GPS Precipitable Water: A Critical Variable in the Atmospheric Hydrological Cycle

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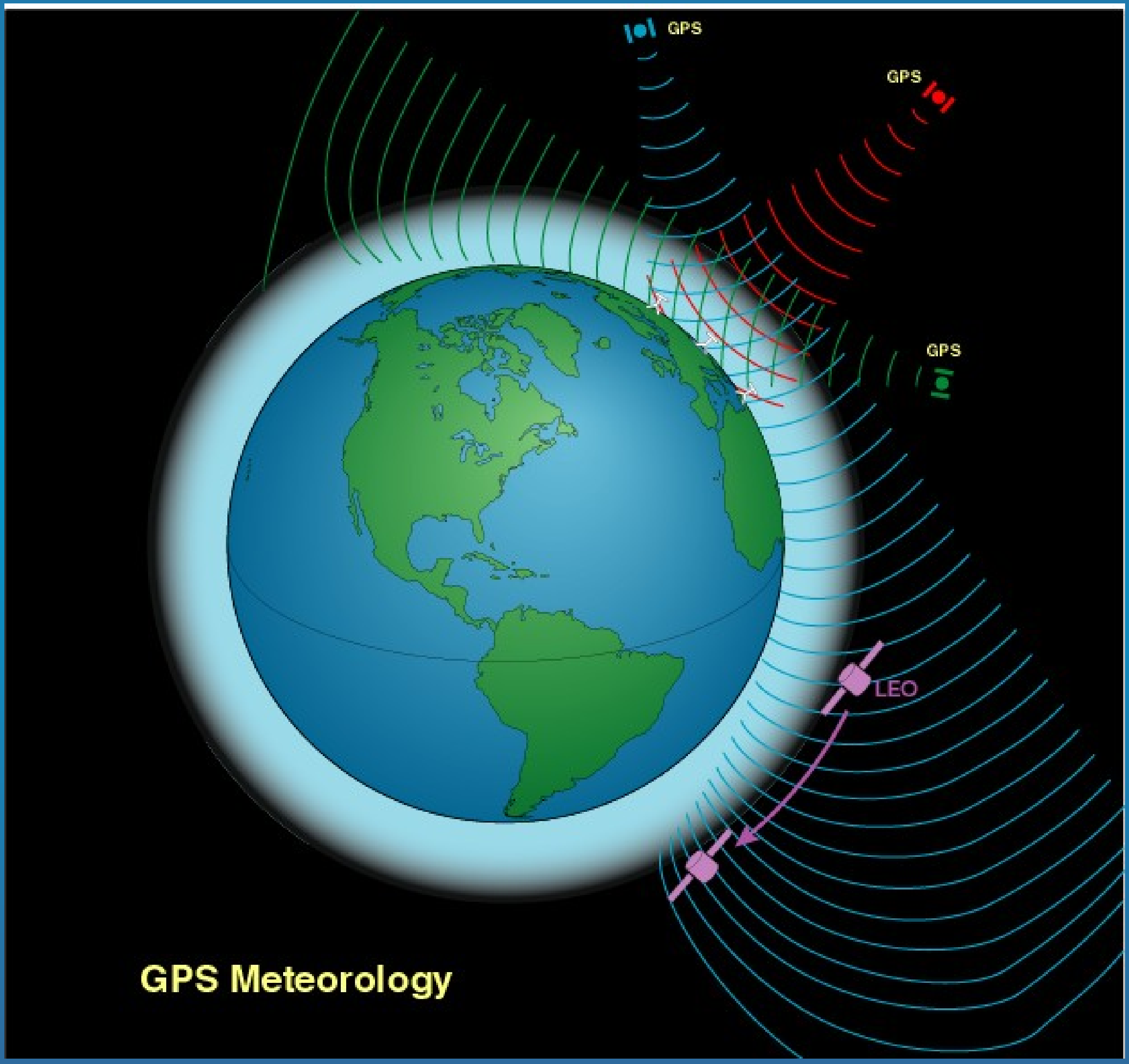
(NOAA, UNAM, UNISON, UACJ, ITSON, UA, ASU, UCSD)

ATMOSPHERIC DELAY OF GPS SIGNALS IS THE BASIS OF GPS METEOROLOGY



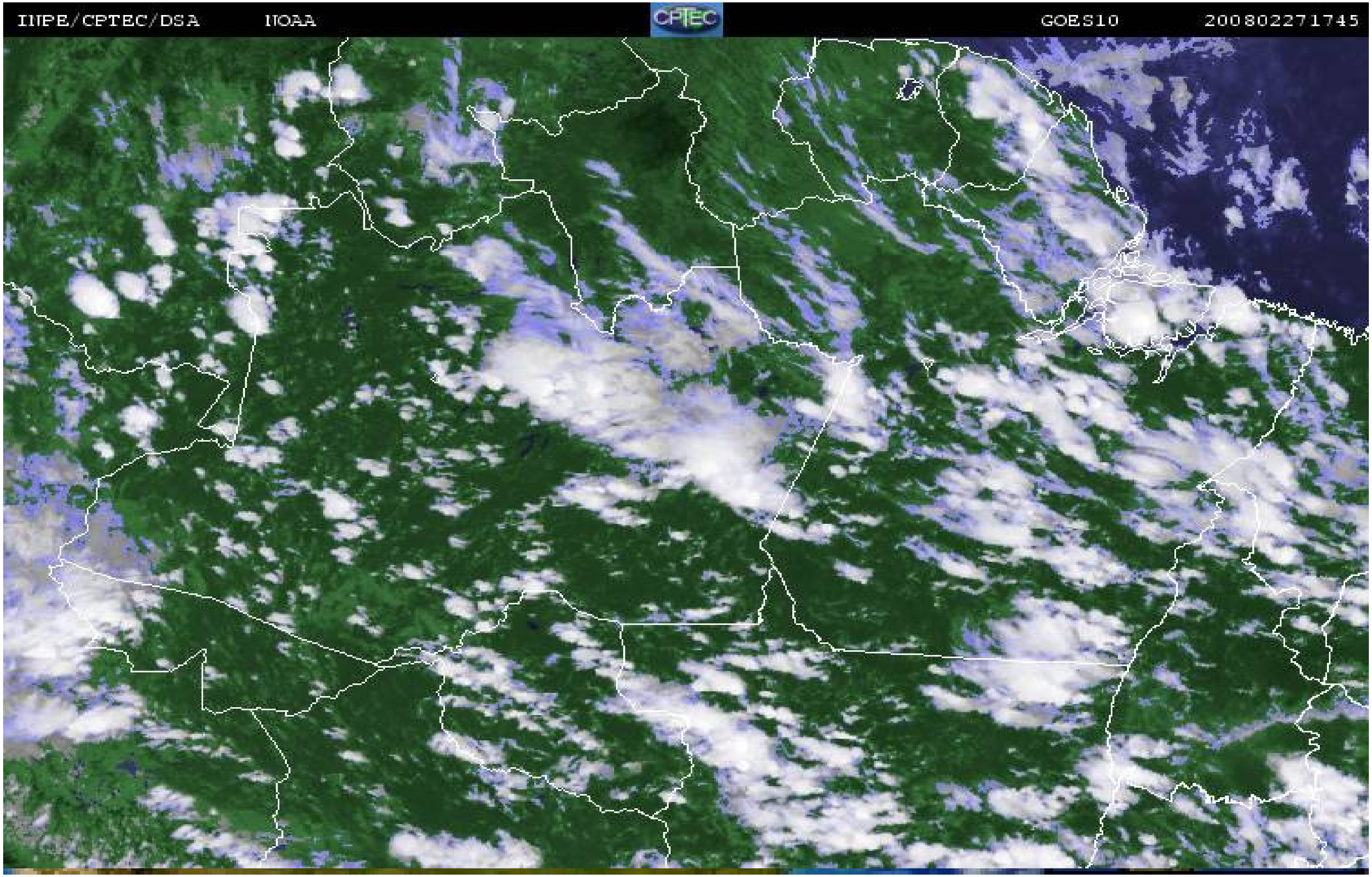
Science Themes and Motivations (over last 10 years or so)

Understanding Large-scale and Convective Scale Interactions
AND VERY IMPORTANT, Challenging Numerical Models.
1)Motivated by Convective Parameterizations and QE-type theories
Data: Long-term GPSmet Observations Central Amazon

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

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

4) **A Surprise**



- In Tropics, how does convection organize from individual cells to mesoscale convective systems?

1) For Atmo Hydrological Cycle
PWV-Precipitation Relationship is Fundamental
(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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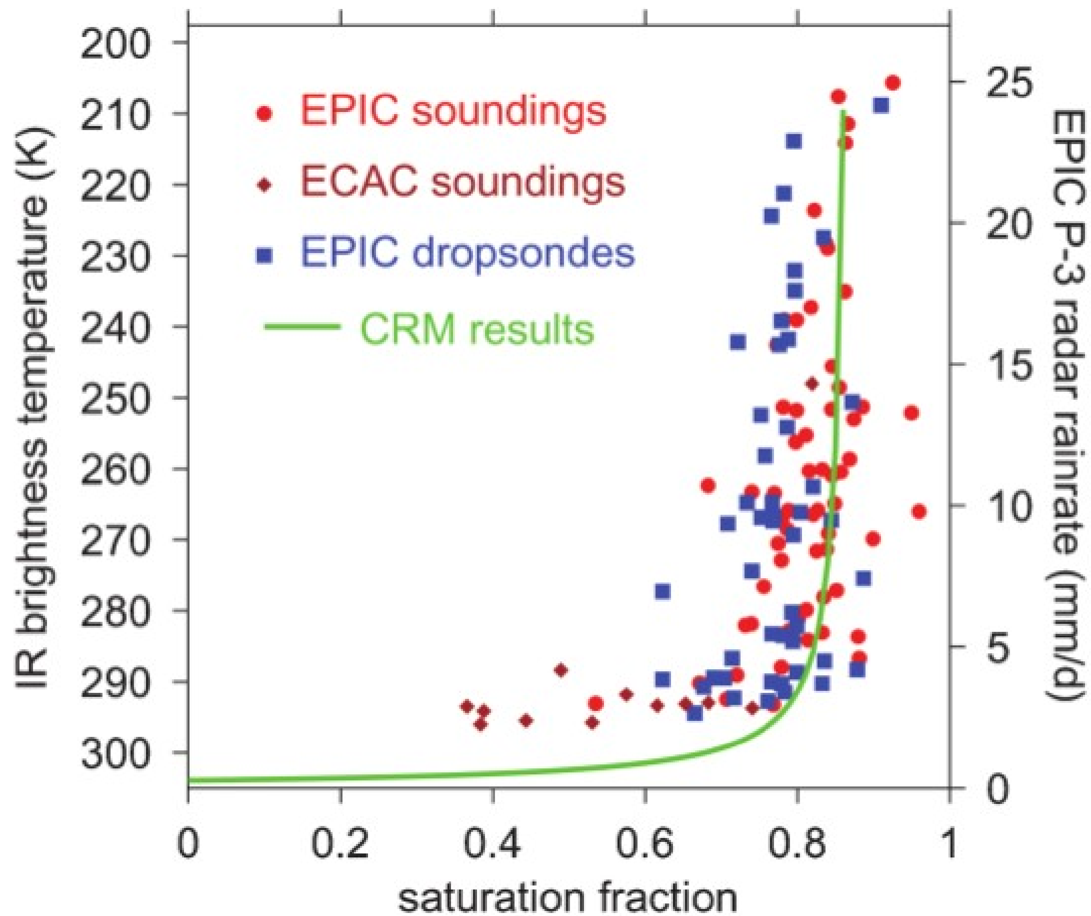
Thermodynamic Control
(Raymond 2000; Raymond et al. 2009)

Two Assumptions

Precipitation a decreasing Function of mean saturation deficit (PWV/PWV_sat)

