Precipitable Water Vapor: The Critical Variable in Tropical Deep Convection

David K. Adams
CCA/UNAM

and Many Colleagues/Students in Mexico, Brazil, Germany, Portugal and the U.S.

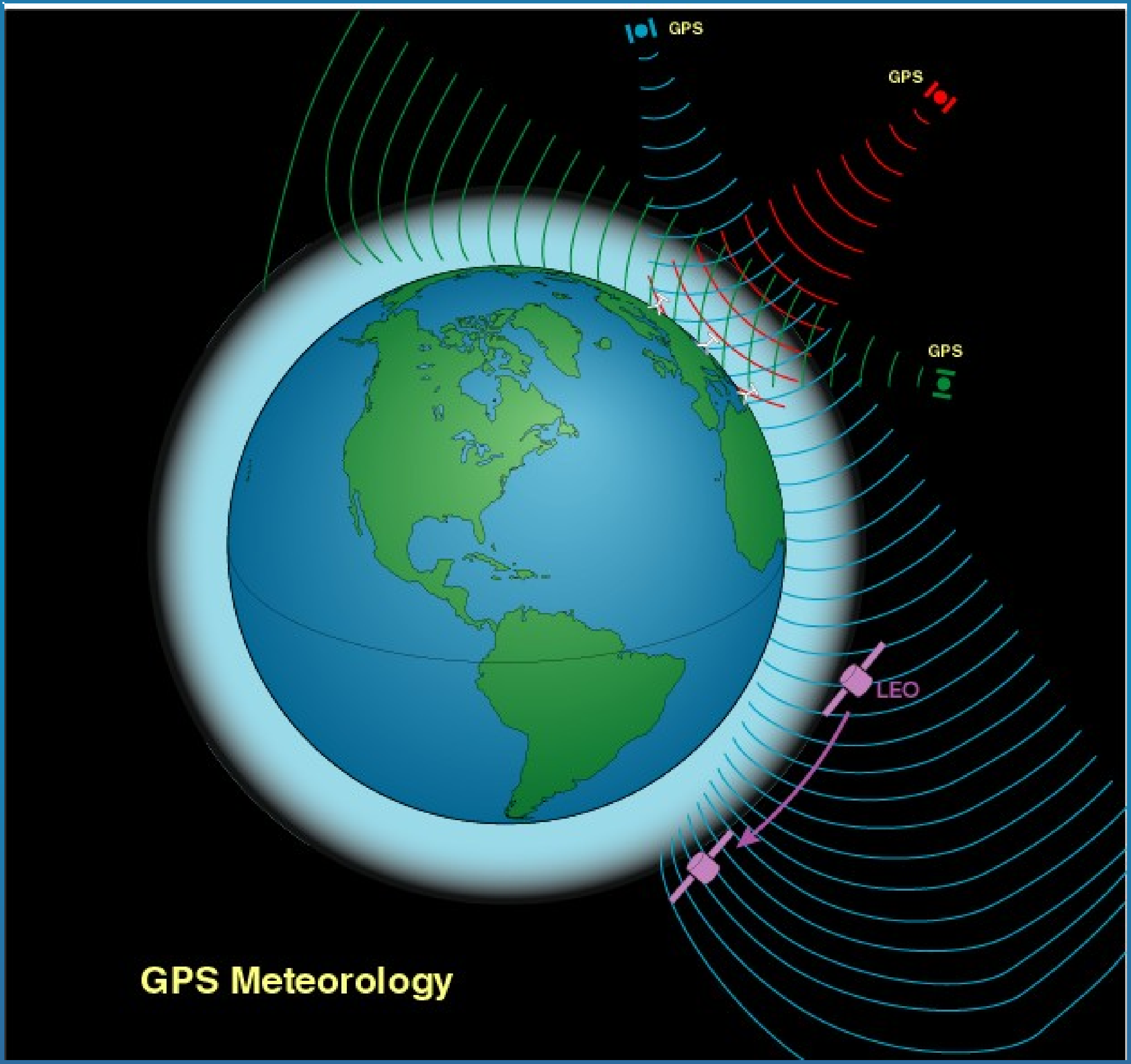


Structure of Presentation

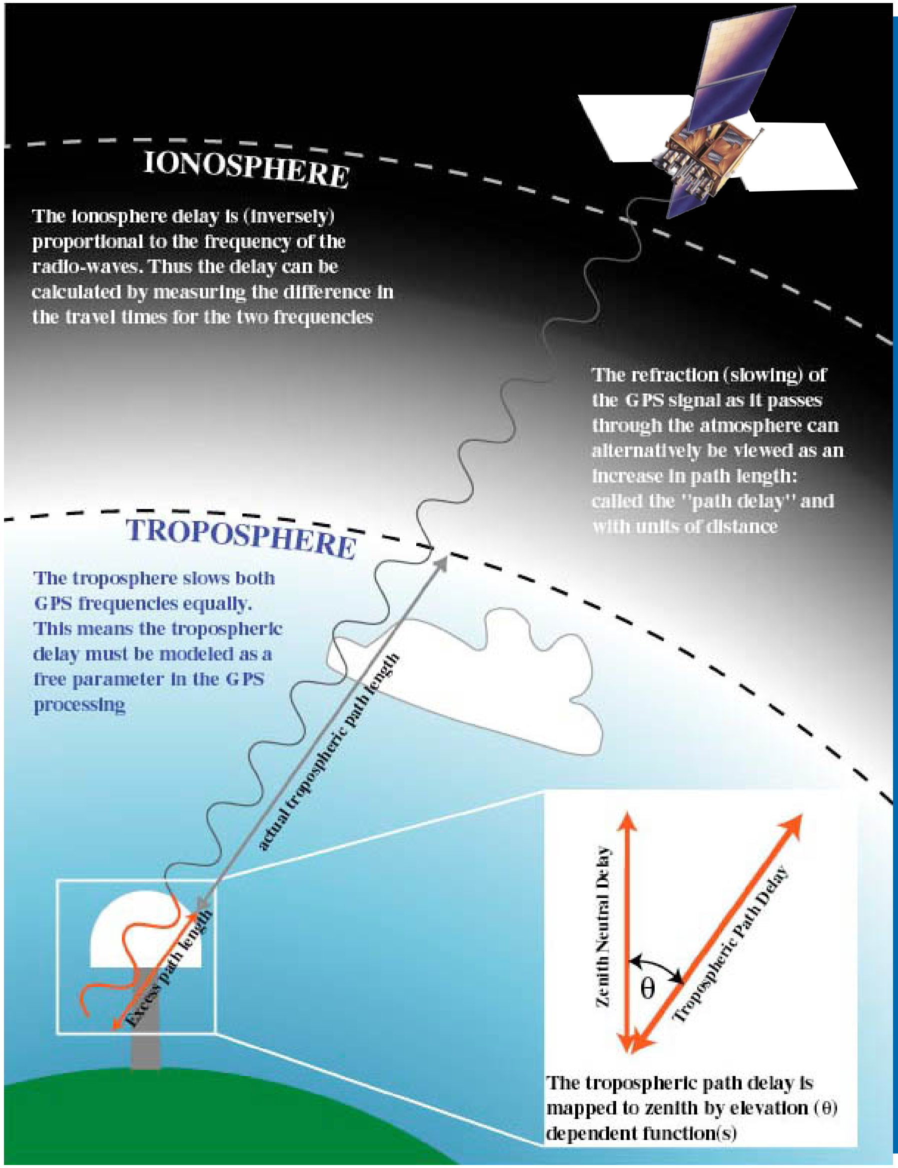
- How does GPSmet Work?
- Basic Science Questions Motivating Our Research
- Applications to Challenge Models&Theory
  1) Large-Scale/Convection Interaction
  2) Shallow-to-Deep Transition
  3) Propagating Convection and Sea Breeze Convection
  4) North American Monsoon WV Sources



ATMOSPHERIC DELAY OF GPS SIGNALS IS THE BASIS OF GPS METEOROLOGY

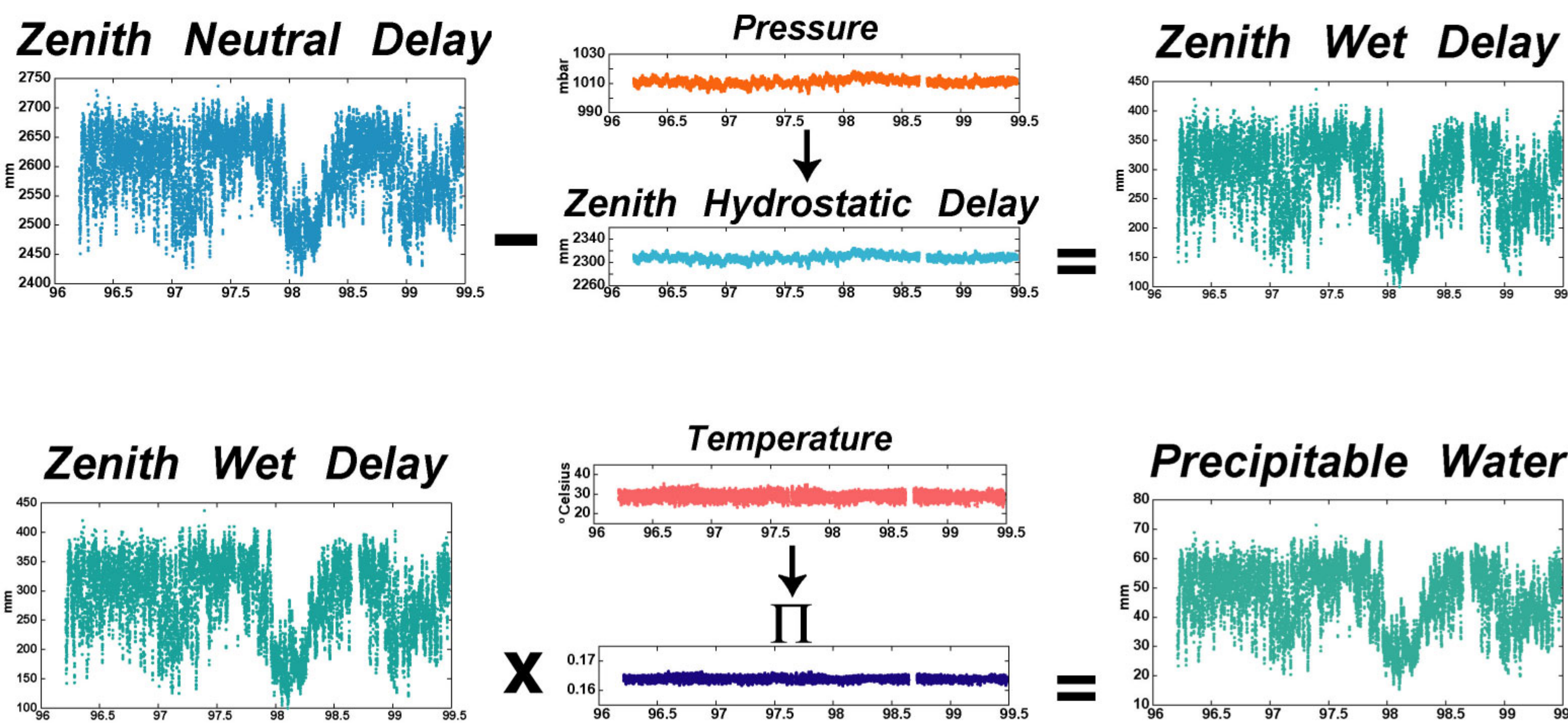


GPS-IPW Measurements



- Signal delays caused by the neutral atmosphere have a wet and dry component.
- The dry delay is caused by the mass of the atmosphere, and can be estimated with high accuracy from a surface pressure measurement.
- The wet delay is simply the difference between the total delay and the dry delay.
- The ratio of the wet delay to the dry delay is the integrated mixing ratio.
- The wet signal delay is nearly proportional to the total quantity of precipitable water vapor in the atmosphere directly above the GPS site.

Transformations of GPS Meteorology

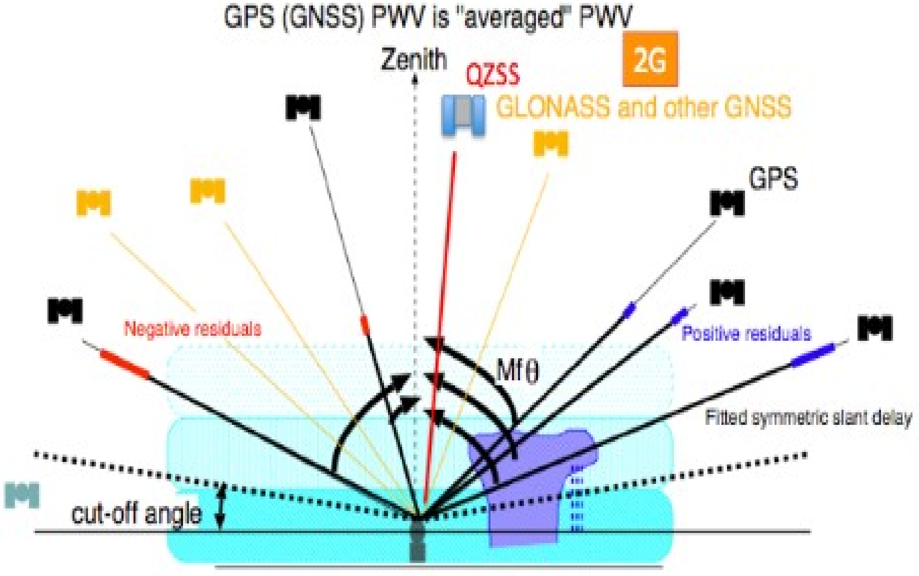


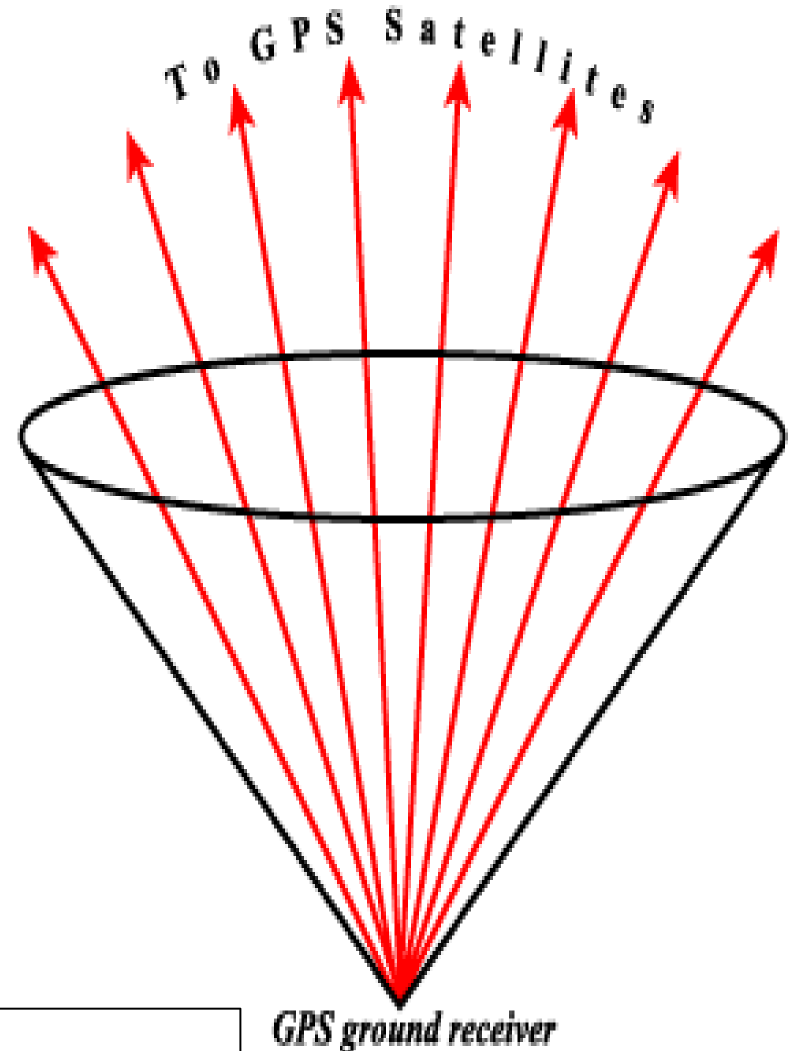
Dense Network Research (Minimum Separation Distance)

~ 2.5 km scale height of wv

Receiver "Cone" Diameter

~ 20km





Science Themes and Motivations (over last 15 years or so)

Understanding Large-scale and Convective Scale Interactions
Motivated by Convective Parameterizations and QE-type theories
Data: Long-term GPSmet Observations Central Amazon

Mesoscale Evolution of Convective Events
Motivated by Difficulties in Understanding and Modeling the Shallow-to-Deep Convective Transition
Data: Dense GPSmet Networks Central and Coastal Amazon

Atmospheric Hydrological Cycle
Motivated by Water Vapor Transport and Moisture Recycling
Data: NAM GPS Hydromet Network 2017 NW Mexico/SW US



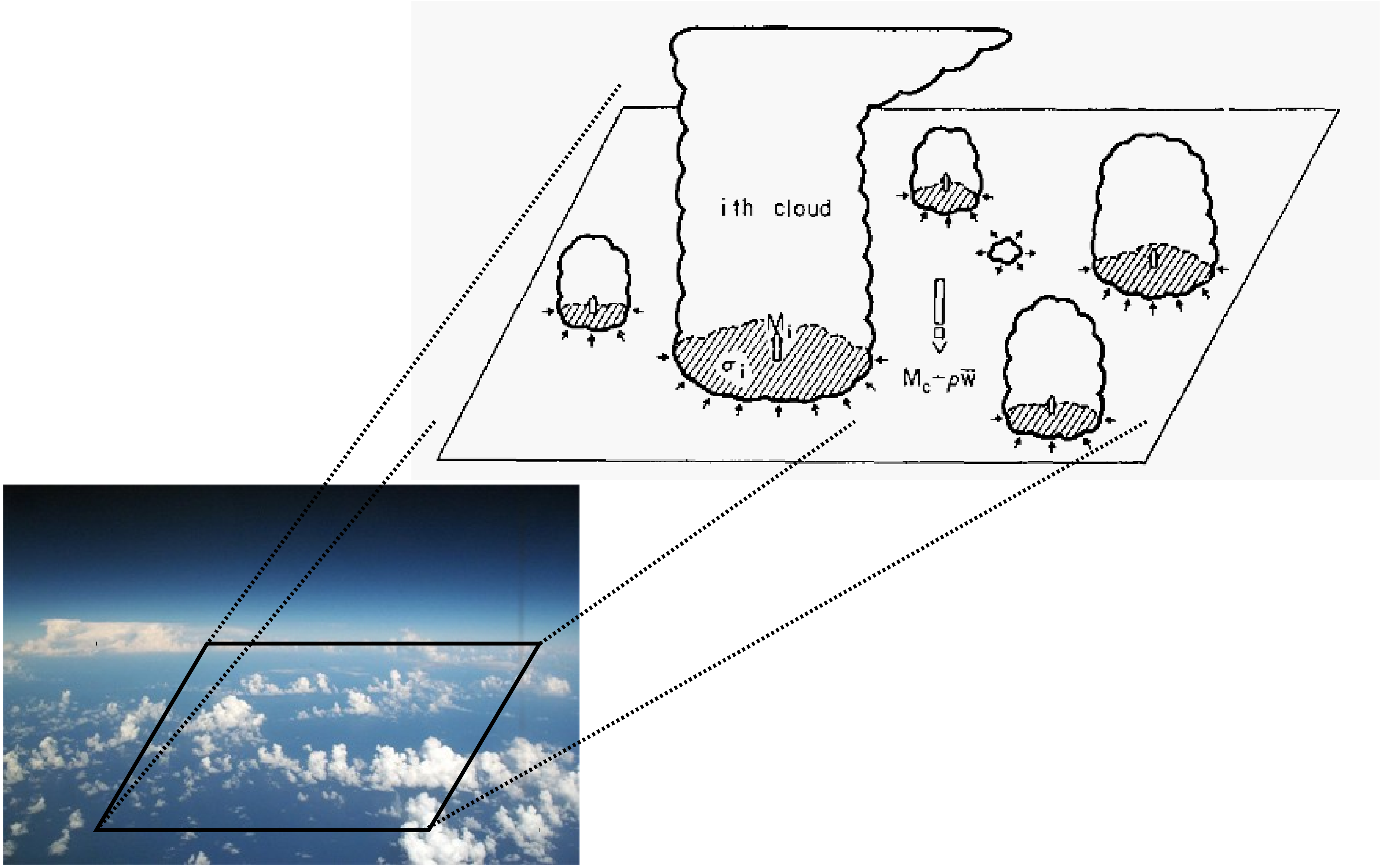
PWV-Precipitation Relationship
Large-scale/Convective Scale Interactions in the Tropics

