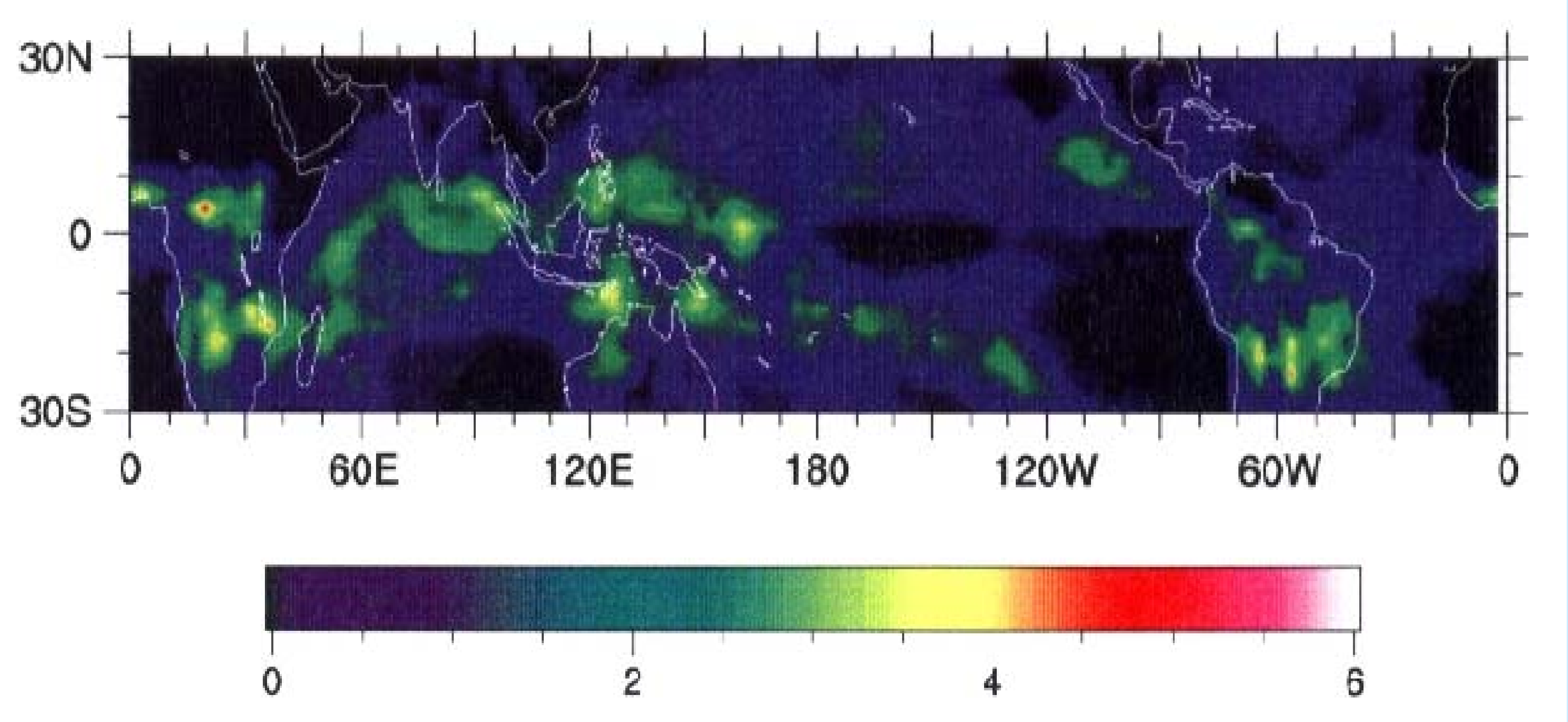
Ricciardulli & Garcia 1999

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



Ricciardulli & Garcia 1999

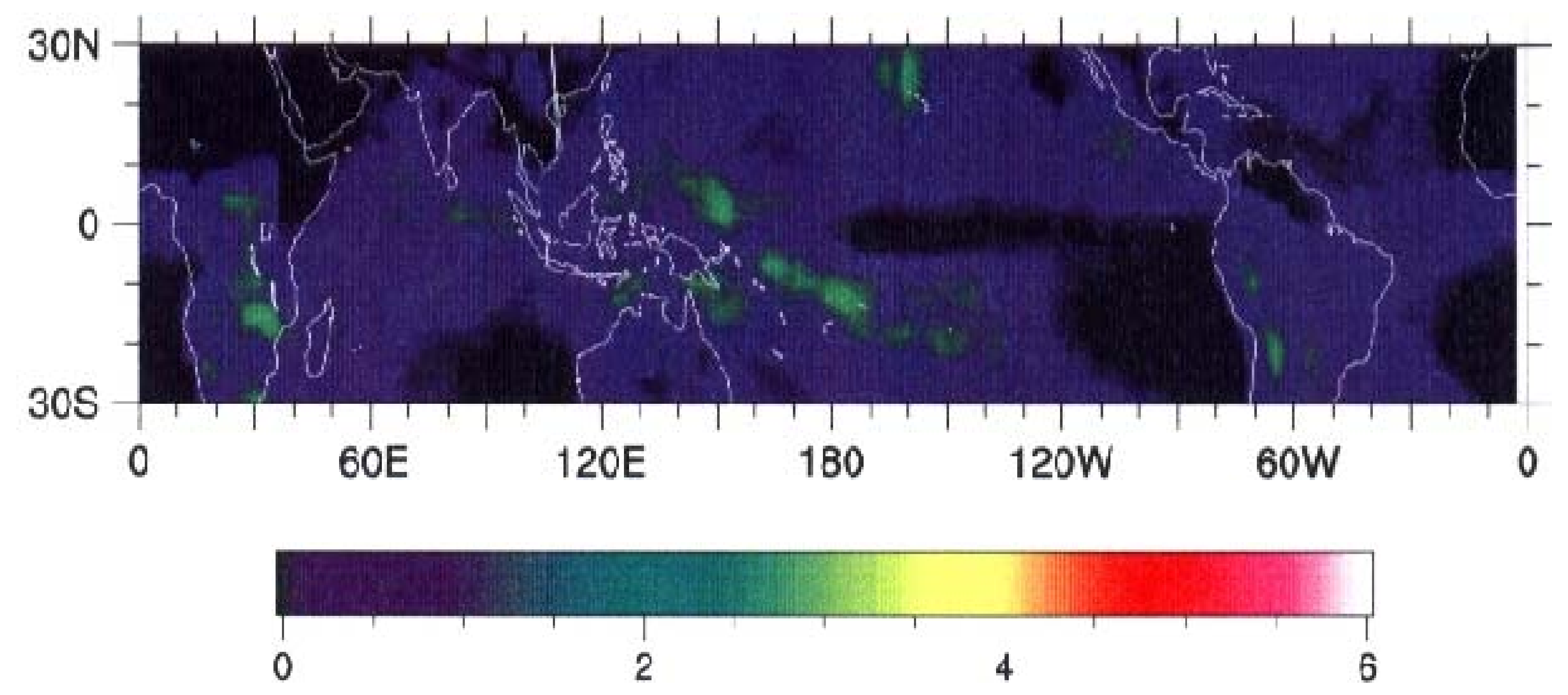
Winter 1984 Modeled DCH Variance [(K/day)^2] (period >10 days)



CCM3 using Zhang-McFarlane convective parameterization

Ricciardulli & Garcia 1999

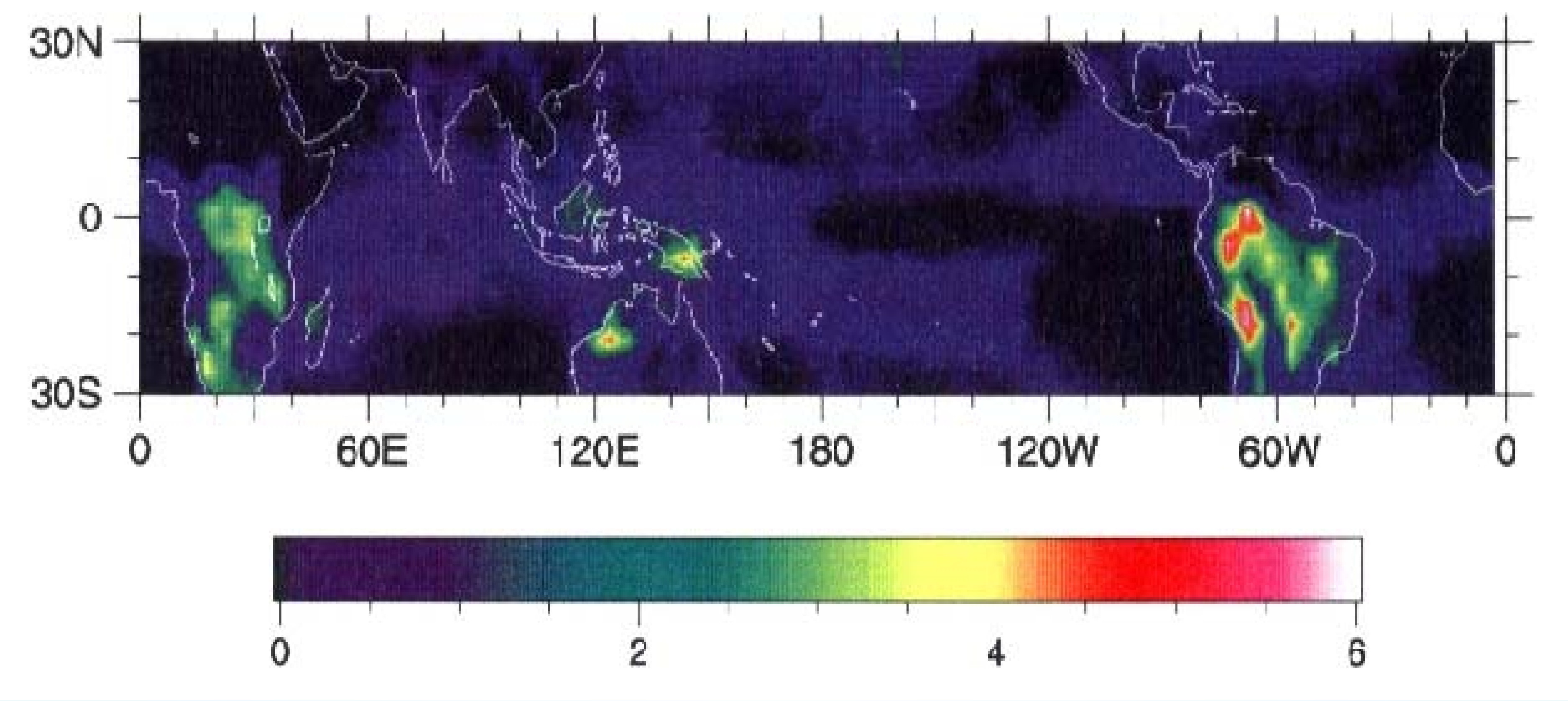
Winter 1984 Modeled DCH Variance [$(K/day)^2$]
(period 2-10 days)



CCM3 using Zhang-McFarlane convective parameterization

Ricciardulli & Garcia 1999

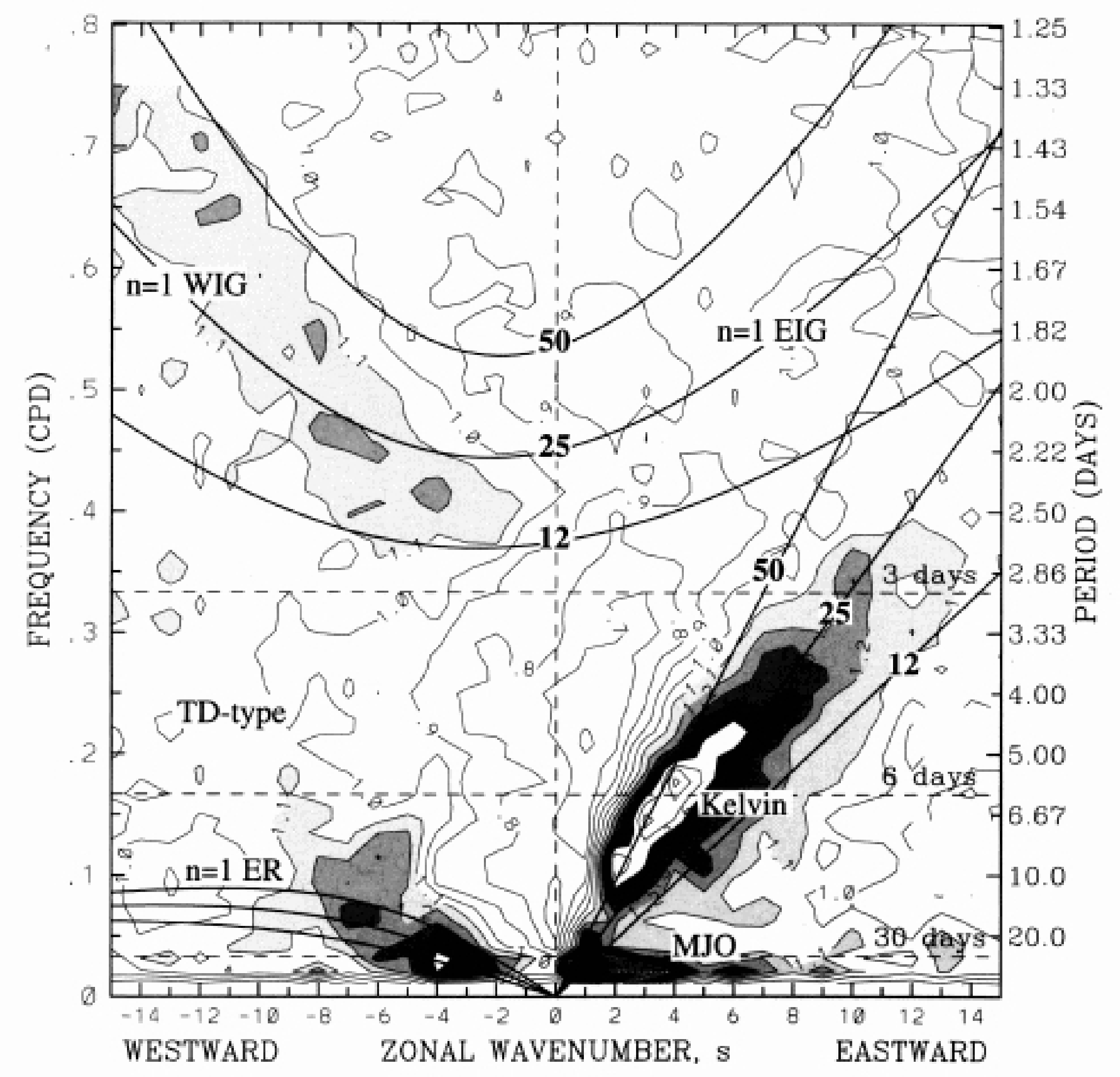
Winter 1984 Modeled DCH Variance [$(K/day)^2$] (period 6 hrs-2 days)



