CFTC Centro de Física Teórica e Computacional

Ciências ULisboa

Structure and robustness of network infrastructures

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01/October/2015

http://www.namaraujo.net

POPH

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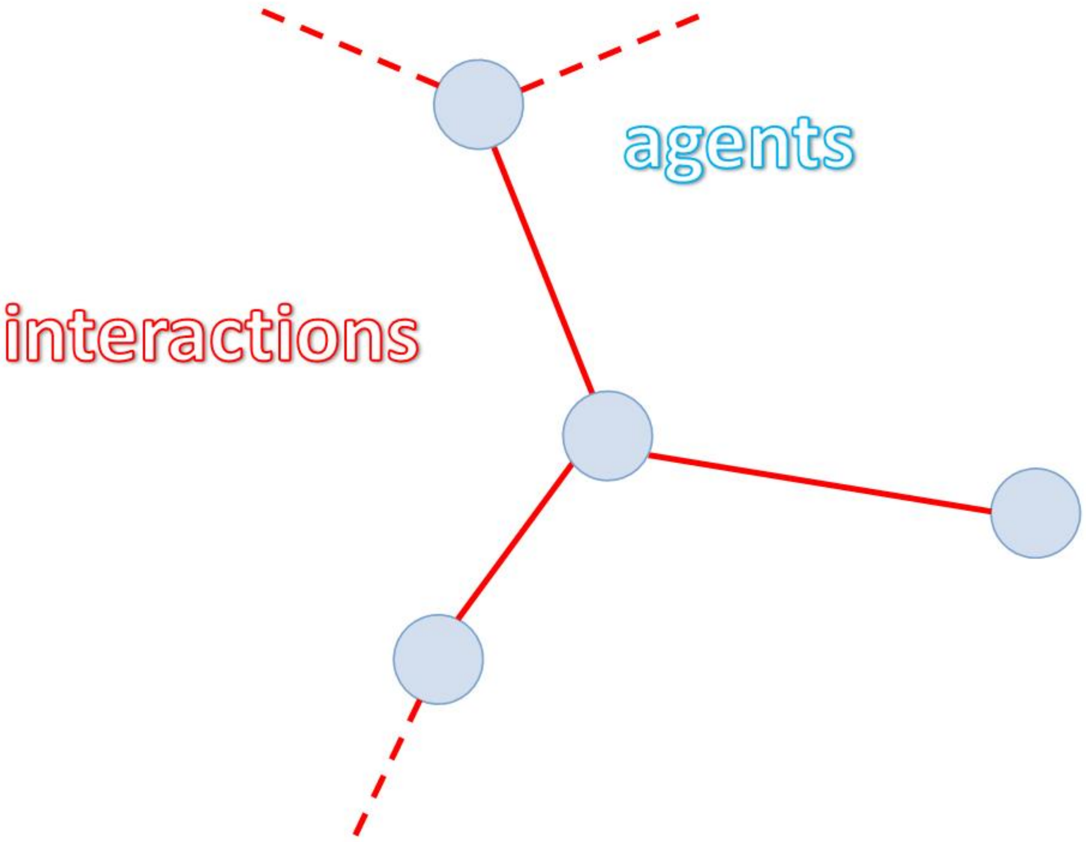
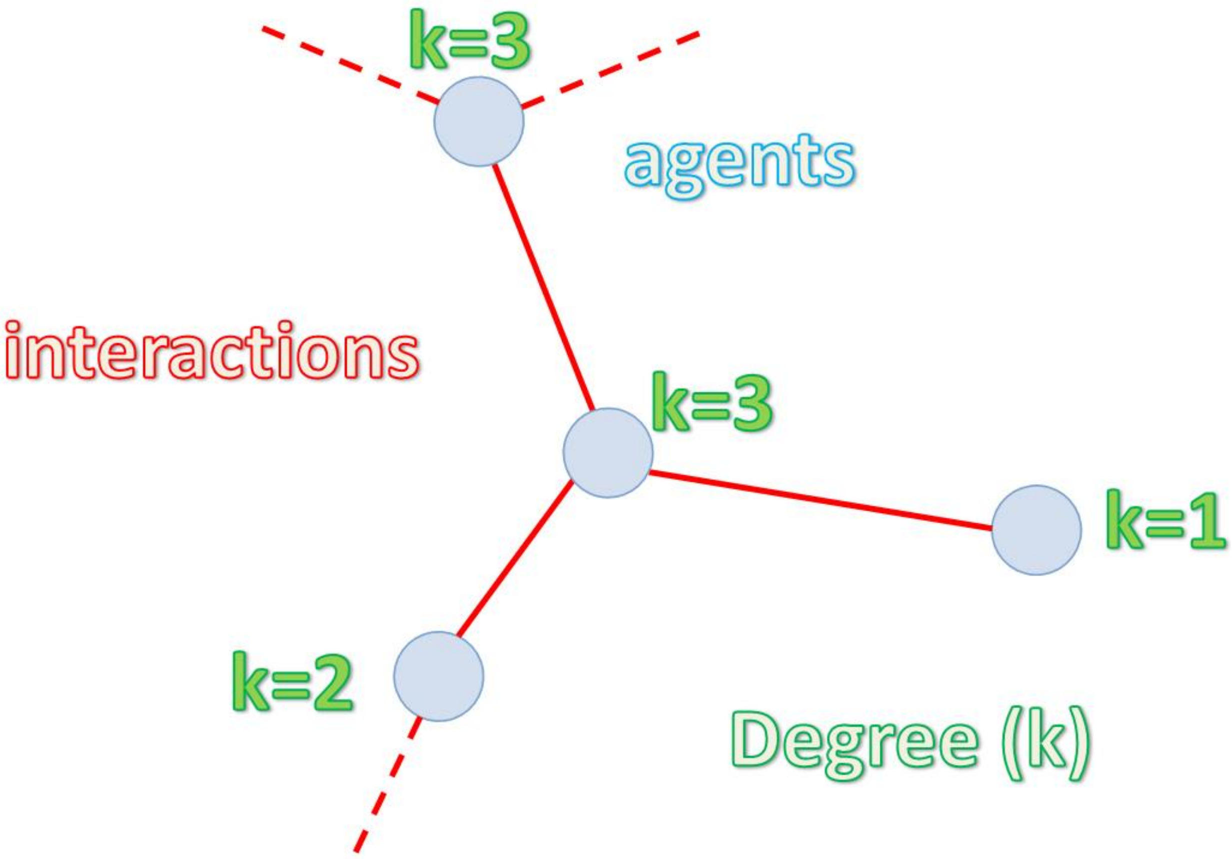
Universidade Ceará