Quasi-Equilibrium (QE) Theory (Arakawa and Schubert 1974)
timescale separation (Large-scale (Slow) and Convective (Fast))
(But see Mapes 1997; Adams and Rennó 2003; Yano 2003)

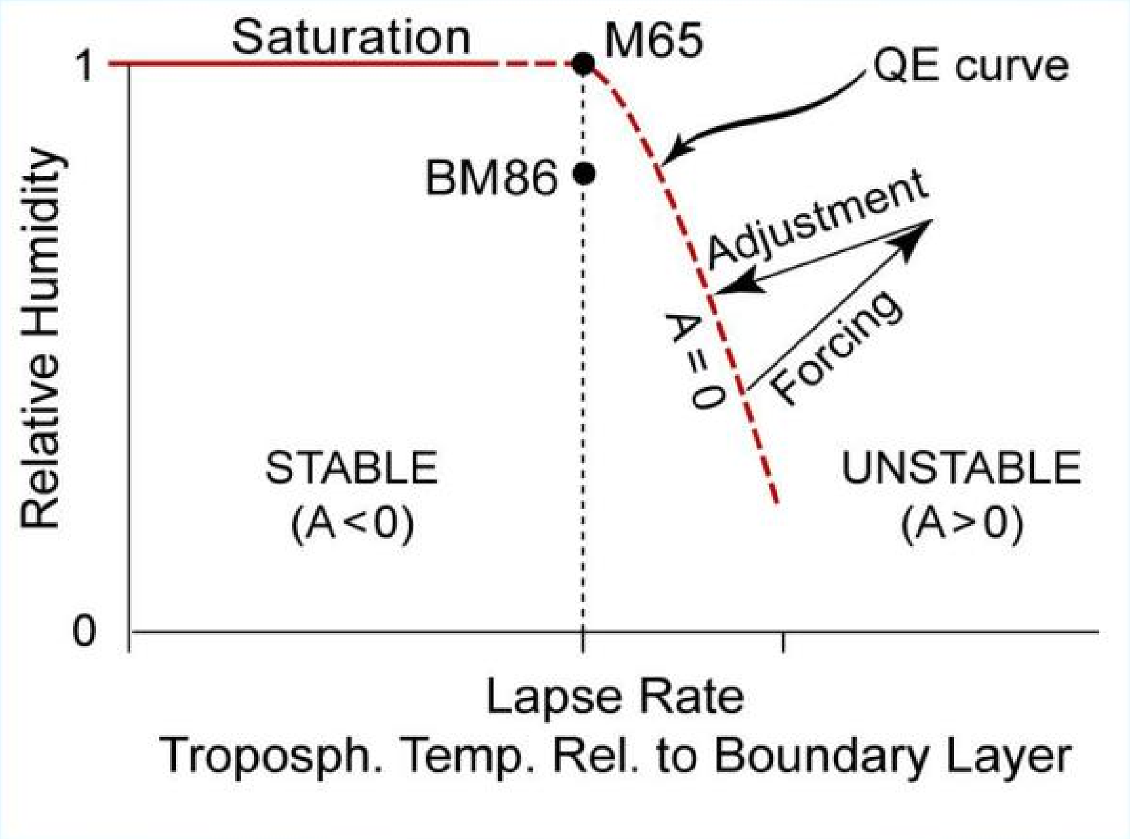
QE sets Tropical Atmosphere to Moist Adiabat tied to “sub-cloud layer parcel” (Emanuel et al. 1994; But see Williams and Rennó 1993)

Theory is silent on water vapor vertical structure and quantity in QE.

Modelling Convective Cloud populations



Convective quasi-equilibrium (Arakawa & Schubert 1974)



Modified from Arakawa (1997, 2004)

- **Convection acts to reduce buoyancy (cloud work function *A*) on fast time scale, vs. slow drive from large-scale forcing (cooling troposphere, warming & moistening boundary layer, …)**
- **M65= Manabe et al 1965; BM86=Betts&Miller 1986 parameterizns**

Cloud Work Function

- Cloud work function A(λ) represents the kinetic energy generation per unit subcloud mass flux of cloud-type λ
- For undiluted plume (λ=0), A(λ) is exactly CAPE

$$\frac{d\mathcal{K}(\lambda)}{dt} = A(\lambda)\mathfrak{M}_B(\lambda) - \mathfrak{D}(\lambda)$$

$$A(\lambda) = \int_{z_B}^{z_D(\lambda)} \frac{g}{c_p \bar{T}(z)} \eta(z,\lambda)[s_{vc}(z,\lambda) - \bar{s}_v(z)]dz$$

$$A(\lambda) = \int_{z_B}^{z_D(\lambda)} \rho(z)\beta(z)\Big[h_M - \bar{h}^*(z_B+) + \int_{z_{B+}}^{z} \eta(z',\lambda) \times \Big\{\lambda[\bar{h}(z') - \bar{h}^*(z')] - \frac{\partial \bar{h}^*(z')}{\partial z'}\Big\}dz'\Big]dz, \quad (139)$$

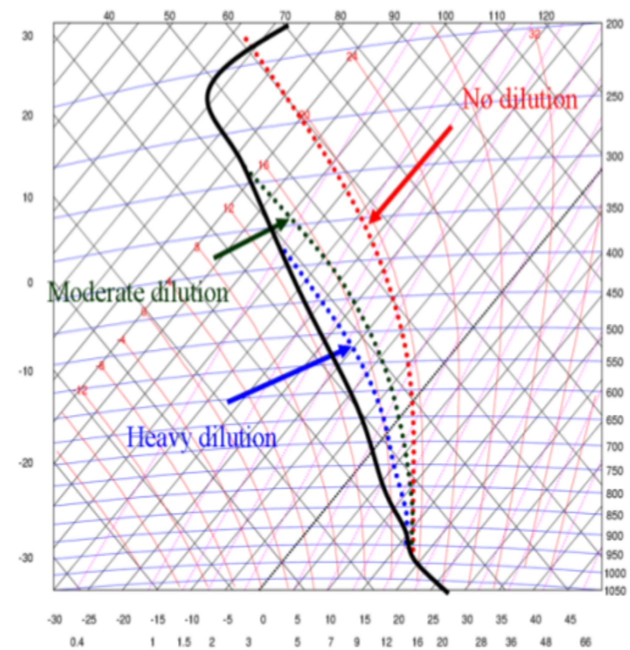
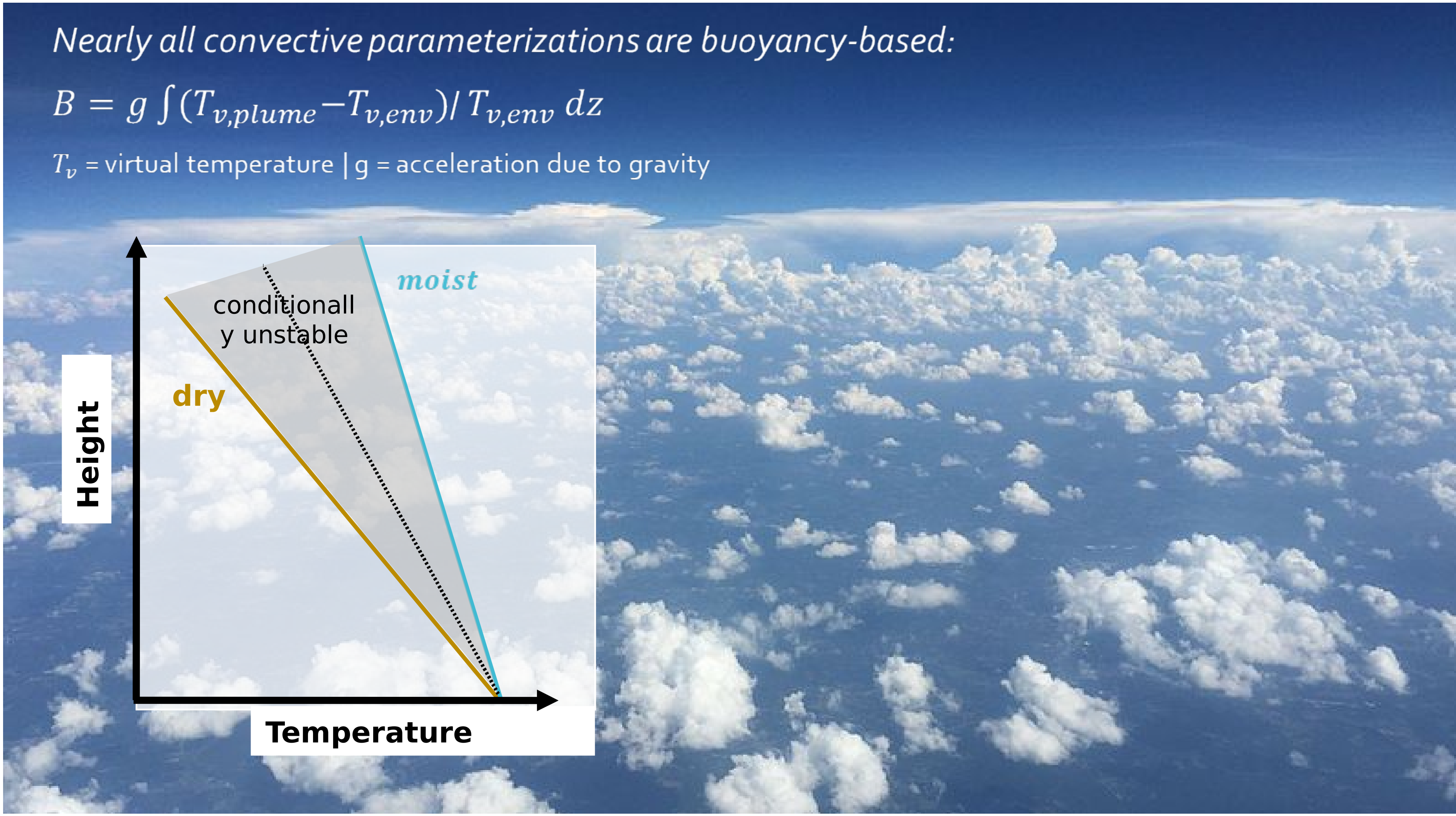


Fig. 1.26, Atmospheric Moist Convection, P. Bechtold, ECMWF 2009

Deep convection in models depends on assumptions regarding interactions between convection and larger-scale environment.



Arakawa-Schubert's Picture of Cumulus Convection

- An ensemble of cumuli that detrain at different levels
- Cumulus affects the environment by compensating subsidence and detrainment (and radiation)

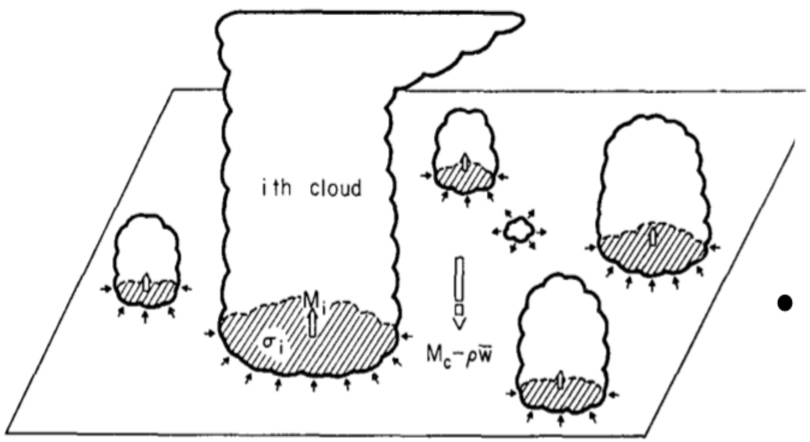


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

$$\rho\frac{\partial\bar{s}}{\partial t}=D(\hat{s}-\bar{s}-L\hat{l})+M_c\frac{\partial\bar{s}}{\partial z}-\rho\bar{\mathbf{v}}\cdot\nabla\bar{s}-\rho\bar{w}\frac{\partial\bar{s}}{\partial z}+\bar{Q}_R,$$

$$\rho\frac{\partial\bar{q}}{\partial t}=D(\hat{q}^*+\hat{l}-\bar{q})+M_c\frac{\partial\bar{q}}{\partial z}-\rho\bar{\mathbf{v}}\cdot\nabla\bar{q}-\rho\bar{w}\frac{\partial\bar{s}}{\partial z}.$$

- Closure is needed for the cumulus mass flux M_c

PWV-Precipitation Relationship in the Tropics (A Look At Two Theories)

Self-Organized Criticality (SOC) (Peters et al. 2002, 2006,2010; Neelin et al. 2009; Holloway et al. 2009)

Thermodynamic Control (Raymond 2000; Raymond et al. 2009)

SOC is more purely “thermodynamic” whereas Raymond´s theories are more “complete” mechanistically.

NOTE: Essentially All Observations for Theories over Oceans

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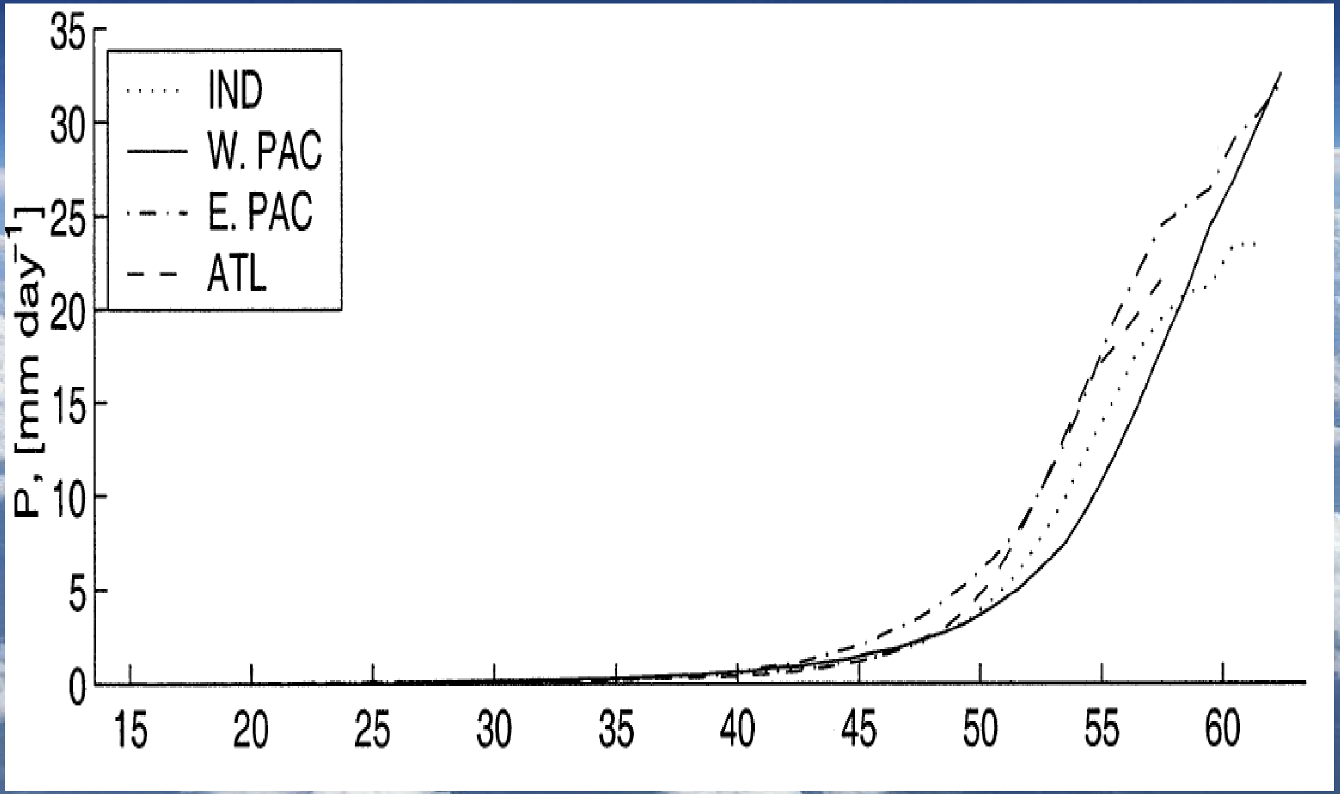
The Relationship between PWV and Tropical Rainfall has been well known for a while(Bretherton et al. 2004)



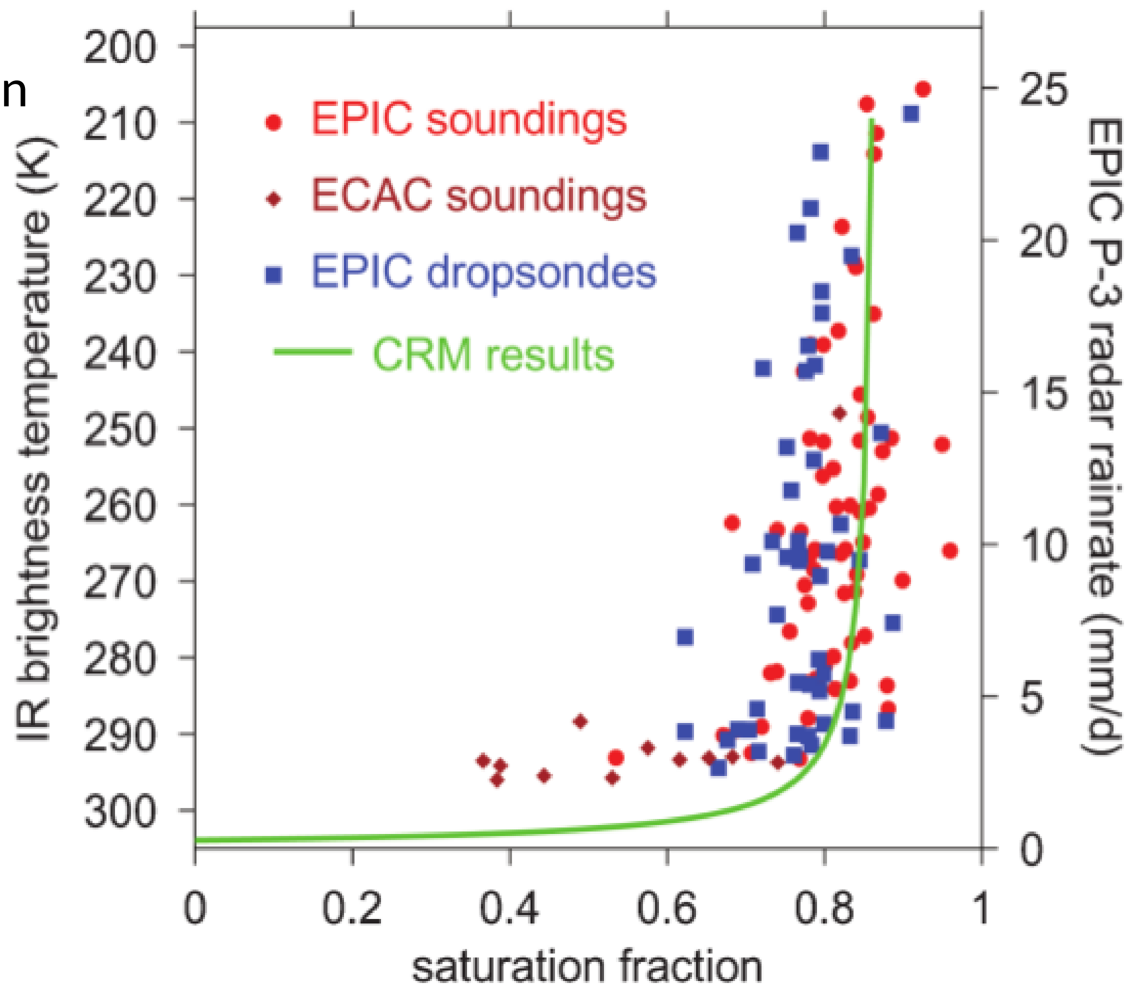
Thermodynamic Control
(Raymond 2000; Raymond et al. 2009)

Two Assumptions

Precipitation a decreasing function of mean saturation deficit,

The temperature profile of the convective environment is constant

Consistent with
BLQ (Raymond 1995),
drier middle troposphere gives less updraught mass-flux for a given surface entropy flux.



SOC and the ***Atmosphere***

The atmosphere is a slowly driven, highly susceptible system that can store energy (in the form of water vapor) and suddenly release it (as rain showers).