CCM3 using Zhang-McFarlane convective parameterization

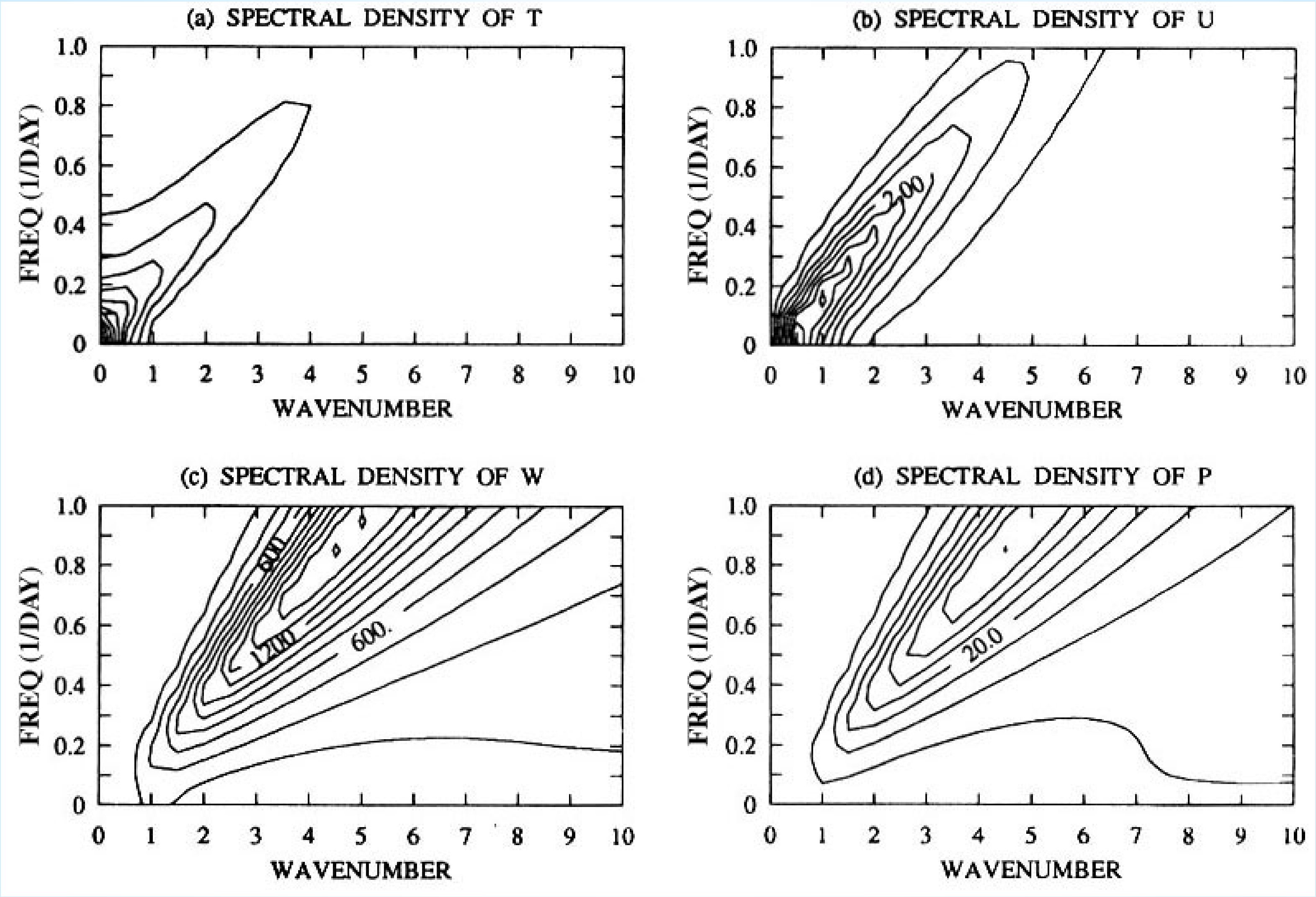
Ricciardulli & Garcia 1999

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)

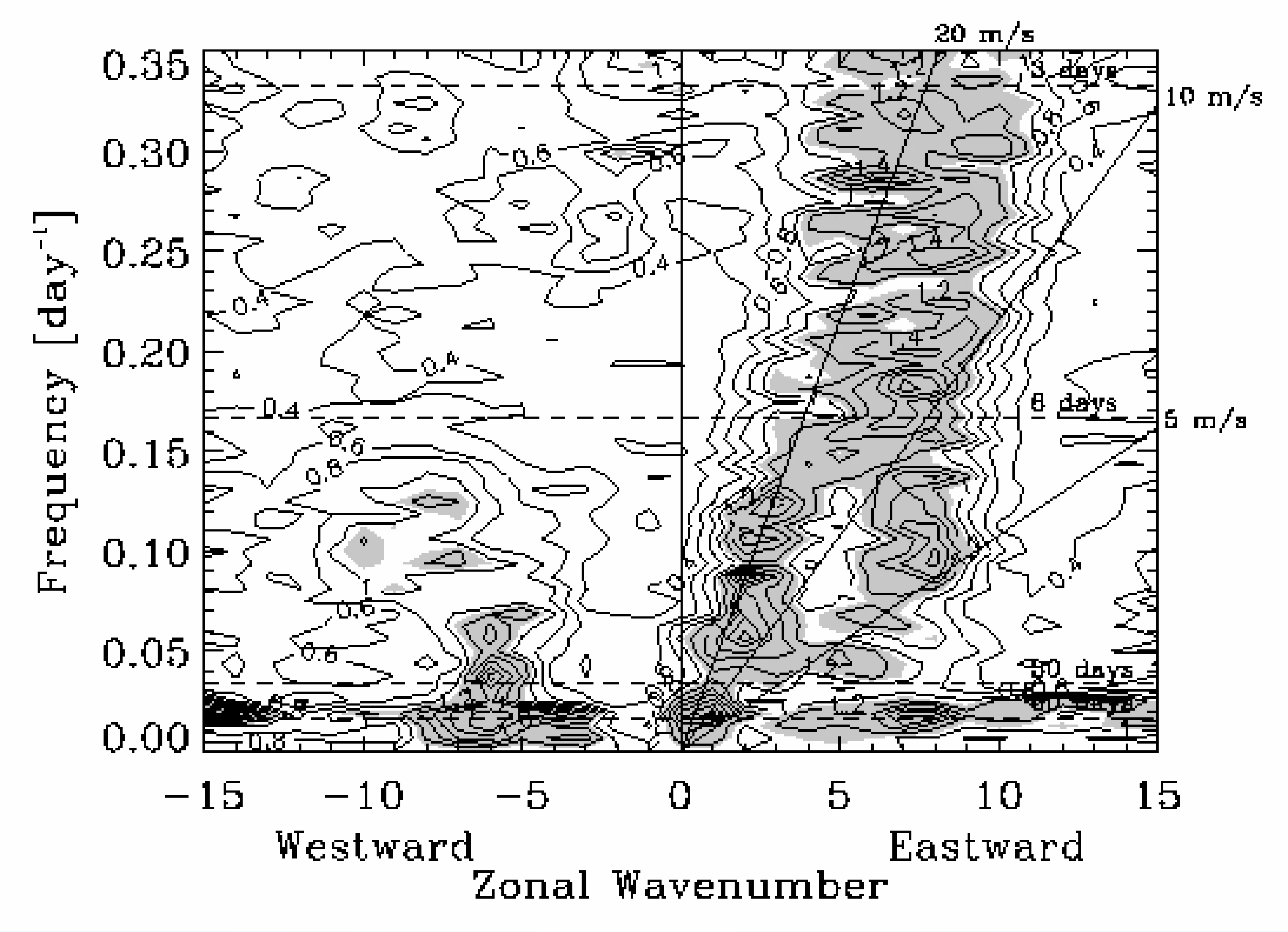
deep convective cloud, CsCc fraction param. on precip

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

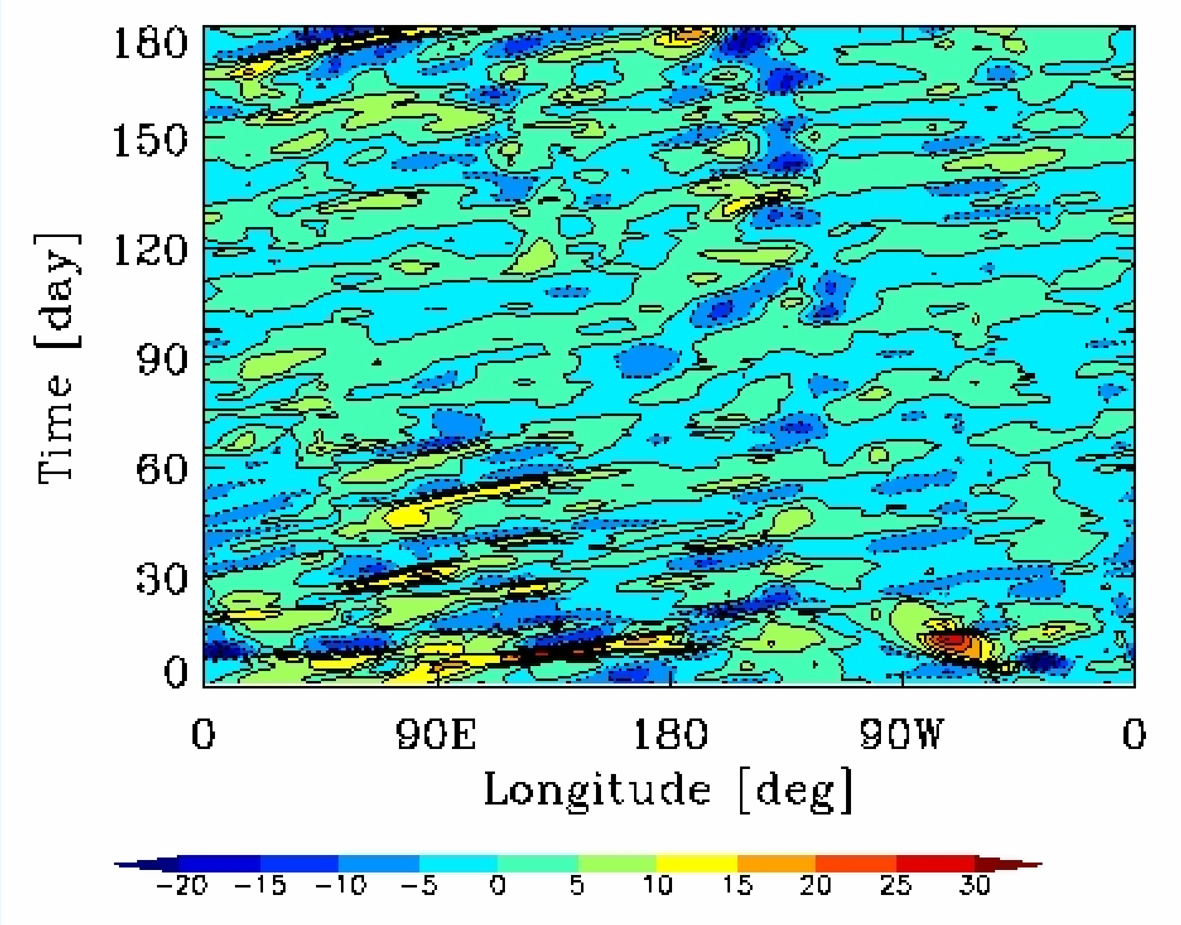
QTCM v1.0 OLR PSD ÷ Background (7.5N-7.5S)



Analysis following Wheeler & Kiladis (1999)

LNZ00

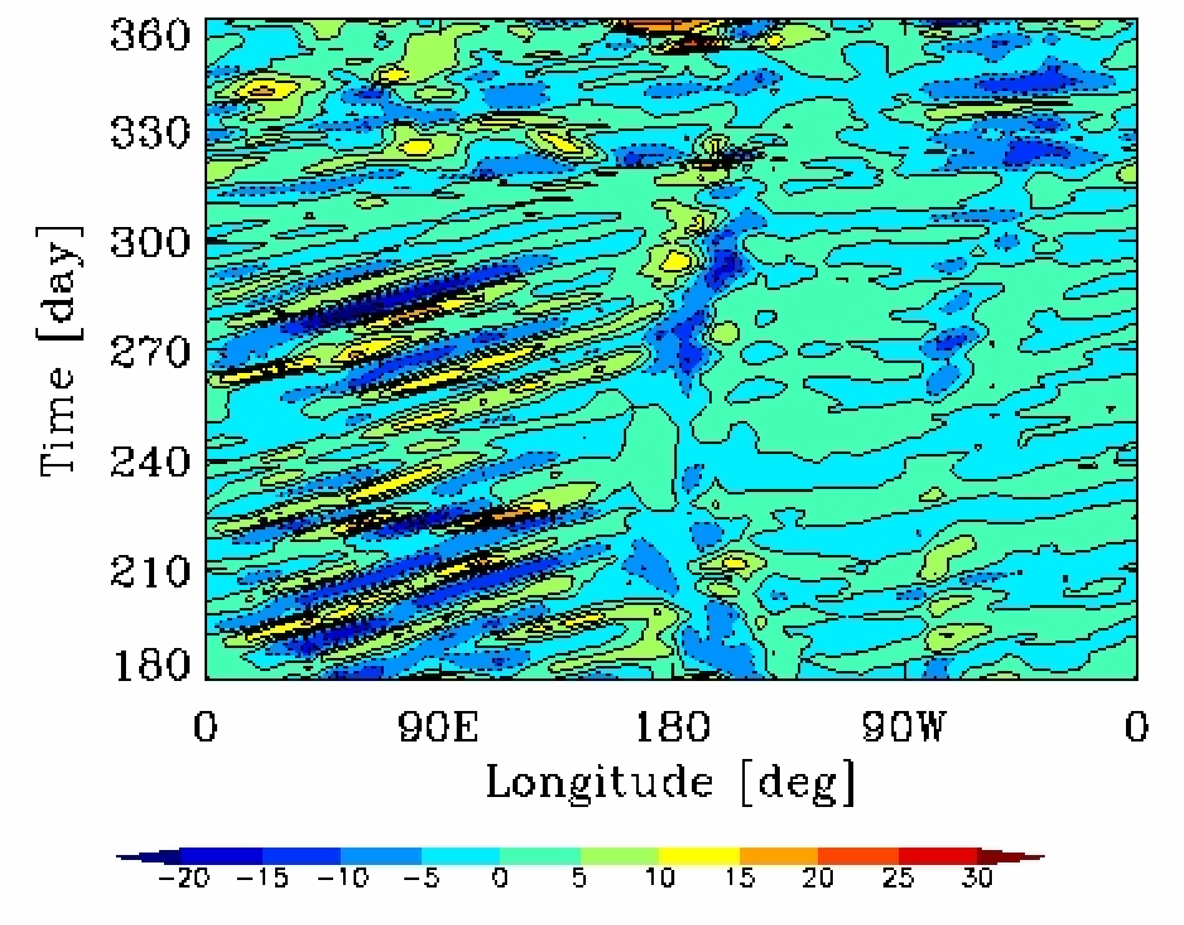
QTCM v1.0 OLR Anomaly [W/m^2] (January–June)



Phase speed: 5–10 m s-1

LNZ00

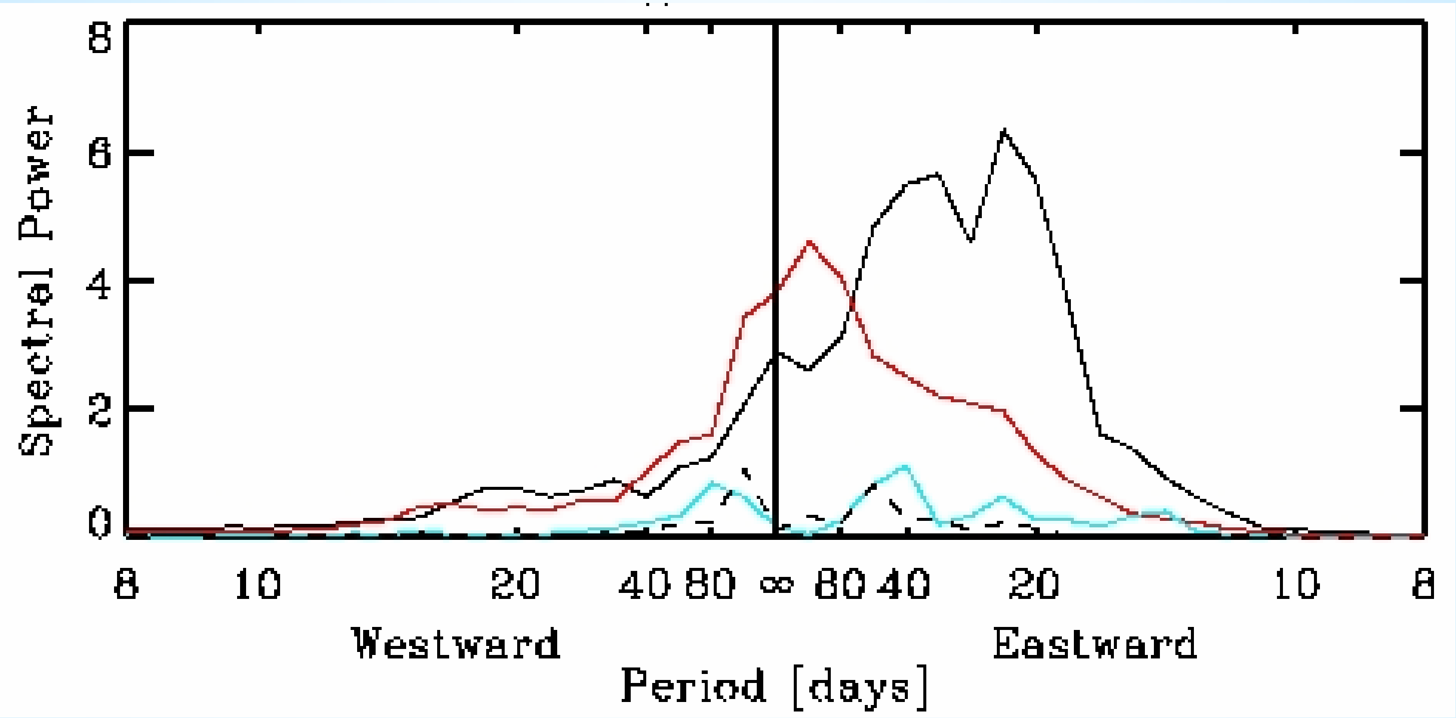
QTCM v1.0 OLR Anomaly [W/m^2] (July–Dec.)



