Rethinking convective quasi-equilibrium*

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- **QE assumptions: Slow driving by large scales, fast removal of buoyancy; Above onset threshold, strong convection/precip. increase to keep system close to onset** Arakawa & Schubert 1974
- **Pick up a function of buoyancy-related fields – temperature *T* & moisture (here column integrated moisture *w*)**
- **Adjustment process (e.g.linear pick-up) makes a difference** Betts & Miller 1986; Moorthi & Suarez 1992; Randall & Pan 1993; Zhang & McFarland 1995; Emanuel 1993; Emanuel et al 1994; Yu and Neelin 1994; Yano et al 2000…
- **Missing variance? Stochastic or super parameterization**
- **Need to characterize this transition**

Background

- Precip increases with column water vapor at monthly, daily time scales **(e.g., Bretherton et al 2004).** Check **short time/strong precip** range needed **for stochastic convective parameterization**
- **Simple e.g. of convective closure (Betts-Miller 1996)** shown for vertical integral**:**

$$Precip = (w - w_c(T))/\tau_c \qquad \text{(if positive, zero otherwise)}$$

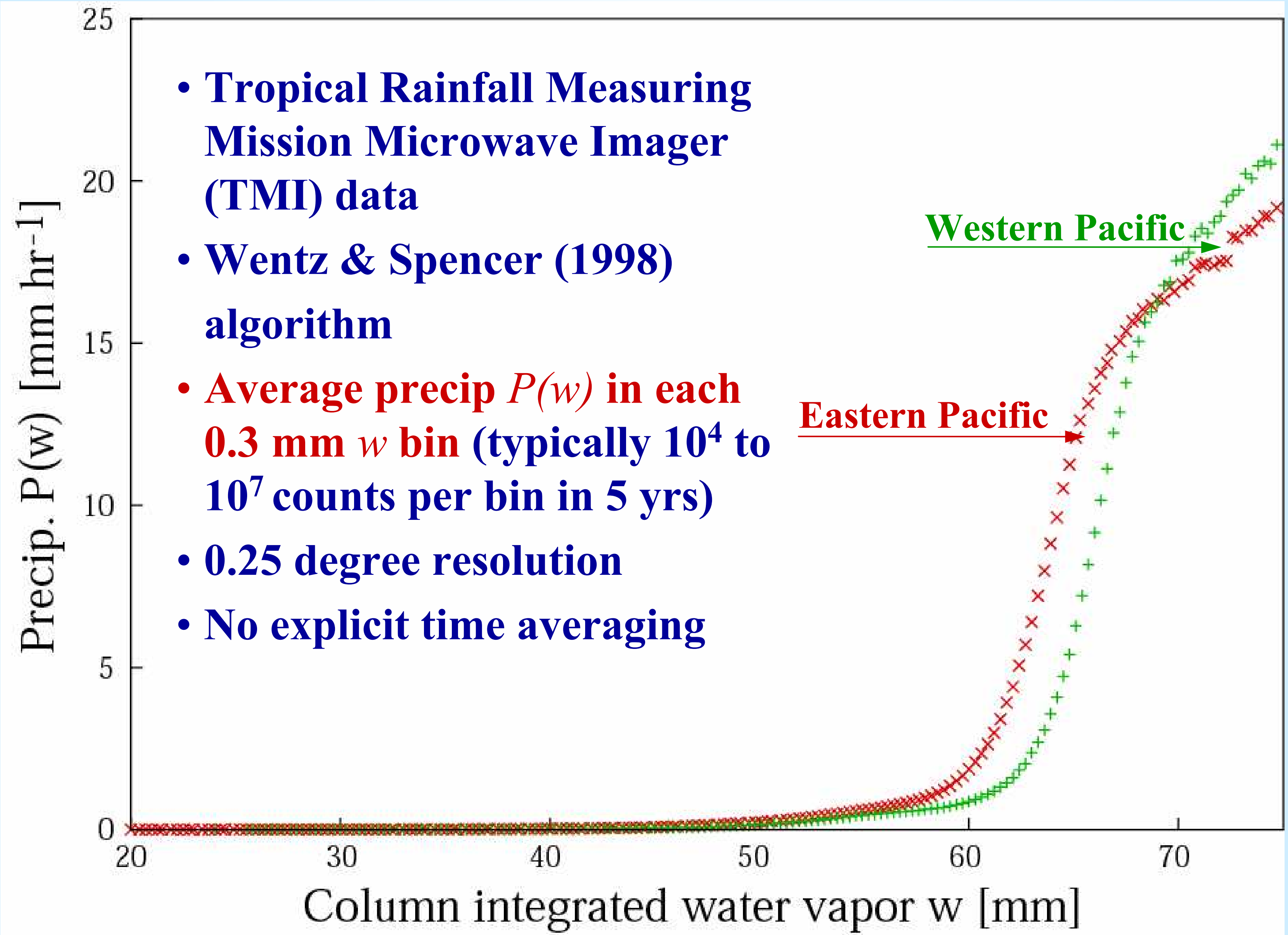
w vertical int. water vapor

w_c convective threshold, dependent on temperature T

τ_c time scale of convective adjustment

- **Data here: Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI) precip and water vapor estimates (mostly Hilburn & Wentz 2007);TRMM radar 2A25; ERA40 reanalysis temperatures. Analysed in tropics 20N-20S**

Western Pacific precip vs column water vapor



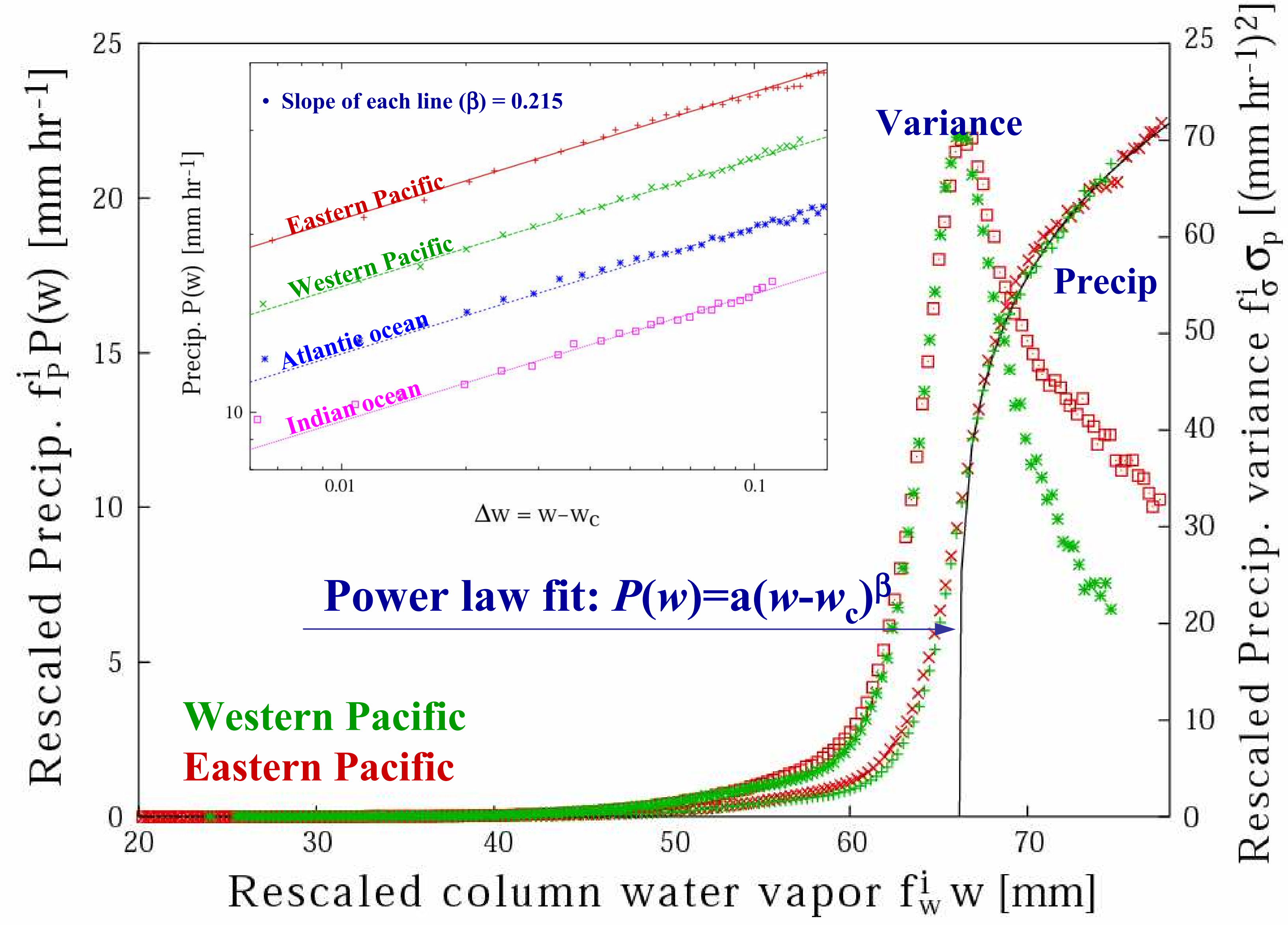
- Tropical Rainfall Measuring Mission Microwave Imager (TMI) data
- Wentz & Spencer (1998) algorithm
- Average precip *P(w)* in each 0.3 mm *w* bin (typically 10^4 to 10^7 counts per bin in 5 yrs)
- 0.25 degree resolution
- No explicit time averaging

Peters & Neelin, *Nature Physics*, 2006

Why consider match to a continuous phase transition?

- Convective **quasi-equilibrium closure** postulates (Arakawa & Schubert 1974) of **slow drive, fast dissipation** sound similar to self-organized criticality (SOC) postulates (Bak et al 1987; …), known in some stat. mech. models to be assoc. with continuous phase transitions (Dickman et al 1998; Sornette 1992; Christensen et al 2004)
- Critical phenomena at continuous phase transition well-known in equilibrium case (Privman et al 1991; Yeomans 1992)

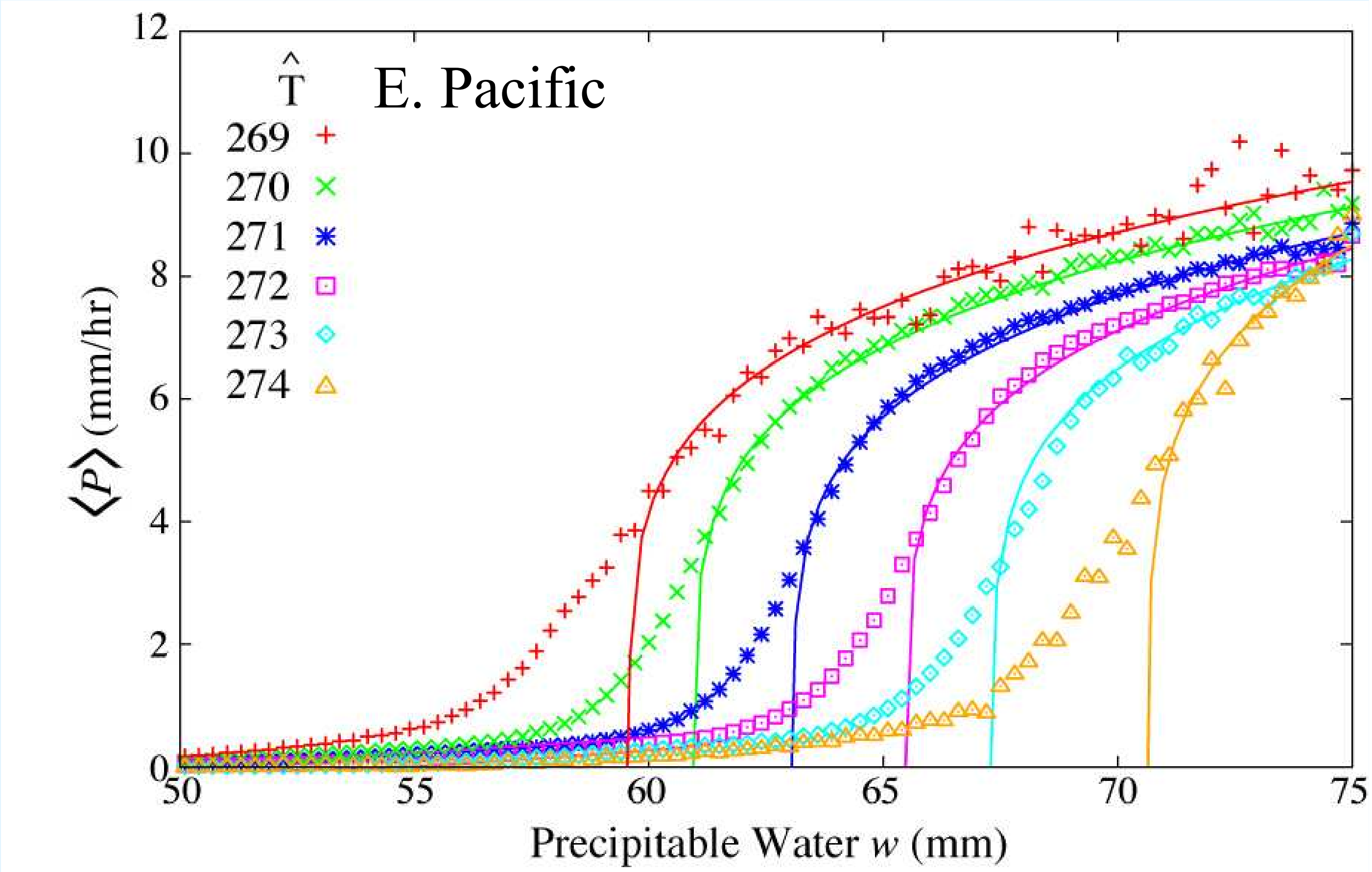
Collapse of Precip. & Precip. variance for different regions



