Introdução a Física Atmosférica - PGF-3521
Aula 4 – Water vapor transport in South America

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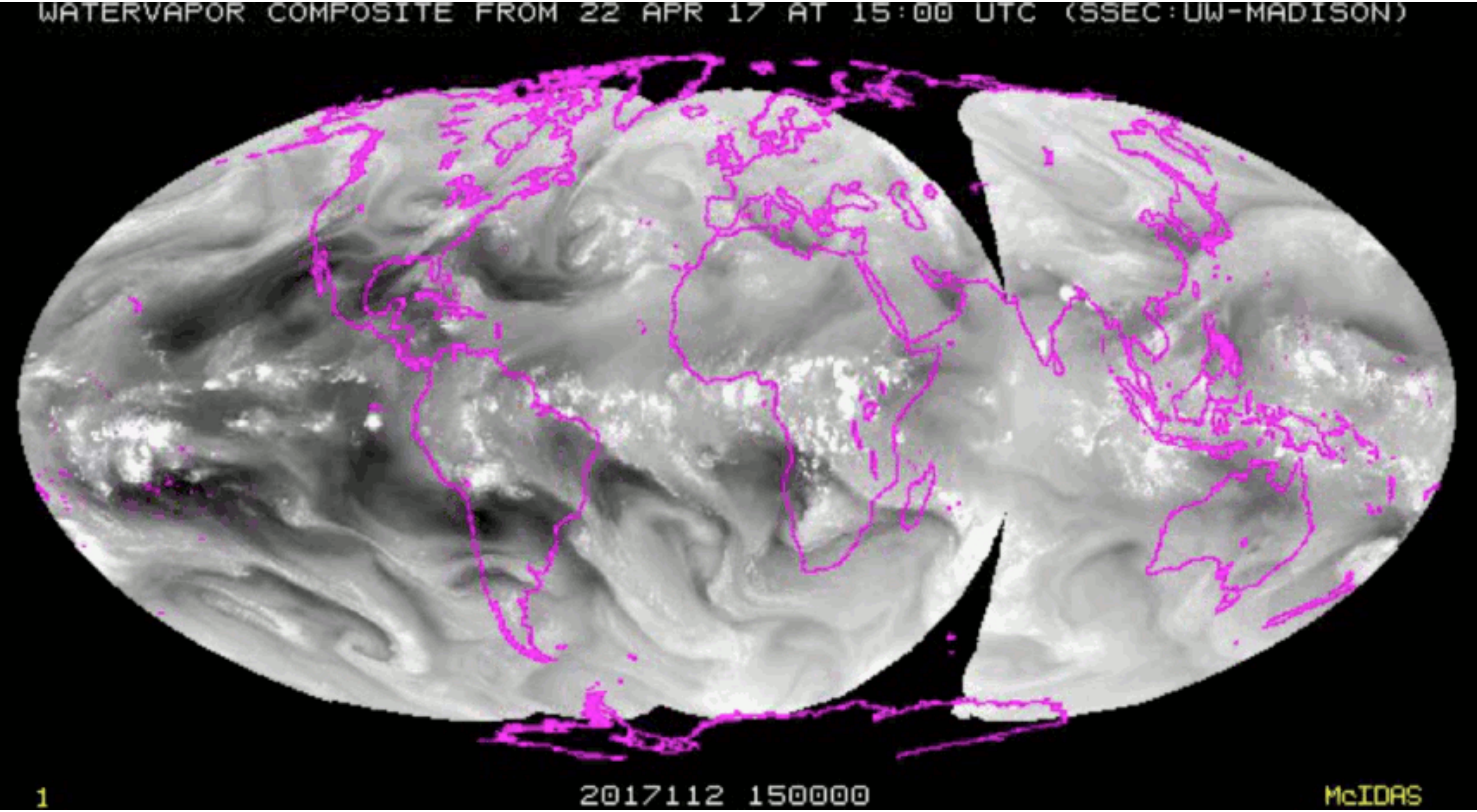
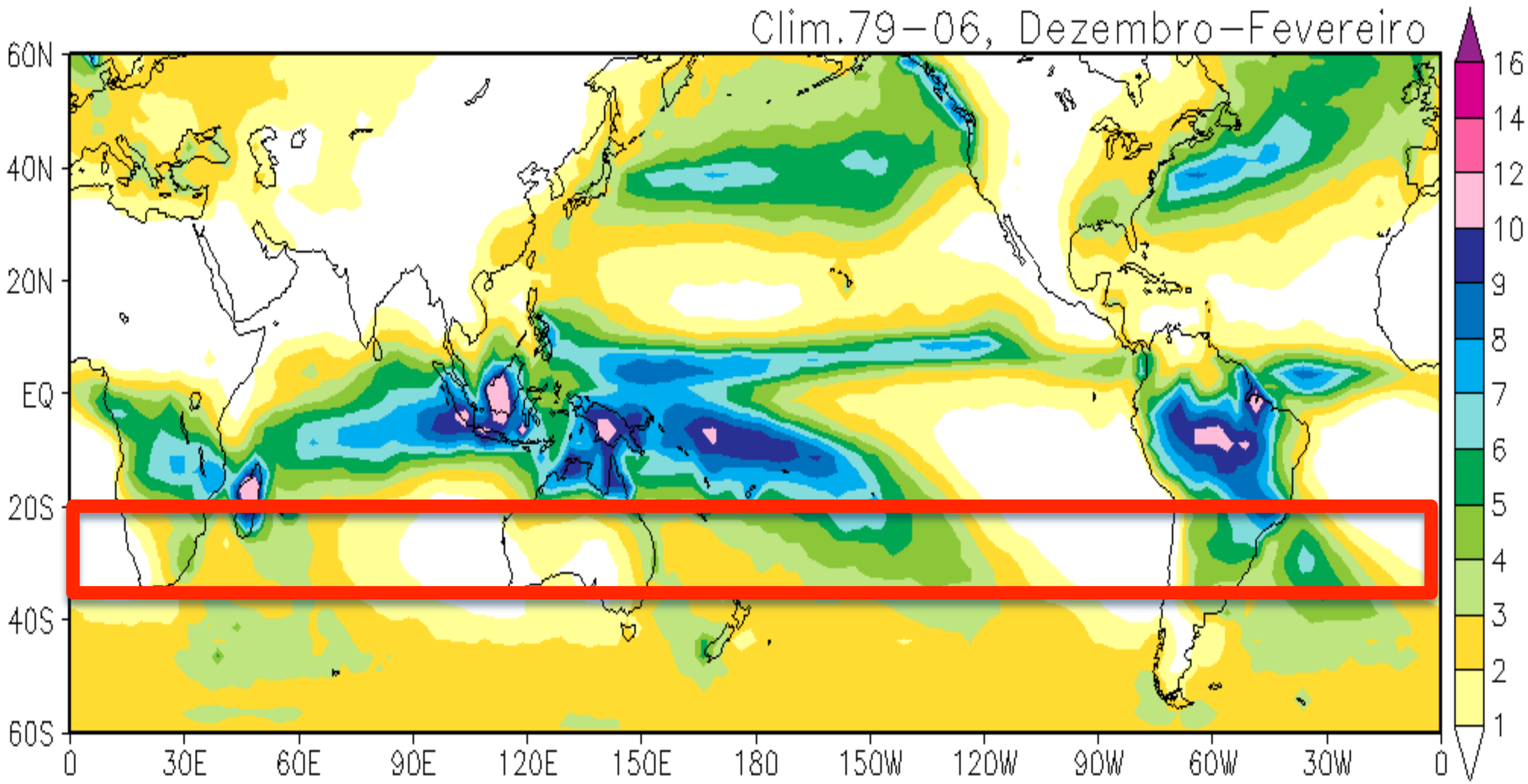
Total column water vapor



GOES, Meteosat, and MTSAT http://www.ssec.wisc.edu/data/comp/wvmoll.html

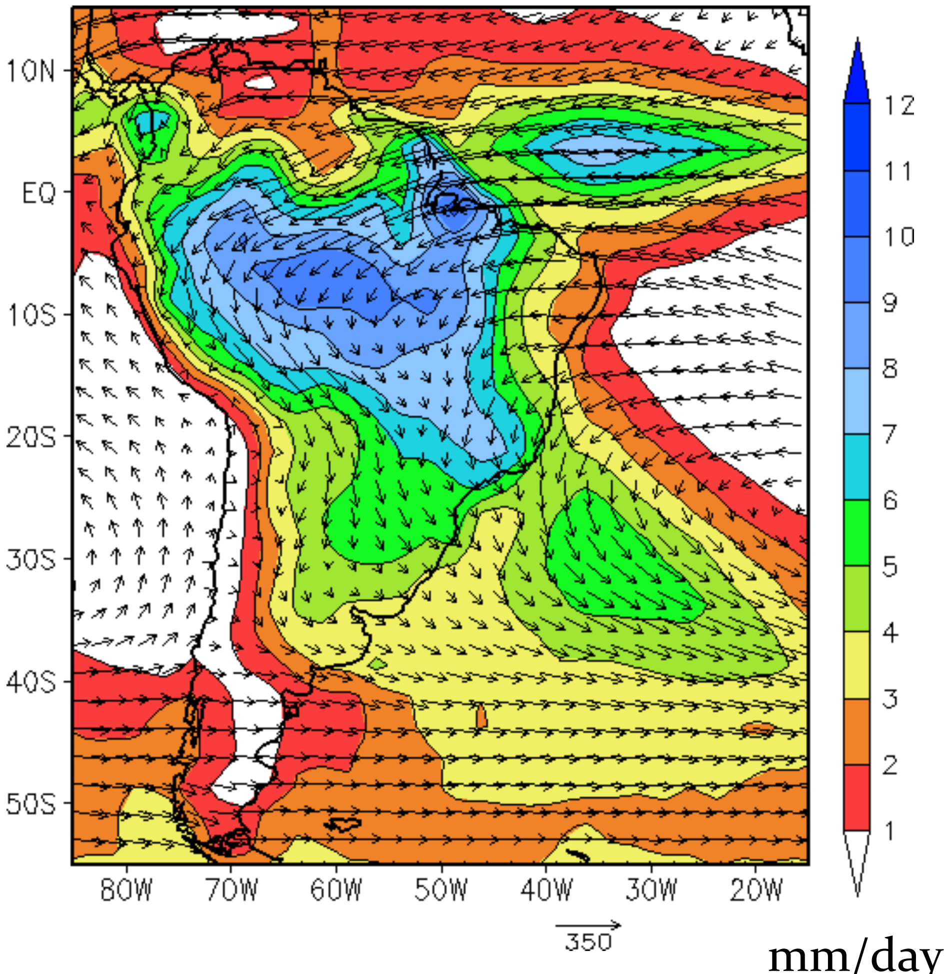
Austral Summer Precipitation 79-06



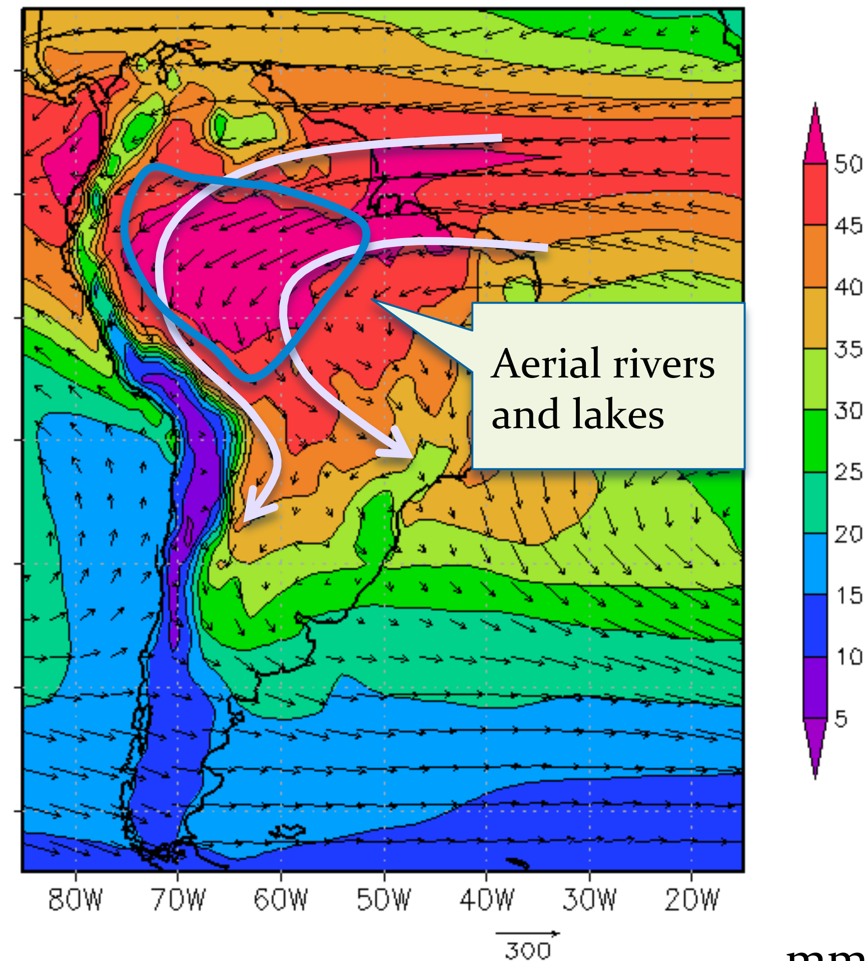
GPCP, mm/day

Precipitation, PWV and Vapor transport GPCP + ERA40 1989-2009

Nov-Mar

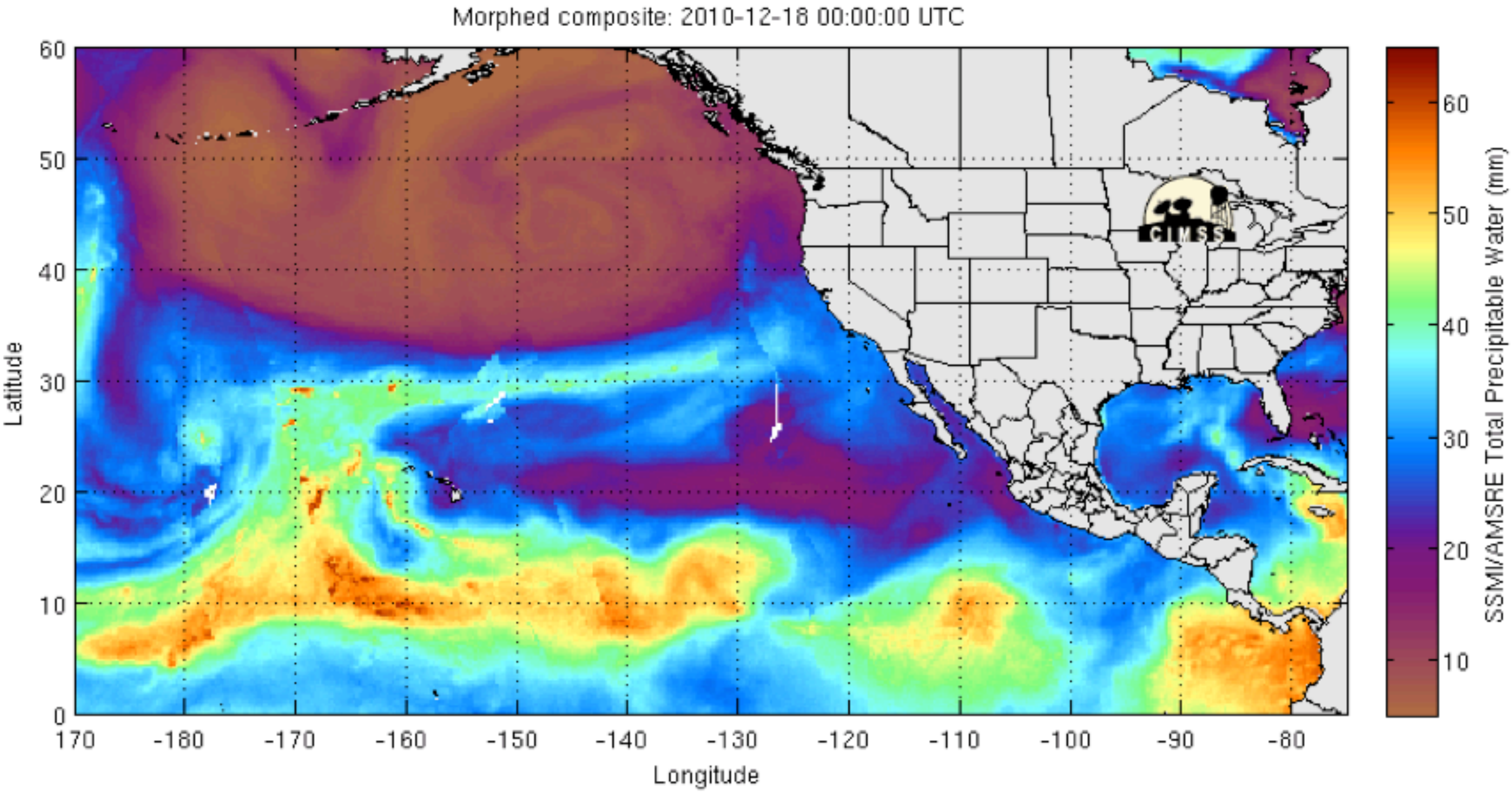


Nov-Mar



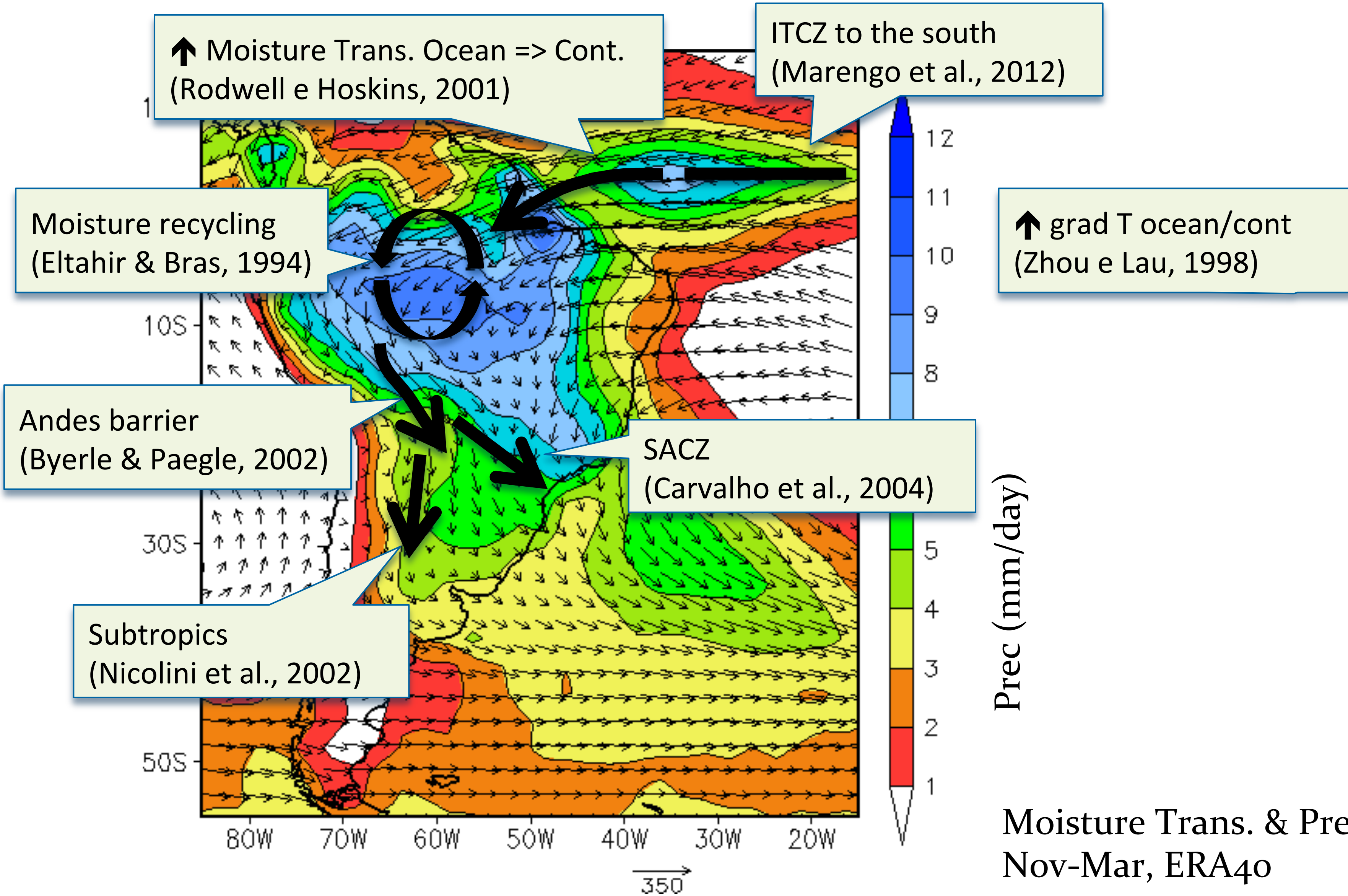
Arraut et al, J. Clim, 2012

Atmospheric Rivers



Satellite water-vapor measurements from Dec. 18, 2010, show an atmospheric river making landfall in California. Water vapor data from SSMI. Credit: Bin Guan, NASA/JPL-Caltech and UCLA.

South American Monsoon



Moisture Trans. & Precip
Nov-Mar, ERA40

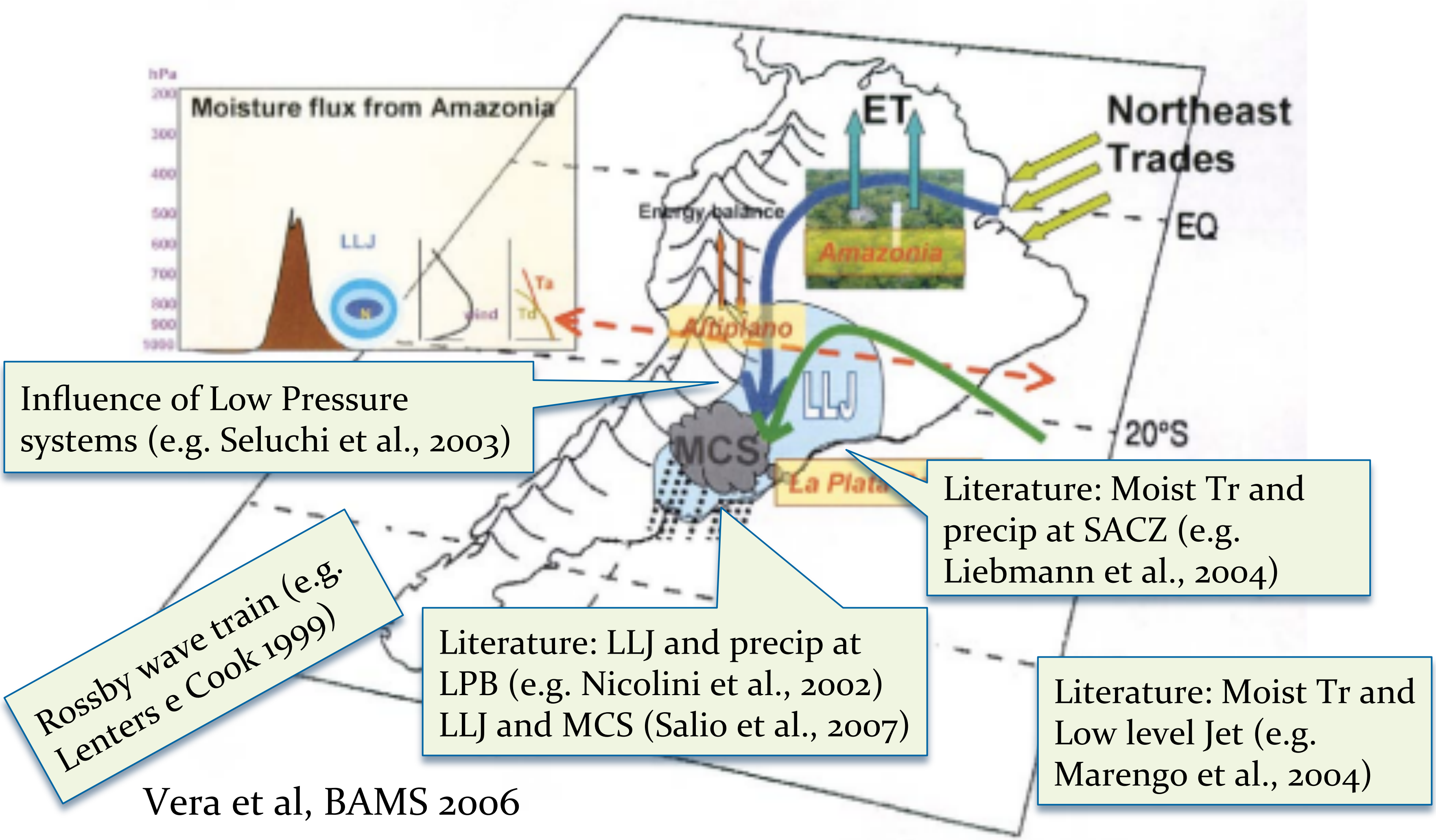
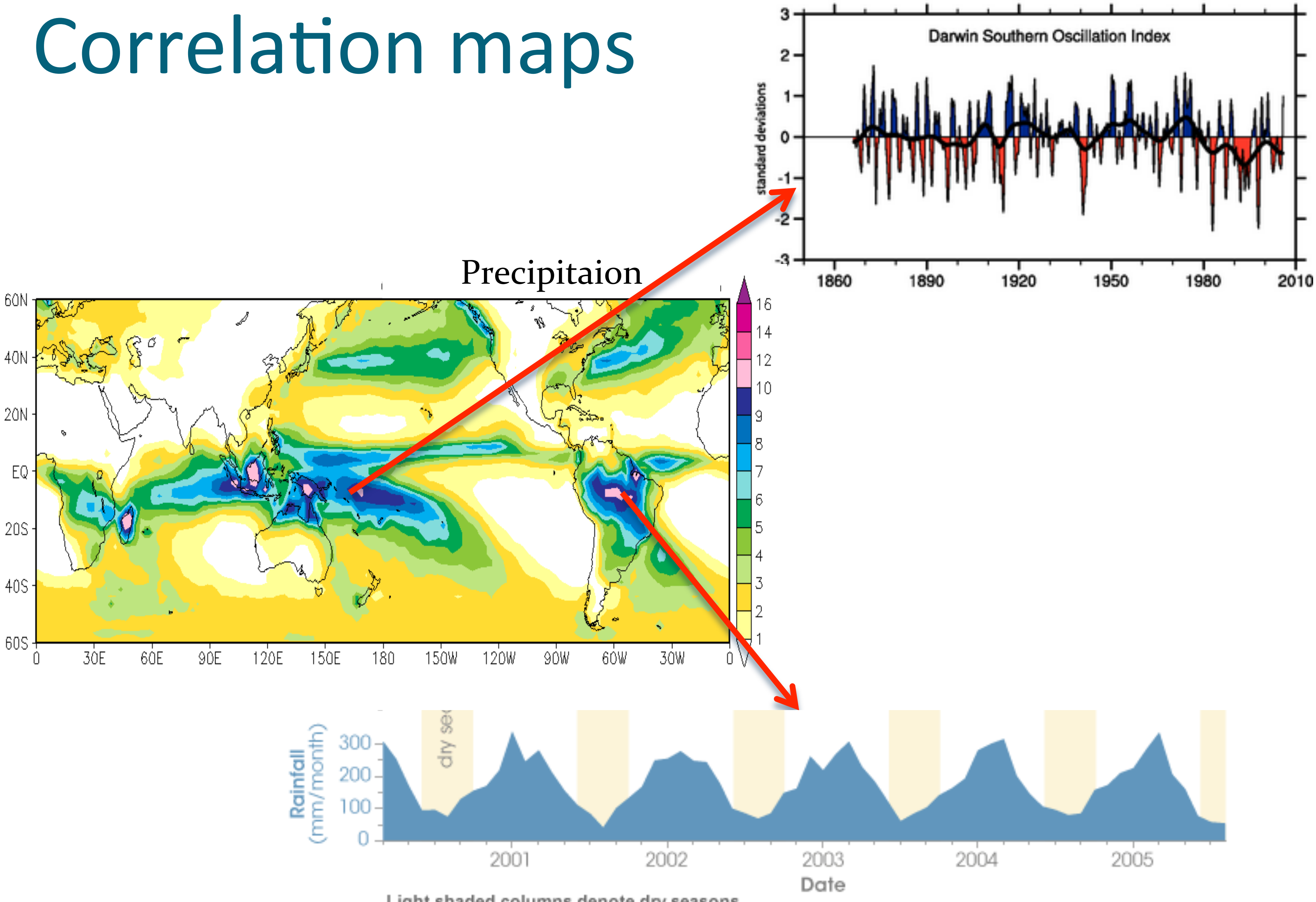


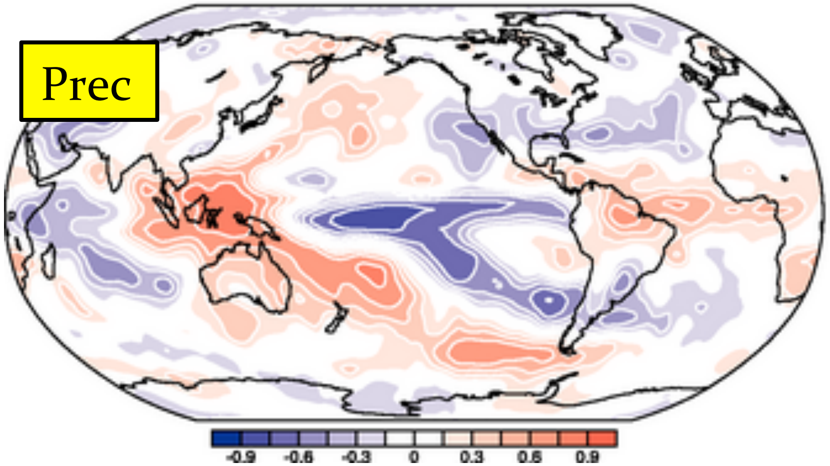
Fig. 1. Schematic diagram of elements relevant to poleward moisture transport over South America. Blue and green arrows depict the moisture transport into the continent from the tropical and South Atlantic Ocean, respectively. The inset represents a vertical cross section of the northerly flow along the red dashed line displayed in the diagram, including wind and temperature profiles representative of the LLJ core.

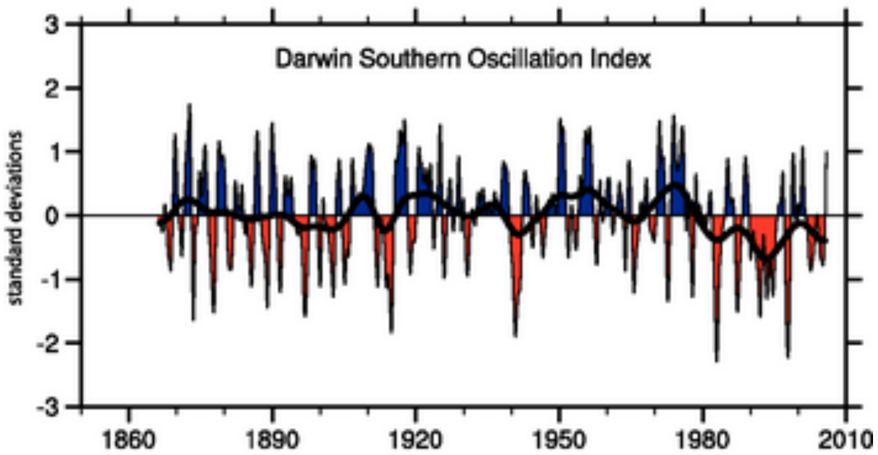
Correlation maps



NASA (Adapted from Myneni et al. 2007)

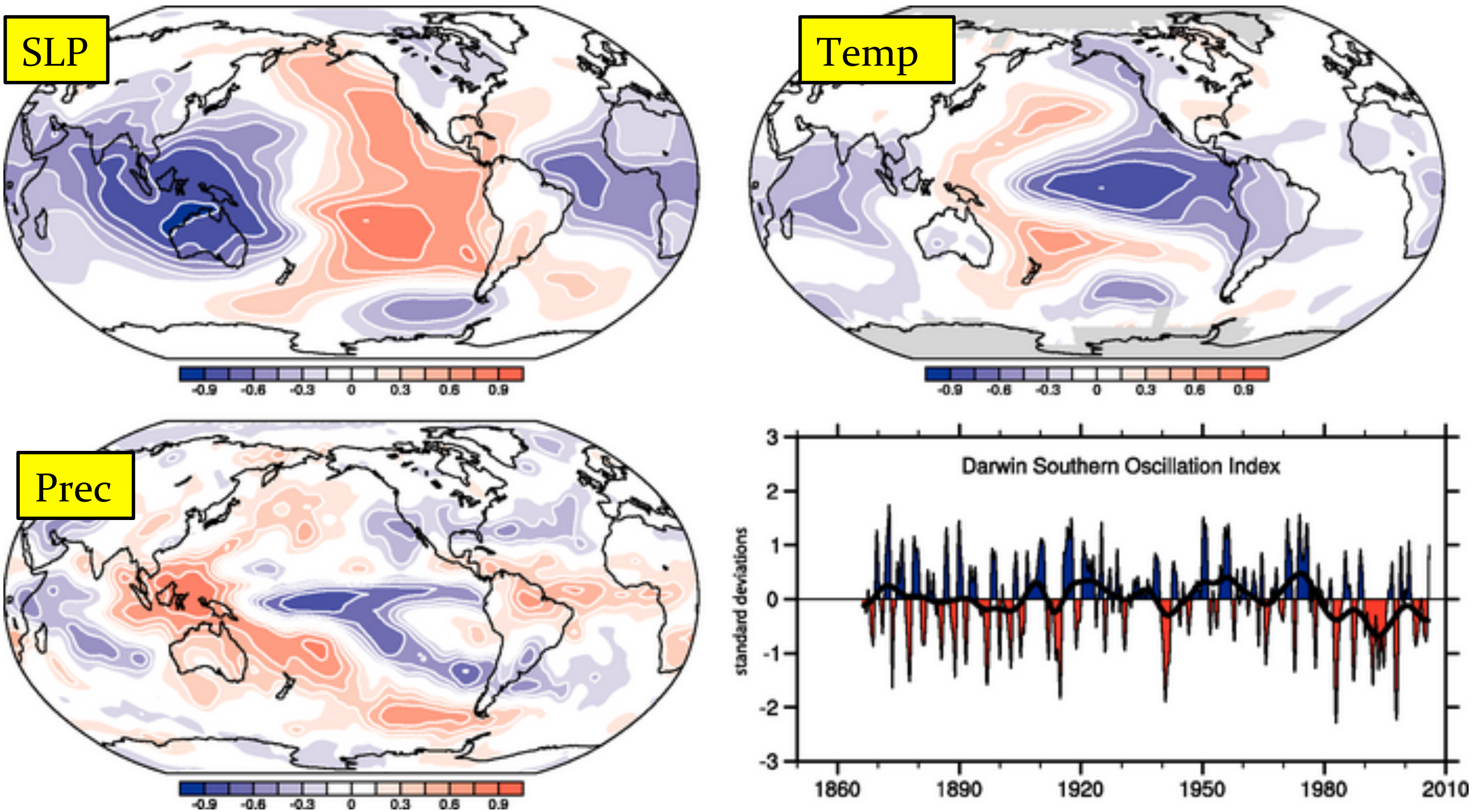
Correlation maps





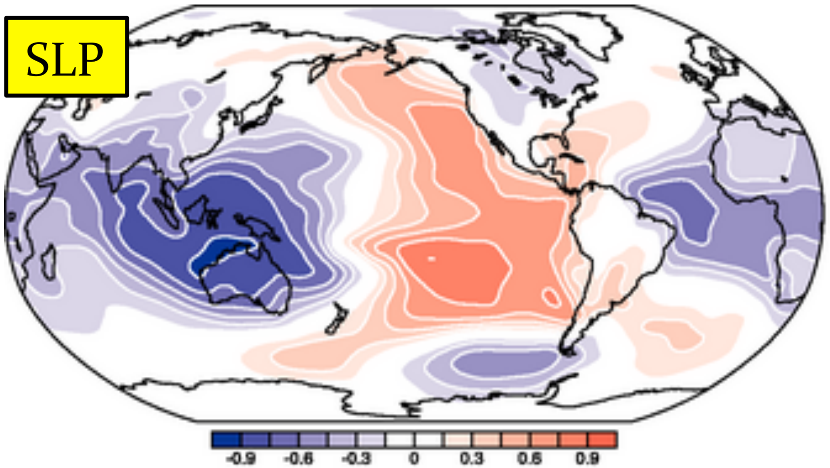
IPCC AR4, Figure 3.27, Source: Trenberth and Caron (2000)

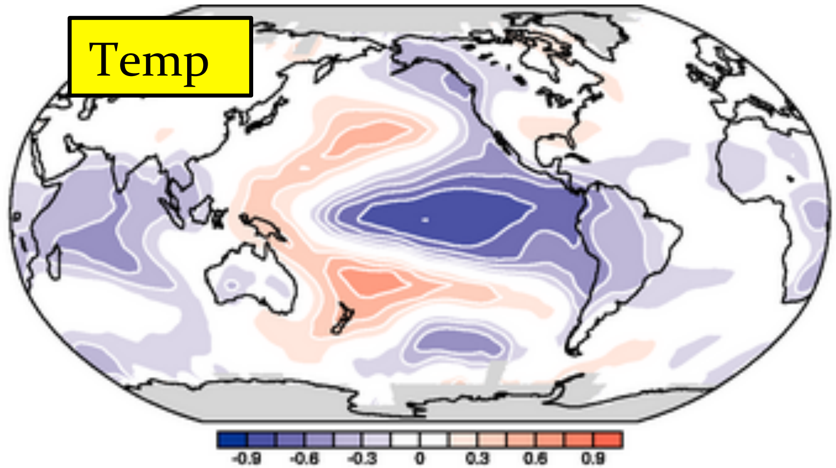
Correlation maps

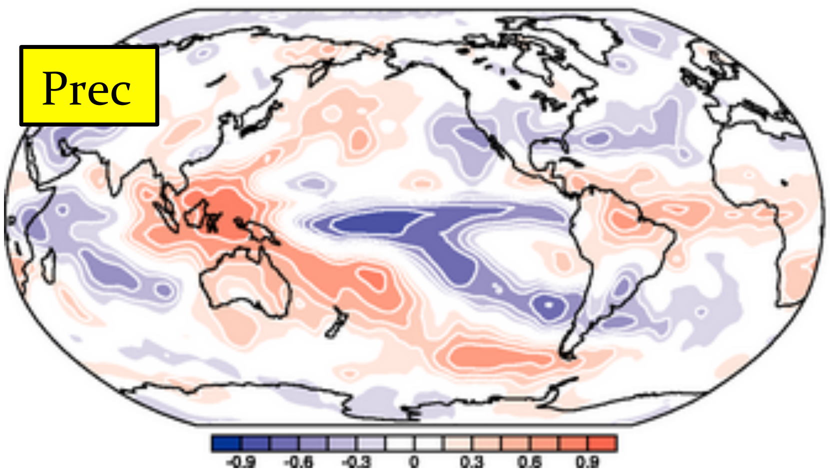


IPCC AR4, Figure 3.27, Source: Trenberth and Caron (2000)

Correlation maps



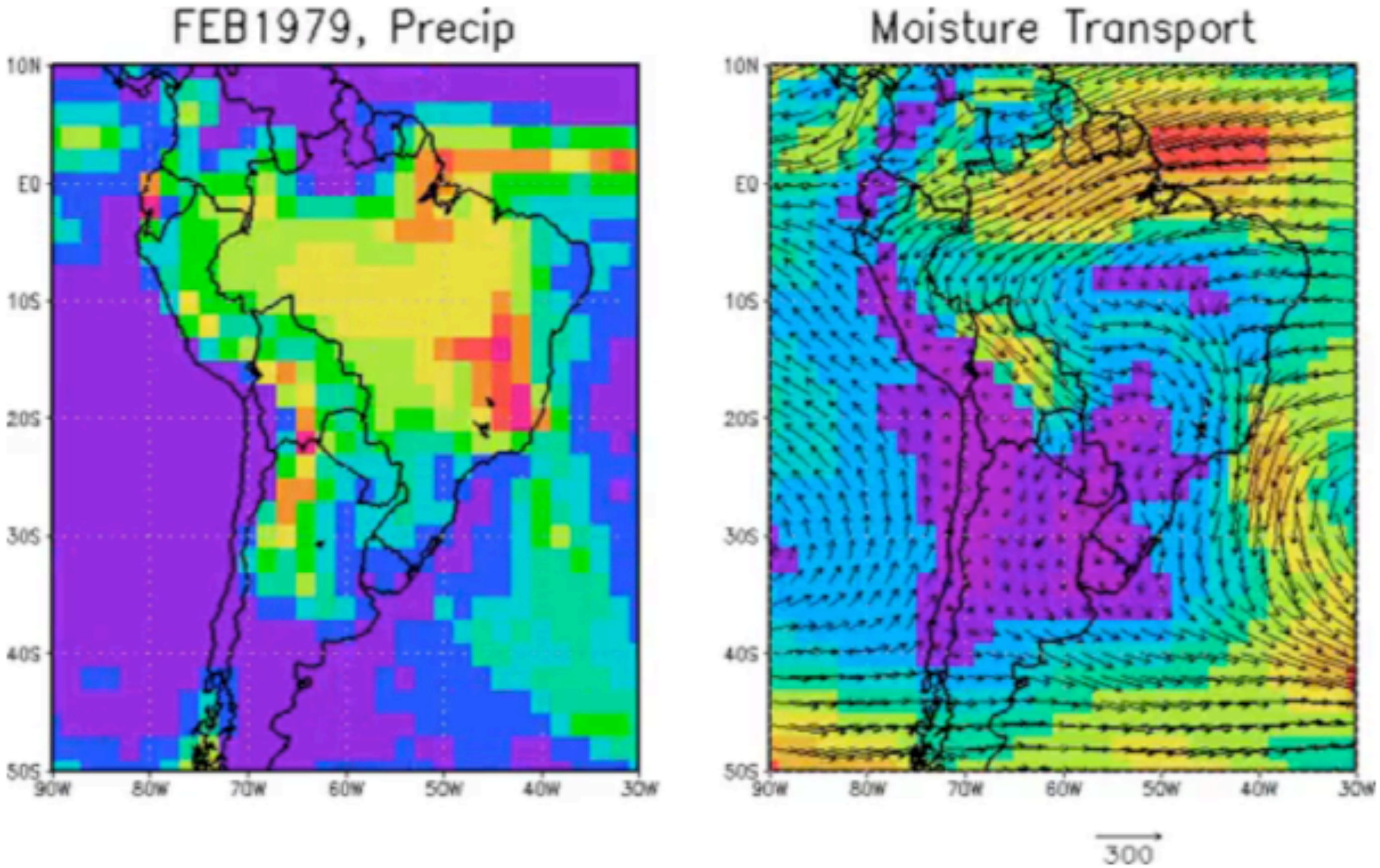




$$\rho_{i,j} = \frac{\mathrm{cov}^{time}\left(prec_{i,j}, SOI\right)}{std^{time}(prec_{i,j}) \cdot std^{time}(SOI)}$$

IPCC AR4, Figure 3.27, Source: Trenberth and Caron (2000)

What if both variables are 2D x t ?