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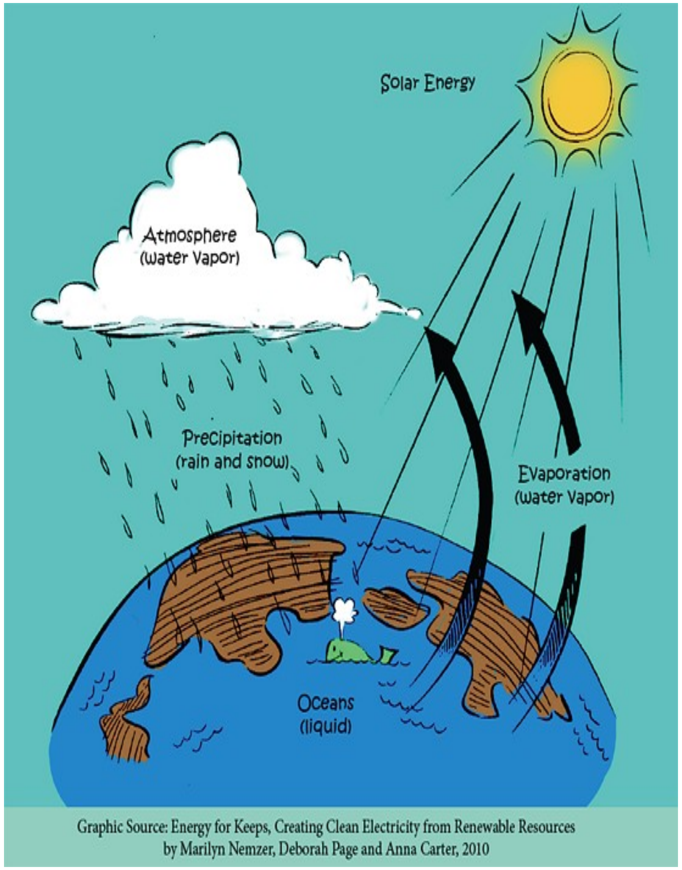
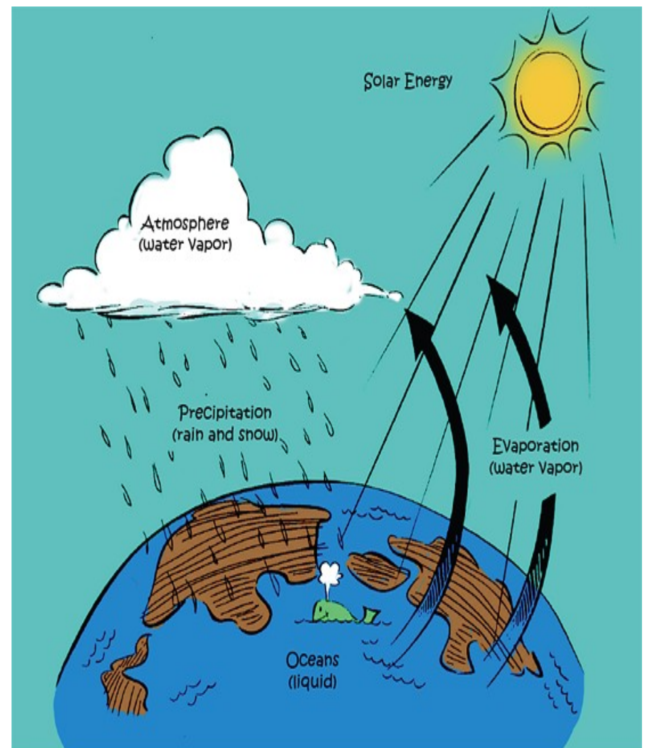


SOC and the ***Atmosphere***

QE refers to a balance between slow large-scale driving processes and rapid release of buoyancy by moist convection. There is evidence that the attractive QE state is the critical point of a continuous phase transition (SOC). *– Peters and Neelin (2006)*



Graphic Source: Energy for Keeps, Creating Clean Electricity from Renewable Resources by Marilyn Nemzer, Deborah Page and Anna Carter, 2010

Peters, O., J. D. Neelin, 2006: Critical Phenomena in Atmospheric Precipitation. Nature, 2, 393-396.

Self-Organized Criticality
in the Atmosphere

Pick-up of precipitation above a critical value of water vapor, ***wc***
At ***w*** > ***w***c behavior given by

$$\langle P\rangle(w) = a(w - w_c)^{\beta}$$

where ***a*** is a system-dependent constant and **β** is a universal exponent.

(***Inset***) The average precipitation as a function of the reduced water vapor *w* ≡ (*w* − *wc*)/*wc* in a double-logarithmic plot. Power laws fitted to these distributions all have the same exponent **β** to within ±0.02.

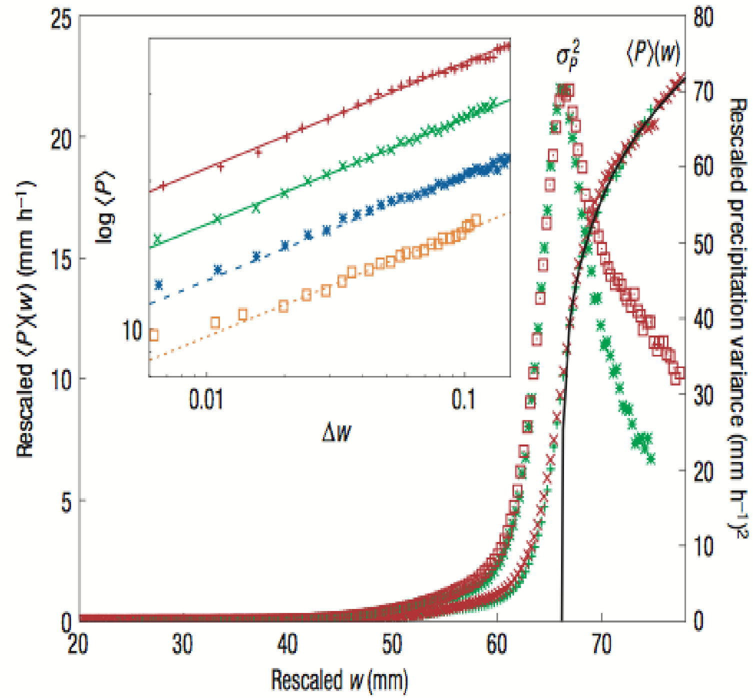


Figure 1 Order parameter and susceptibility. The collapsed (see text) precipitation rates $\langle P\rangle(w)$ and their variances $\sigma_P^2(w)$ for the tropical eastern (red) and western (green) Pacific as well as a power-law fit above the critical point (solid line). The inset shows on double-logarithmic scales the precipitation rate as a function of reduced water vapour (see text) for western Pacific (green, 120E to 170W), eastern Pacific (red, 170W to 70W), Atlantic (blue, 70W to 20E), and Indian Ocean (pink, 30E to 120E). The data are shifted by a small arbitrary factor for visual ease. The straight lines are to guide the eye. They all have a slope of 0.215, fitting the data from all regions well.

Peters, O., J. D. Neelin, 2006: Critical Phenomena in Atmospheric Precipitation. Nature, 2, 393-396.

GPS Meteorology in the Amazon, Brazil

Long-term (3.5 years) station in Manaus

1 year Dense Network (20 stations) in Manaus

~7 weeks Dense Network (15 stations in Belem GPM-CHUVA IOP)

GPSmet Site INPA/LBA Central Amazon

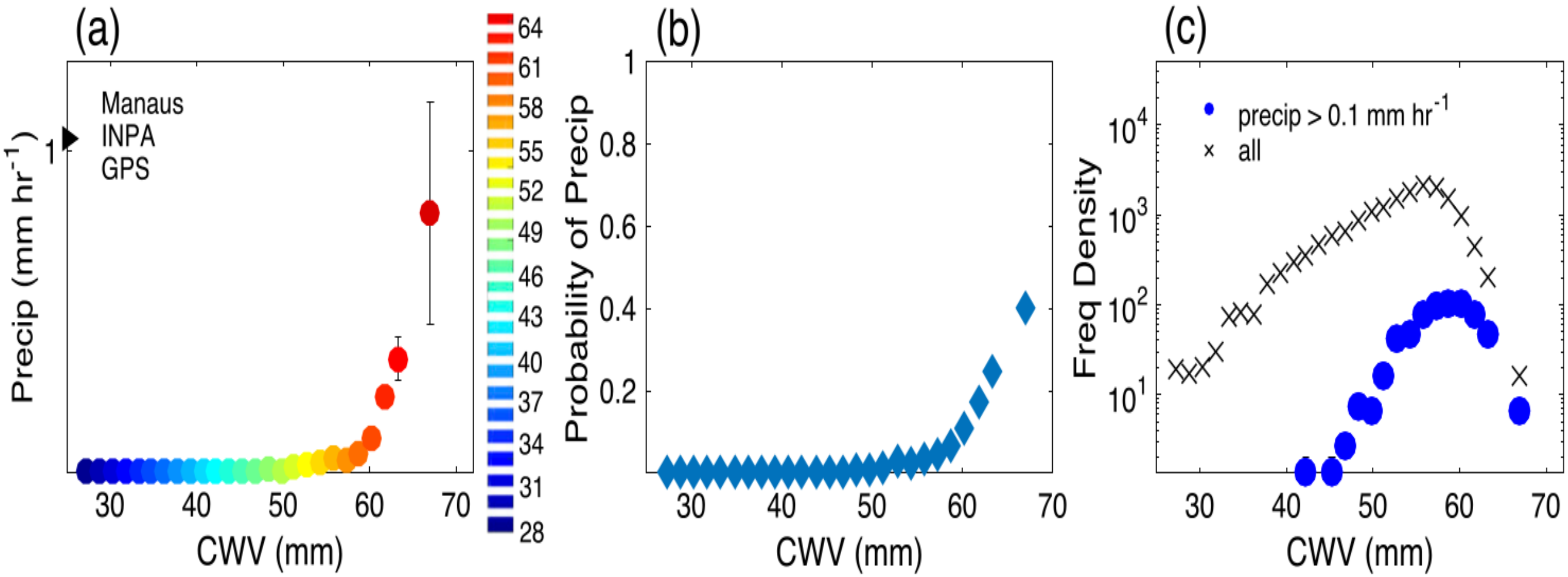
(NOAA Near Real Time Site)

July 2008 to December 2011

What does GPSmet show w.r.t. Water Vapor Criticality?

(Schiro et al. 2016 JAS)

- **For comparison 3.5 years of GPS PWV INPA Site**
- **Consistent with Ocean Observations**
- **How does this fit with Theories?**



A Critique: What holds for CWV-Precipitation for in Tropical Continental Location? (J.I. Yano et al 2012)

(a) SOC Precipitation Constrained Above critical value, but CWV is not

(b) Homeostasis CWV is constrained at Critical value, but Precipitation rate increases without bound. Analogous to Raymond´s Thermodynamic Control

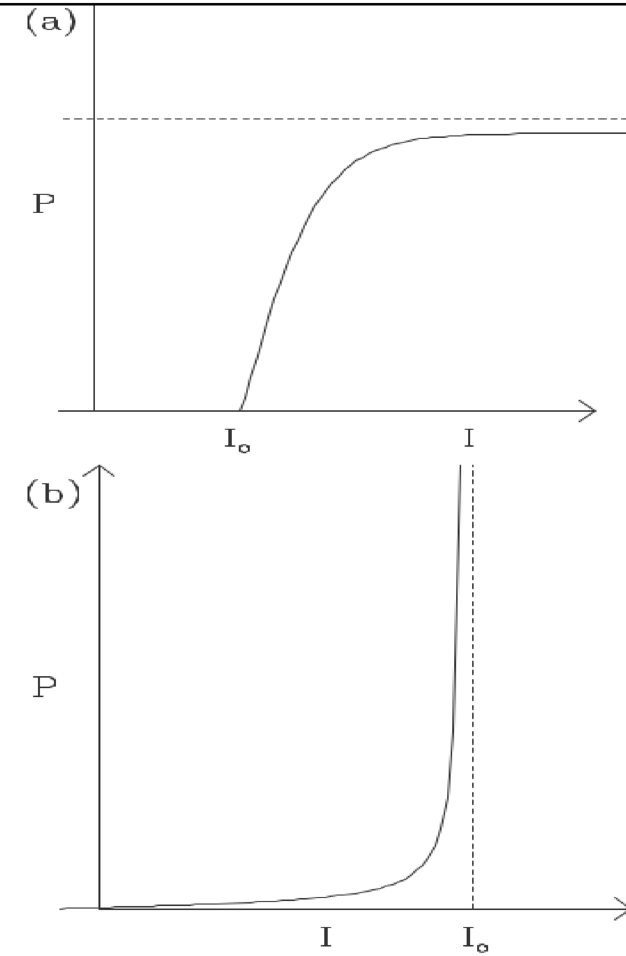


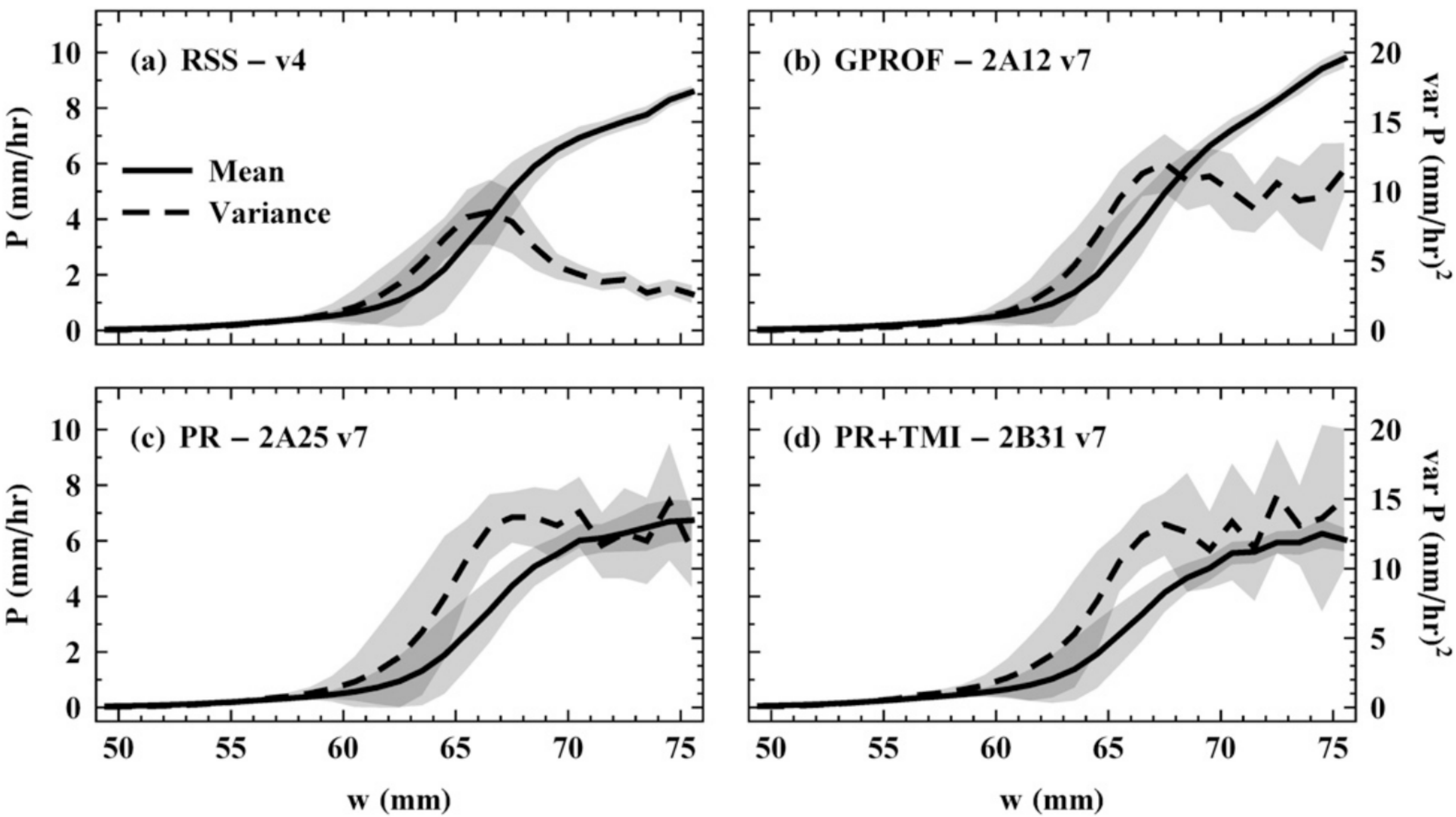
FIG. 1. Conceptualization of (a) self-organized criticality and (b) homeostasis. The solid curves schematically show expected dependence of a system response P (e.g., precipitation rate), on an internal-state variable I (e.g., column-integrated water), under respective mechanisms.

A Criticism of SOC (Gilmore 2015)

(Radiometers/Precipitation Platforms are Problematic)

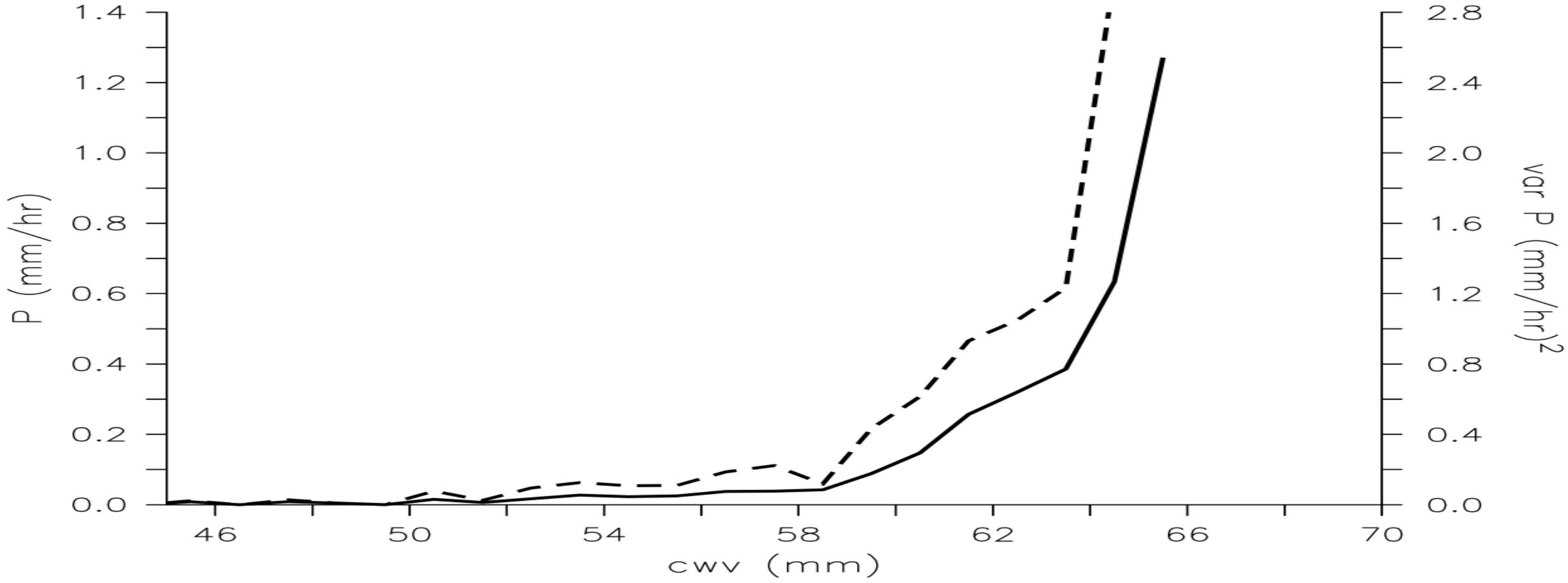
Precipitation Rate-w (i.e., PWV) Relationship

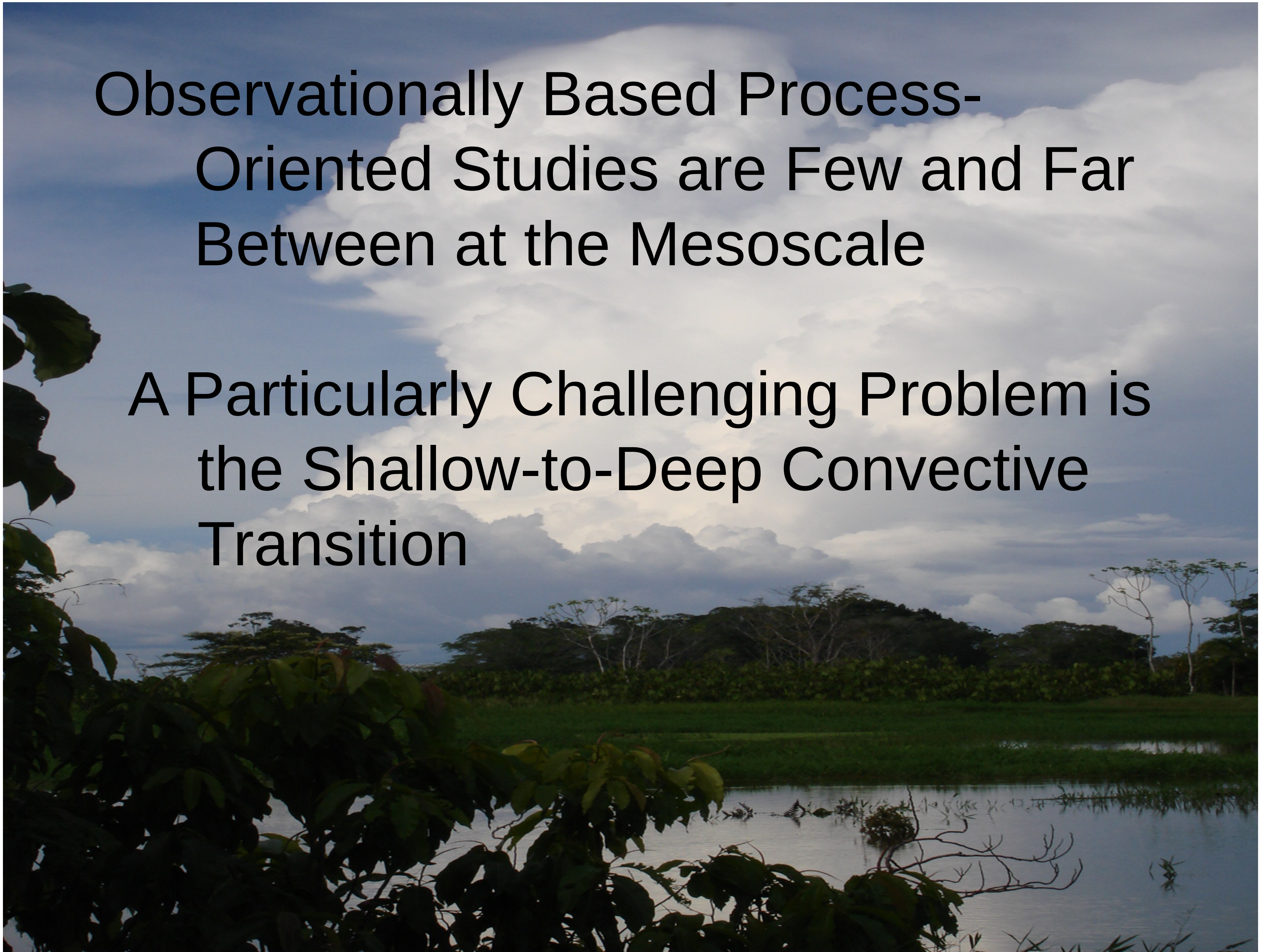
(His Figure 2)



What do the 3.5 years GPS PWV data from INPA say about SOC?