Ingredients: nodes and links

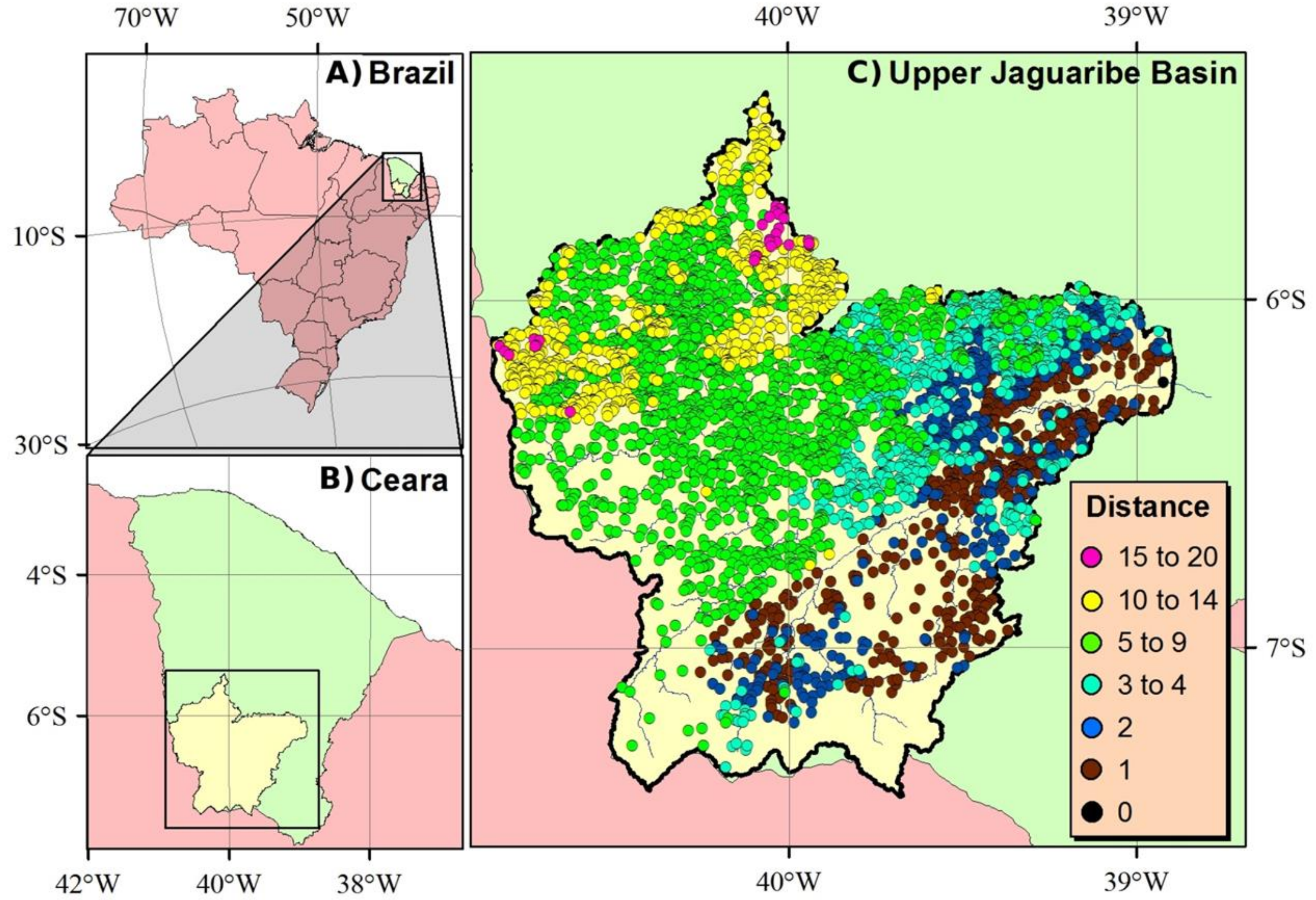


Ingredients: nodes and links



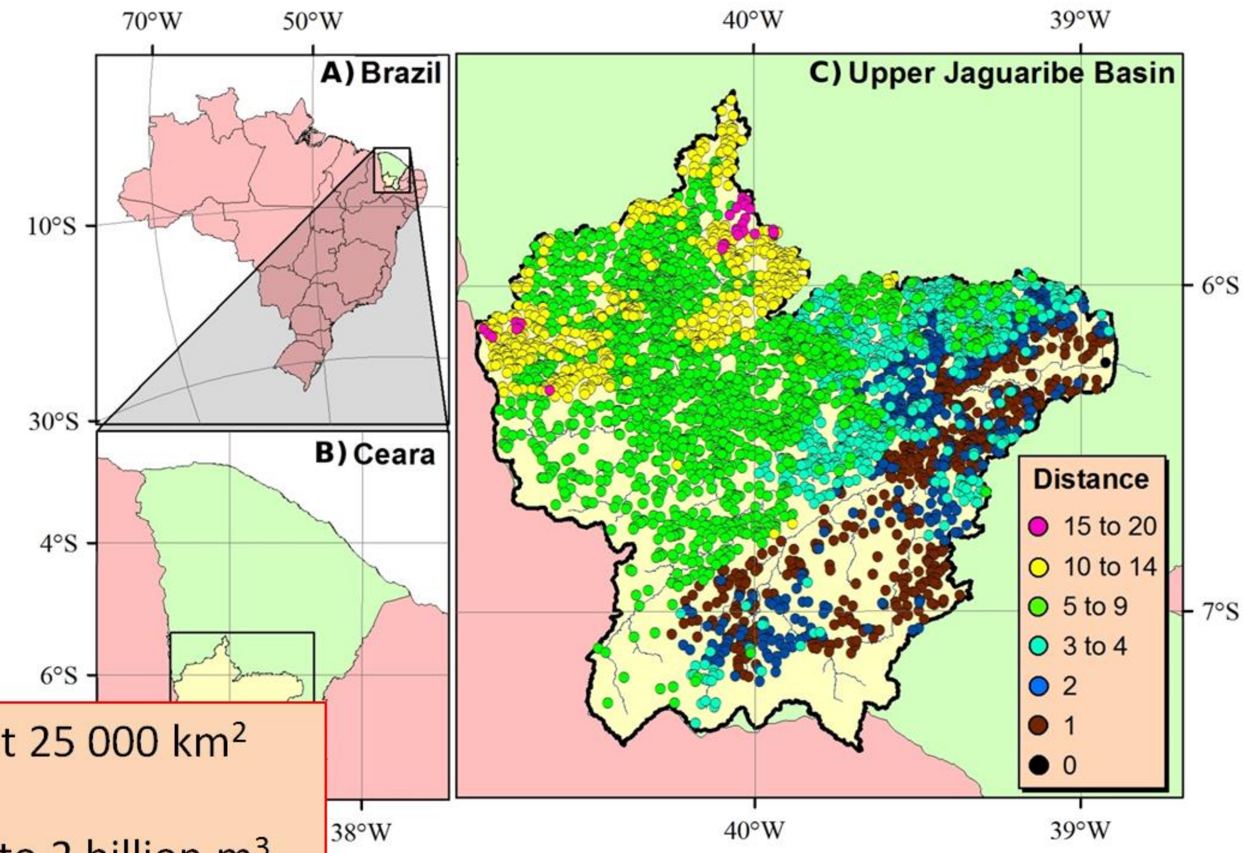
Water Reservoirs

The Upper Jaguaribe Basin



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

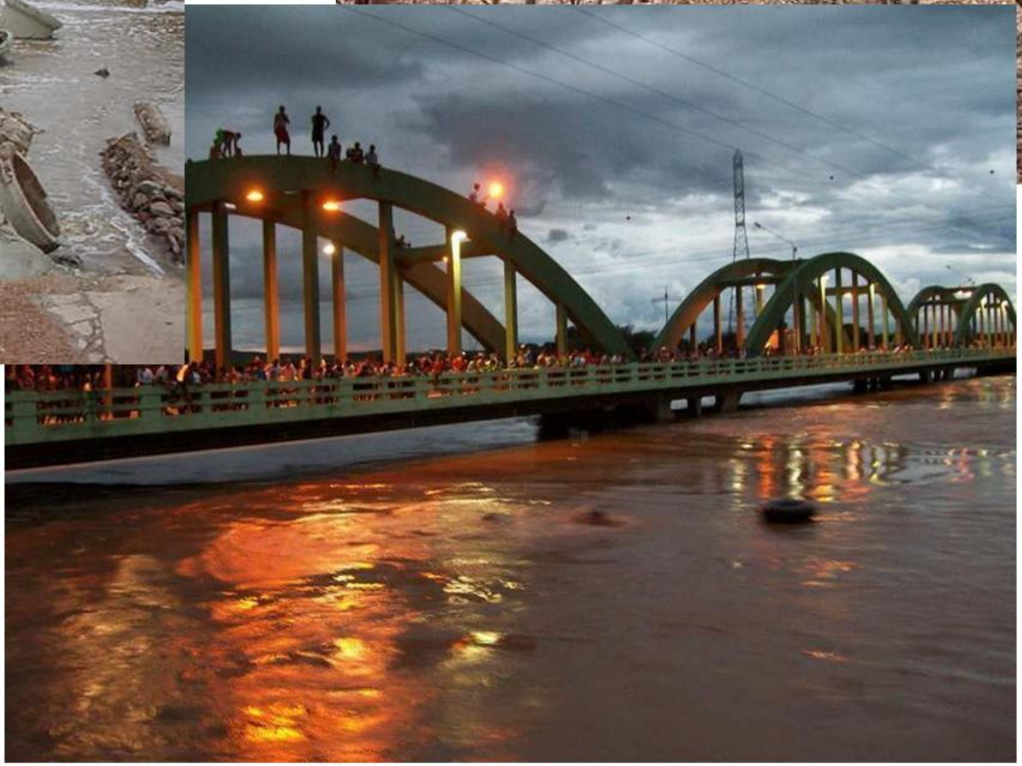
The Upper Jaguaribe Basin

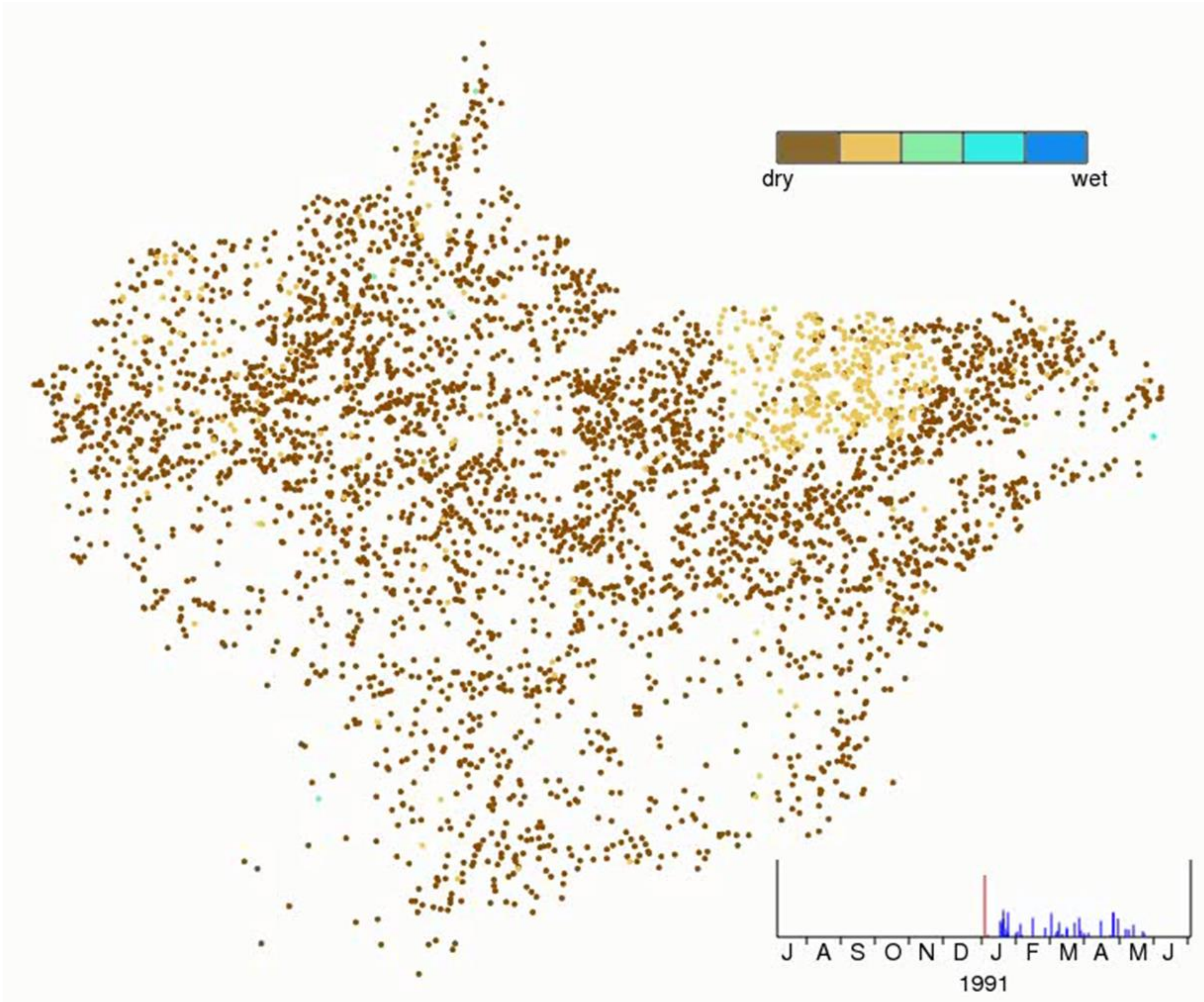


- Catchment area of about 25 000 km^2