Peters & Neelin, 2006

Precip. dependence on tropospheric temperature & column water vapor

- Averages conditioned on vert. avg. temp. $\hat{T}$, as well as w (T 200-1000mb from ERA40 reanalysis)
- Power law fits above critical: w_c changes, same β
- [note more data points at 270, 271]

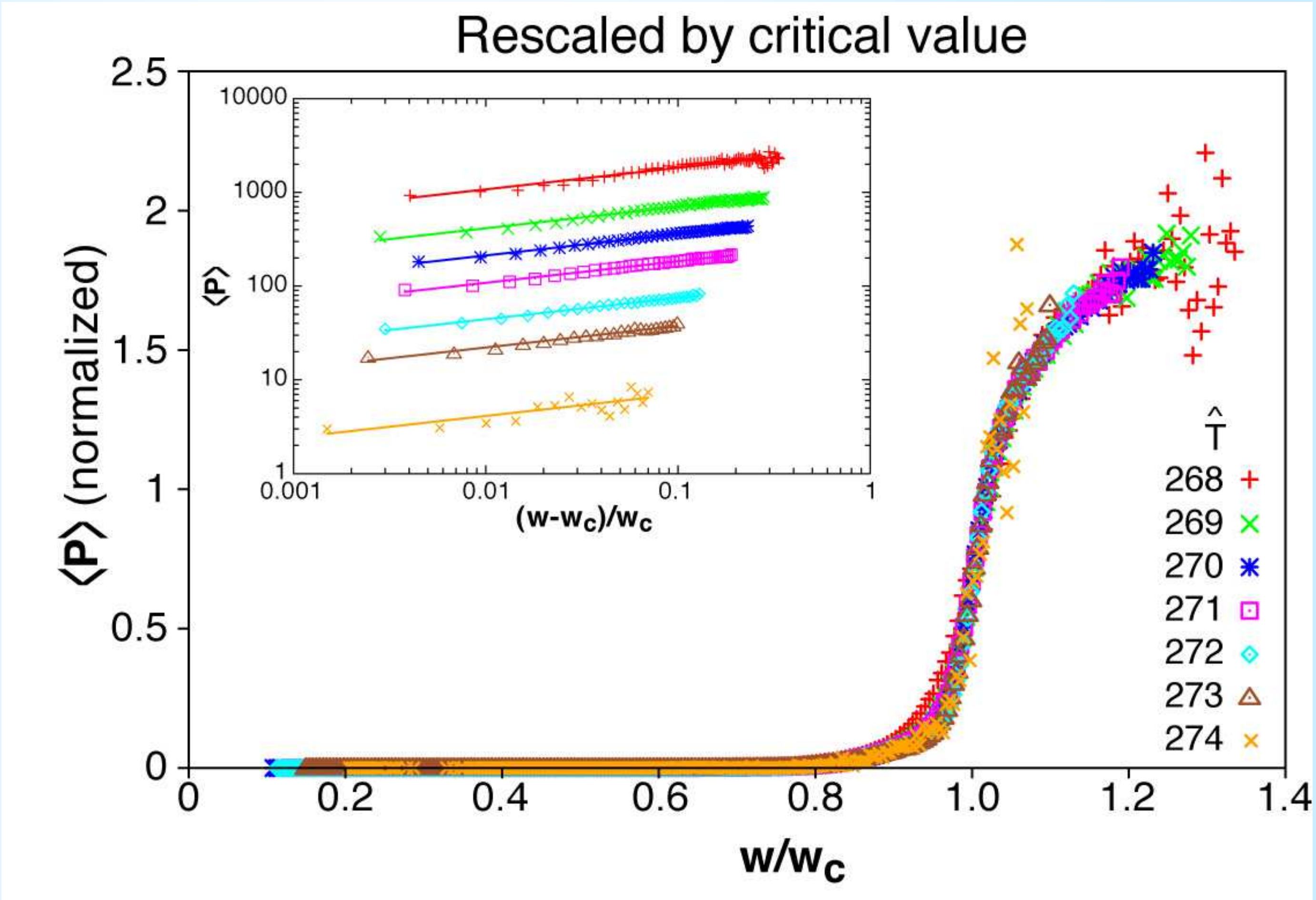


- Analysed in tropics 20N-20S

Neelin, Peters & Hales in prep.

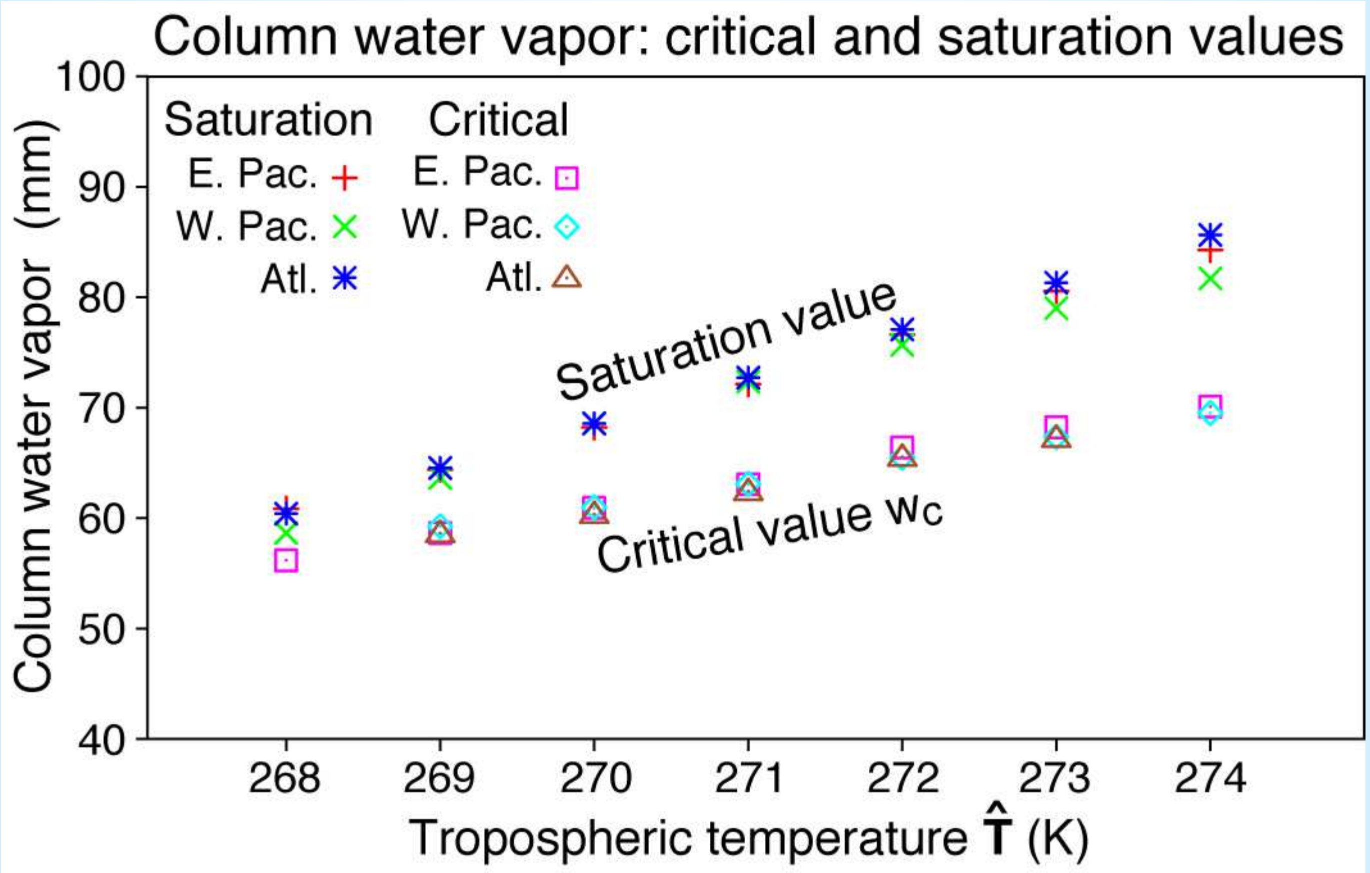
Precip. Collapse for various temperatures

- For various temp. $\hat{T}$, as function of w rescaled by critical value (E. Pacific)
- Quality of the collapse supports w_c fits
  - [note scatter at hi/lowest T assoc with fewer data]
- Inset: log-log above w_c