- **w.r.t. Continuous Phase Transition, it is not obvious**
- **Continued Increase in mean P (w) and no Variance peak Near Critical Value**
- **In principle, GPS PWV is more robust in rainy conditions.**




Observationally Based Process-Oriented Studies are Few and Far Between at the Mesoscale
A Particularly Challenging Problem is the Shallow-to-Deep Convective Transition

Our Approach for Process Oriented Studies: Water Conservation Equation

$$\frac{\partial}{\partial t}(IWV) + \frac{\partial}{\partial t}\int q_c \frac{dp}{g} + \nabla \cdot \int q\vec{V}\frac{dp}{g} = E - P.$$

Precipitable Water Vapor is Integrated (or Column) Water Vapor divided by the density of water

$$PWV = \frac{1}{\rho_w}\int q\frac{dp}{g} = \frac{IWV}{\rho_w}$$

To first order, the time-rate-of-change of PWV is simply moisture flux convergence:

$$|\frac{\partial}{\partial t}(PWV)| \sim |\nabla \cdot \frac{1}{\rho_w}\int q\vec{V}\frac{dp}{g}|$$

Shallow-to-Deep Convective Transition in Tropics

Models do not replicate well, often skip shallow-to-deep transition entirely (Betts and Jakob 2002a,b) (A major theme from LBA Experiment)

What controls shallow-to-deep transition?
Different Authors, Different Arguments

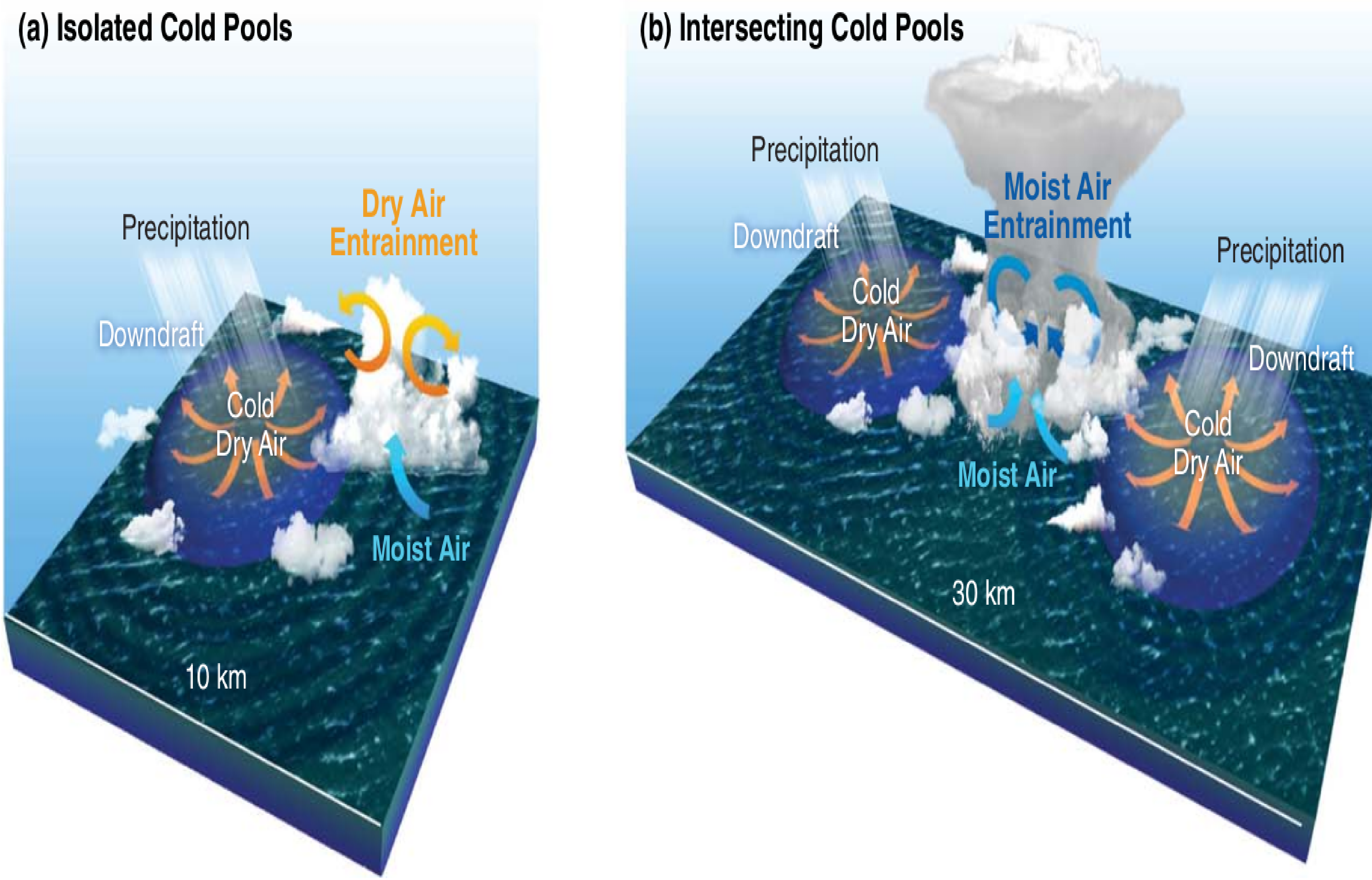
Kuang and Bretherton (2006) Dry mid-troposphere impedes transition to deep convection, must have moist mid-troposphere

Chaboreau et al. (2004) Shallow Cumulus must moisten just above boundary layer for transition to deep convection

Shallow-to-Deep Convective Transition in Tropics

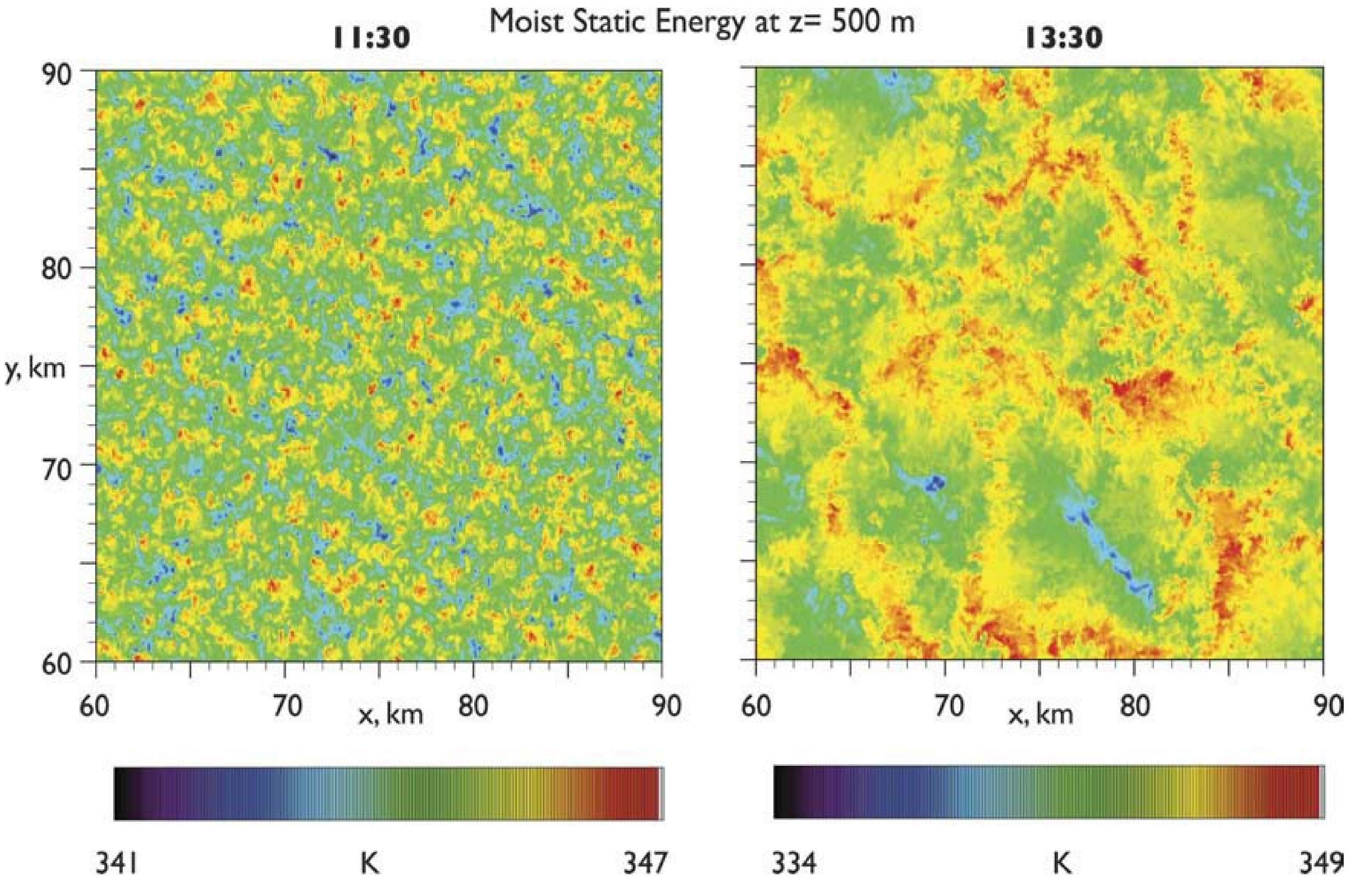
Khairoutdinov and Randall (2006); Make clouds larger so entrainment is less important. Congestus cold pools create convergence zone leading to deeper convection and so on…

Wu et al. (2009) Critical lapse rate above boundary layer needed for transition to deep convection to occur

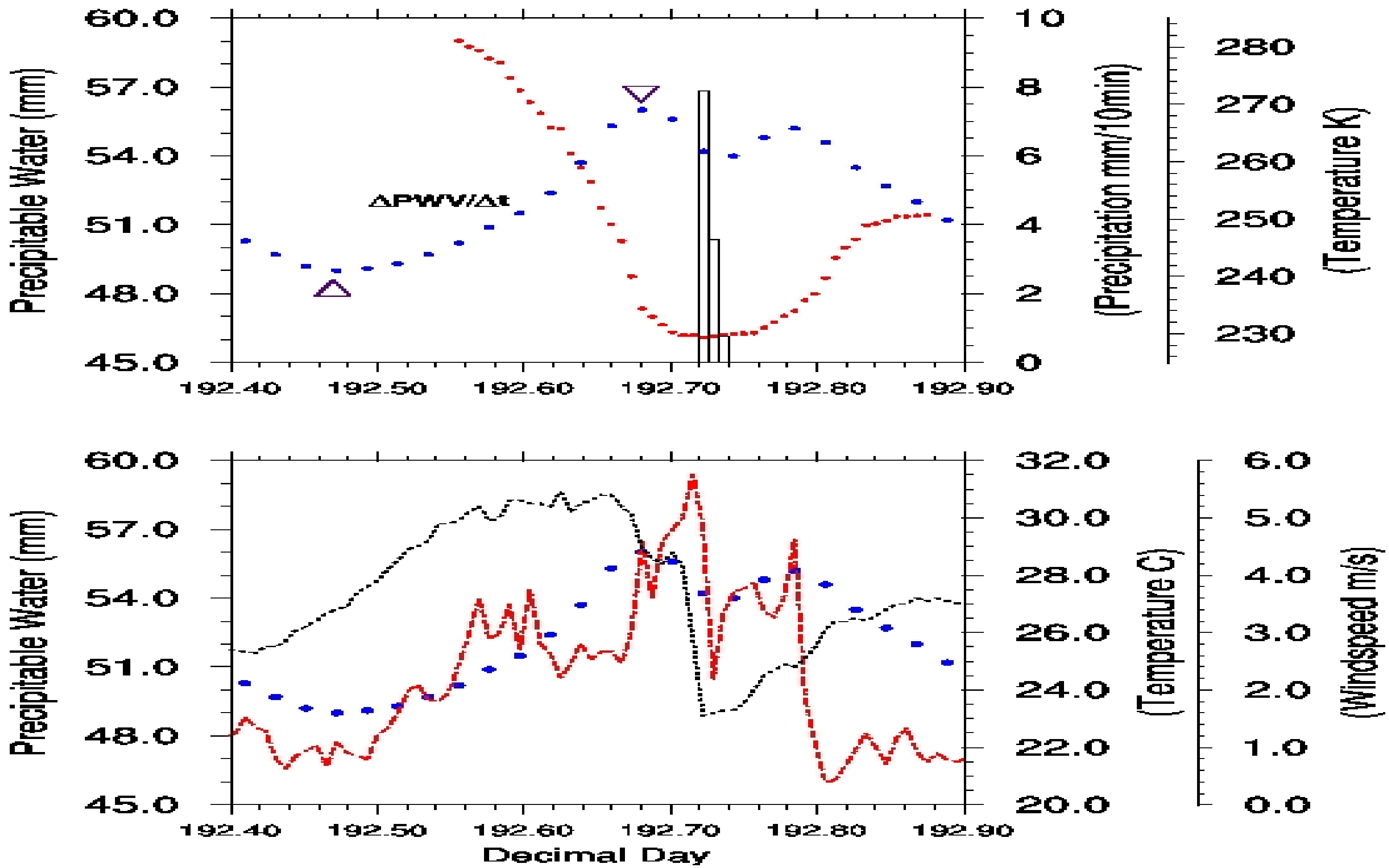


(a) Isolated Cold Pools
Precipitation
Dry Air
Entrainment
Downdraft
Cold
Dry Air
Moist Air
10 km
(b) Intersecting Cold Pools
Precipitation
Moist Air
Entrainment
Downdraft
Cold
Dry Air
Precipitation
Downdraft
Cold
Dry Air
Moist Air
30 km

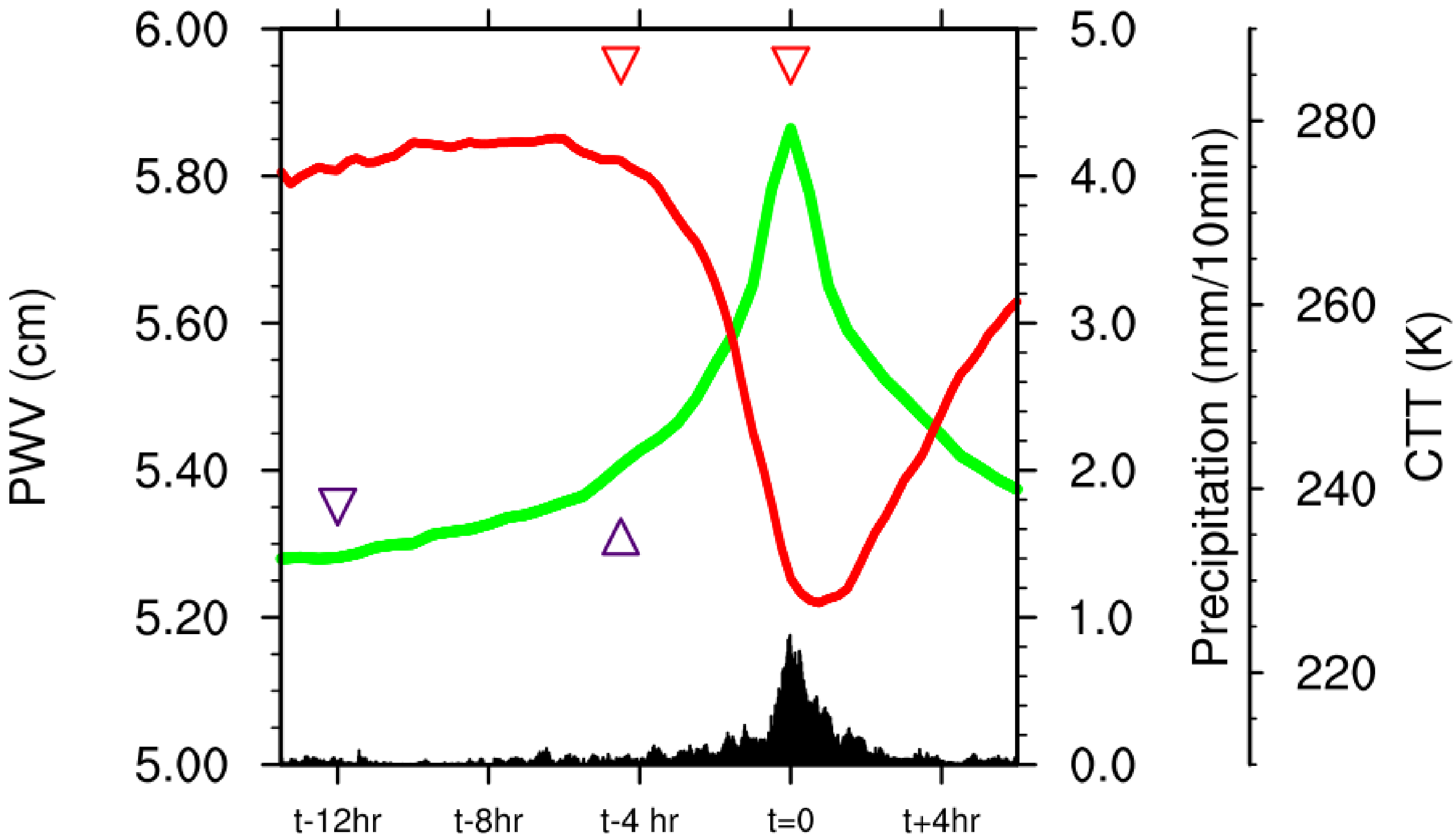
Cold Pools may play a dominant role in organization of convection in the central Amazon (Khairoutdinov and Randall 2006)