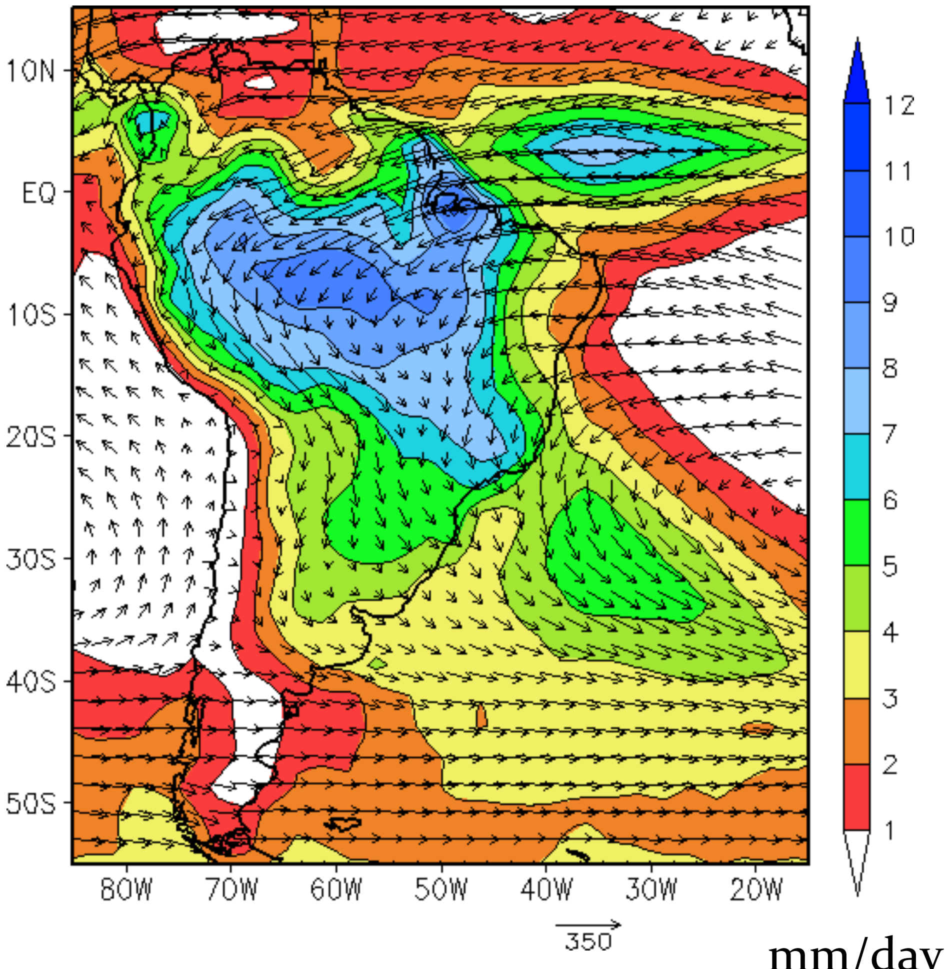
Take the Pearson's **correlation, for each pair** of points:

$$\rho_{i,j,k,l} = \frac{\mathrm{cov}^t(P_{i,j}, MT_{k,l})}{std^t(P_{i,j})\, std^t(MT_{k,l})}$$

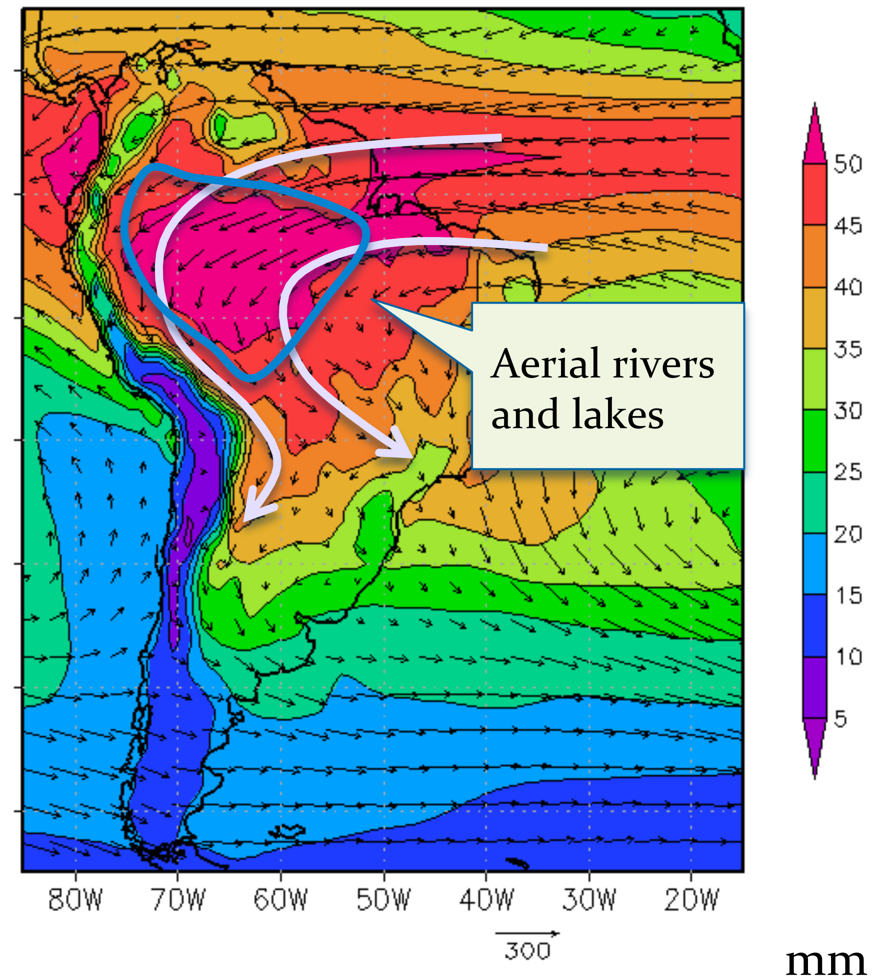
- Se não sabemos estudar estas correlações complicadas, podemos fazer da maneira tradicional…

Precipitation, PWV and Vapor transport GPCP + ERA40 1989-2009

Nov-Mar



Nov-Mar



Arraut et al, J. Clim, 2012

OCEAN-AMAZON, Vapor mix ratio AIRS, ERA, NCEP 2003-2009

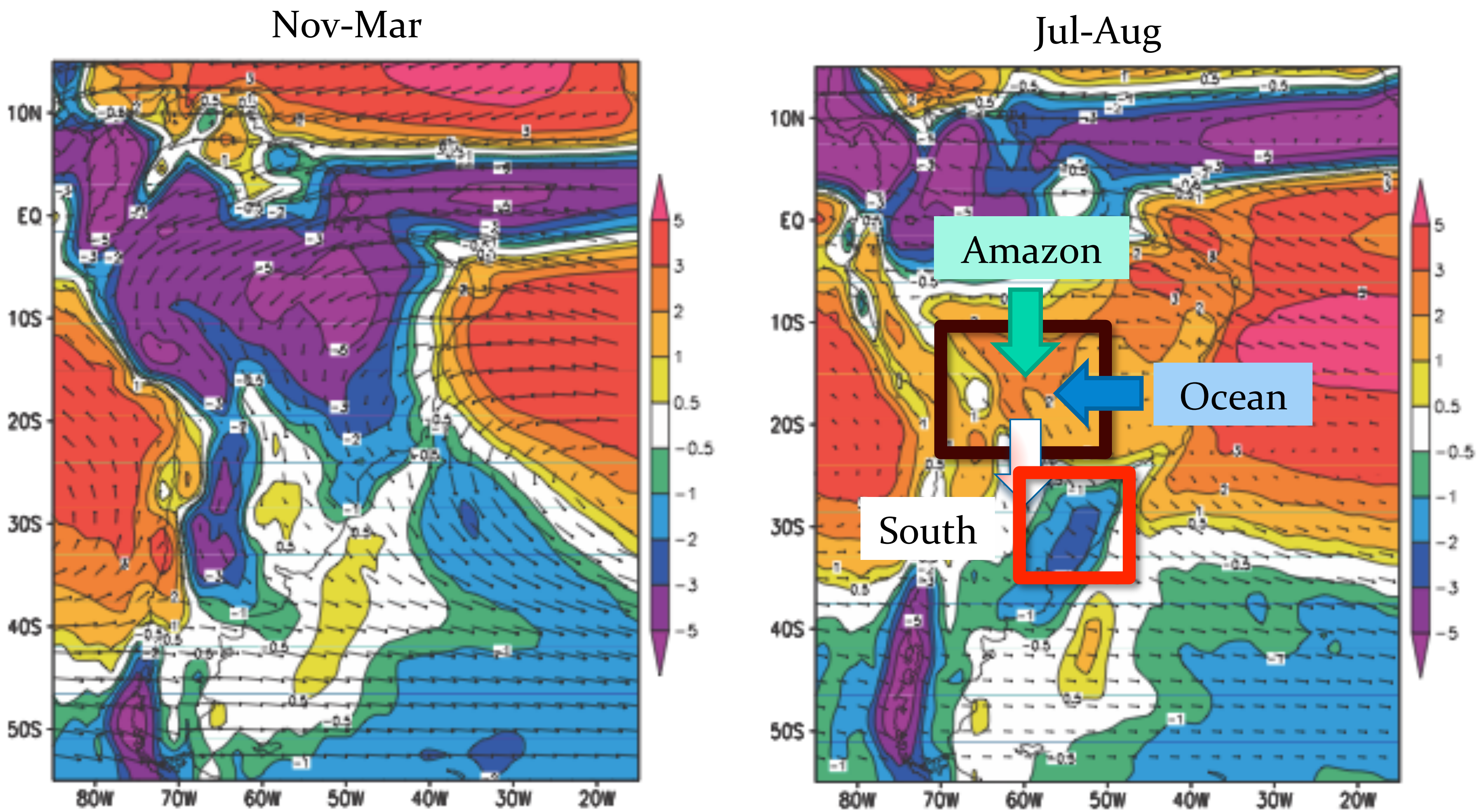


FIG. 6. Mean seasonal vertically integrated moisture transport (arrows) and its divergence (colors, mm day^{-1}) are shown for NM, AJ, JA, and SO.

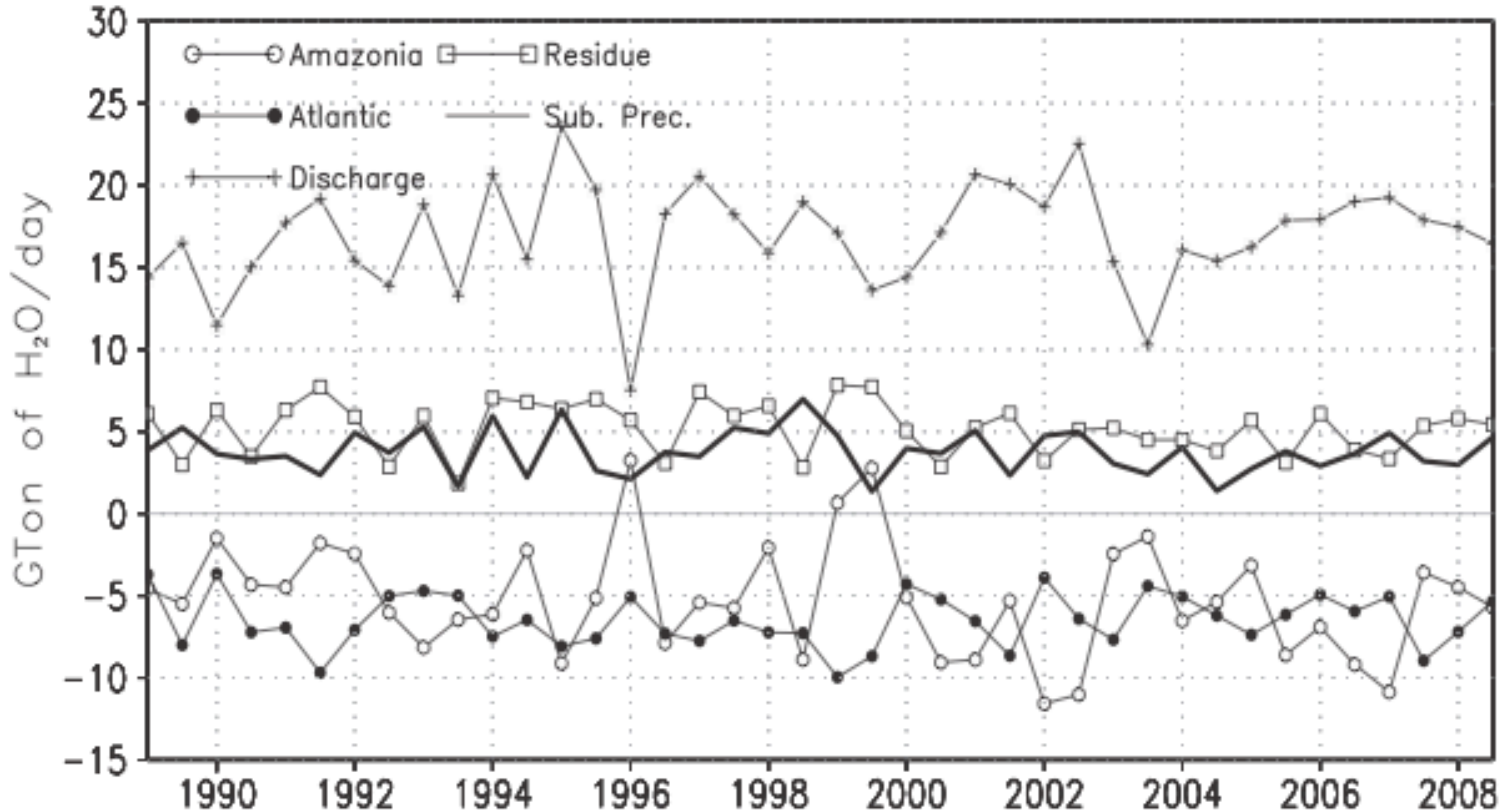
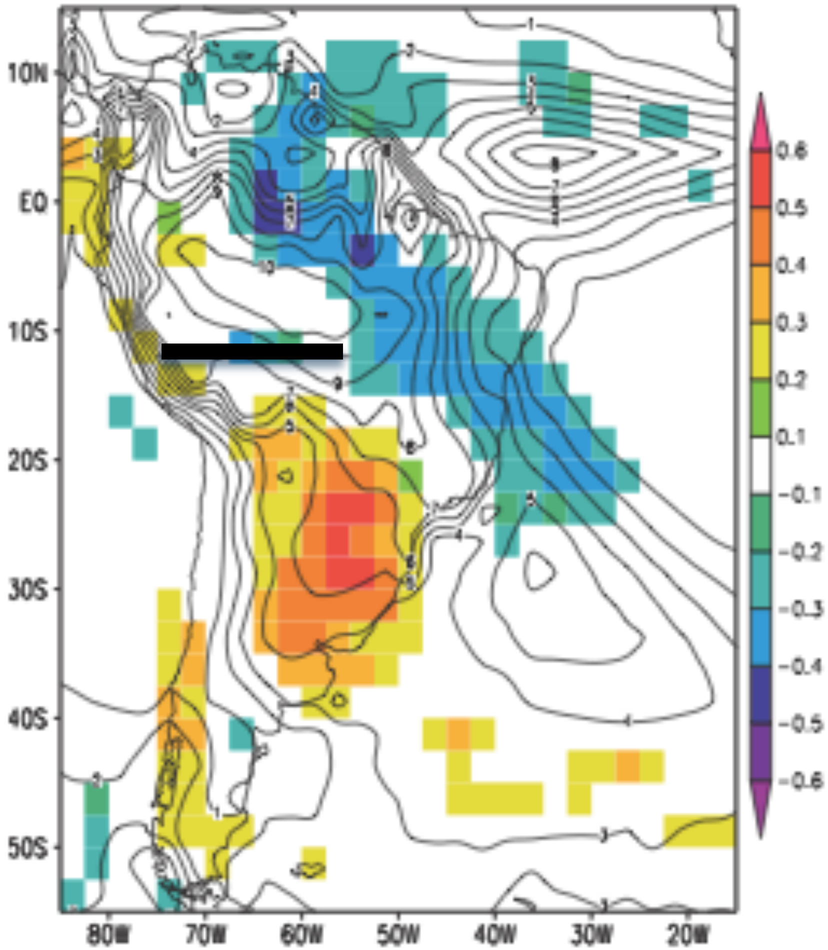


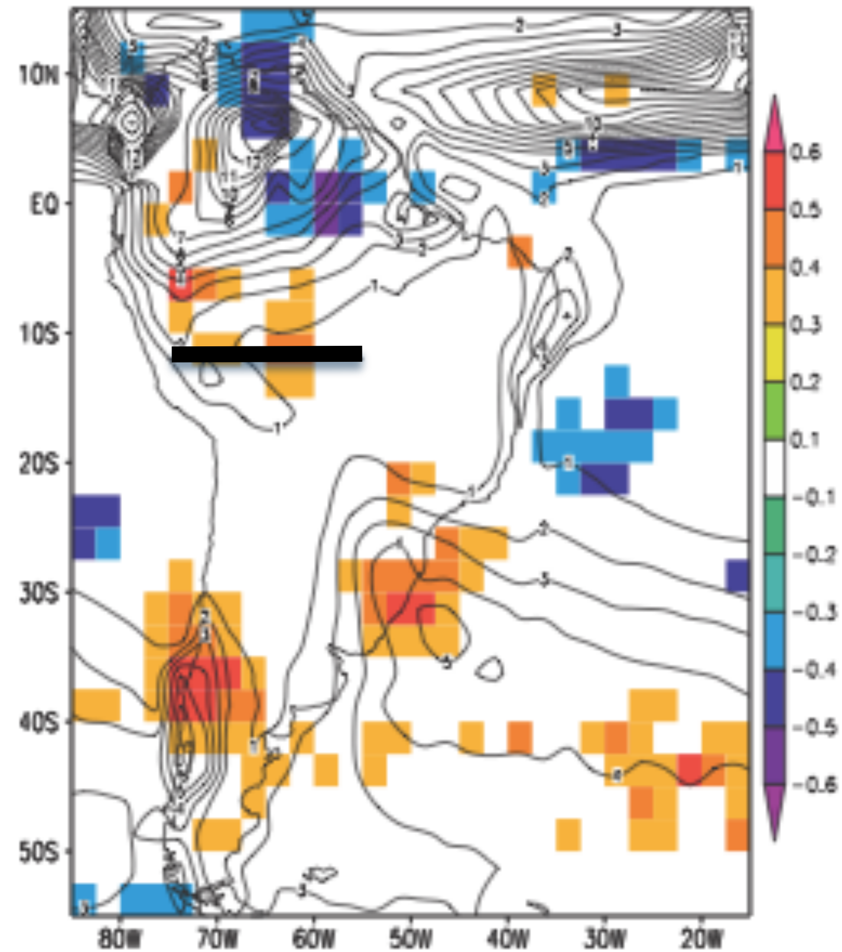
FIG. 7. Water balance (Gt day^{-1}) for the area depicted in Fig. 6 (23°–10°S, 70°–50°W) for the dry months between 1989 and 2008. Inflow is divided into two contributions: Amazonia (open circle) and Atlantic Ocean (filled circle). Discharge (+) is the outflow from this region into the subtropics, and the residue (squares) is the difference between inflows and outflows. The line without symbols is the precipitation averaged over 34°–23°S, 57°–48°W.

Again, a simple correlation gives:

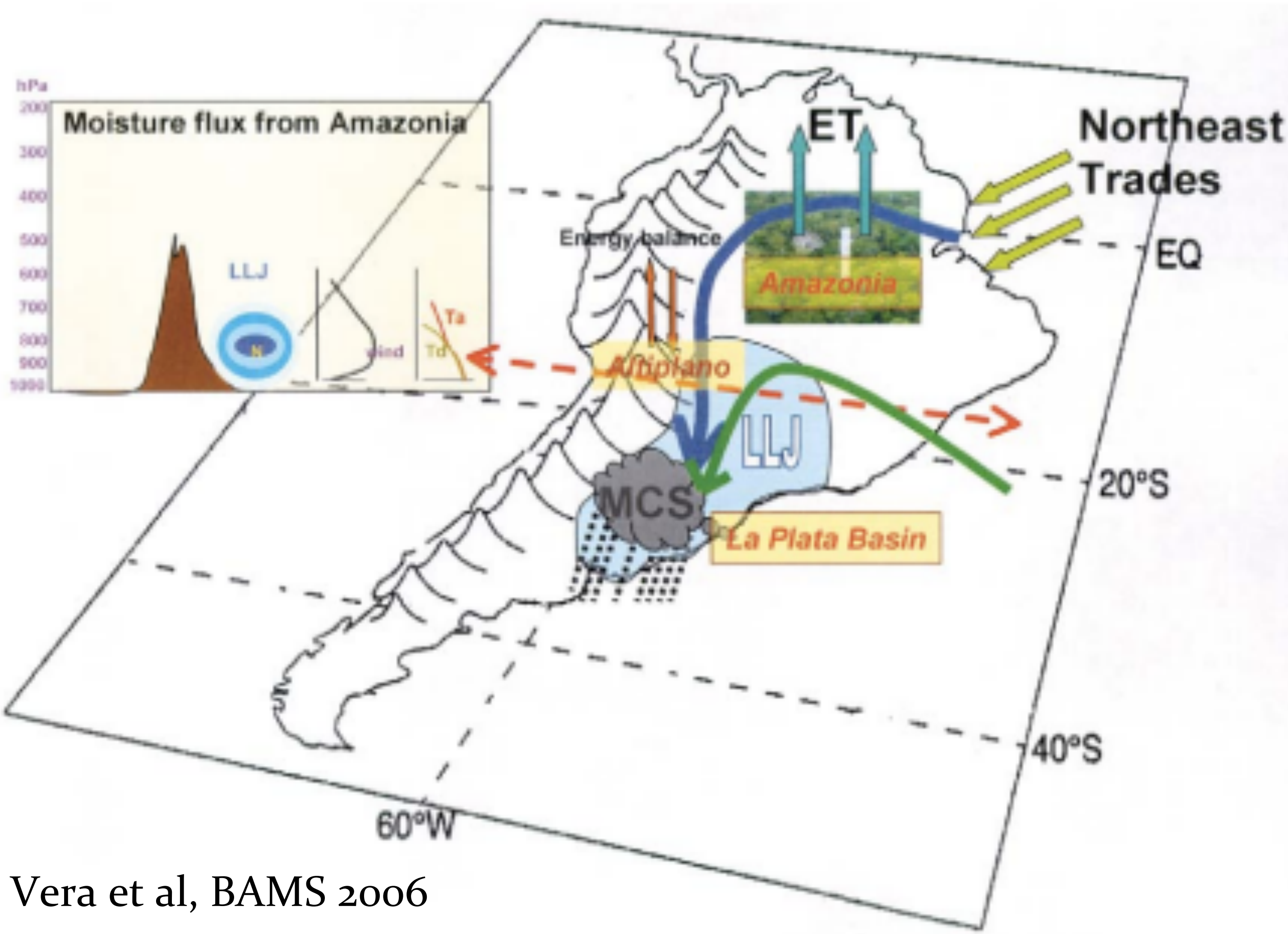
Nov-Mar



Jul-Aug



Arraut et al, J. Clim, 2012



Vera et al, BAMS 2006

Ok, so climatologically the water transport from the Amazon to the subtropics is always there… Does it mean the LLJ is not important at al !?!?

Geopotential Height @ 850 hPa(m)

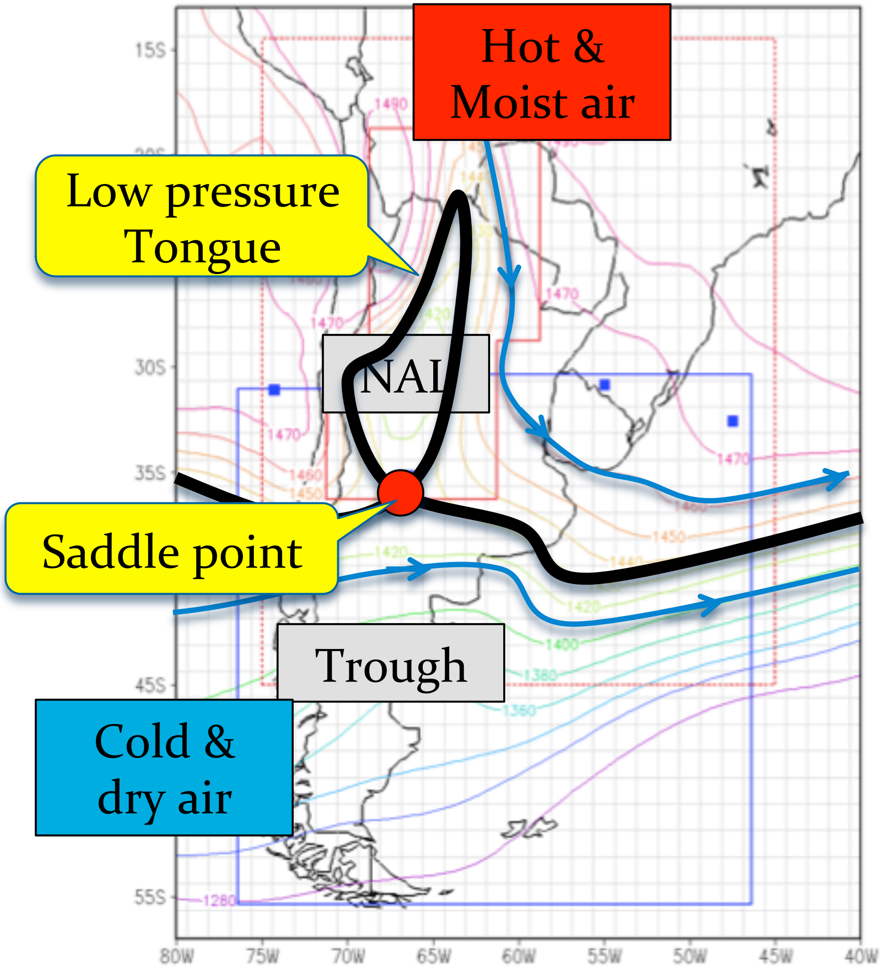
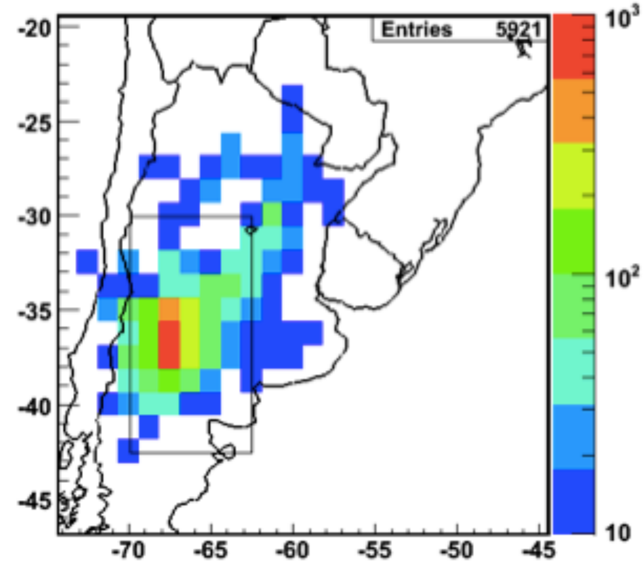
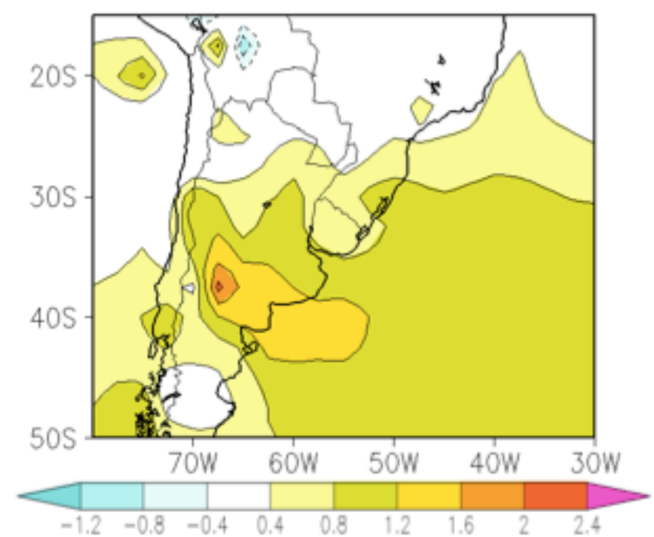


Fig. 1. Contours show ϕ_{850} (m) at 12Z 24th Dec 91. Polygons delimit search regions for: minimums of ϕ_{850} (dotted red); NAL position (red); AC position (blue). Markers indicate: lows (red), NAL (big red), cols (blue), AC (blue square)

Saddle point occurrence

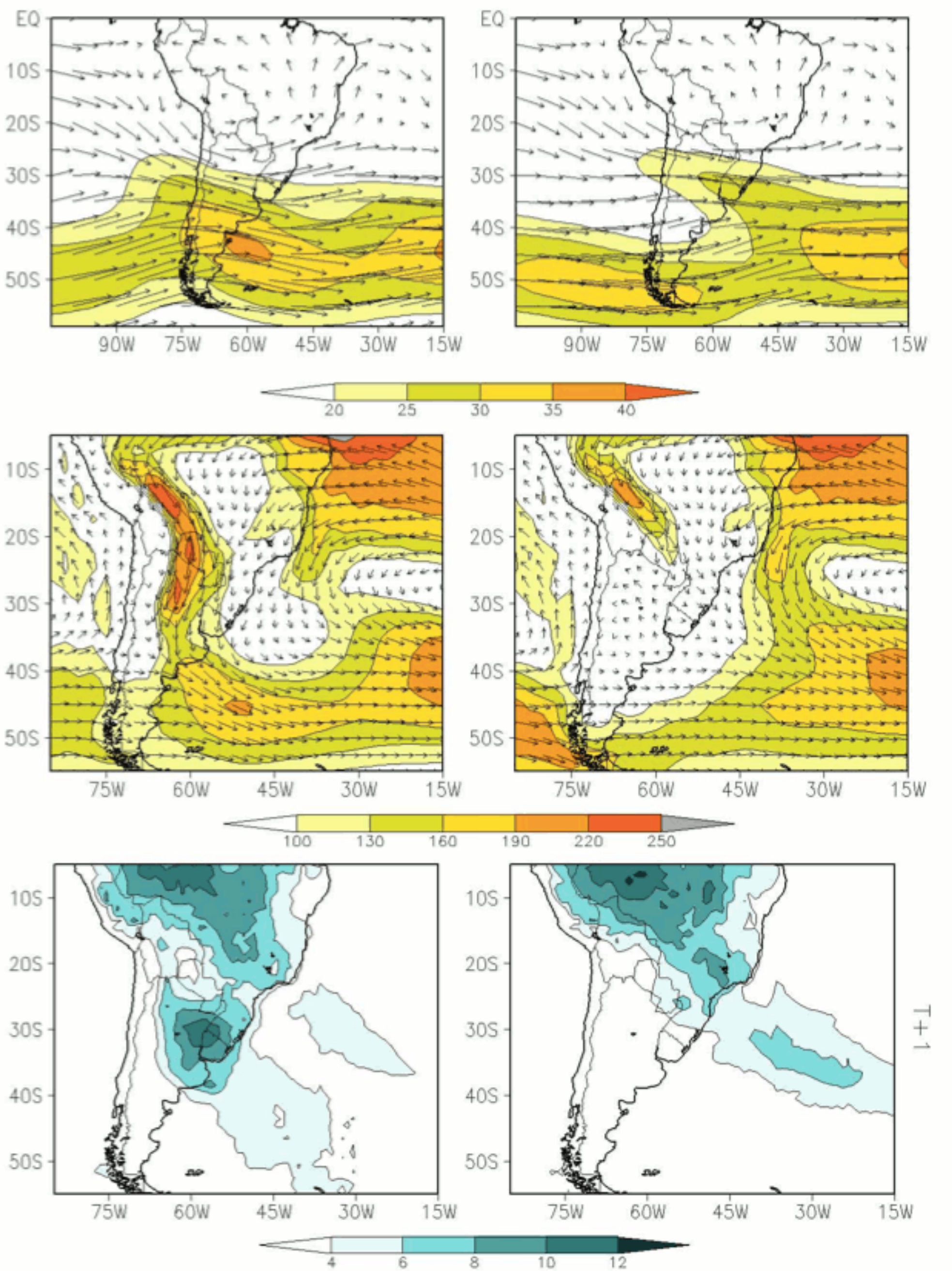




Frontogenesis in θe (K/100km/day)

Barbosa and Arraut, Adv. Geo. 2009

With LPT Without LPT



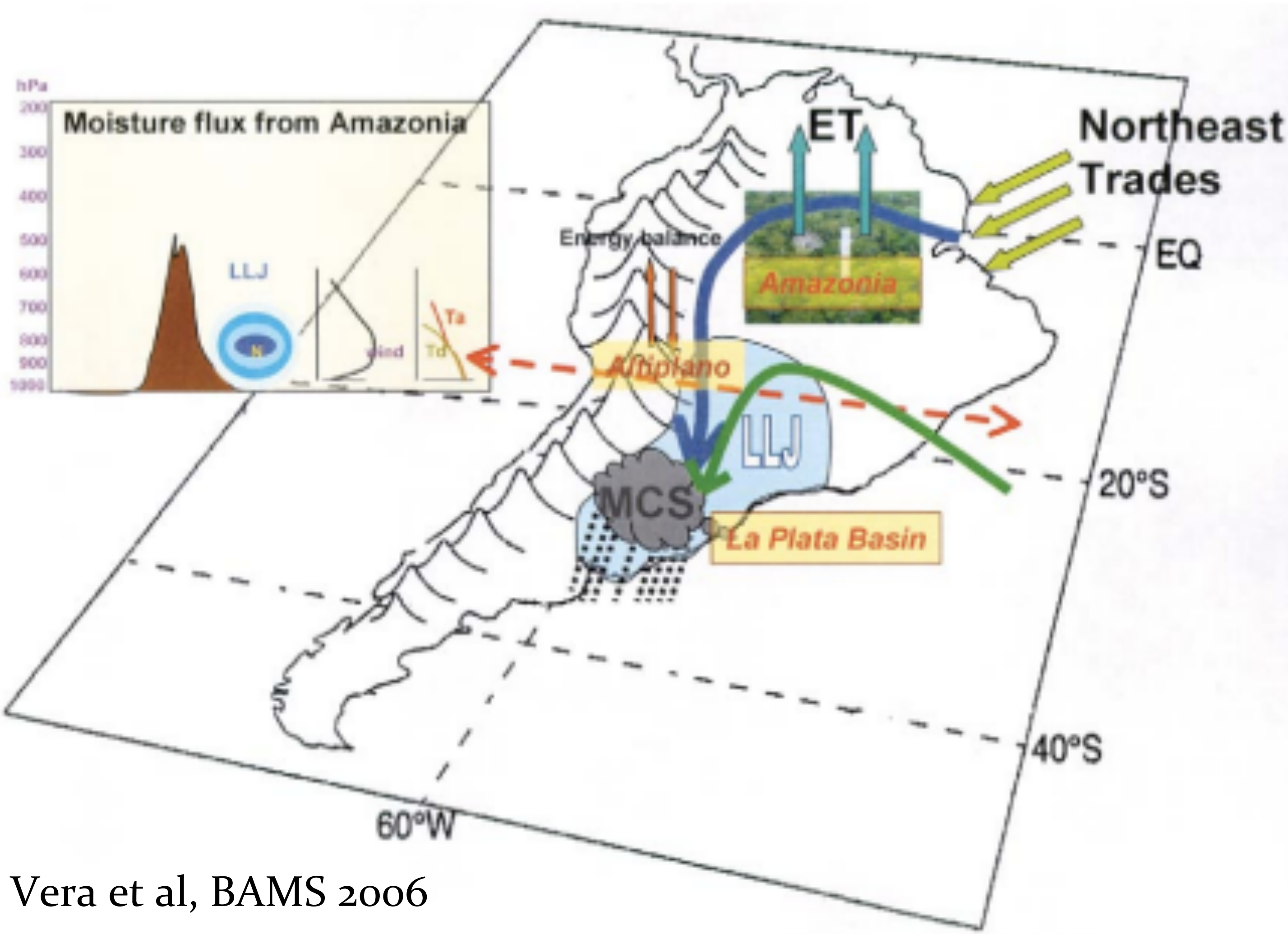
Wind at 250hPa
m/s

Moisture transport
Kg/m/s

Precipitation +1 day
mm/day

Fig. 3. Composites for cases with (left) and without (right) AC and LPT inside the selected region. From top to bottom, the panels show geopotential height (m) and FG_3 (K/100 km/day) at 850 hPa, wind vectors and its magnitude (m/s) at 250 hPa, vertically integrated humidity transport and its magnitude (kg/m/s), and precipitation (mm/day) with 1-day lag.

Arraut and Barbosa, Adv. Geo. 2009



Vera et al, BAMS 2006

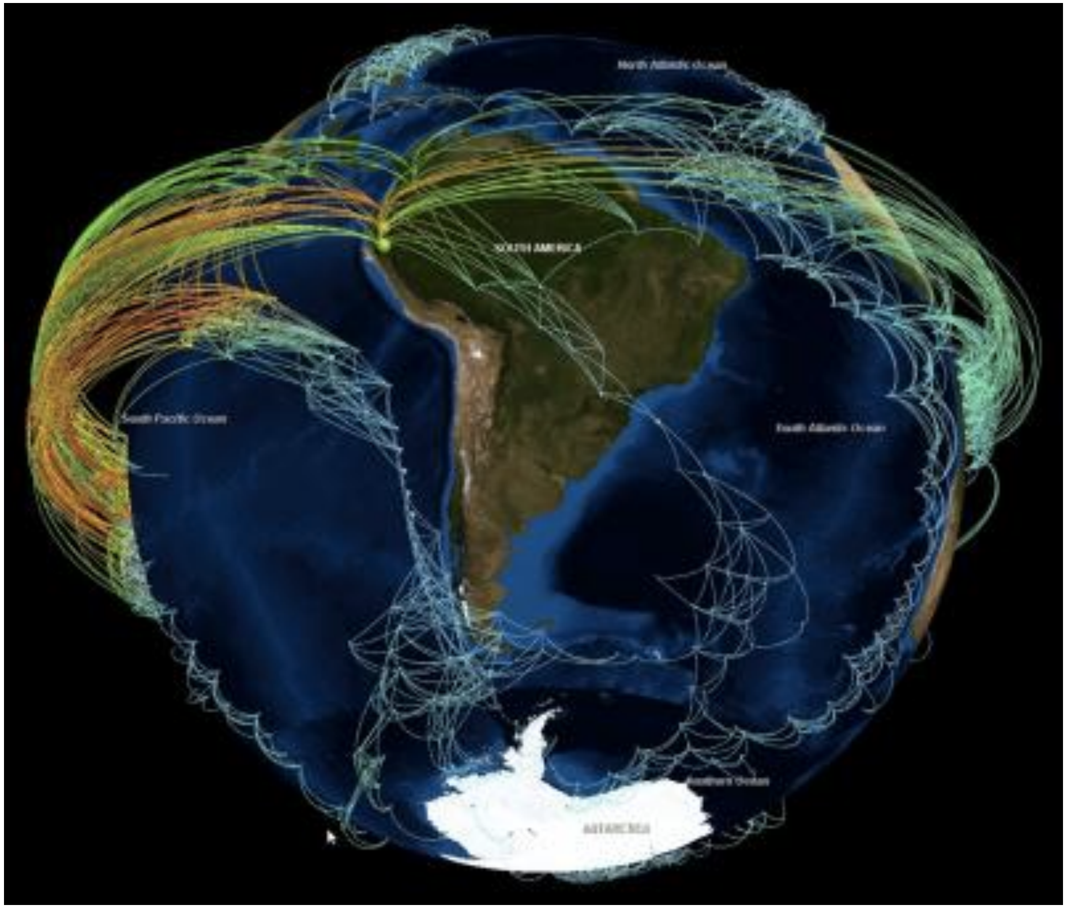
It looks like the southward transport is controlled by the NAL and the geostrophic winds around it. Sometimes, the winds are strong enough to be called LLJ…

- Mas conseguimos lidar com aquelas correções de 4 termos??