Behavior approaches $P(w)= a(w-w_c)^{\beta}$ **above transition**

Critical point dependence on temperature

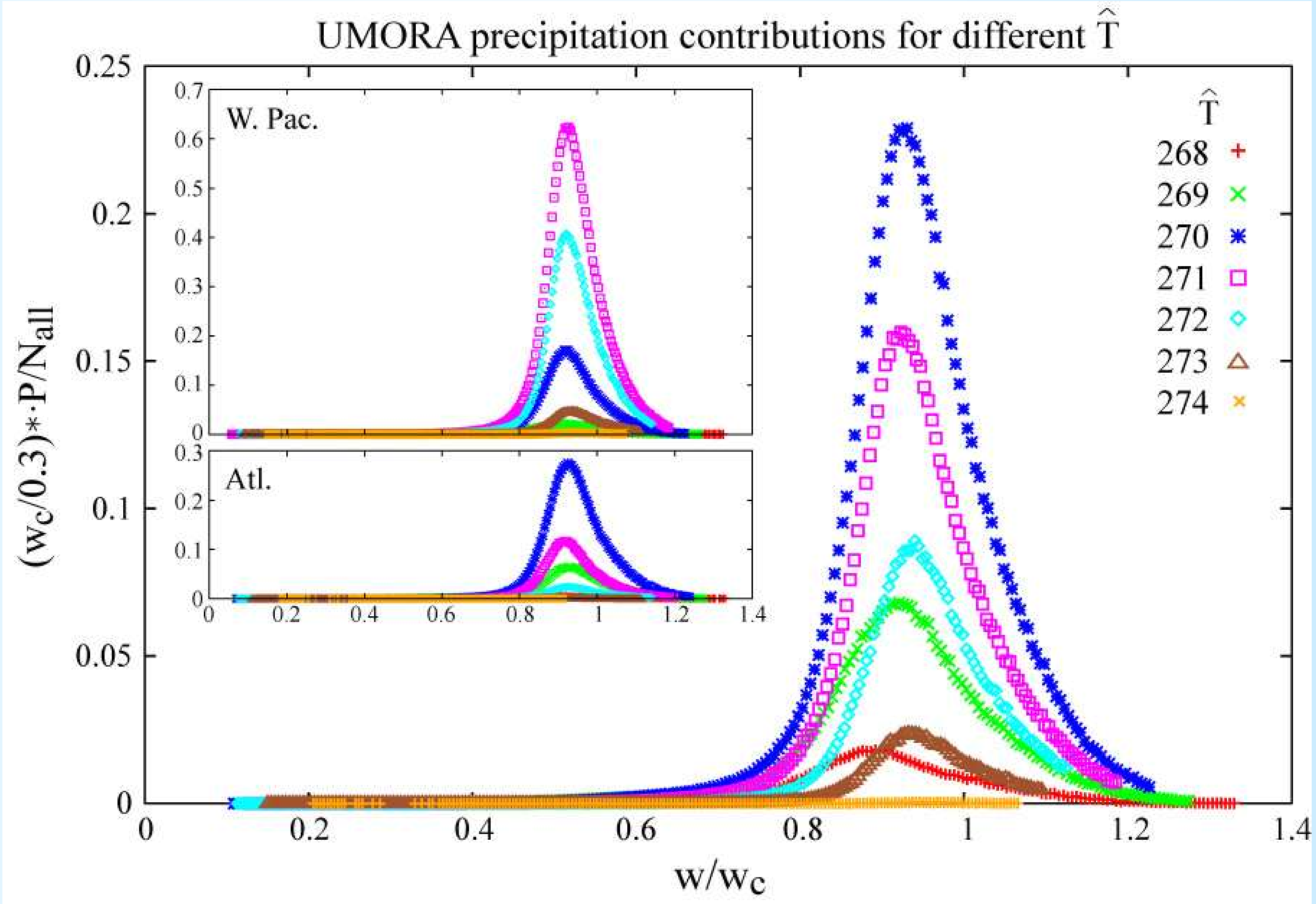


- **Find critical water vapor w_c for each vert. avg. temp. $\hat{T}$**
- **Compare to vert. int. saturation vapor value binned by same $\hat{T}$**
- ***Not* e.g., a constant fraction of column saturation**
- **[Using universal properties to probe system-specific properties]**

How much precip occurs near critical point?

Contributions to Precip from each $\hat{T}$

- **95% of precip in the region occurs above 80% of critical (25% above critical)---even for imperfect estimate of w_c**

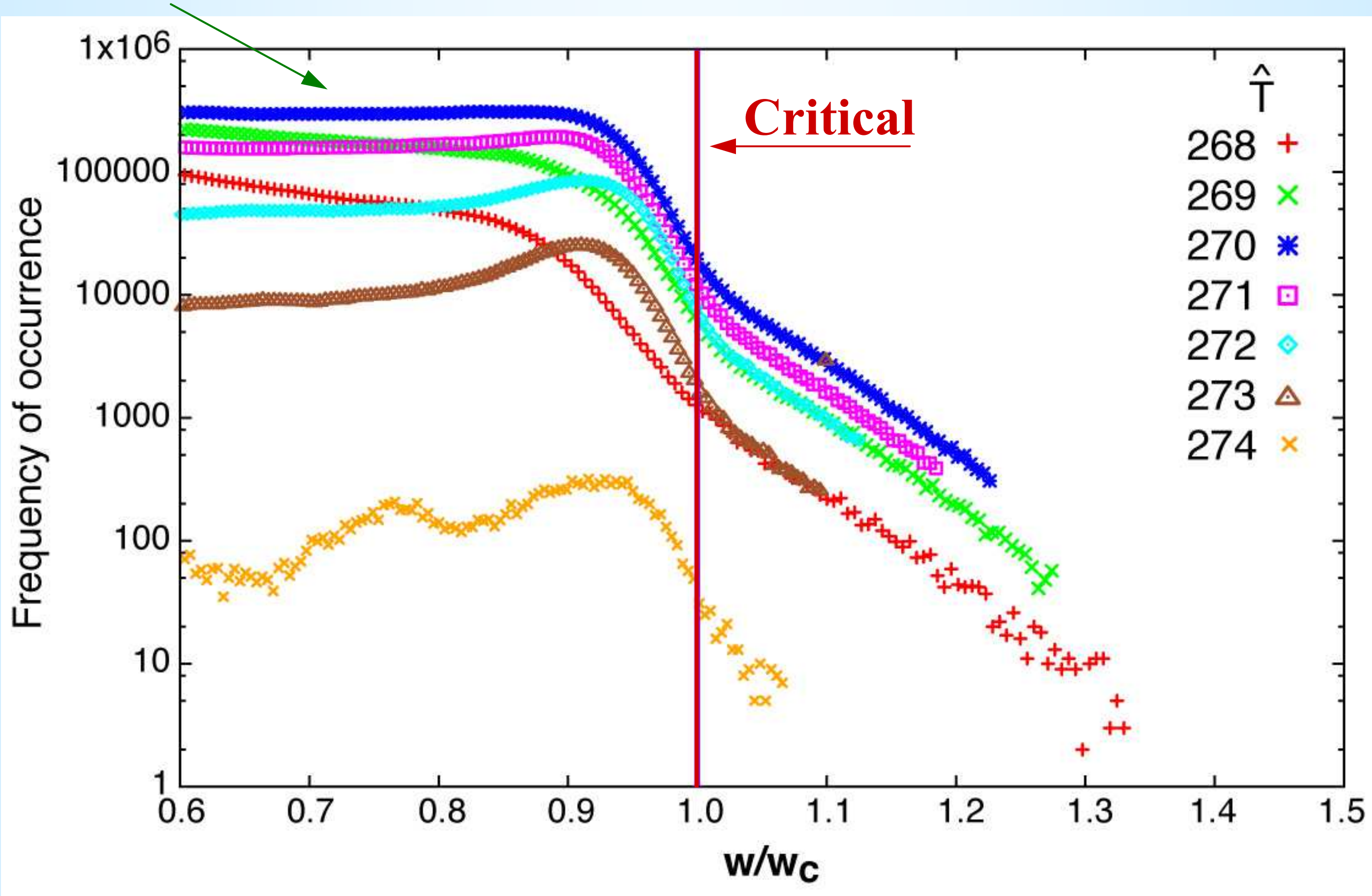


Frequency of occurrence vs normalized w

Eastern Pacific for various tropospheric temperatures

- drop across critical region and above, negative feedback of convection on water vapor ⇒ self-organization toward w_c

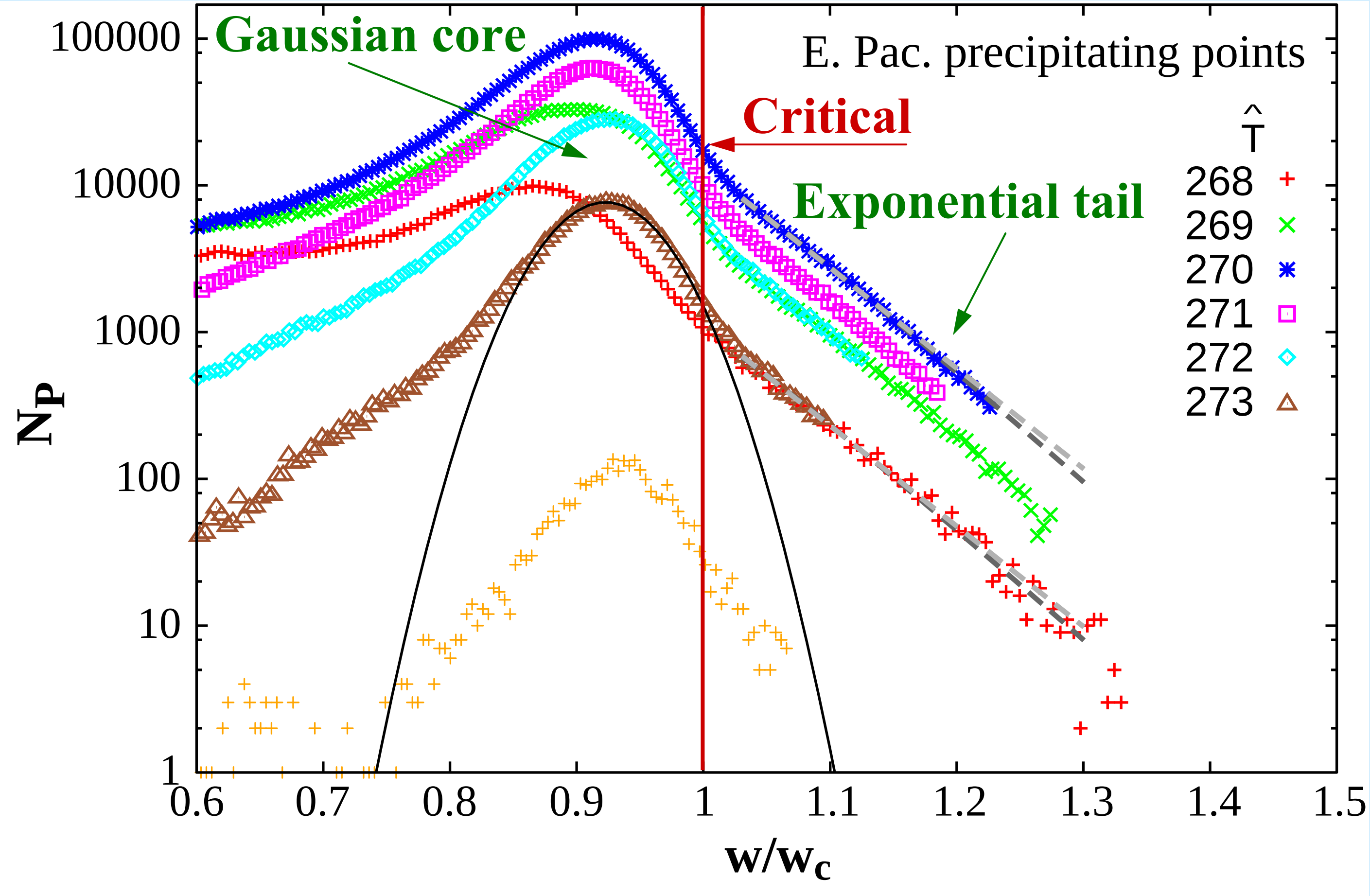
Below critical, other effects set residence time