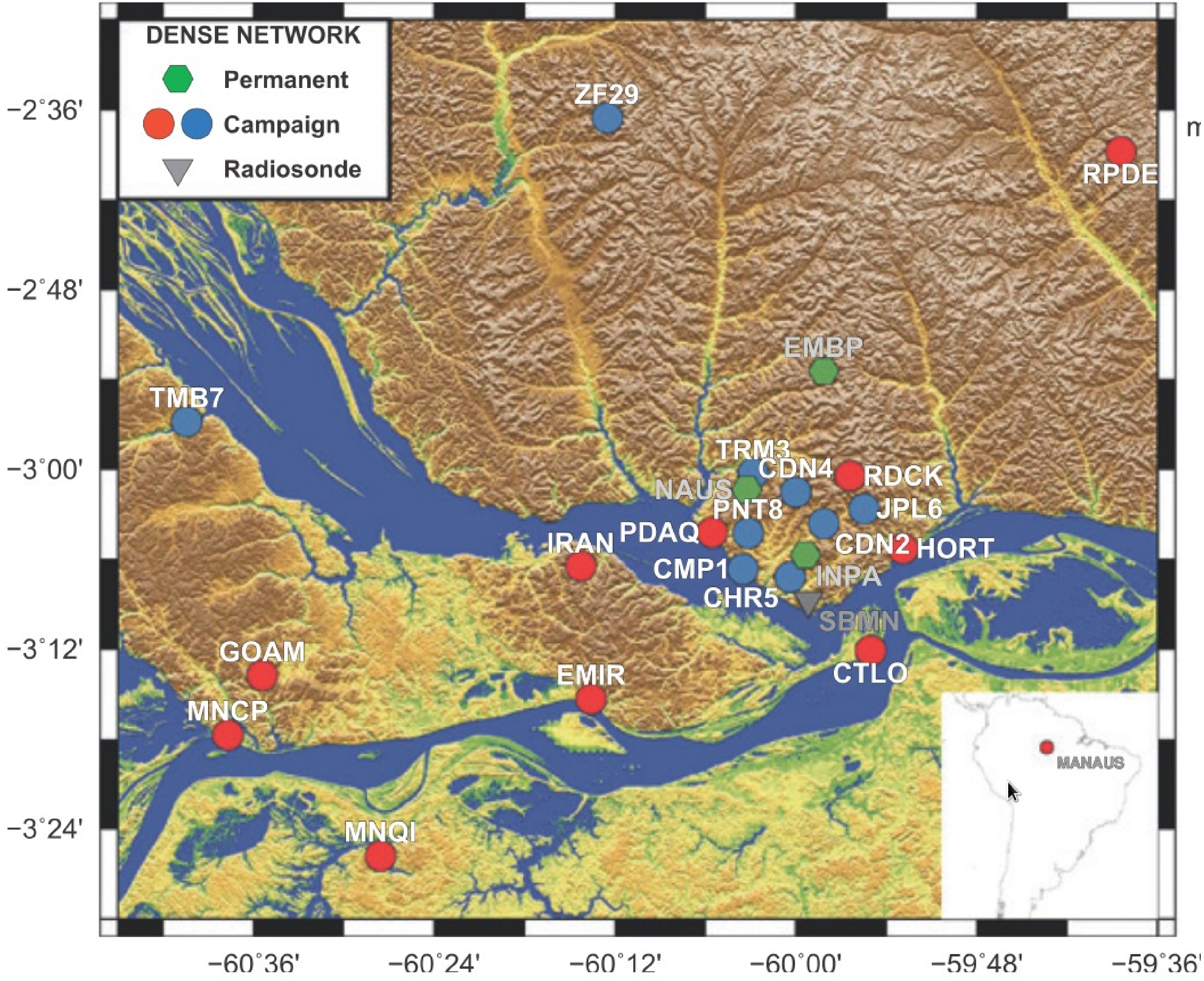
GPS Met at INPA (Central Amazon)
Observation ofConvective Event with Downdraft



Timescale Analysis for the Shallow-to-Deep Transition
Composite of 320 Convective Events
~4hr WV Convergence Timescale
(*Adams et al. 2013 GRL*)

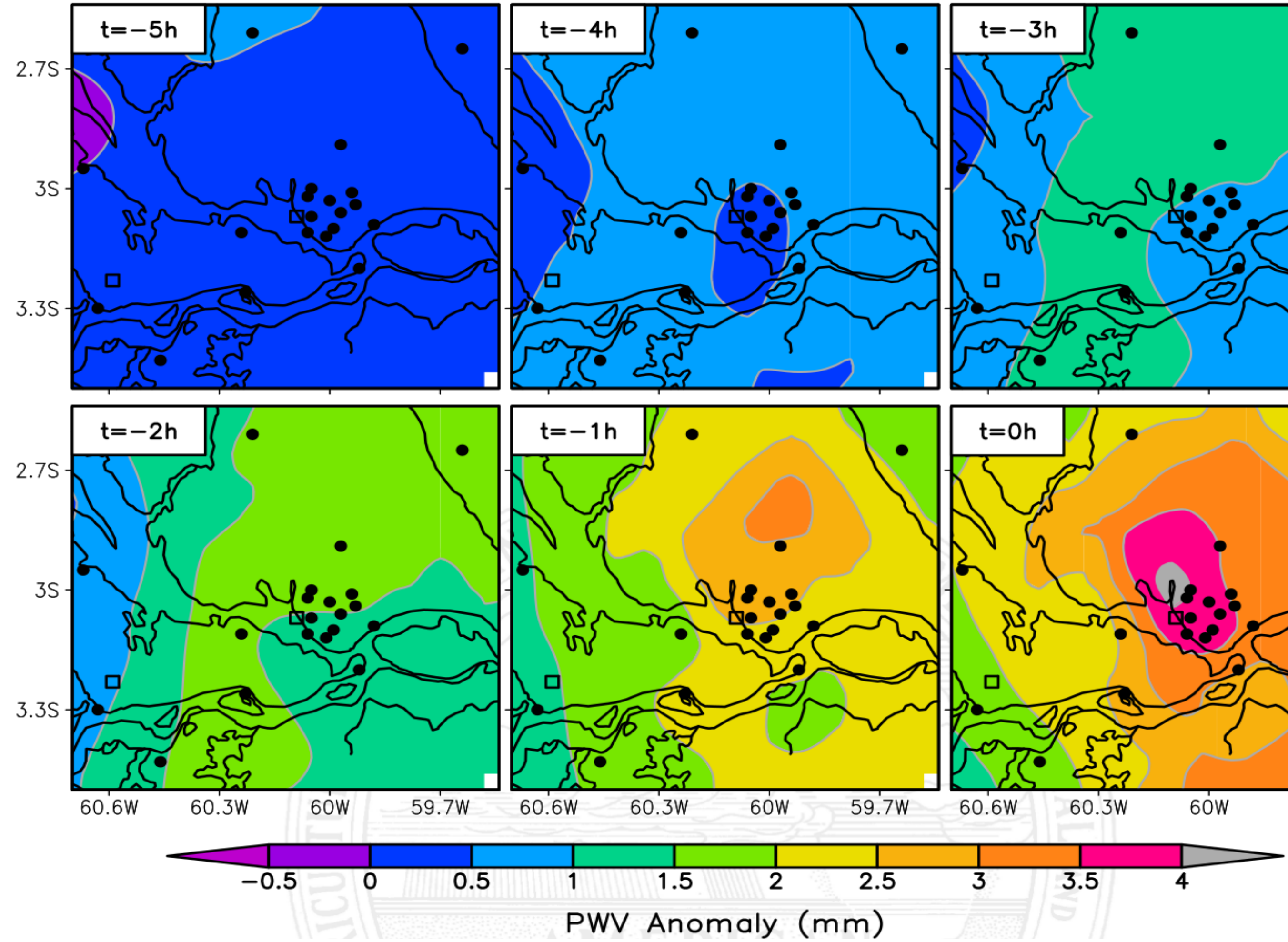


Dense GNSS Meteorological Network in Manaus (2011-2012)
Adams et al. 2015 (BAMS)



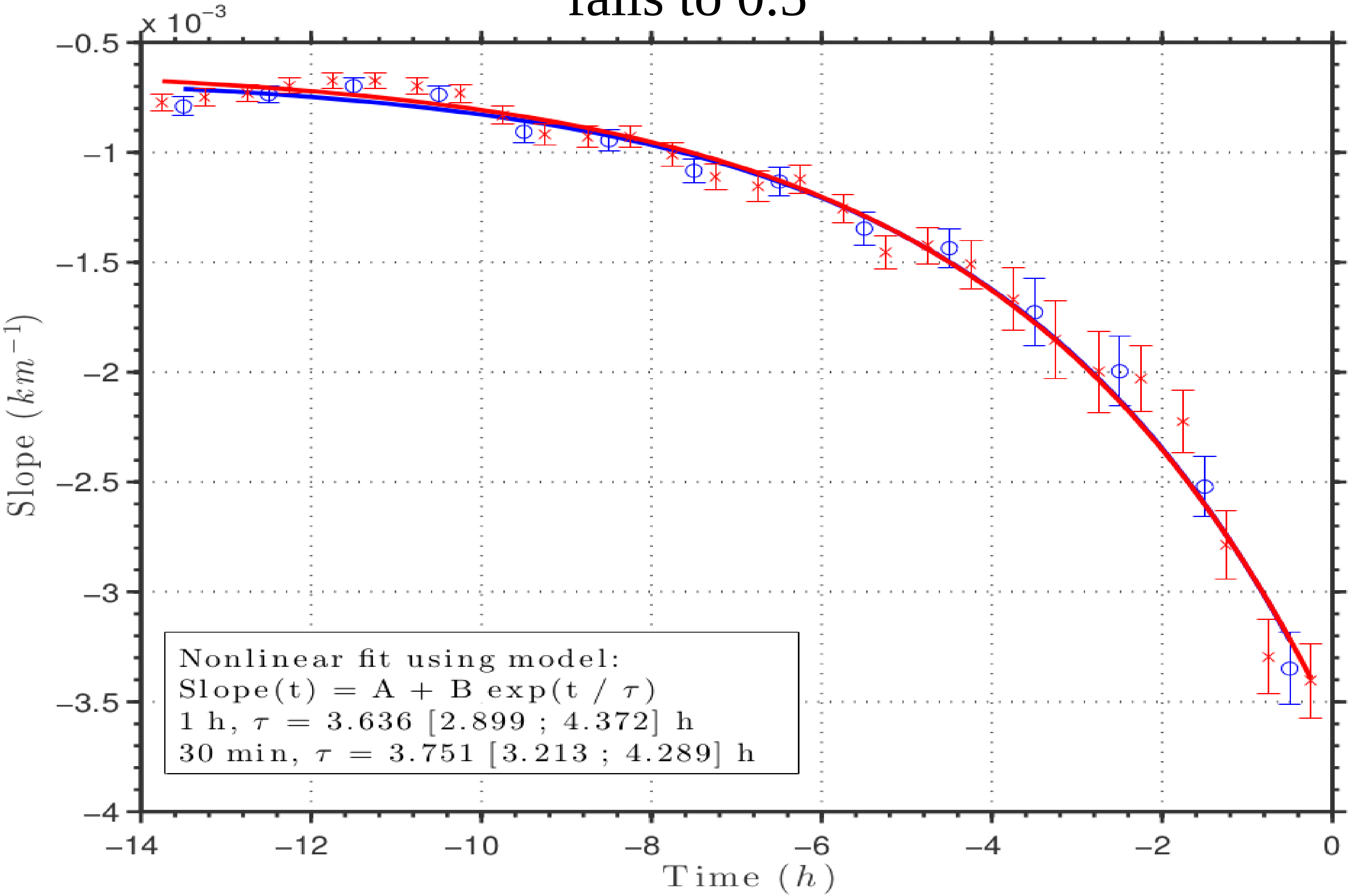
But what spatial scale of CWV should we expect during the STD Transition?
Adams et al. 2017 (MWR)

A spatial decorrelation timescale was calculated for 67 convective events



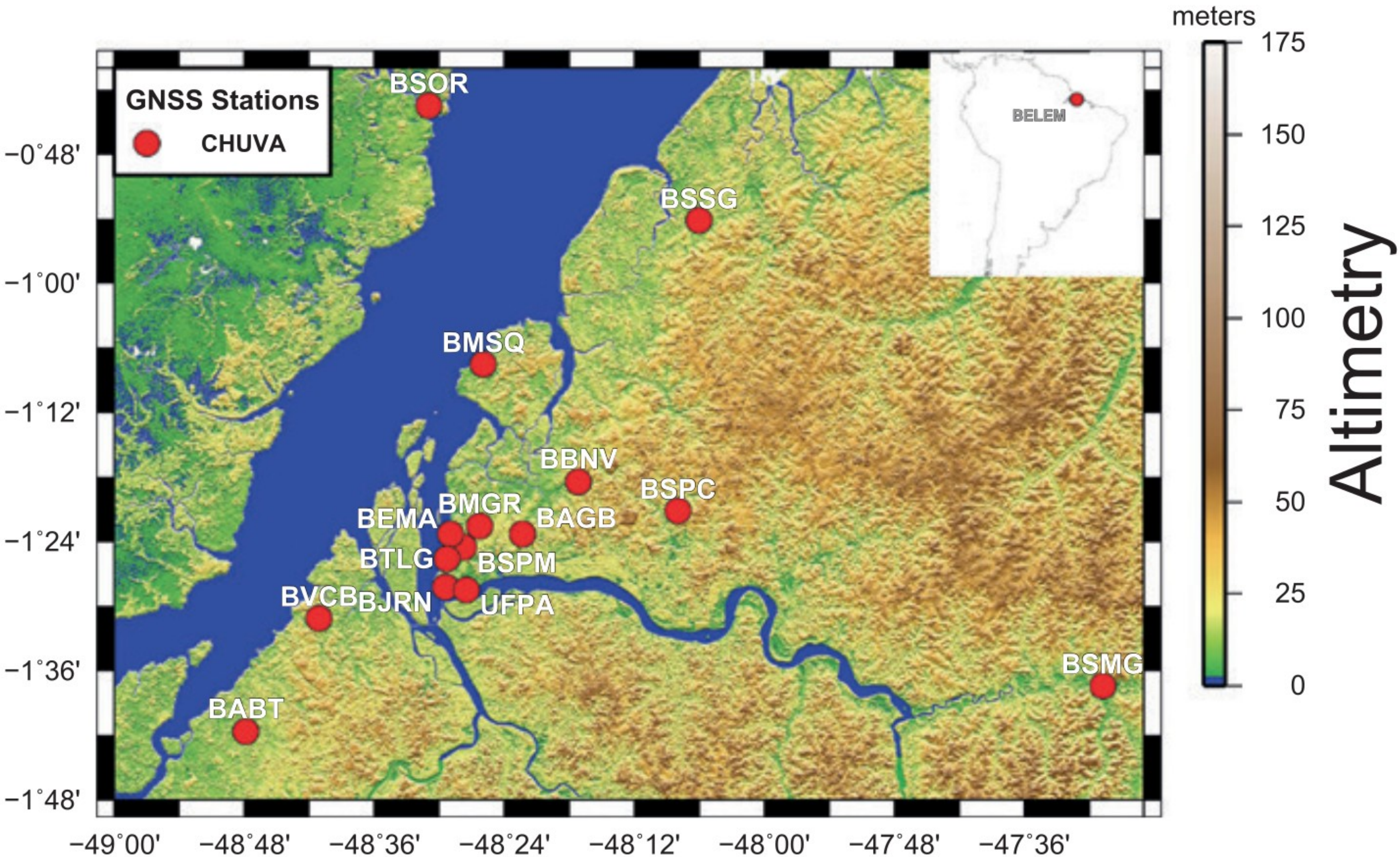
Decorrelation Timescale of 3.5 hours during Shallow-to-Deep Convective Transition

At Max. Station separation distance of 150km CWV correlation falls to 0.5



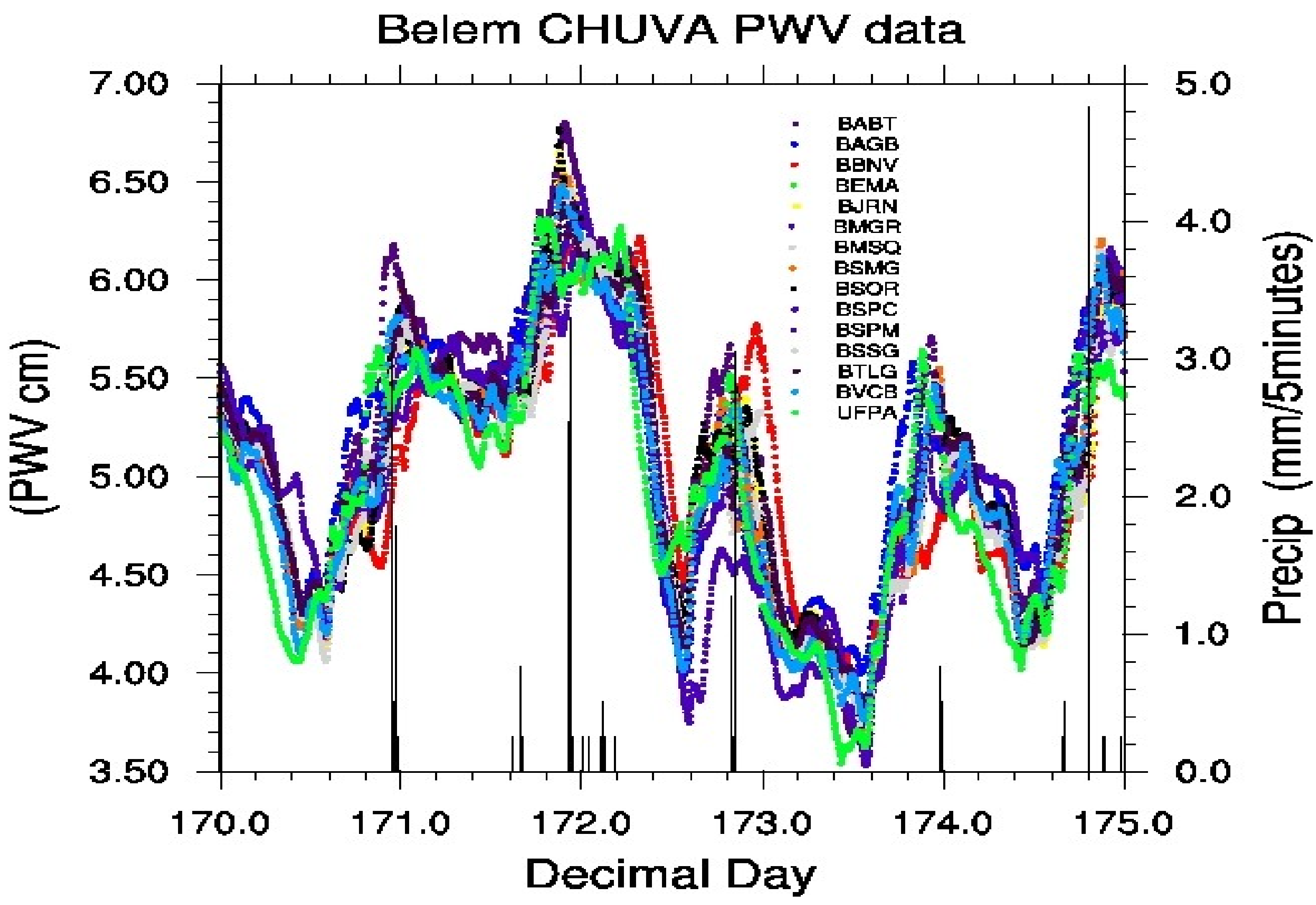
Amazon Dense GNSS Meteorological Network
(Belem *Global Precipitation Measurement* CHUVA)
(Adams et al. 2015 BAMS, Machado et al. 2014 BAMS)

Tropical Sea Breeze Regime Convection

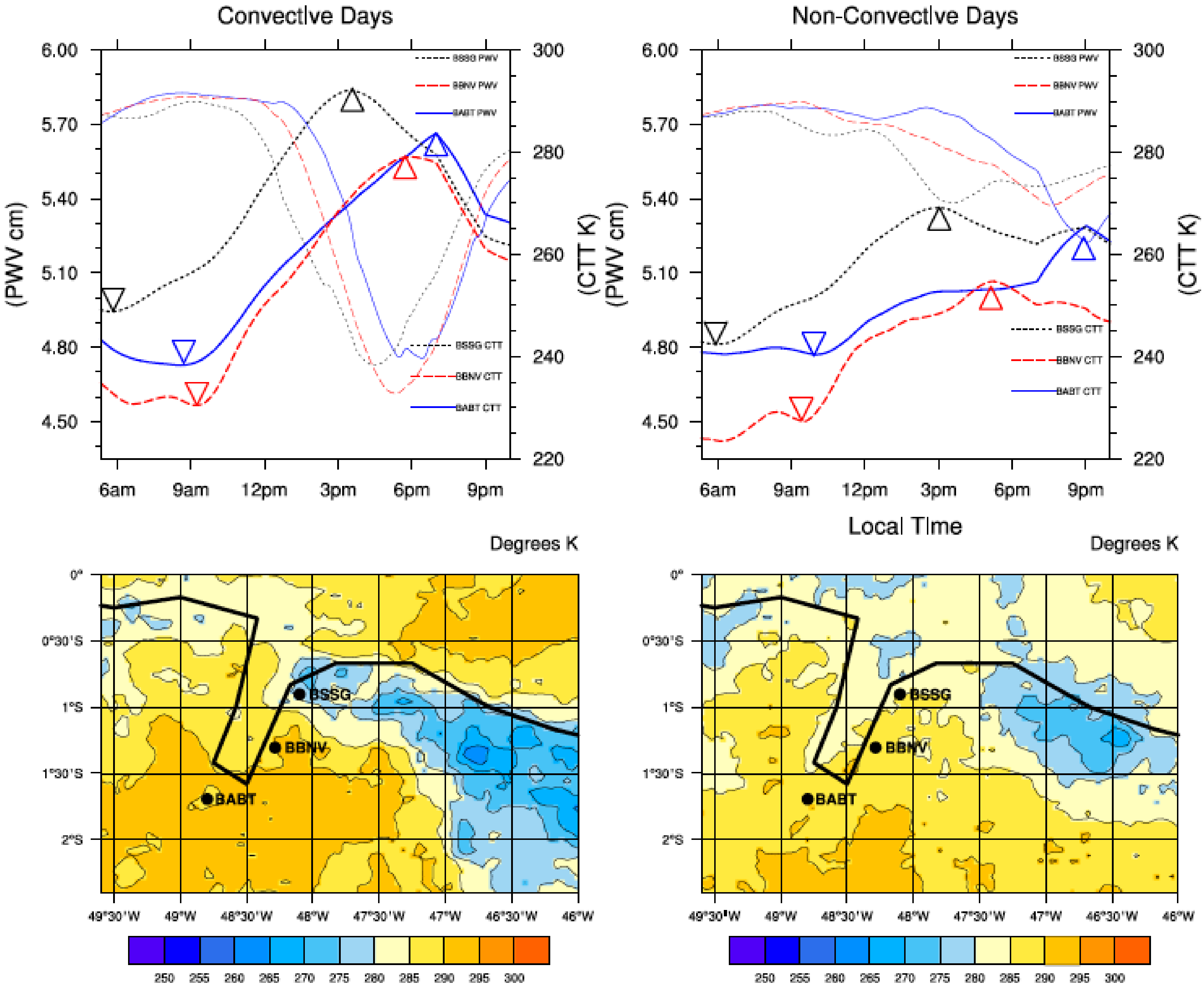


Sea-Breeze Convection Belem

“A gente se encontra antes ou depois da chuva?”