What if both variables are 2D x t ?

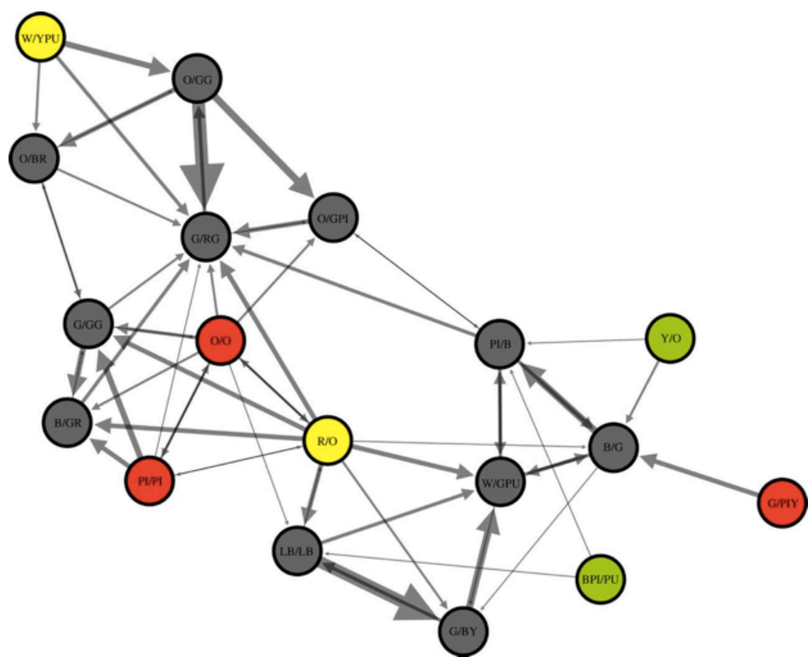
$$\rho_{i,j,k,l} = \frac{\text{cov}^t(P_{i,j}, MT_{k,l})}{std^t(P_{i,j})std^t(MT_{k,l})}$$

Set a threshold for correlations to be considered important, and draw links between points with high correlation.



Complex Networks

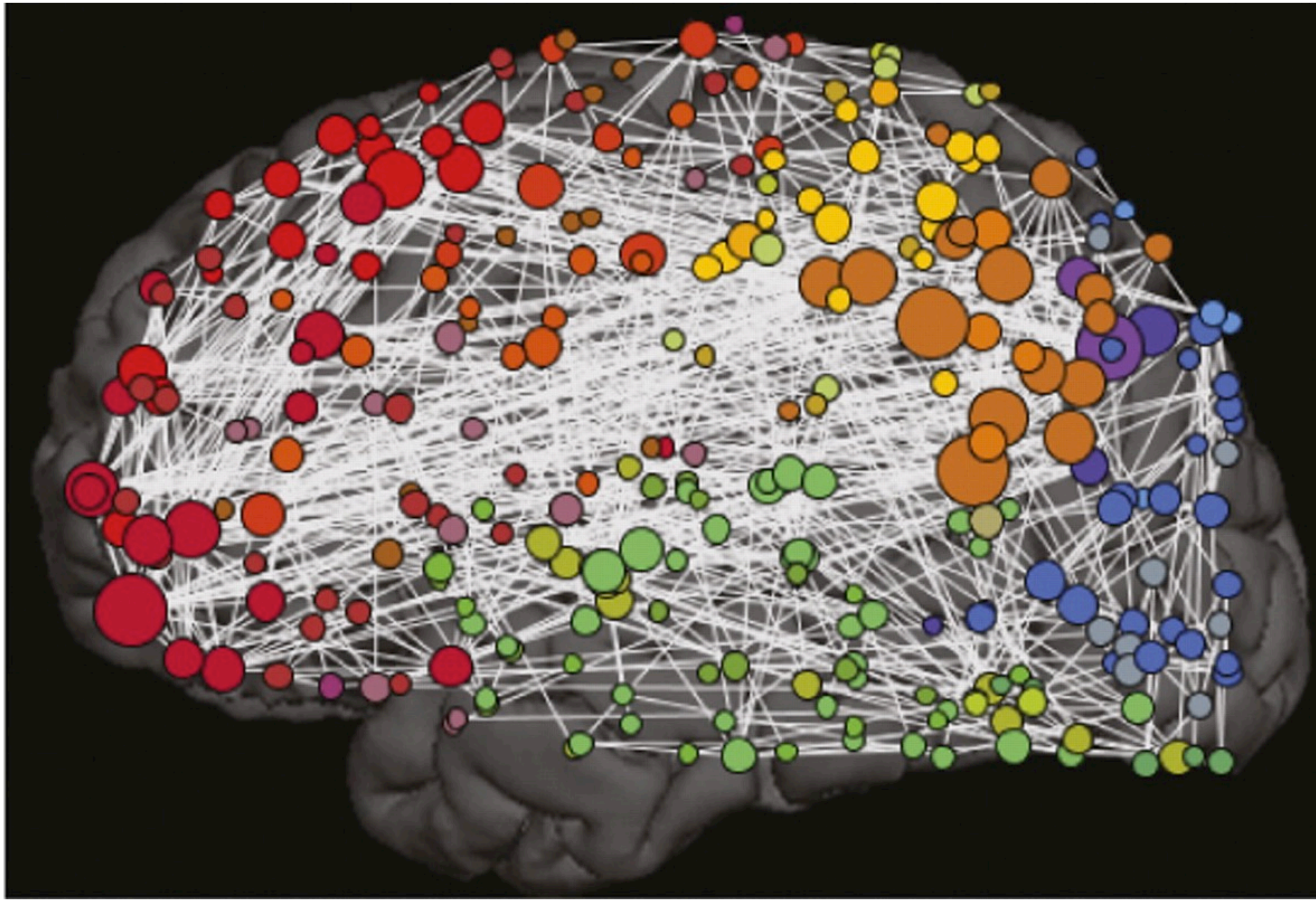
- *"In the context of network theory, a complex network is a graph (network) with non-trivial topological features —features that do not occur in simple networks such as lattices or random graphs but often occur in graphs modeling real systems*". - Wikipedia



Examples:

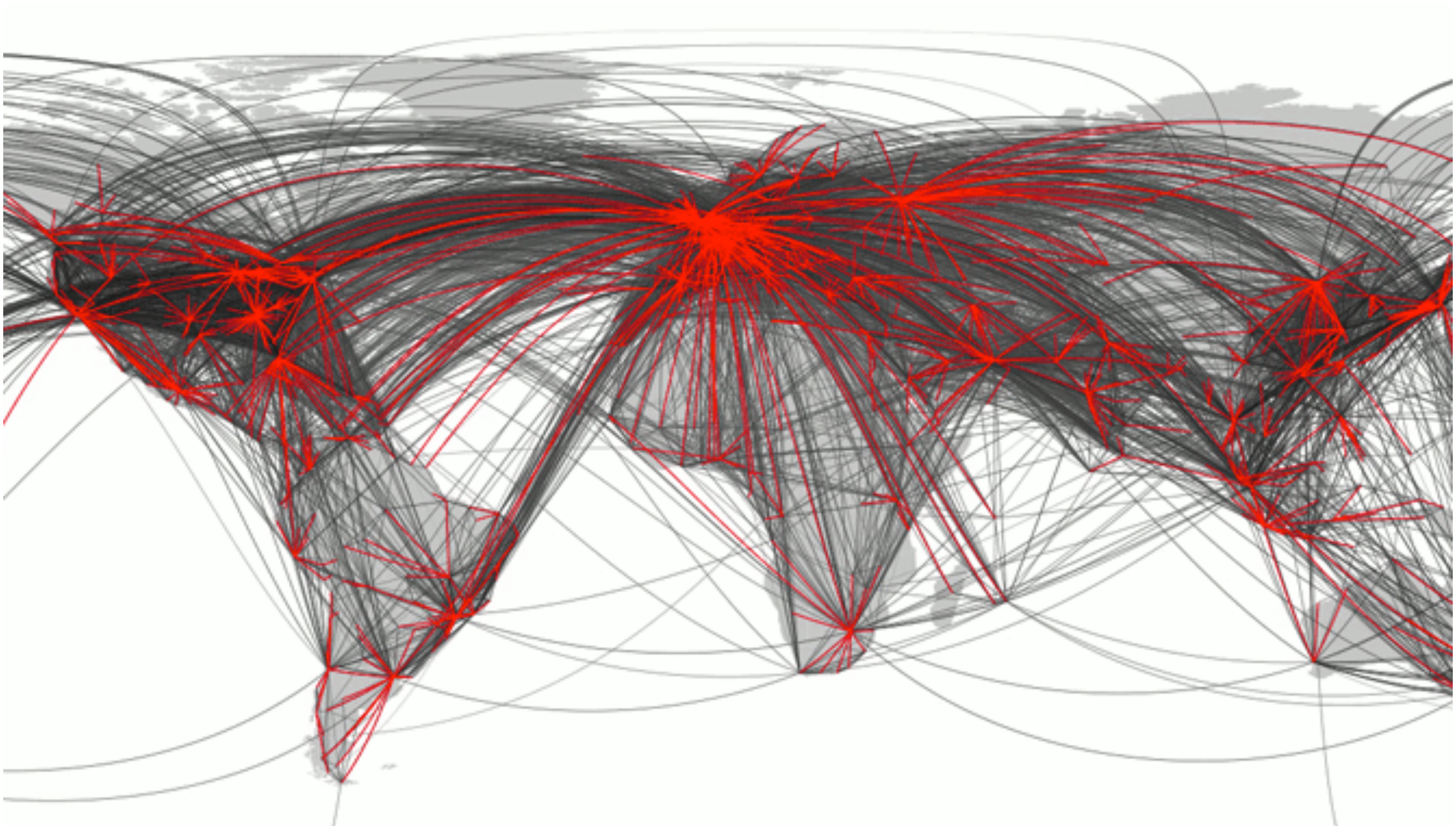
- people that are friends
- computers that are interconnected
- web pages that point to each other
- proteins that interact
- brain cells transmitting information
- phone-call networks
- transportation networks
- transmission grids

Complex brain network topology produced by a simple two-parameter model.



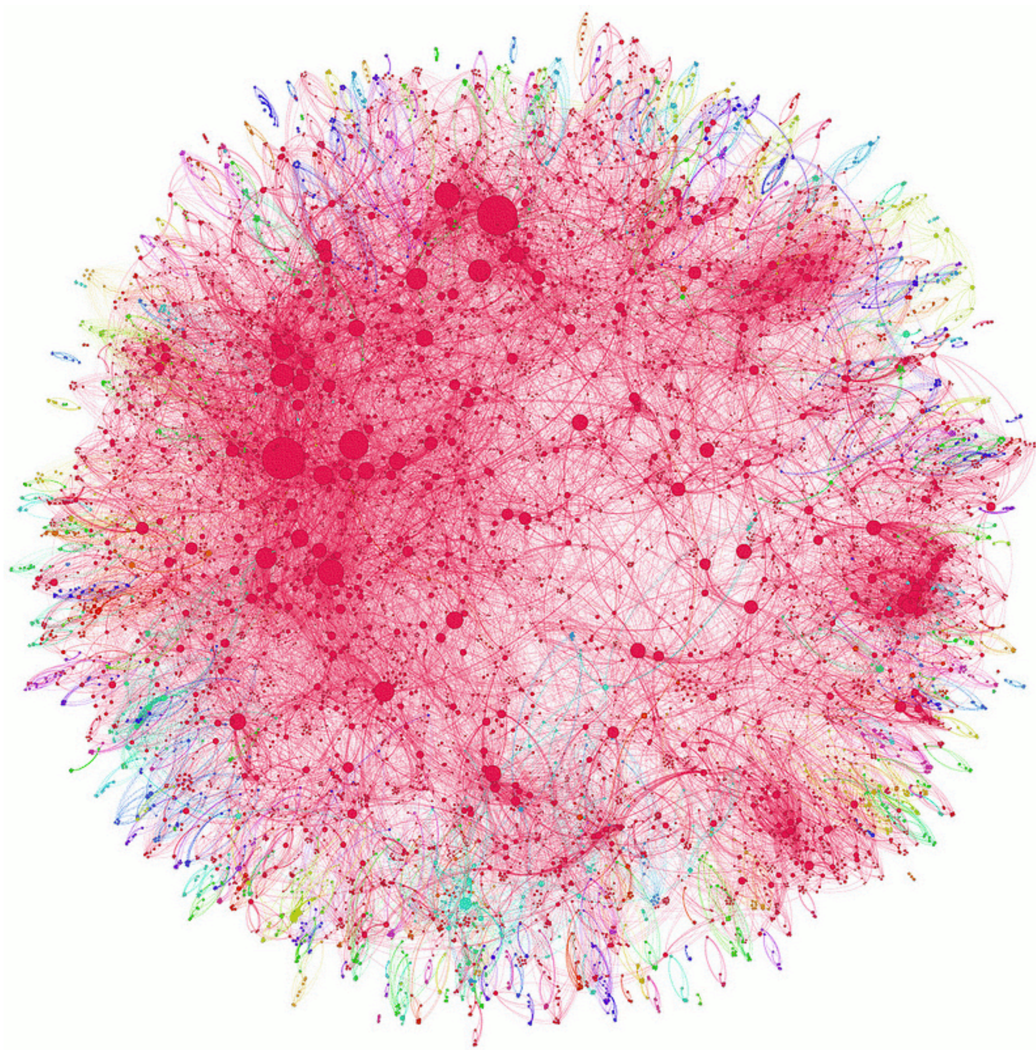
National Academy of Sciences PNAS 2012;109:5549-5550

PNAS

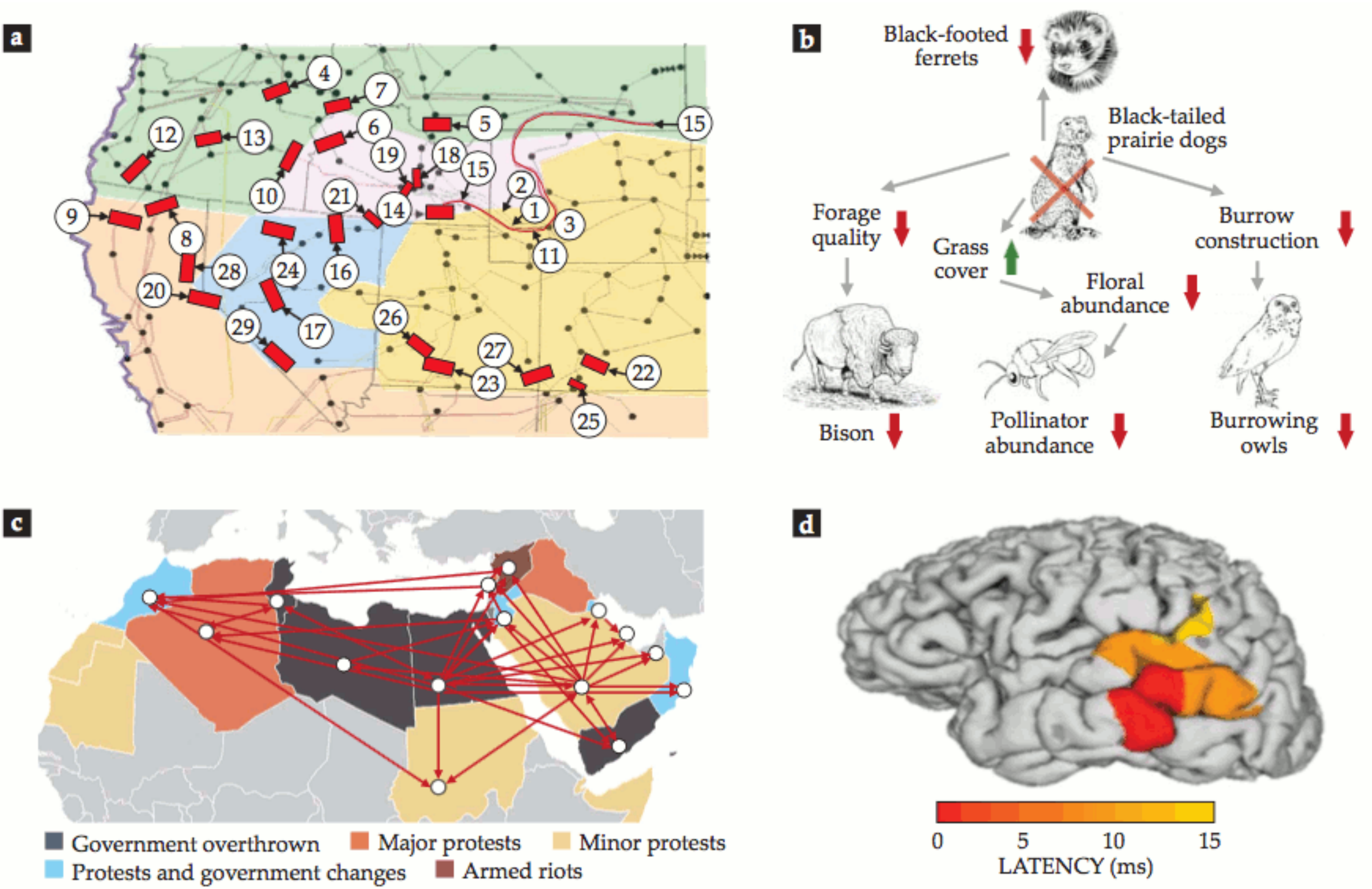


Robust classification of salient links in complex networks
https://www.nature.com/articles/ncomms1847

research papers on 'hepatitis C virus'. Each of the 8,500 spots is a single author, and the lines between spots represent co-authorship across scientific papers.



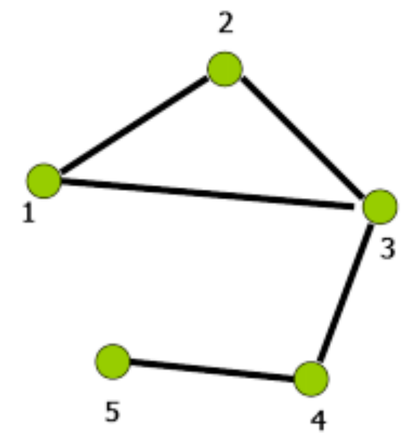
http://social-physics.net/visualizing-scientific-collaboration-using-pubmed/

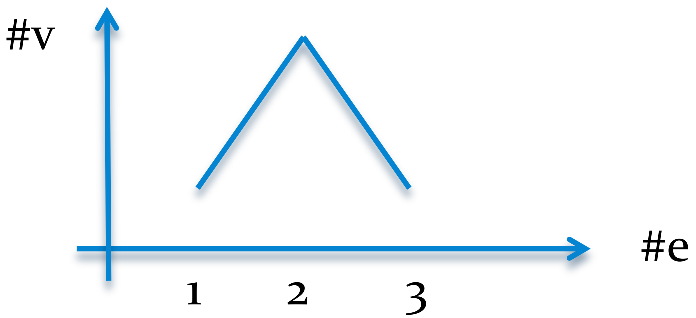


Physics Today 70, 1, 32 (2017)

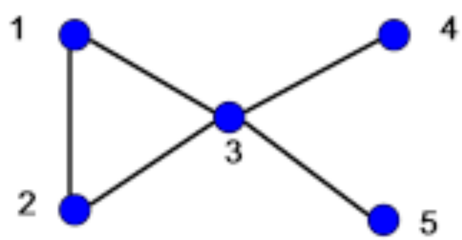
Basic measures

- Degree distribution (number of edges)
  - 1v/1e; 3v/2e; 1v/3e





- clustering coefficient of vertex i:
  - d(i) = number of edges between neighbors divided by maximum possible



Properties of Real Networks

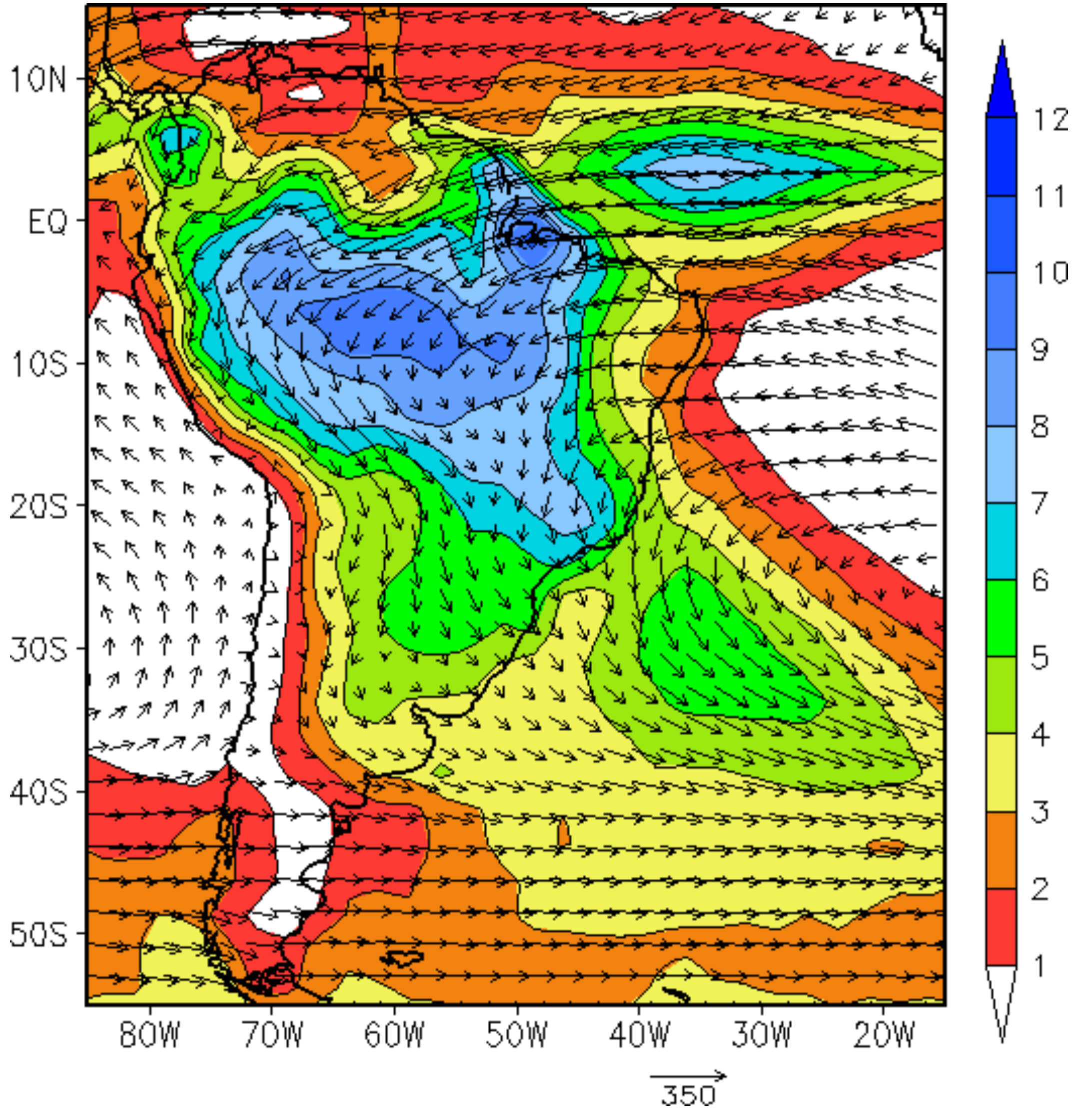
- Most vertices have only a small number of neighbors (degree), but there are some vertices with very high degree (power-law degree distribution)
  - scale-free networks
- If a vertex **x** is connected to **y** and **z**, then **y** and **z** are likely to be connected
  - high clustering coefficient
- Most vertices are just a few edges away on average.
  - small world networks

My intent today is…

Give examples of how we applied Complex Networks for

1. Propagation of extreme events
2. Cascading moisture recycling
3. Self-amplified forest loss (with climate change)
4. Hysteresis of deforestation

Summer Precipitation



Extreme precipitation events

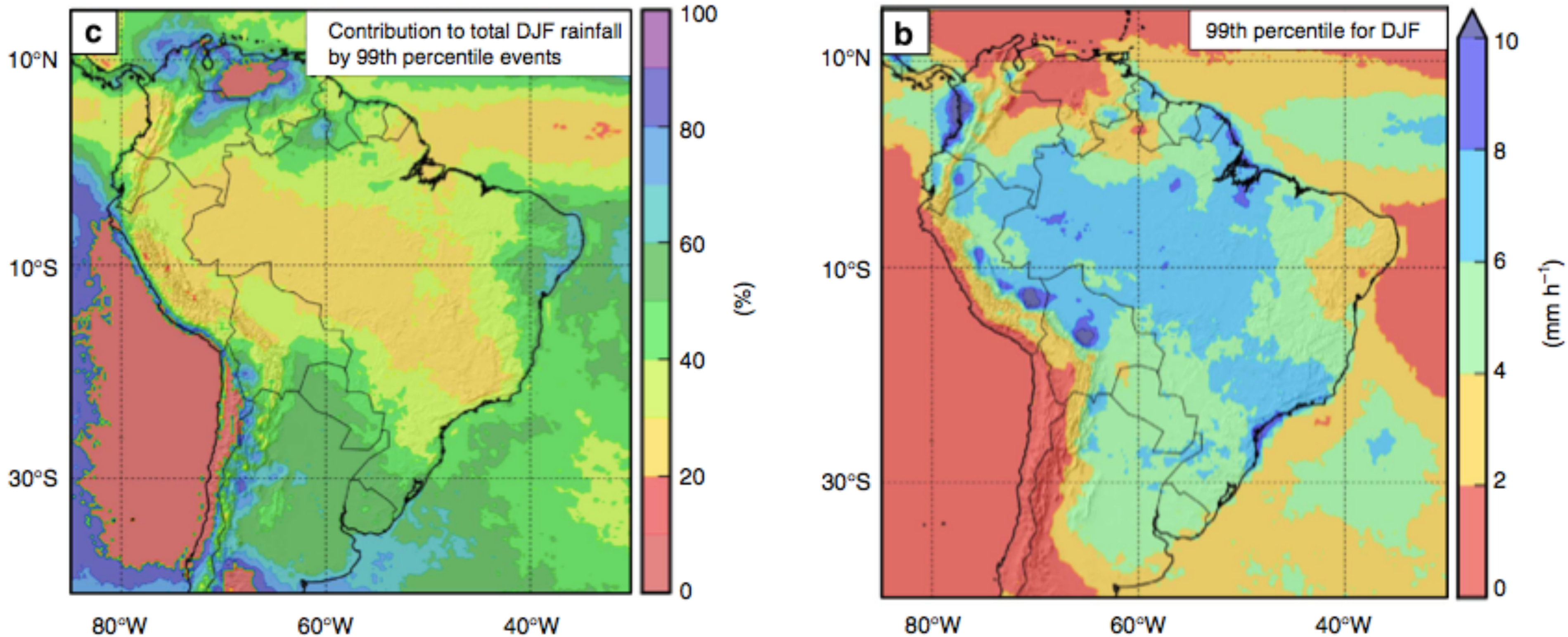
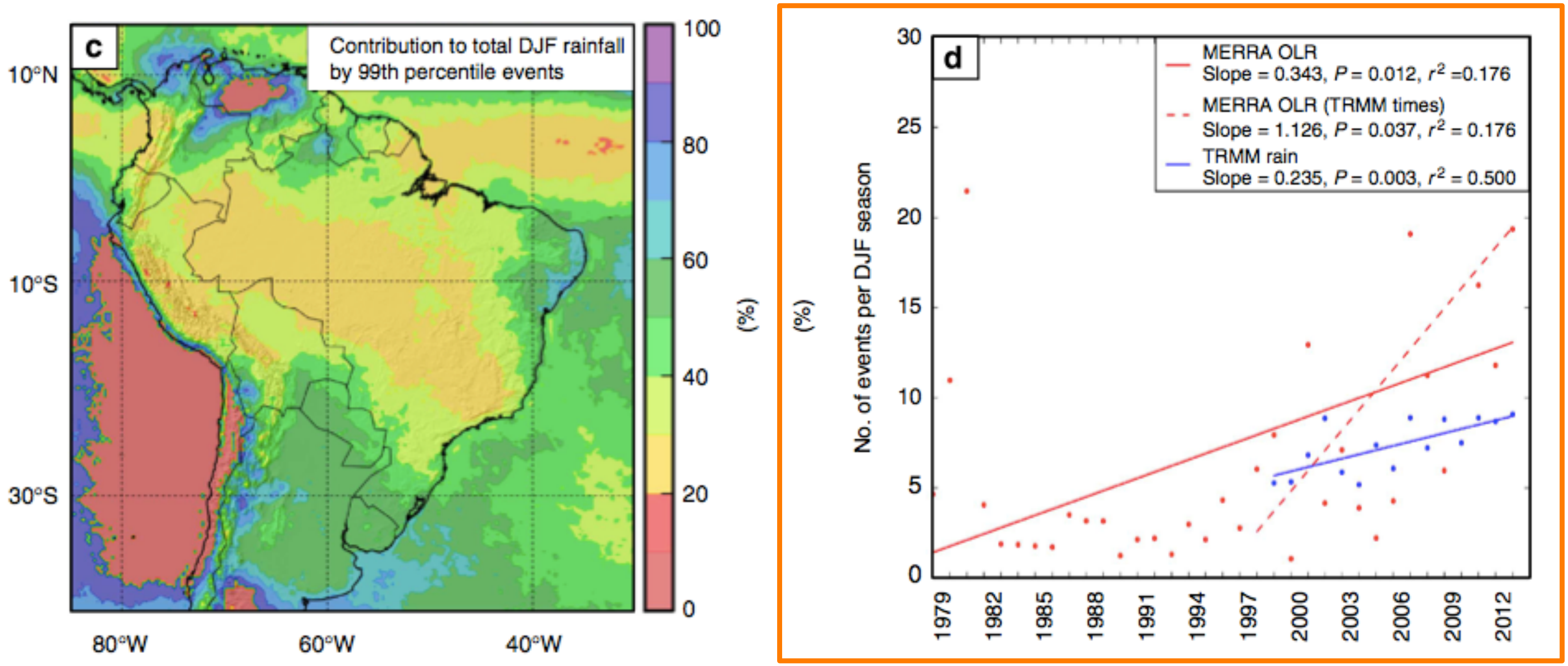


Figure 1 | Geographic and climatic setting. (**a**) Topography and simplified South American Monsoon System mechanisms. The boxes labelled 1 to 7 indicate the climatological propagation path of extreme events as revealed by the network analysis. (**b**) 99th percentile of hourly rainfall during DJF derived from TRMM 3B42V7 (ref. 27 in the spatial domain 85°W to 30°W and 40°S to 15°N, at a horizontal resolution of 0.25° × 0.25° and 3-hourly temporal resolution. (**c**) Fraction of total DJF rainfall accounted for by events above the 99th percentile. (**d**) Trend lines for the number of extreme

Boers et al, Nature Comm. 2014

Extreme precipitation events



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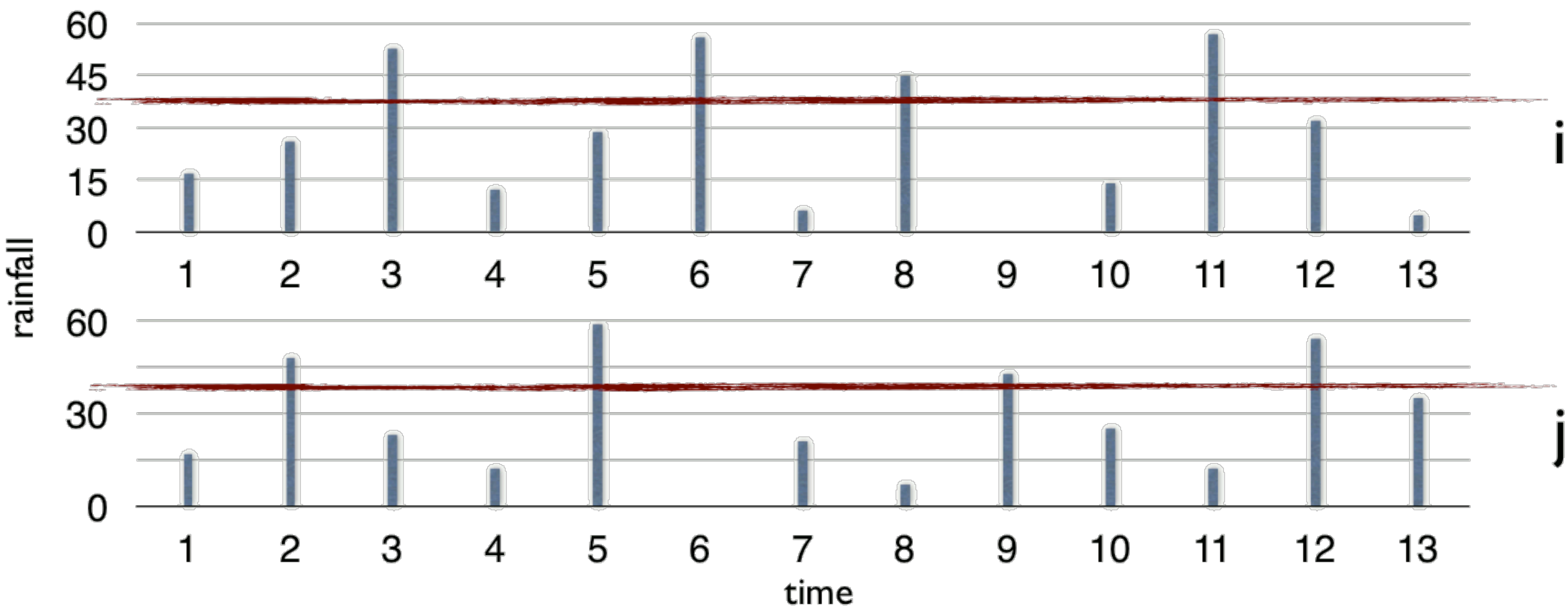
Boers et al, Nature Comm. 2014

event synchronization

(extreme events: above 99th percentile of all DJF times)



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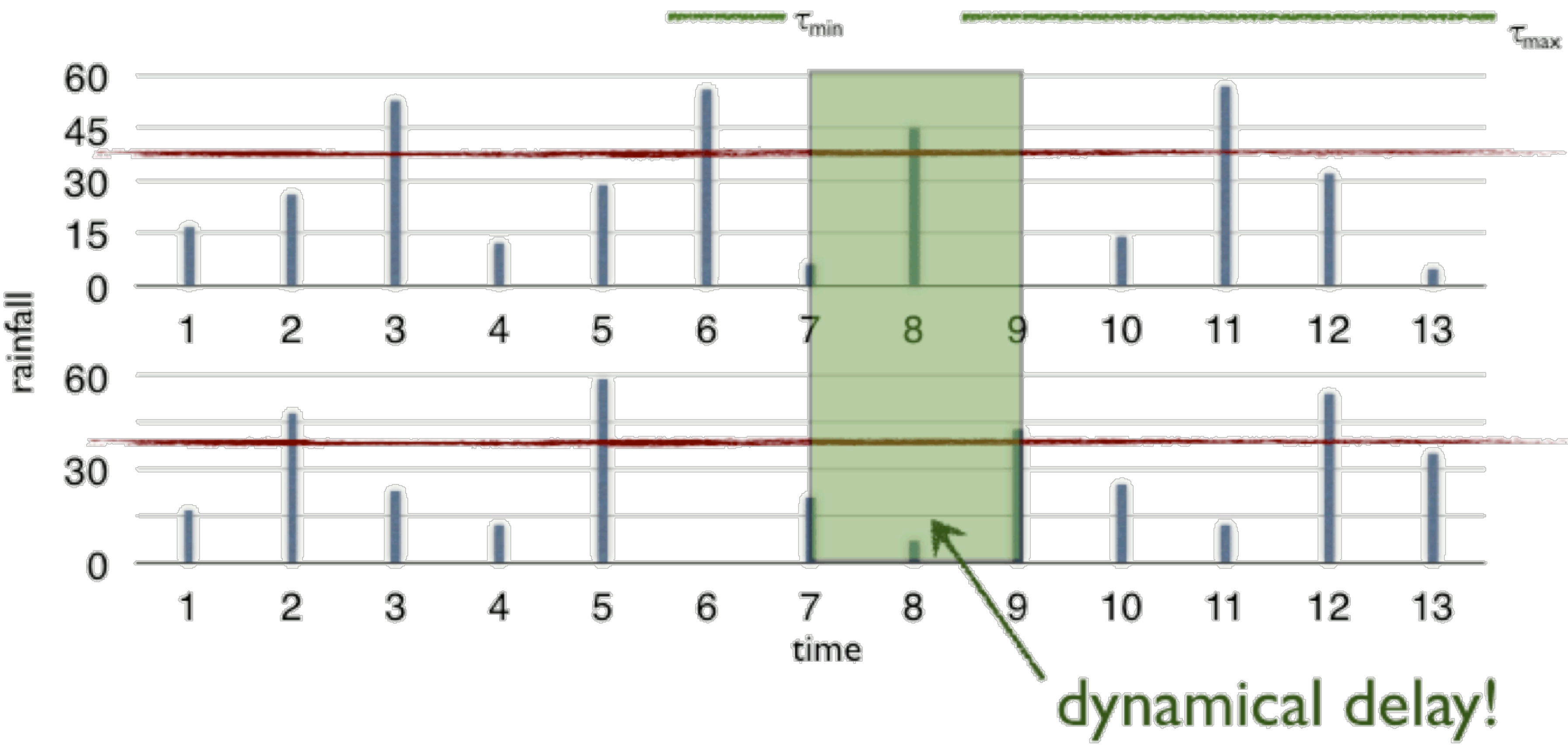