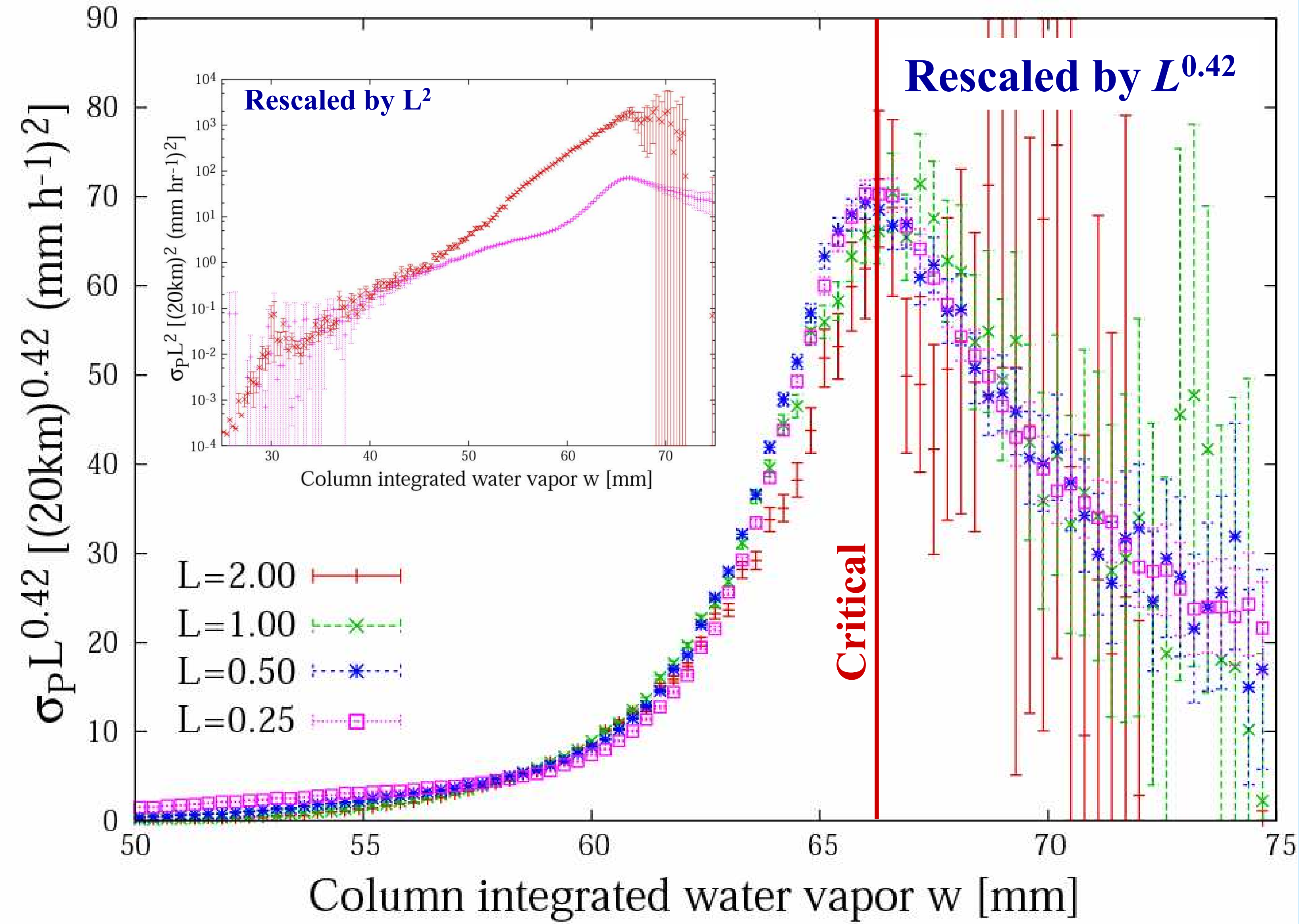
Precipitating freq. of occurrence vs. w/w_c

Eastern Pacific for various tropospheric temperatures

- Peak just below critical pt. ⇒ self-organization toward w_c
- But exponential tail above critical pt. ⇒ *more large events*
- with Gaussian core, characteristic of forced tracer advection-diffusion problems (e.g. Shraiman & Siggia 1994, Pierrehumbert 2000)



Precip. variance collapse for different averaging scales, *L*



($L^{0.42}$ W. Pacific case; 0.46 ±0.04 all basins)

Peters & Neelin, 2006

Back-of-envelope implications of variance scaling

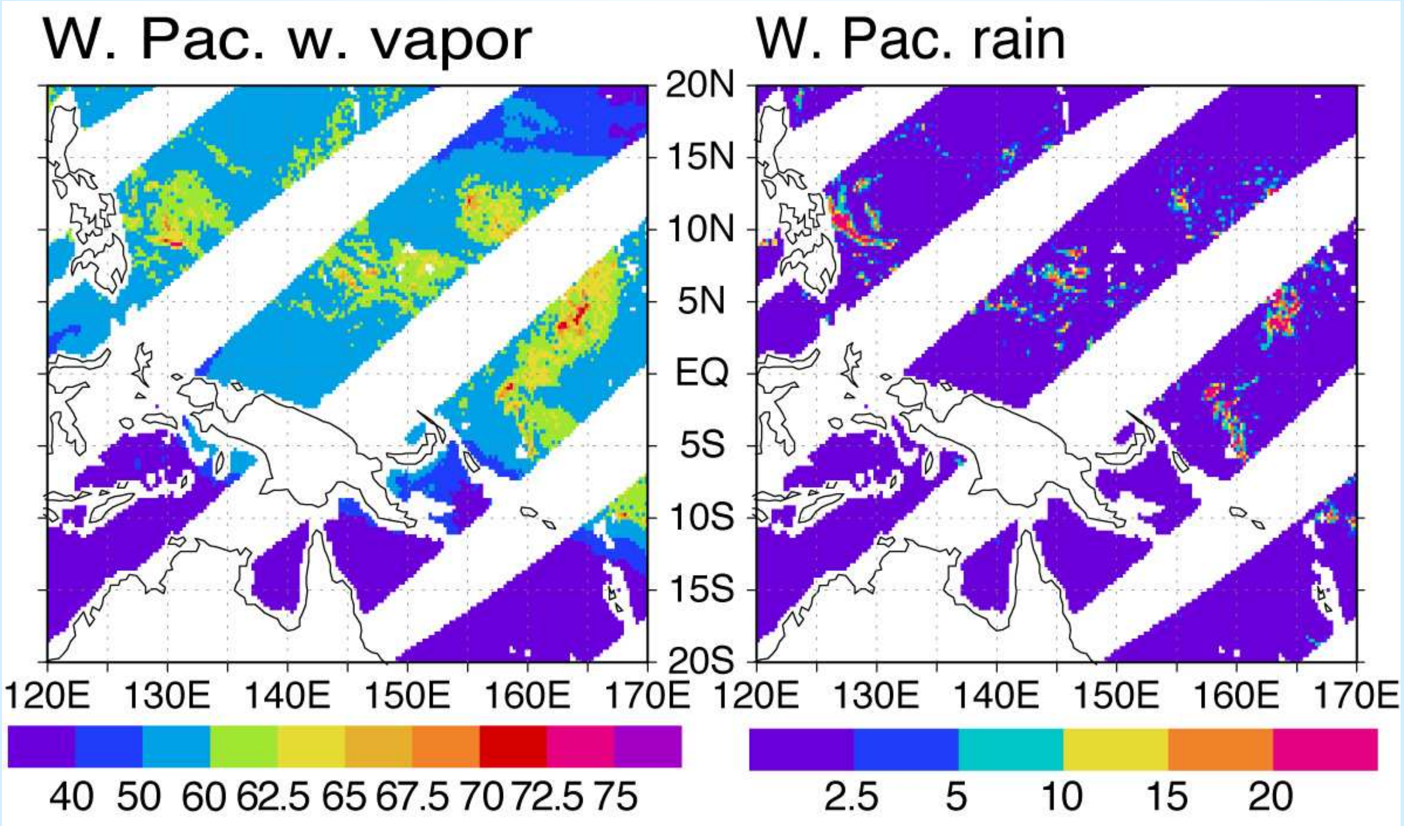
- Precipitation variance decreases as $\sim \boldsymbol{L}^{-0.46}$ instead of $\boldsymbol{L}^{-2}$ when data are coarse-grained to an L by L box; so what?

- **Traditionally, parameterize ensemble mean** assuming large ensemble within grid area yields small variance---**but variance does not decrease quickly under spatial averaging.**
- **E.g.,** when going from **25 to 200 km grid size**, precip. variance **decreases by only factor of $8^{-0.46} \sim 0.4$ instead of $8^{-2} \sim 0.02$**
- **Applies in critical region --- where most precipitation occurs**

- **Conversely, may help "super parameterization" (a few Cloud Resolving Model cells embedded in larger grid; Grabowski 2001; Khairoutdiov & Randall 2001; Randall et al. 2003)**

Neelin, Peters, Lin, Holloway & Hales, *Phil. Trans. Roy. Soc. A*, 2008

TMI column water vapor and Precipitation Western Pacific example

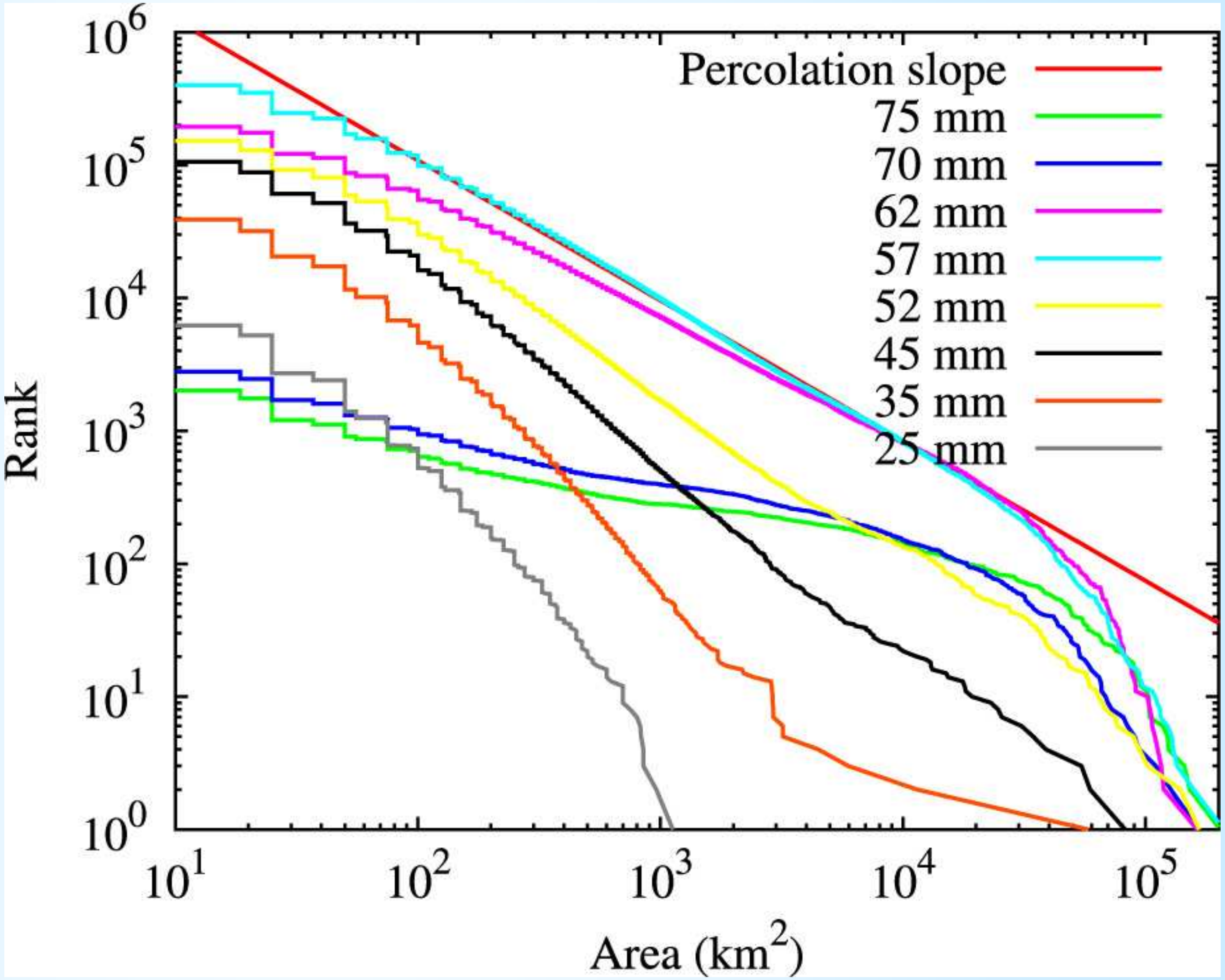


Nontrivial variance scaling ⇒ range of power law spatial correlation, assoc. w. critical clusters

⇒ Mesoscale Convective Systems

Mesoscale cluster sizes from TRMM radar

- Clusters of contiguous pixels with radar signal > threshold (Nesbitt et al 2006)
- Ranked by size
- Cluster size distribution: scale free range near criticality
- For $w > w_c$ increase rel. probability of large clusters