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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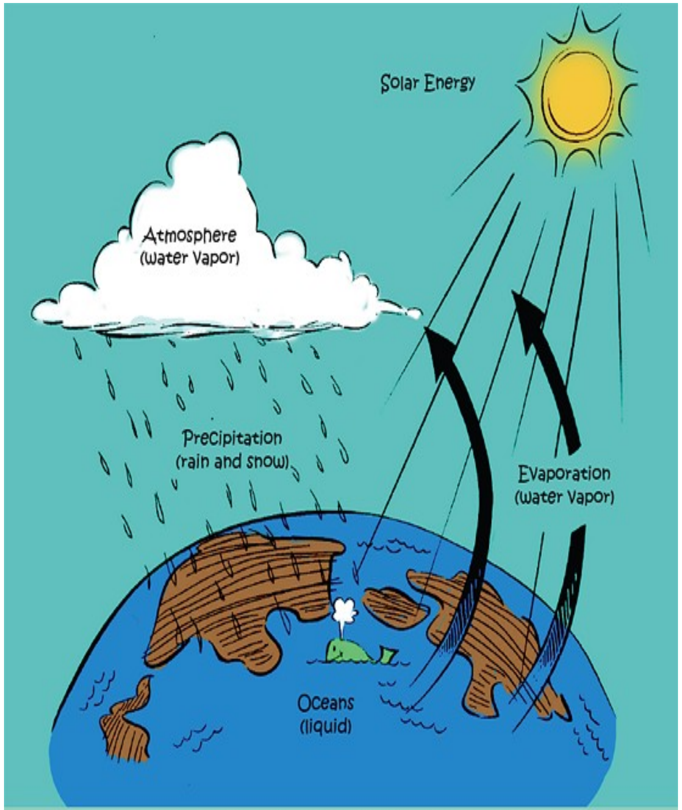
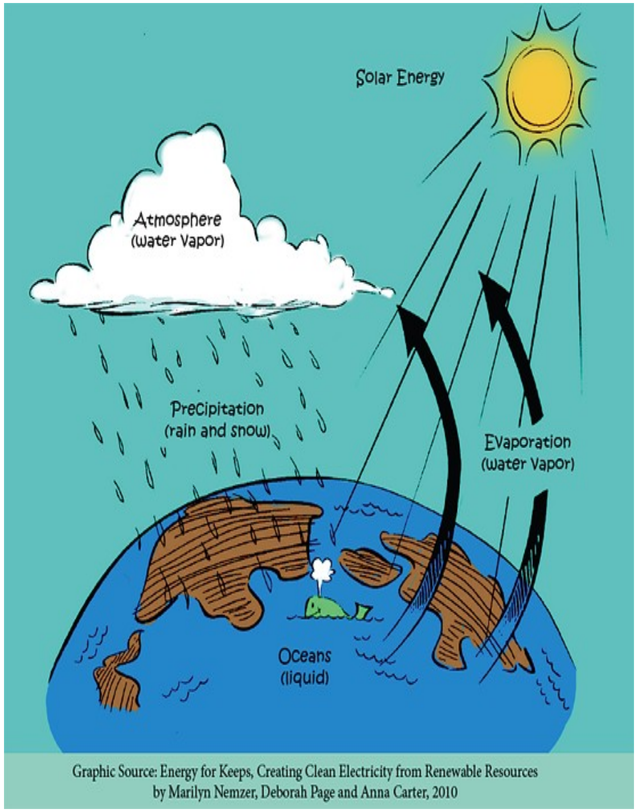


Graphic Source: Energy for Keeps, Creating Clean Electricity from Renewable Resources
by Marilyn Nemzer, Deborah Page and Anna Carter, 2010

SOC and the ***Atmosphere***

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



Peters, O., J. D. Neelin, 2006: Critical Phenomena in Atmospheric Precipitation.

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) Precipitation as a function of the reduced water vapor *w* ≡ (*w* − *w*c)/*wc.* Power laws fitted to these distributions all have the same exponent **β** ±0.02.

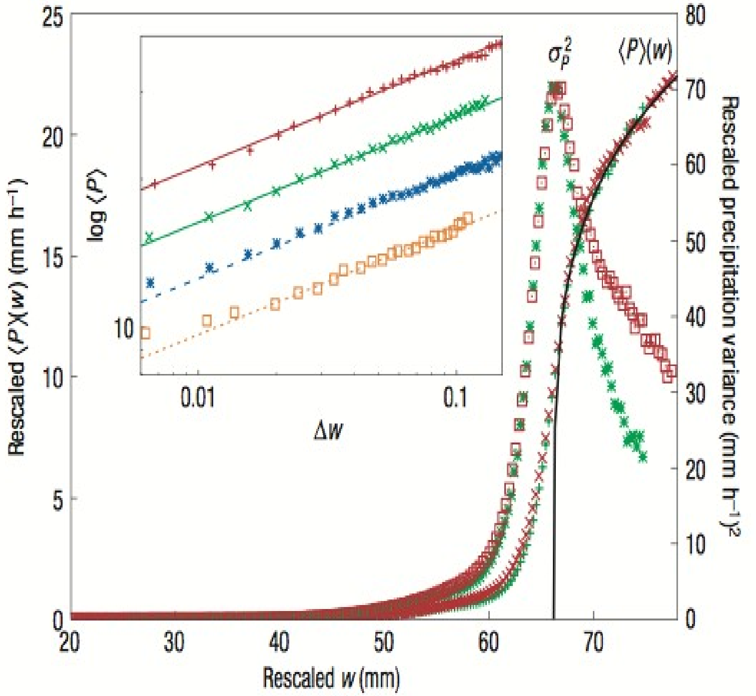


Figure 1 Order parameter and susceptibility. The collapsed (see text) precipitation rates $\langle P\rangle(w)$ and their variances $\sigma_P^2(w)$ for the tropical eastern (red) and western (green) Pacific as well as a power-law fit above the critical point (solid line). The inset shows on double-logarithmic 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.

And Over Land? What is the PWV-Precipitation Relationship?

GPS Meteorology in the Amazon, Brazil

Long-term (3.5 years) station in Manaus

1 year Dense Network (20 stations) in Manaus

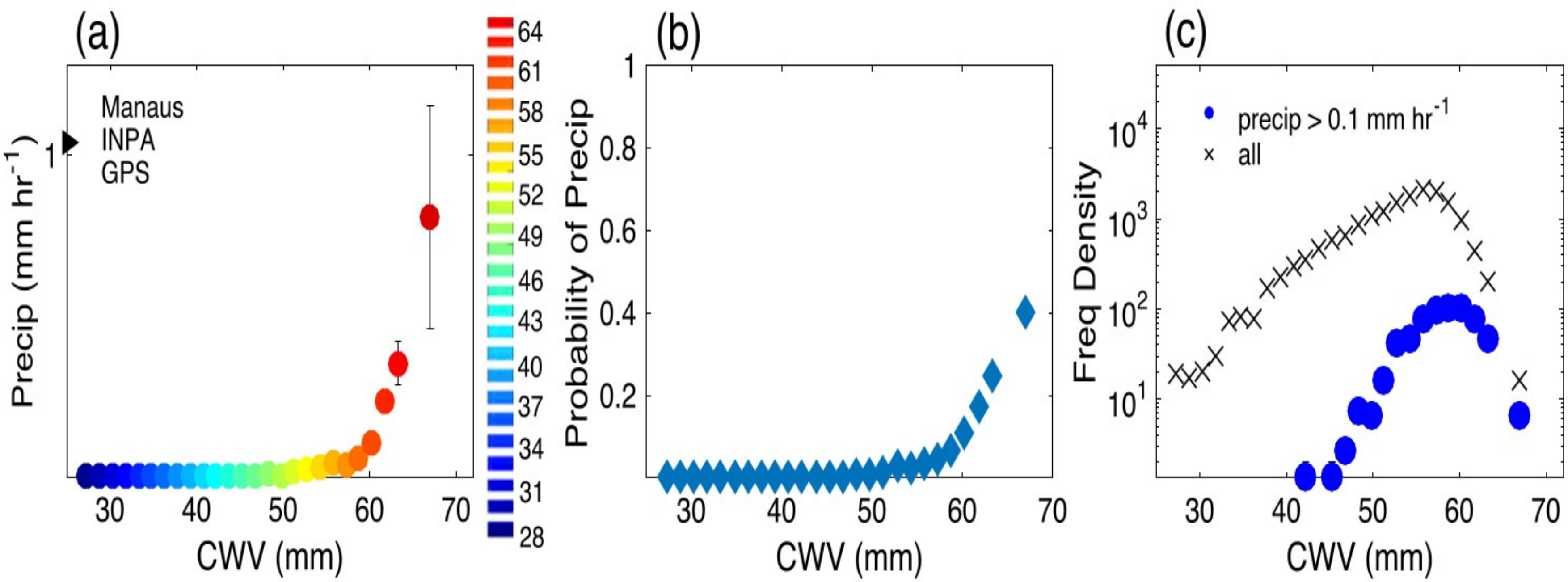
6 weeks Dense Network (15 stations in Belem GPM-CHUVA IOP)

A Single GPSmet Site INPA/LBA
Central Amazon
(NOAA Near Real Time Site)
July 2008 to December 2011

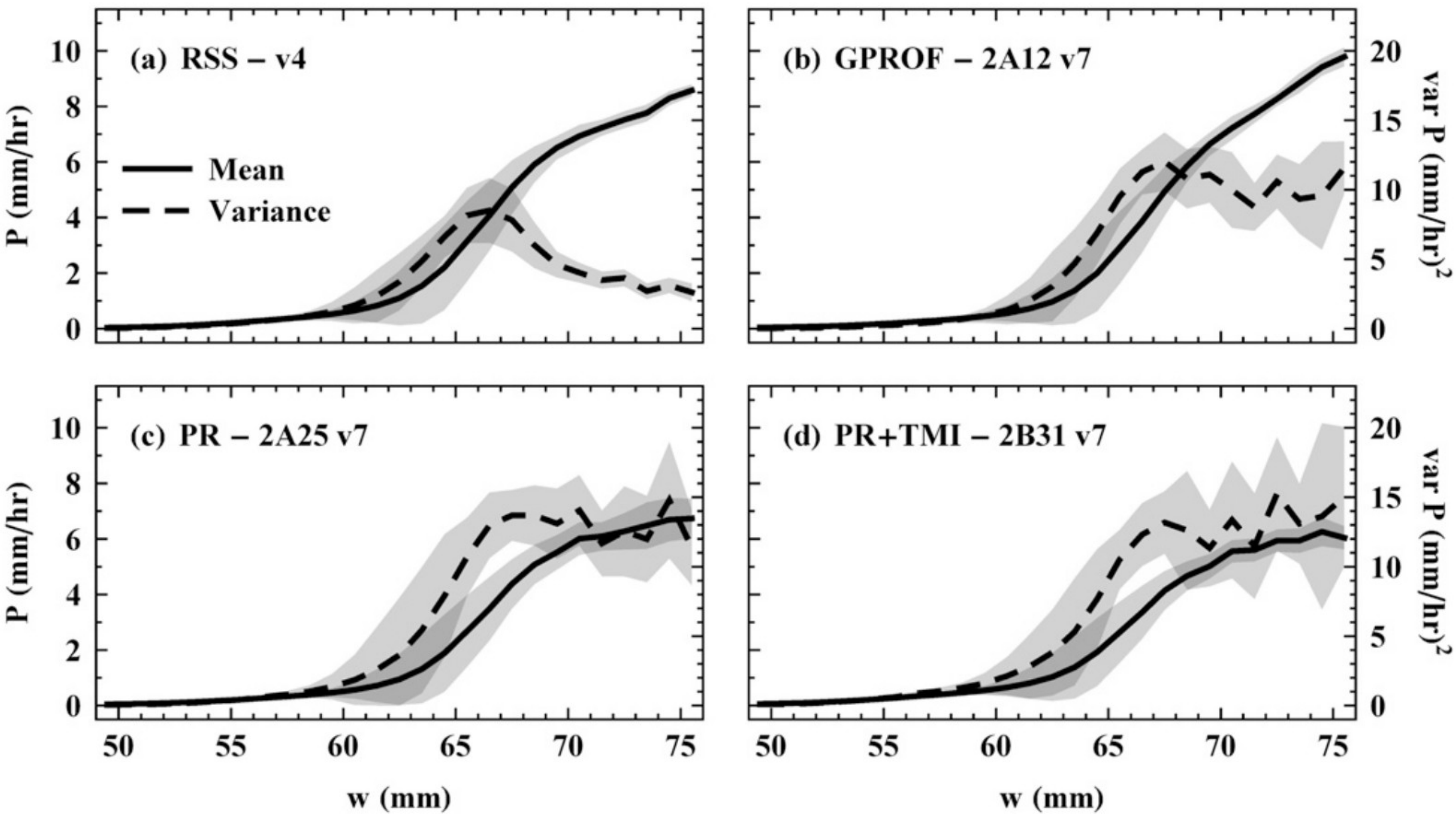
What does GPS PWV show w.r.t. Water Vapor Criticality?