- Almost 4 000 reservoirs
- Capacity from 2 500 m^3 to 2 billion m^3
- Affects half a million people
- Average annual rainfall: 860 mm
- Evaporation: 2 000 mm

G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

The Upper Jaguaribe Basin




dry
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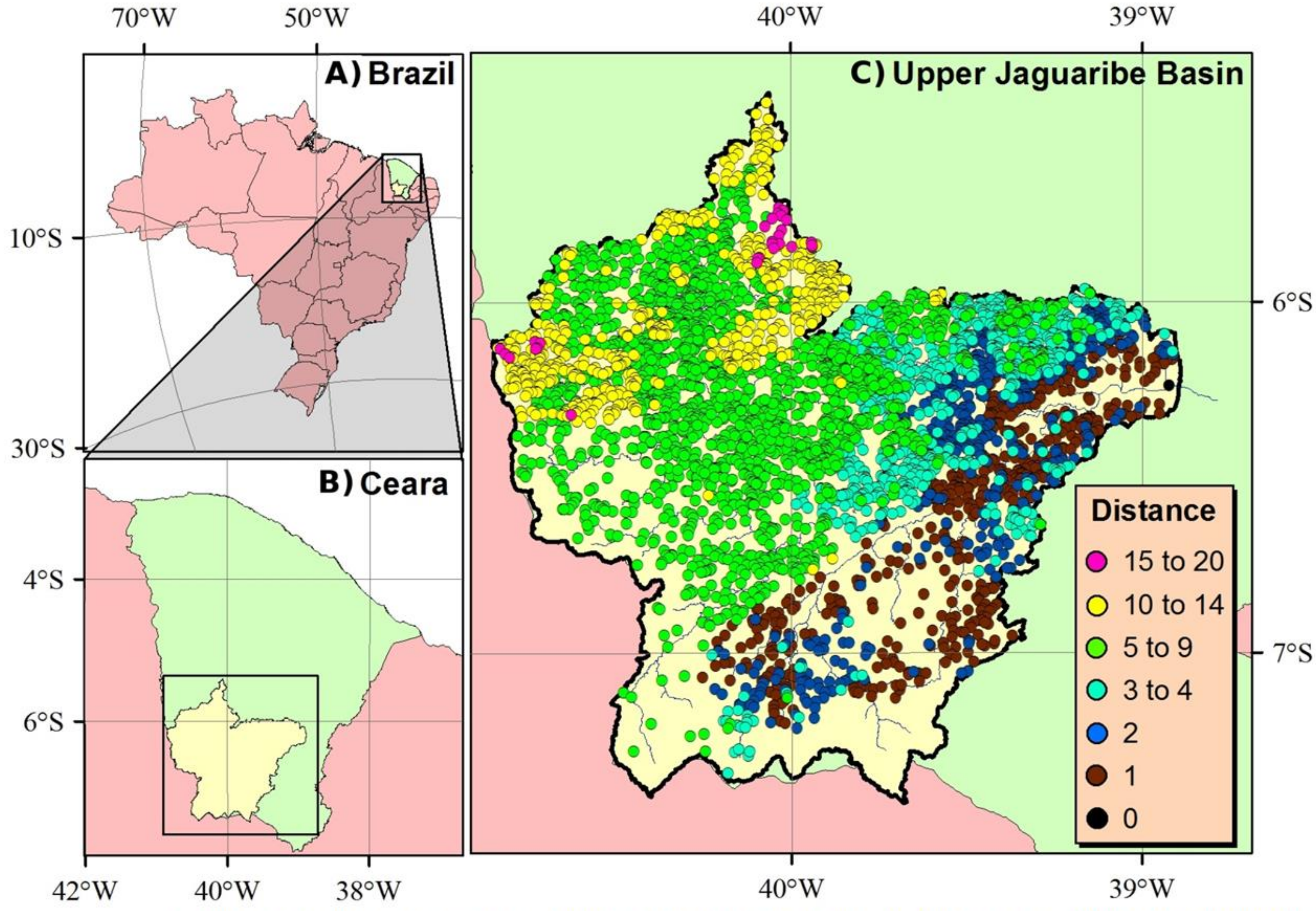
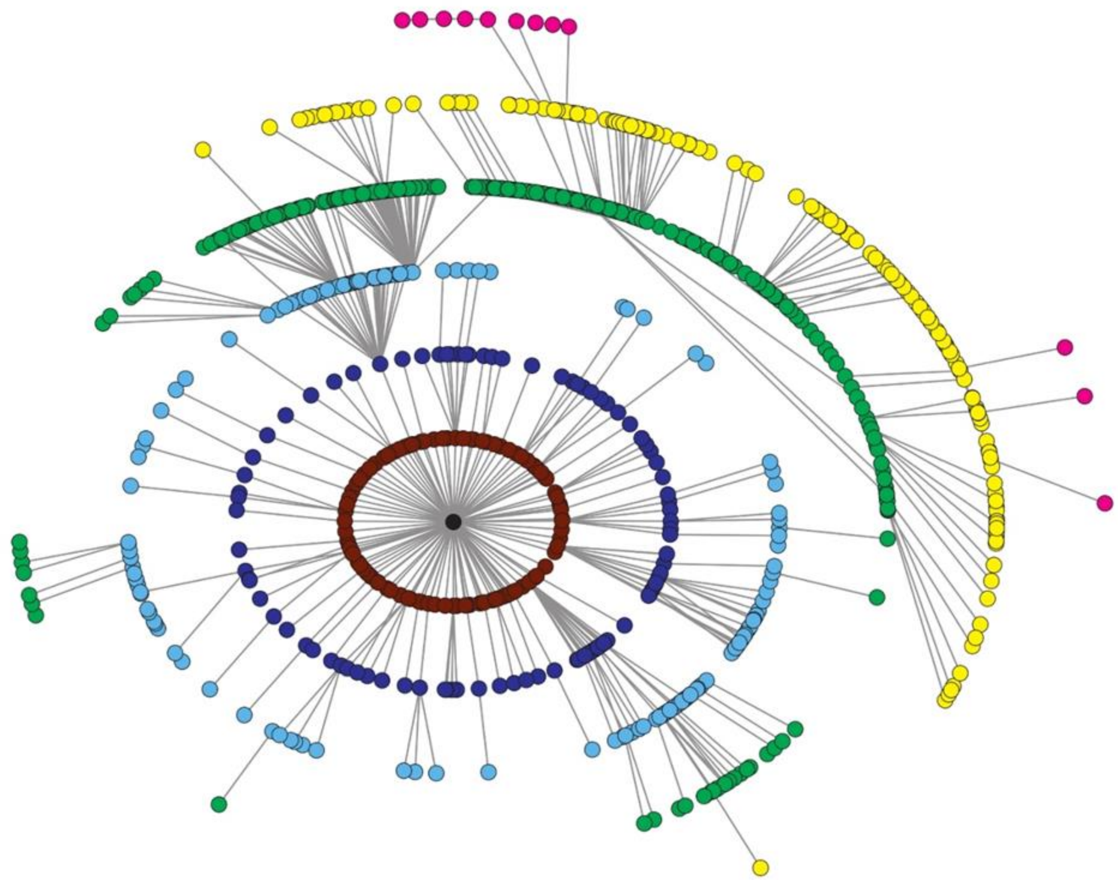
1991