- But more large clusters from w near w_c. Why?: w distribution

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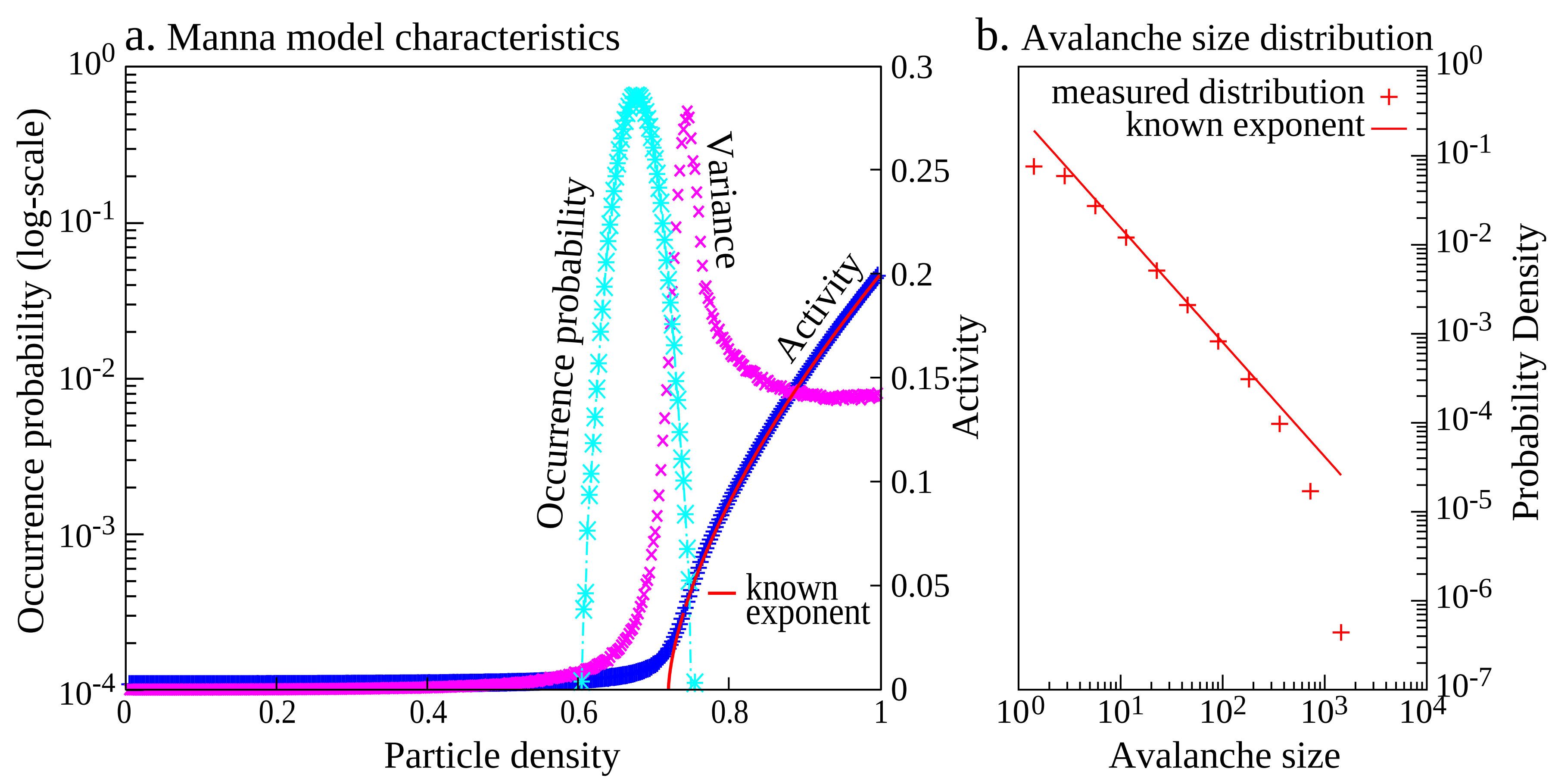
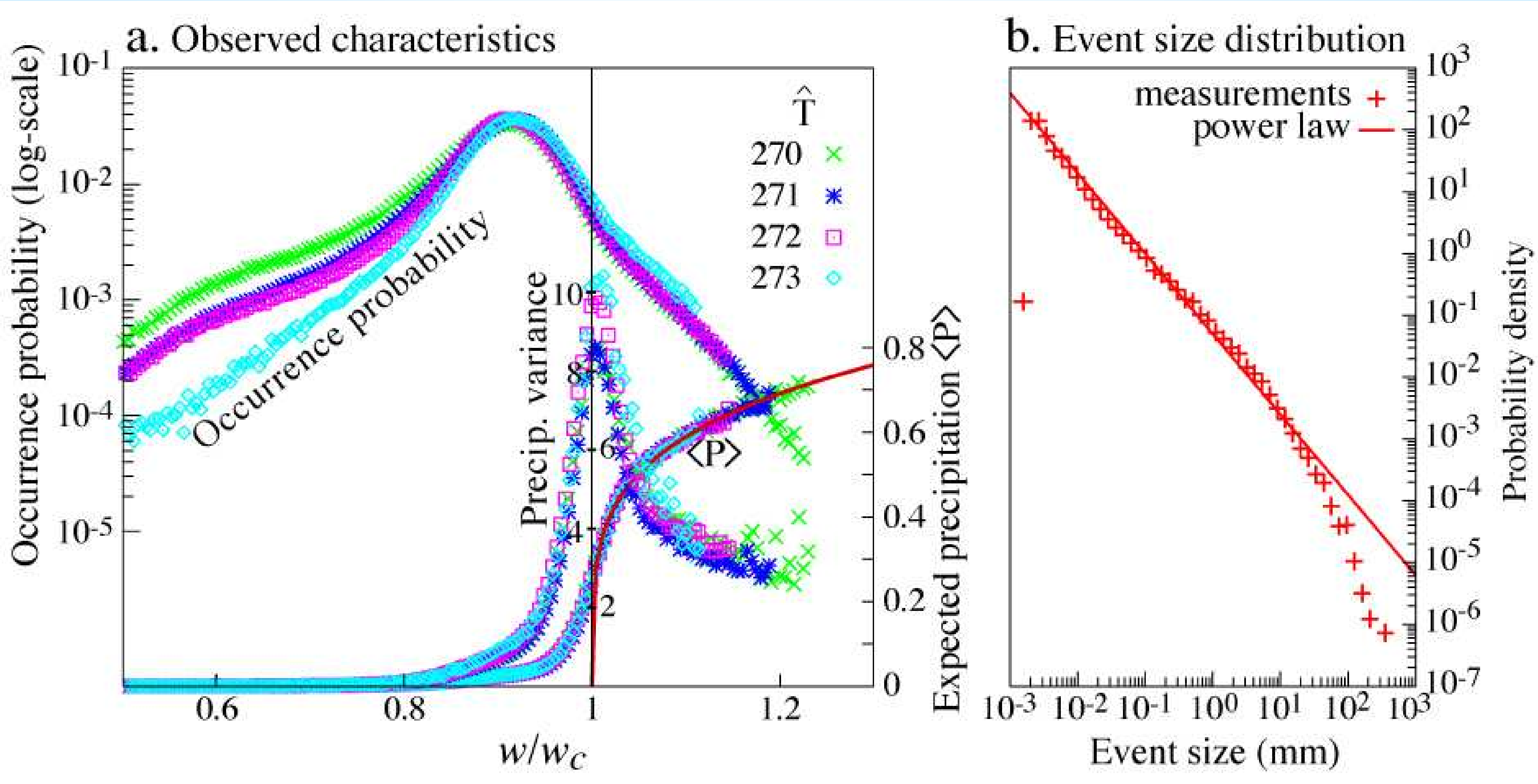
Example from Manna (1991) lattice model

(hopping particles—not a model of convection! 20x20 grid shown)



- **Activity (order parameter) & variance dependence on particle density (tuning parameter) [conserving case]**
- **Occurrence probability (log scale; very Gaussian) & event size distribution [self organizing case]**

Collapsed statistics for observed precipitation



- **Precip. mean & variance dependence on *w* normalized by critical value w_c; occurrence probability for precipitating points (for 4 *T* values); Event size distribution at Nauru**

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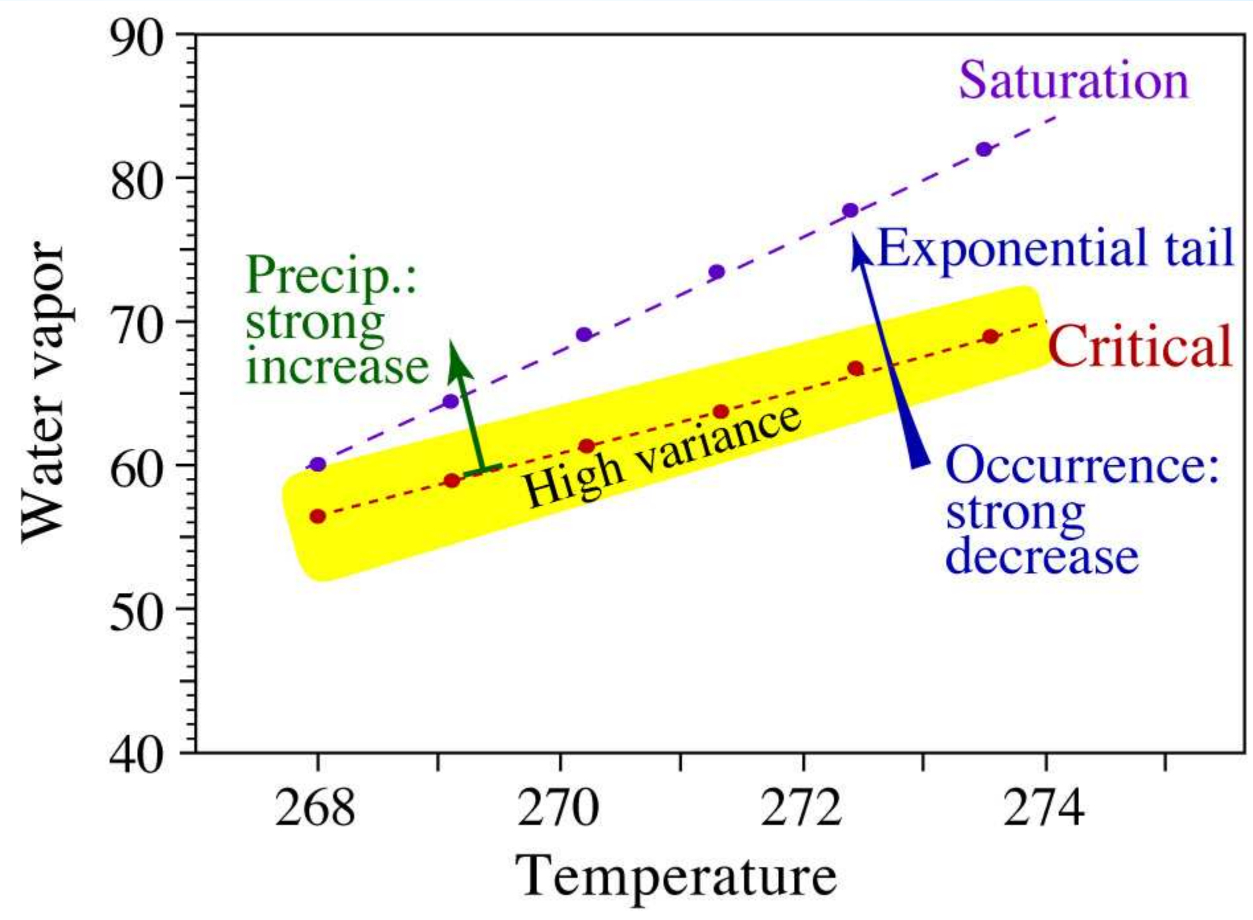
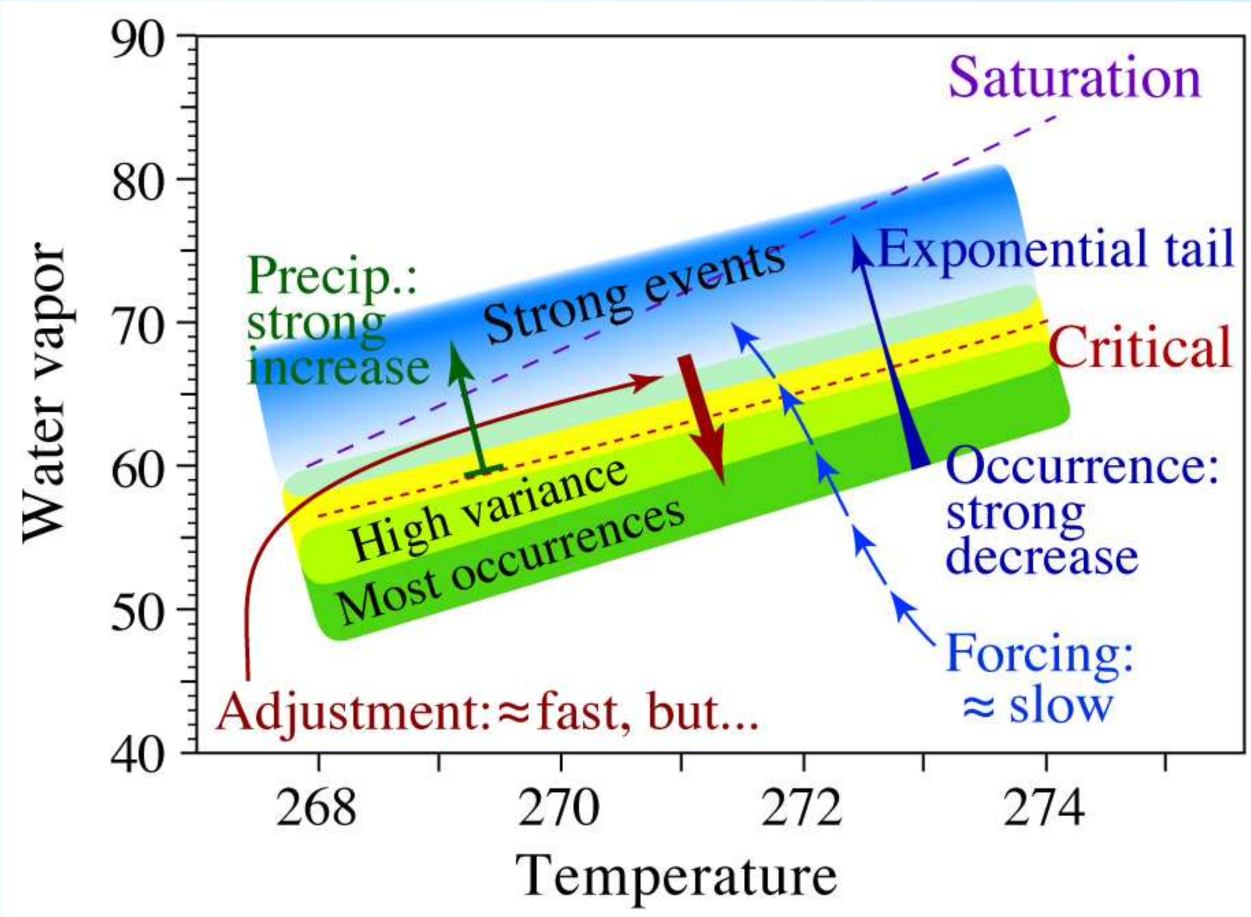
Rethinking convective quasi-equilibrium…