(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?**

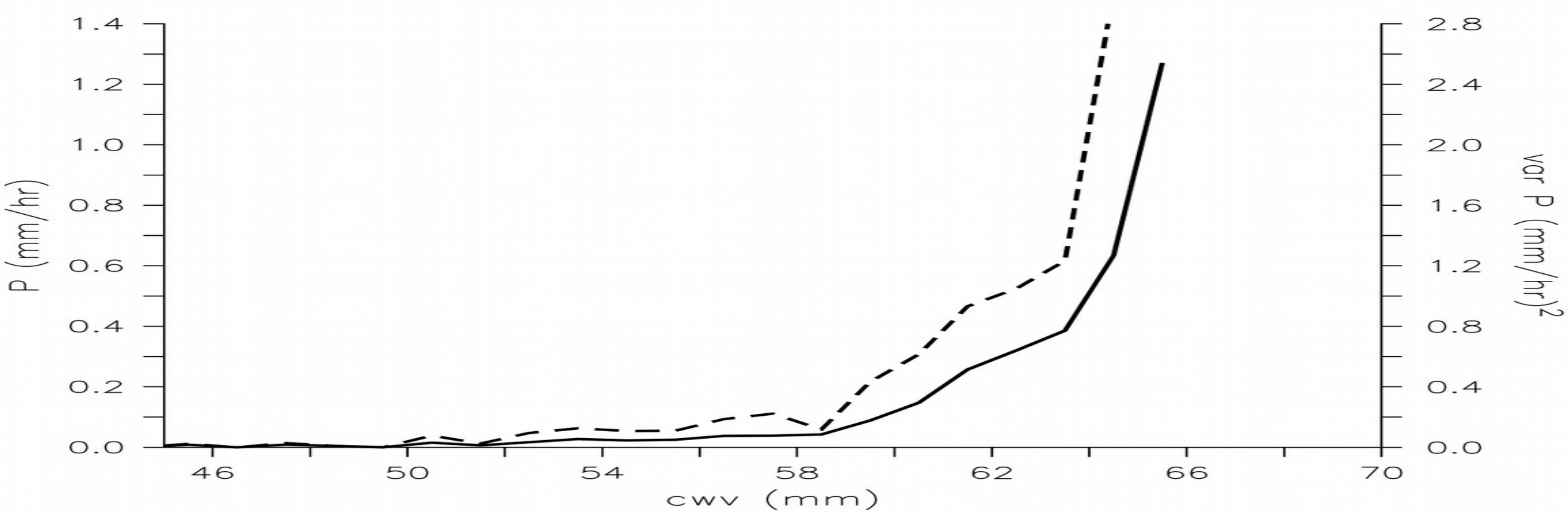


Criticisms of SOC (Gilmore 2015)
(Radiometers/Satellite Precipitation Platforms are Problematic)
Precipitation Rate-w (i.e., PWV) Relationship (His Figure 2)



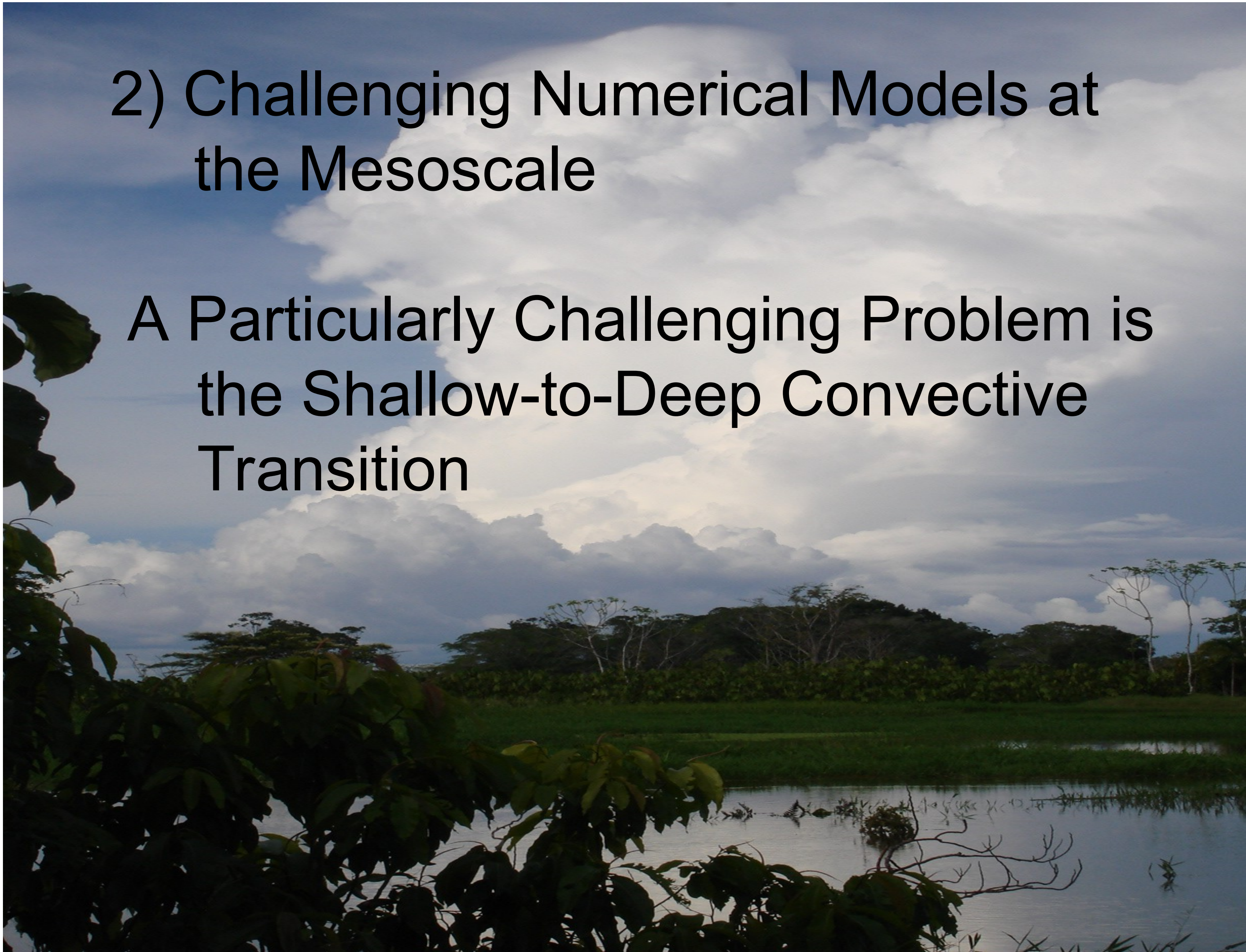
What do the 3.5 years GPS PWV data from INPA say about SOC?

- **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. However, Vaisala Met. Pack does not capture full range.**



2) Challenging Numerical Models at the Mesoscale

A Particularly Challenging Problem is the Shallow-to-Deep Convective Transition



Our Approach for Process Oriented Studies: Water Conservation Equation

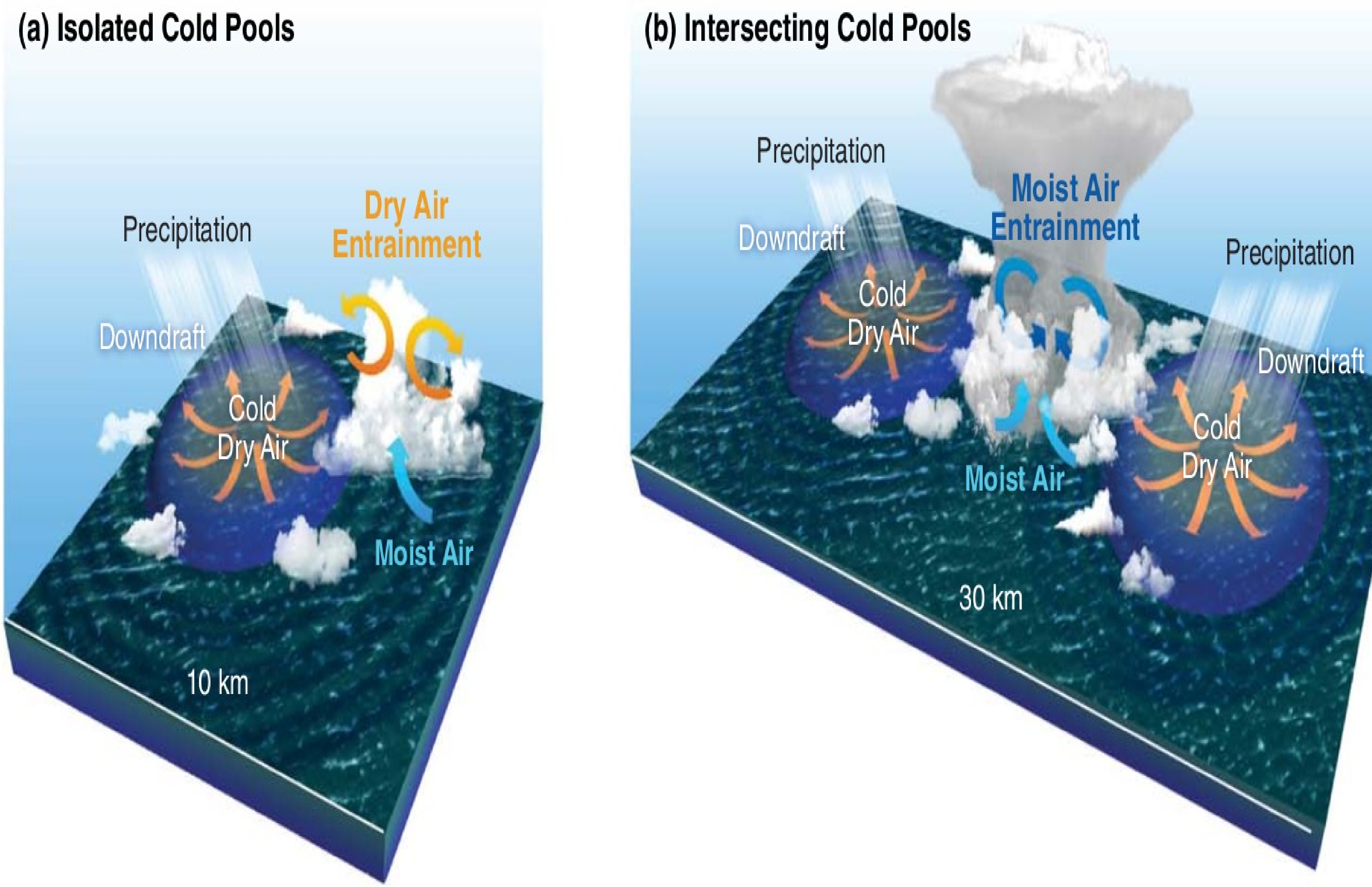
$$\frac{\partial}{\partial t}(IWV) + \frac{\partial}{\partial t}\int q_c \frac{dp}{g} + \nabla \cdot \int q\vec{V}\frac{dp}{g} = E - P.$$