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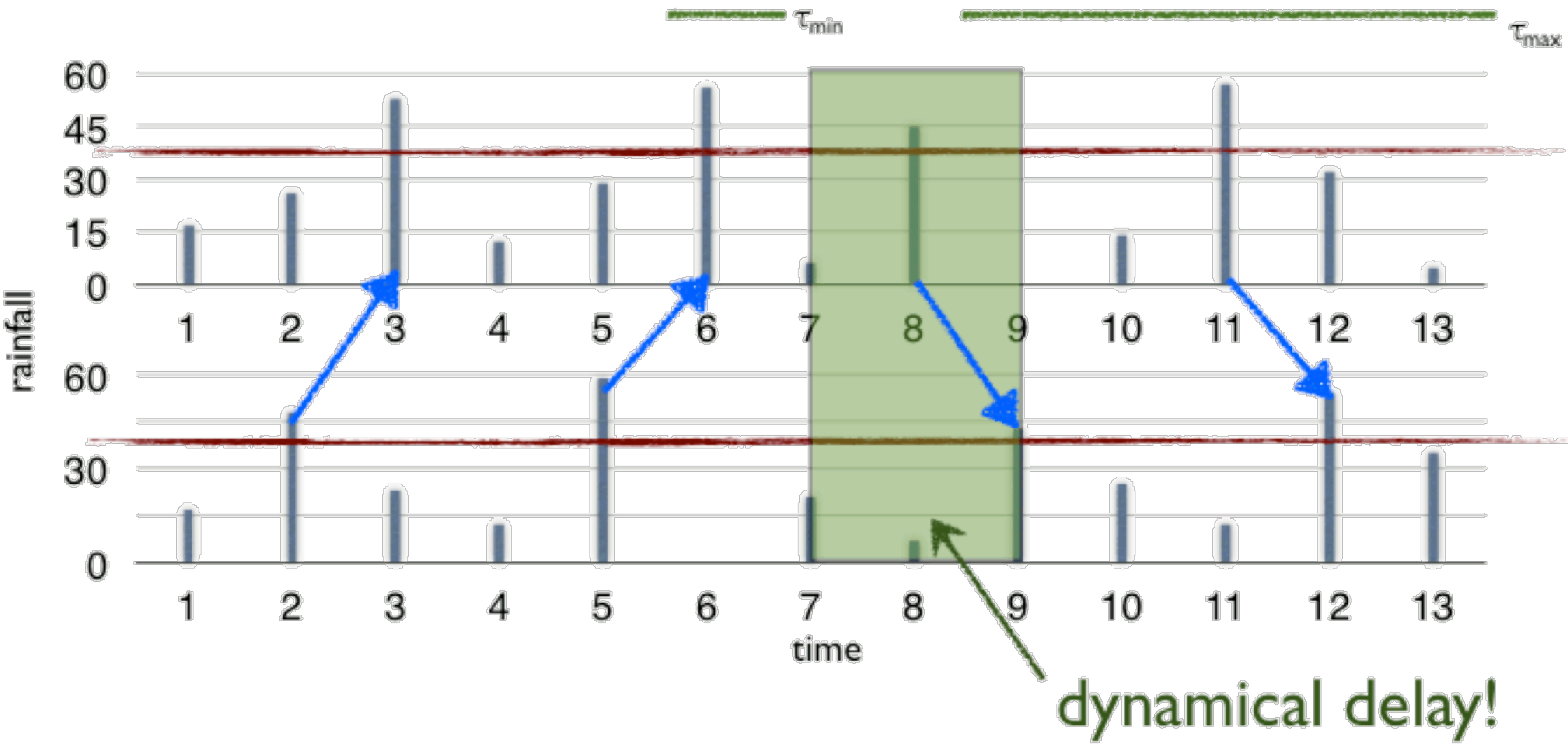


network construction

represent strongest synchronizations (2%) as directed and weighted network links:

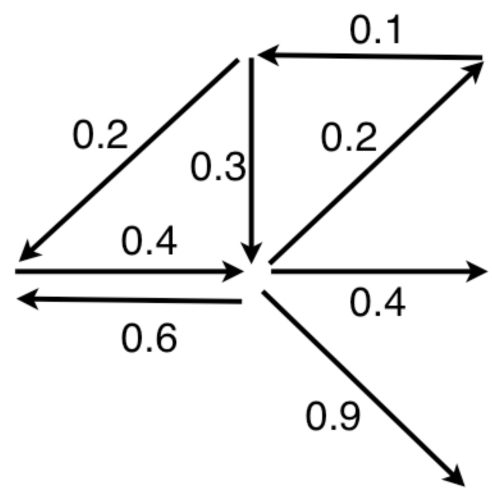
$$A = (A_{ij})_{1 \leq i,j \leq N}$$

definition:

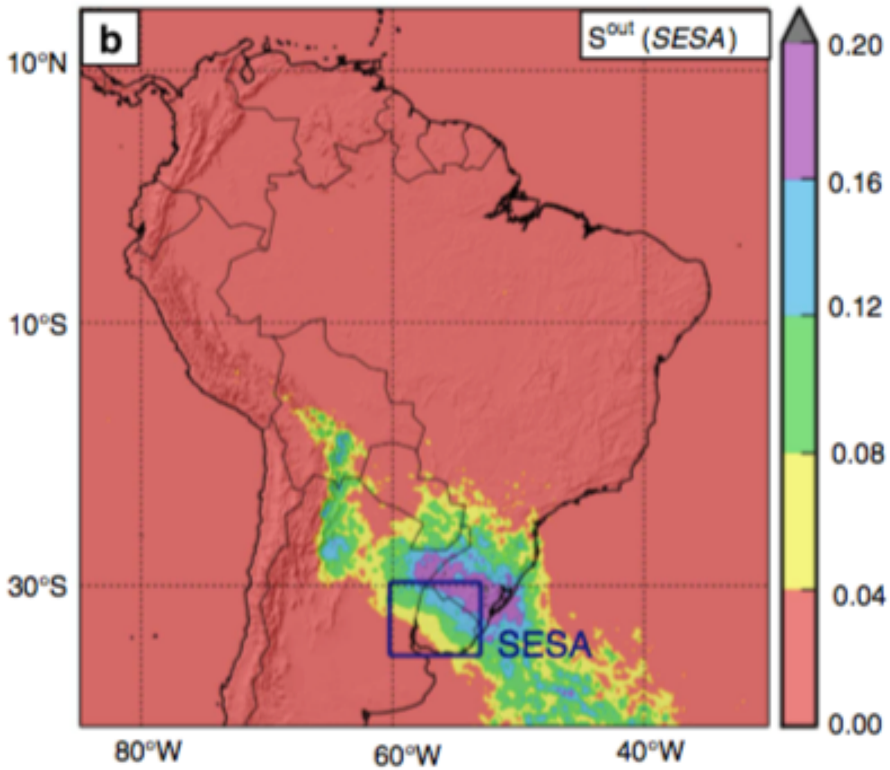
in-strength(i) = sum of all weights at links pointing to i: $$\mathcal{IS}(i) = \sum_{j=1}^{N} A_{ij}$$

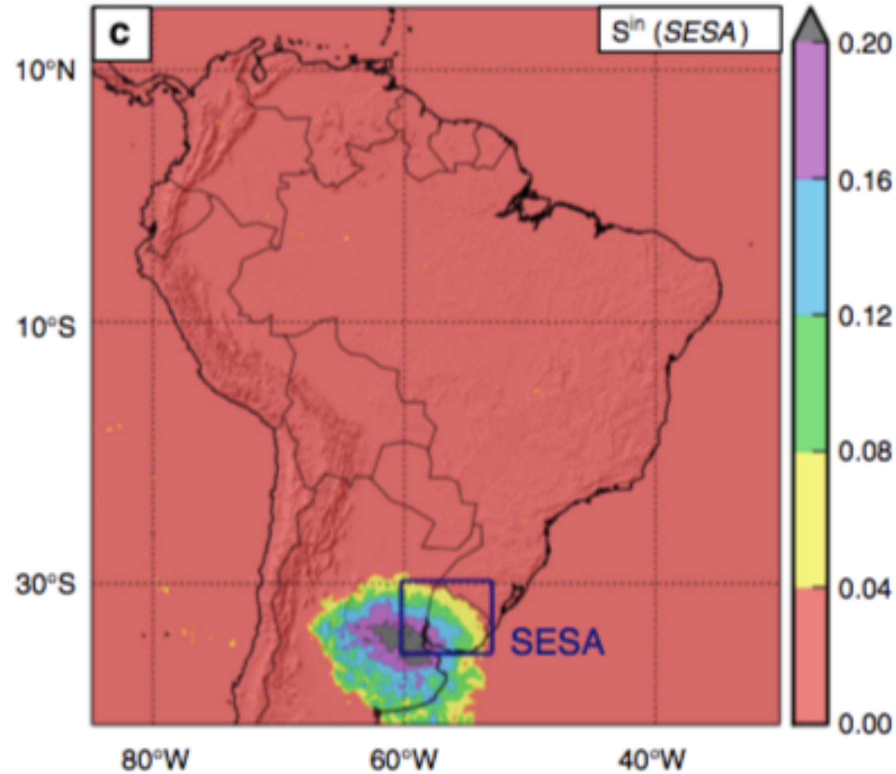
out-strength(i) = sum of all weights at links pointing from i: $$\mathcal{OS}(i) = \sum_{j=1}^{N} A_{ji}$$

network divergence = Δstrength(i) = in-strength(i) - out-strength(i): $$\Delta\mathcal{S}(i) = \mathcal{IS}(i) - \mathcal{OS}(i)$$



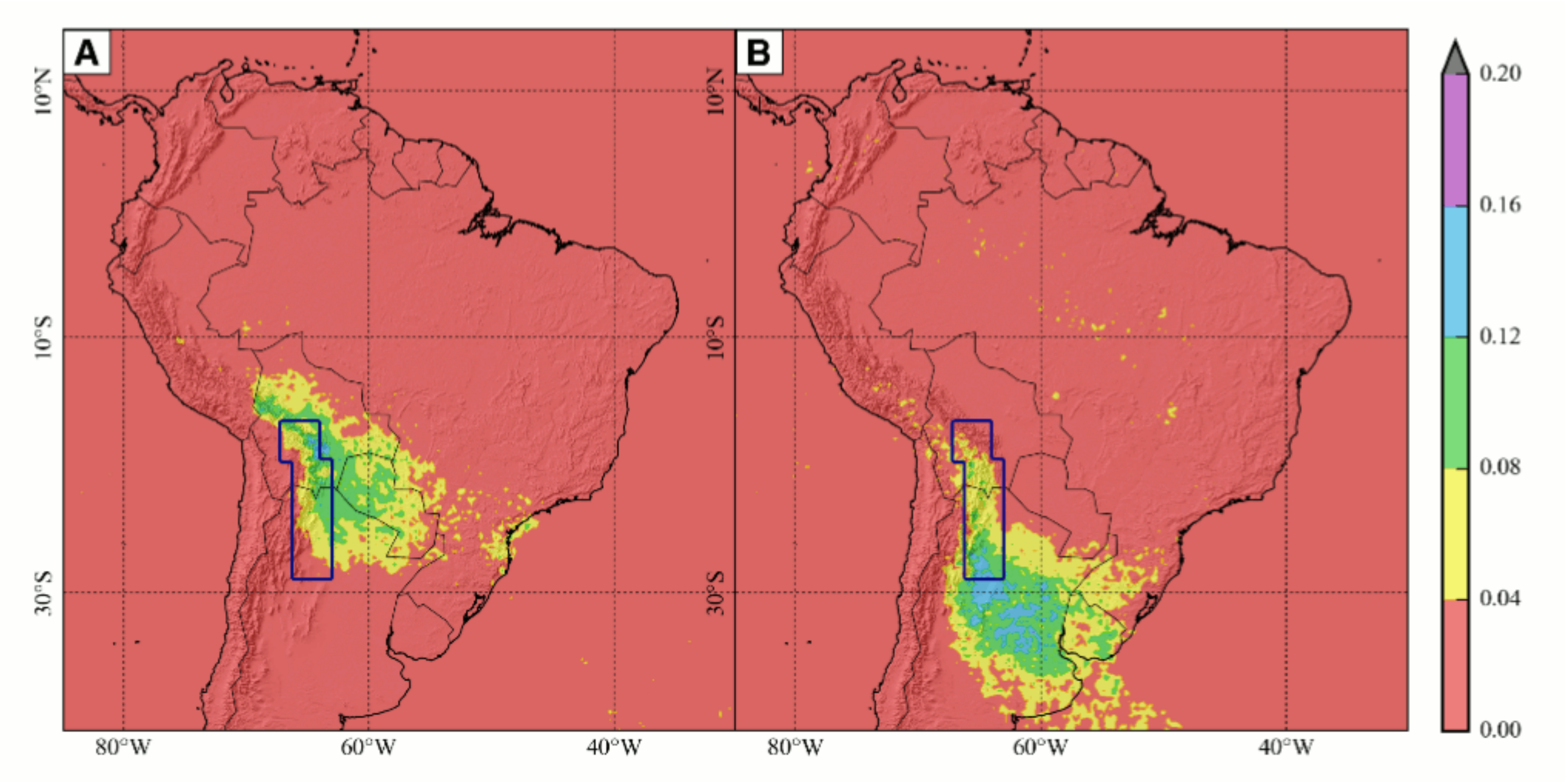
SESA OUT strengh IN strengh





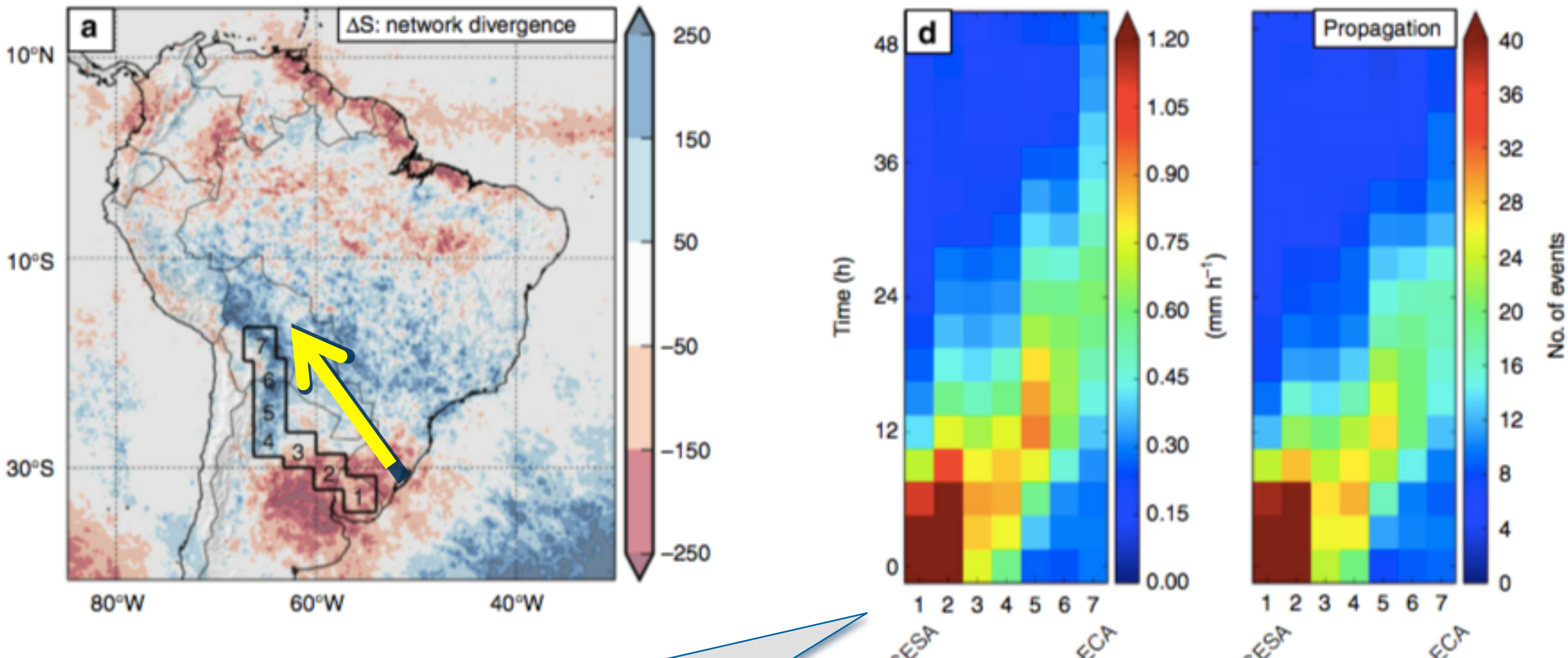
Boers et al, Nature Comm. 2014

ECA OUT strengh IN strengh



Boers et al, Nature Comm. 2014

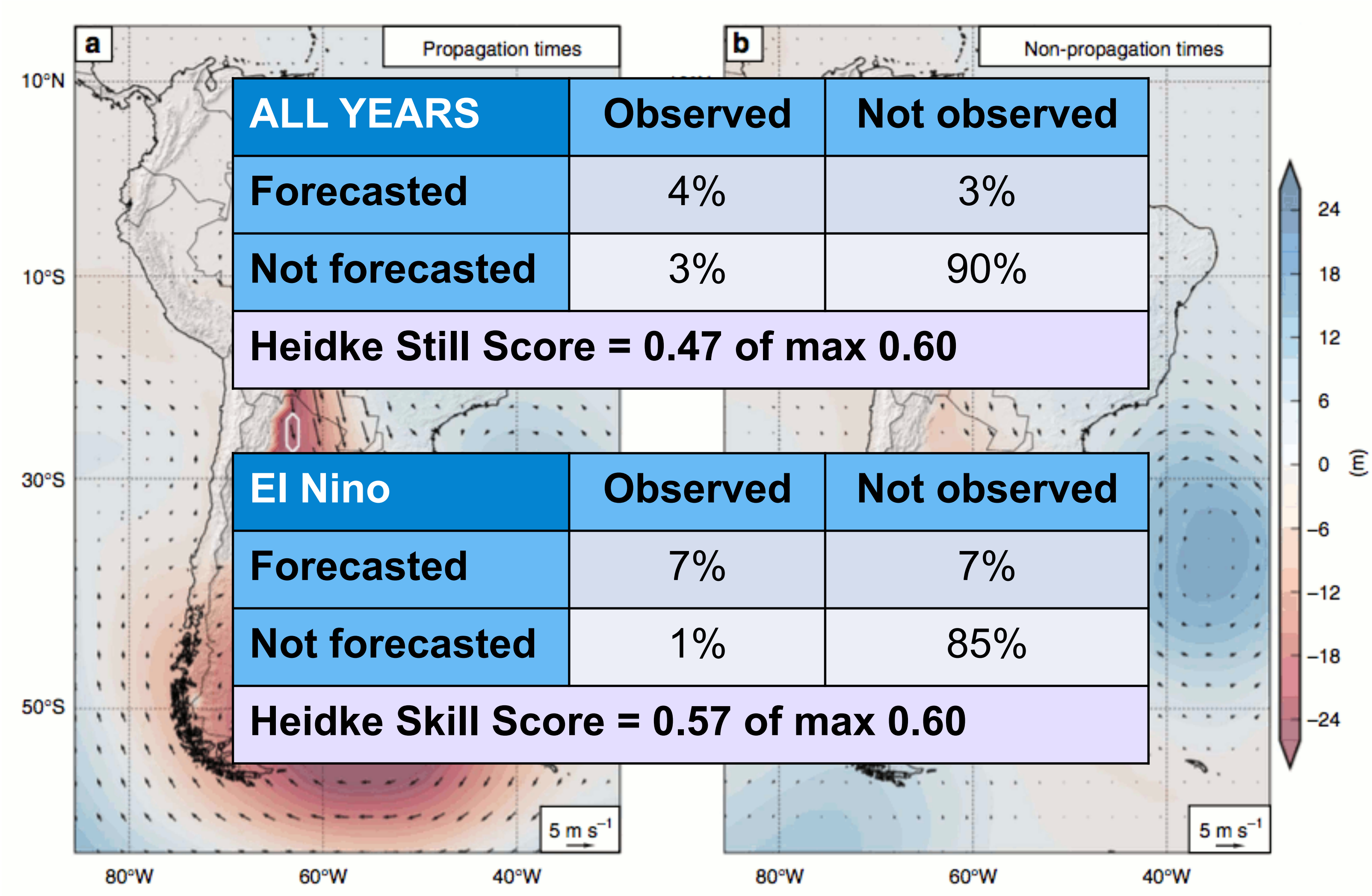
Network Divergence



Precipitation propagating north,
contrary to moisture flux!
~ 80 km /h

Boers et al, Nature Comm. 2014

Can we predict?

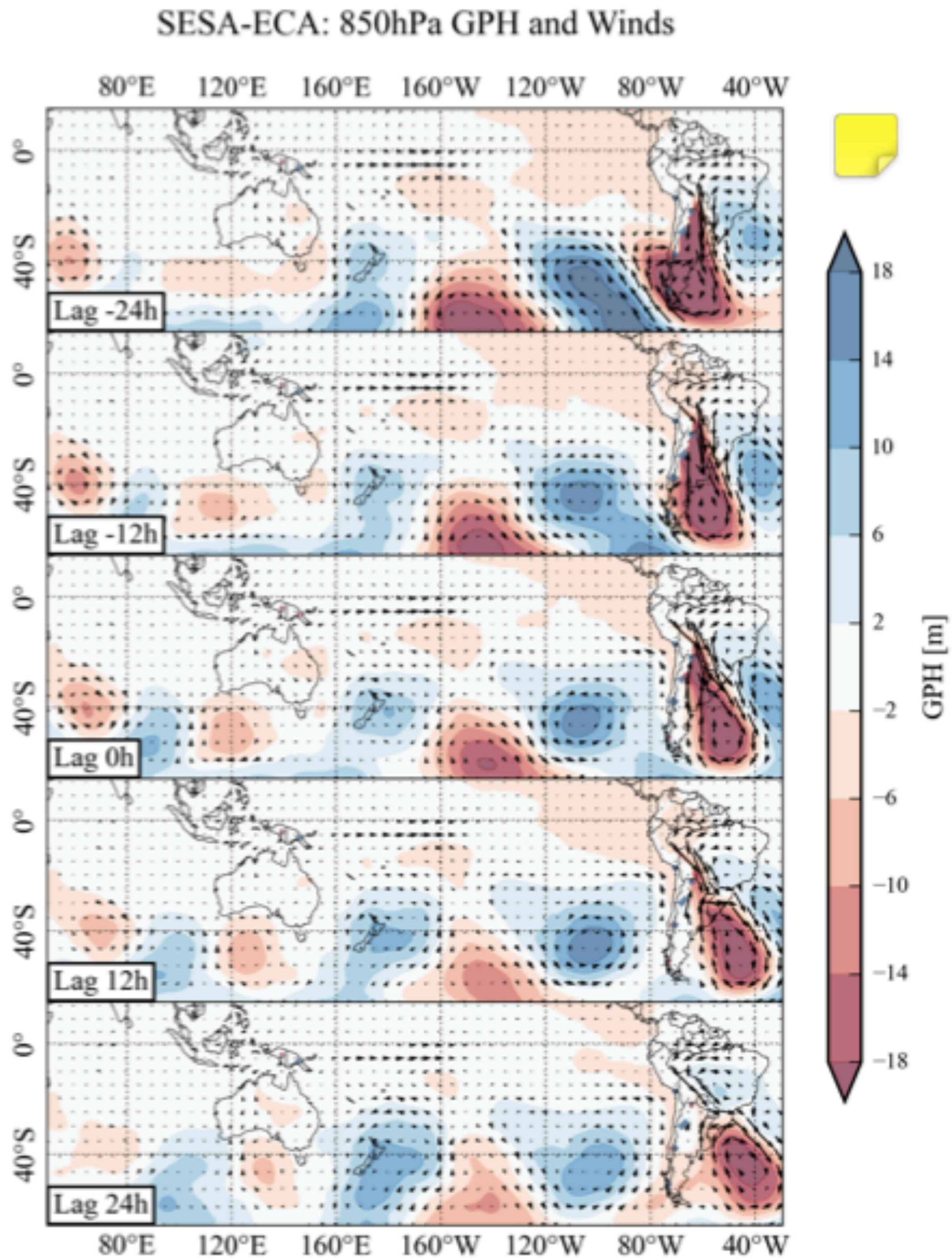


ALL YEARS	Observed	Not observed
Forecasted	4%	3%
Not forecasted	3%	90%
Heidke Still Score = 0.47 of max 0.60		

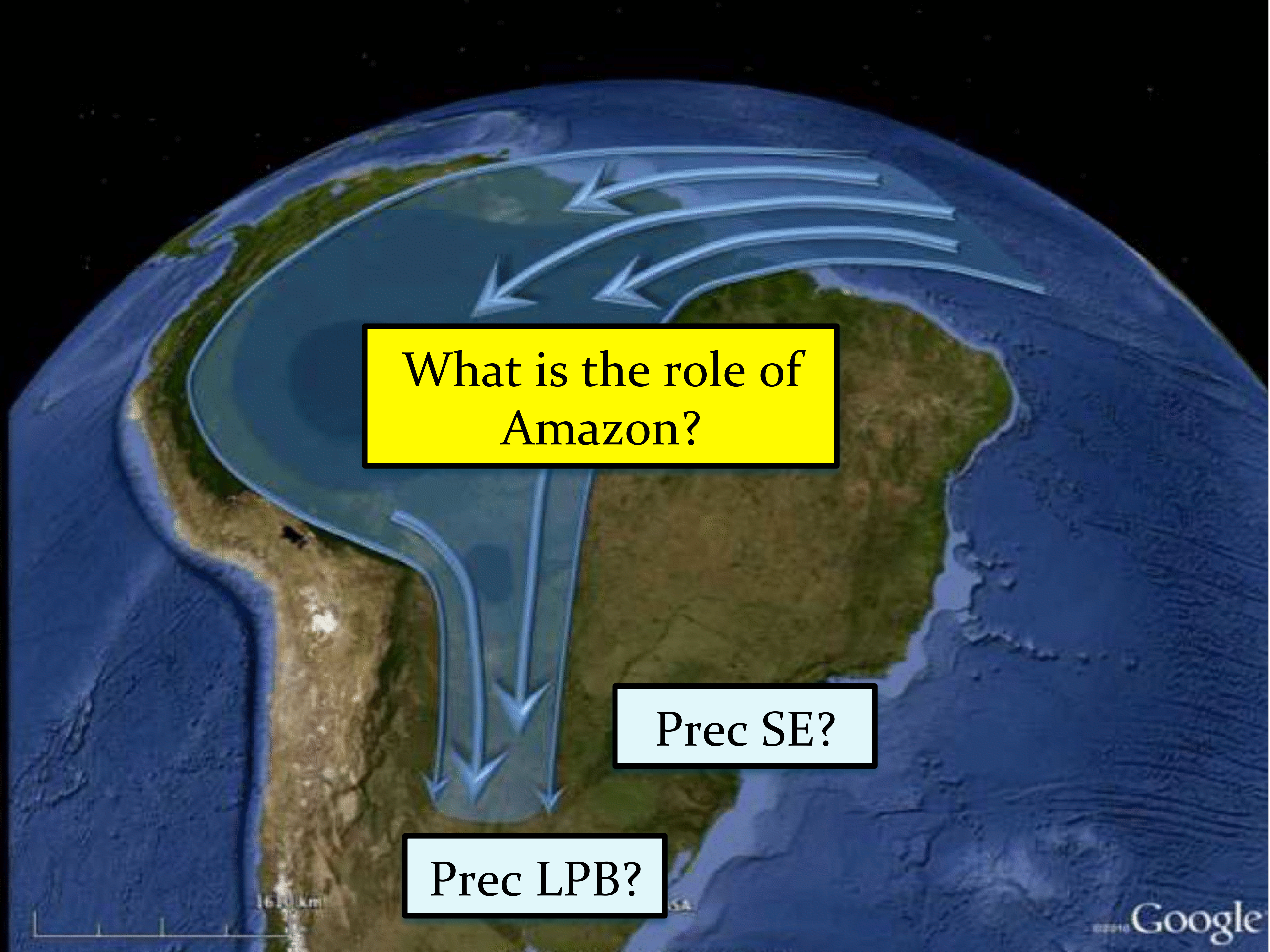
El Nino	Observed	Not observed
Forecasted	7%	7%
Not forecasted	1%	85%
Heidke Skill Score = 0.57 of max 0.60		

- Besides the
  - Saddle point
  - Low pressure tongue
  - NA Low
  - Through
  - ...

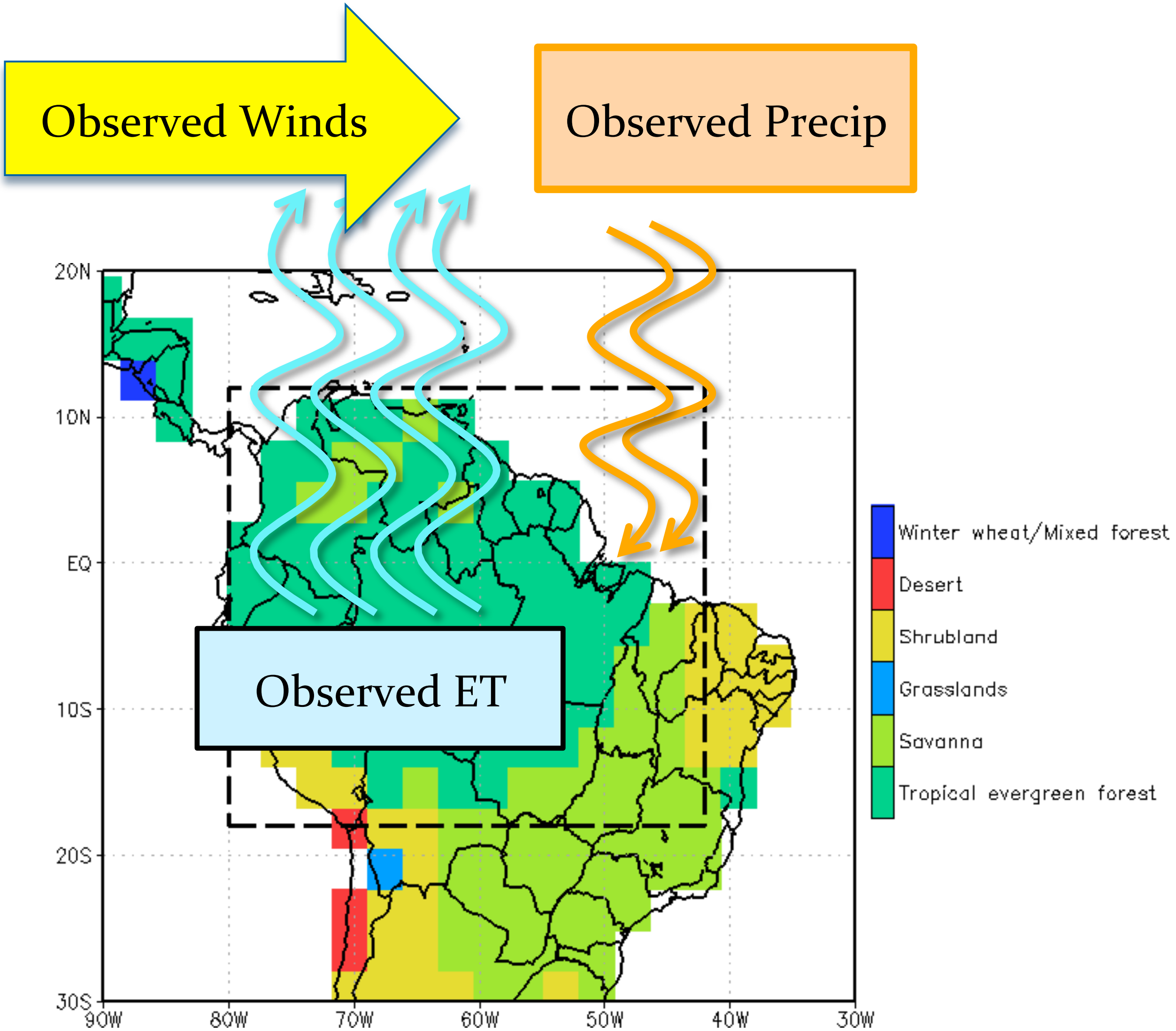
- There is a Rossby wave train propagating from the extra tropics!

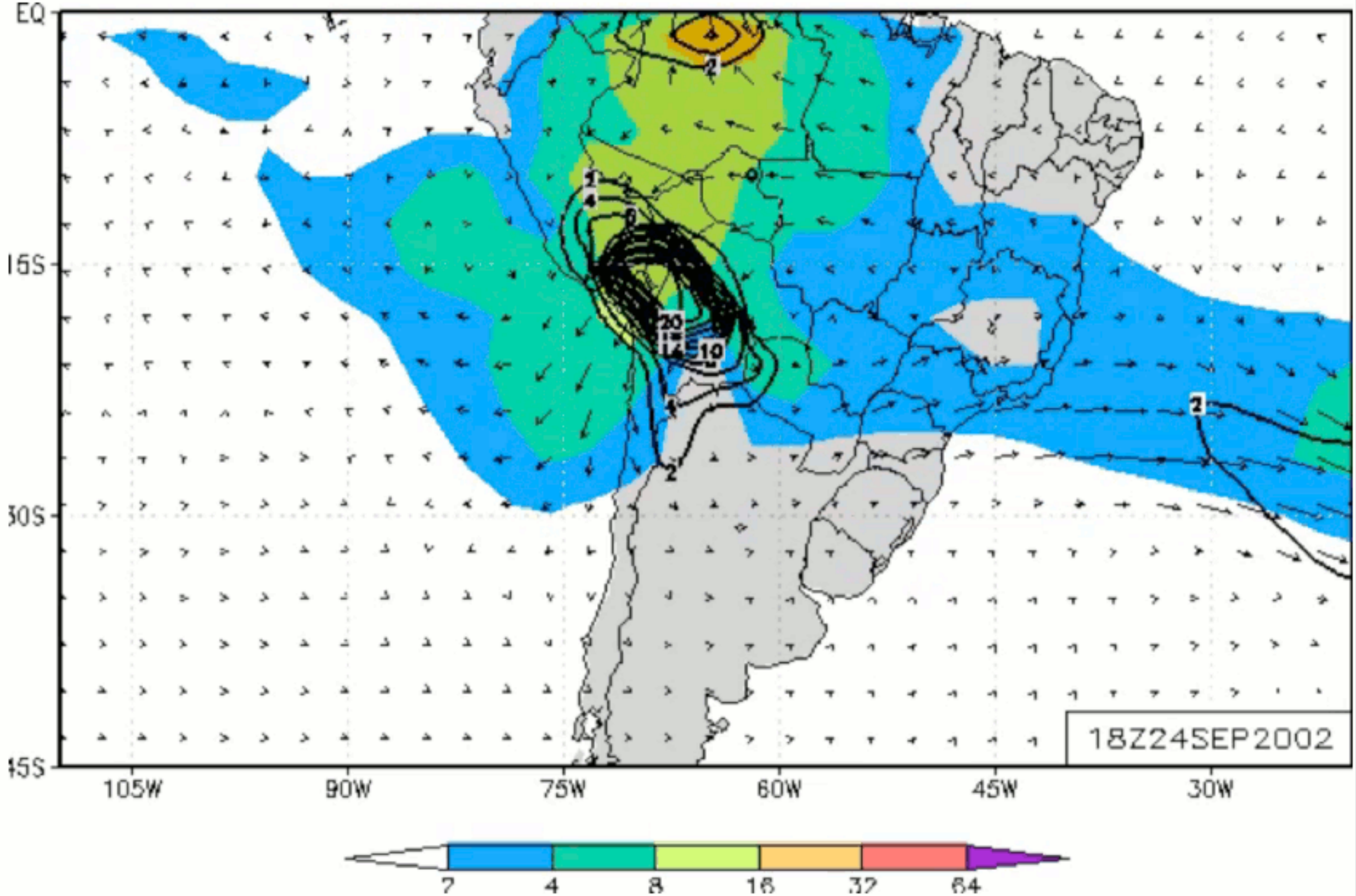


Boers, Barbosa et al, J. Clim. (2015)

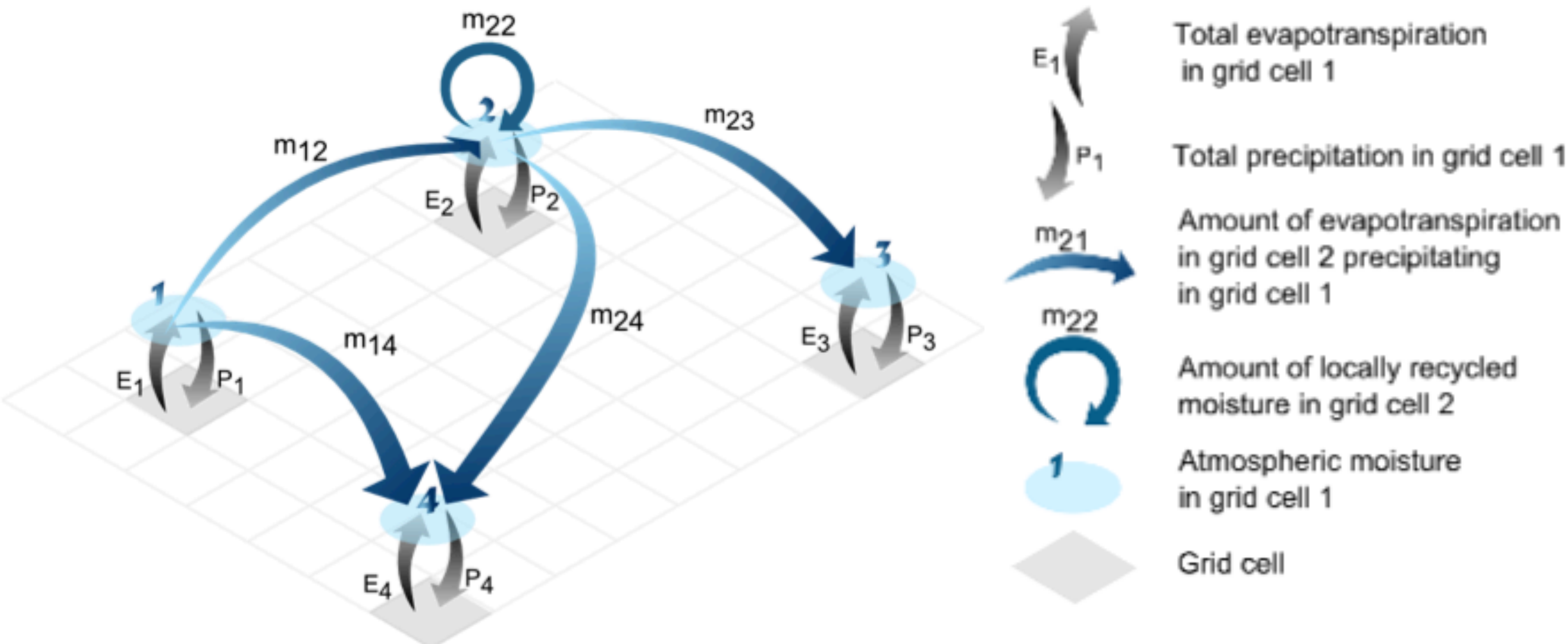

What is the role of Amazon?
Prec SE?
Prec LPB?
Google

2-Layer Moisture Transport Model




EQ
15S
30S
45S
105W
90W
75W
60W
45W
30W
18Z24SEP2002
7
4
8
16
32
64

Moisture (complex) network



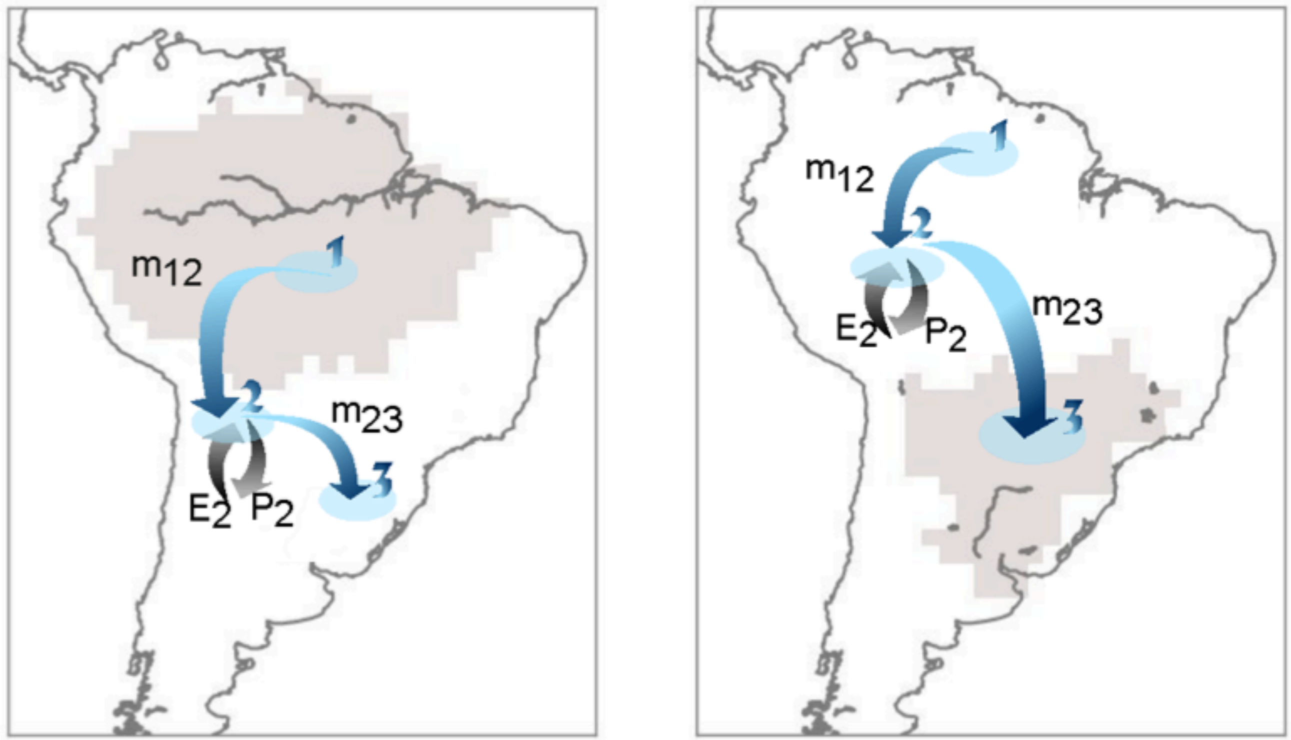
Just for grid 2

E2 = m22 + m23 + m24

P2 = m22 + m12

Zemp et al, ACP 2014

Cascading



Different paths for water, and possible cascading before getting to "final" destination!

Zemp et al, ACP 2014

Cascading

- For 45% of the pairs of nodes, the direct transport the most important
- Hence, for 55% a transport with at least one stop is more efficient!