The Upper Jaguaribe Basin

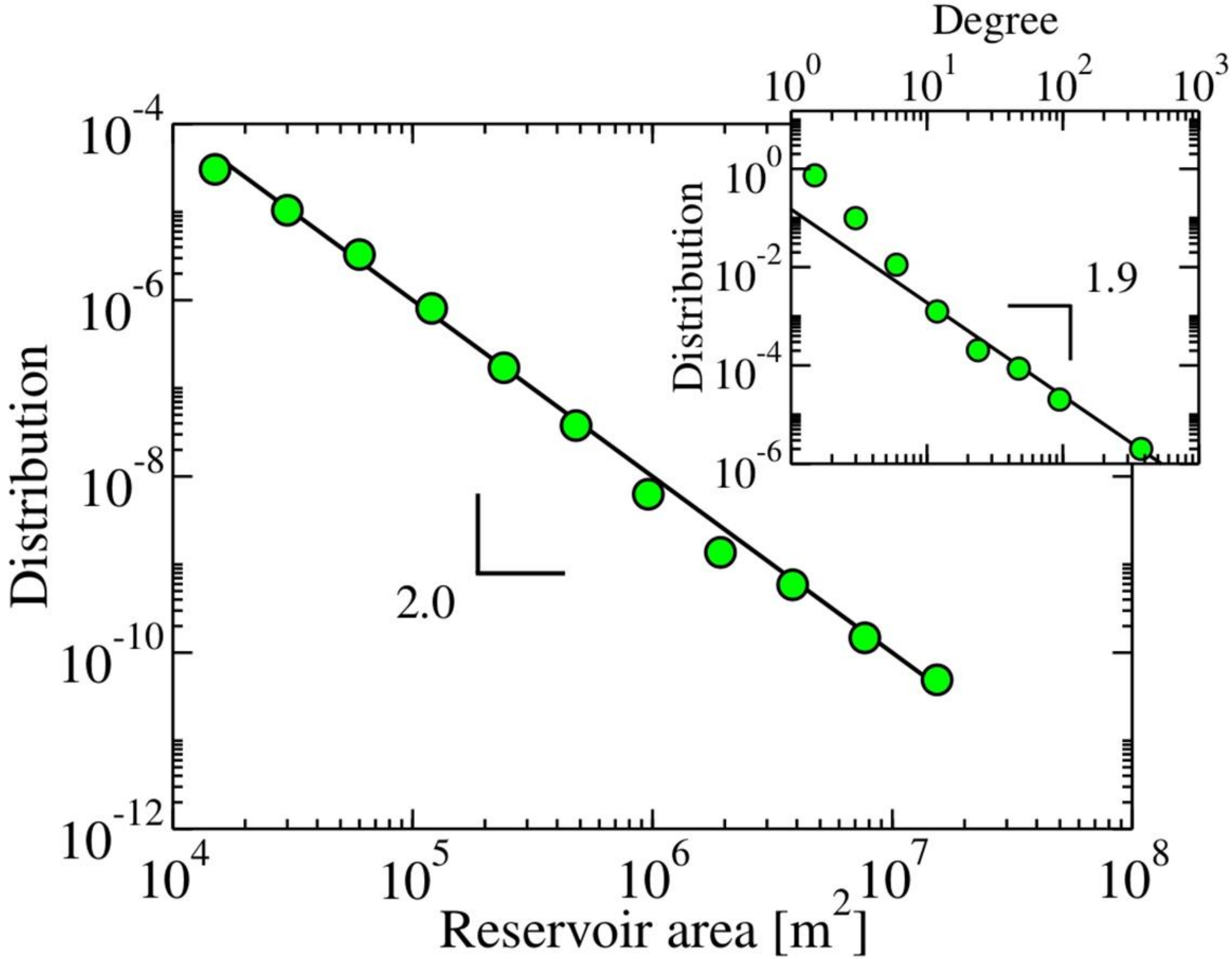


G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

The topology of the network



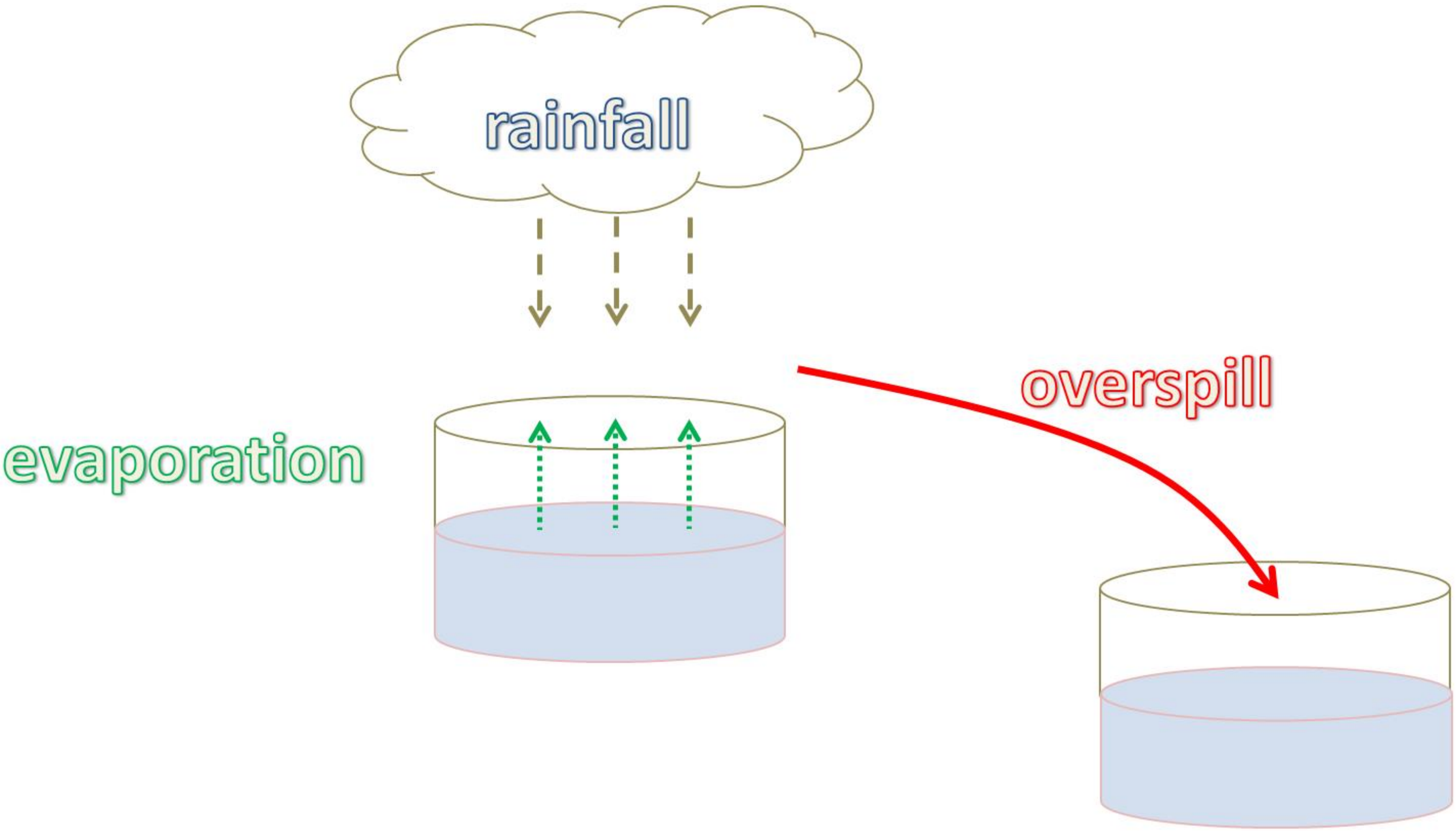
Size and degree distributions