Phase speed: 5–10 m s-1

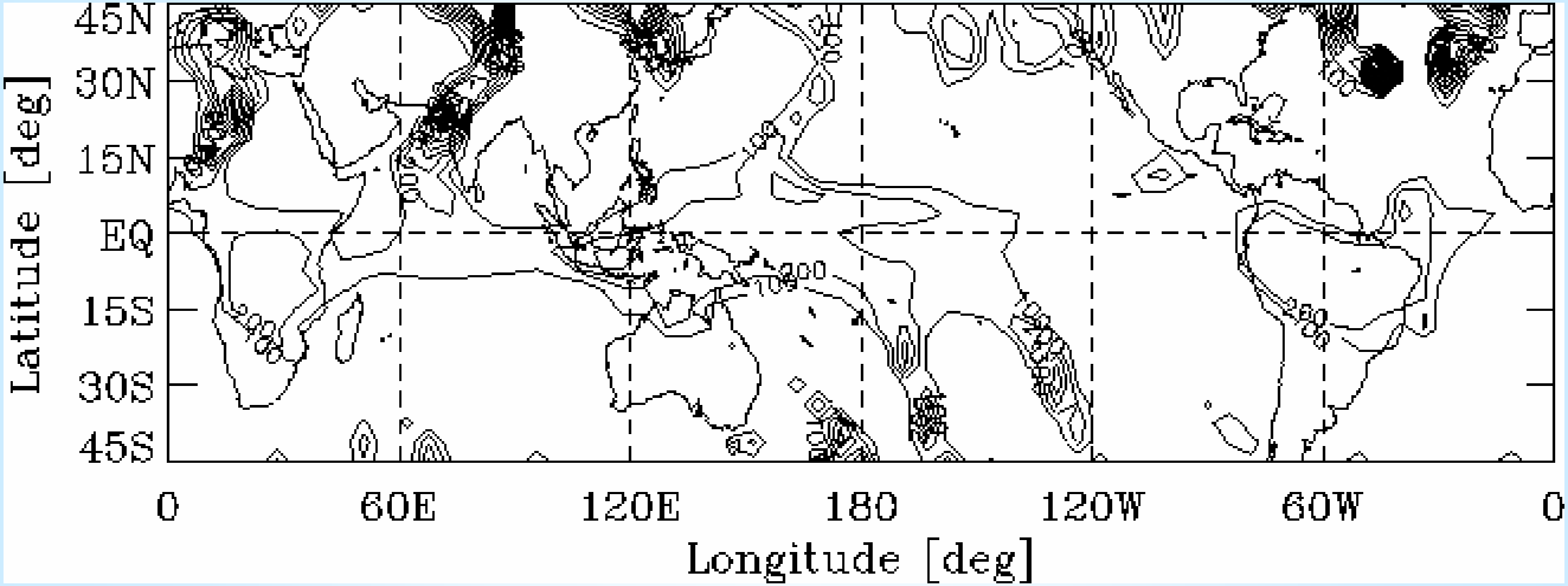
LNZ00

QTCM v1.0: 850 hPa Zonal Wind PSD
Zonal Wavenumber 1 (7.5N-7.5S) [$m^2\ s^{-2}$ day]



━━ **Control run**
━━ **EWF suppressed**
━━ **Extratropical disturbances suppressed**
– – – **EWF and extratropical disturbances suppressed**

Excitation from Mid-Latitude Storms



January 6 (Year 2) precipitation (W/m^2) in QTCM1 v1.0

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 $R(x) = x,\ x > 0;\ = 0,\ x \leq 0$, 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

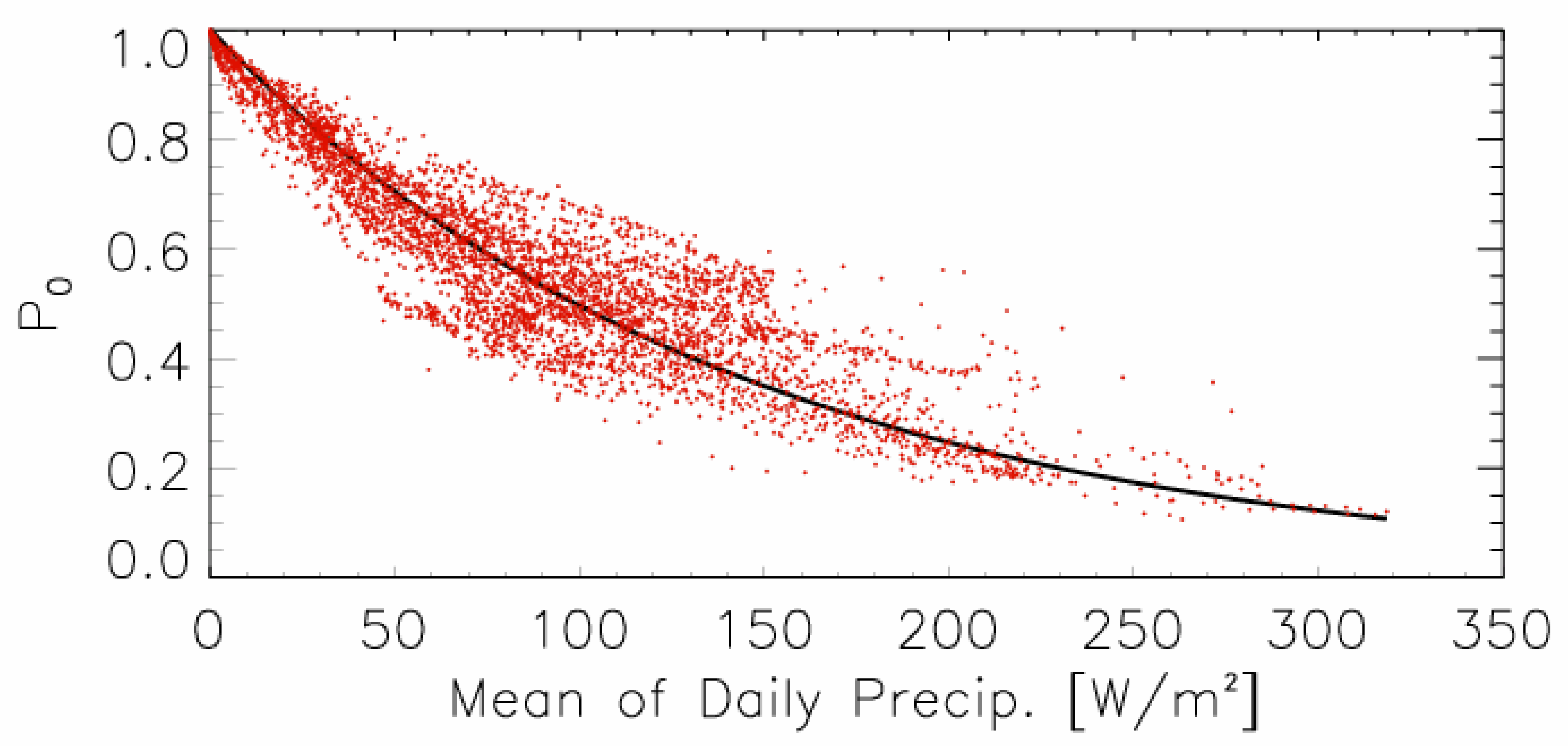
$Q_c = \alpha \xi_t Q_c^{BM}$ with cap on extreme values (50,000 Wm^{-2}!) for numerical reasons. α for sensitivity testing (rescales τ_c^{-1})

$\xi_t = \varepsilon_\xi \xi_{t-1} + (1 - \varepsilon_\xi) y_t$ 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 $P(y>\acute{y}) = P_o \mathrm{H}(\acute{y}) + (1 - P_o) F(\acute{y})$ 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 $\overline{Q}_c$

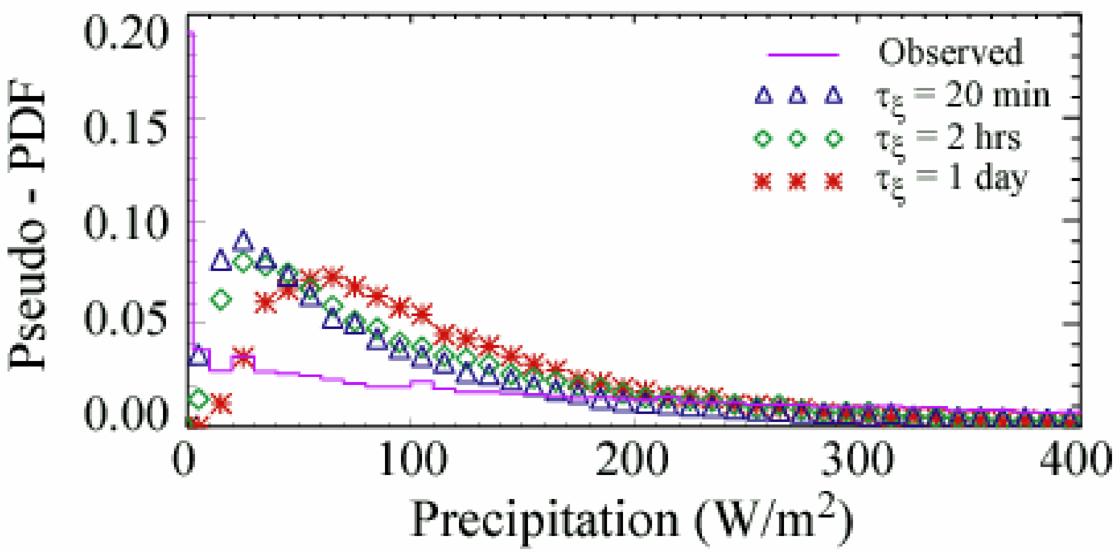
- **Fit: $P_o = \exp(-\mu_p \overline{Q}_c)$**



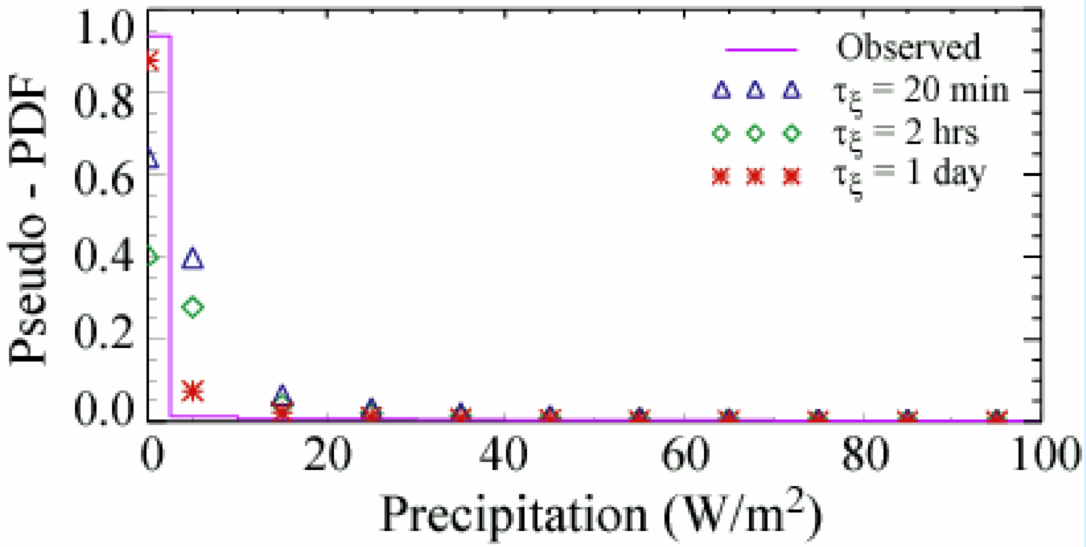
Microwave sounding unit (MSU) ocean region daily data (Jan 1979-Dec 1995). Annual mean used as mean.