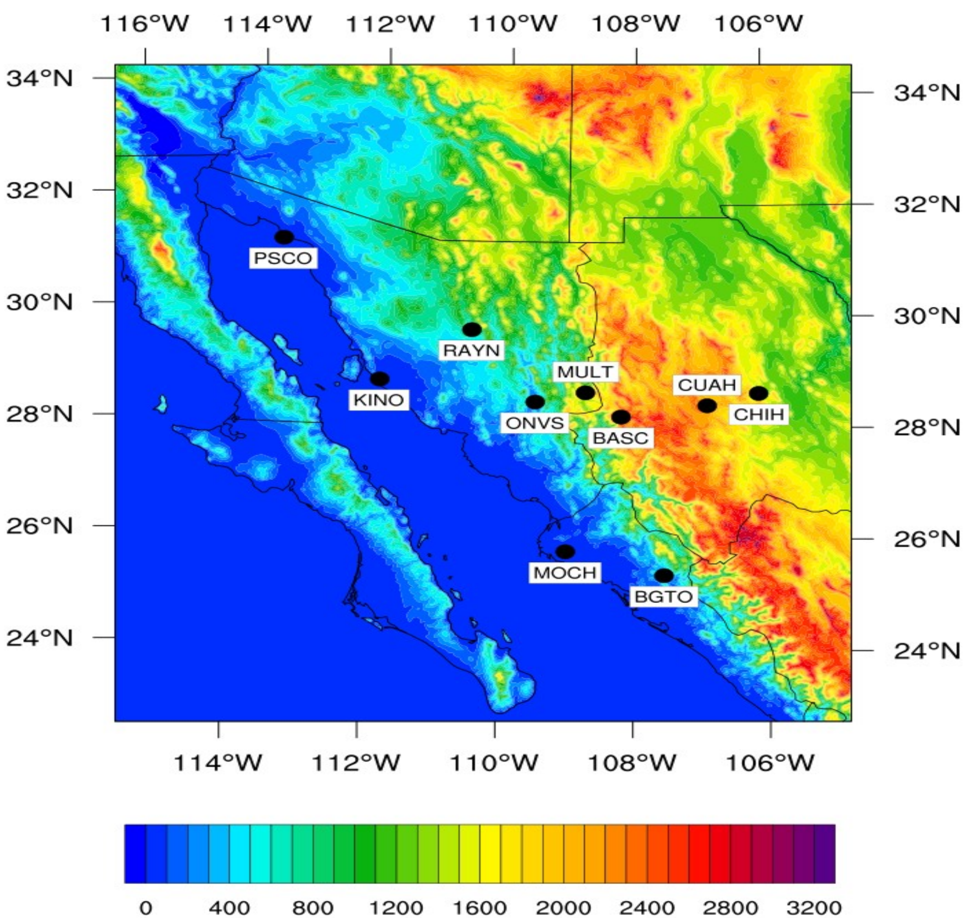
A Squall Line Entering Belem from the Atlantic Coast

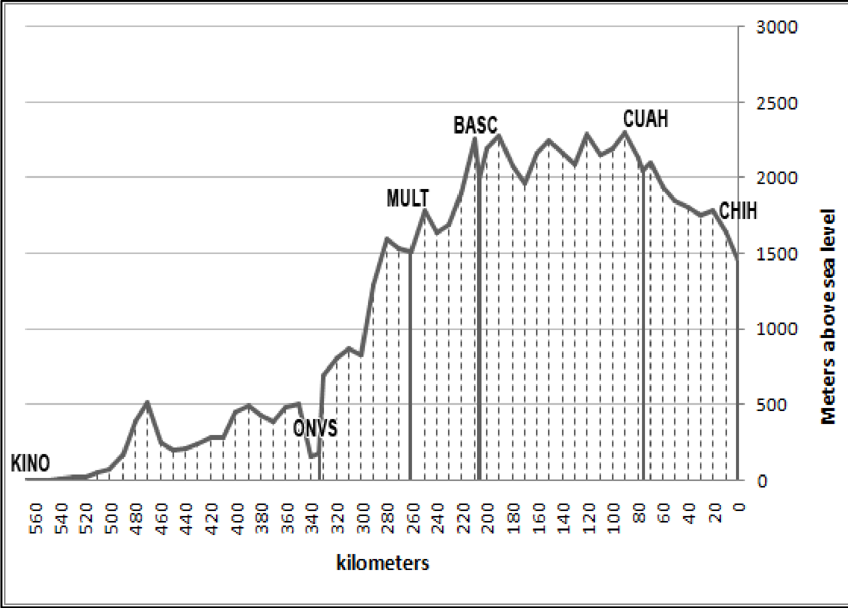

Convective Days
Non-Convective Days
(PWV cm)
(CTT K)
6.00
5.70
5.40
5.10
4.80
4.50
300
280
260
240
220
BSSG PWV
BBNV PWV
BABT PWV
BSSG CTT
BBNV CTT
BABT CTT
6am
9am
12pm
3pm
6pm
9pm
Local Time
Degrees K
0°
0°30'S
1°S
1°30'S
2°S
BSSG
BBNV
BABT
49°30'W
49°W
48°30'W
48°W
47°30'W
47°W
46°30'W
46°W
250
255
260
265
270
275
280
285
290
295
300

North American Monsoon GPS Transect Experiment 2013

Serra et al. 2016 BAMS

- High Resolution Model Comparison and Data Assimilation
- Strongly Forced Days vs Weakly Forced Data
- MCS formation and Propagation

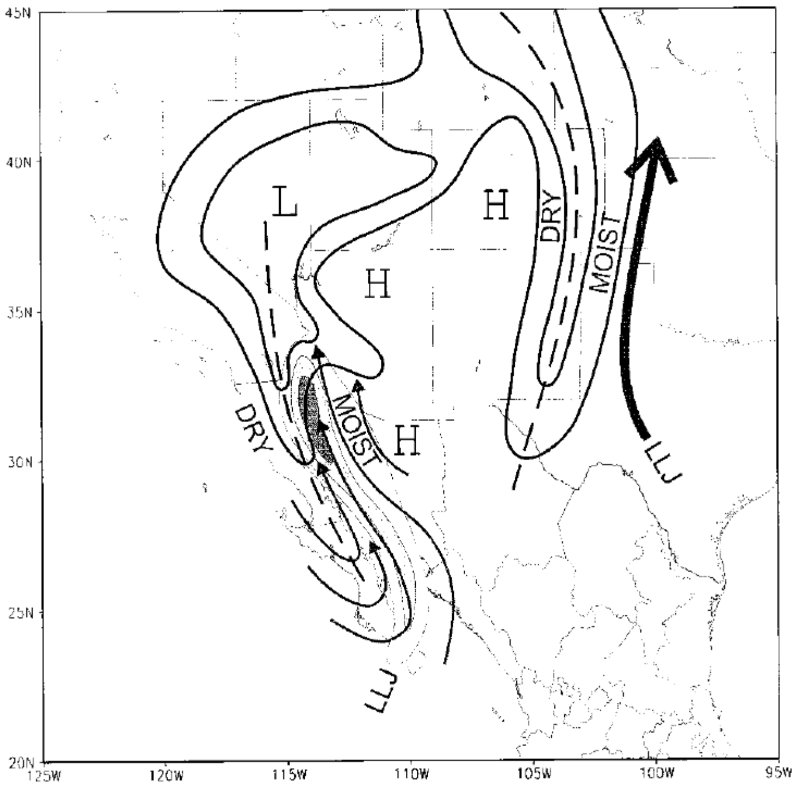


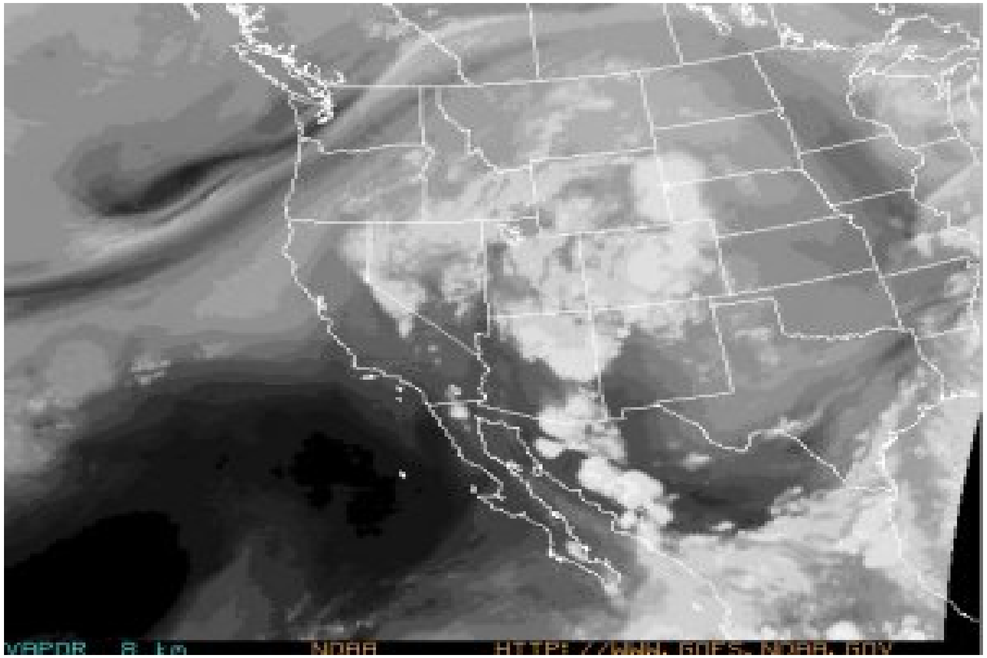


Water Vapor Transport and Land-Atmosphere Interactions

The North American Monsoon GPS Hydromet Network 2017

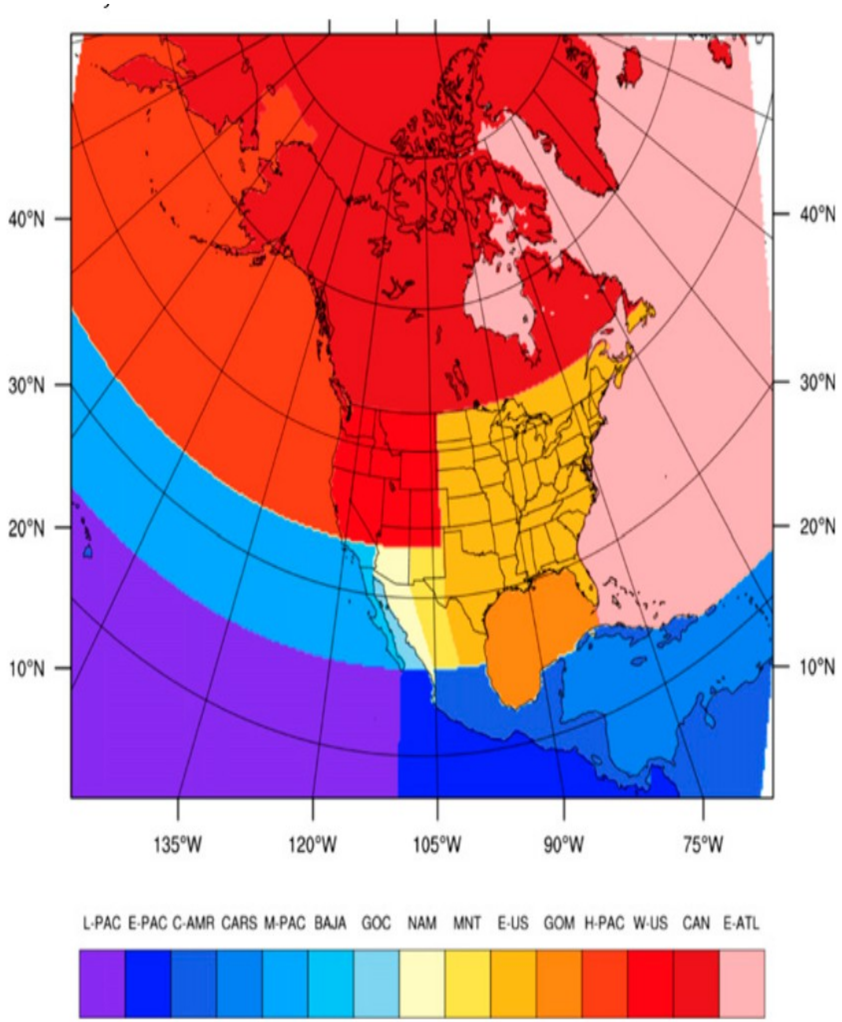
Traditional View of GofC and Eastern Pacific as Dominant Moisture Sources (Maddox et al 1995)

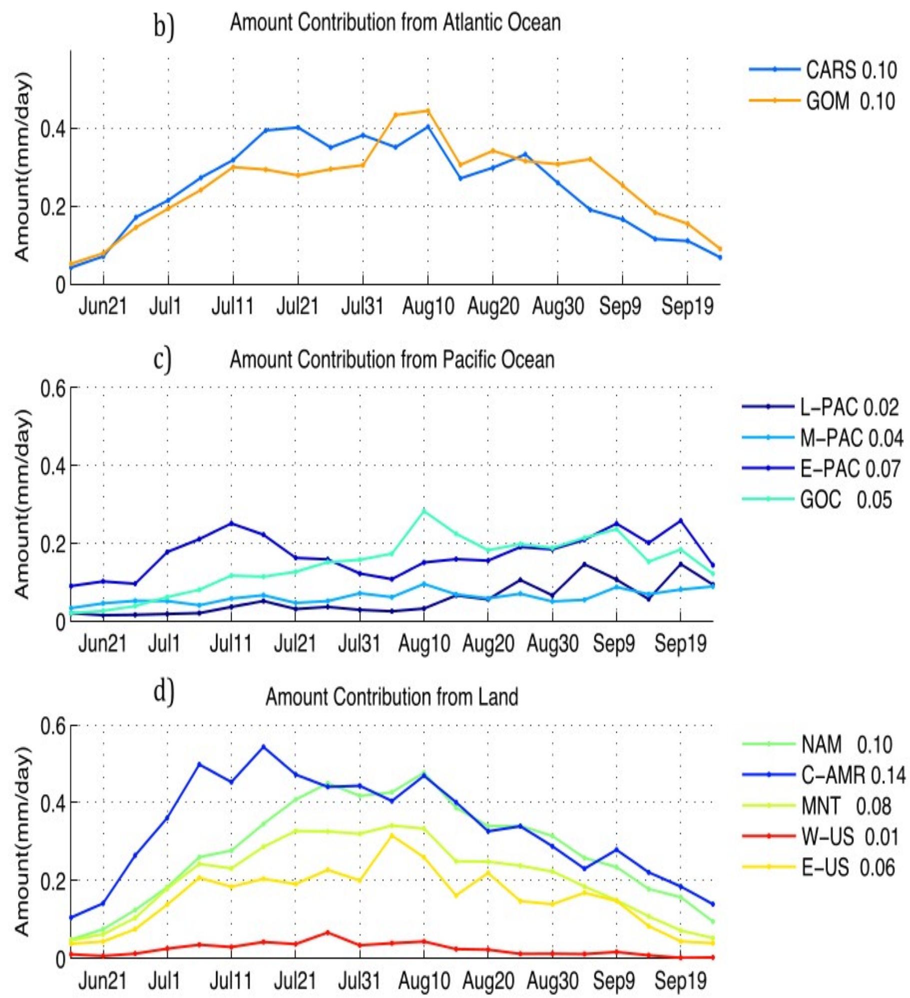




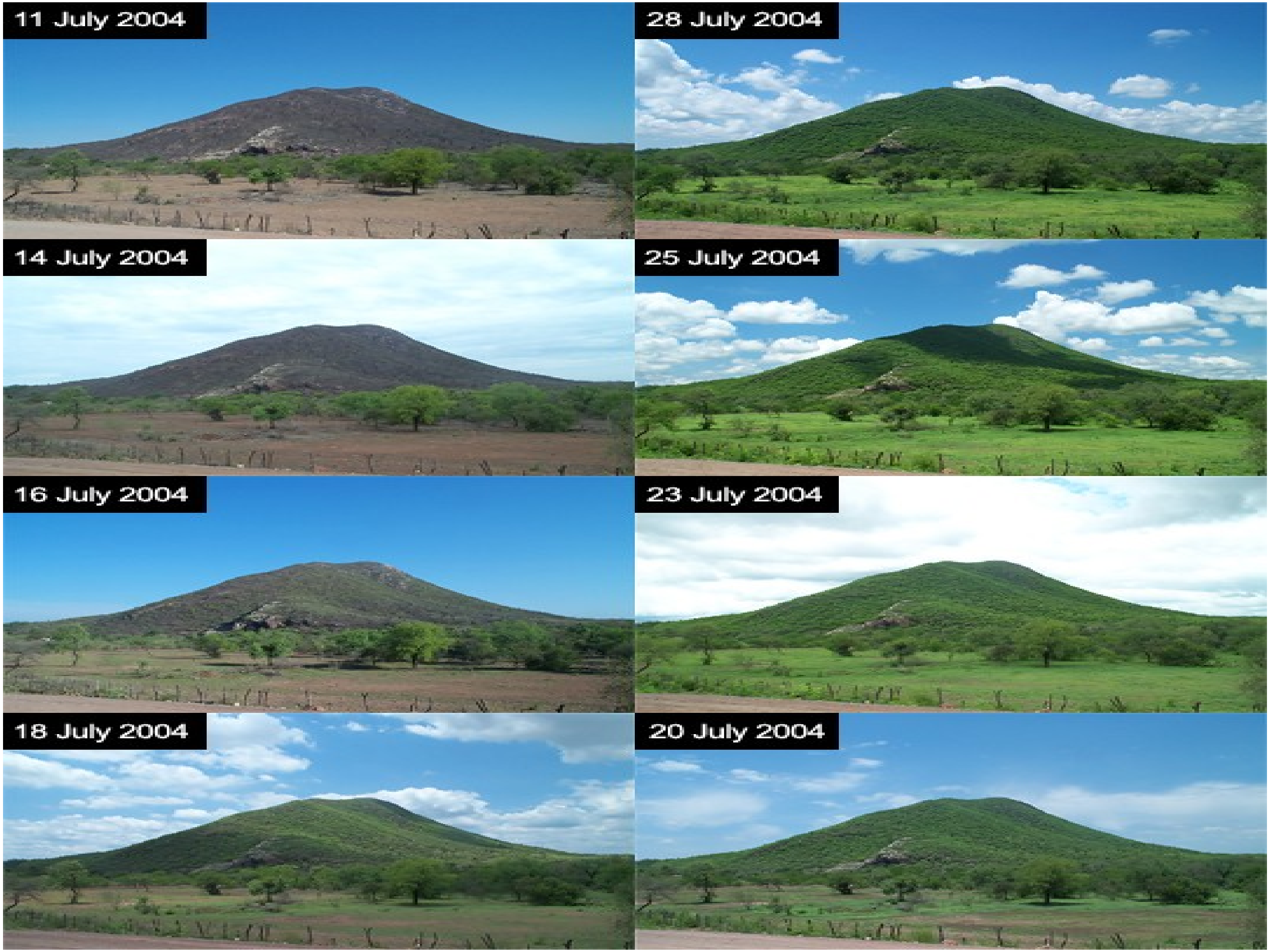
Adams and Comrie 1997 BAMS

Hu and Domínguez (2015) and Domínguez et al (2016) have re-elevated the status of the GoM,Moisture Recycling and Atlantic (Water Vapor Flux Models,WRF, Isotope Analysis)