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

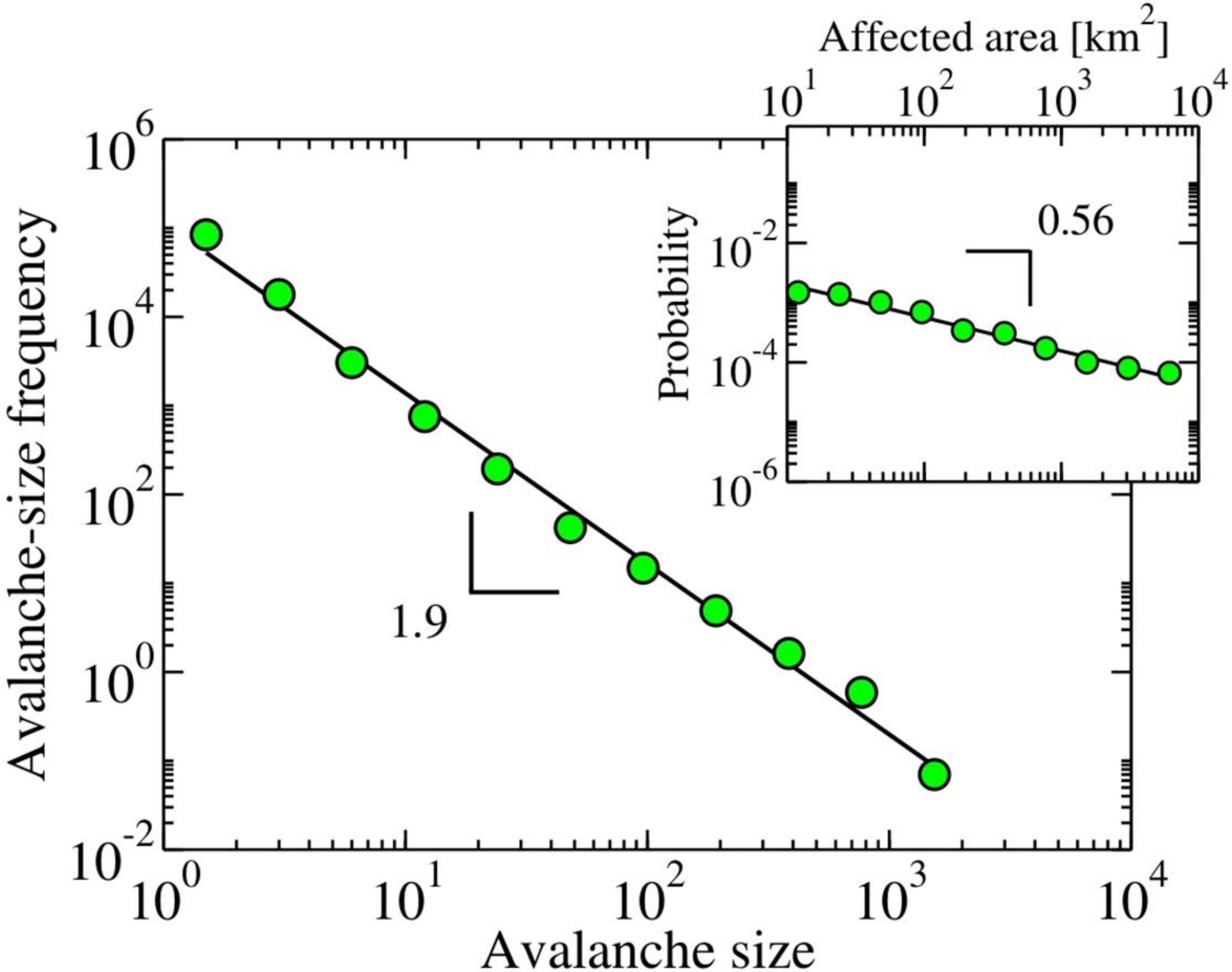
Climatic data

The hydrological model



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

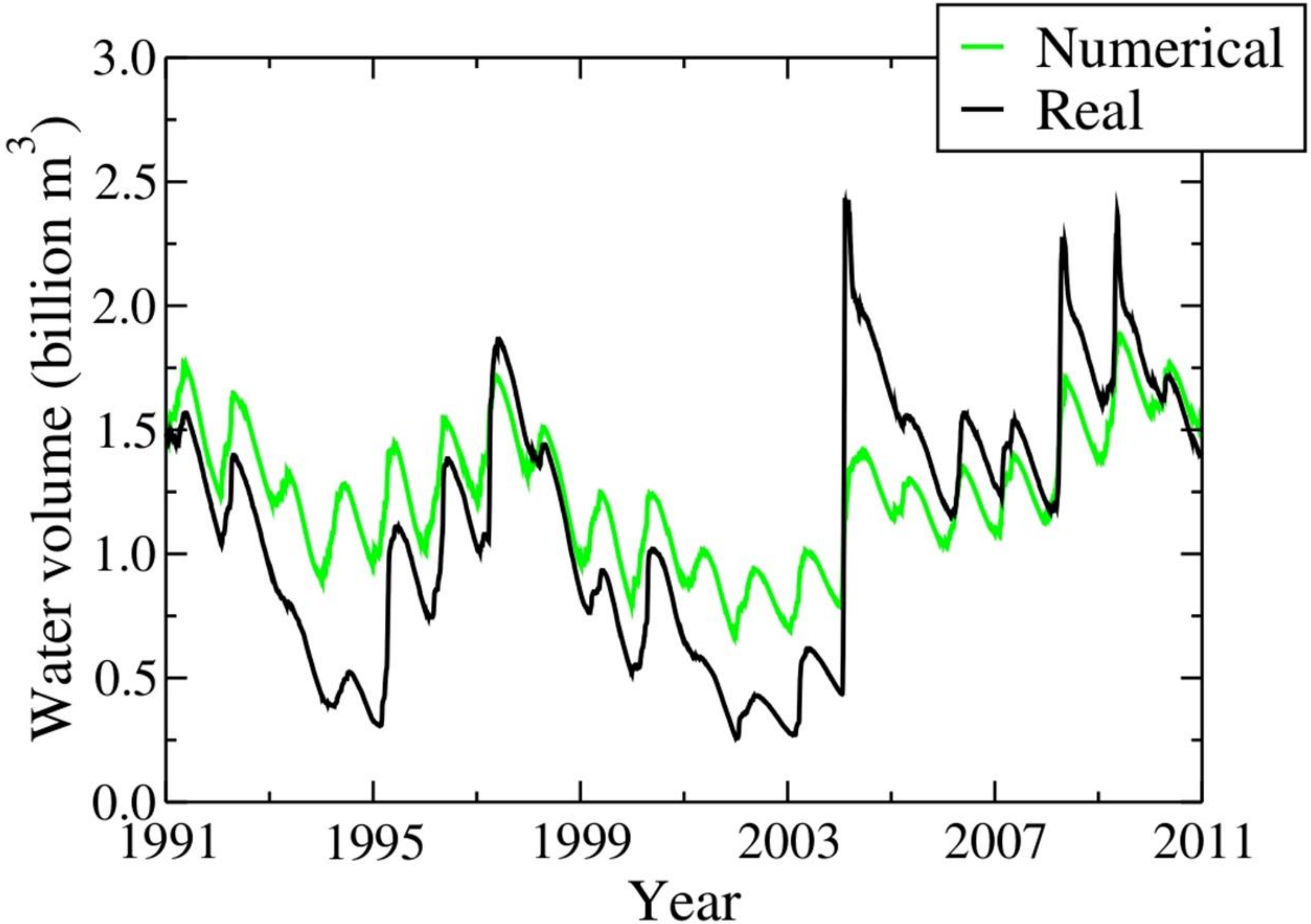
Avalanche-size distribution