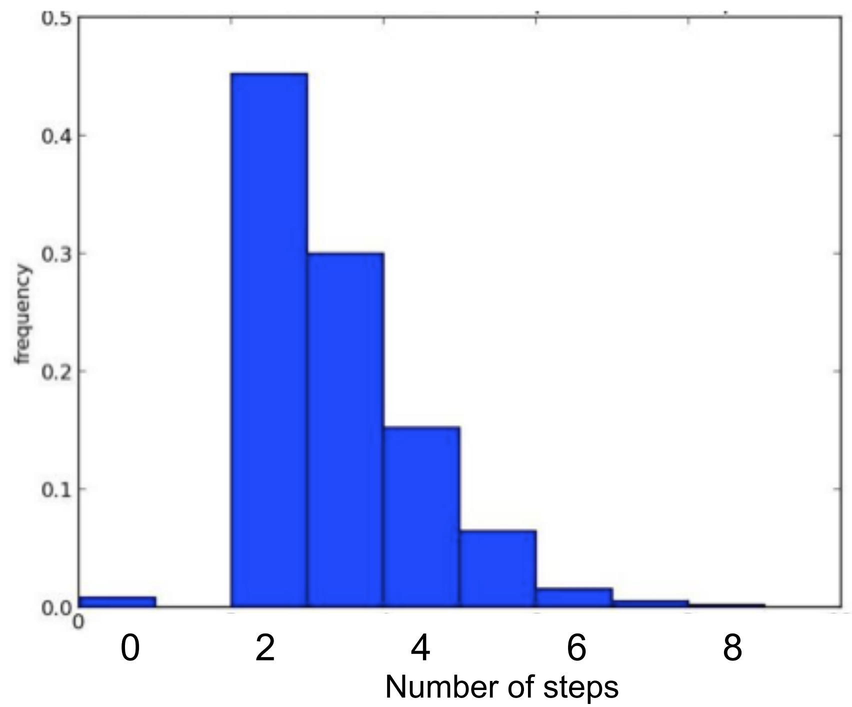
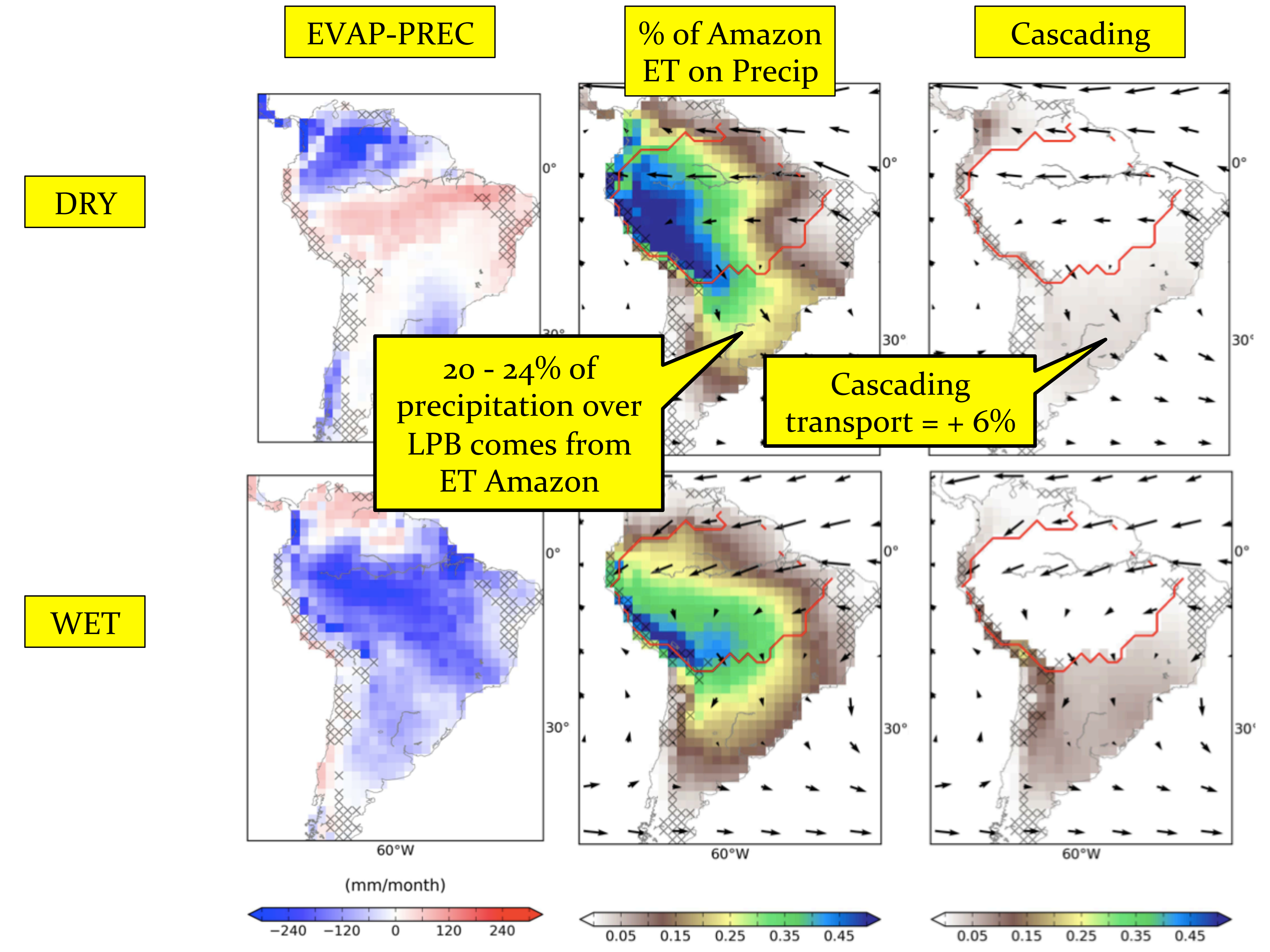
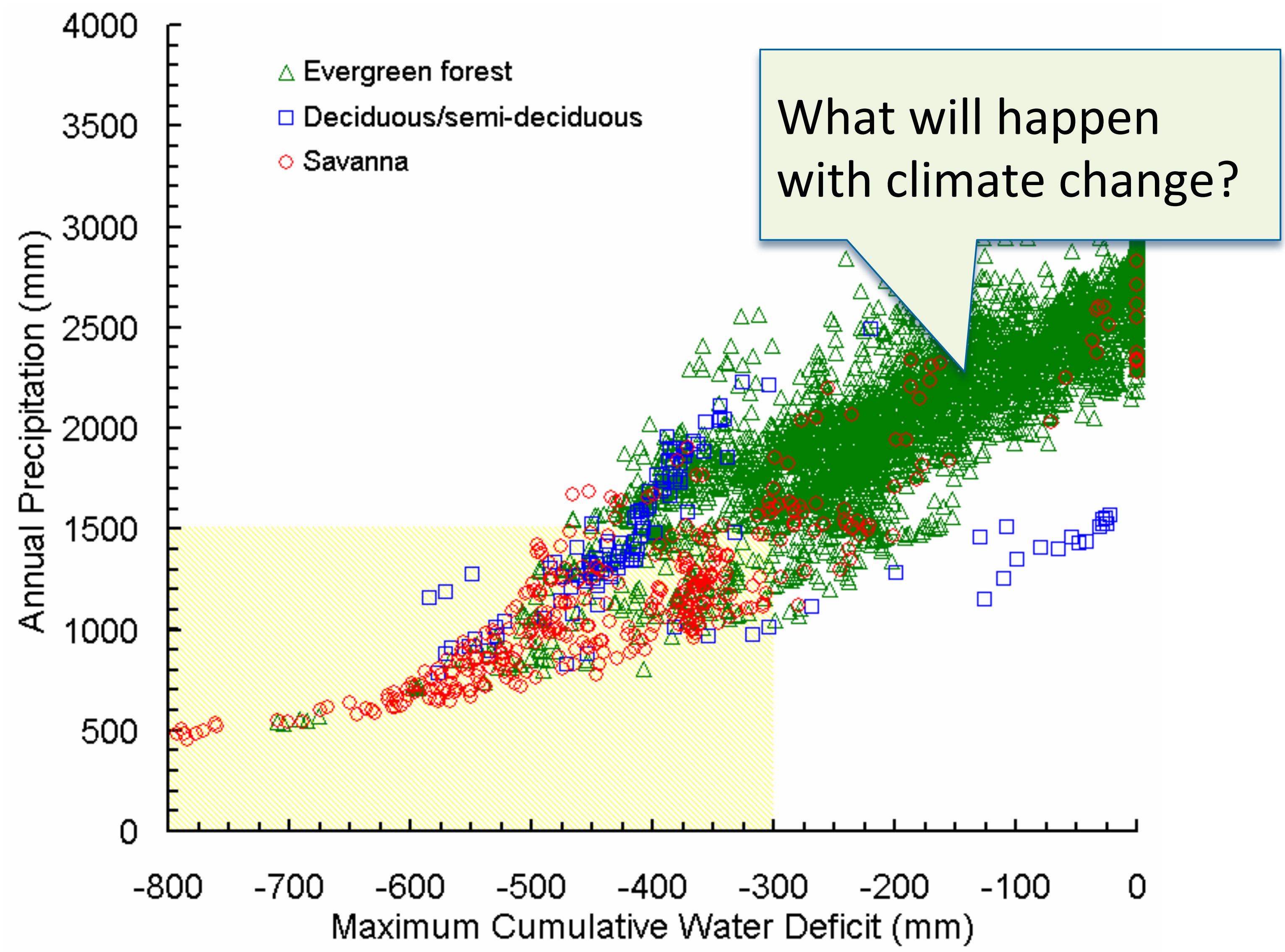


Fig. - Distribution of optimal paths
For 0 steps, local recycling
For 2 steps, direct transport
For 3 or more steps, path with cascading

Zemp et al, ACP 2014


EVAP-PREC
% of Amazon ET on Precip
Cascading
DRY
WET
20 - 24% of precipitation over LPB comes from ET Amazon
Cascading transport = + 6%
0°
30°
60°W
(mm/month)
−240
−120
0
120
240
0.05
0.15
0.25
0.35
0.45

Malhi *et al.*, **Exploring the likelihood and mechanism of a climate-change induced dieback of the Amazon rainforest,** *Proceedings of the National Academy of Sciences*, 2010



Probability of finding forest

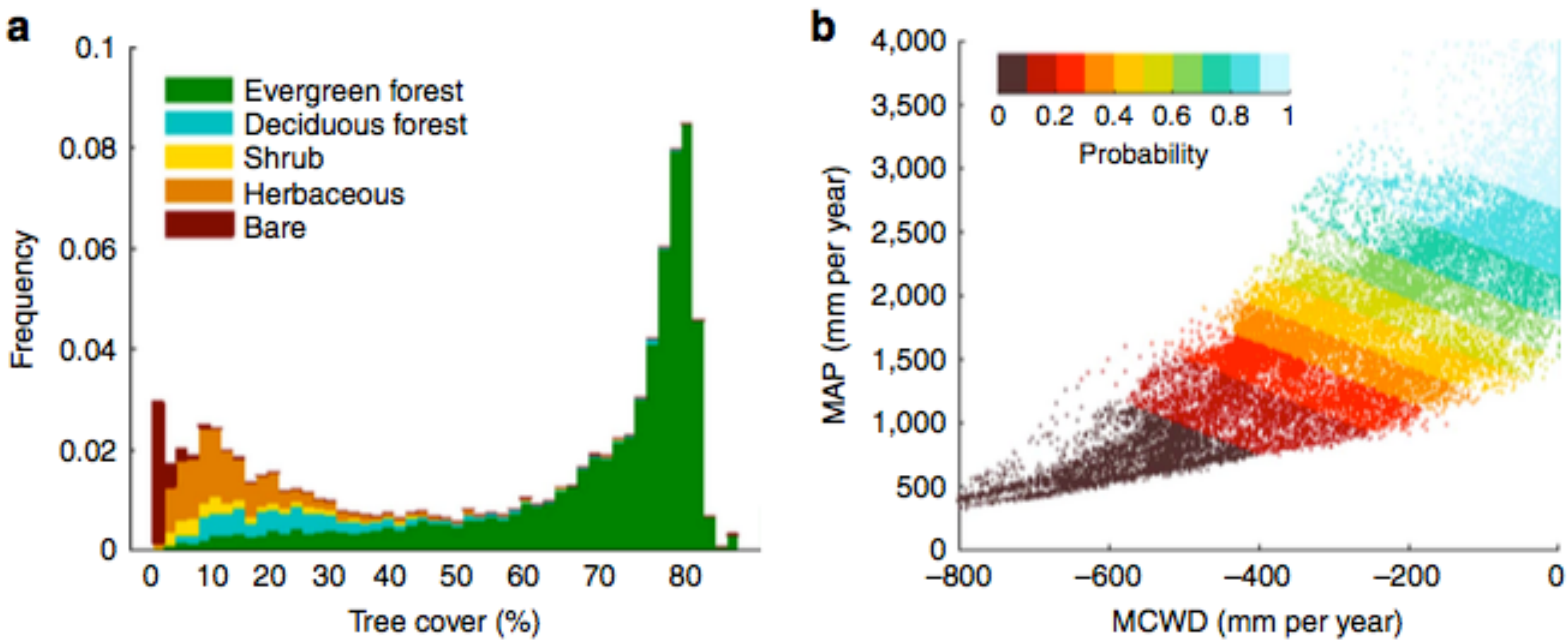
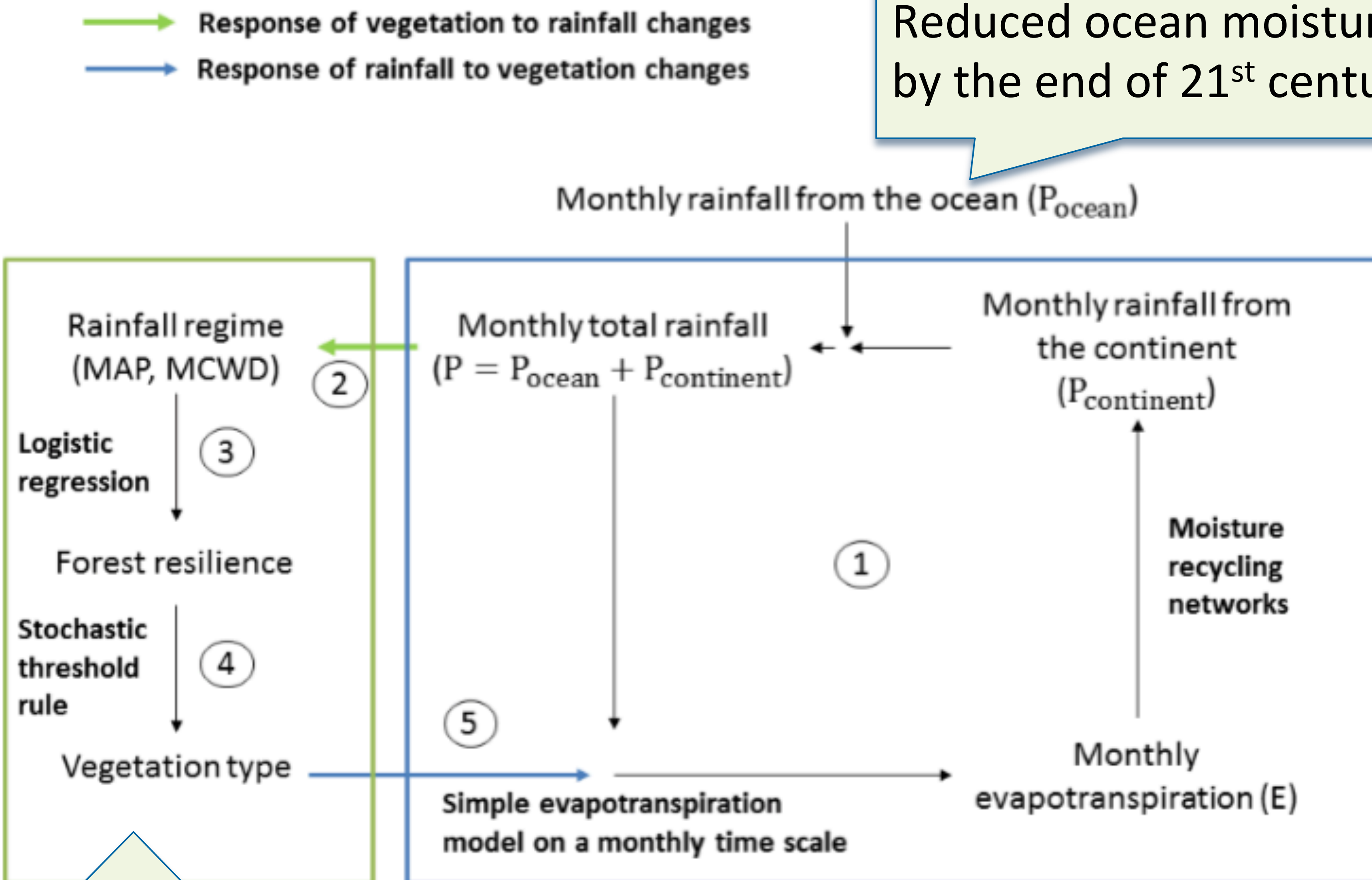


Figure 2 | Probability of finding forest in tropical South America depending on rainfall regime. (**a**) Frequency distribution of tree-cover (TC) data (MOD44B v5 for the period 2001–2010) and associated land-cover types (from GLC2000 classification). (**b**) Probability of finding forest (TC ≥ 55%) as a function of mean annual precipitation (MAP) and maximum cumulative water deficit (MCWD) calculated from a logistic regression model (equation (4 and 5)) using monthly rainfall data (TRMM 3B42 for the period 2000–2012).

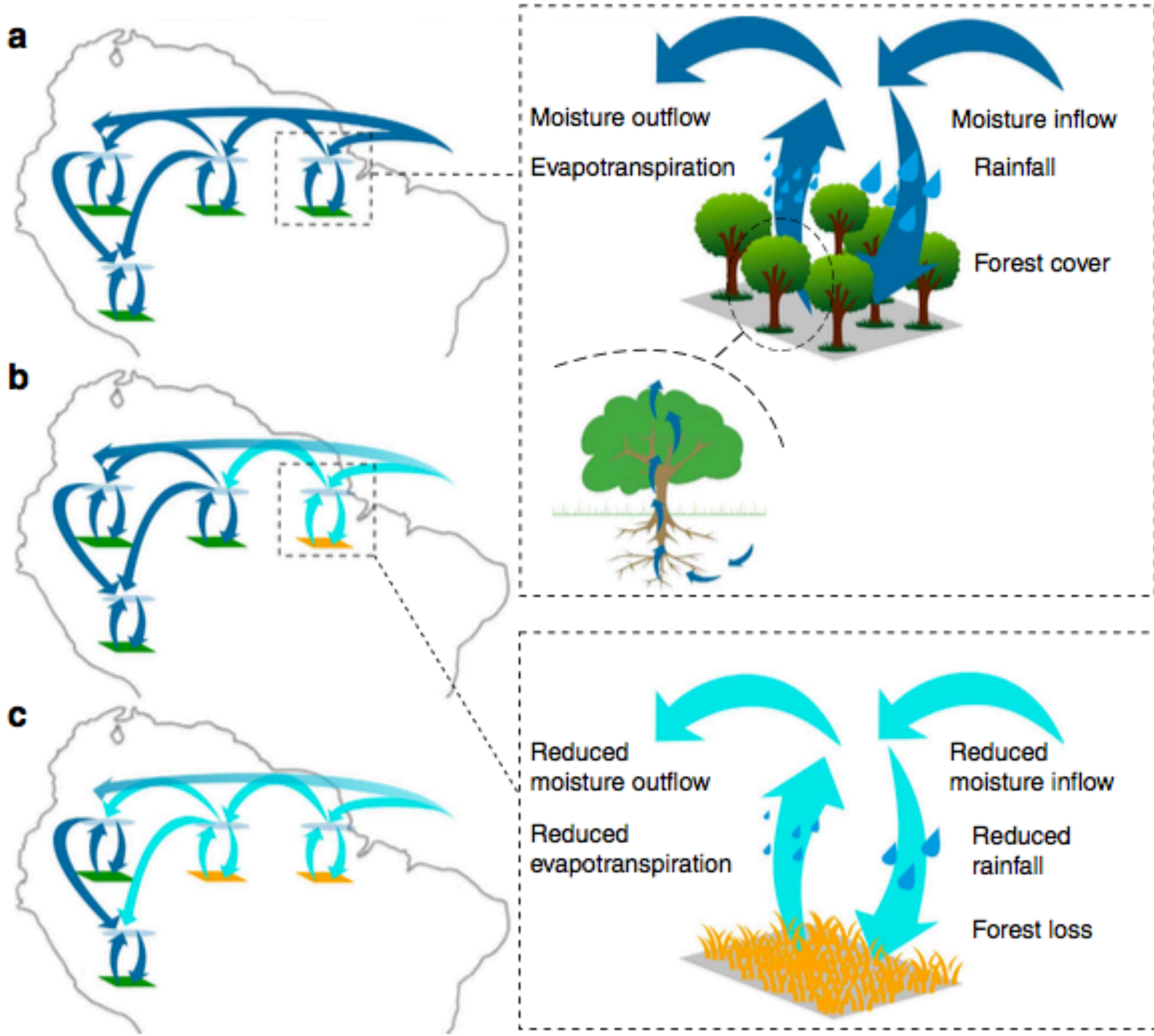
Zemp et al., Nature Comm. (2017)

Reduced ocean moisture by the end of 21st century

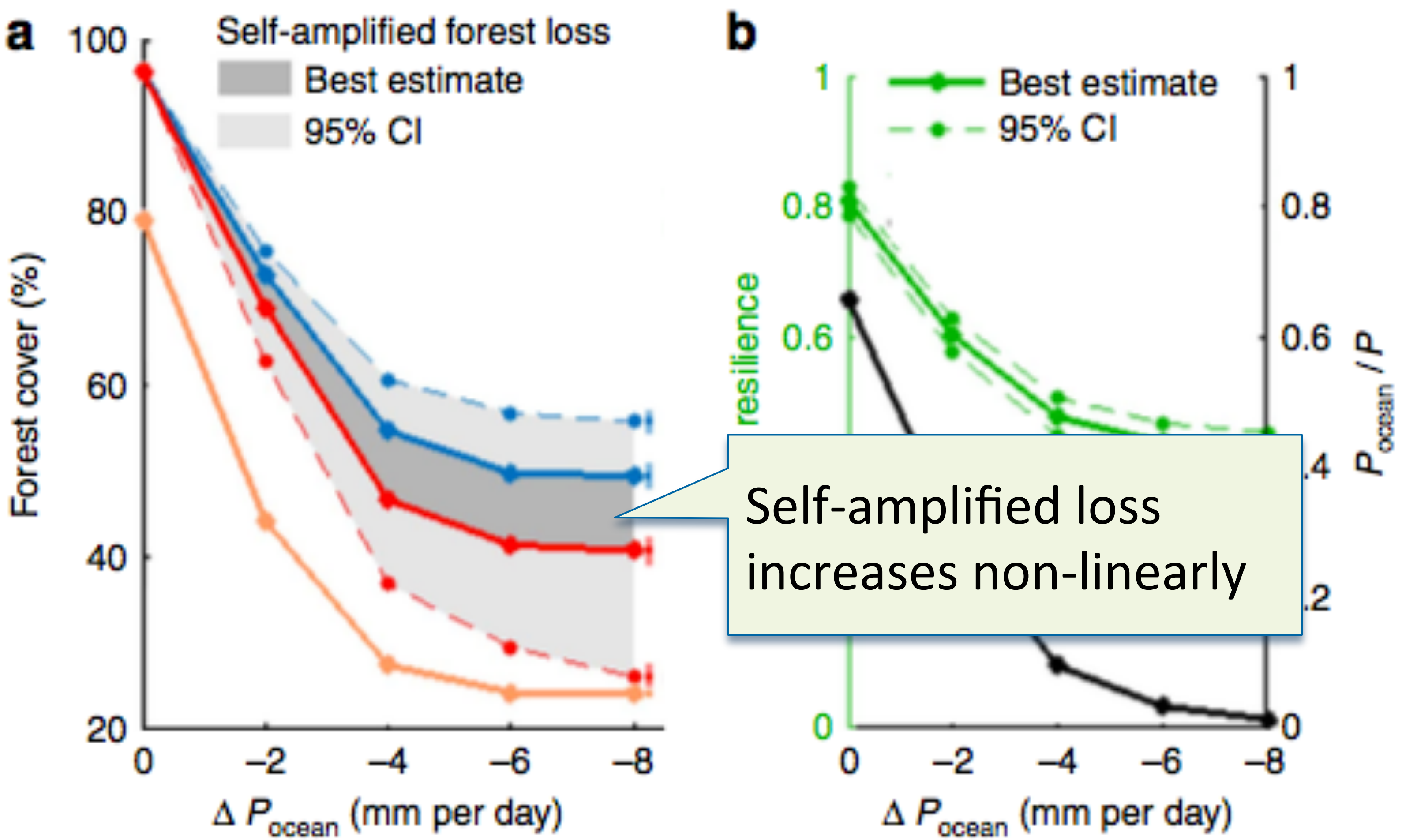


What would happen with the vegetation?

Zemp et al., Nature Comm. (2017)


a
b
c
Moisture outflow
Moisture inflow
Evapotranspiration
Rainfall
Forest cover
Reduced
moisture outflow
Reduced
moisture inflow
Reduced
evapotranspiration
Reduced
rainfall
Forest loss

Non-linear response



One-way coupling P➔Veg

Fully coupled system P⇔Veg

Zemp et al., Nature Comm. (2017)

End of 21st century

- Self-amplified forest loss increases nonlinearly with decreasing oceanic moisture inflow because of:

1. a nonlinear decrease of forest resilience,
2. a stronger reduction of evapotranspiration after forest loss and
3. an increased contribution of moisture recycling to total rainfall

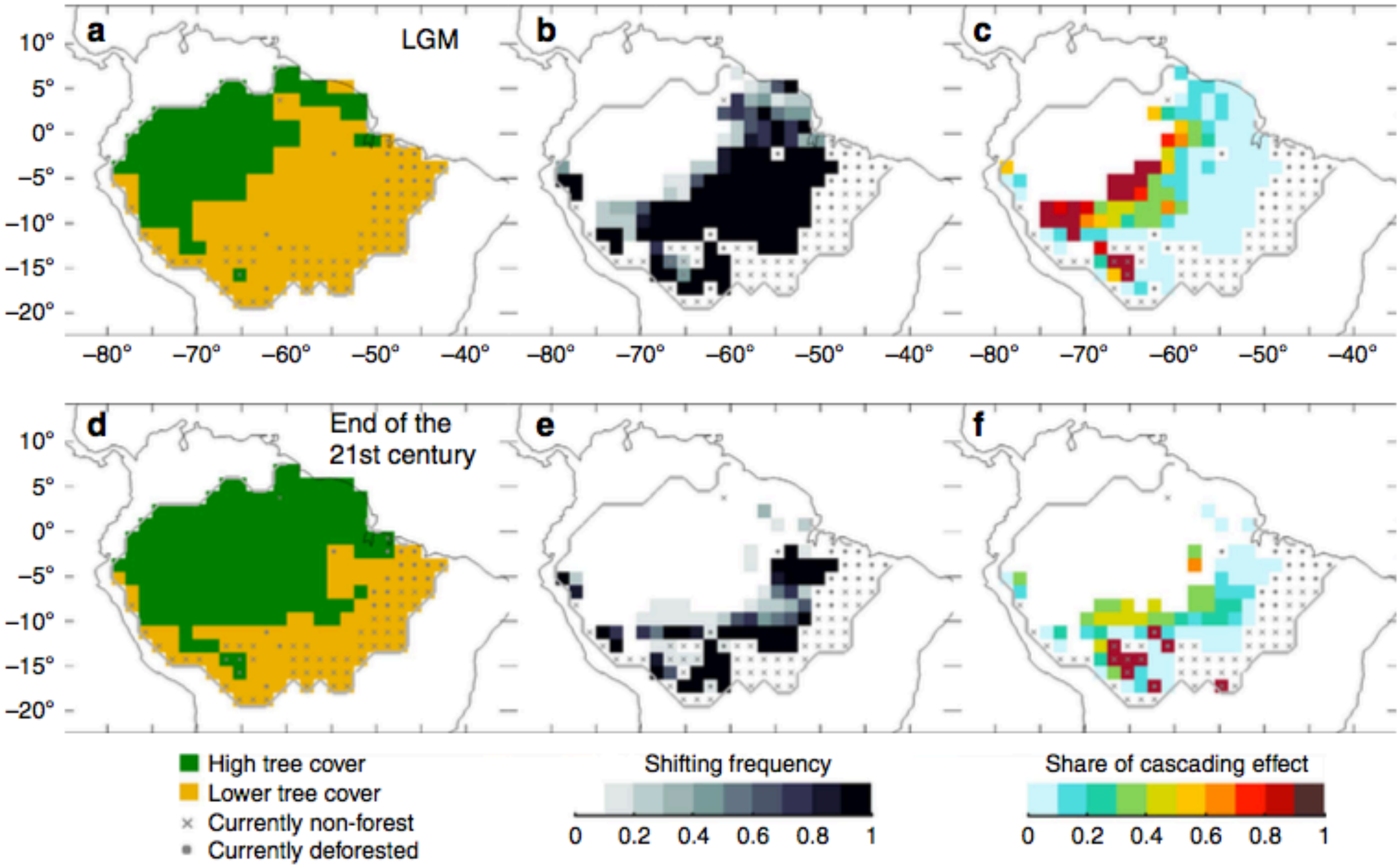
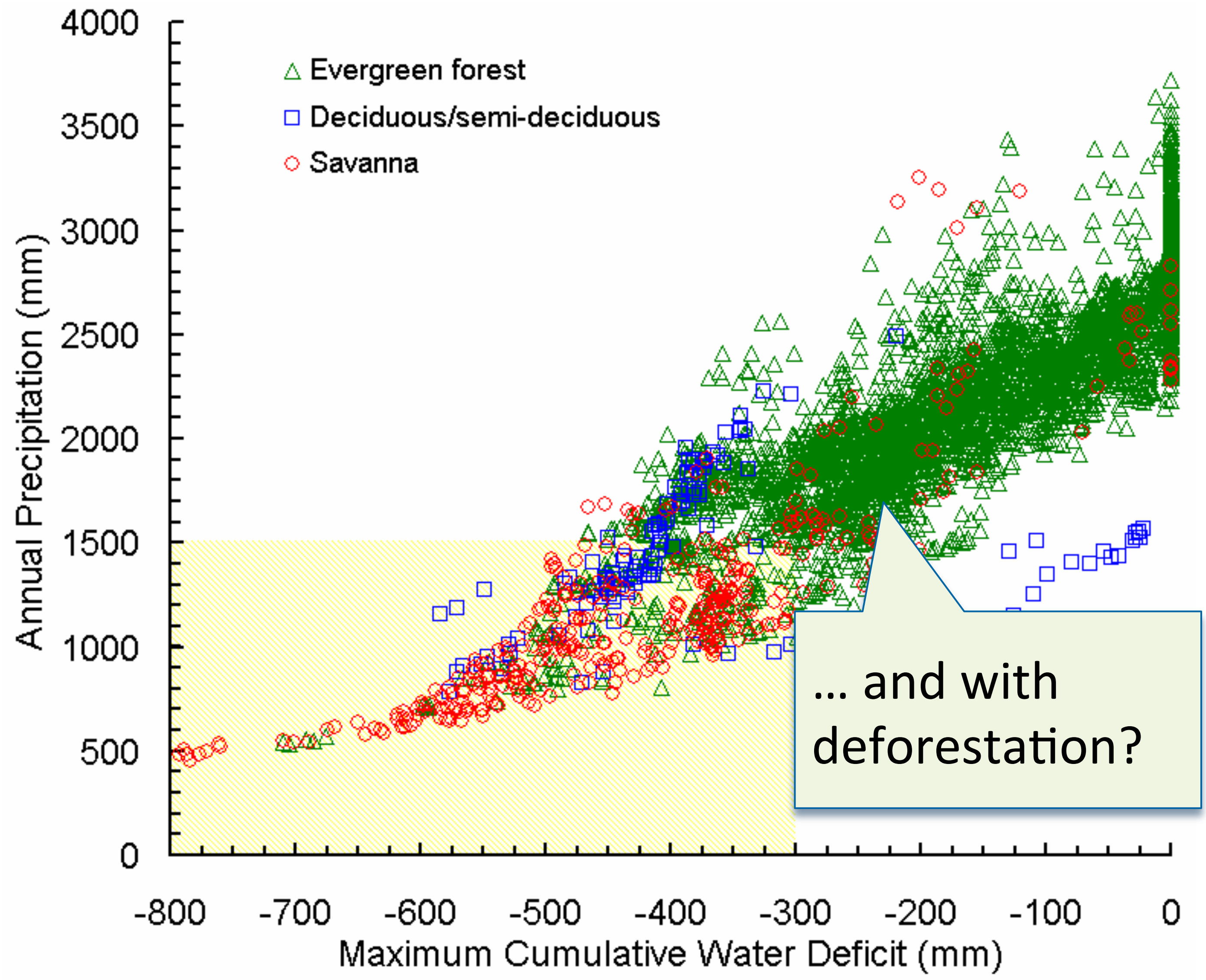


Figure 5 | Self-amplified forest loss for the Last Glacial Maximum (LGM) and for the end of the twenty-first century. (**a**,**d**) Most frequent vegetation cover for 1,000 realizations of the cascade model. (**b**,**e**) Shifting frequency of Amazon forest. (**c**,**f**) Share of cascading effects in causing forest shifts (see Methods). Results are shown (**a**–**c**) for the 'LGM' scenario and (**d**–**f**) for the 'end of twenty-first century' scenario (see Methods).

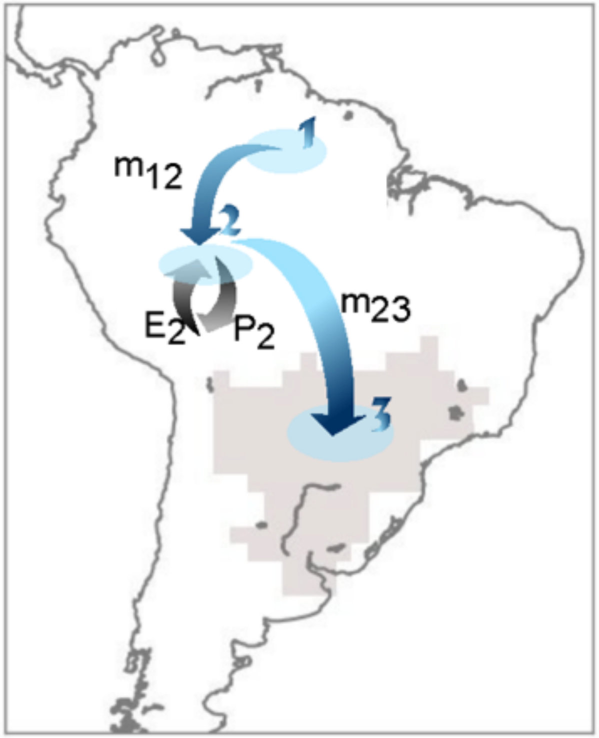
Zemp et al., Nature Comm. (2017)

Malhi *et al.*, **Exploring the likelihood and mechanism of a climate-change induced dieback of the Amazon rainforest,** *Proceedings of the National Academy of Sciences*, 2010

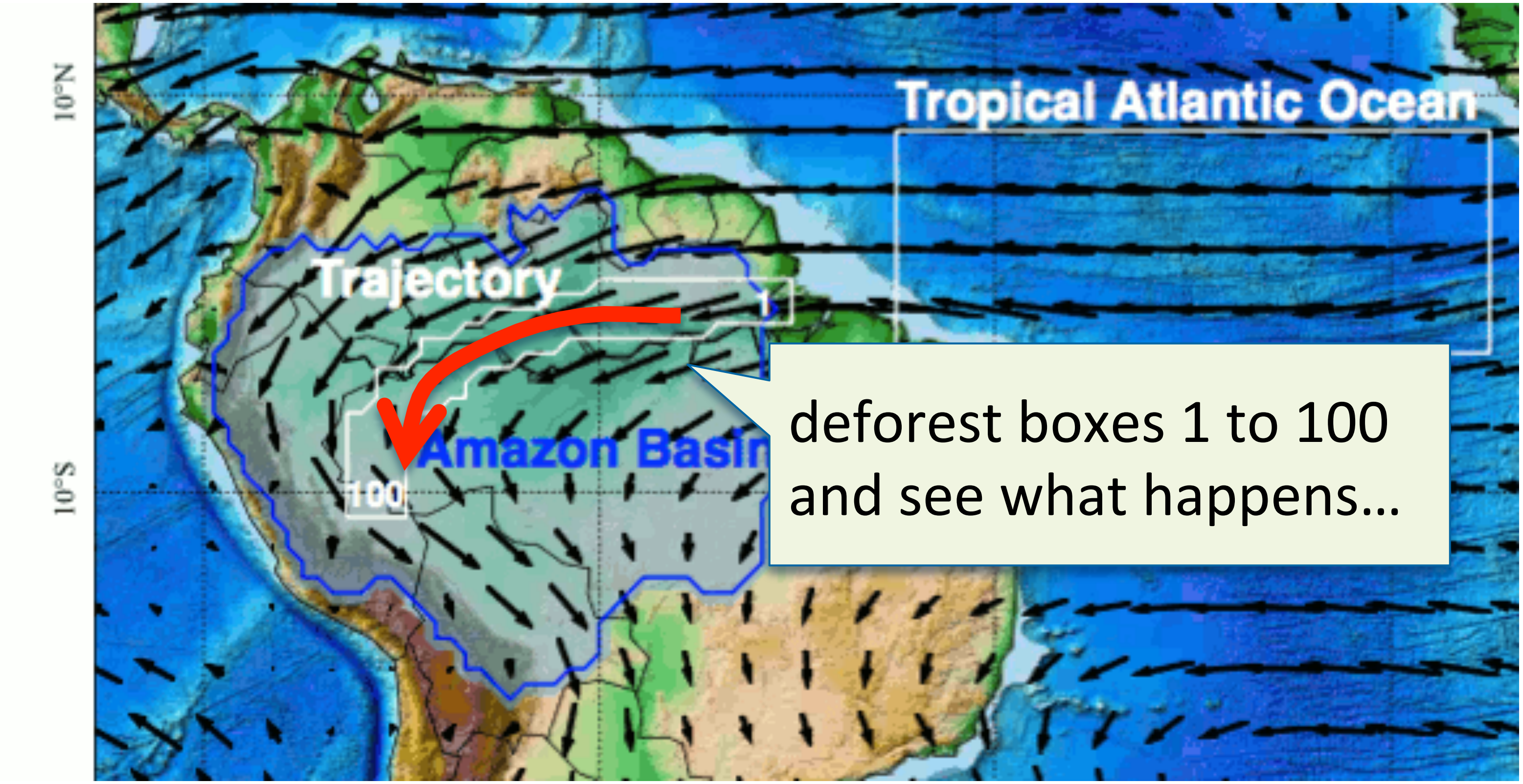


It could be that…

1. Land-use changes that reduce recycling over the Amazon…
2. will reduce the water vapor transport southward (> previously imagined without cascading)…
3. less transport => less precipitation downwind…
4. Important question : How much can we reduce the moisture flux before reaching a tipping point?