- Recall: Critical water vapor w_c empirically determined for each vert. avg. temp. $\hat{T}$
- Here use to schematize relationship (& extension of QE) to continuous phase transition/SOC properties



Rethinking QE

- “Slow” forcing eventually moves system above critical
- Adjustment: relatively fast **but** with a spectrum of event sizes, power law spatial correlations, (mesoscale) critical clusters, no single adjustment time …



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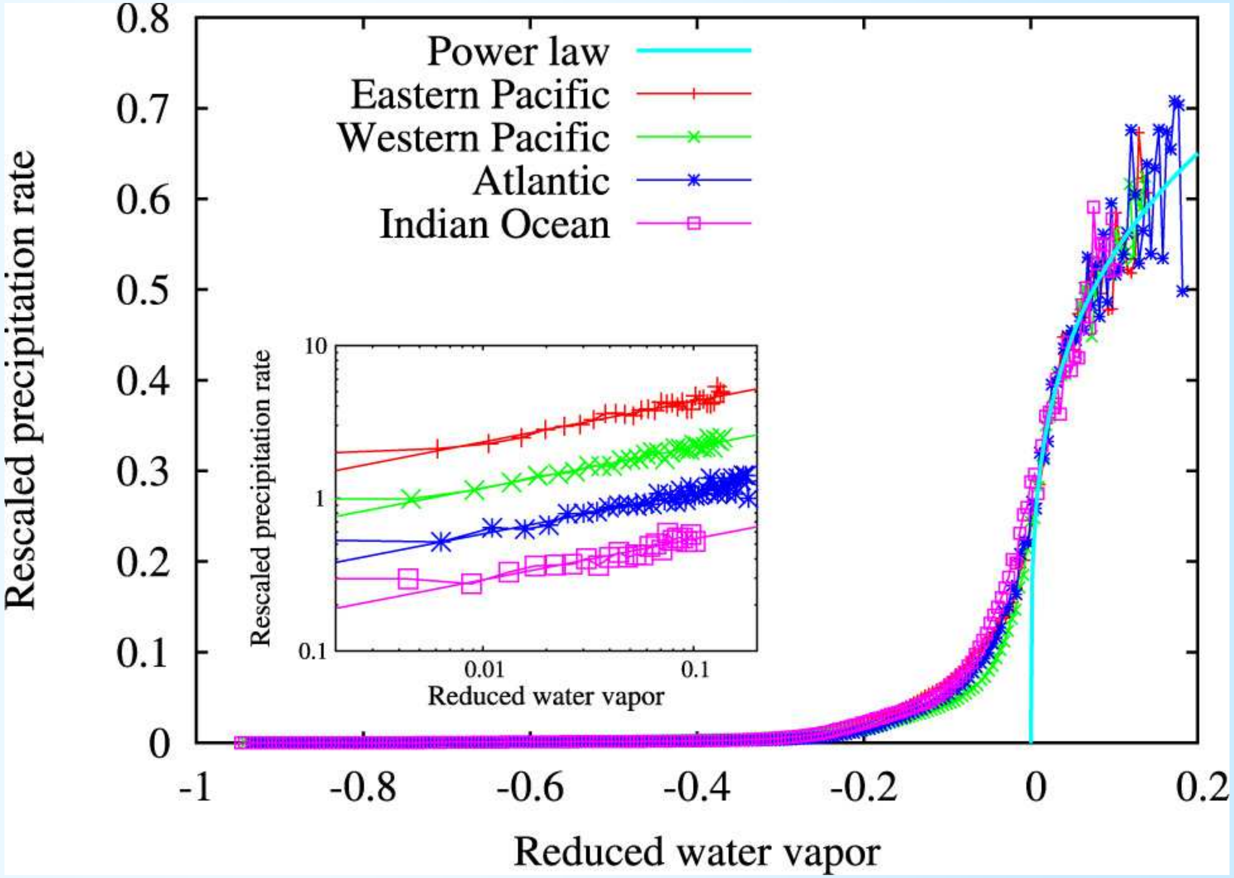
Rethinking convective quasi-equilibrium

- Transition to strong precipitation in TRMM observations conforms to properties of a continuous phase transition
- evidence of self-organized criticality (with long tail above critical)
- convective quasi-equilibrium (QE) assoc with the critical point (& most rain occurs near or above criticality)
- but additional properties than in traditional QE parameterization (e.g. not exponential decay; distribution of precip events, high variance at critical,…)
- empirical critical point dependence on water vapor, temperature
- spatial scale-free range in the mesoscale assoc with QE
    - Suggests mesoscale convective systems like critical clusters in other systems; connection to mesocale cluster size distribution
- suggests importance of excitatory short-range interactions (traditional QE convective elements interact only with mean field)
- TBD: steps from the new observed properties to better representations in climate models

Check pick-up with radar precip data

- TRMM radar data for precipitation
- 4 Regions collapse again with w_c scaling
- Power law fit above critical even has roughly same exponent as from TMI microwave rain estimate
- (2A25 product, averaged to the TMI water vapor grid)



$(w\text{-}w_c)/w_c$

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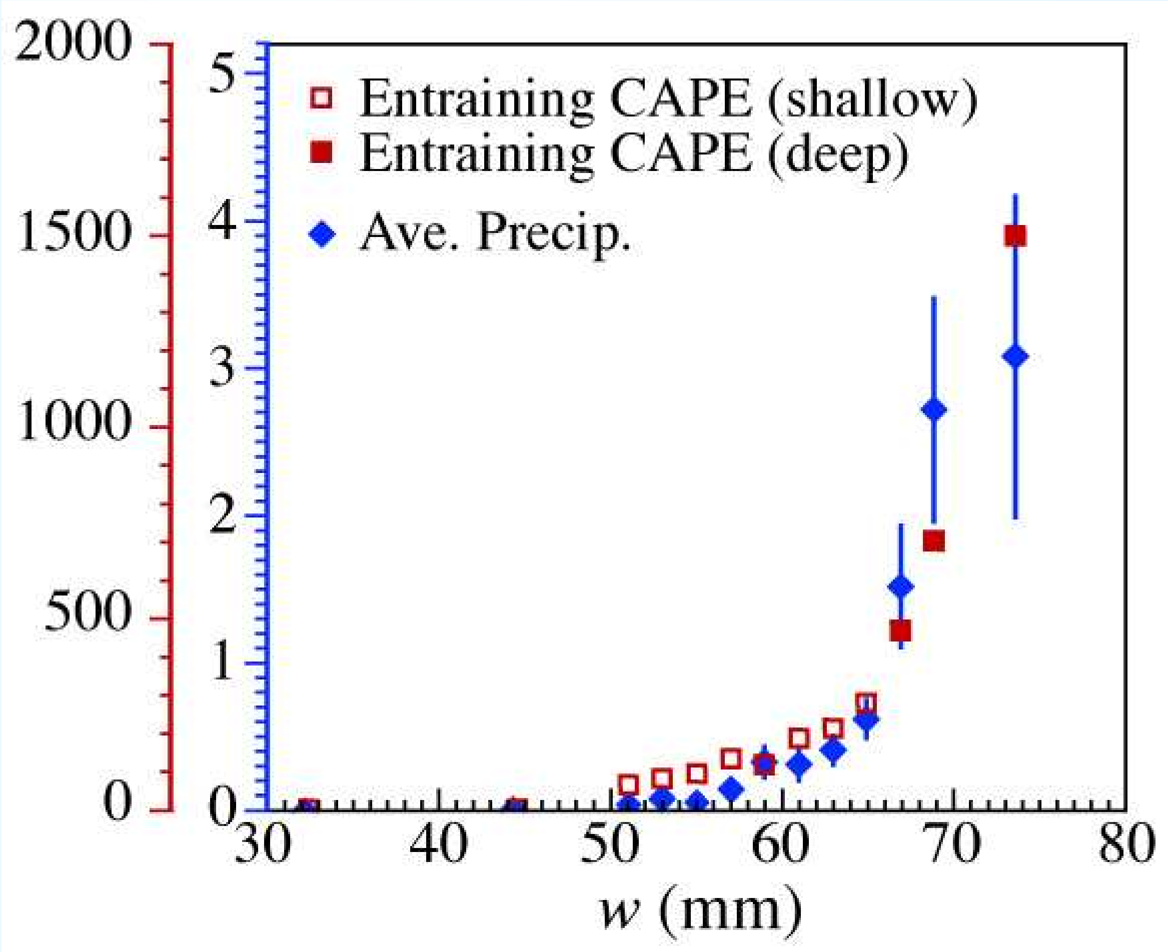
Entraining convective available potential energy and precipitation binned by column water vapor, *w*