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

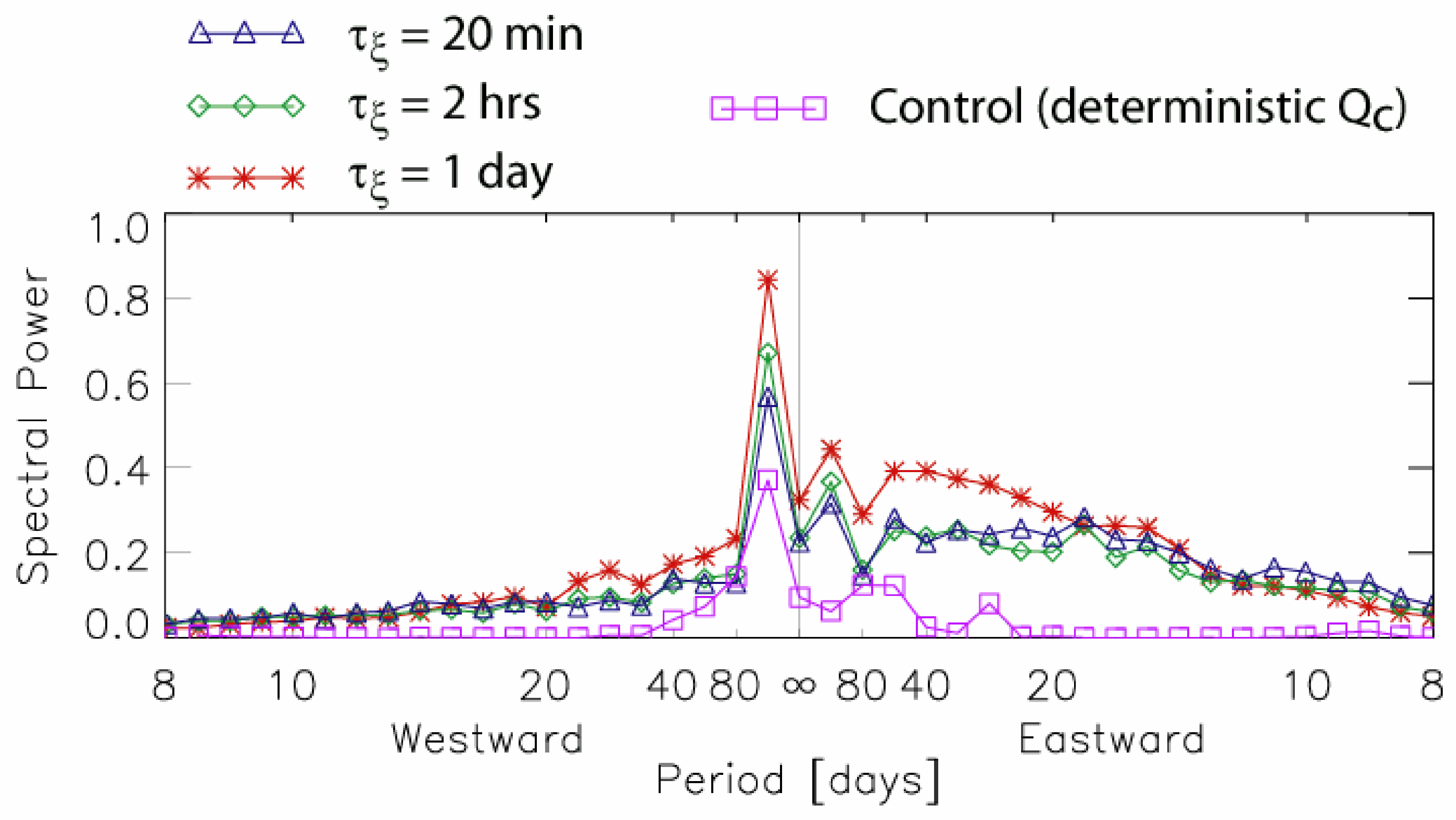
Region of **frequent** convection
(in equatorial
Western Pacific)



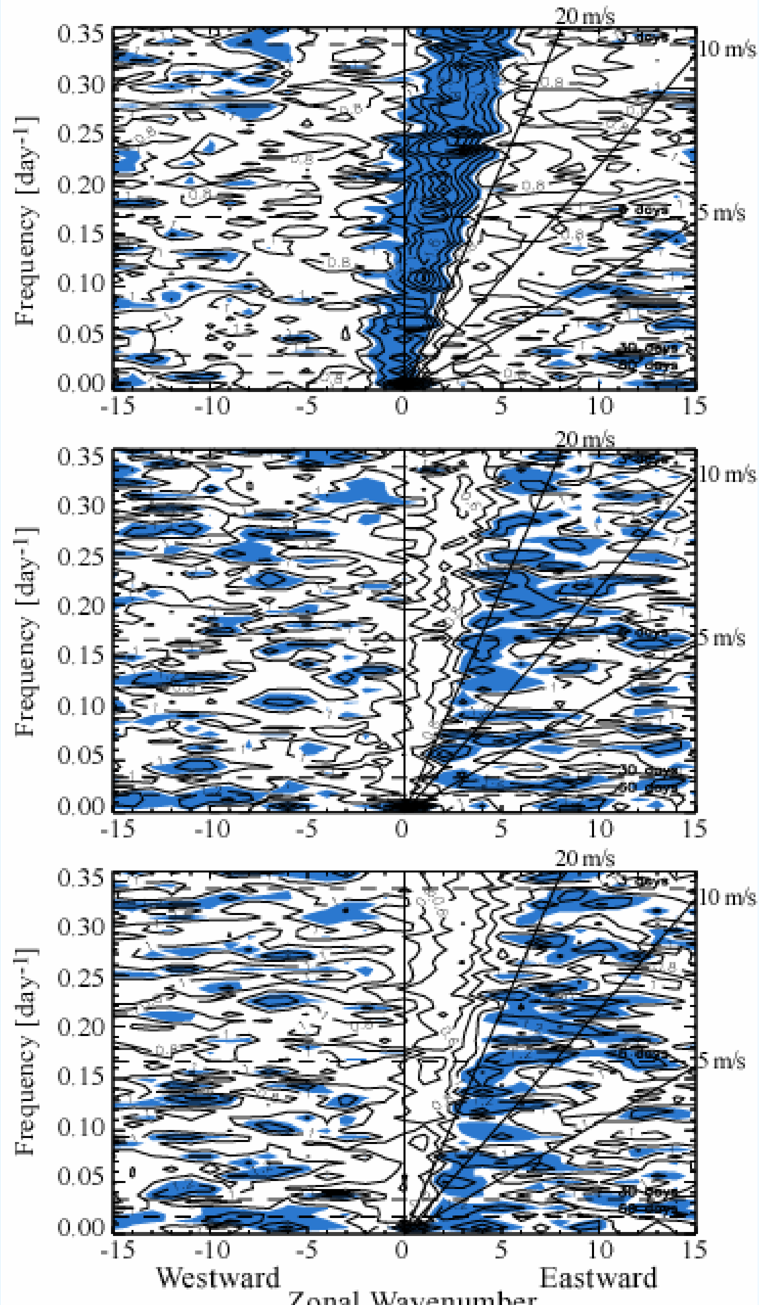
Region of **infrequent** convection
(in tropical
Southeastern Pacific)



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

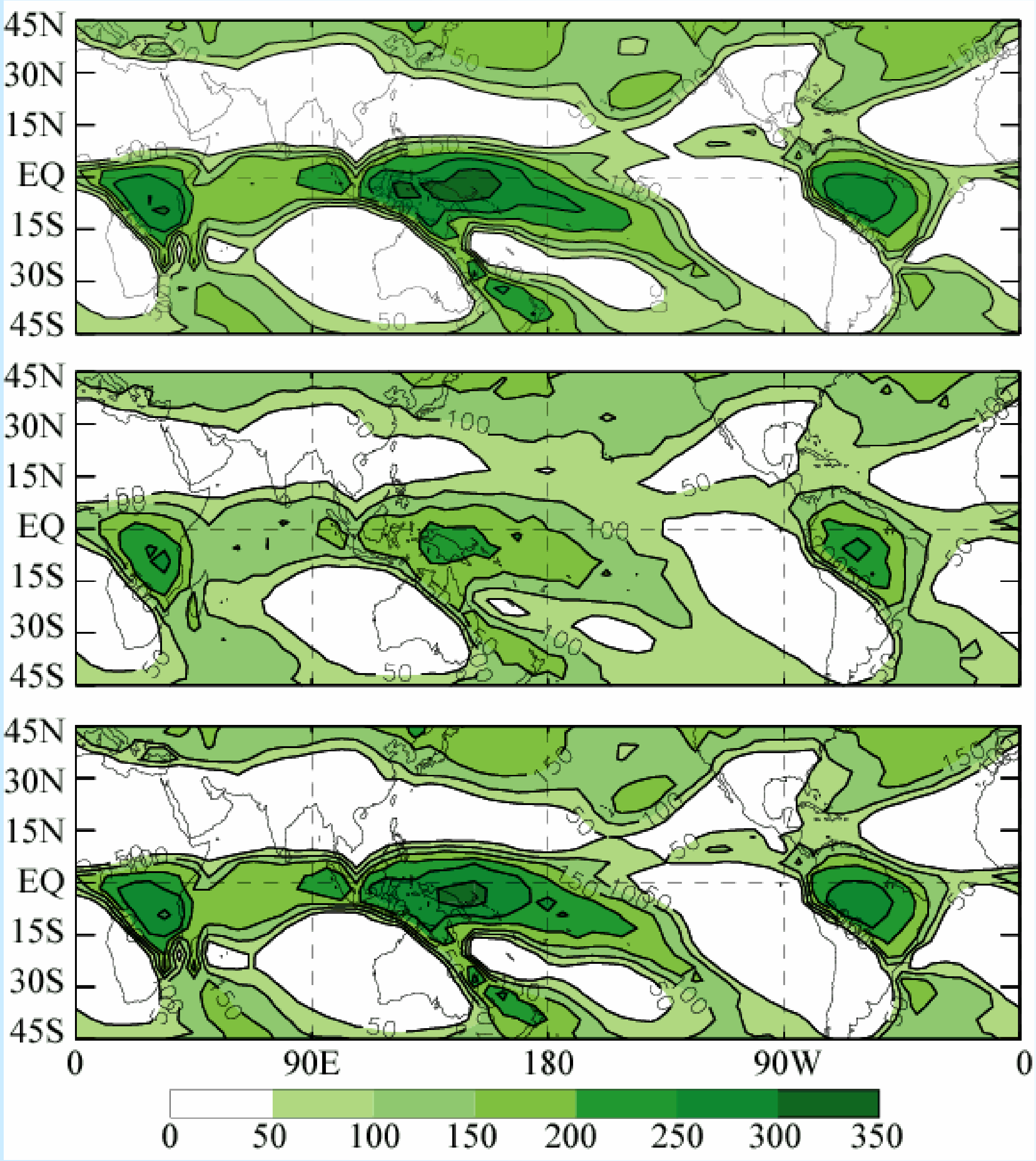
$\tau_\xi = 20$ min

$\tau_\xi = 2$ hrs

$\tau_\xi = 1$ day

Analysis following Wheeler & Kiladis (1999)

Large-scale dynamics reduces sensitivity of clim.



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

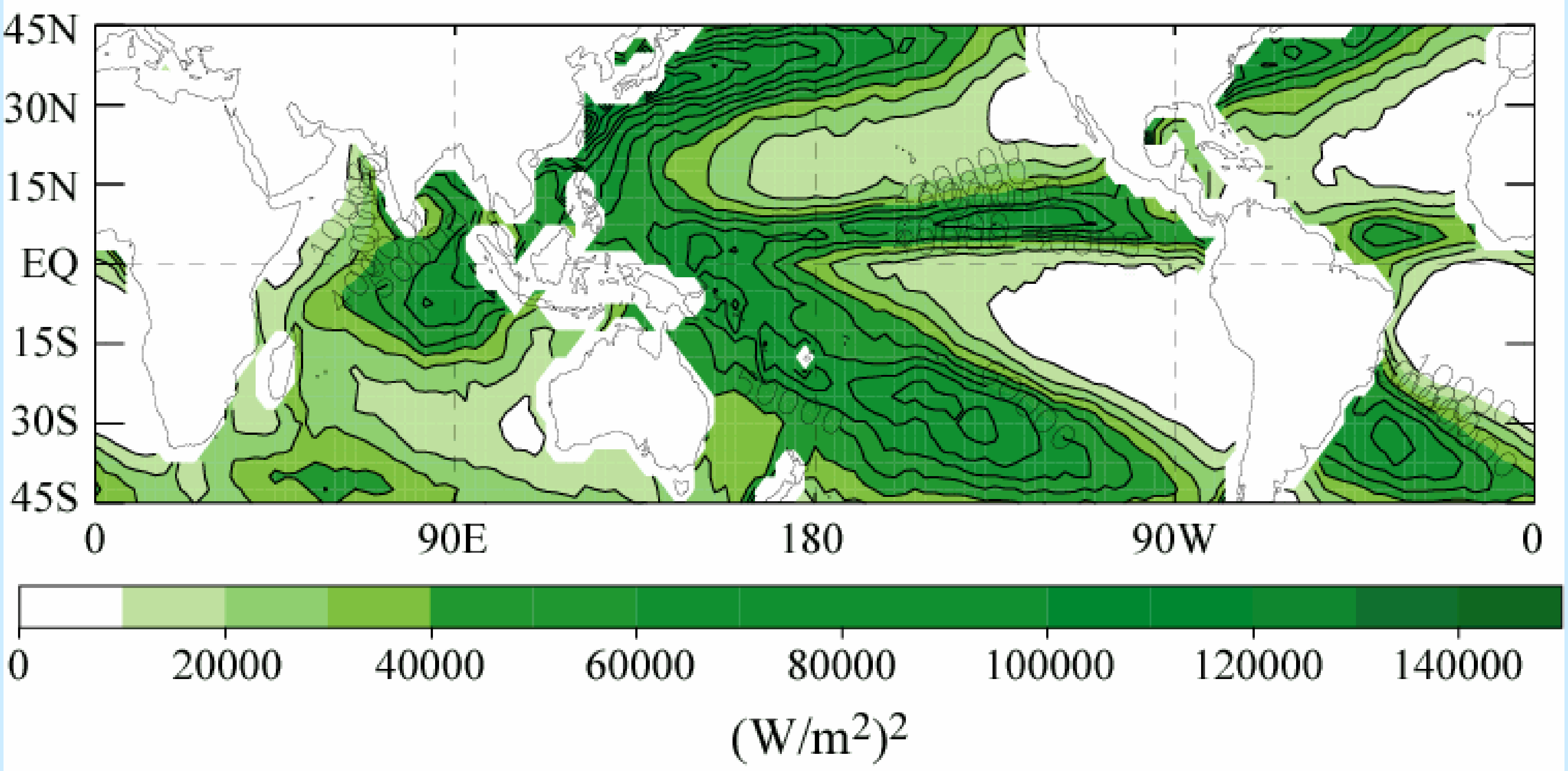
Control

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

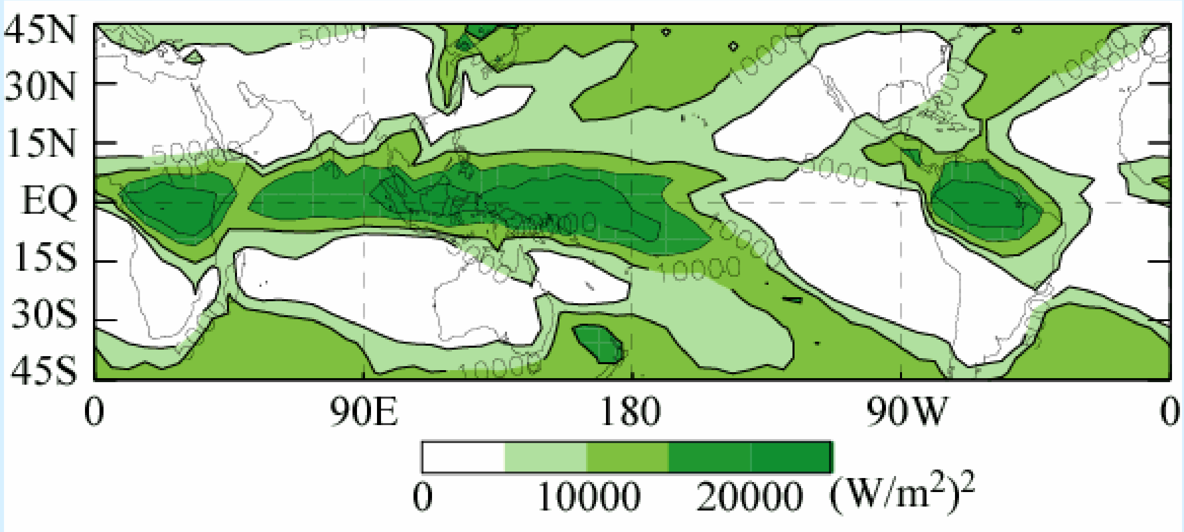
$\alpha = 11$
(Not a factor of 11 different)

January Precipitation

Variance of daily mean precipitation from observations (MSU)