1d dynamical system



isolation of the specific relationship between a deforestation-induced decrease of surface heat flux (including, in particular, the decrease of E), and the positive feedback associated with atmospheric LH release

Our simple model:

- From the conservation equations, we wrote a non-linear set considering moisture transport and evap/convergence feedback:

$$\textbf{atmos:} \quad A_i(t+1) = A_i(t) + E_i(t) - P_i(t) - \frac{W_i(t)A_i(t) - W_{i-1}(t)A_{i-1}(t)}{l}$$

$$\textbf{ocean:} \quad S_i(t+1) = S_i(t) + P_i(t) - E_i(t) - R_i(t) \, ,$$

- Wind = sum of "trade winds" slowing down towards the Andes

$$W_i^{trade} = (w_0 - w_c)\left(1 + \frac{1}{1 + e^{w_1 * i - w_2}}\right)$$

- And a wind dependent e

Wc gives the coupling strength

$$W_i^H(t) = w_c L_T(t)\left(1 + \frac{1}{1 + e^{w_1 * i - w_2}}\right)$$

Boers et al., Nature Scientific Reports (2017)

Our simple model (2)

- We also need to calculate, based on empirically fitting the observations,
  - Precip:

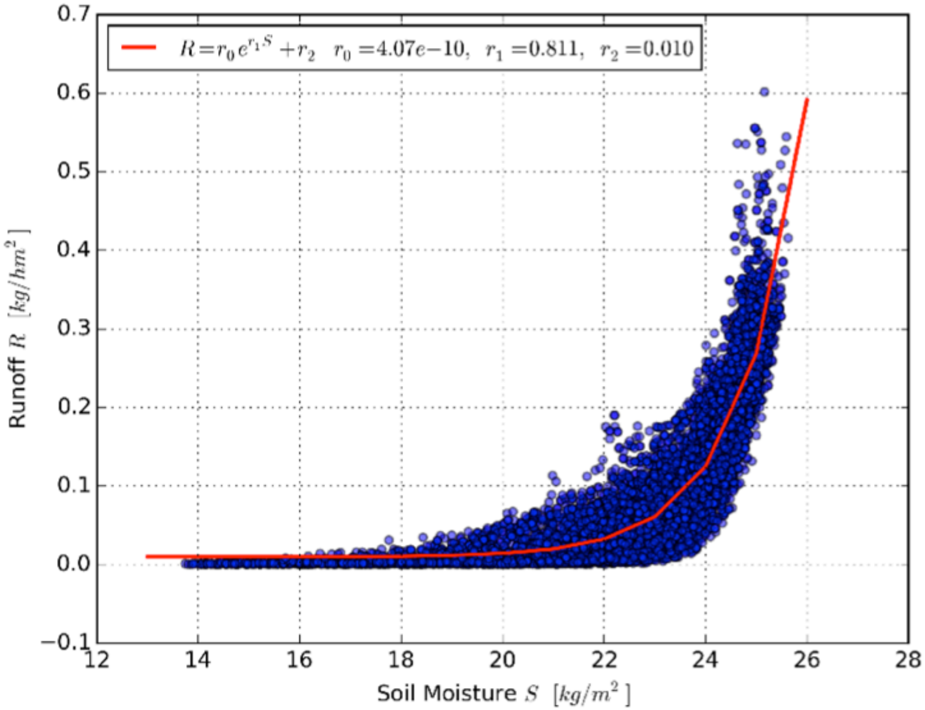
    P = p1 + po * A

  - Evap:

    E = eo / (1 + e(S-e2))

  - and Runoff:

    R = ro exp (r1*S)



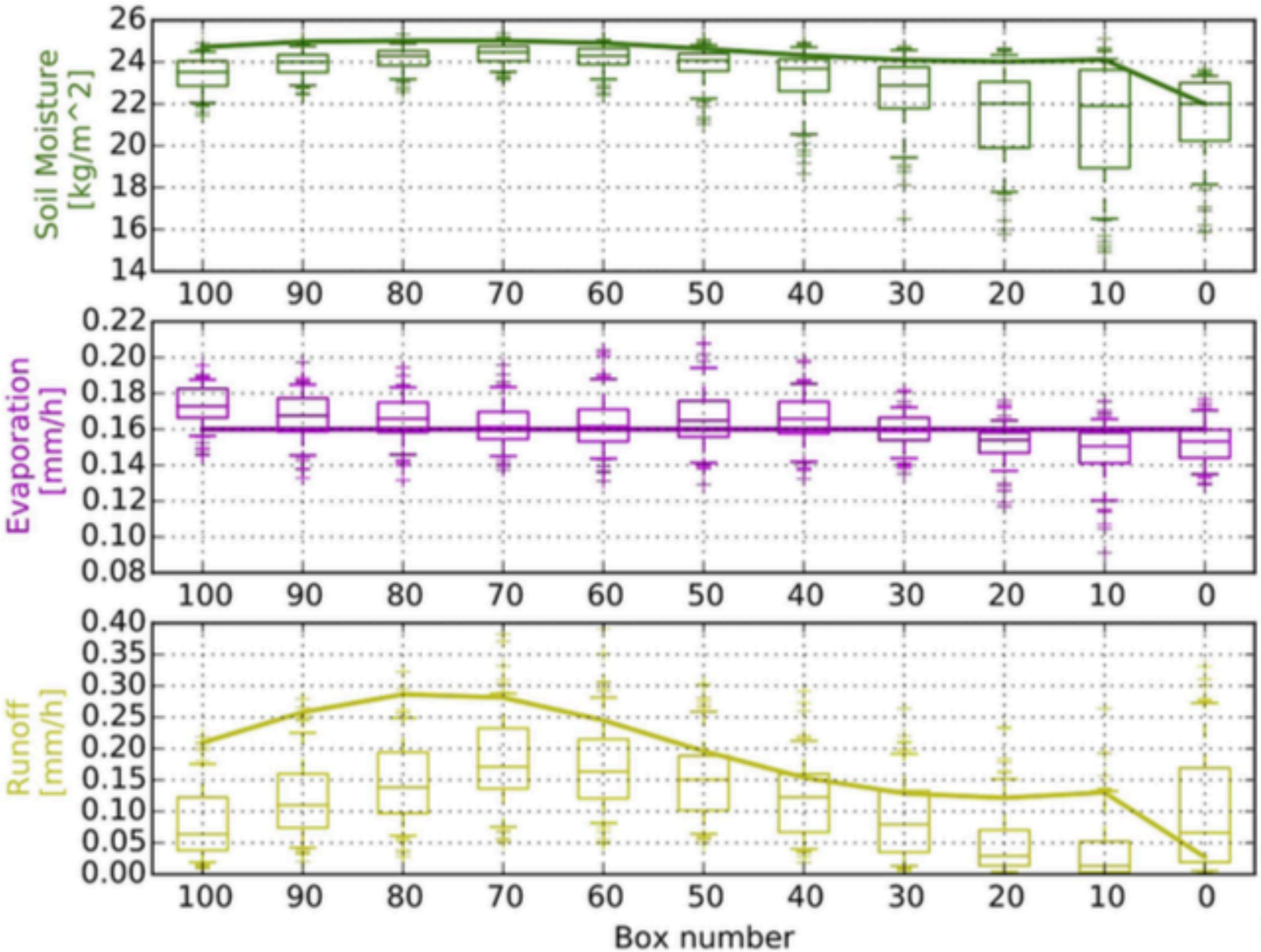


Figure 2. Comparison between ERA interim reanalysis values (box plots) and model results (solid lines) along the trajectory indicated by a white contour line in Fig. 1. Mean values of atmospheric vapour content

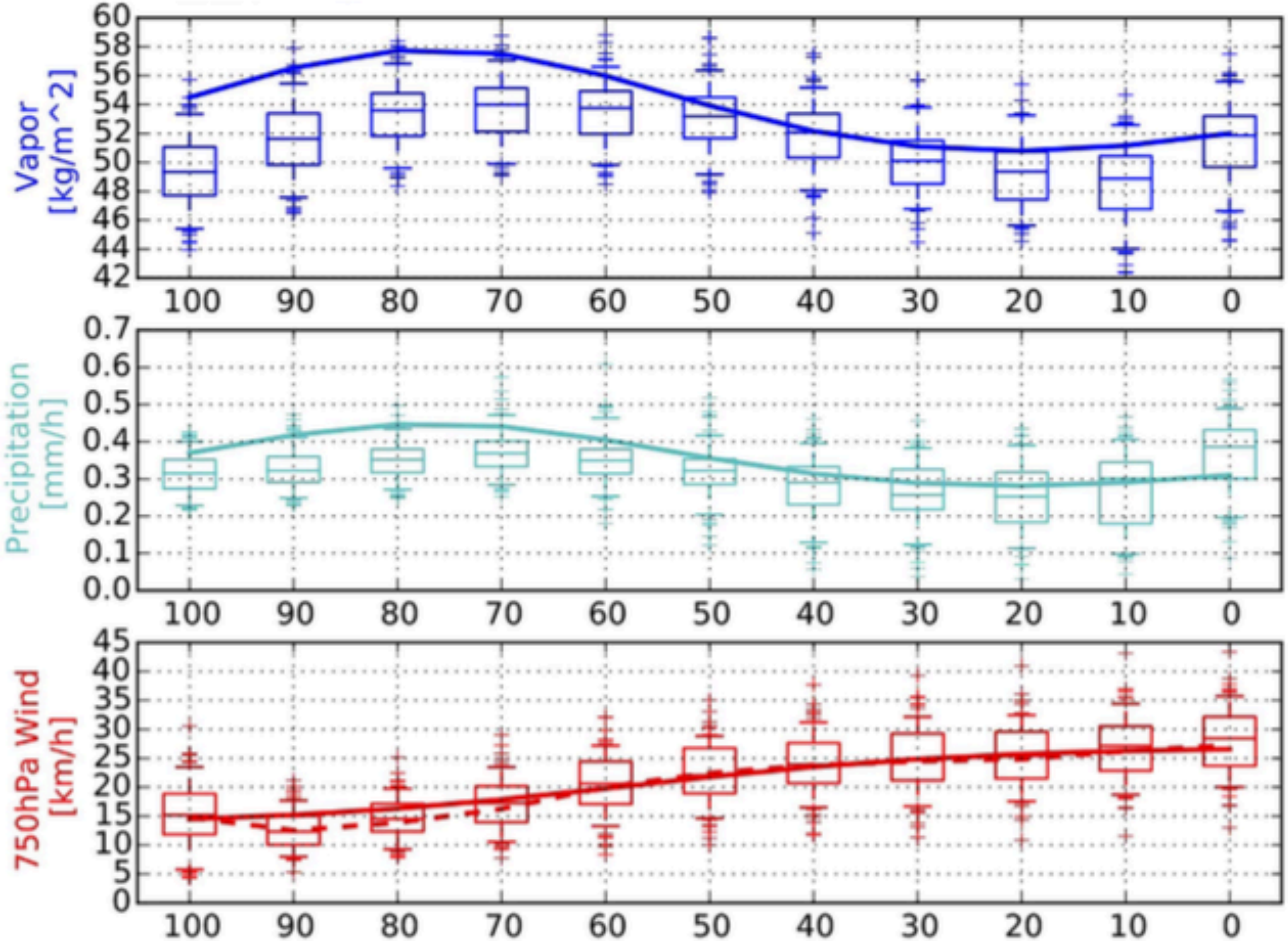
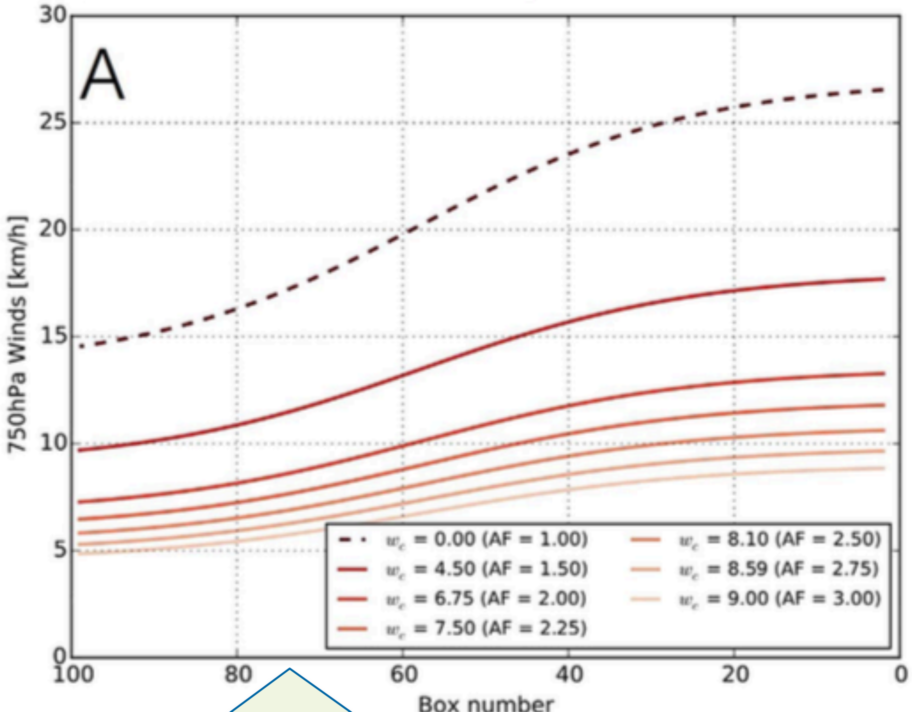


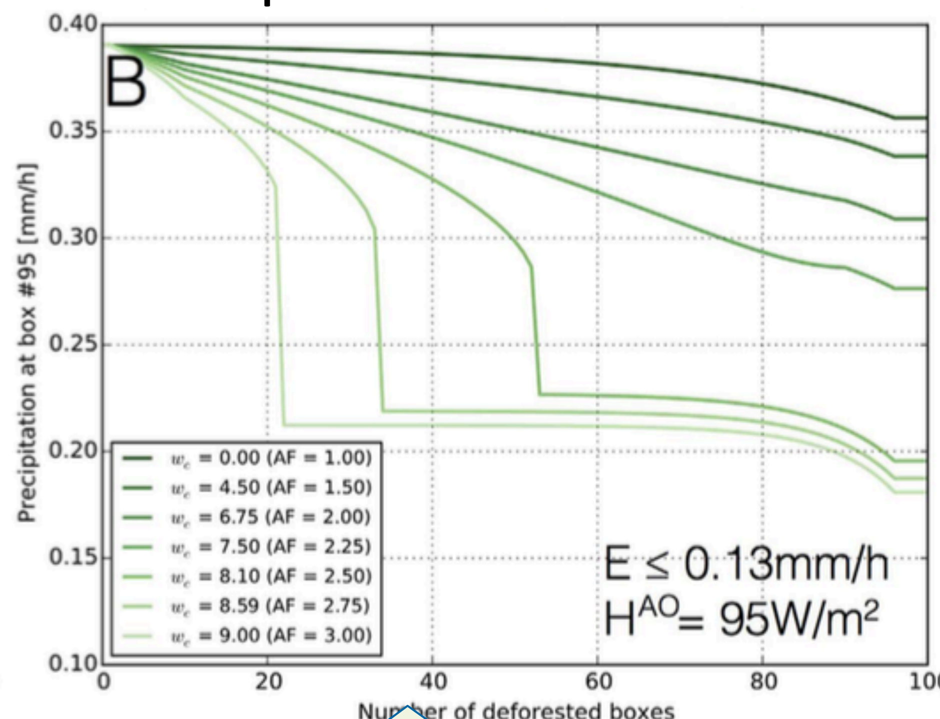
Figure 2. Comparison between ERA interim reanalysis values (box plots) and model results (solid lines) along the trajectory indicated by a white contour line in Fig. 1. Mean values of atmospheric vapour content

Deforesting 1->100 (east->west)



Stronger coupling, stronger wind reduction

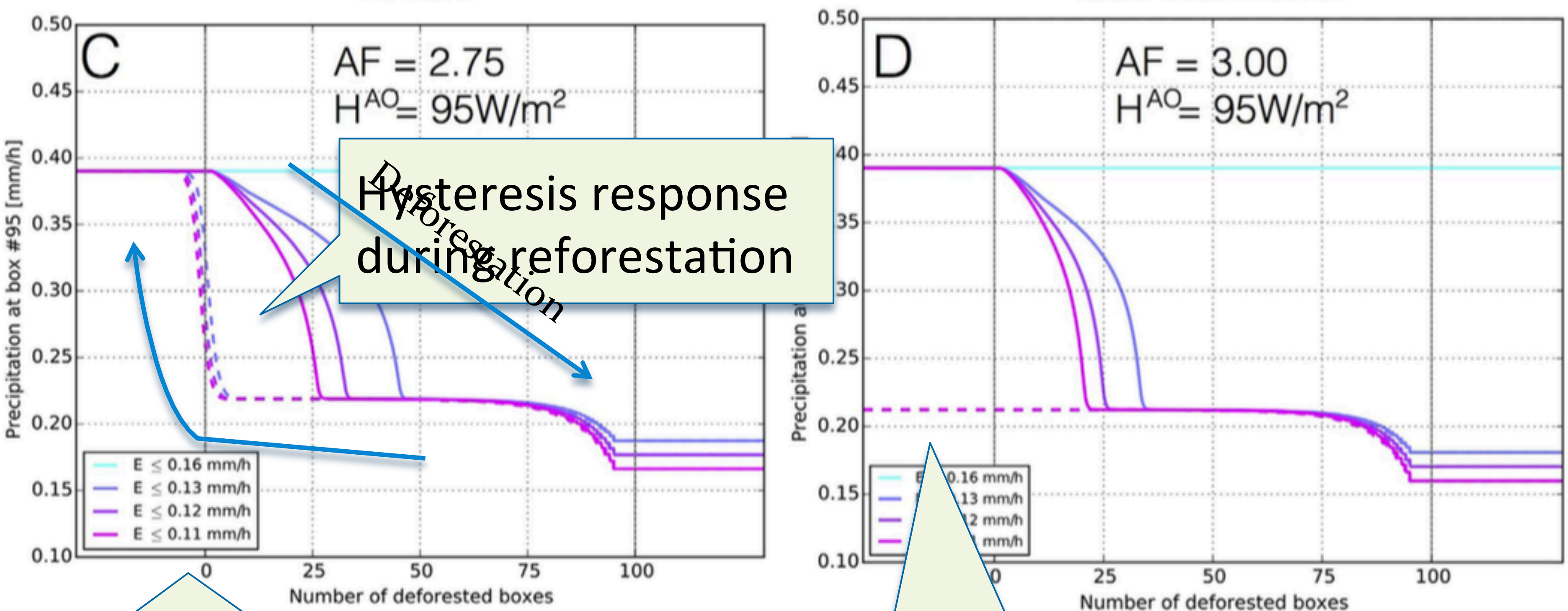
Precipitation at box #95



For strong coupling, 22-55% deforestation induces a dramatic change

Boers et al., Nature Scientific Reports (2017)

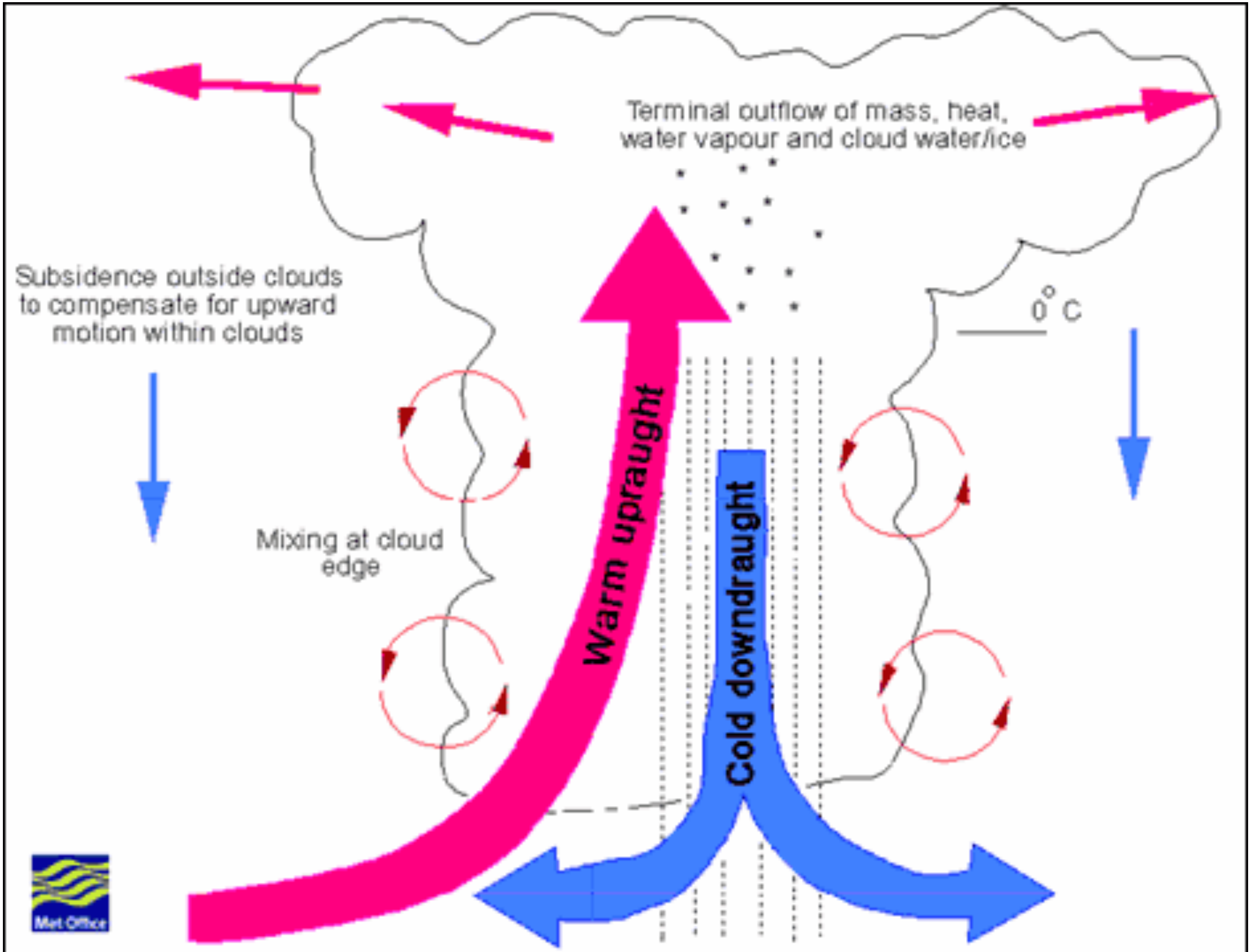
Is it reversible?



Response depends on Evap after deforestation... But shape is the same

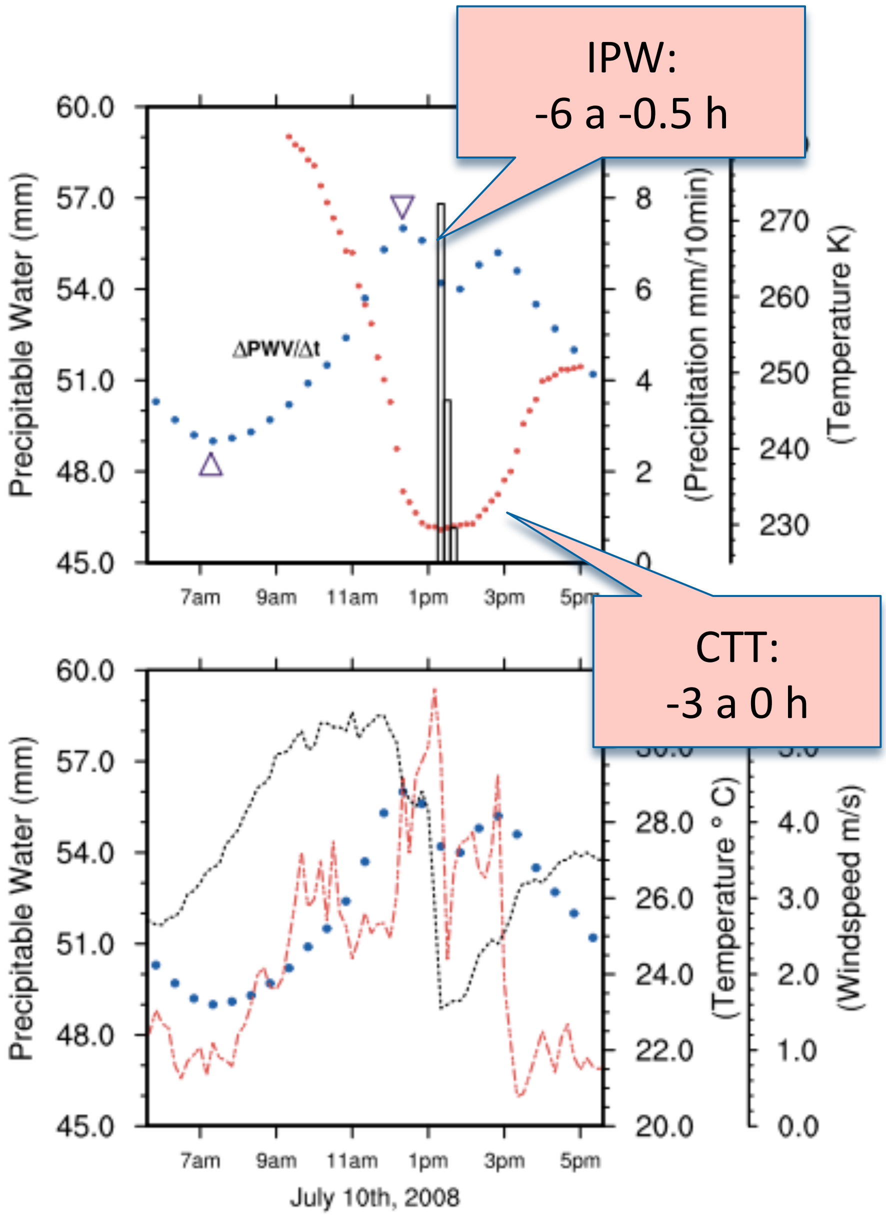
Or it never come back, if coupling is very strong

Boers et al., Nature Scientific Reports (2017)



Terminal outflow of mass, heat,
water vapour and cloud water/ice
Subsidence outside clouds
to compensate for upward
motion within clouds
0°C
Warm upraught
Cold downdraught
Mixing at cloud
edge
Met Office

GNSS Dense Network



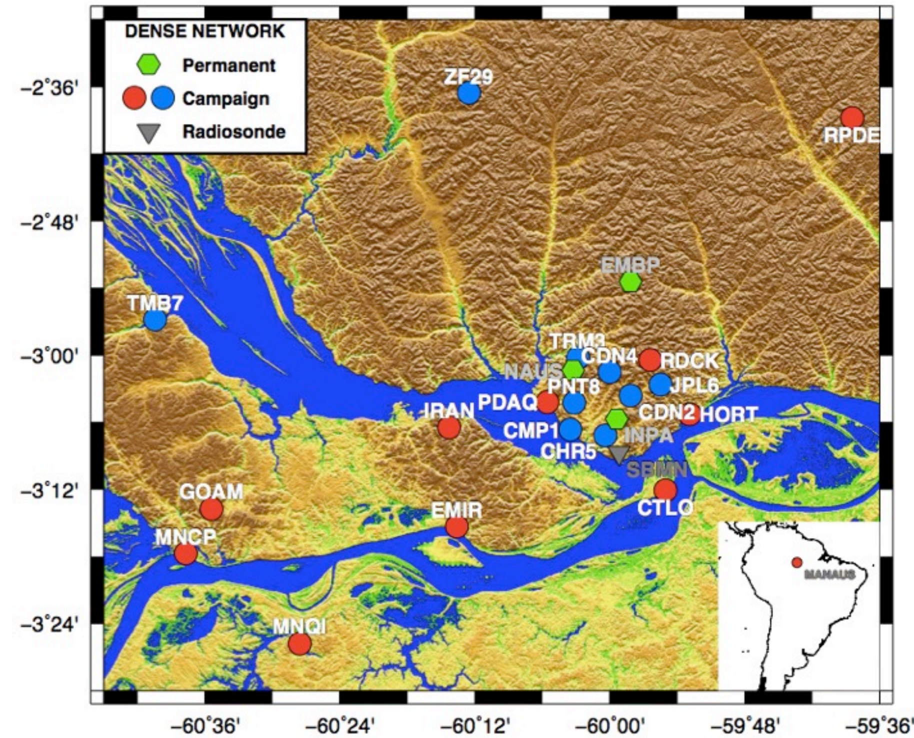
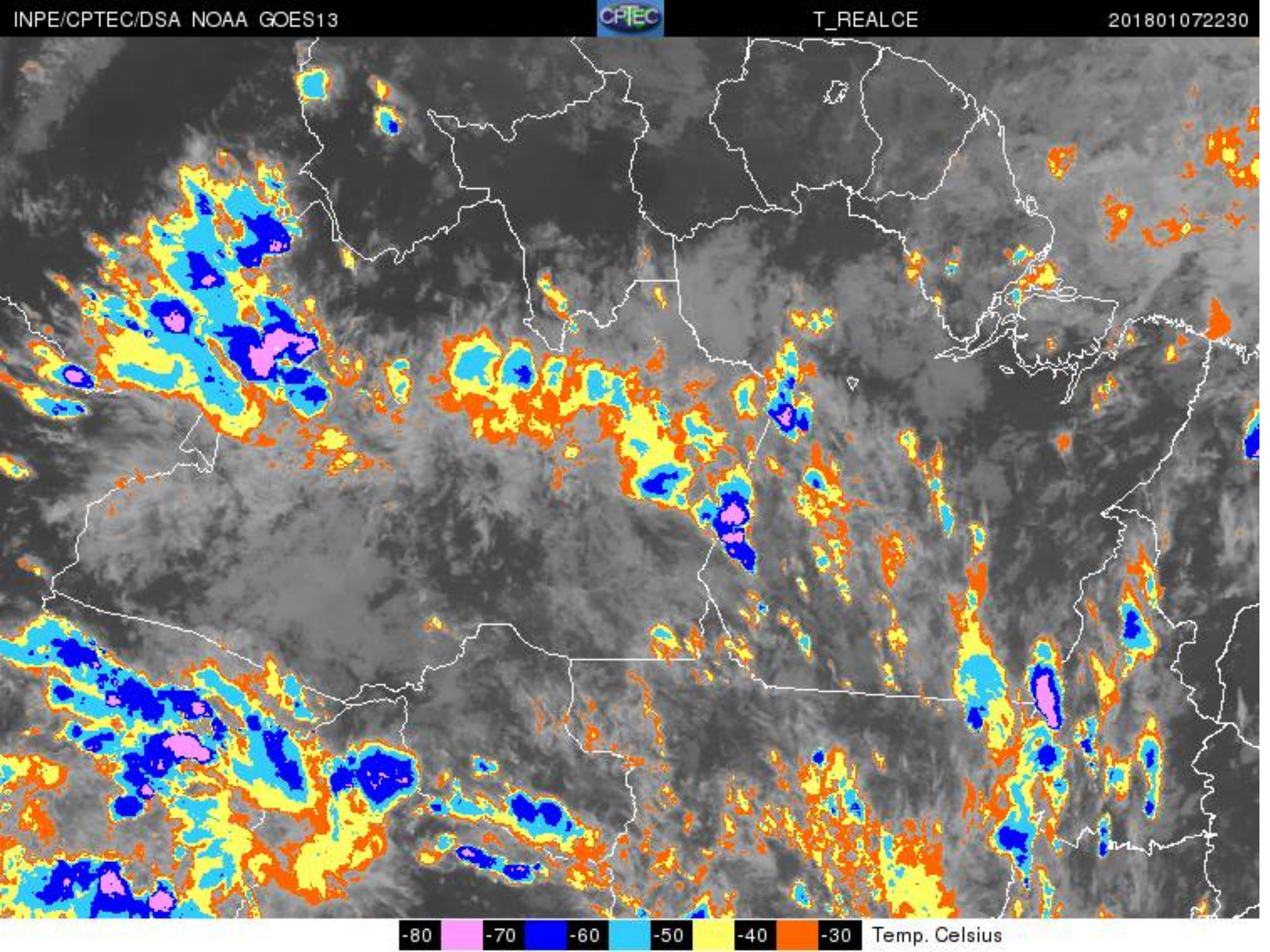
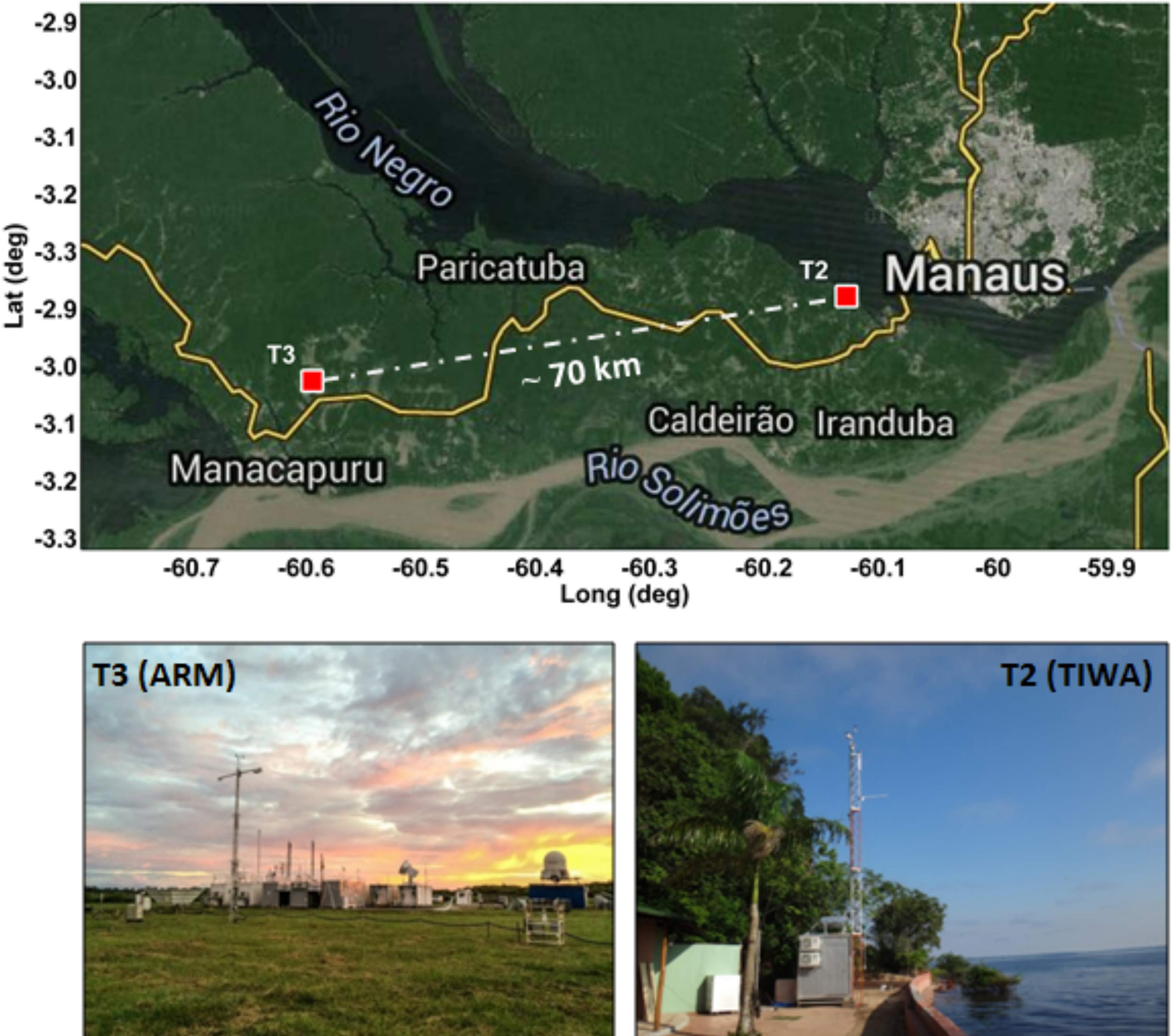


Figure 3. A typical afternoon deep convective event over INPA GNSS/meteorological station. The upper plot contains PWV (blue dots) *versus* average cloud top temperature (red) and precipitation rate (bars). The 'ramp-up' time calculated for the average $\Delta PWV/\Delta t$ (between triangles) represents the timescale of column convergence (see Equation (2) and text for discussion). The bottom graph plots wind speed (red), temperature (black) and PWV(blue) for the deep convective event.

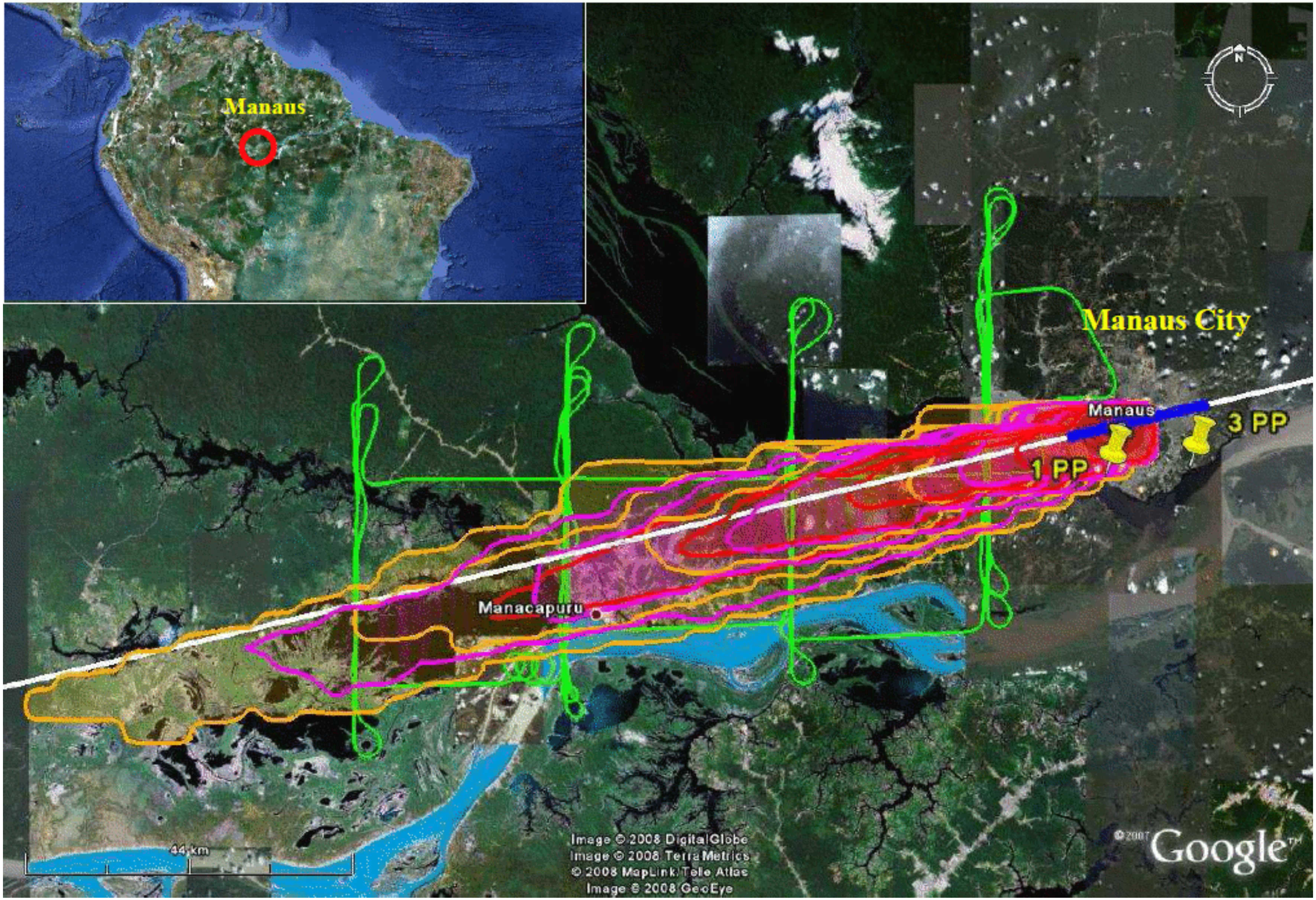
- Adams et al, Atmos. Sci. Let. 2011
- Adams et al, BAMS 2014 (accepted)


INPE/CPTEC/DSA NOAA GOES13
CPTEC
T_REALCE
201801072230
-80
-70
-60
-50
-40
-30
Temp. Celsius



-2.9
-3.0
-3.1
-3.2
-3.3
-2.9
-3.0
-3.1
-3.2
-3.3
Lat (deg)
Rio Negro
Paricatuba
T2
Manaus
T3
~ 70 km
Caldeirão
Iranduba
Manacapuru
Rio Solimões
-60.7
-60.6
-60.5
-60.4
-60.3
-60.2
-60.1
-60
-59.9
Long (deg)
T3 (ARM)
T2 (TIWA)