- **buoyancy & precip. pickup at high *w***
- ***w* more than a proxy, since moisture in boundary layer and lower free troposph. contribute comparably***
- **useful because lots of microwave *w* data available…**



*Caveats: entrainment scheme and microphysics affect buoyancy absolute value, though not to ordering. More: invite Chris to talk

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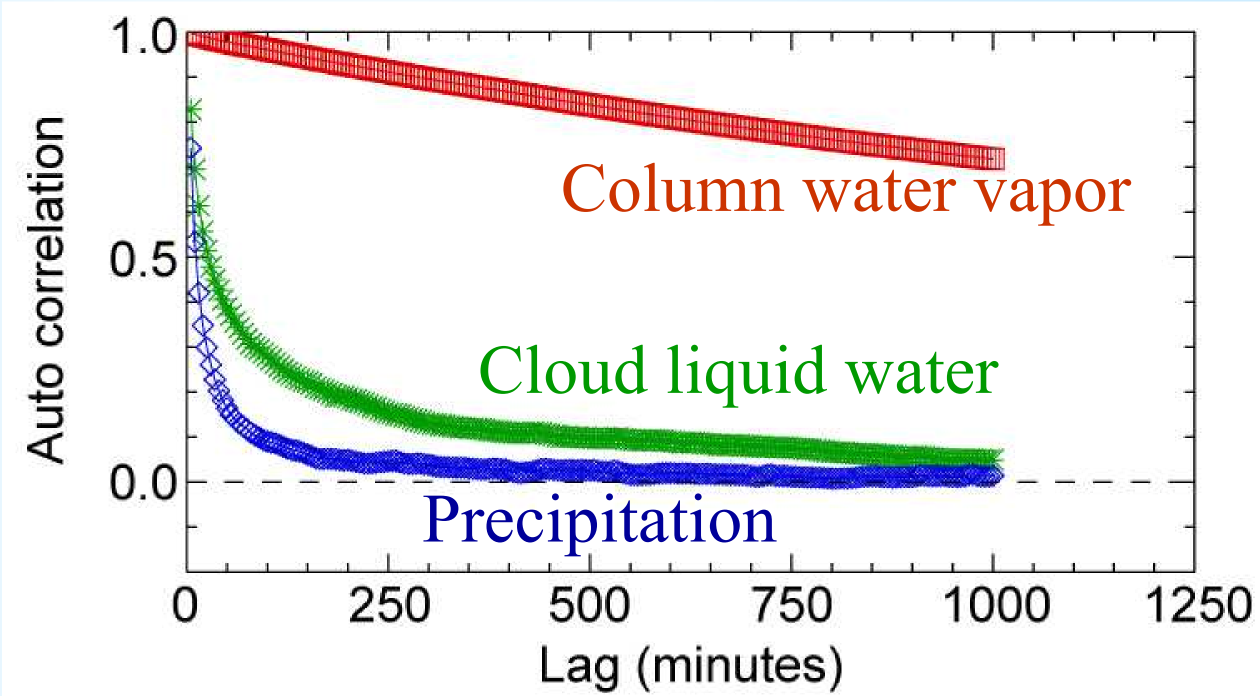
Autocorrelations in time

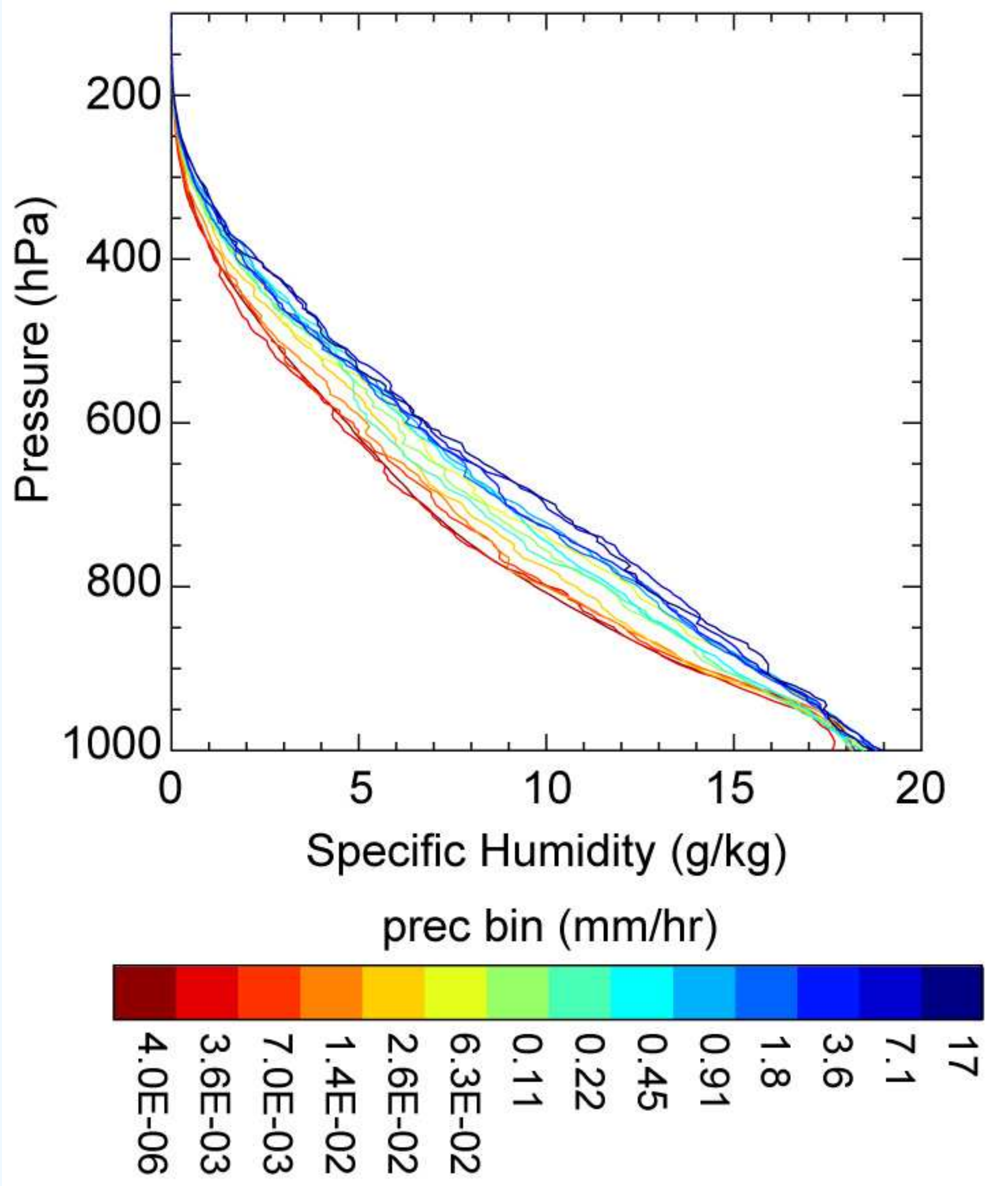
- Long autocorrelation times for vertically integrated moisture (once lofted, it floats around)
- Nauru ARM site upward looking radiometer + optical gauge



Vertical structure of moisture

- **Ensemble averages of moisture from rawinsonde data at Nauru*, binned by precipitation**
- **High precip assoc. with high moisture in free troposphere**

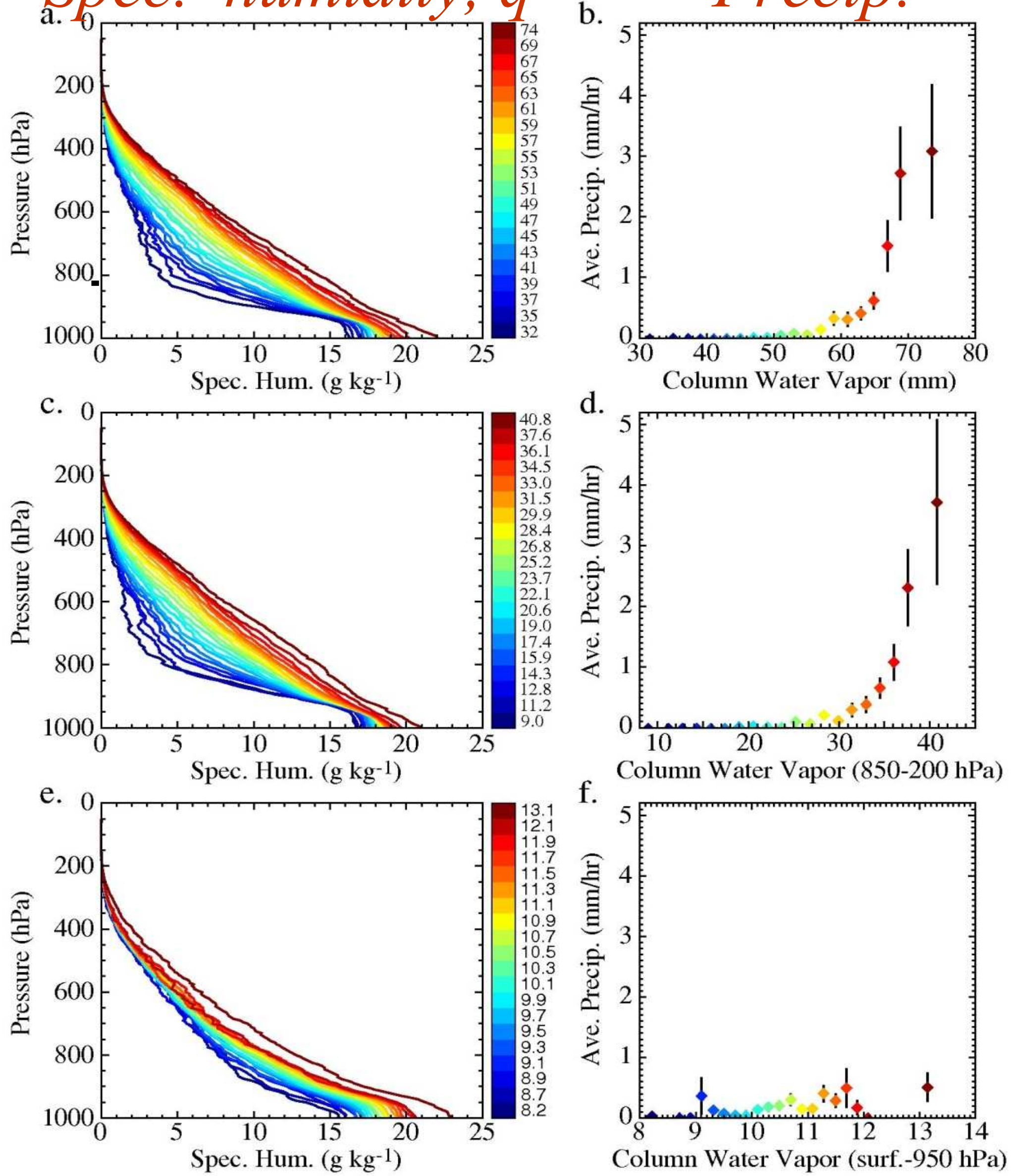
(consistent with Parsons et al 2000; Bretherton et al 2004; Derbyshire et al 2005; Neale et al 2008)



*Equatorial West Pacific ARM (Atmospheric Radiation Measurement) project site

Binning *q*, precip. on vert. int. water vapor

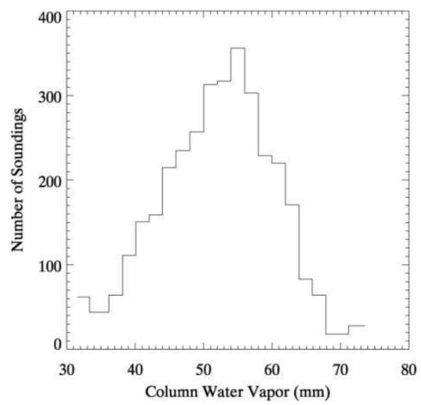
Spec. humidity, q *Precip.*



Binned by: Column water vapor

850-200 mb

Surface-950mb



[Note fewer soundings in high bins]

Holloway & Neelin, in prep.