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

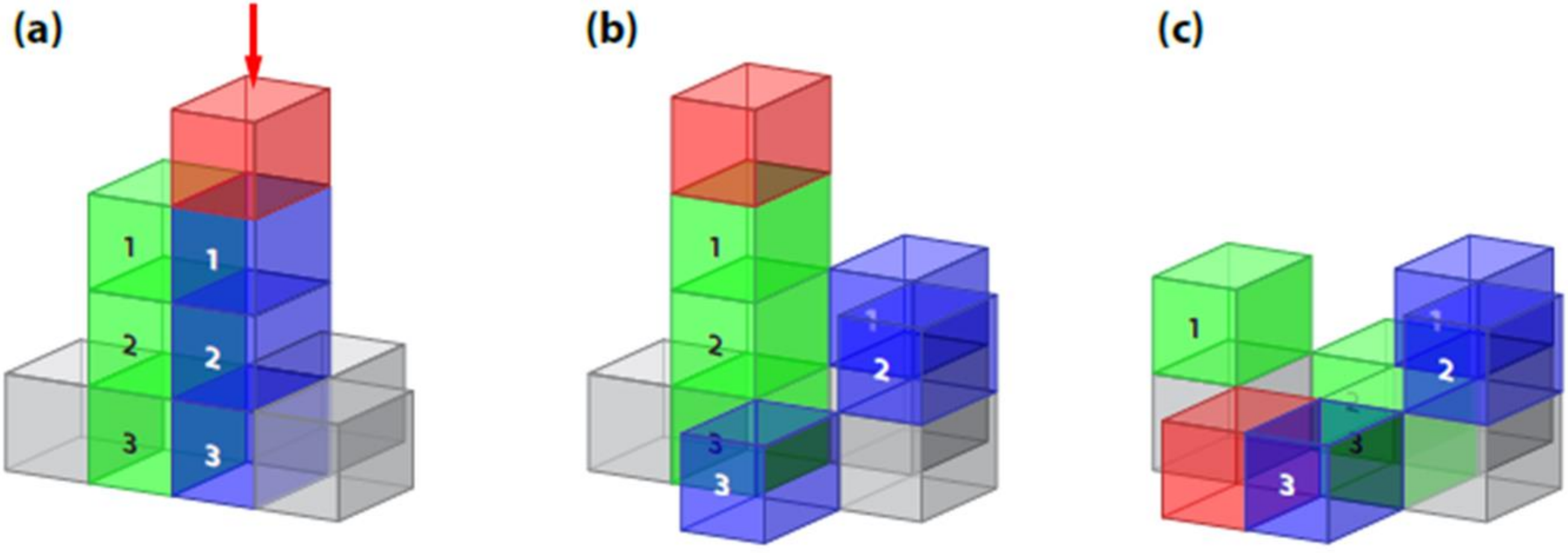
Reservoir water level

Reservoir water level



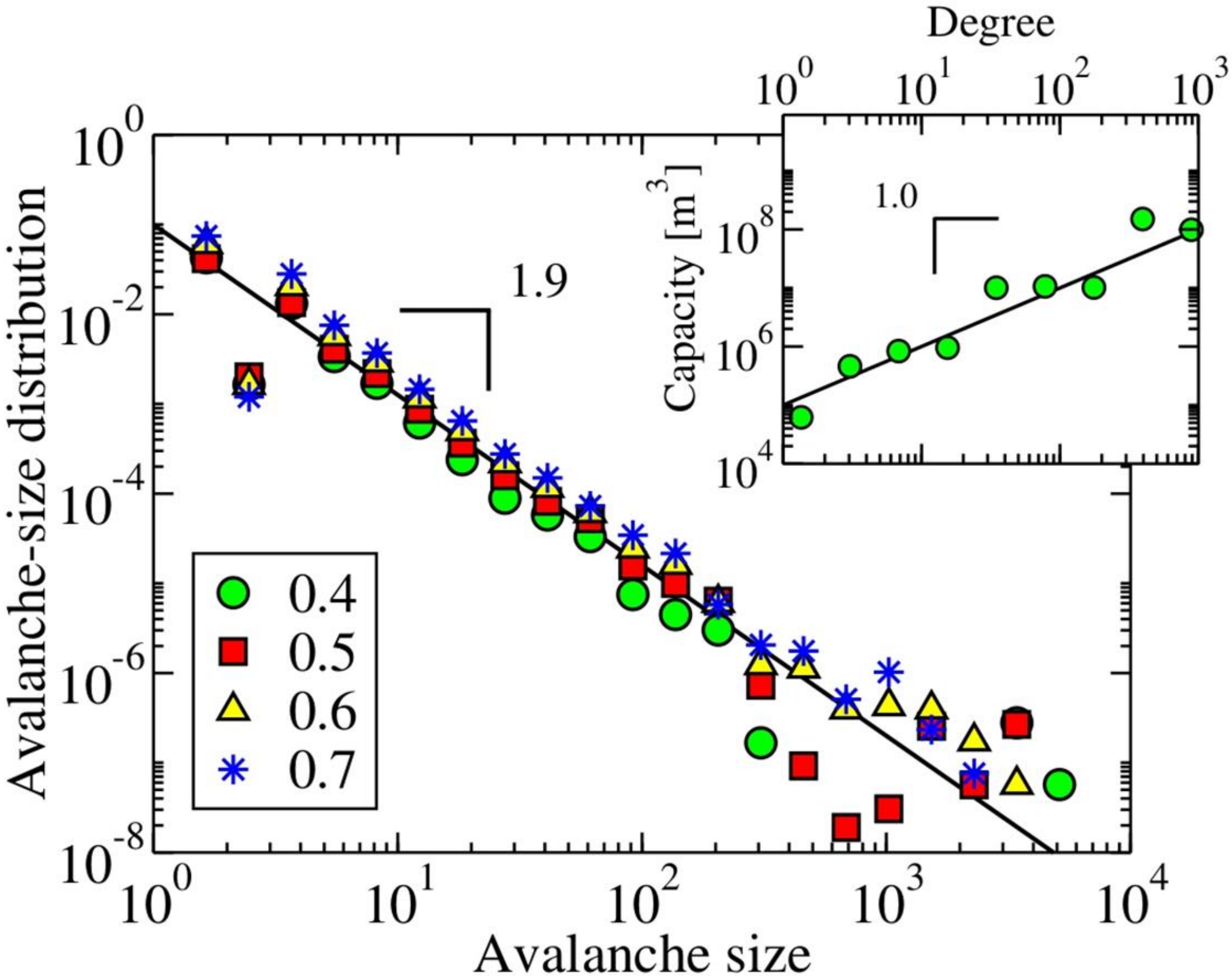
G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