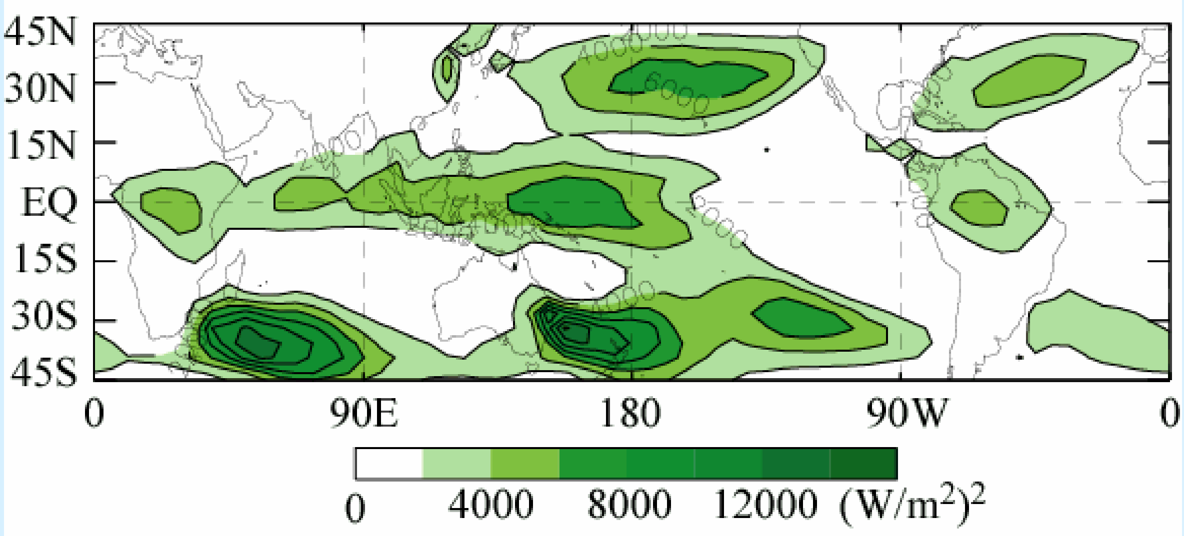
Model dynamics can increase or decrease precip. variance relative to "no dynamics" case (Q_c^{BM} from clim. input to stoch. scheme)



No dynamics case

$\alpha = 11$

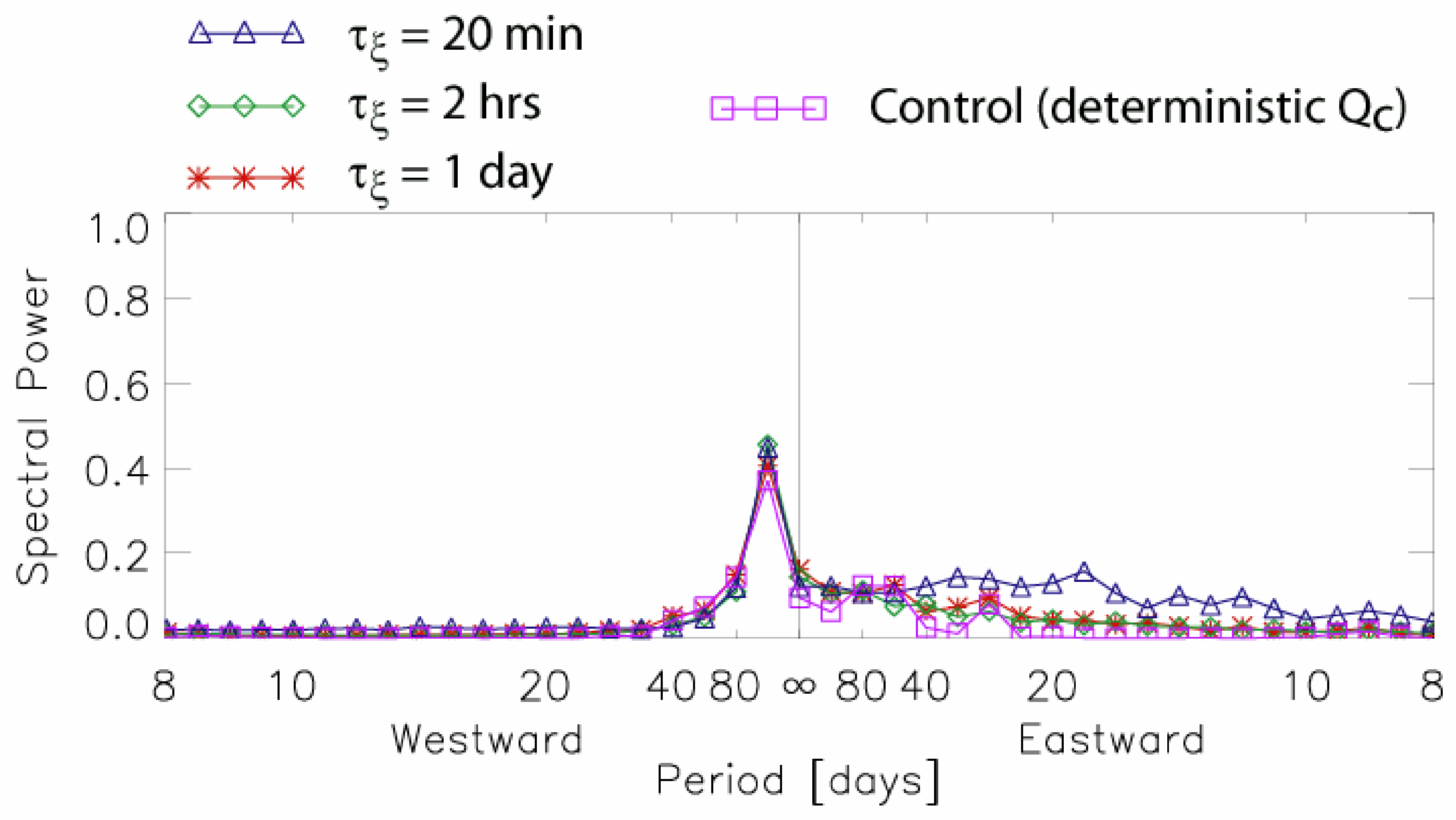
$\tau_\xi = 1$ day



$\alpha = 11$

$\tau_\xi = 1$ day

QTCM with $\alpha = 11$ empirical lognormal stochastic convective parameterization. Equatorial low-level zonal wind (u_{850}) power spectrum for wave number 1



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**

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

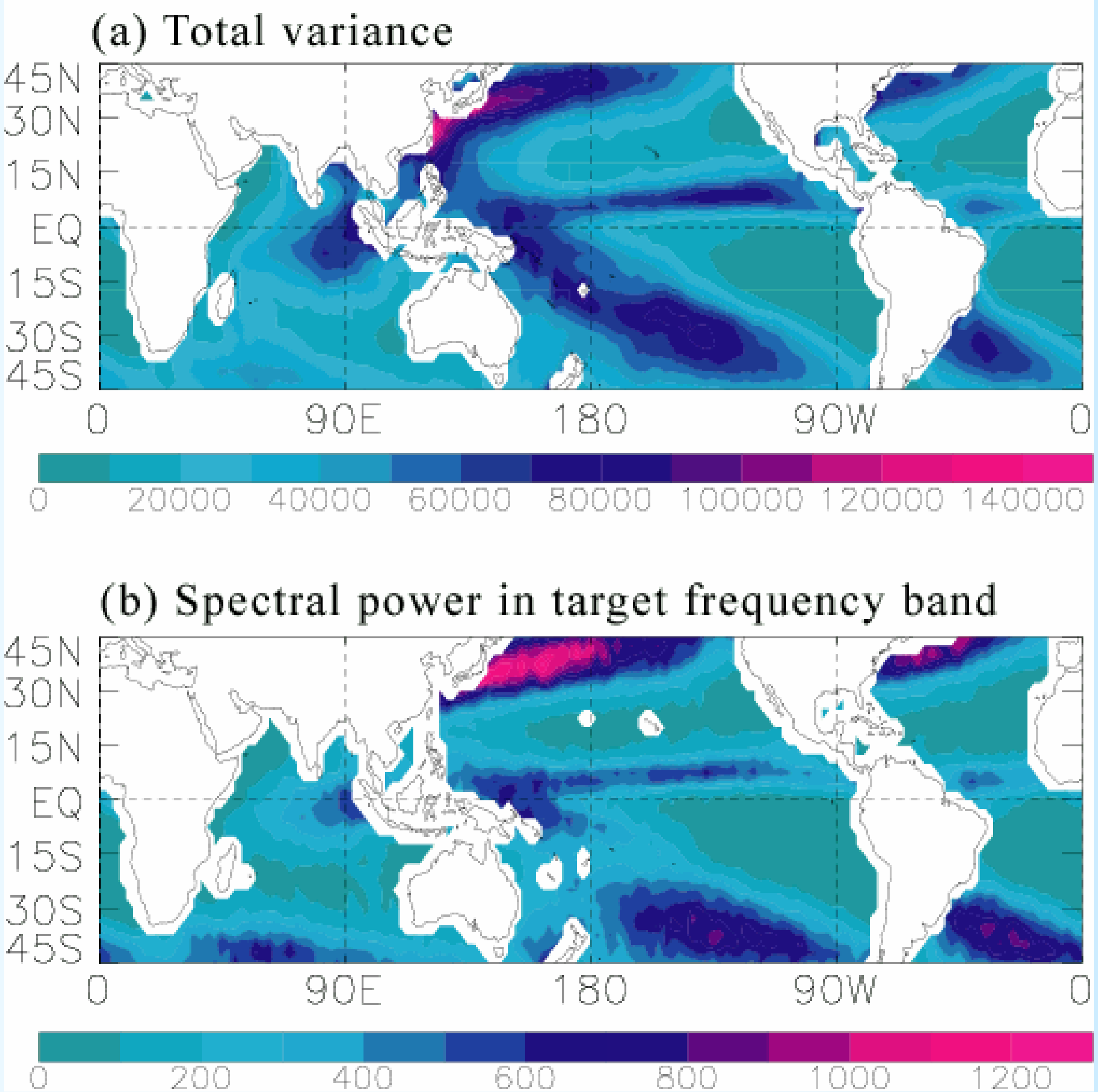
  - $\xi_t = \varepsilon_\xi \xi_{t-1} + z_t$

- **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})

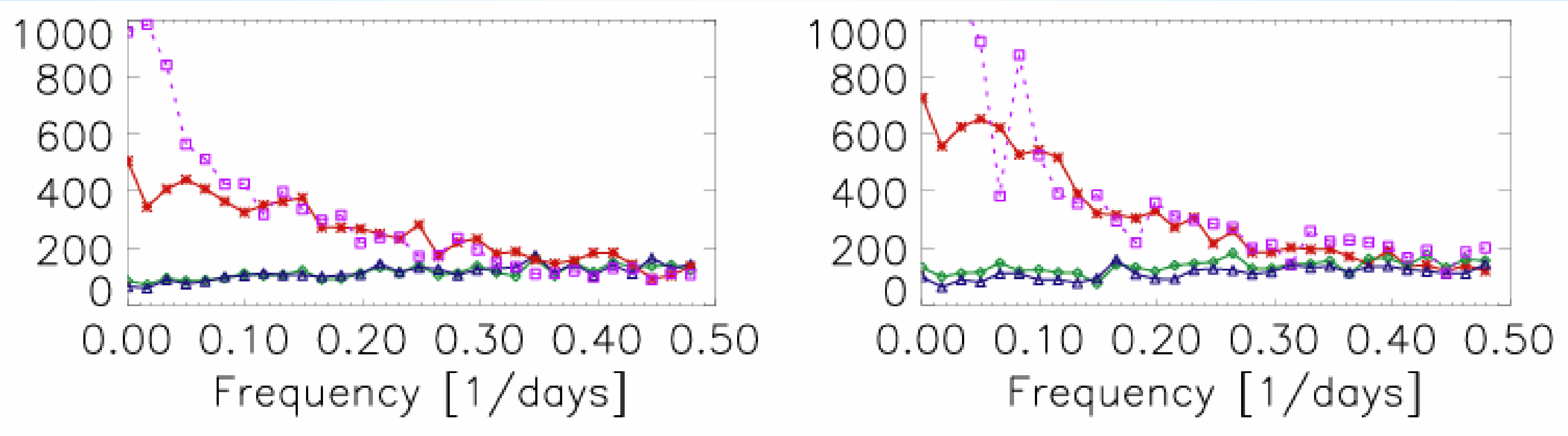
Observed (MSU) variance of daily mean precip

Variance and spectral power in 0.4 to 0.5 day^{-1} band



LN00

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:

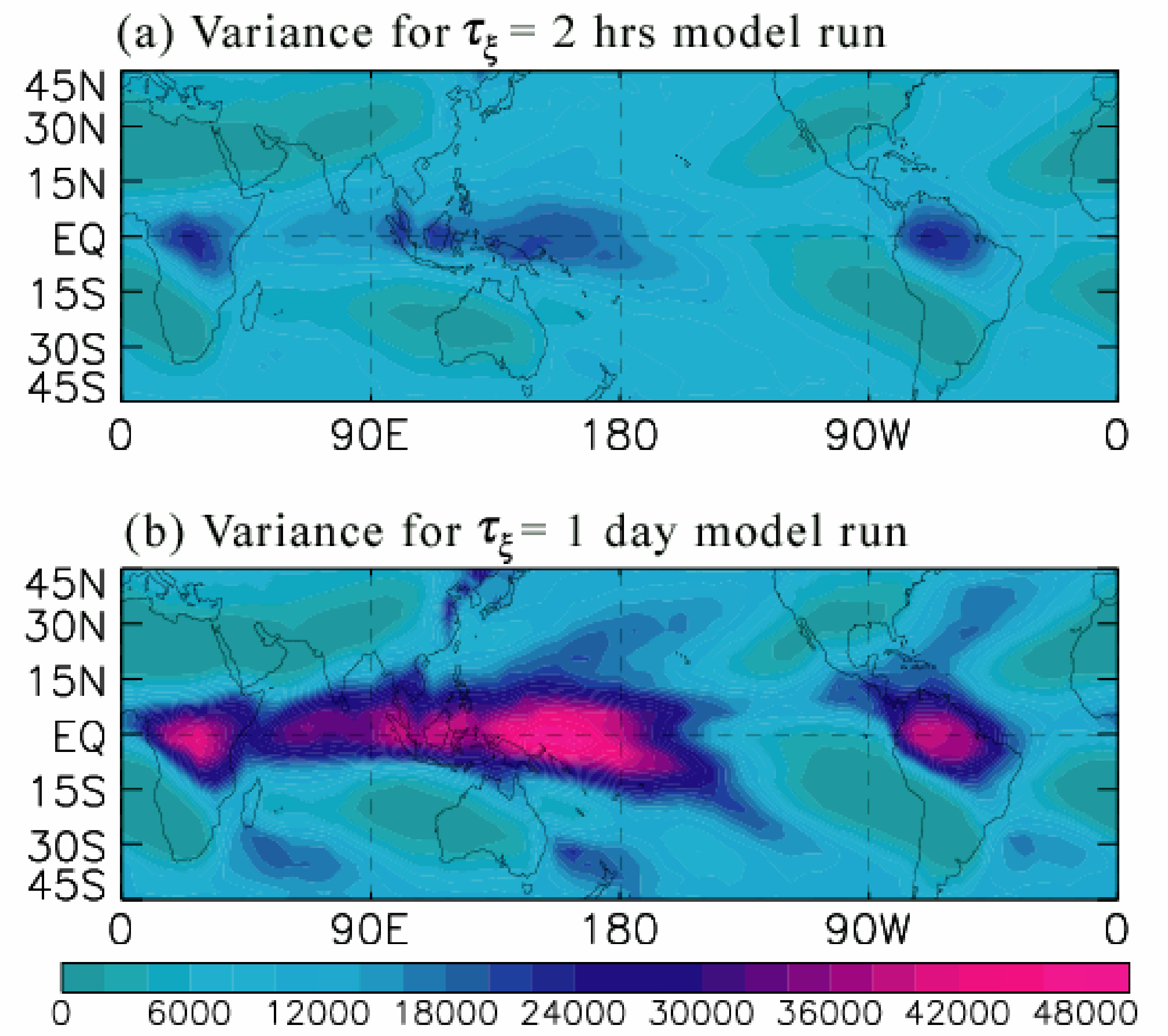
τ_ξ = 20 min ———

τ_ξ = 2 hrs ———

τ_ξ = 1 day ———

LN00

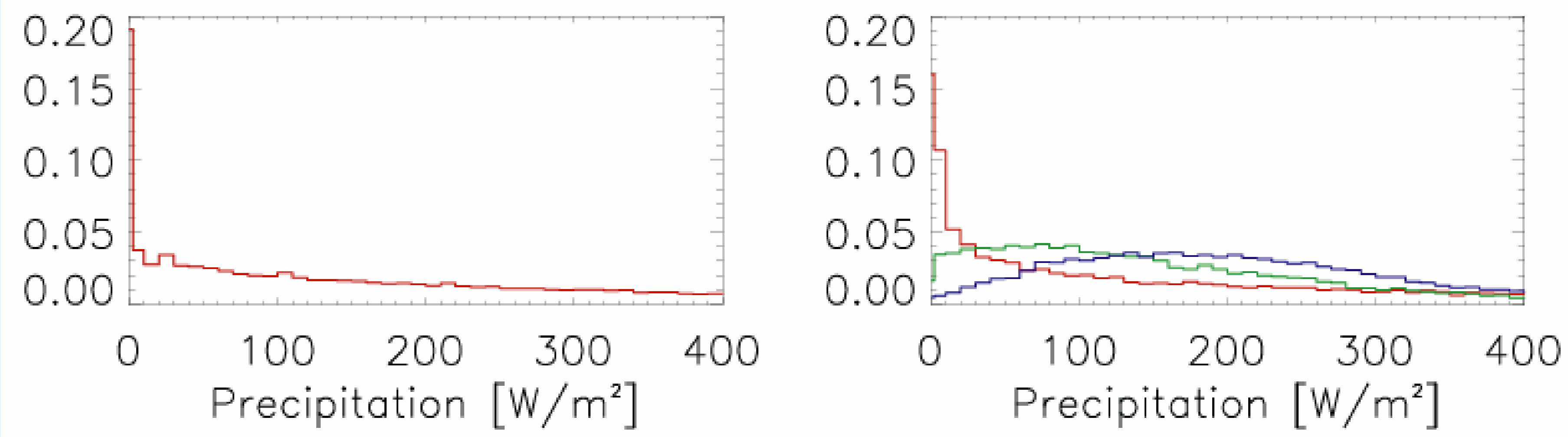
Variance of QTCM with stochastic CAPE scheme for two values of τ_ξ



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 ——

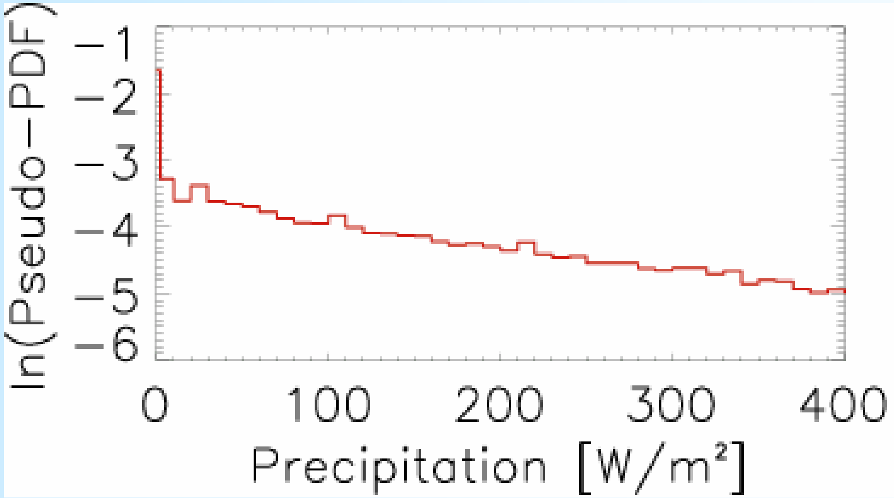
τ_ξ = 1 day ——

LN00

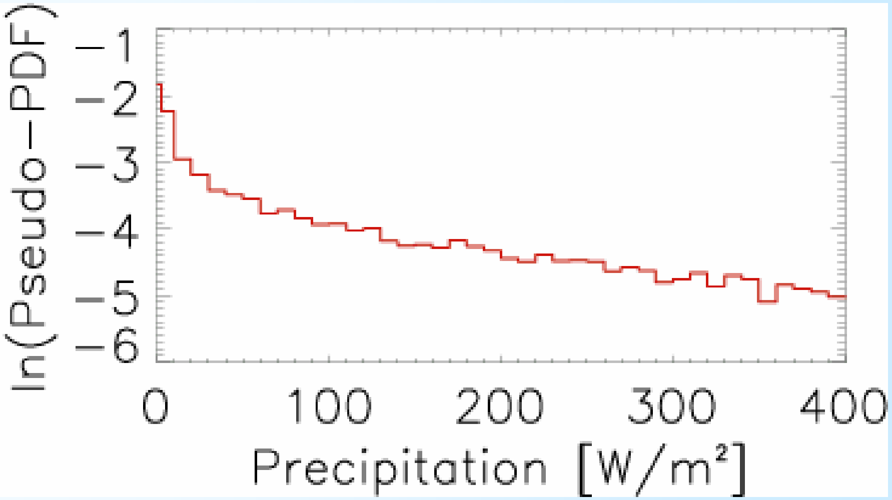
Probability density function of daily precip (in west Pacific, 5N)

- **Log-linear**

MSU Observations

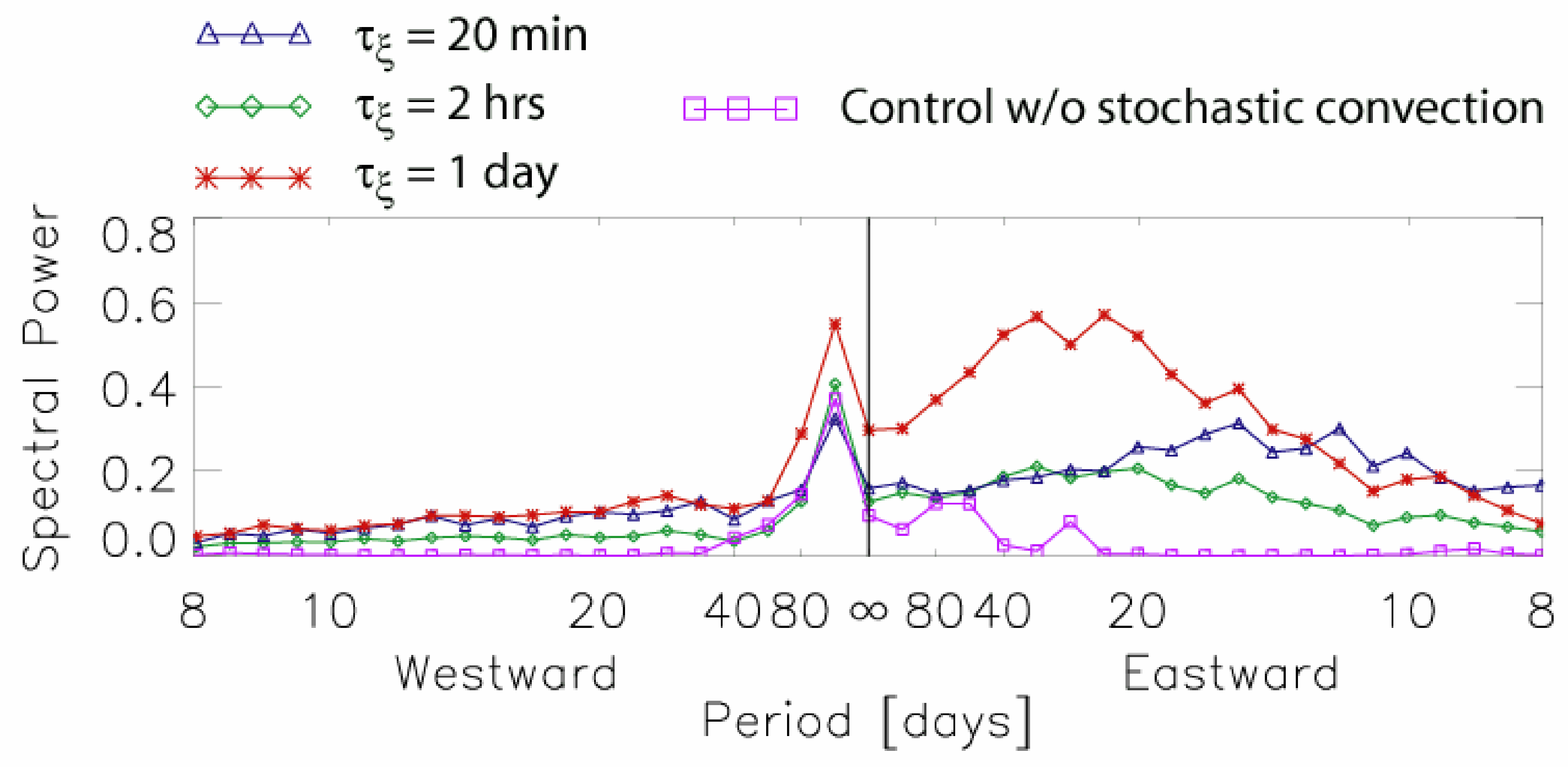


QTCM with stochastic CAPE scheme, τ_ξ = 1 day



LN00

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

$$\partial_t A_{\ c} = -\tau^{-1} A$$

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

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

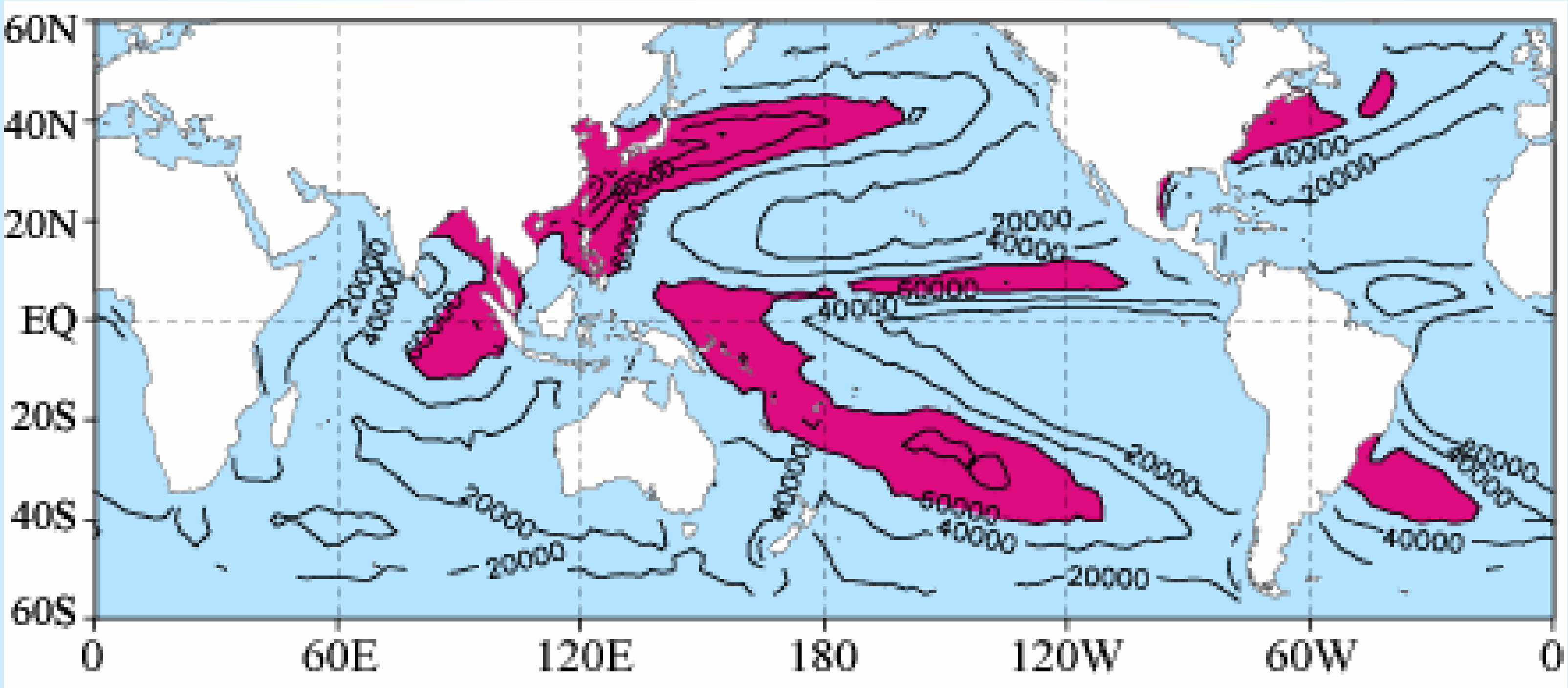
CCM3 Test scheme for stochastic effects in vertical structure of heating (VSH scheme)

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

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

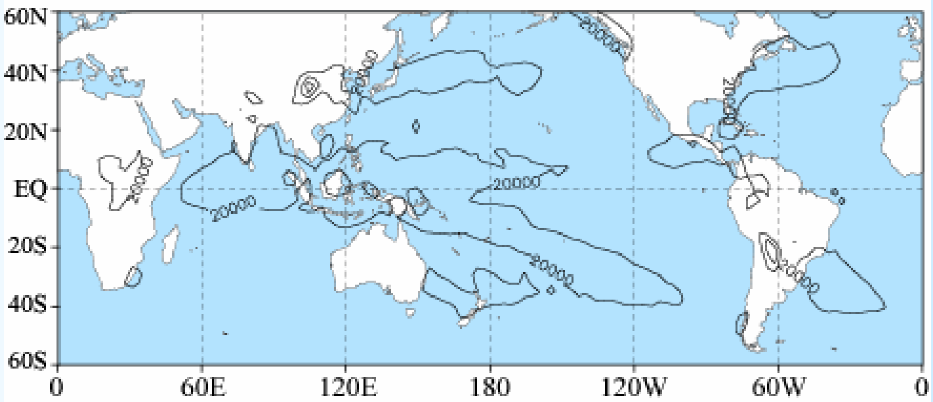
- Simple test for potential impacts of variations in vertical structure
- Contrasts with CAPE-M_b scheme which has no direct alteration of vertical structure from ZM scheme

Variance daily precipitation (Microwave Sounder Unit product)