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

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

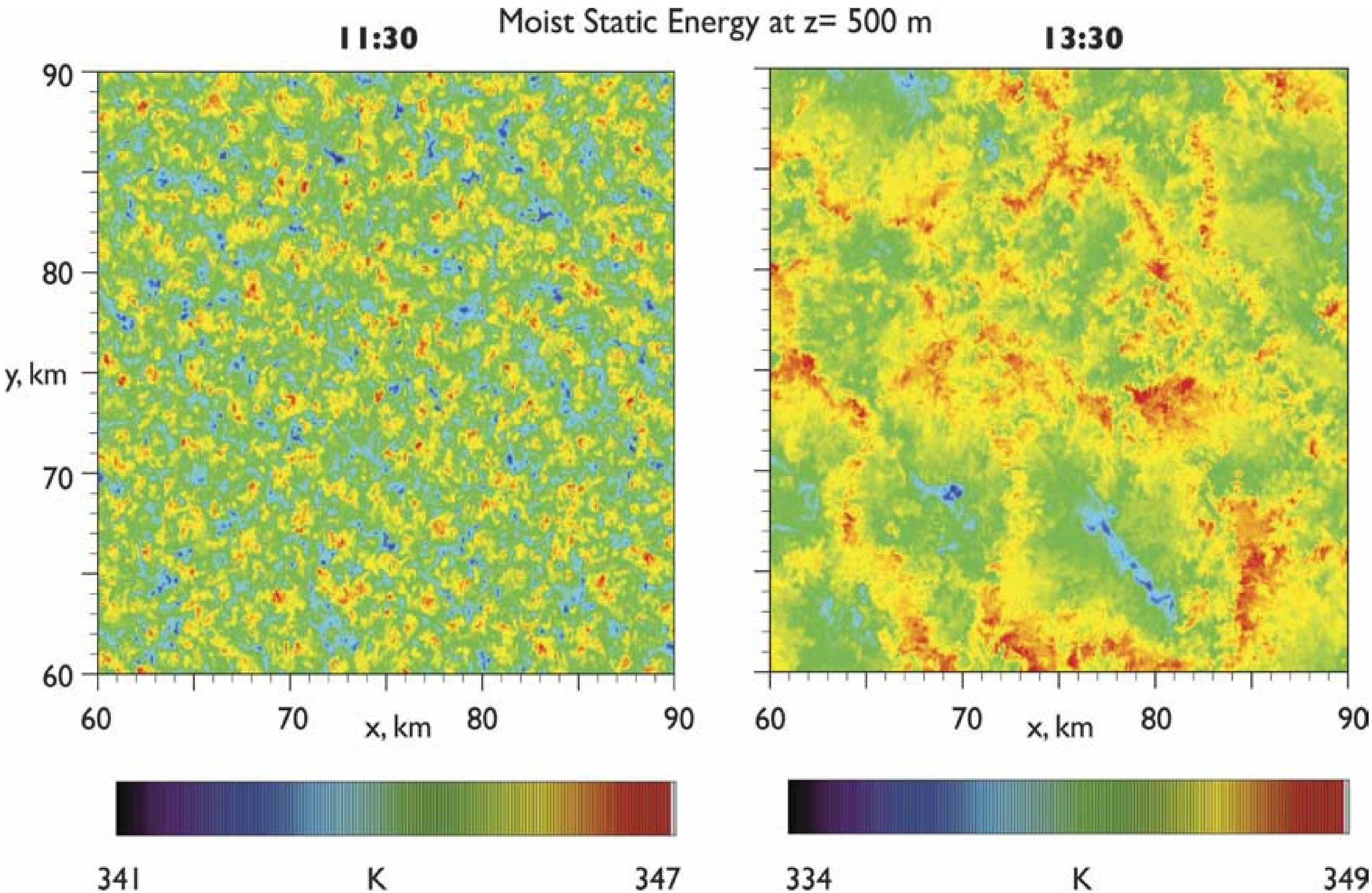
To first order, the time-rate-of-change of PWV is simply moisture flux convergence:

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

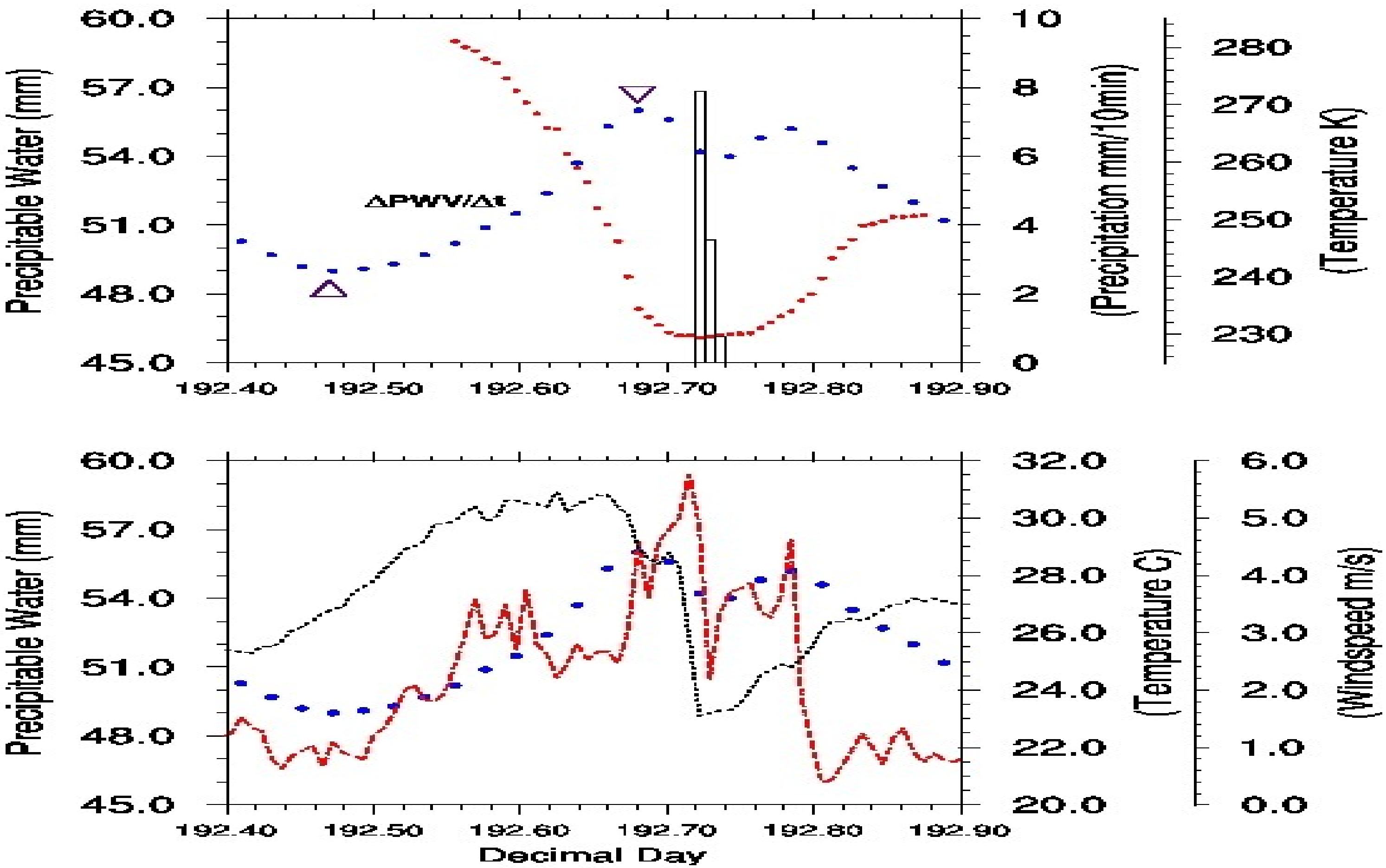


(a) Isolated Cold Pools
Precipitation
Dry Air
Entrainment
Downdraft
Cold
Dry Air
Moist Air
10 km
(b) Intersecting Cold Pools
Precipitation
Moist Air
Entrainment
Downdraft
Cold
Dry Air
Precipitation
Downdraft
Cold
Dry Air
Moist Air
30 km

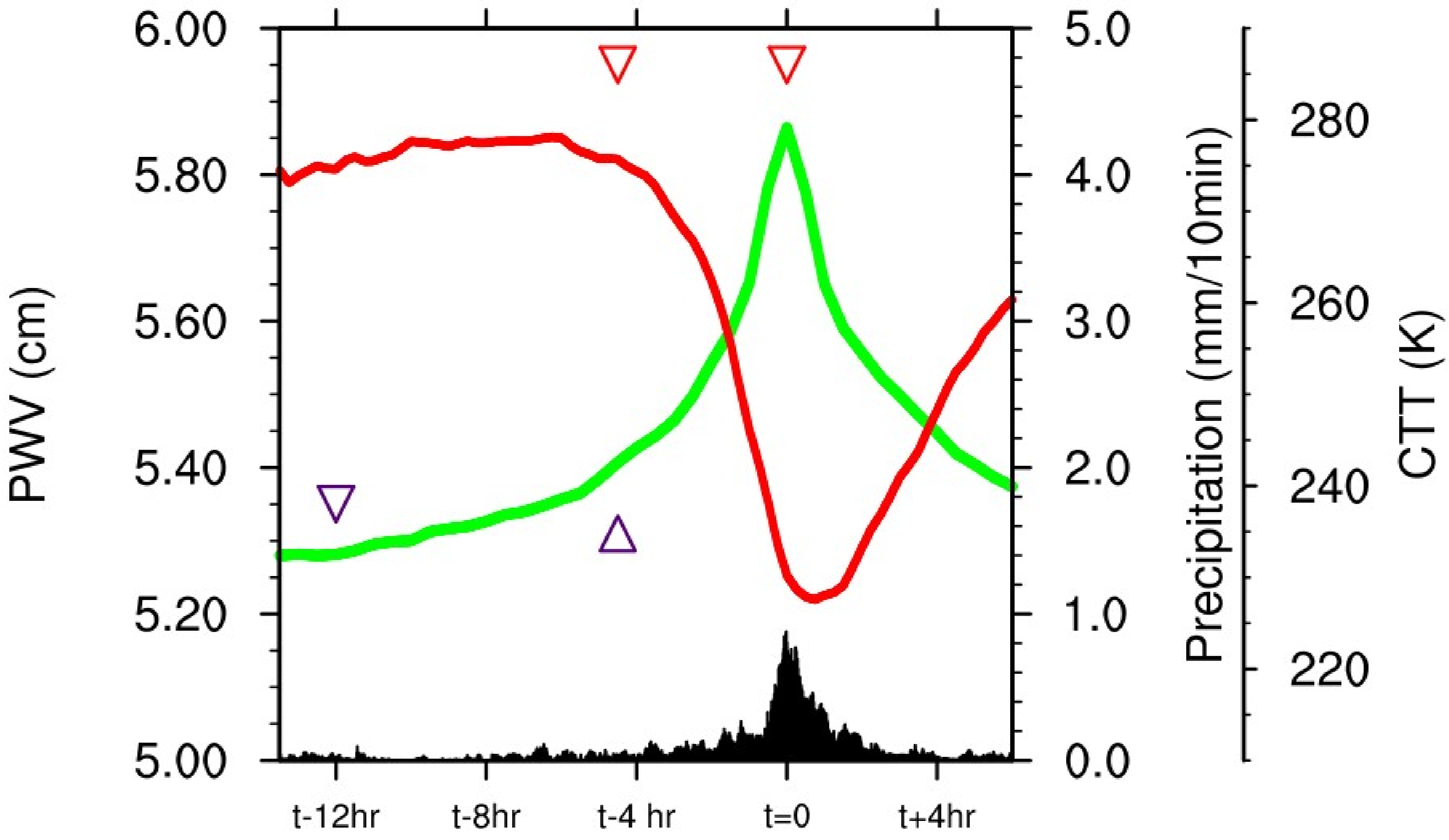
Cold Pools may play a dominant role in organization of convection in the central Amazon (Khairoutdinov and Randall 2006)