Stochastic model



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

Stochastic model



G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, H. J. Herrmann. *PNAS* **109**, 7191 (2012)

Summary

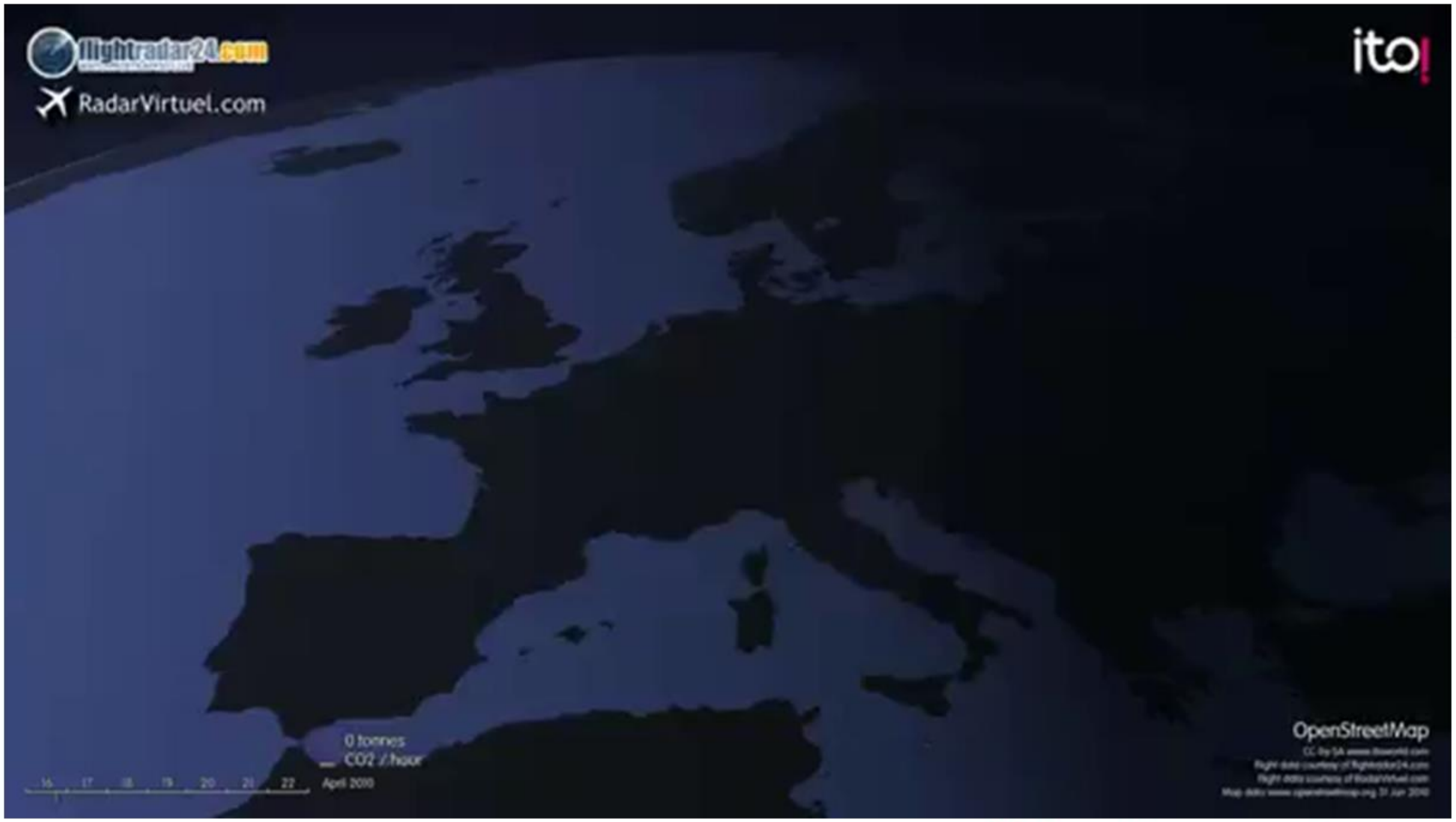
- We found unexpected scale-free behavior in the dynamics of water reservoirs;
- The network of reservoirs has a tree-like structure with power-law distribution of capacities;
- The hydrological model reveals an excellent qualitative and, in most cases, quantitative agreement;
- The stochastic model grasps the main features.

G. L. Mamede, N. A. M. Araújo, C. M. Schneider, J. C. de Araújo, and H. J. Herrmann. *PNAS* **109**, 7191 (2012)
S. J. Peter , J. C. de Araújo, N. A. M. Araújo, and H. J. Herrmann. *Journal of Hydrology* **512**, 408 (2014)

World Airline Network

Networks can fail to work

Eyjafjallajökull



ItoWorld, http://vimeo.com/11739091

107,000 flights cancelled during an 8 day period, accounting for 48% of total air traffic and roughly 10 million passengers

What is the structure of the *WAN* and how resilient is it?

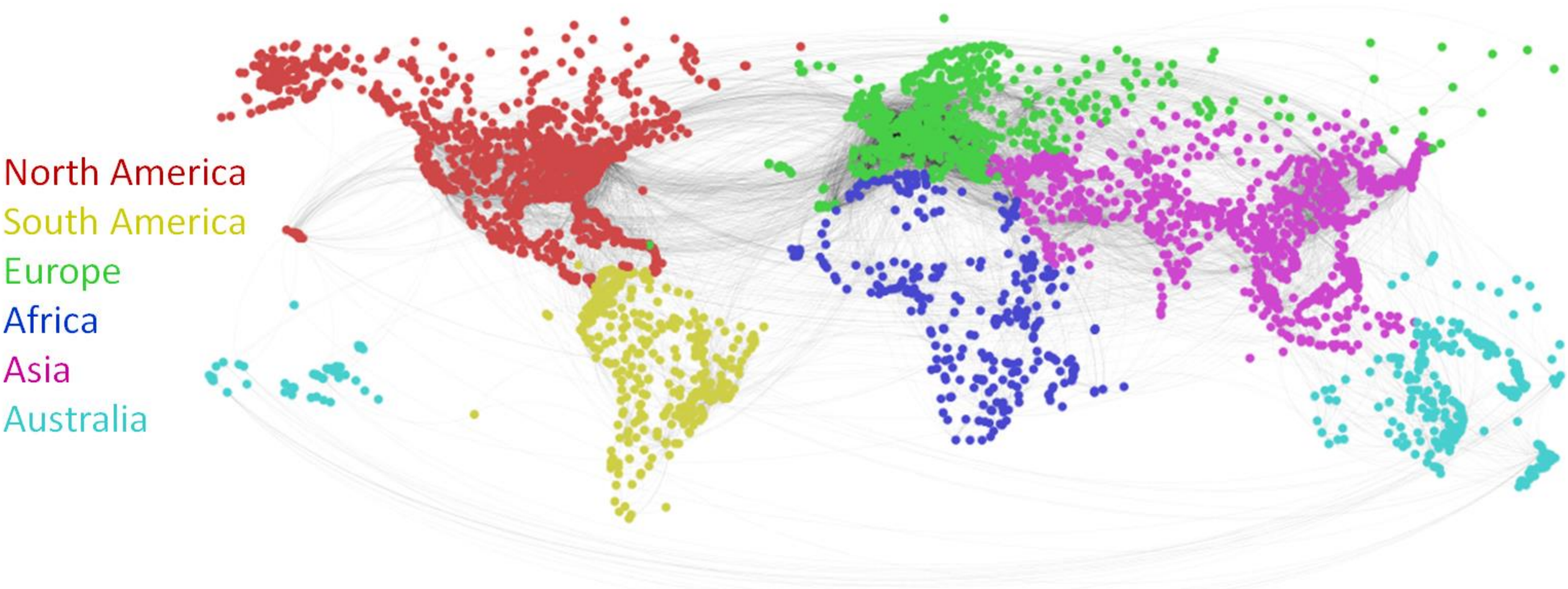
World Airline Network (WAN)