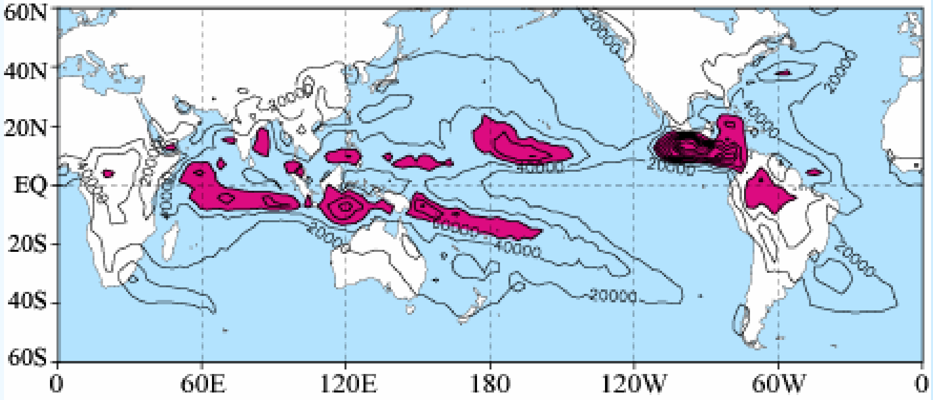


CCM3 variance of daily precipitation

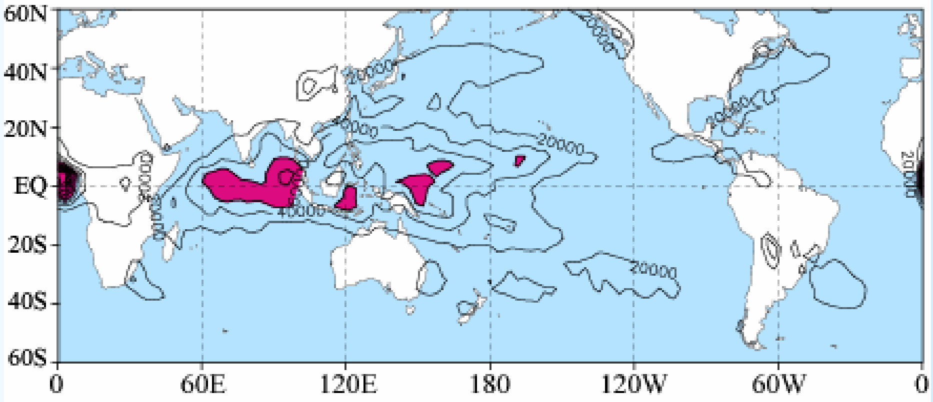
Control run



CAPE-M_b scheme



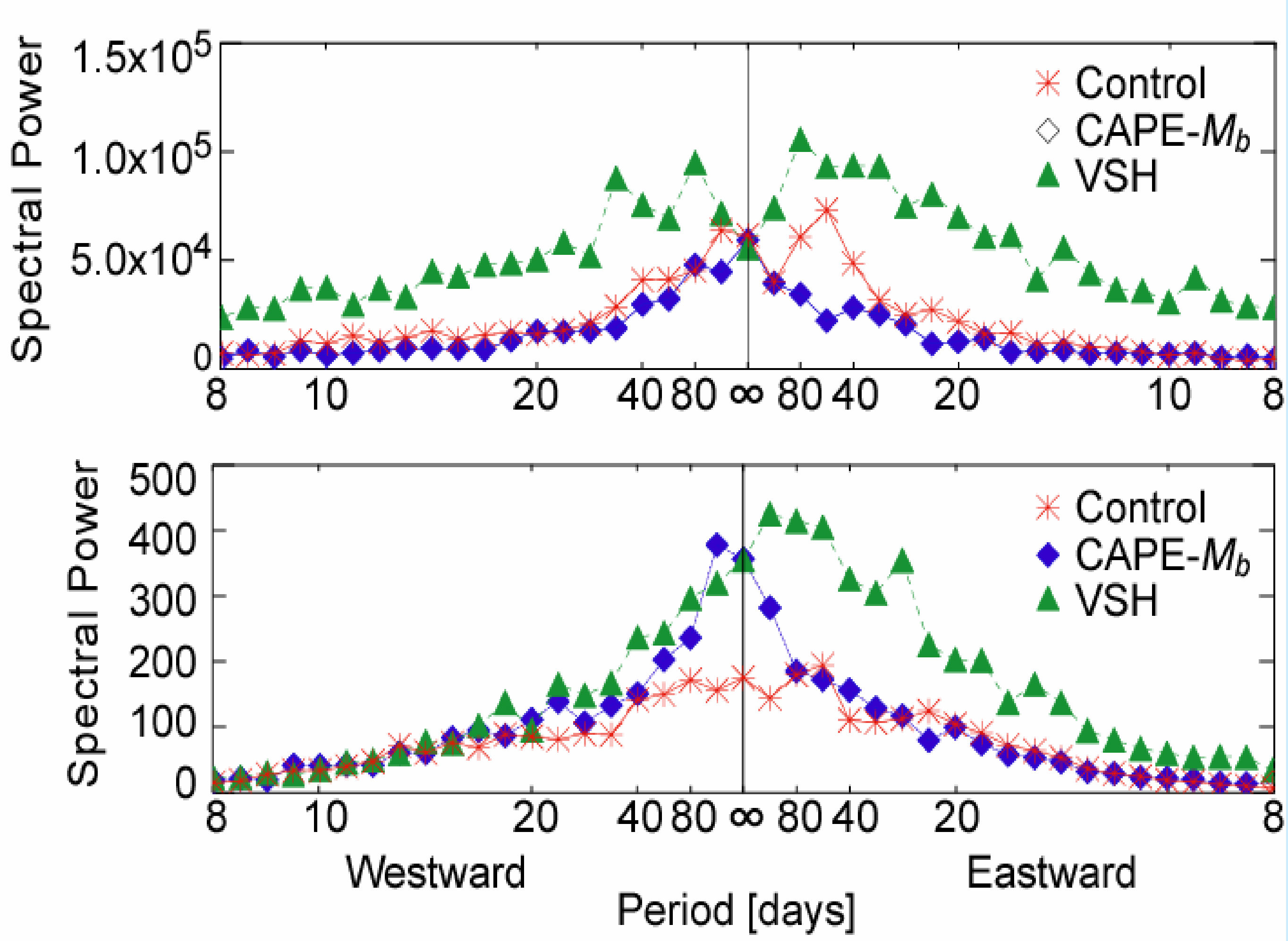
VSH scheme



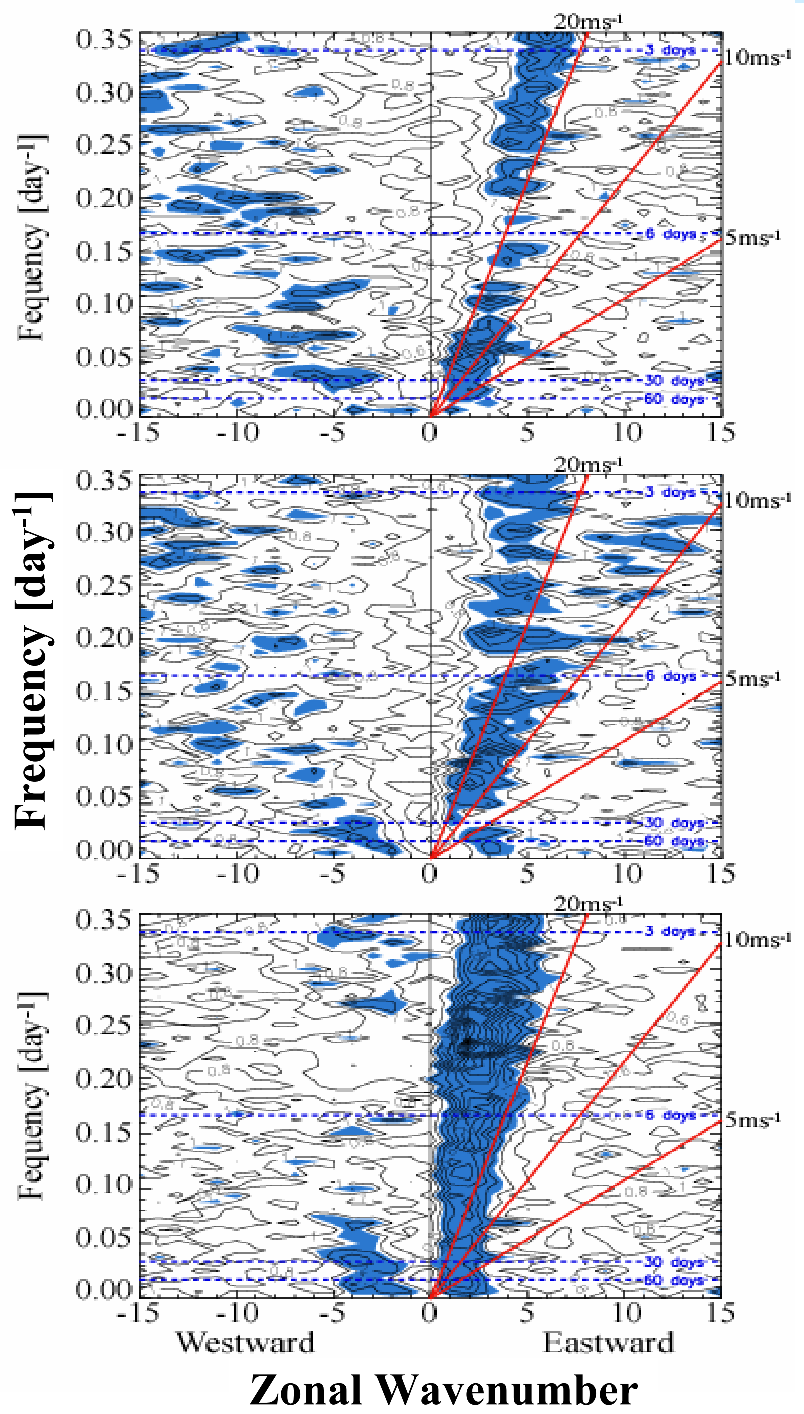
CCM3 Equatorial wavenumber one spectral power: precipitation and-low level winds

Precipitation anomalies

850 hPa zonal wind anomalies



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



Control run

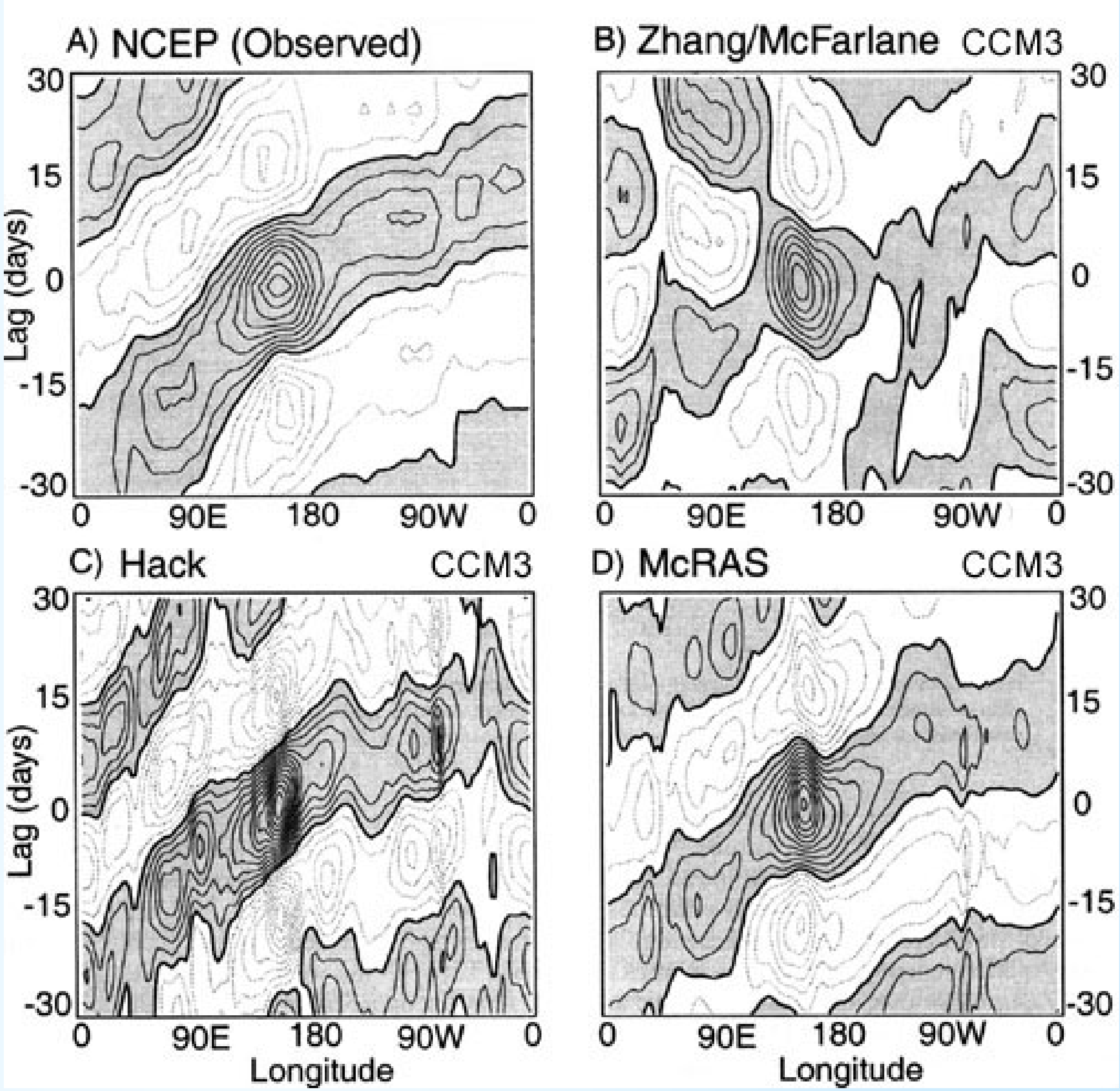
CAPE-M_b scheme

VSH scheme

Analysis following Wheeler & Kiladis (1999)

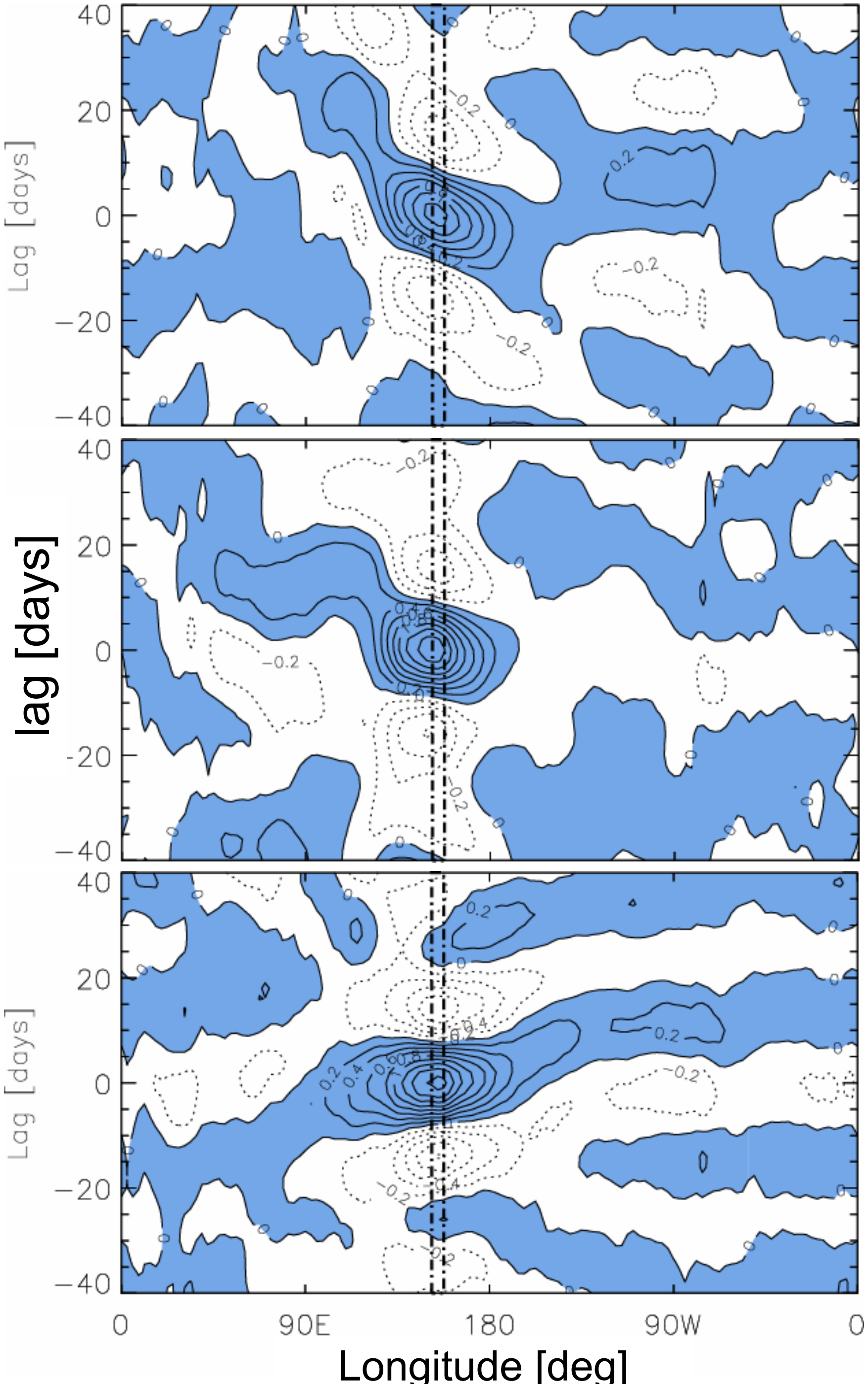
Equatorial zonal wind at 850mb (u_{850}) regressed on u_{850} avg. near 155E (10S-10N)