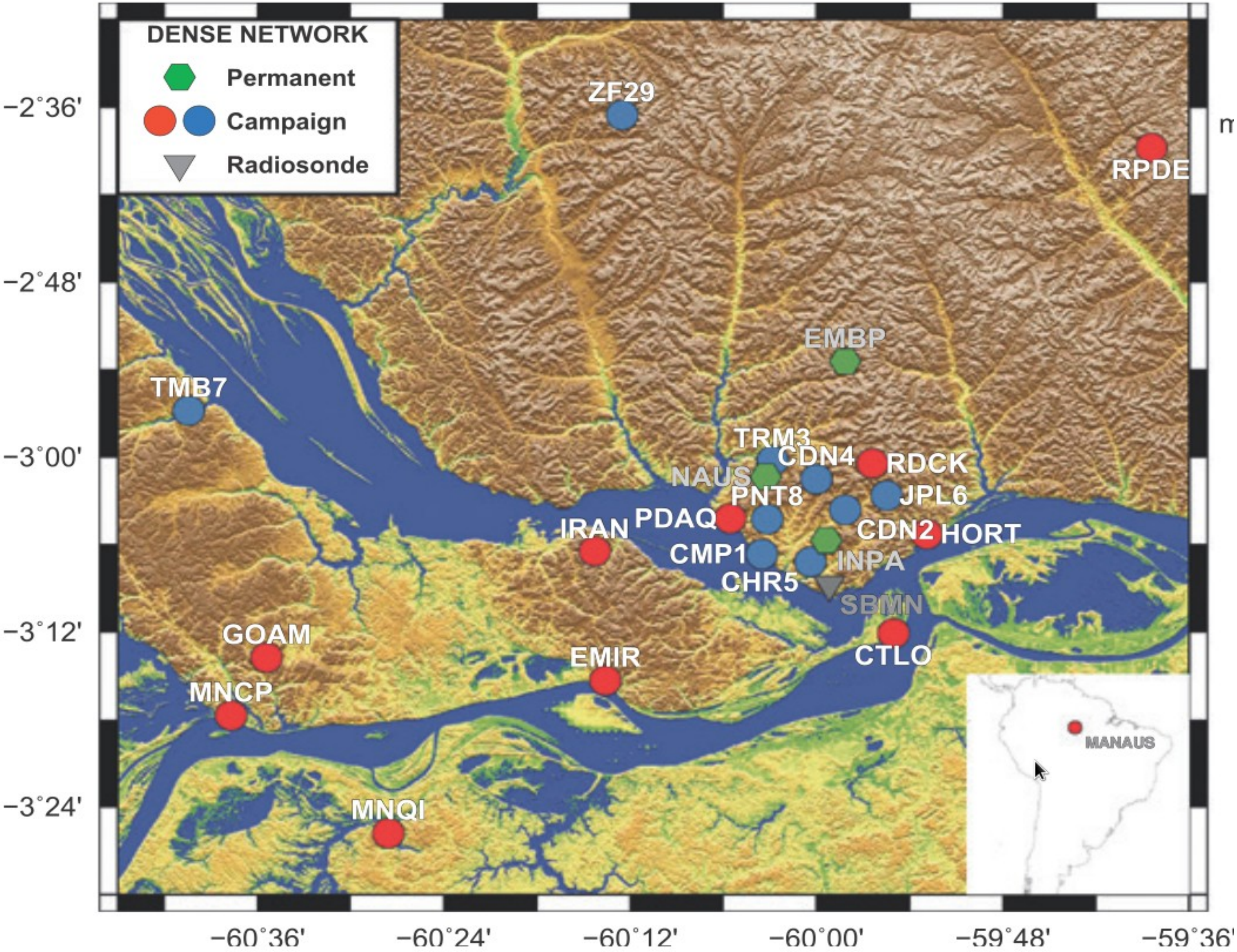
GPS Met at INPA (Central Amazon)
Observation ofConvective Event with Downdraft



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

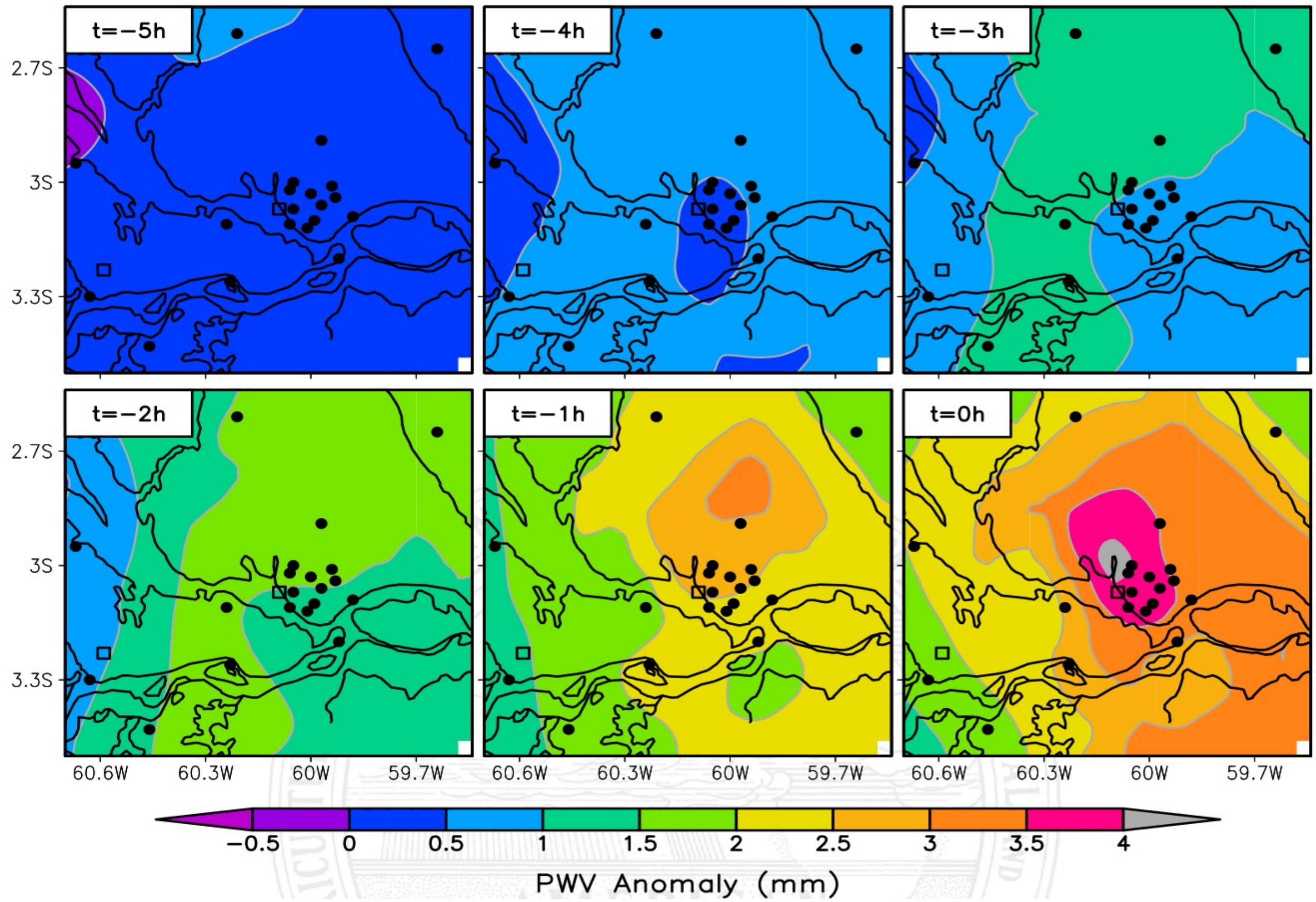


Spatial Behaviour Dense GPS Meteorological Network in Manaus (2011-2012)
Adams et al. 2015 (BAMS)



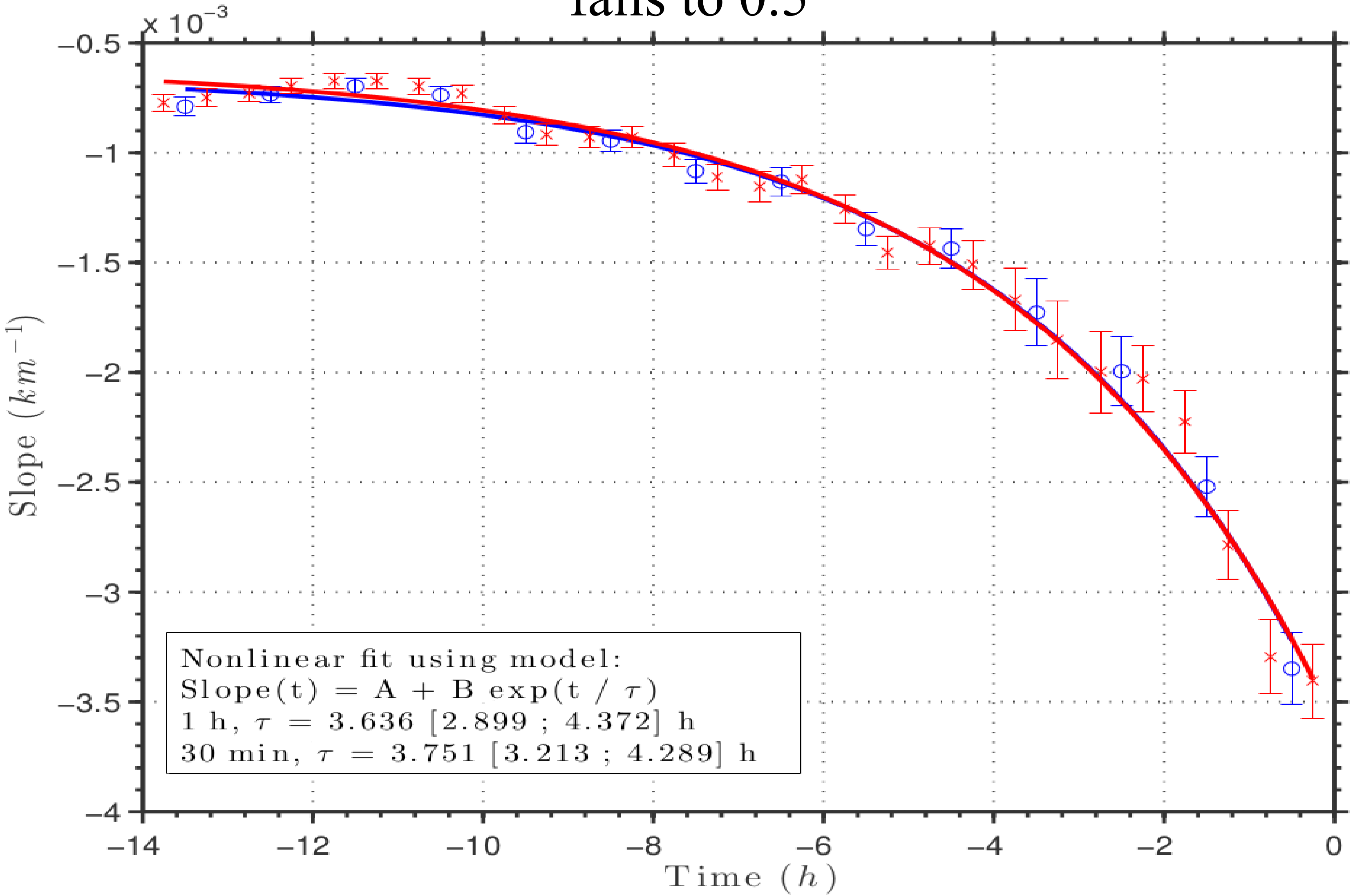
But what spatial scale of PWV should we expect during the STD Transition? Adams et al. 2017 (MWR)