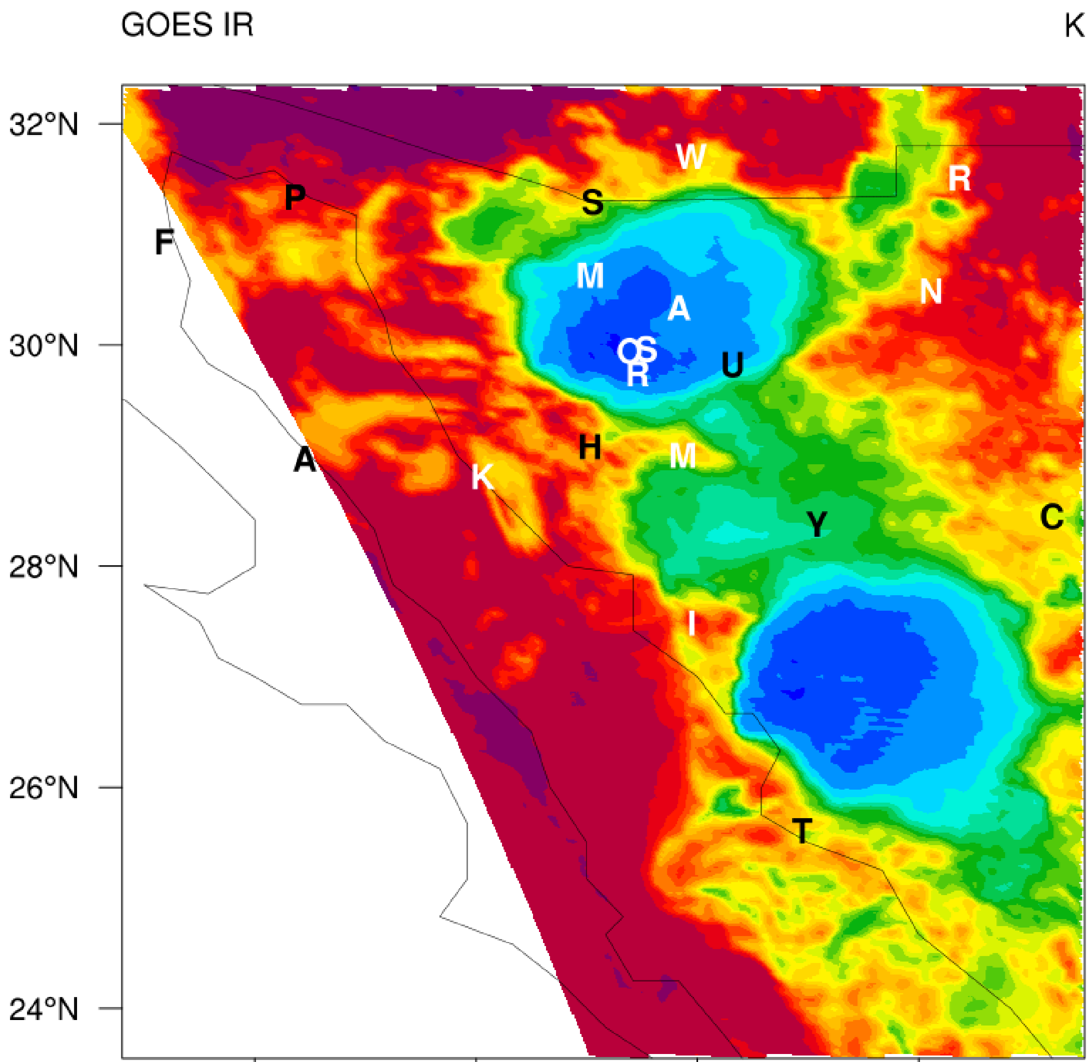


Green up near Tesopaco, Sonora

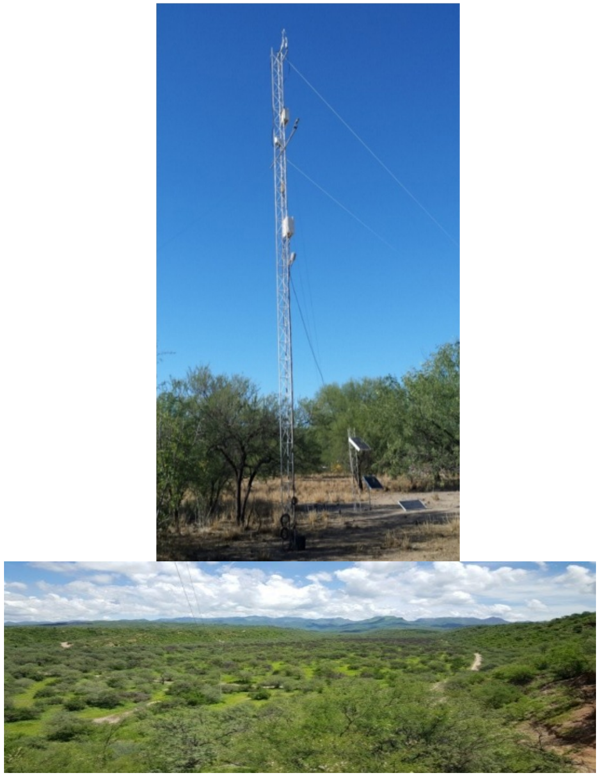


NAM GPS Hydromet Network 2017

(11 Experimental GPS Met Sites, 8 TLALOCNet sites,Suominet GPSmet Sites (Real time), Triangular Flux Array, 1 week Sondes



ASU and UNISON
Triangular Network of Water Vapor, Heat and Carbon Flux Stations



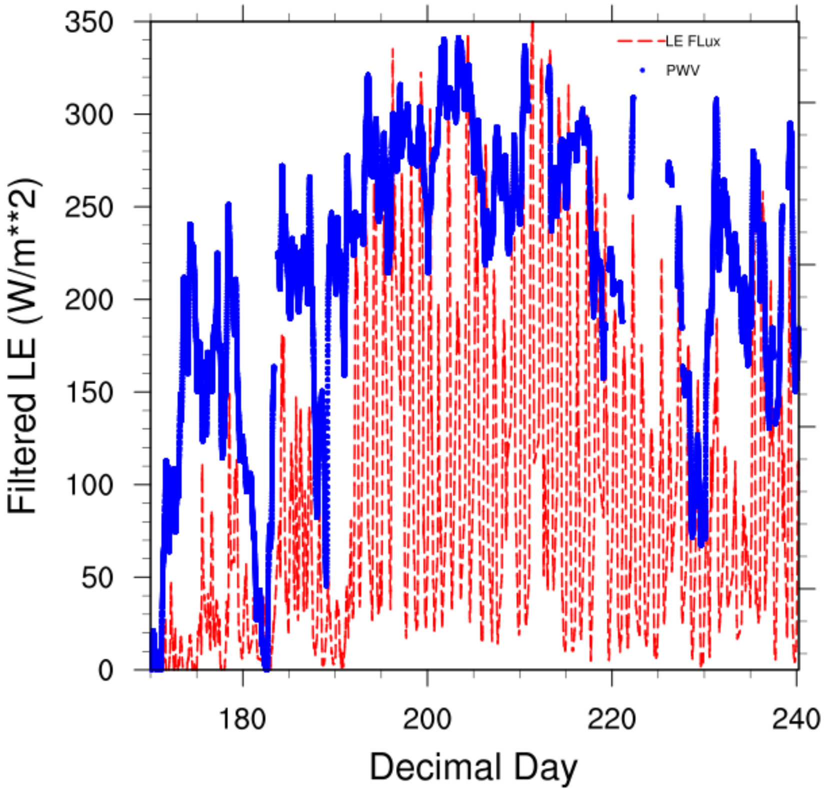
Mesquite Trees in Valley Bottom

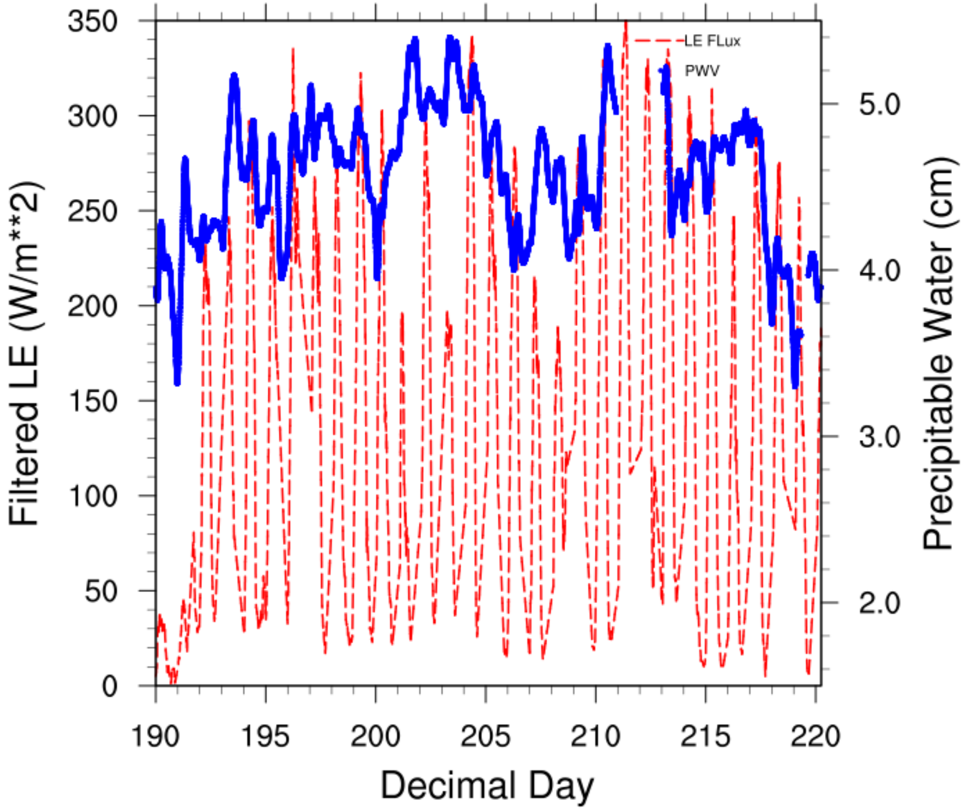
Oak Savanna at Mountain Top

Subtropical Scrubland in Alluvial Fan

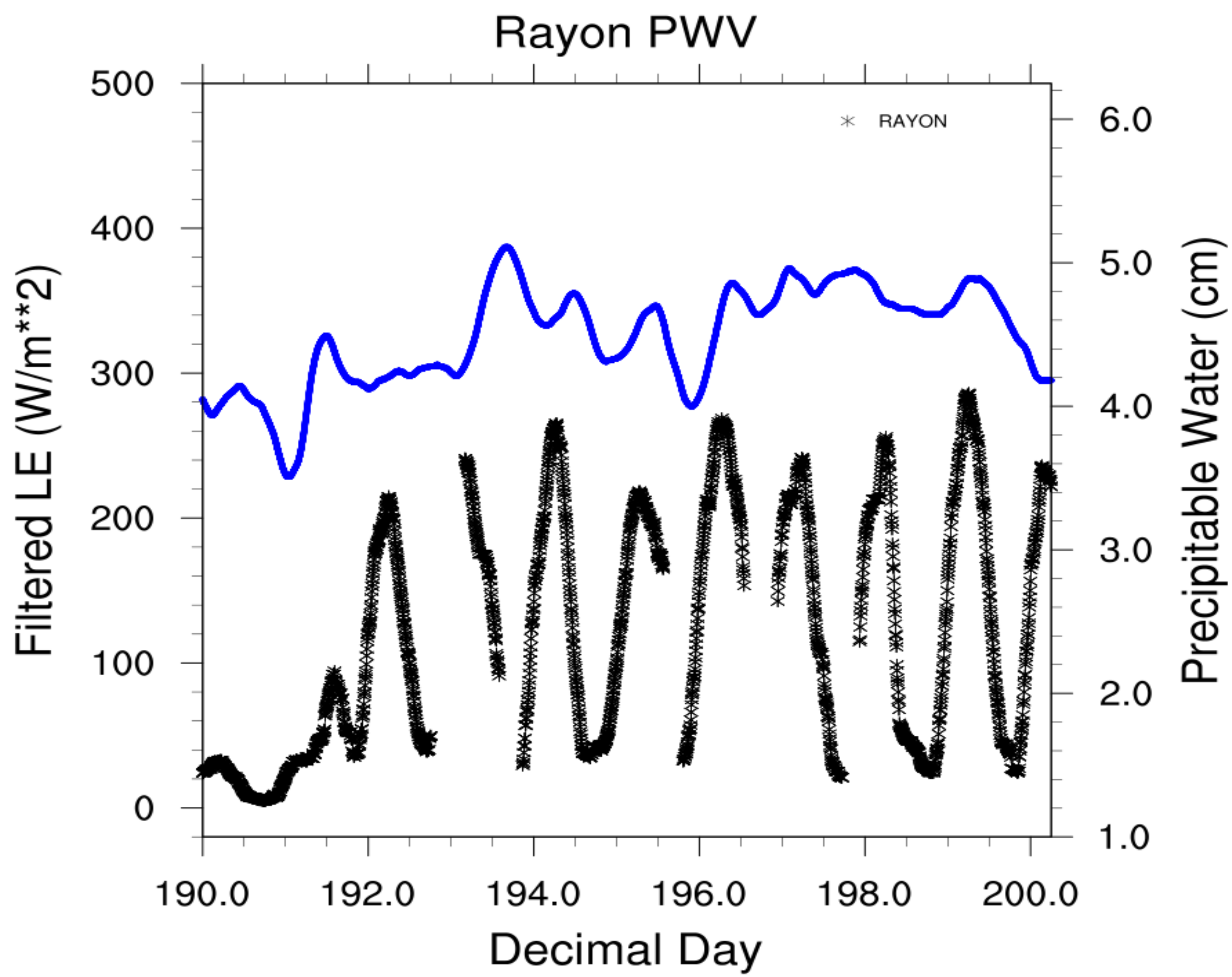
<u>Eddy Covariance Method for Turbulent Flux Measurements in Ecosystems</u>

Latent Heat Fluxes vs Colloated GPS CWV During Campaign Rayón Sonora (5 minute LH Flux and CWV)

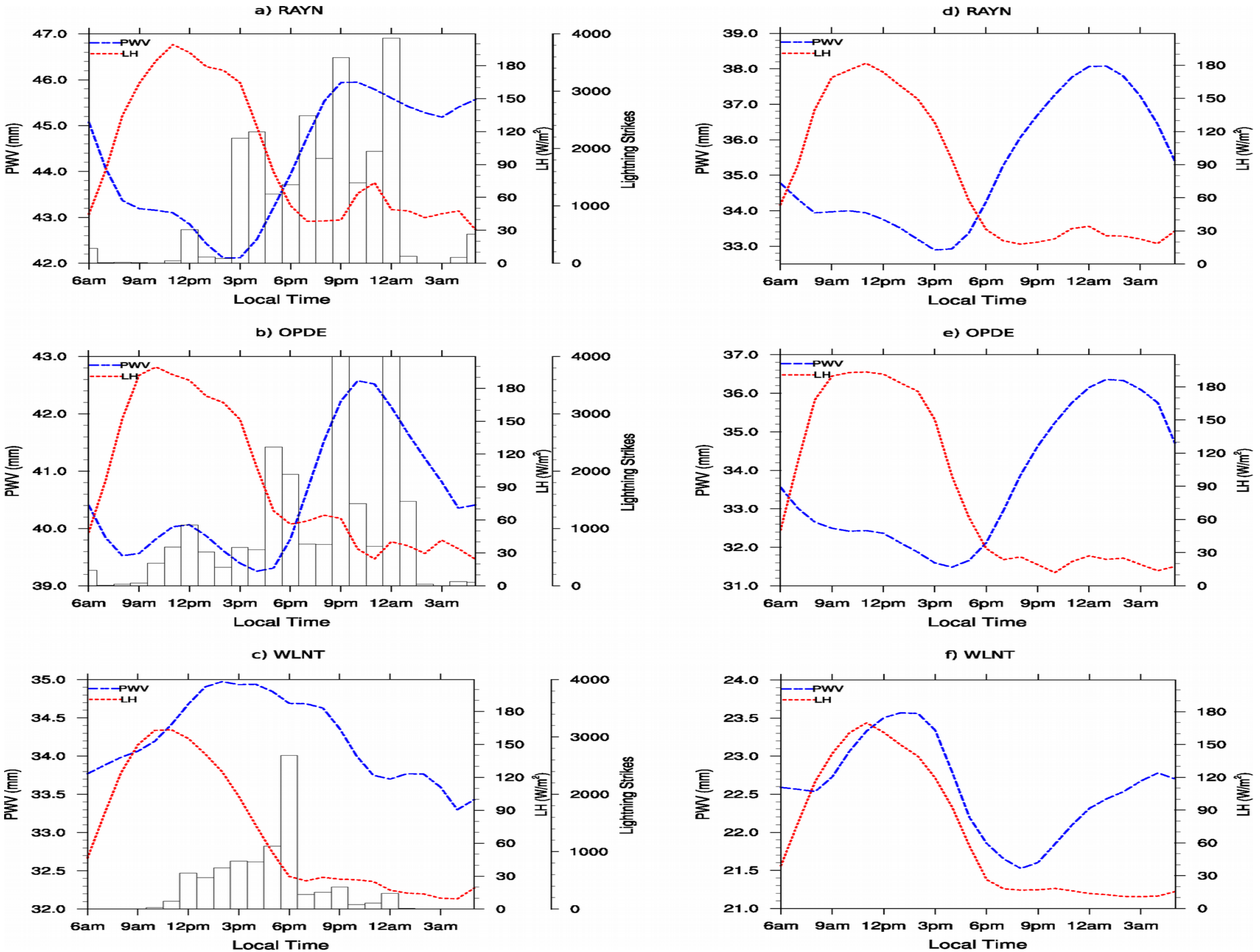




At Higher Temporal Resolution (LH Flux and PWV),



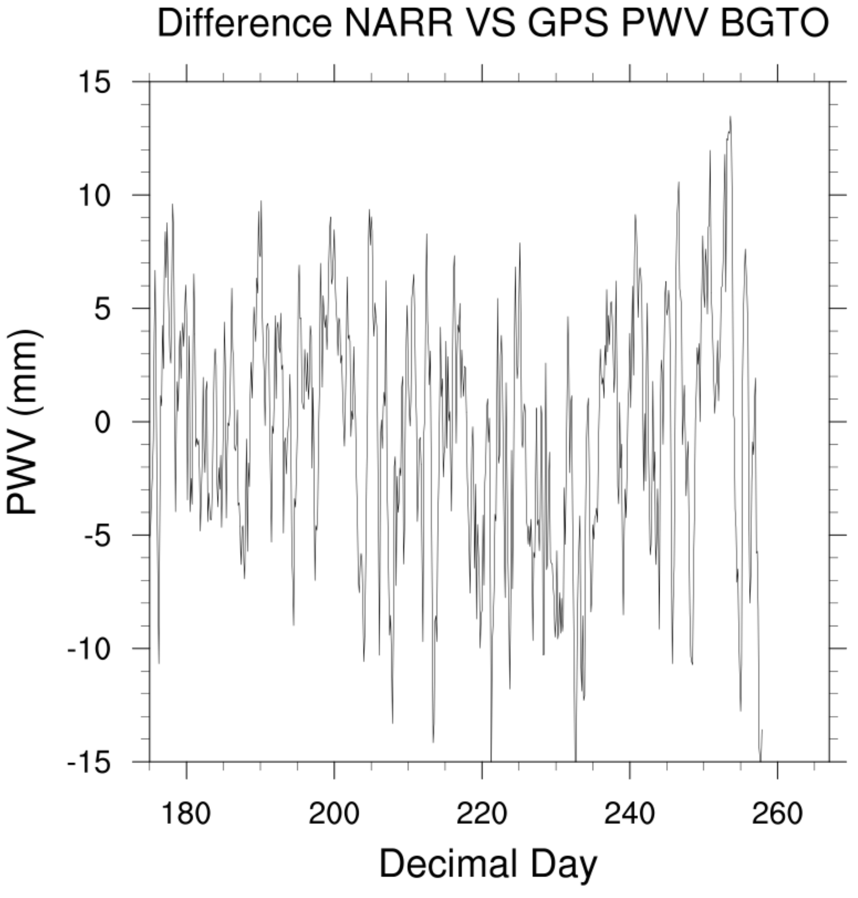
Surface LH Flux Contribution to PWV (Con. Vs Non.)