Experimento GoAmazon 2014

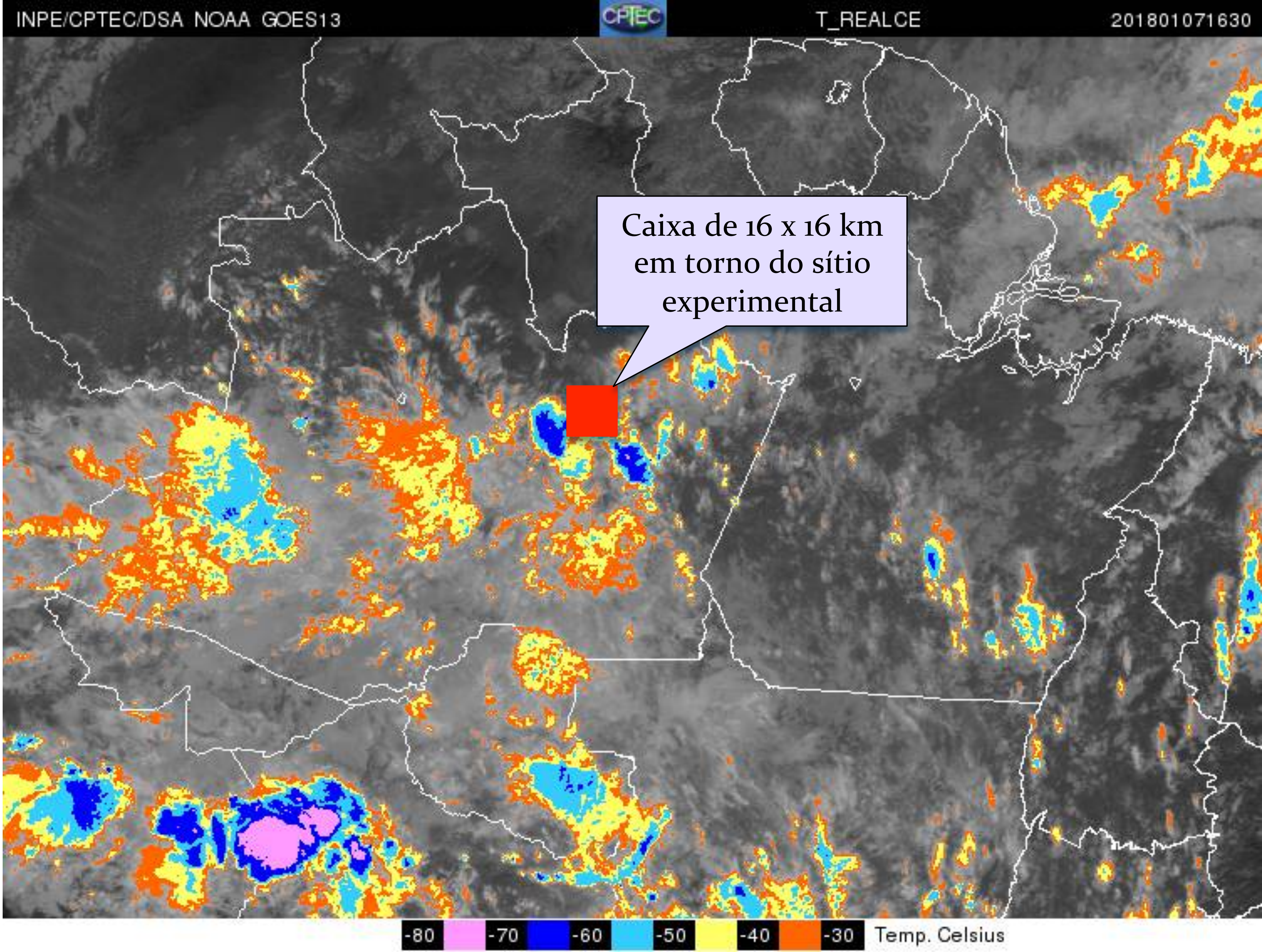


T3 site – 70km downwind

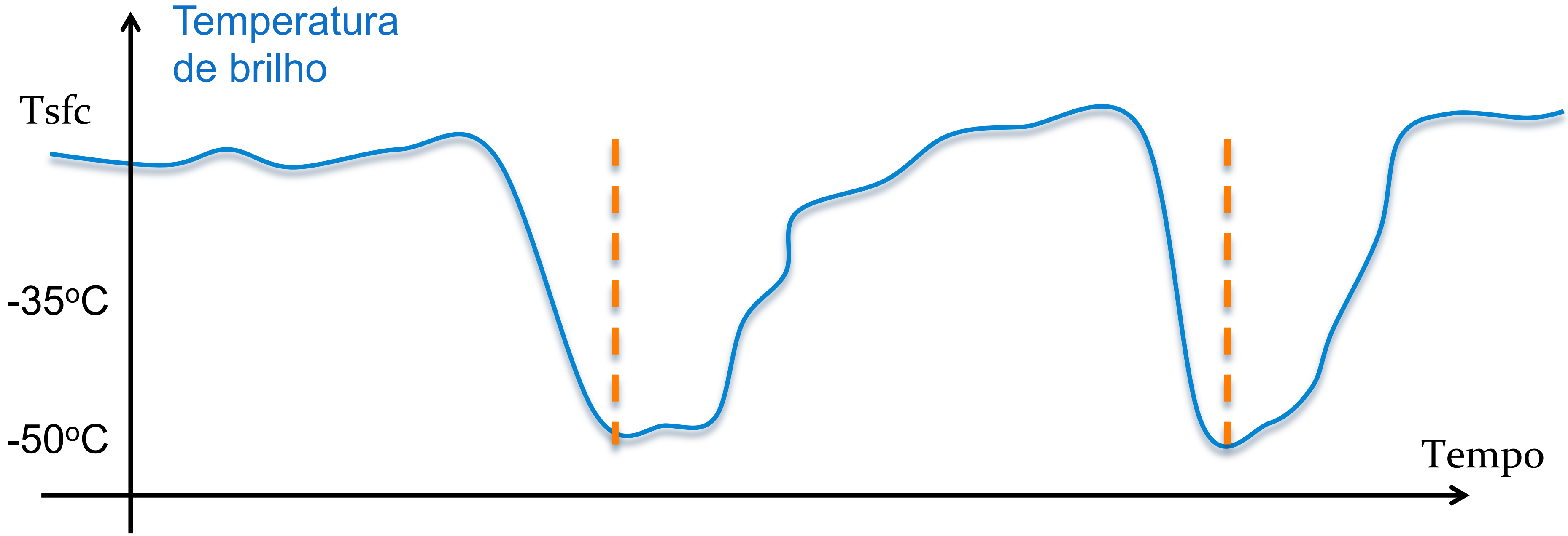
Photo: R. Thalman

- Mixed medium-field Manaus aged plume and clean conditions
- Affected by long and short-range BB

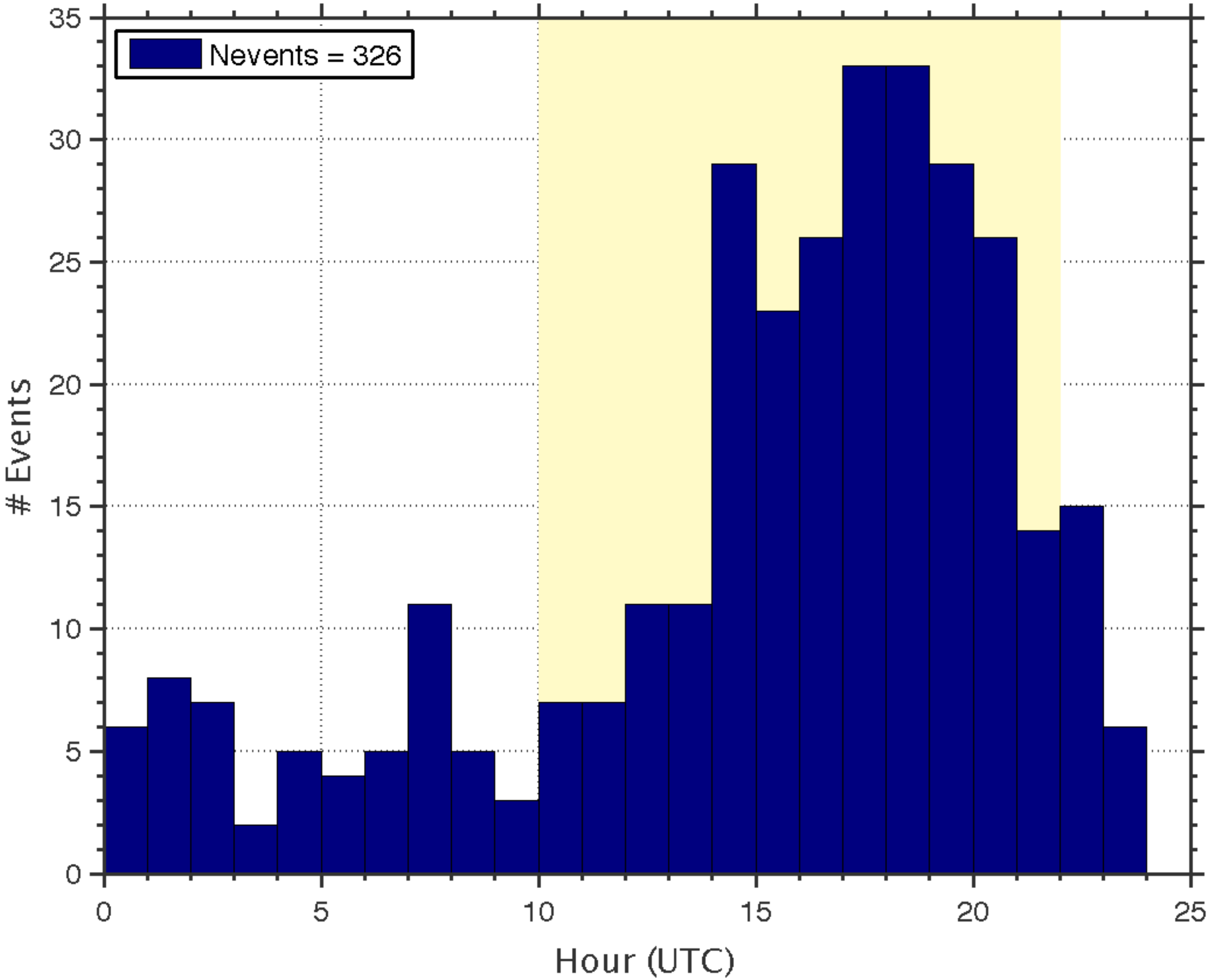
Photo: J. Beat

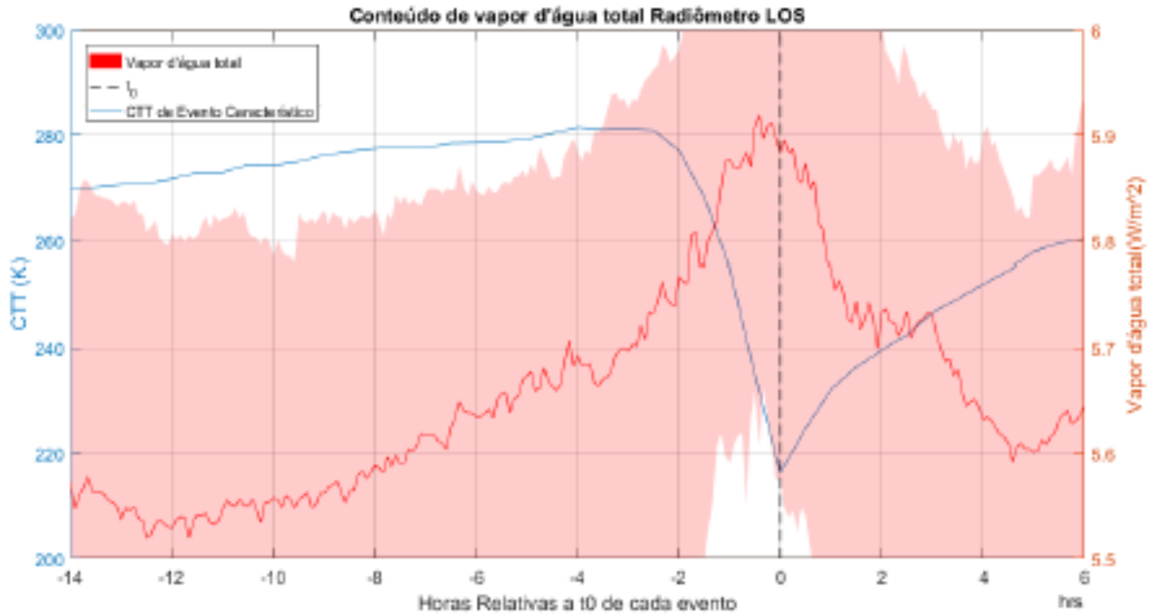

INPE/CPTEC/DSA NOAA GOES13
CPTEC
T_REALCE
201801071630
Caixa de 16 x 16 km em torno do sítio experimental
-80
-70
-60
-50
-40
-30
Temp. Celsius

Eventos convectivos com CTT

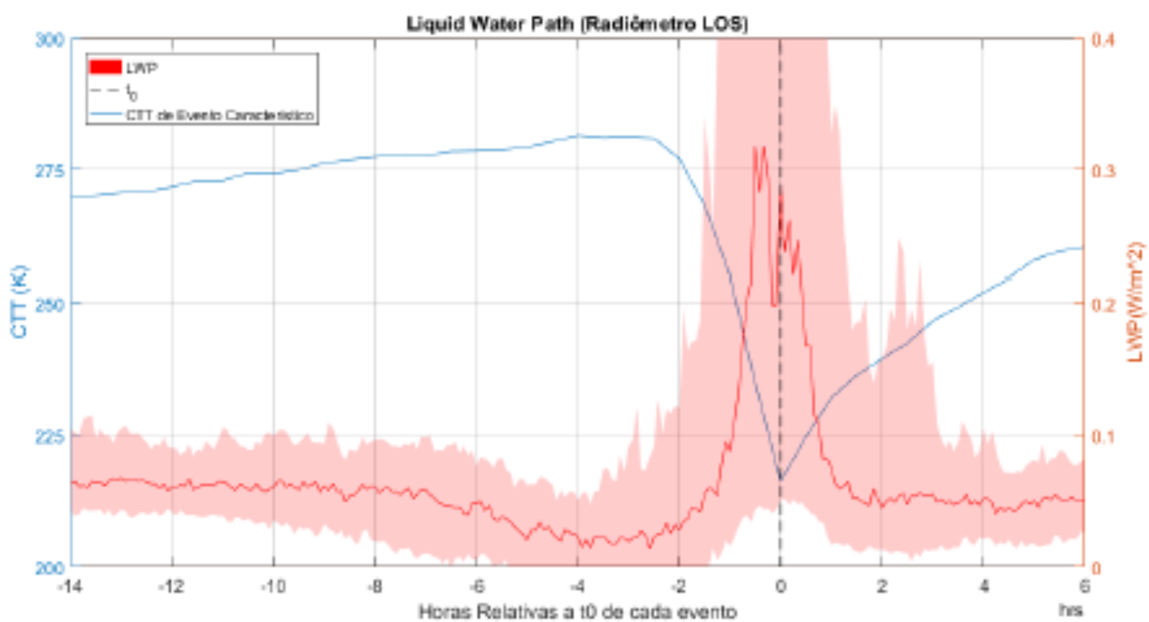


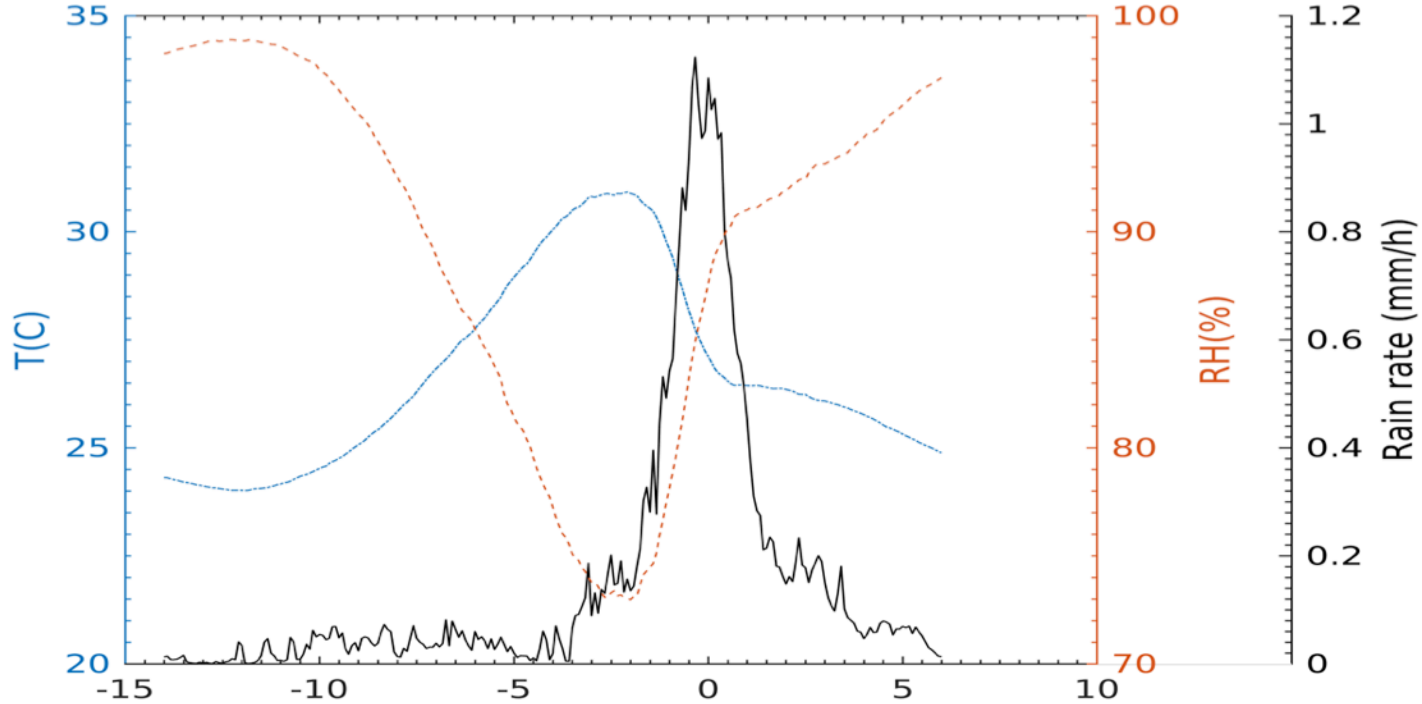
- Queda de pelo menos 50K em 2h
- T0 = horário de mínimo CTT
- *Presença de precipitação*
- *Presenção de rajada de vento*

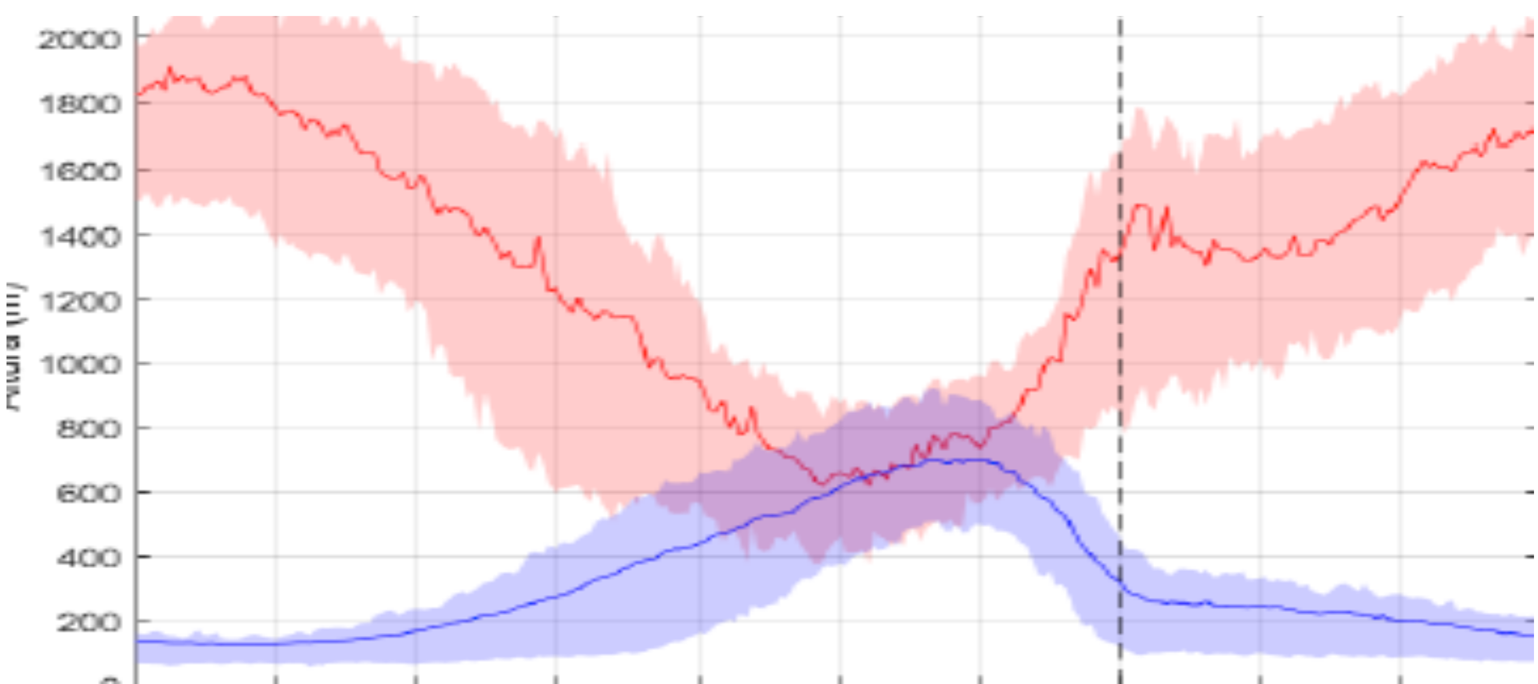

Nevents = 326
# Events
Hour (UTC)
0
5
10
15
20
25
30
35
0
5
10
15
20
25

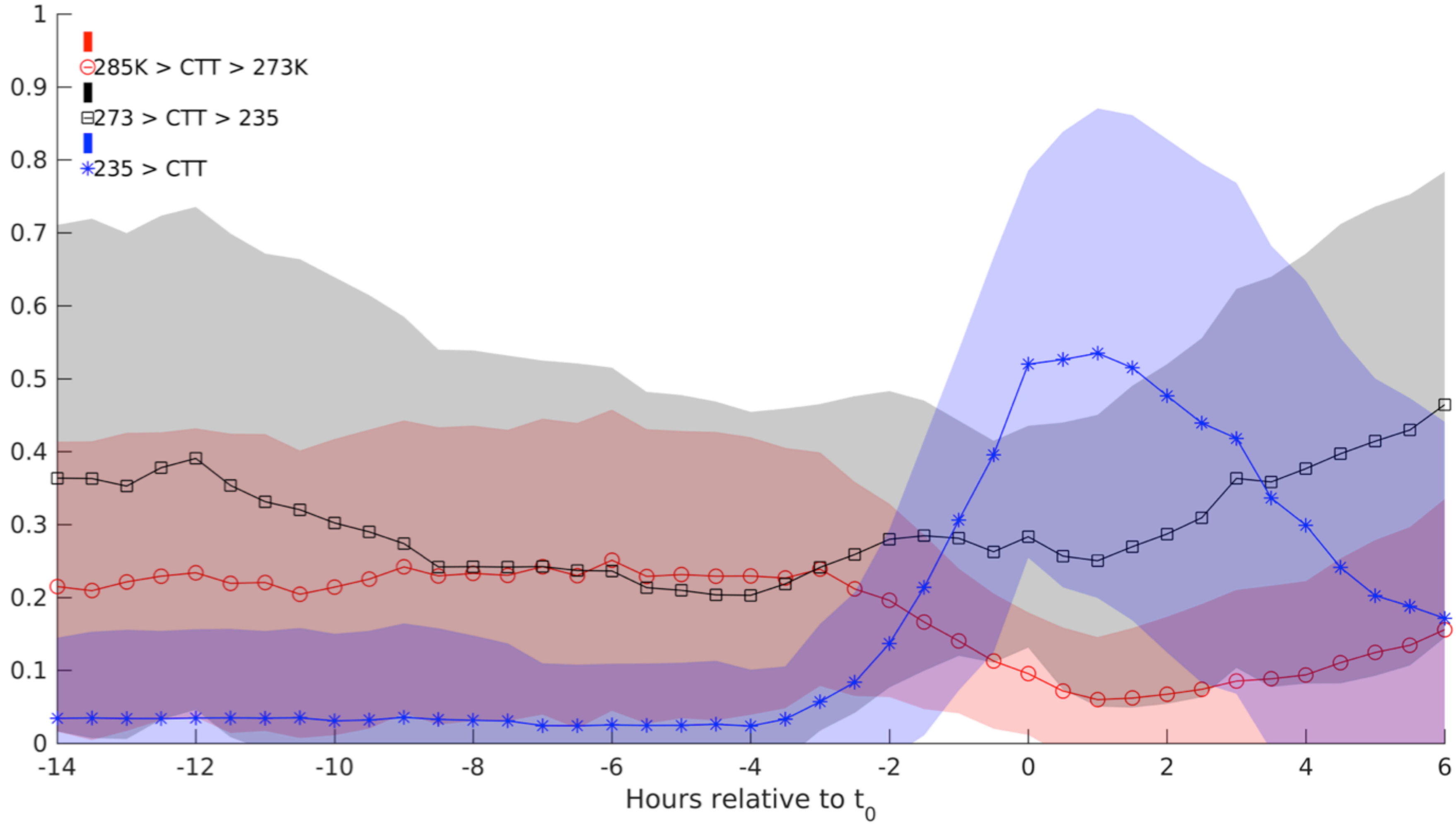

Conteúdo de vapor d'água total Radiômetro LOS
Vapor d'água total
t_0
CTT de Evento Característico
CTT (K)
Vapor d'água total(W/m^2)
Horas Relativas a t0 de cada evento
hrs

(a)


Liquid Water Path (Radiômetro LOS)
LWP
t_0
CTT de Evento Característico
CTT (K)
LWP(W/m^2)
Horas Relativas a t0 de cada evento
hrs


35
30
25
20
T(C)
100
90
80
70
RH(%)
1.2
1
0.8
0.6
0.4
0.2
0
Rain rate (mm/h)
-15
-10
-5
0
5
10


2000
1800
1600
1400
1200
1000
800
600
400
200



285K > CTT > 273K
273 > CTT > 235
235 > CTT
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
Hours relative to t_0

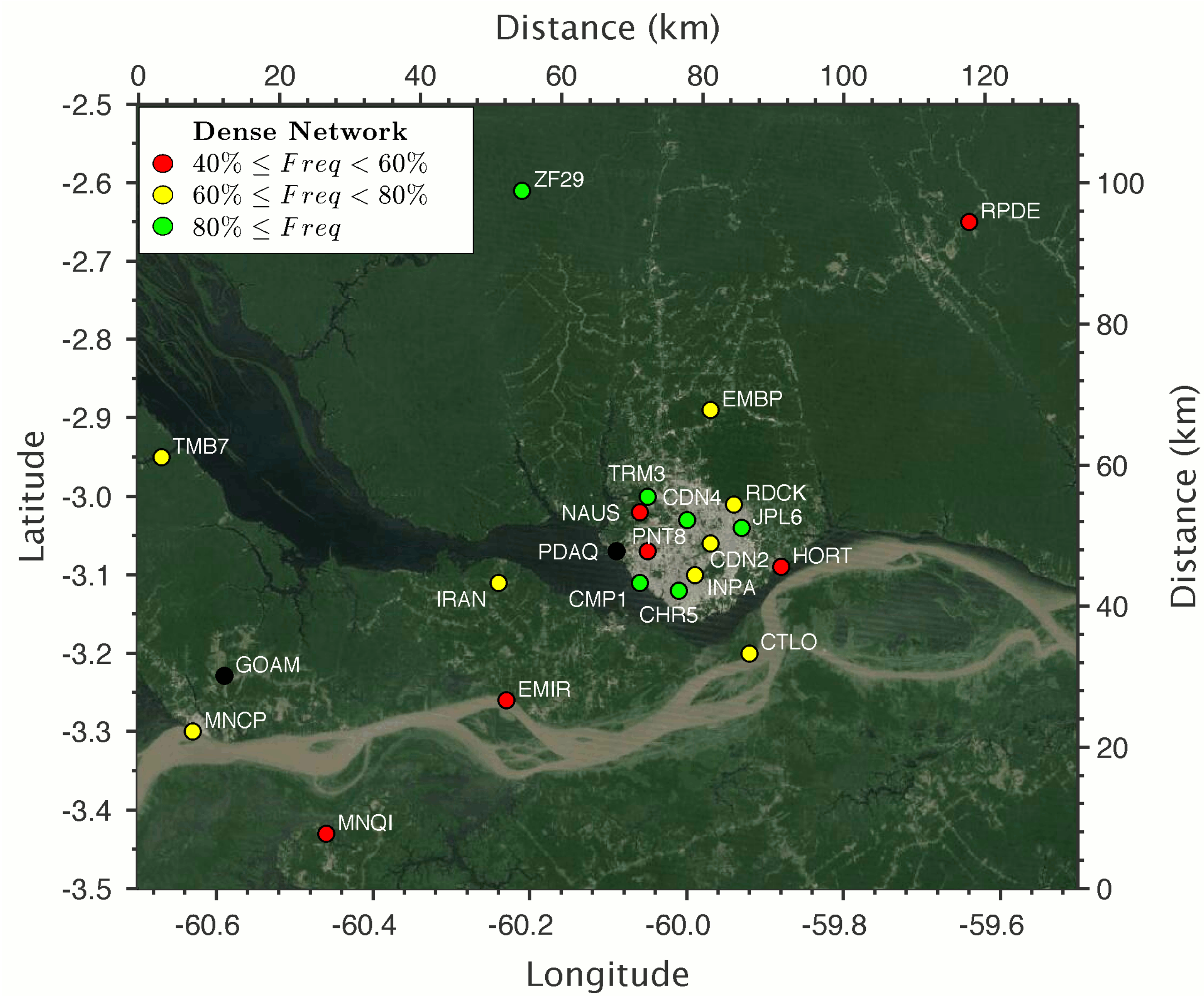


FIG. 1. Map of the Manaus Dense GNSS Meteorological Network from April 2011 to April 2012. The color scheme represents the frequency of PWV data (11256 total data values) for the 67 convective events used in this study. GOAM data were not utilized. PDAQ failed in October and was not utilized in the PWV anomaly plot (Figure 4), but was used in correlation vs distance statistics to better assess the data-denial tests.

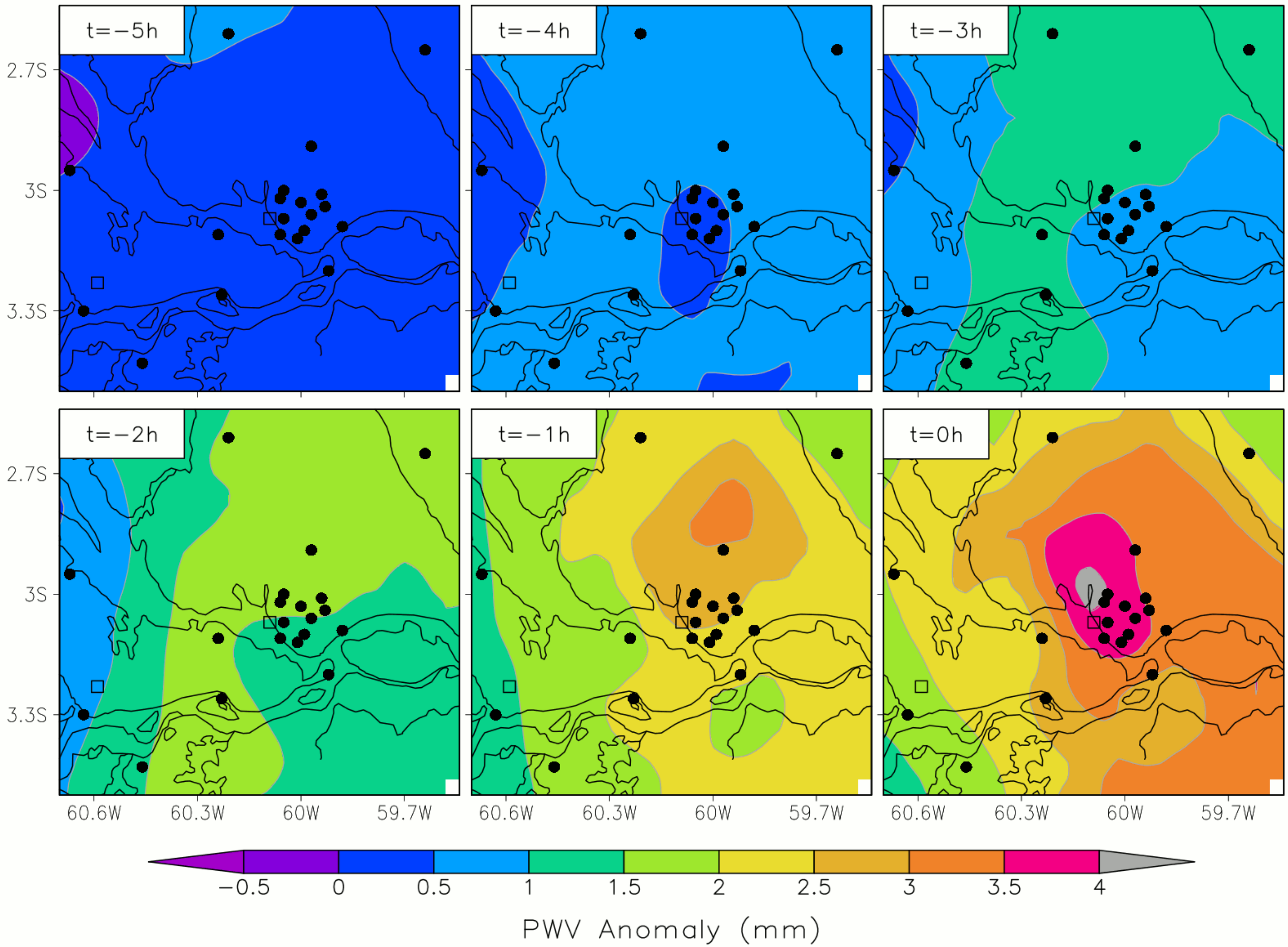
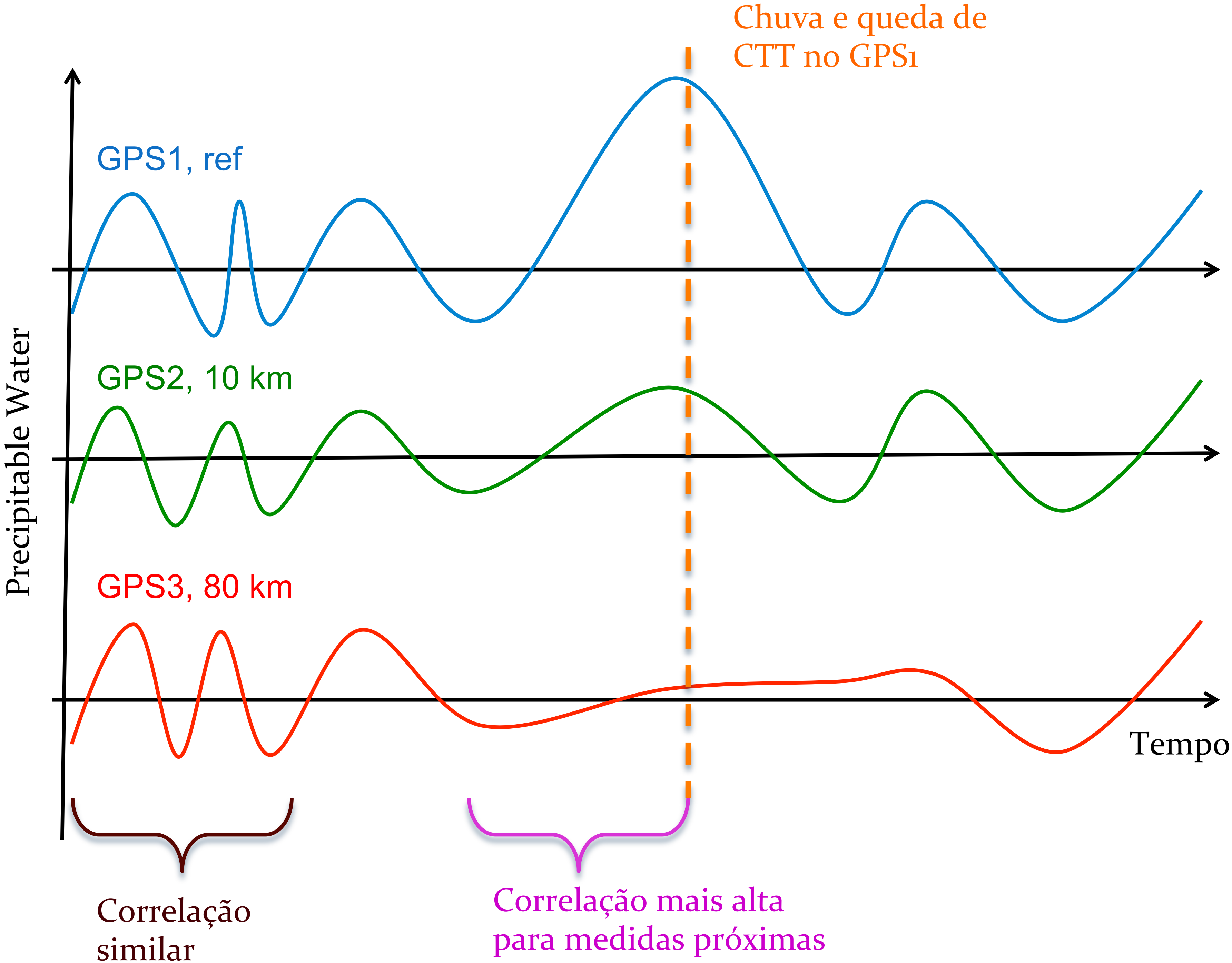


FIG. 4. Plot of PWV anomalies (mm) fields calculated from average of 67 convective events for 5 hours before convective events.


Chuva e queda de
CTT no GPS1
GPS1, ref
GPS2, 10 km
GPS3, 80 km
Precipitable Water
Tempo
Correlação
similar
Correlação mais alta
para medidas próximas

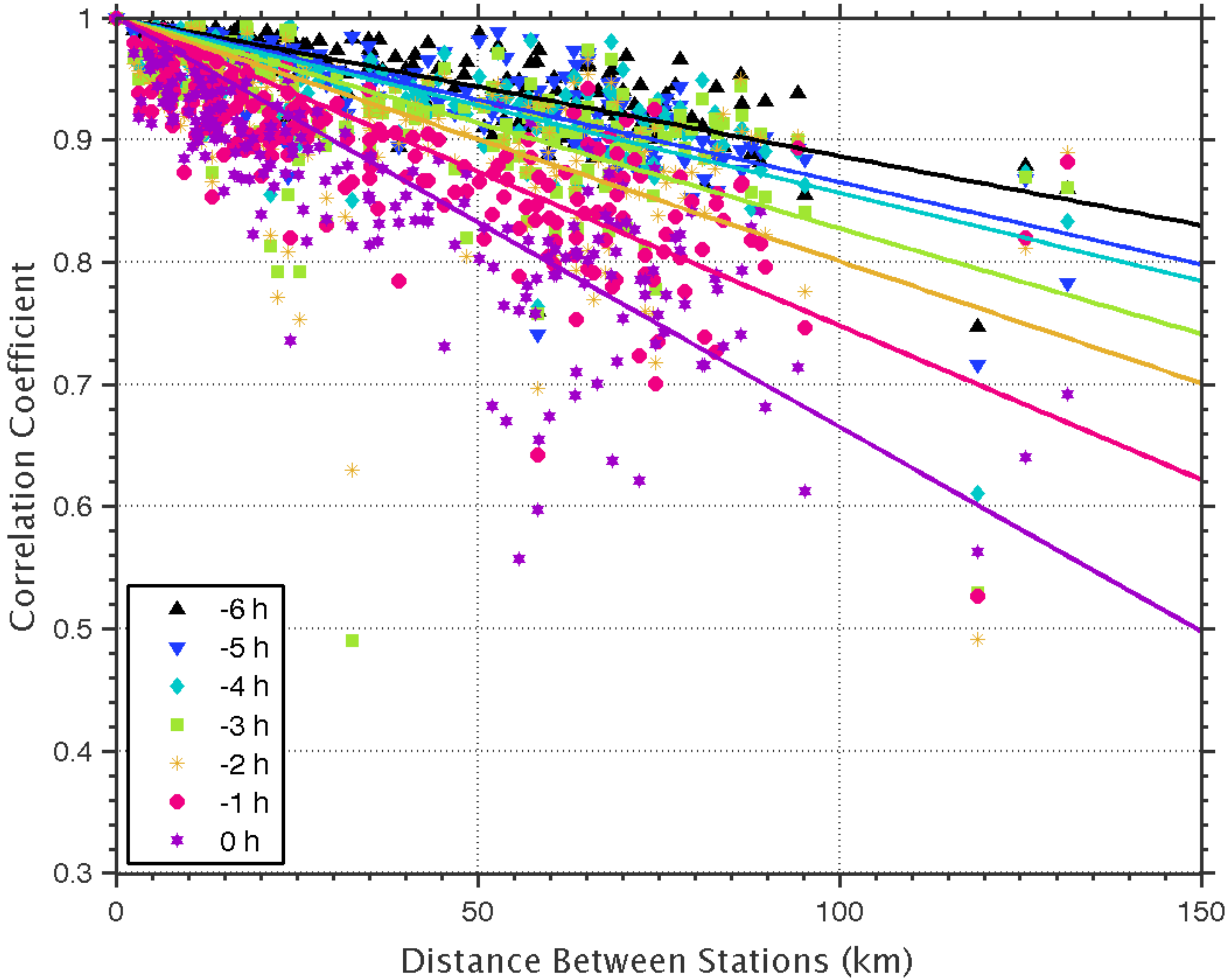


FIG. 2. Scatterplot of correlation vs separation distance as a function of different one-hour time bins, between t = 0h and t = -6h for the 67 events. The slope of the fitted lines is statistically significant at the 95th percentile.