A spatial decorrelation timescale was calculated for 67 convective events



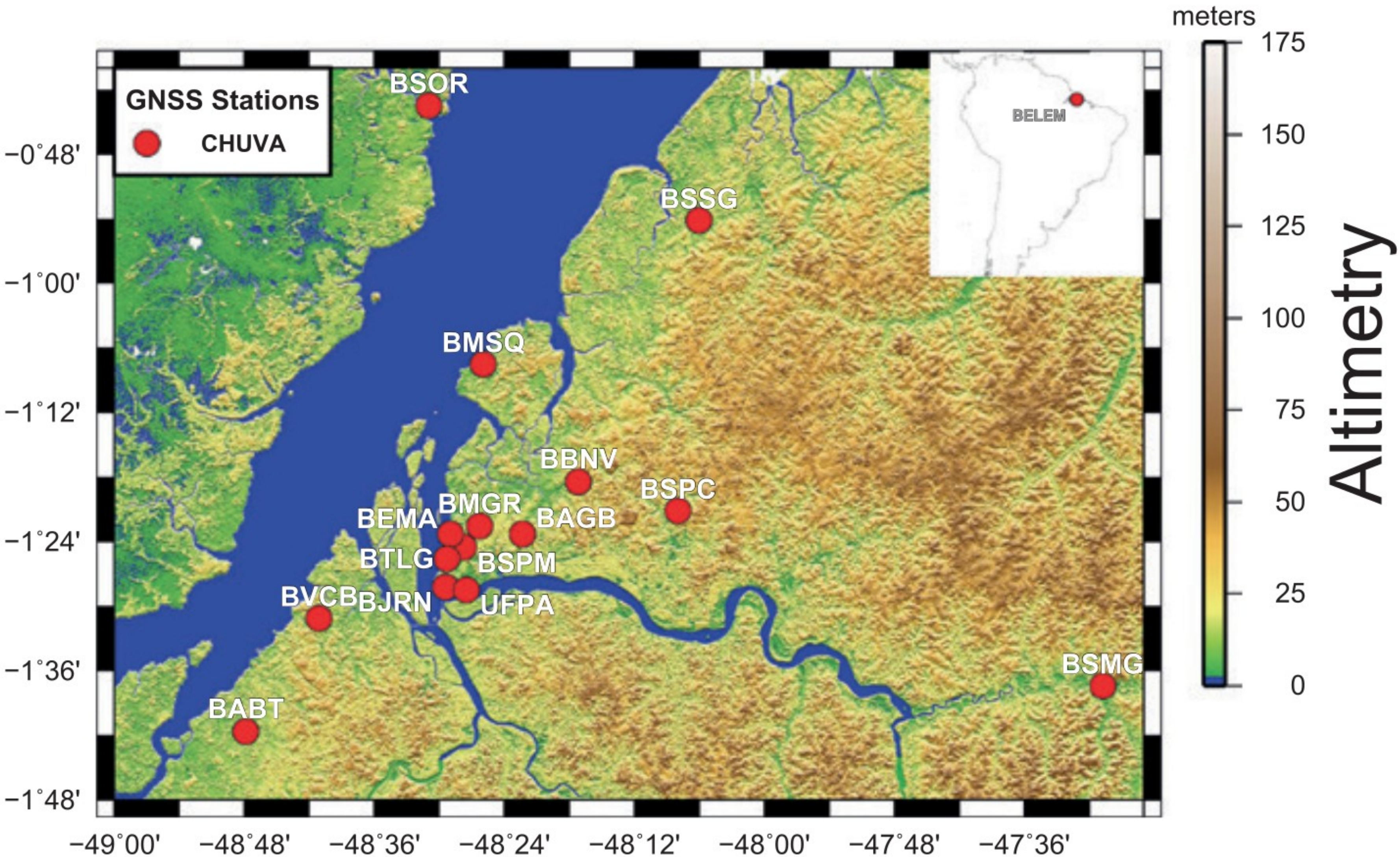
Decorrelation Timescale of 3.5 hours during Shallow-to-Deep Convective Transition

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

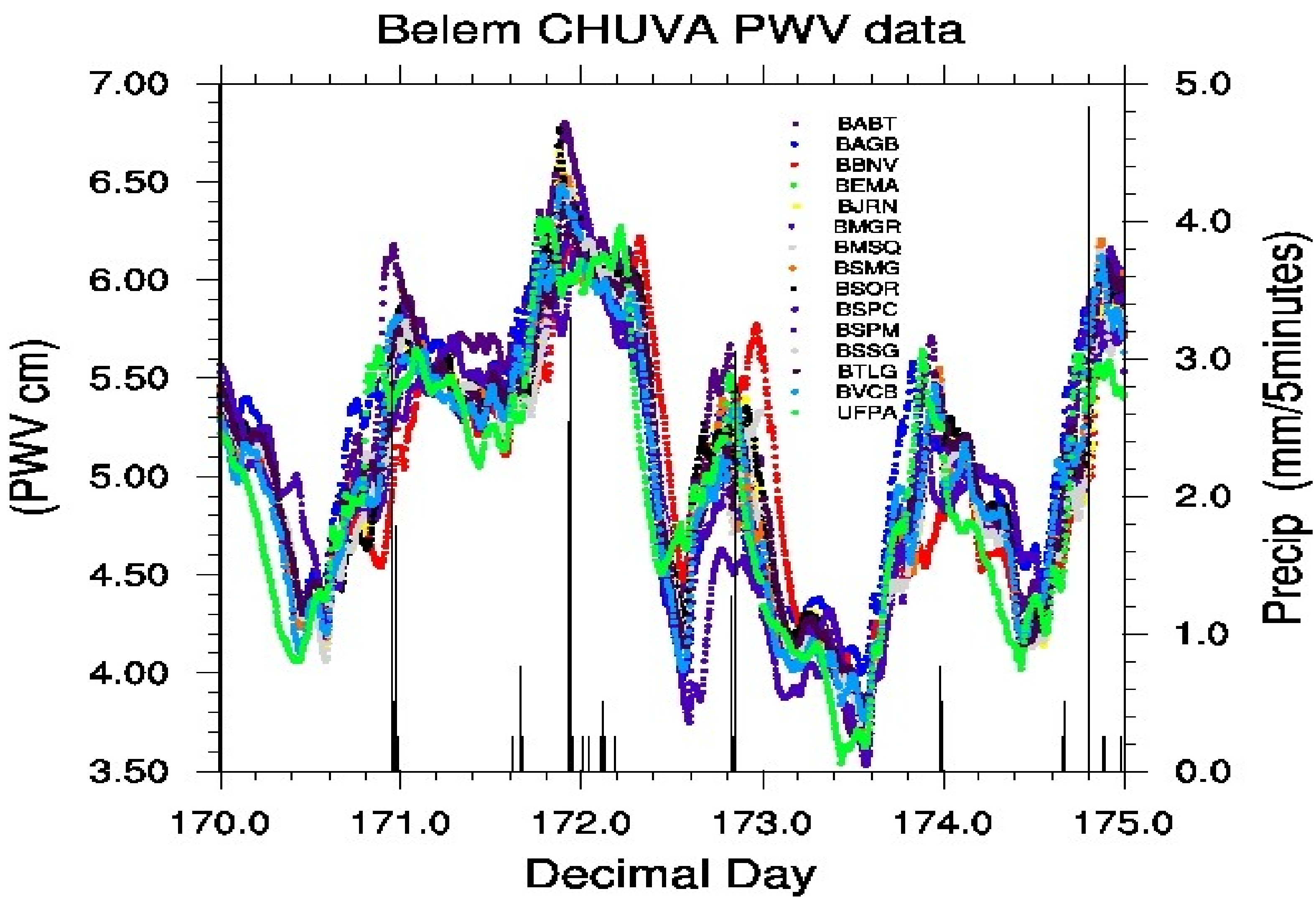


Amazon Dense GNSS Meteorological Network
(Belem *Global Precipitation Measurement* CHUVA)
(Adams et al. 2015 BAMS, Machado et al. 2014 BAMS)

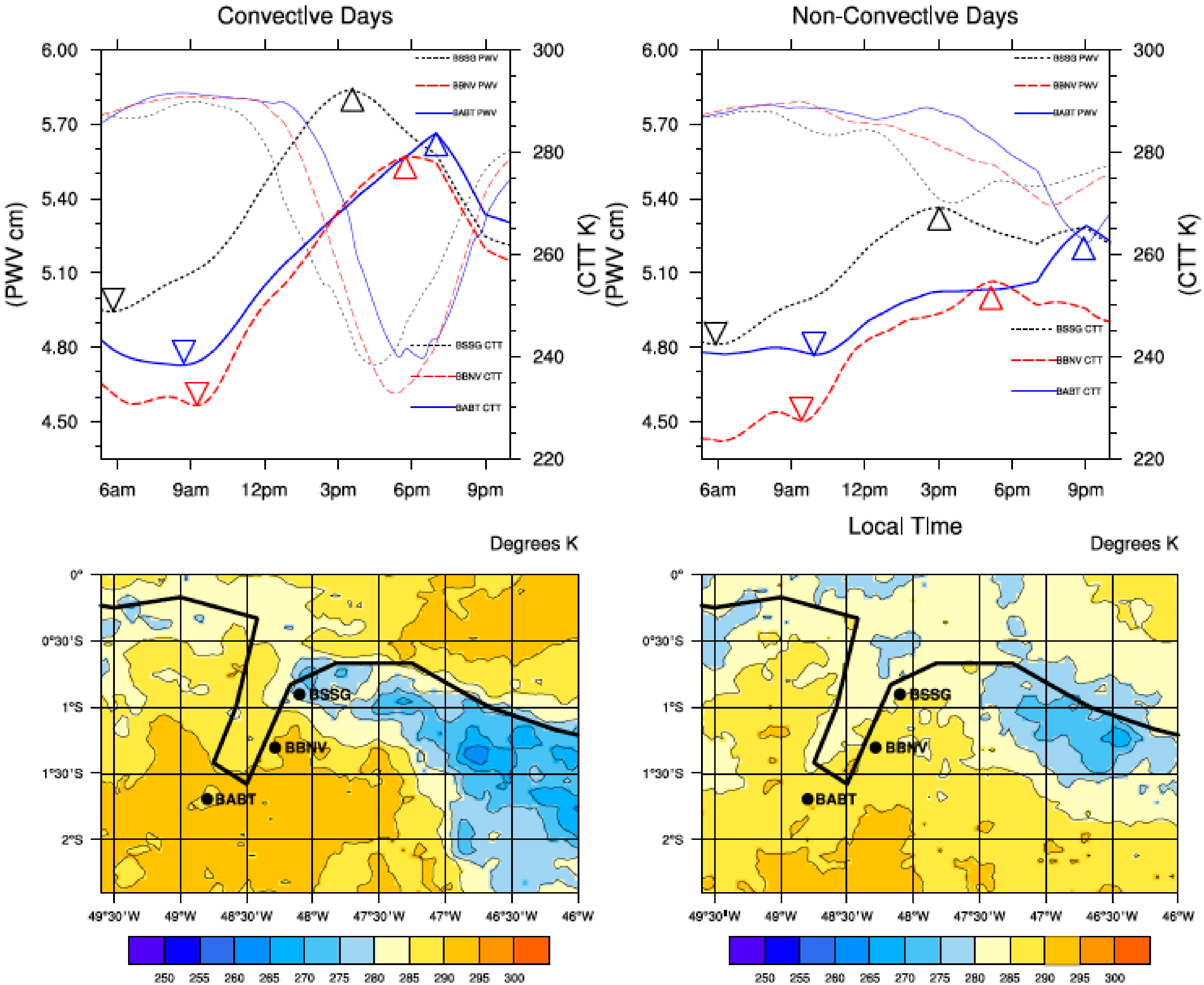
Tropical Sea Breeze Regime Convection



Large-Scale/Mesoscale Sea-Breeze Convection Belem
"Should we meet before or after the rain"