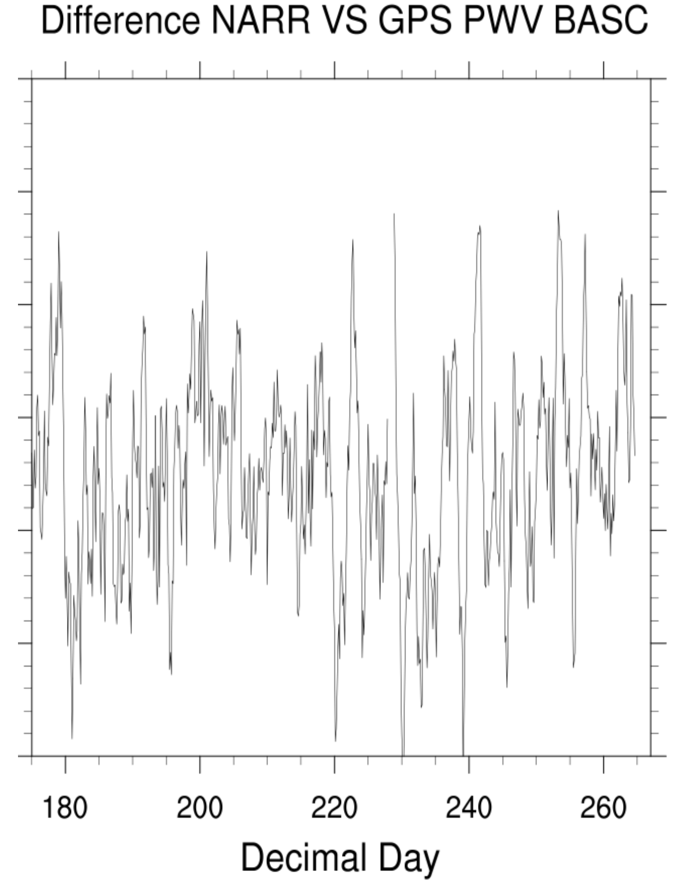


An Aside: Criticism of Reanalysis in a Topographically Complex Region
(How to Make Friends and Influence People)

Errors in PWV are quite large over the Complex Topograpy of NW Mexico
NARR and ERA-Interim

NARR Reanalysis vs GPS PWV 2013

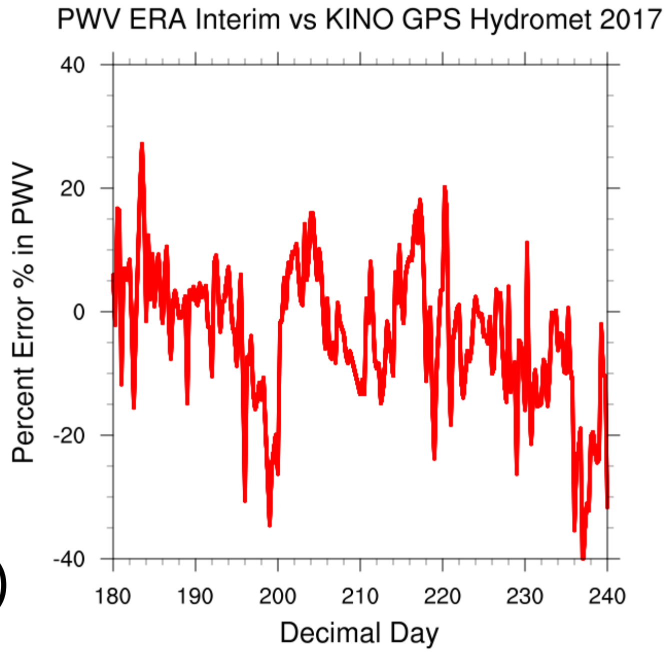


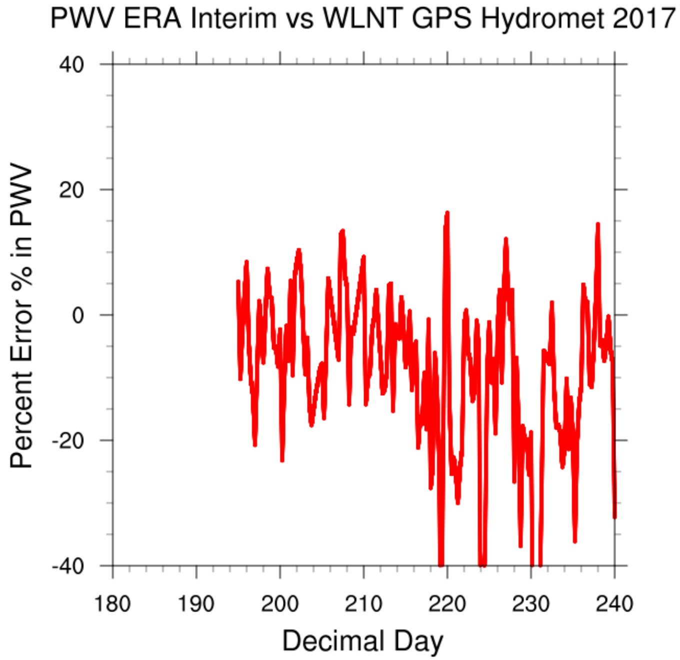


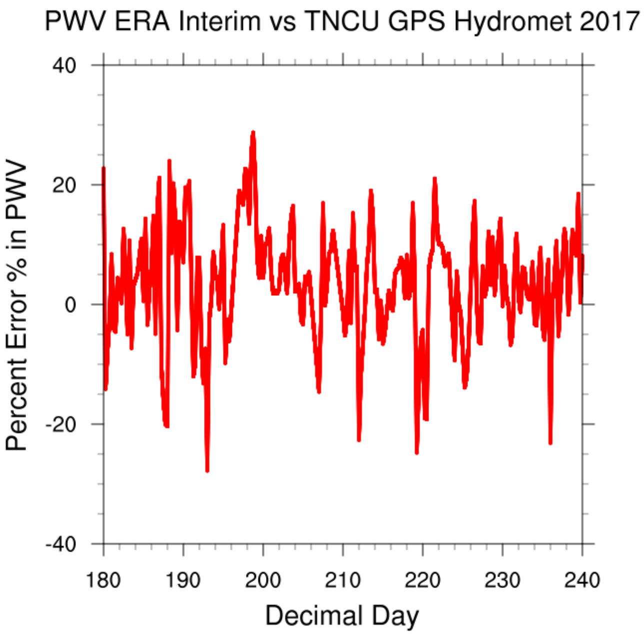
Reanalysis Data: A Word of Caution
(ERA-Interim 0. 125 degrees,
6 hours PWV)

A Large Number Studies on WV Transport/Recycling use Reanalysis Data

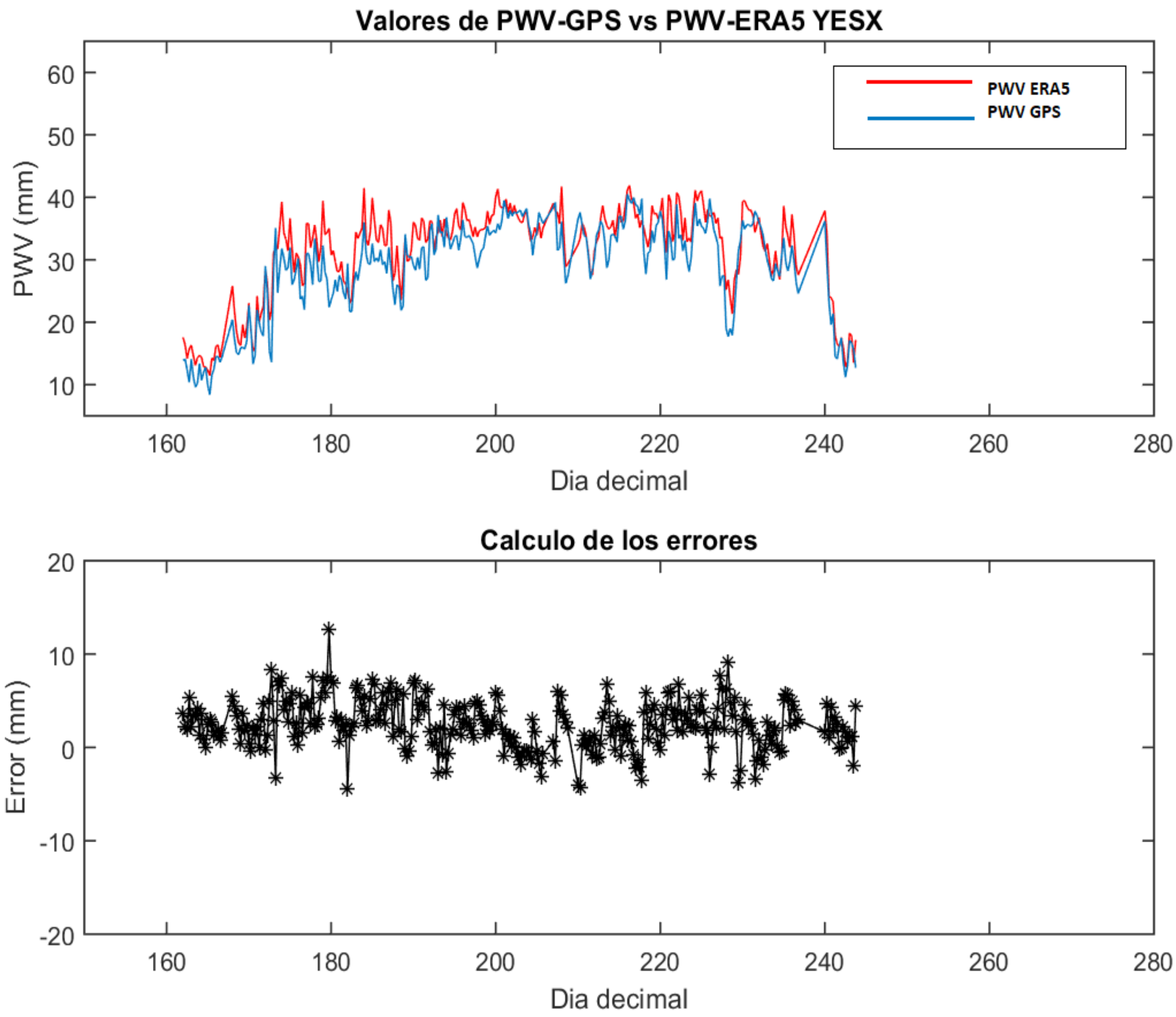
(See also Radhakrishna et al. (2014) for Poor NARR PWV at Subdaily Timescales)







More Recent ERA_5 Performs Better in NAM Region



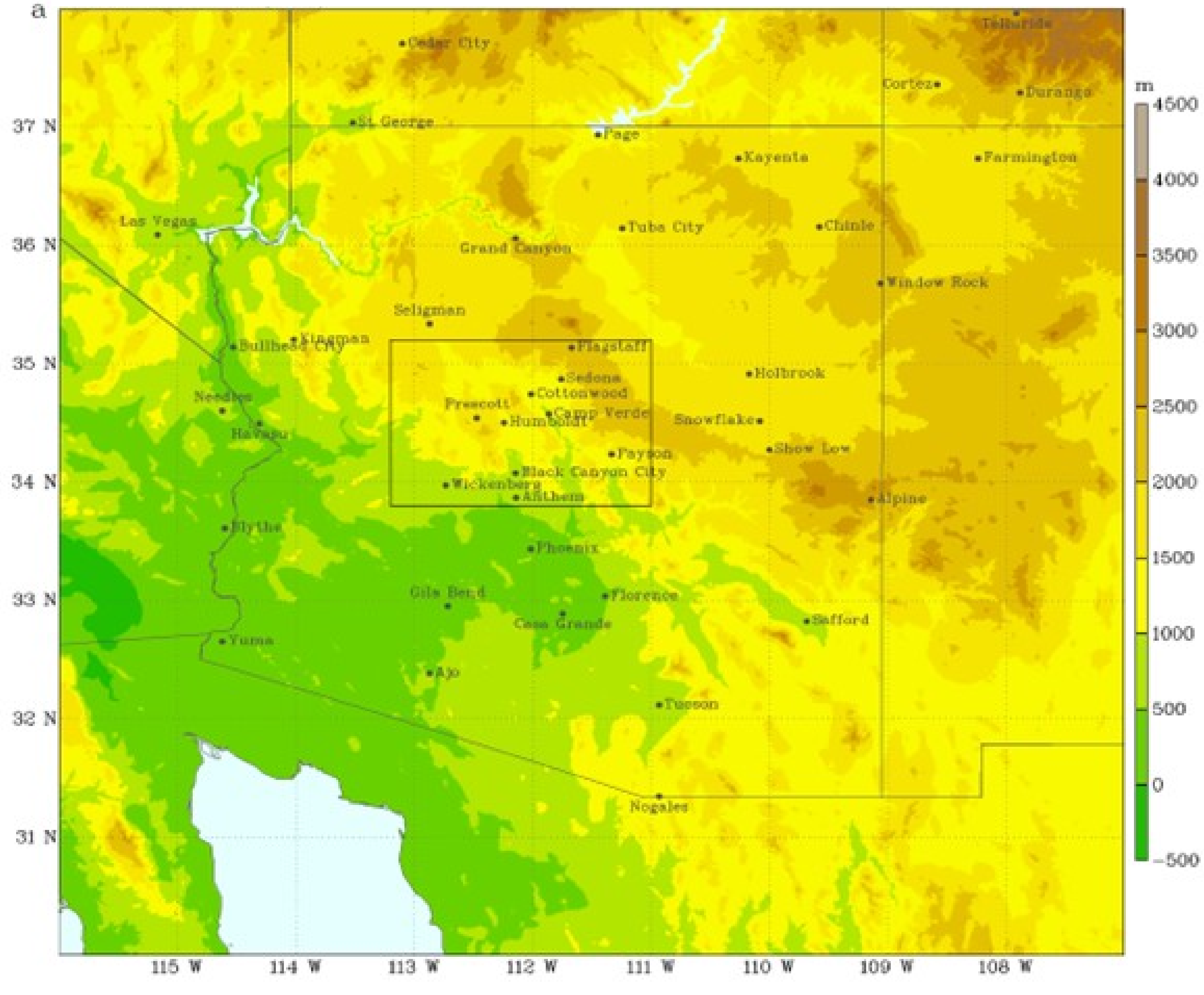
Summary/Conclusions

- CWV-Precipitation relationship shows criticality (in general sense) for Tropical Continental Regime.
- SOC for Tropical Continental Regime (Jury is still out). More consistent with Thermodynamic Control (from Yano 2012)
- The STD Transition is a robust 4 hours (based on temporal or spatio-temporal evolution).
- GPS met Sites in Transects/Networks allow for estimating Propagation Speed of Convective Events and Advection of WV
- From NAM, Preliminary Results suggests little (local) wv flux contribution to PWV (for NAM region)

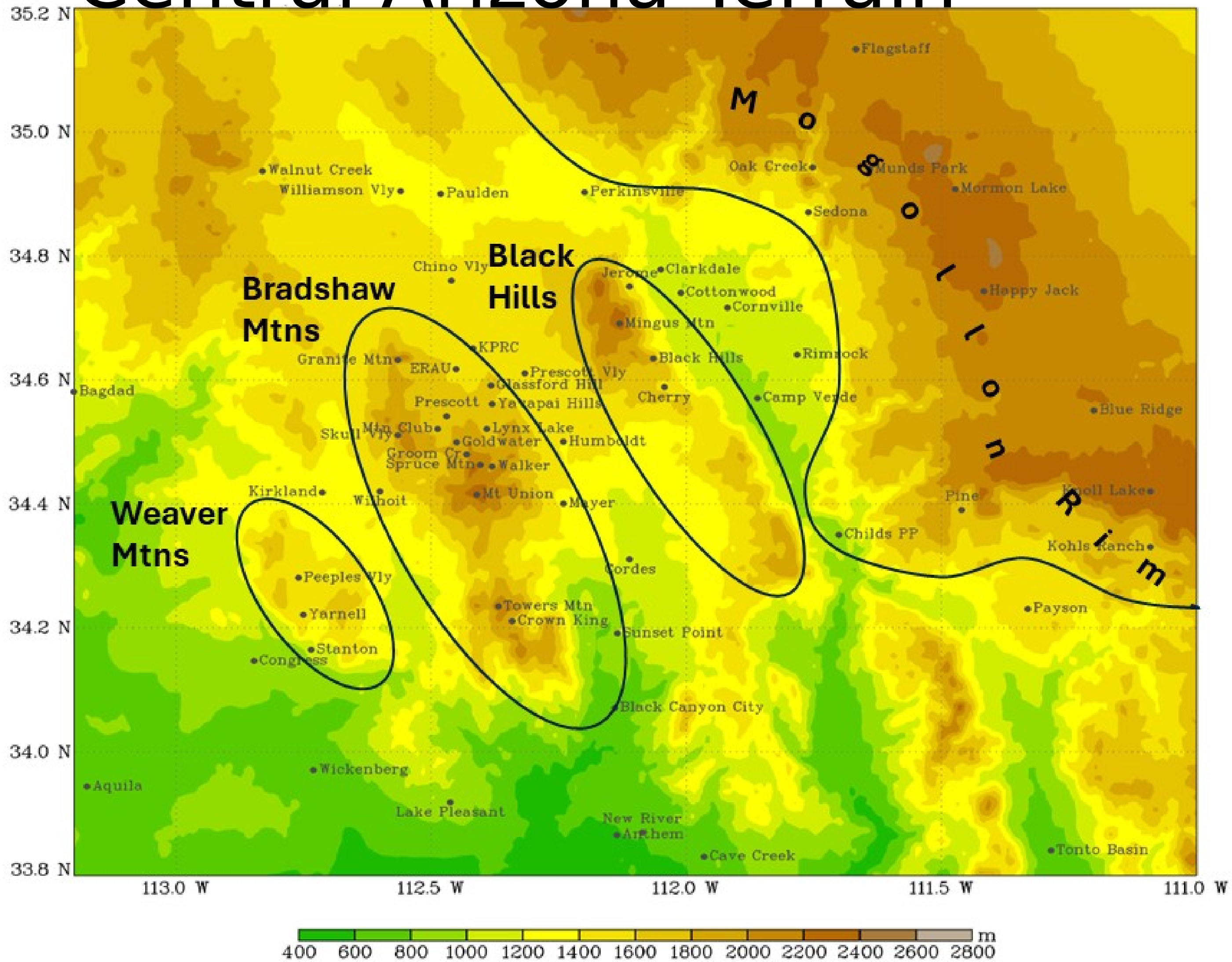
CONVECT

CONvection and water Vapor Exchange in Complex Terrain (July – Aug 2027)

Southwest Terrain



Central Arizona Terrain




Thank you
dave.k.adams@gmail.com