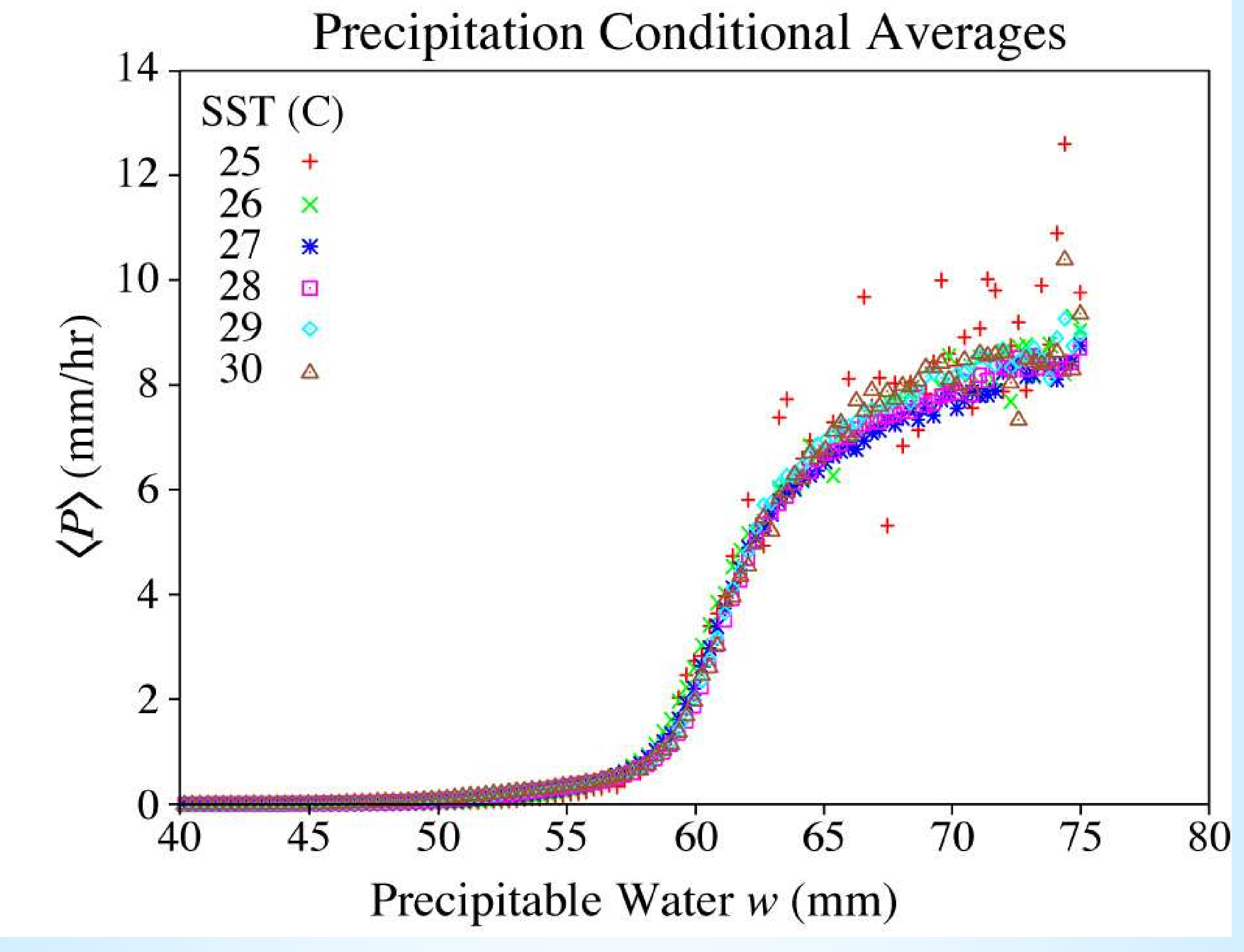
Back-of-envelope implications of variance scaling

- Precipitation variance decreases as ~$L^{-0.46}$ instead of L^{-2} when data are coarse-grained to an *L* by *L* box; so what?—continued

- **Conversely, this probably helps "super parameterization"** **(a few Cloud Resolving Model cells embedded in larger grid; Grabowski 2001; Khairoutdiov & Randall 2001; Randall et al. 2003)**
- **Super parameterization variance estimation problem:** if 200km large-scale grid cell should have e.g. **50x50** 4km **CRM** cells but instead has only **10,** trivial scaling would yield a **variance over-estimate by a factor of ~250 (*if* the CRM has the correct variance). Nontrivial scaling yields factor of ~3.**

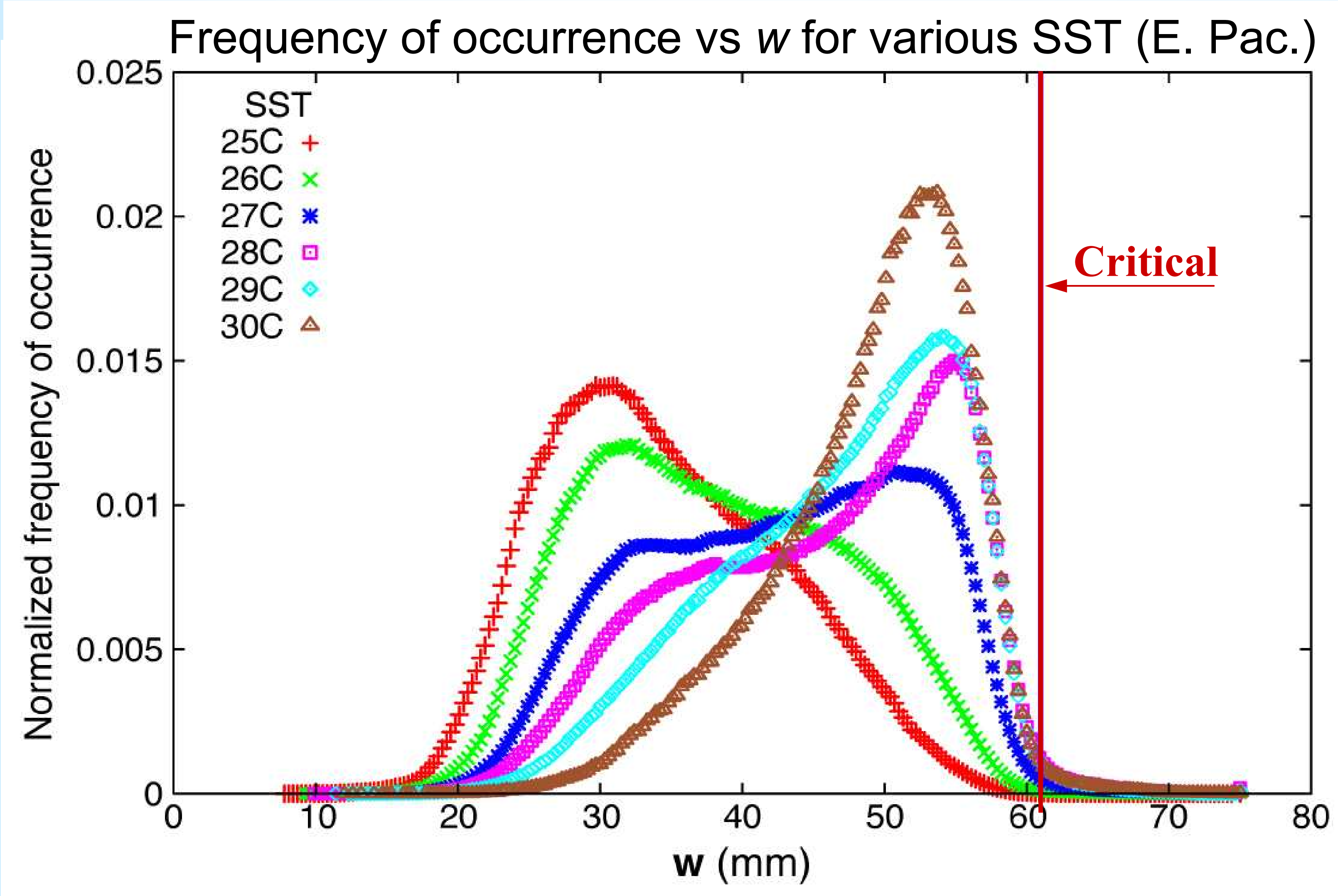
SST has little effect on the critical point

- Eastern Pacific precipitation for T=270 (largest contribution to precip) for sea surface temperature bins from 25-30C



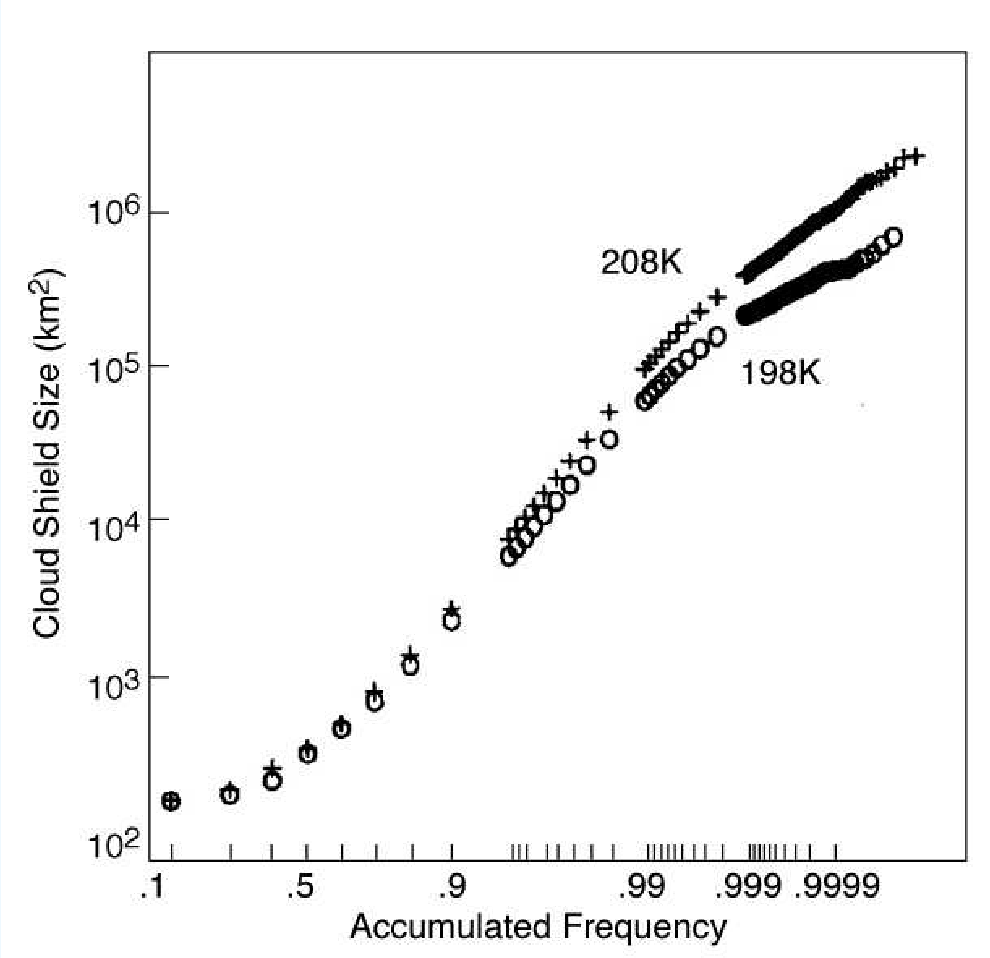
How does SST affect clim. precip?

- SST acts like external forcing: little effect on critical value; changes fraction of time the system spends in critical region



Mesoscale convective systems

- **Cluster size distributions of contiguous cloud pixels in mesoscale meteorology: “almost lognormal”** **(Mapes & Houze 1993)** **since Lopez (1977)**



Mesoscale cluster size frequency (log-normal = straight line).
From Mapes & Houze (MWR 1993)