A Squall Line Entering Belem from the Atlantic Coast

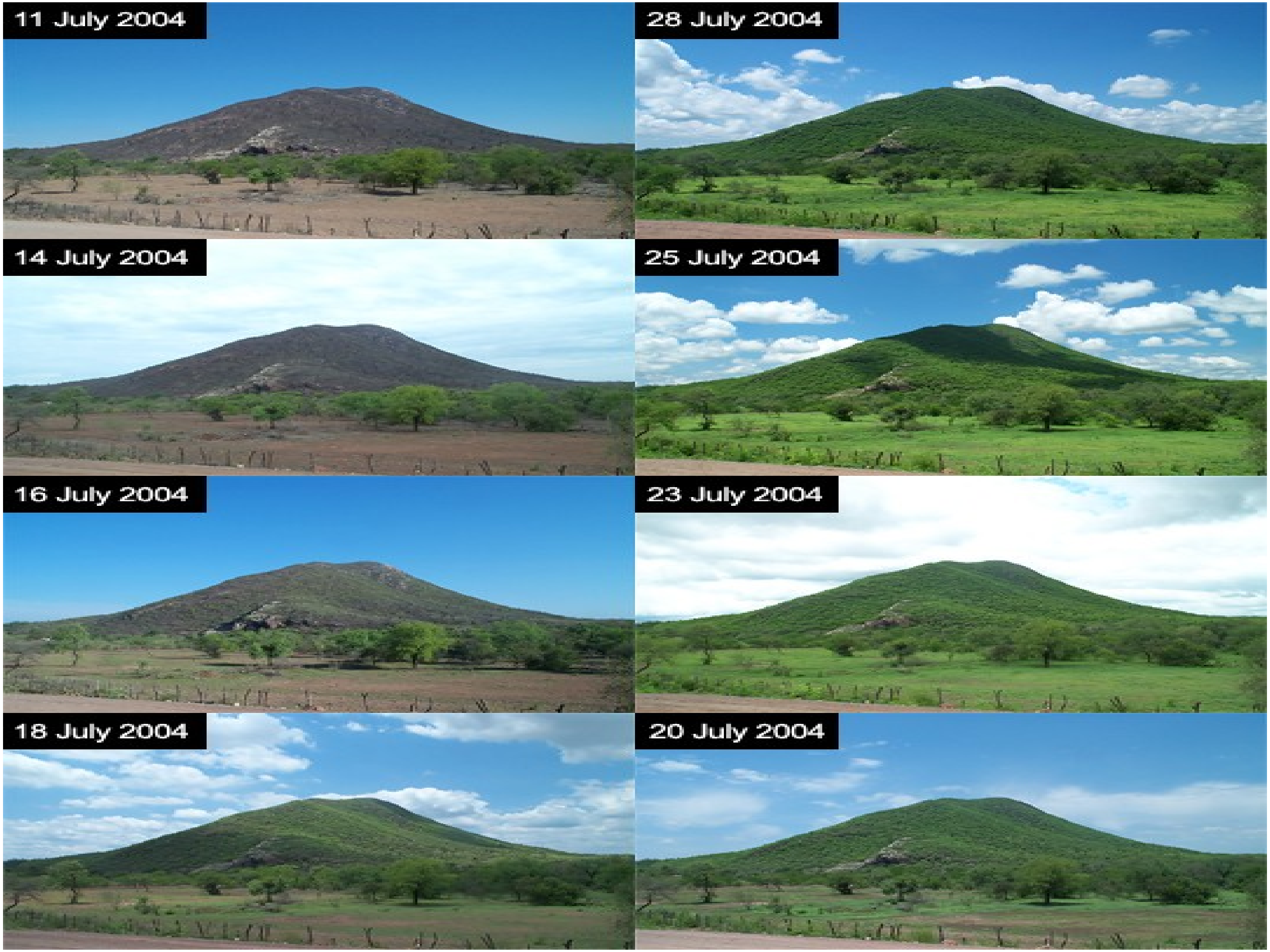


Convective Days
Non-Convective Days
(PWV cm)
(CTT K)
6am
9am
12pm
3pm
6pm
9pm
Local Time
BSSG PWV
BBNV PWV
BABT PWV
BSSG CTT
BBNV CTT
BABT CTT
Degrees K
BSSG
BBNV
BABT
0°
0°30'S
1°S
1°30'S
2°S
49°30'W
49°W
48°30'W
48°W
47°30'W
47°W
46°30'W
46°W
250
255
260
265
270
275
280
285
290
295
300

3) Water Vapor Transport and Land-Atmosphere Interactions

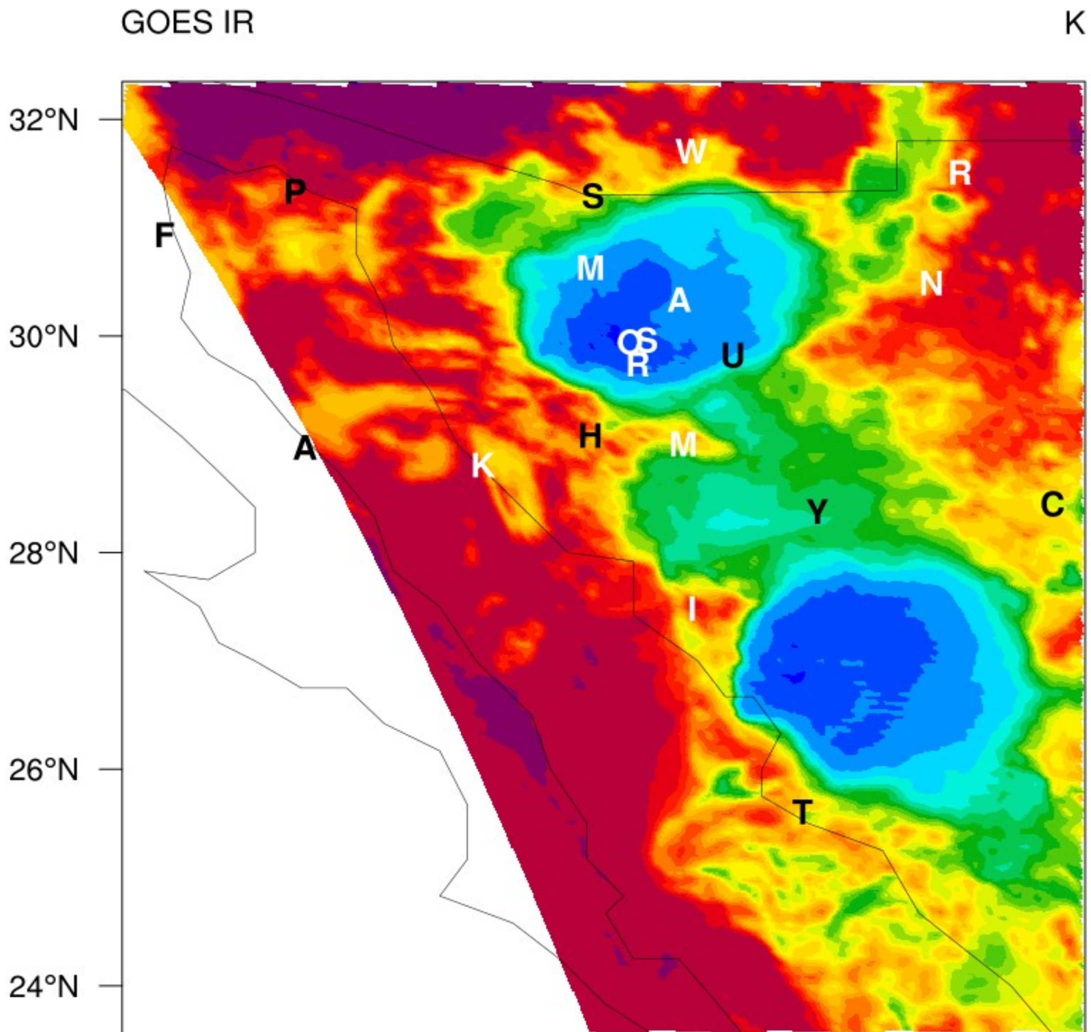
The North American Monsoon GPS Hydromet Network 2017

Moisture Recycling and Green Up NW Mexico

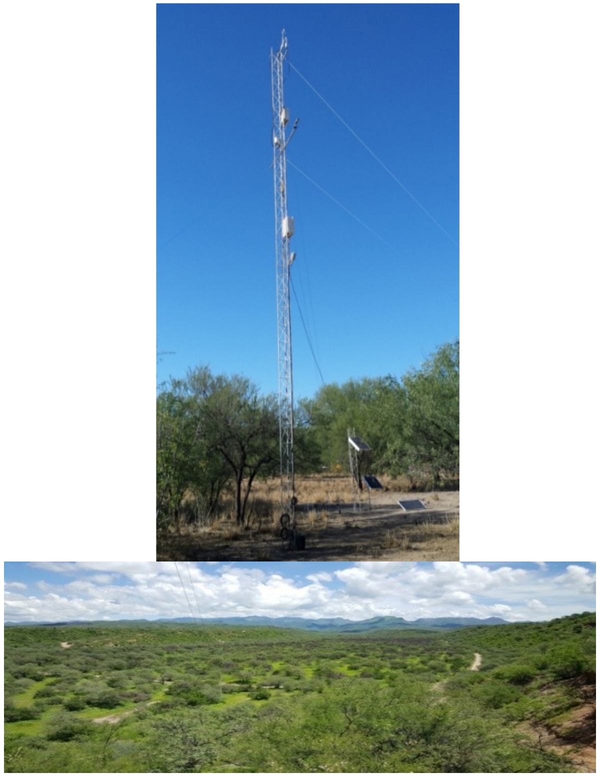


NAM GPS Hydromet Network 2017
(Connecting Surface Fluxes to the Atmosphere)