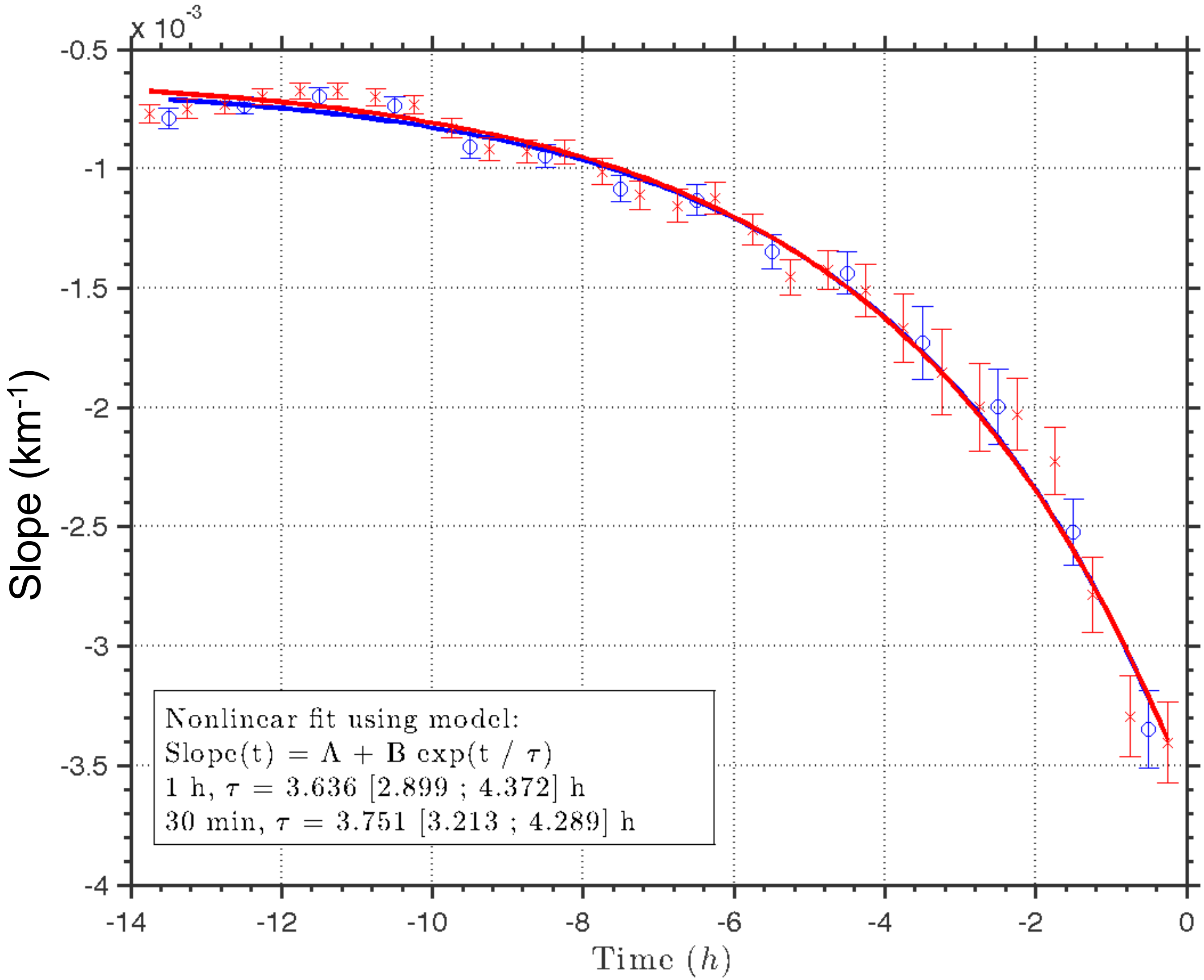


FIG. 3. Temporal evolution of correlation vs separation distance slope with exponential fit and error bars for 67 convective events. Both 1 hour (blue lines and circles) and 30 minute (red line and x symbols) time bins are included for comparison purposes. Functional form, average decay timescale, τ and 95th percentile confidence intervals are shown.

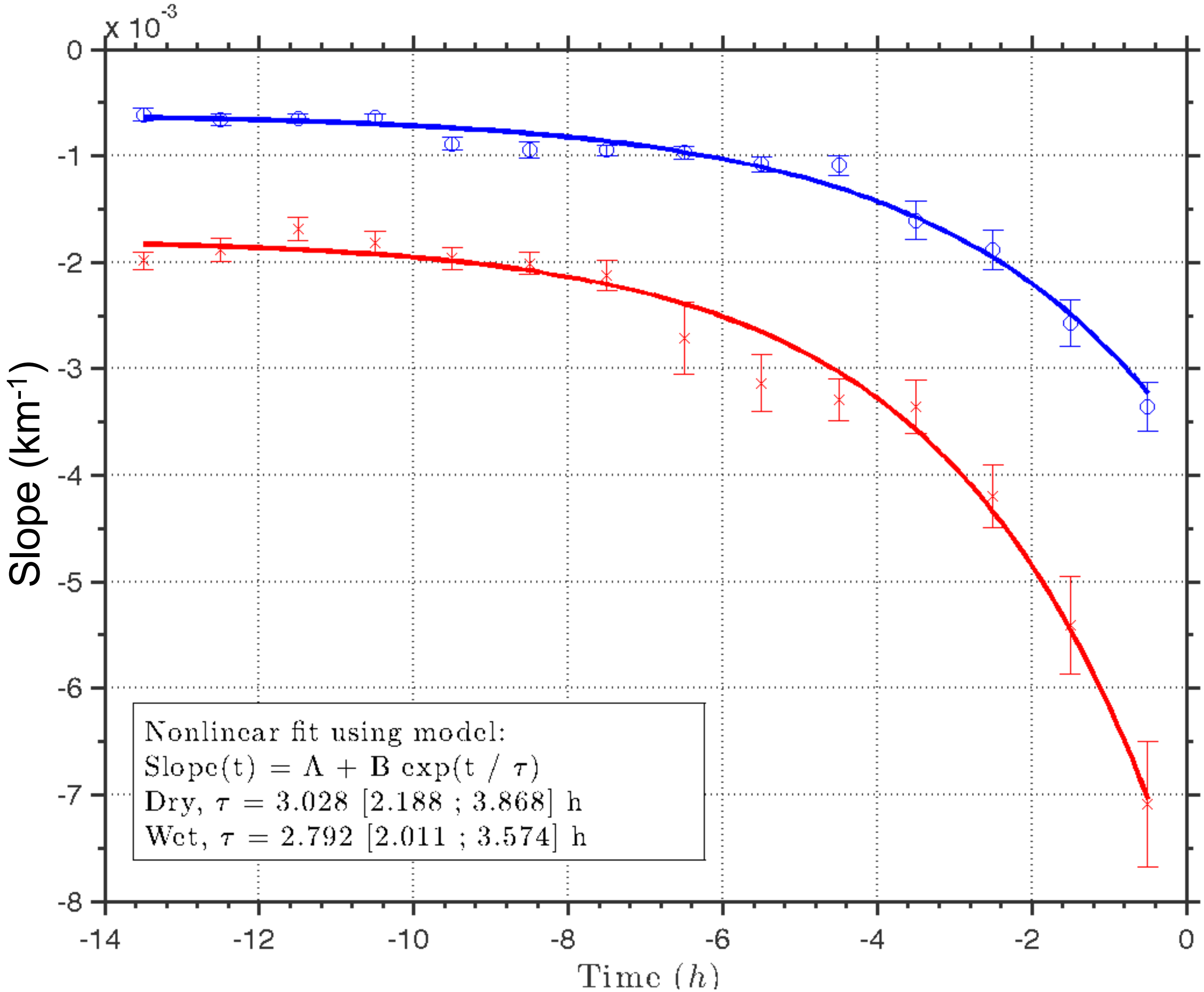
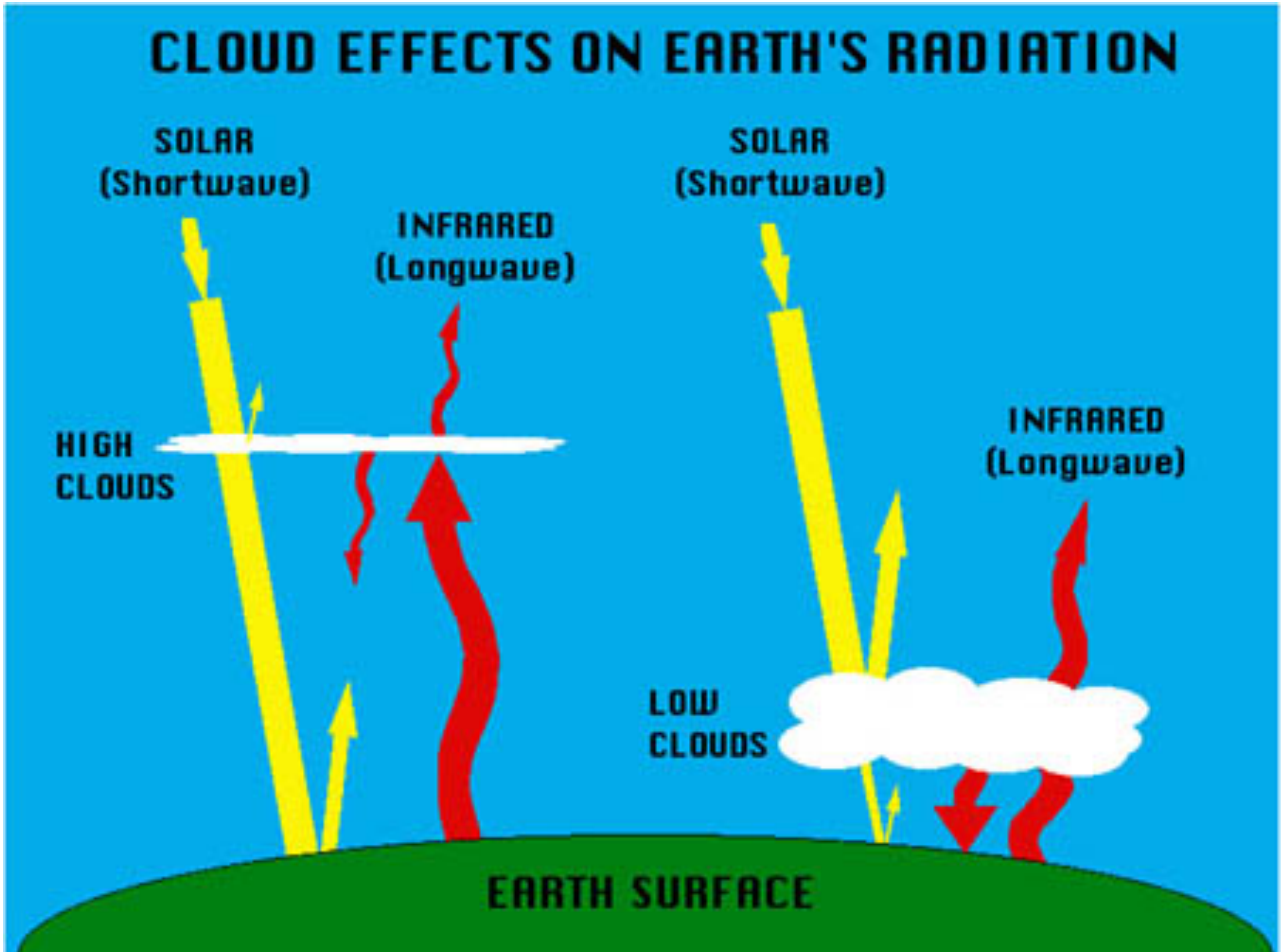
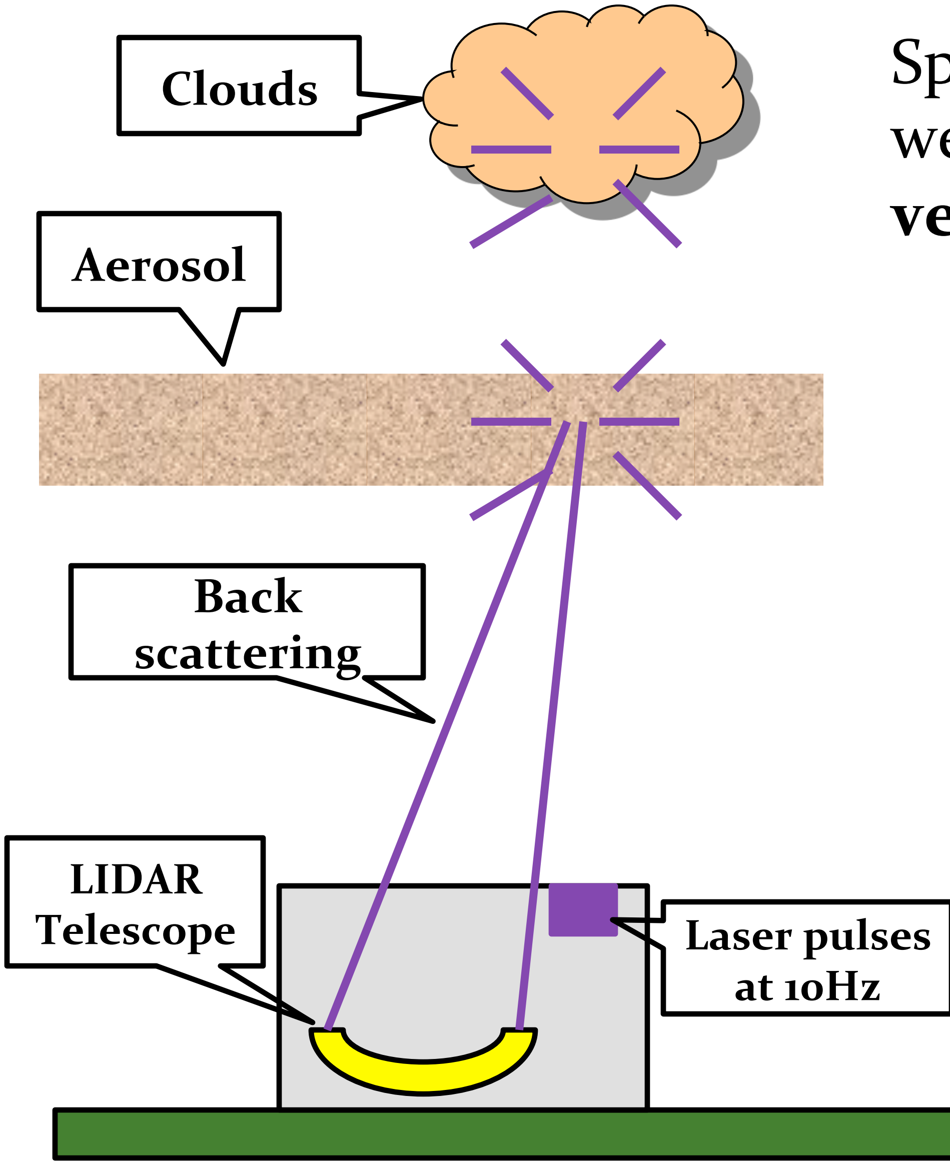


FIG. 5. Temporal evolution of correlation vs separation distance slope with exponential fit and error bars for wet (red, 24 events) versus dry and dry-to-wet season (blue, 27 events). The 16 events occurring during the wet-to-dry transition are not included.

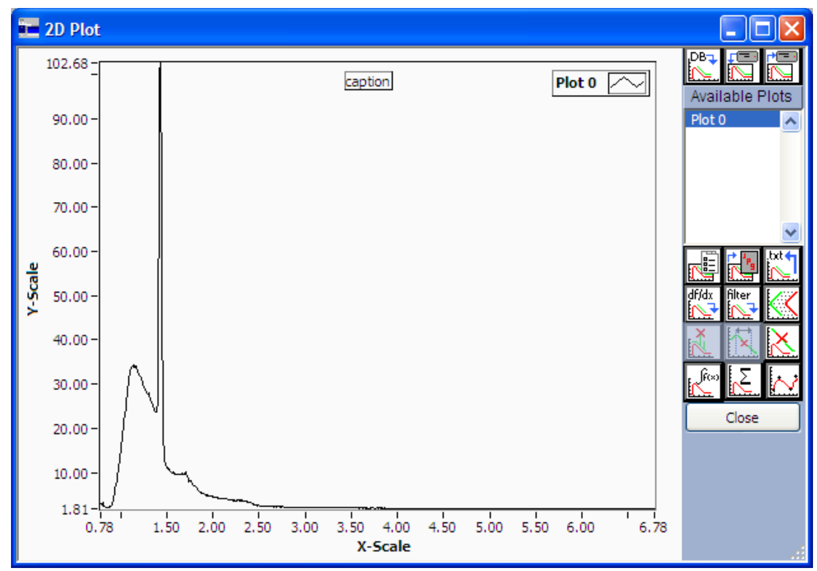

CLOUD EFFECTS ON EARTH'S RADIATION
SOLAR
(Shortwave)
INFRARED
(Longwave)
HIGH
CLOUDS
SOLAR
(Shortwave)
INFRARED
(Longwave)
LOW
CLOUDS
EARTH SURFACE

Lidar

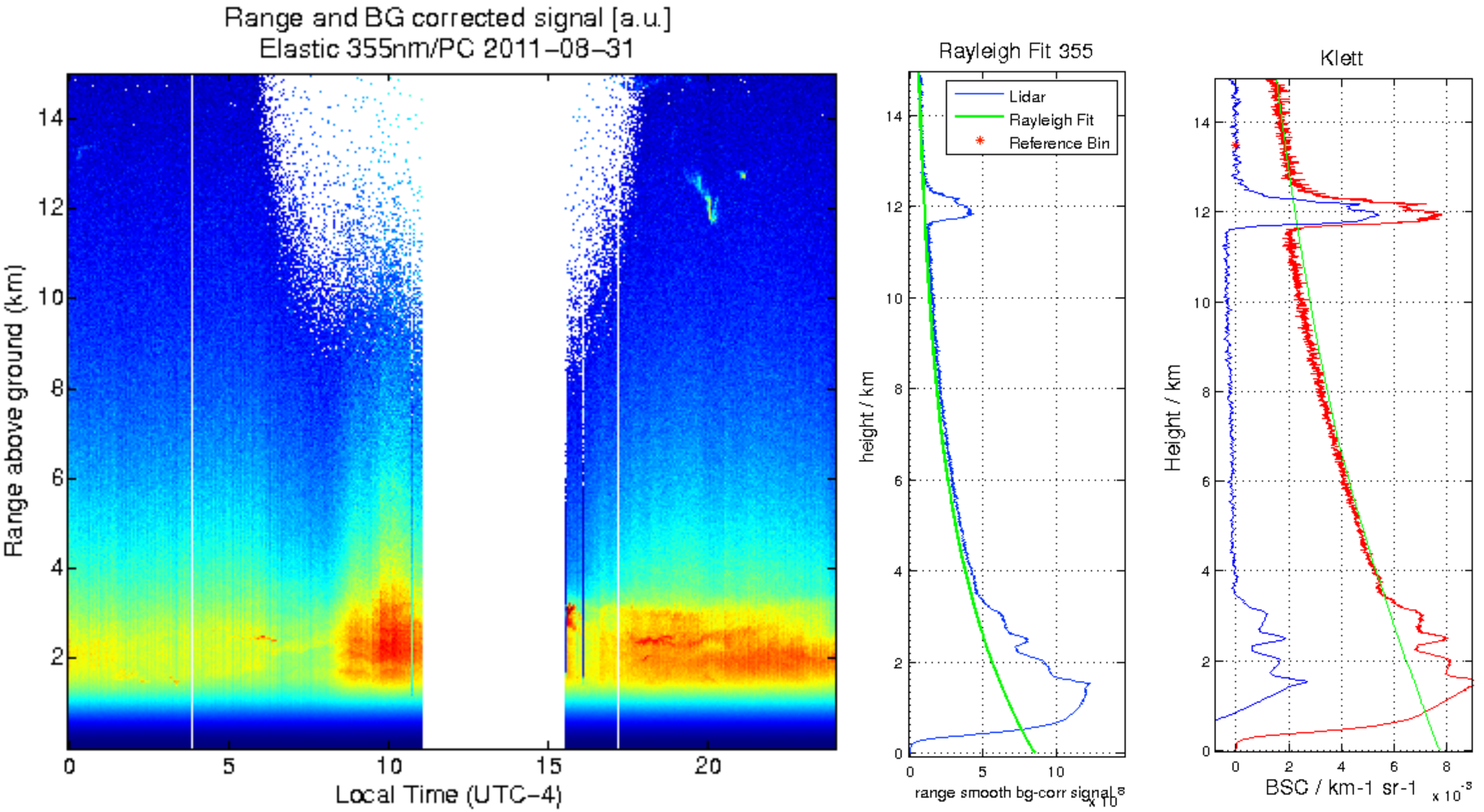


Speed of light is **3 x 10⁸ m/s** and we measure at **20Mhz**, hence **vertical resolution is 7.5m**

We measure light intensity vs time

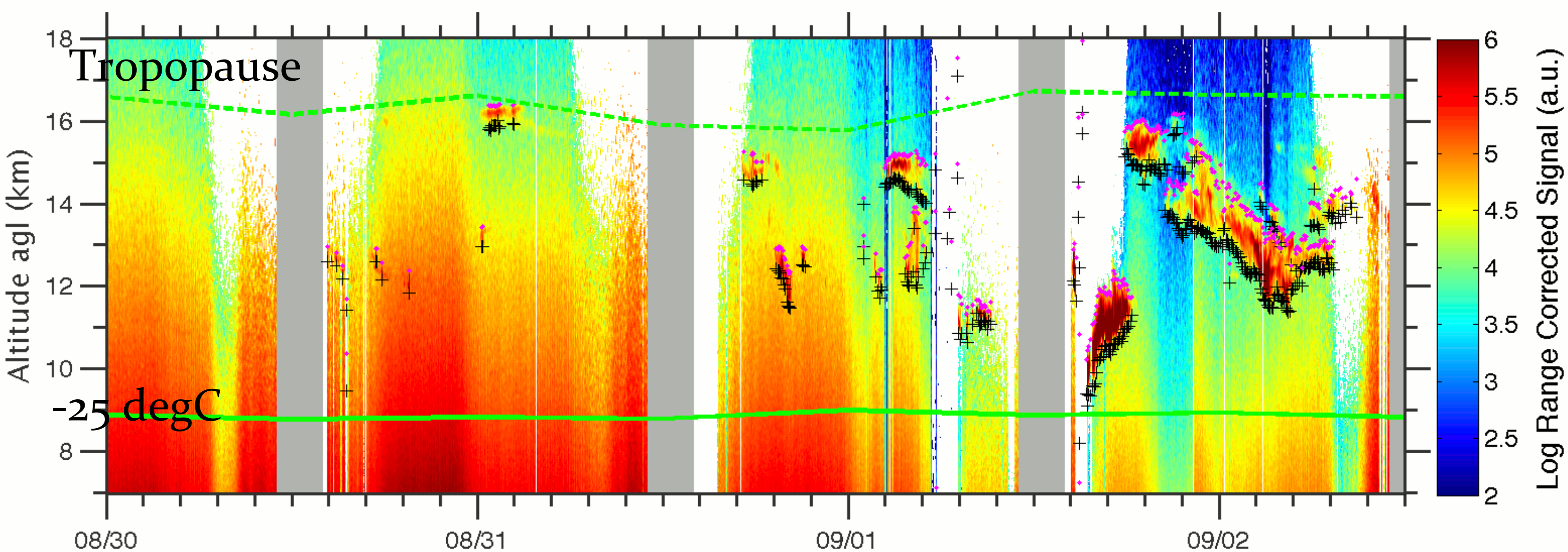


Lidar


Range and BG corrected signal [a.u.]
Elastic 355nm/PC 2011–08–31
Range above ground (km)
Local Time (UTC–4)
Rayleigh Fit 355
Lidar
Rayleigh Fit
Reference Bin
height / km
range smooth bg-corr signal
Klett
Height / km
BSC / km-1 sr-1

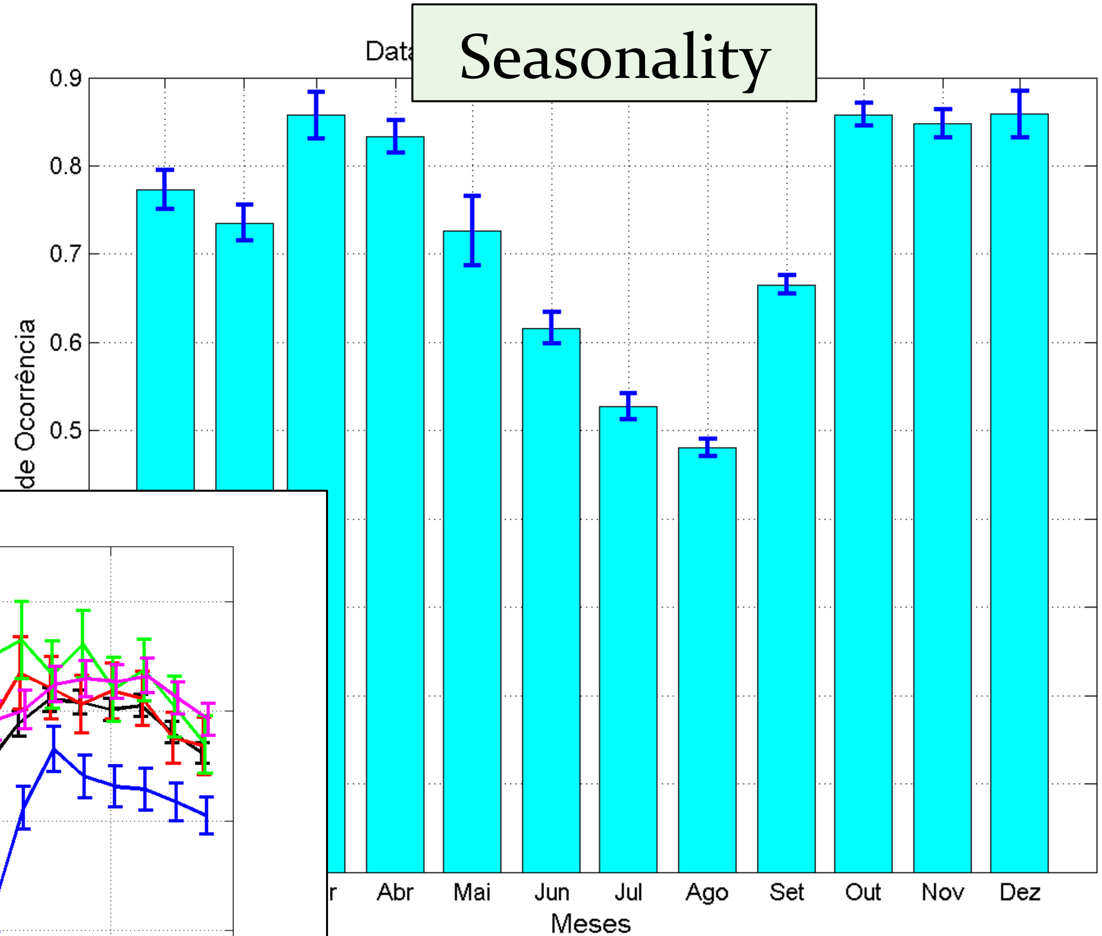
Cirrus Clouds

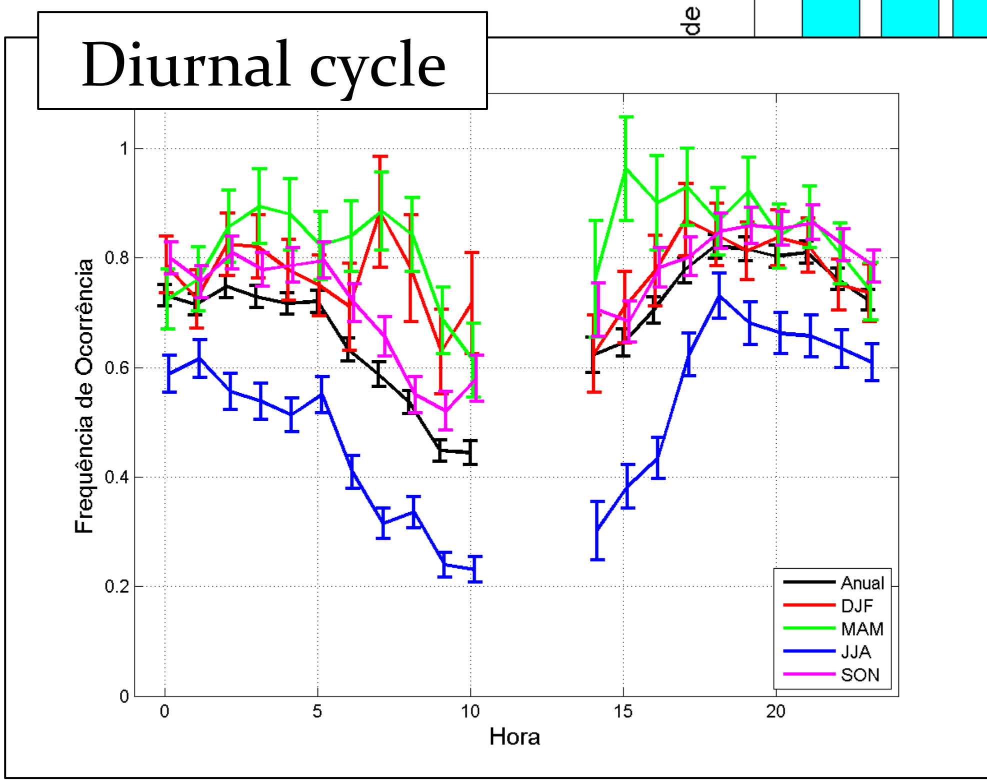
- Cirrus found from 8 to 19.6km
  - Base 12.5±2.4 km
  - Top 14.2±2.2 km



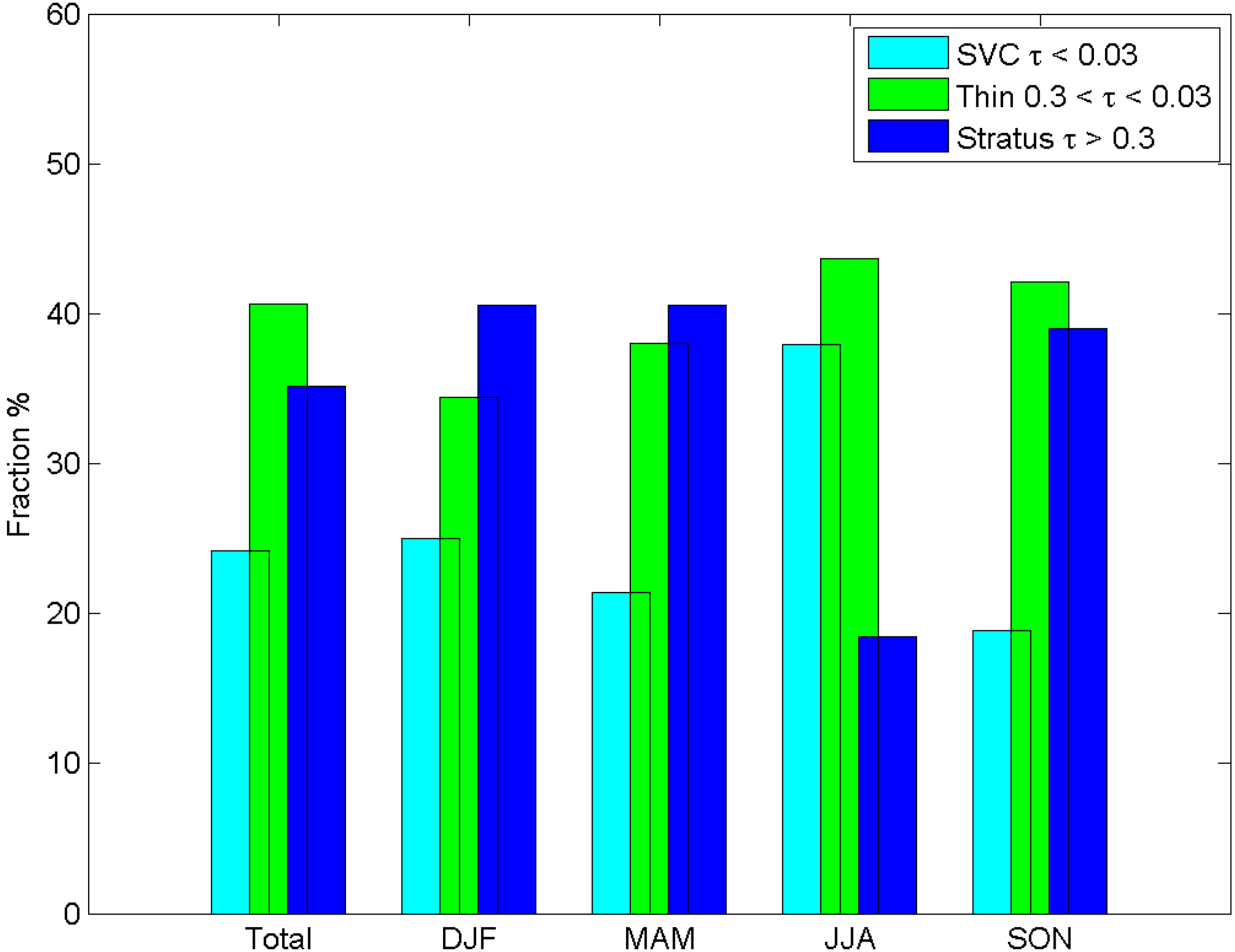
Barja & Gouveia, priv comm

- Cirrus cloud cover at Manaus
  - 83% MAM
  - 52% JJA



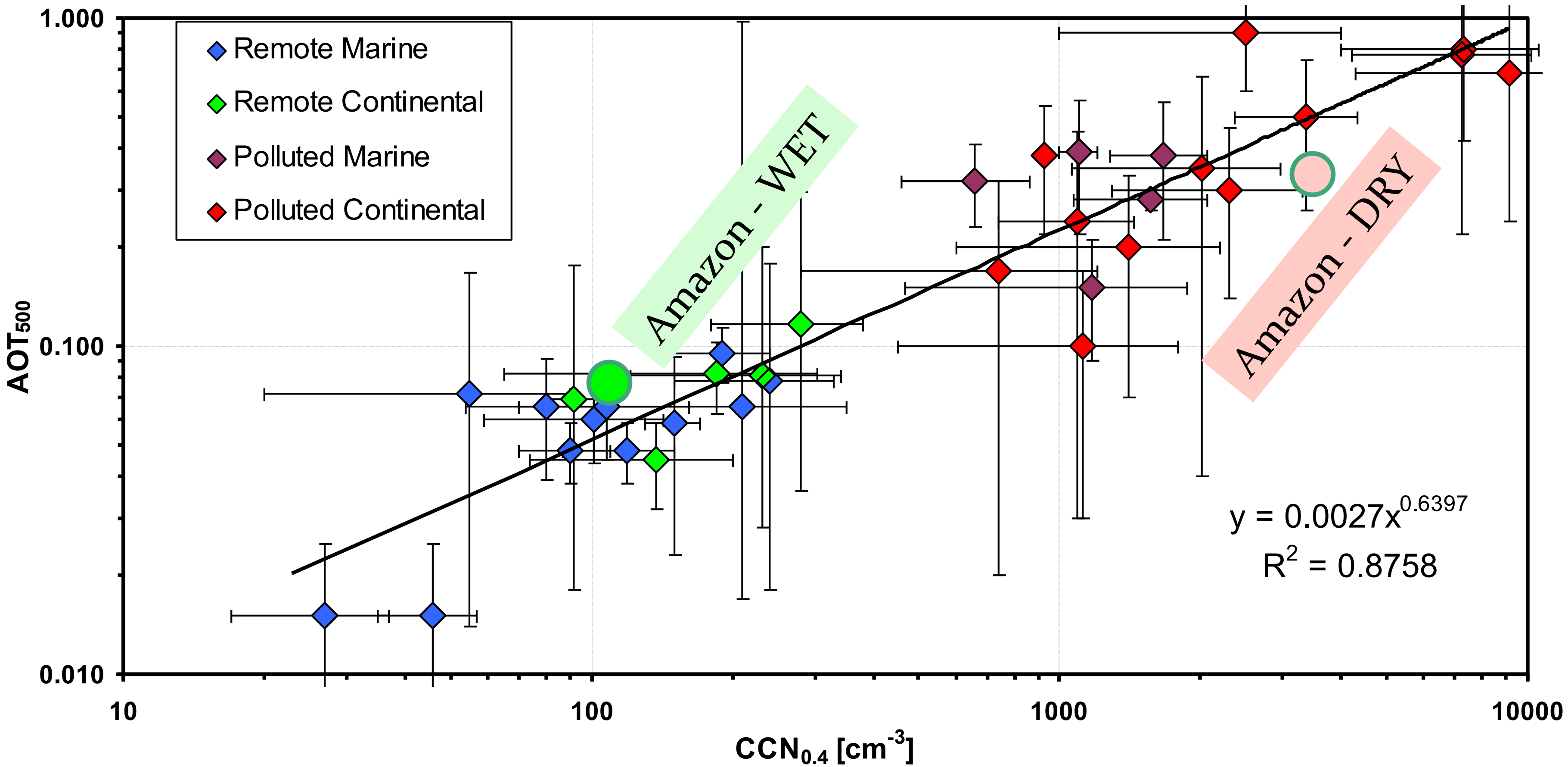


D. Gouveia, Msc dissertation, USP



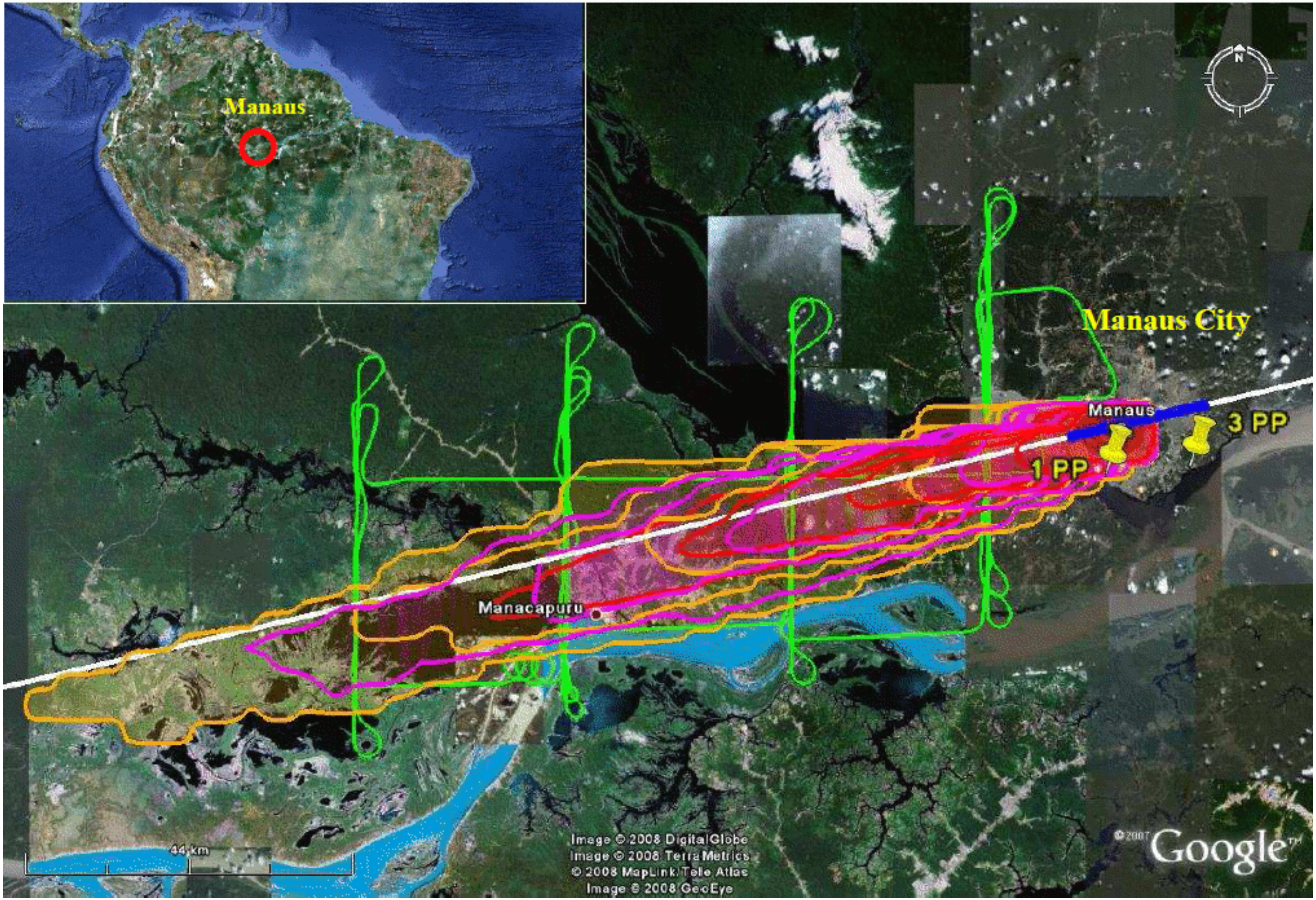
Frequency 78 % 83 % 52 % 77 %

Observations of CCN and AOT



CCN concentrations and AOT over the cleanest continental sites are similar to the cleanest marine sites!

Experimento GoAmazon 2014



Thanks!

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