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)



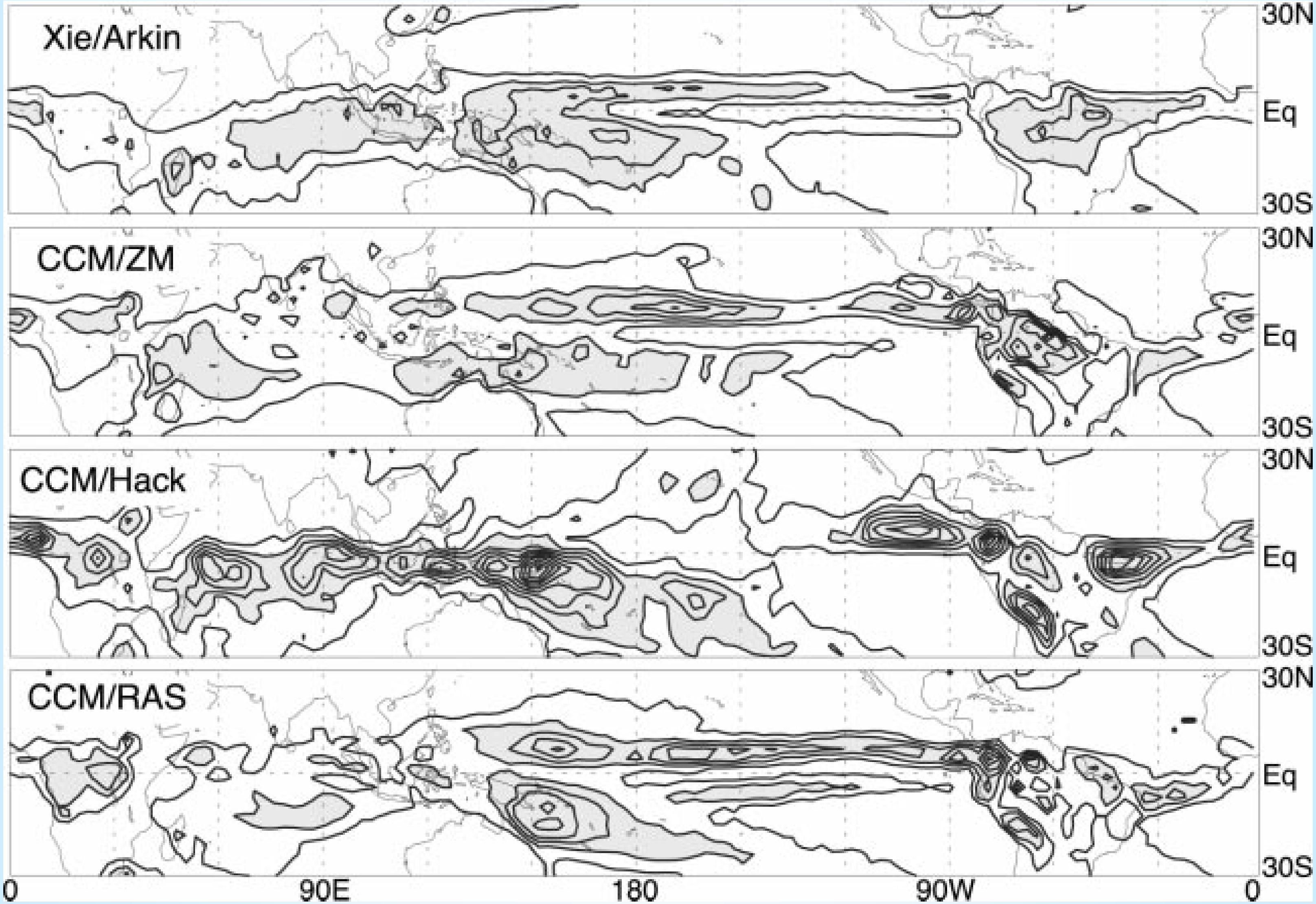
Control run

CAPE-M_b scheme

VSH scheme

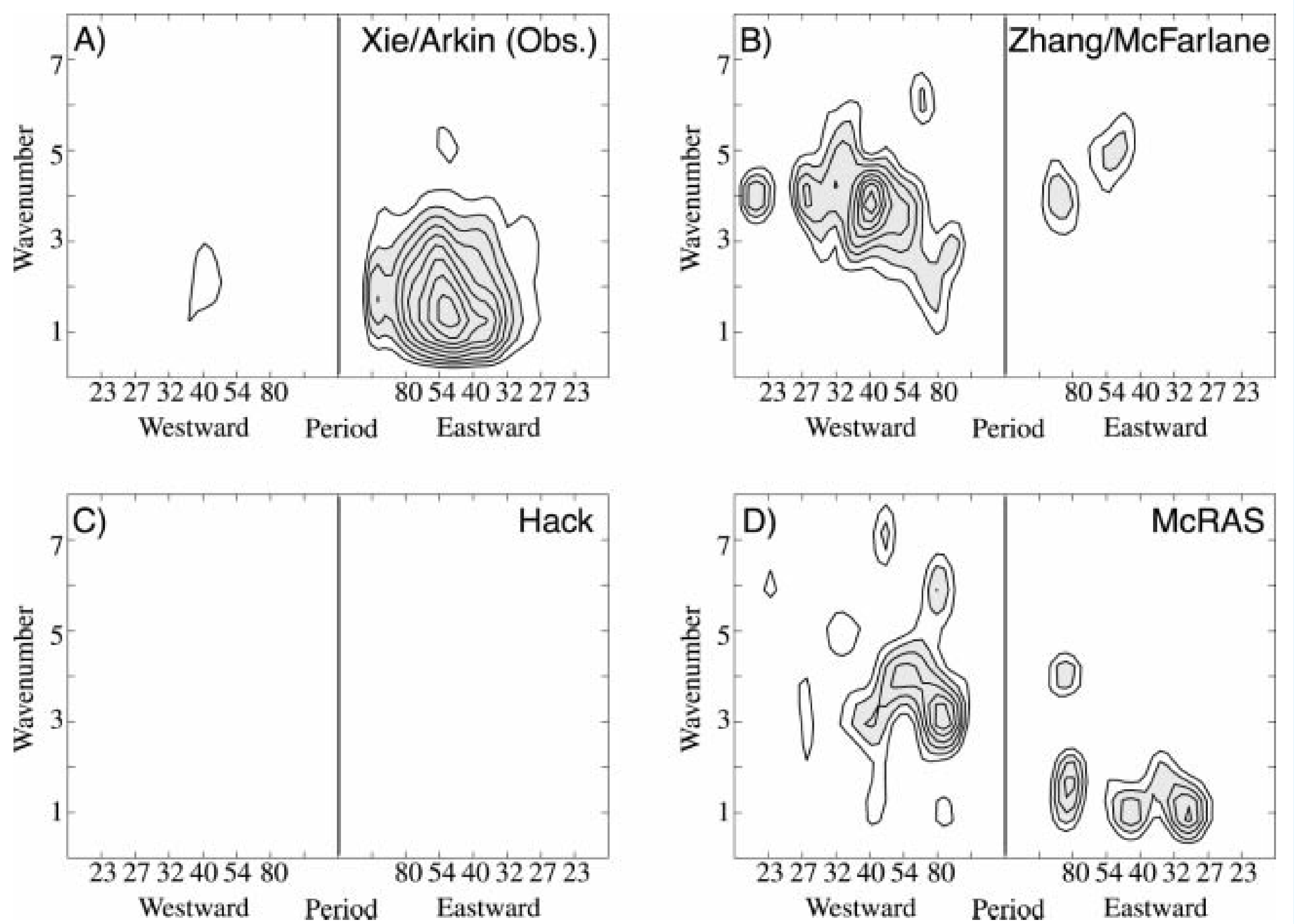
CCM3 precipitation climatology (March) vs. obs.

Maloney and Hartmann, 2001; three convective parameterizations



Precip. power spectral density CCM3 vs. obs.

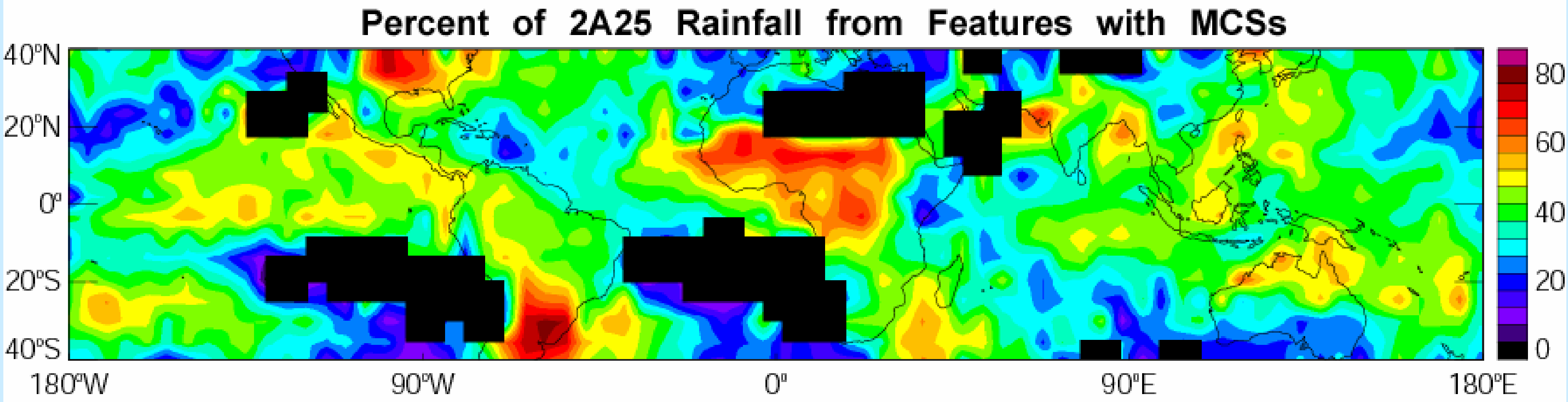
Three convective parameterizations



Maloney and Hartmann, 2001

Percent of precip. from mesoscale convective systems

Nesbitt et al., 2002; analysis of TRMM data



Prototype for convective interaction with large-scale dynamics

$$(\partial_t + u\partial_x)u + \partial_x T = -\varepsilon_u u \qquad (1)$$

$$(\partial_t + u\partial_x)T + M_s\partial_x u = Q_c + R \qquad (2)$$

$$(\partial_t + u\partial_x)q - M_q\partial_x u = -Q_c + E \qquad (3)$$

$$Q_\mathrm{c} = \xi_2\tau_\mathrm{c}^{-1}(q - T + \xi_1)$$

CAPE $\propto q - T$, $\bar{R} = R - \varepsilon_R T$, $E = \varepsilon_\mathrm{E}(u)(\mathrm{q}^*(\mathrm{T}_\mathrm{s}) - \mathrm{q})$

q, T projection coeffs of vertical structure

Prototype (cont.)

Add (2) + (3)

$$\left(\partial_t + u\partial_x\right)(T+q) + M\partial_x u = R + E \qquad (4)$$

$M = M_s - M_q$ gross moist stability

Dry gravity/Kelvin wave speed ~ $M_\mathrm{s}^{1/2}$

Moist gravity/Kelvin wave speed ~ $M^{1/2}$

$\tau_\mathrm{c} << \varepsilon_\mathrm{E}^{-1}, \varepsilon_\mathrm{R}^{-1}, \varepsilon_\mathrm{u}^{-1}$ Large scales: $\tau_\mathrm{c} << L/M_\mathrm{s}^{1/2}$

Convective QE $q \approx T$ at leading order in τ_c

Q_c diagnostic from (1) and (4)

ξ_2 irrelevant unless can deviate from strict QE

ξ_1 modifies QE $q \approx T - \xi_1$

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

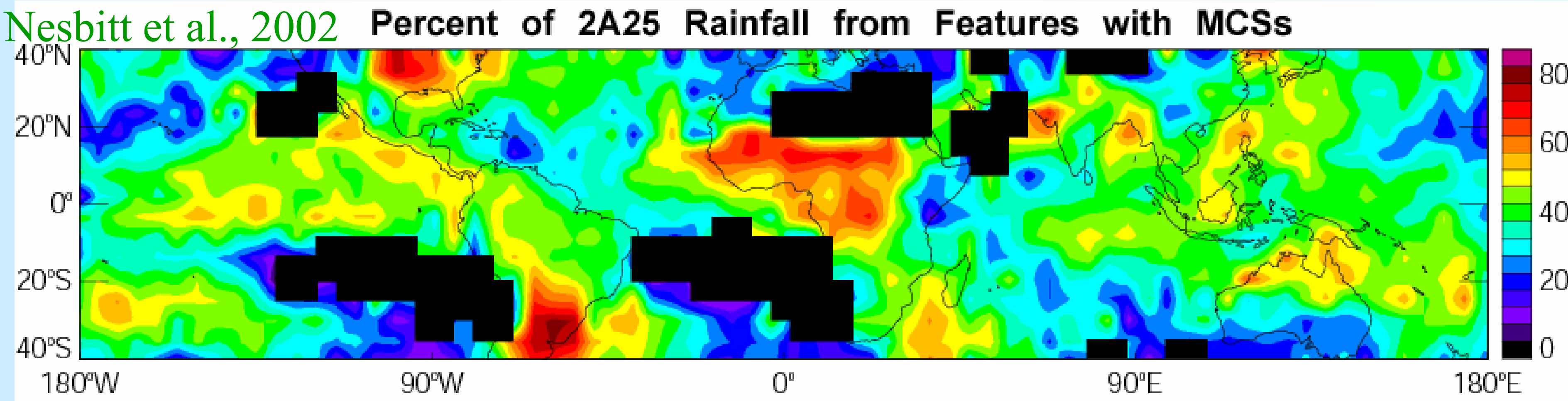
- **Even simple version, e.g., CAPE scheme, can yield encouraging results (incl. probability distribution of heating)--but there is parameter sensitivity.**
- **Autocorrelation time of the stochastic processes matters.**
  - Longer autocorrelation time, on the order of a day, yields more impact and better 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



Two tropical topics:
1. Stochastic deep convective parameterization &
2. Global warming drought mechanisms

J. David Neelin[*]
Johnny Lin[**], **Hui Su**[*], **and Chia Chou**[***]
[*]Dept. of Atmospheric Sciences & Inst. of Geophysics and Planetary Physics, U.C.L.A.
[**]Univ. of Chicago, [***]Inst. of Earth Sciences, Academia Sinica, Taiwan

1. 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. Can a stochastic representation capture additional effects arising from small-scales?

2. Tropical regional precipitation anomalies under global warming, especially drought regions: mechanisms? Relationship to El Niño case?