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

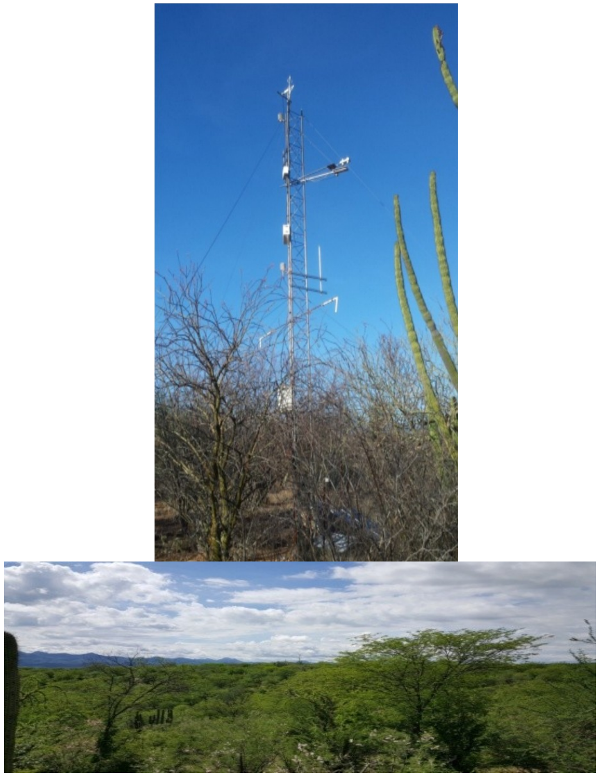


ASU and UNISON
Triangular Network of Water Vapor, Heat and C02 Fluxes



Mesquite Trees in Valley Bottom

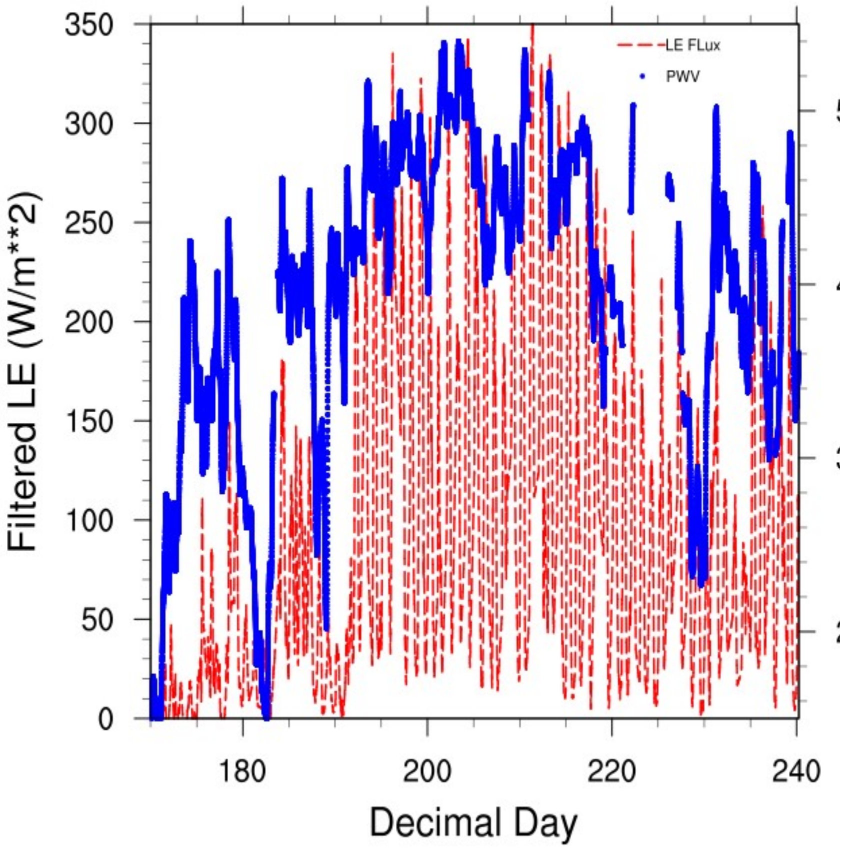
Oak Savanna at Mountain Top

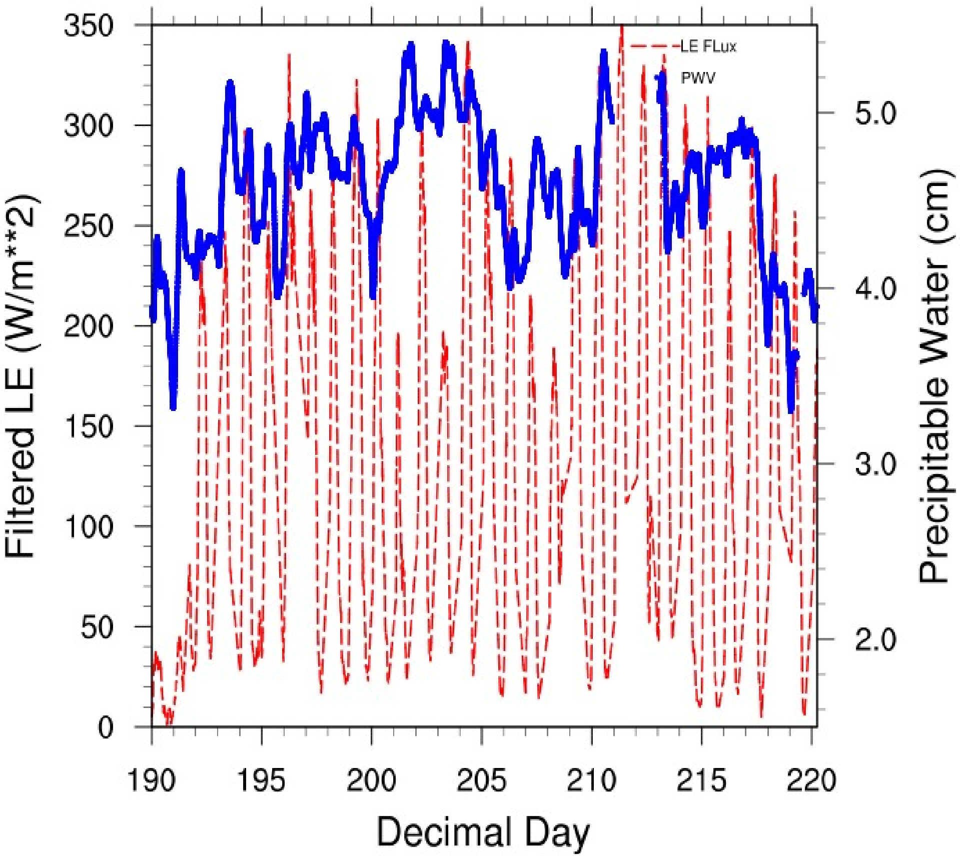


Subtropical Scrubland in Alluvial Fan

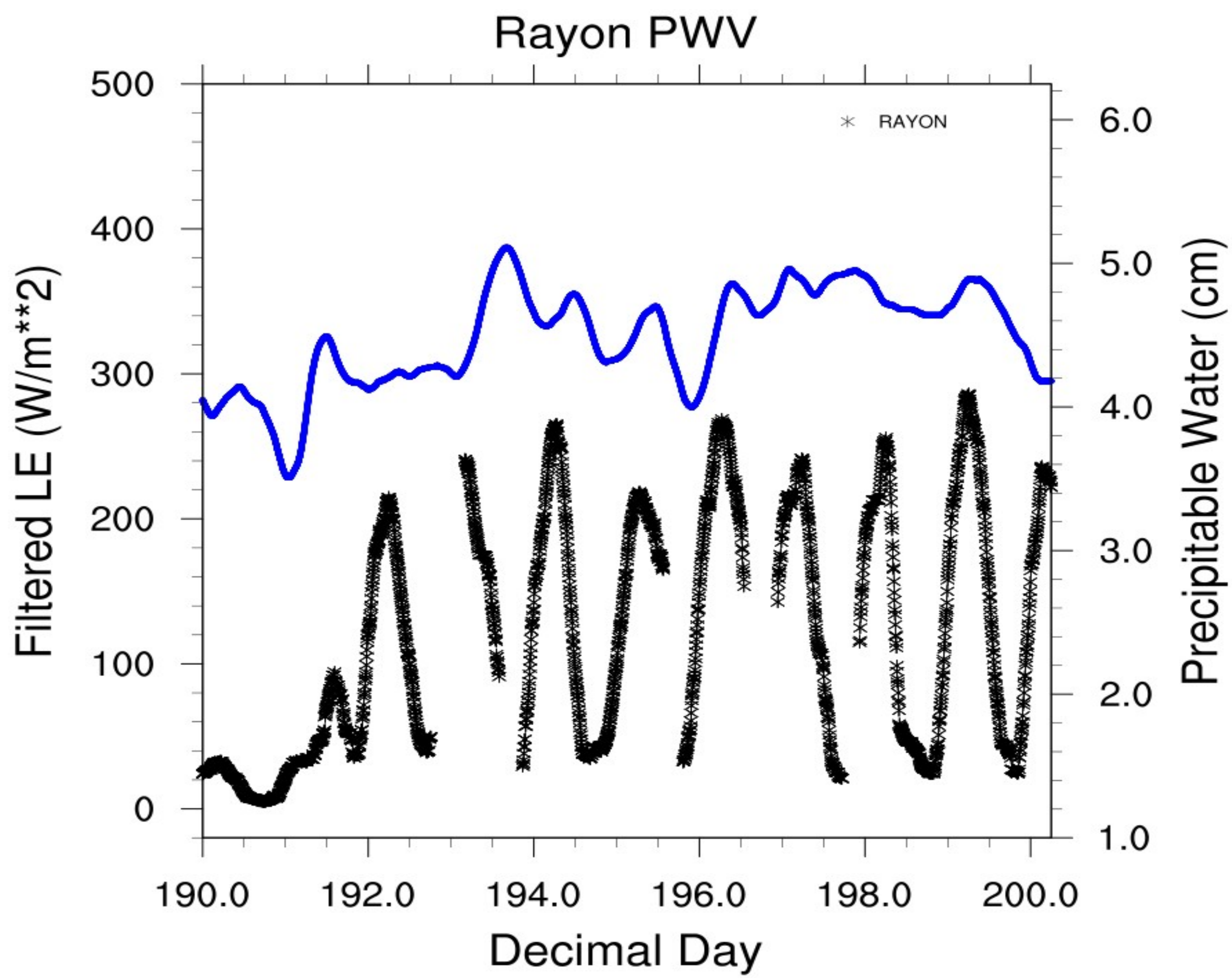
Eddy Covariance Method for Turbulent Flux Measurements in Ecosystems

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

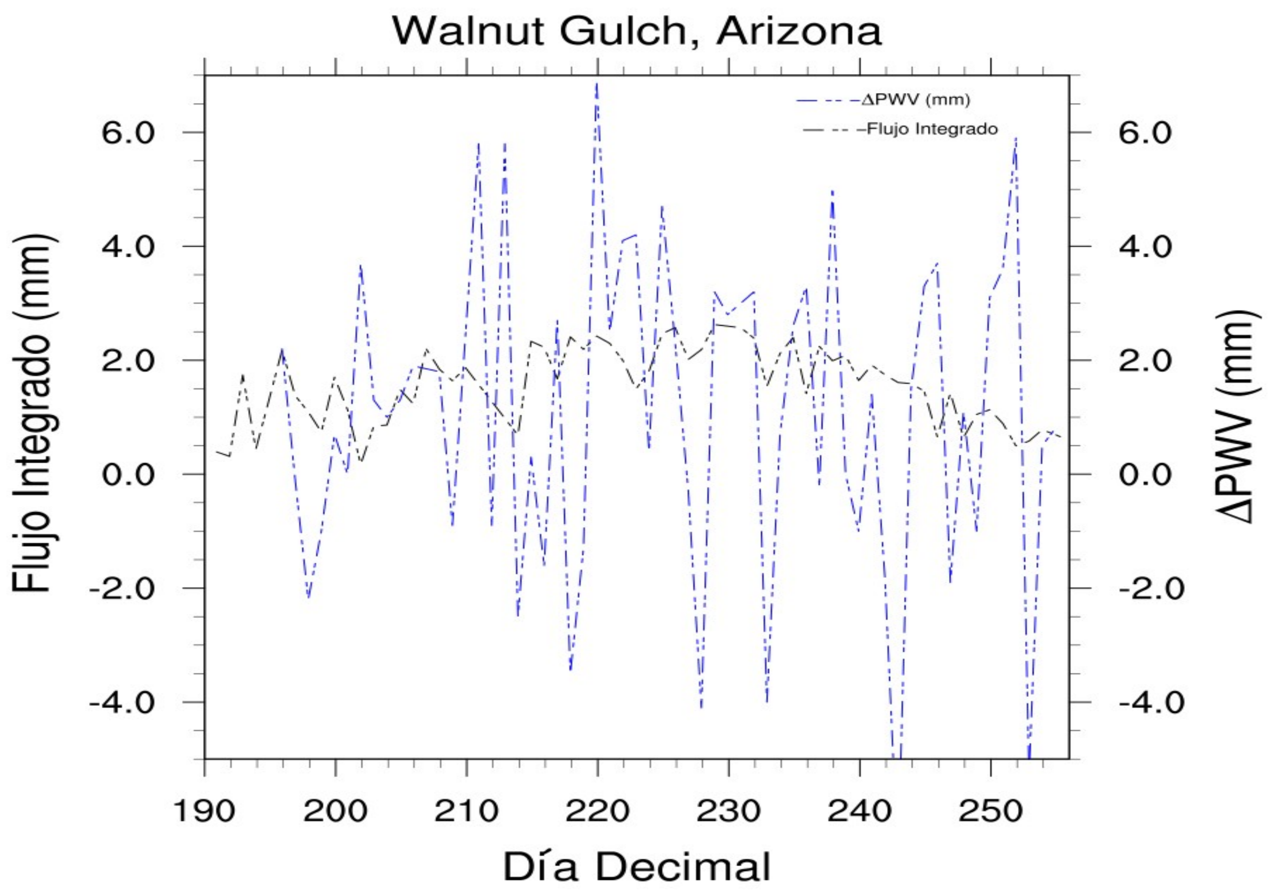




At Higher Temporal Resolution (LH Flux and PWV),



Over Entire Experiment WV Flux Contribution to PWV
Walnut Gulch, Arizona




Thank you
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