Airports	3237
Connections	18125
Flights	62202

$$< k^w >= 19.21$$

$$< l >= 4.05$$

$$l_{\max} = 12$$



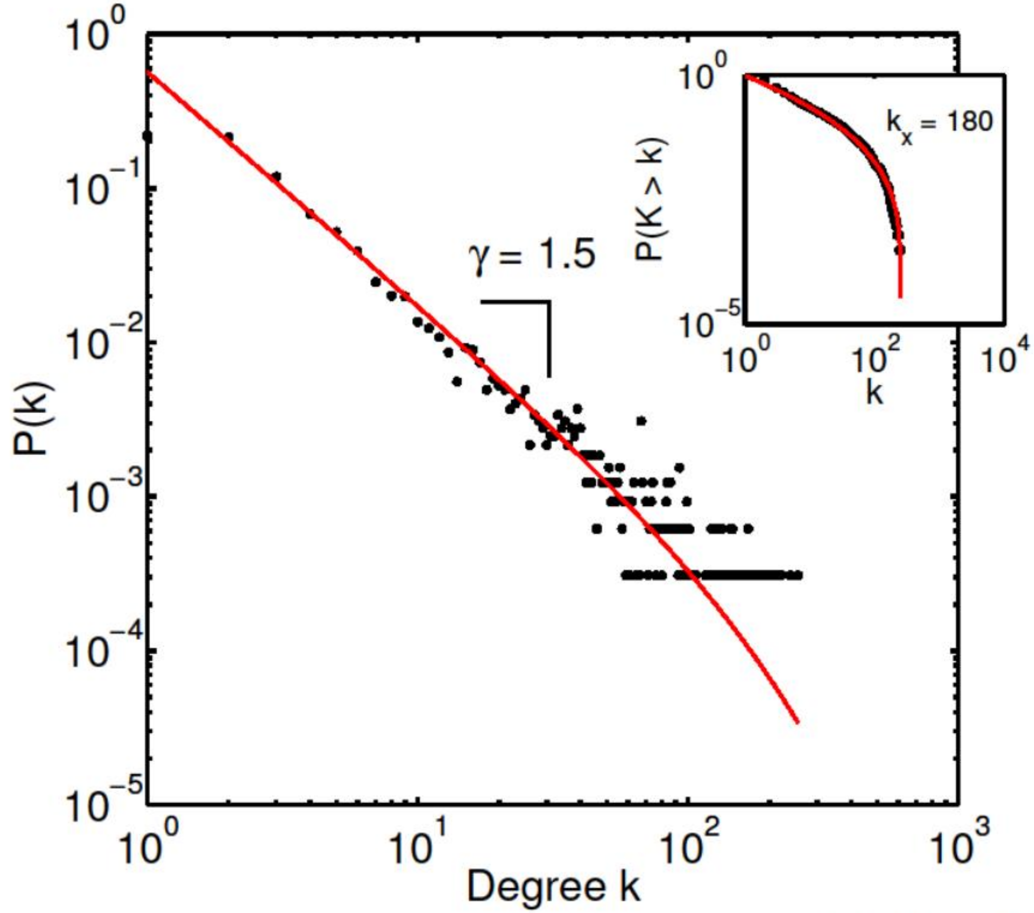
http://openflights.org/data.html

Degree Distribution

$\gamma = 1.5 \pm 0.1$

$k_x = 180 \pm 5$

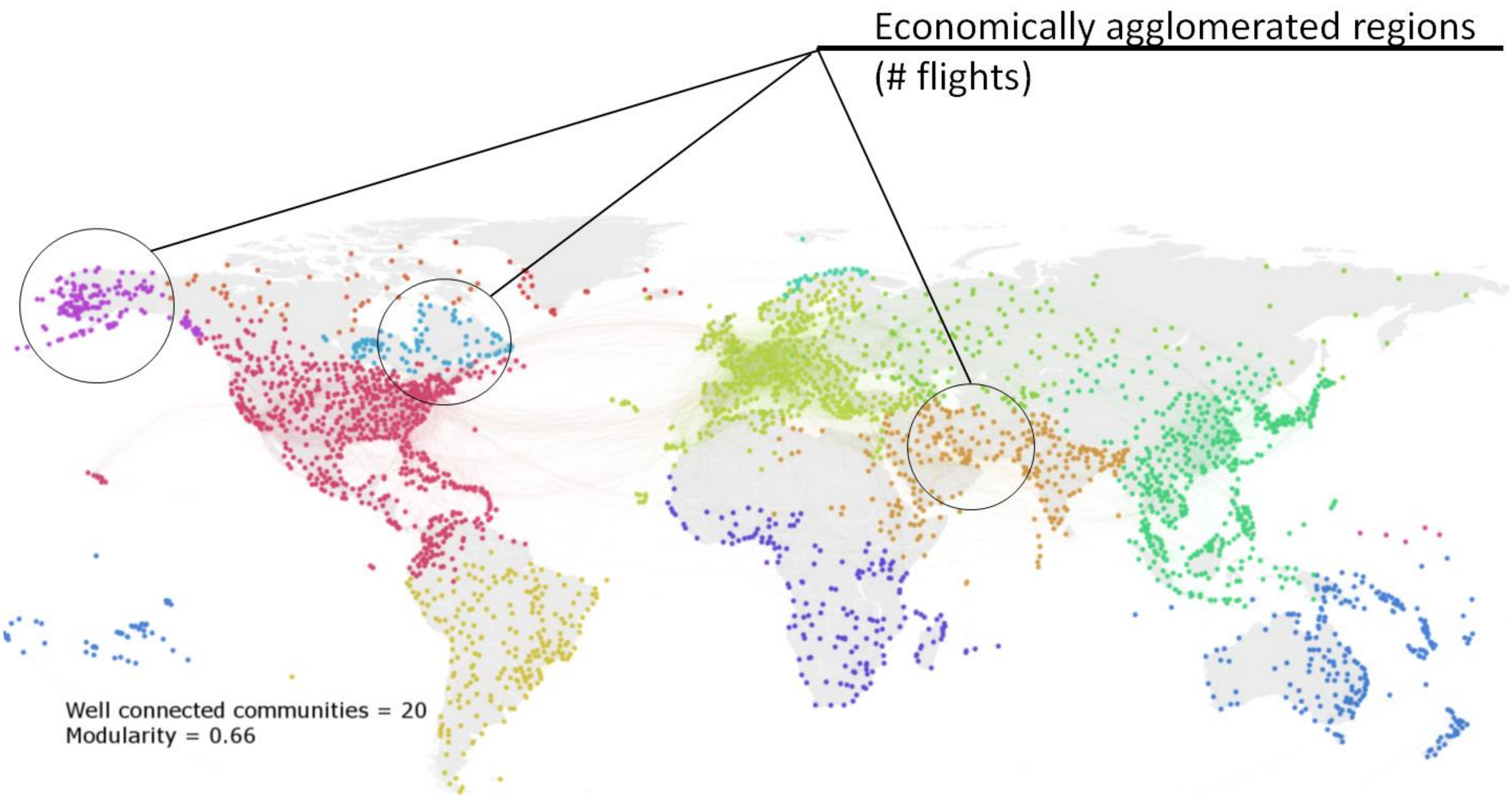
$$P(k) \sim k^{-\gamma} \exp(-k / k_x)$$



$$P(K > k) = 1 - \int_0^k P(k')dk'$$

Communities

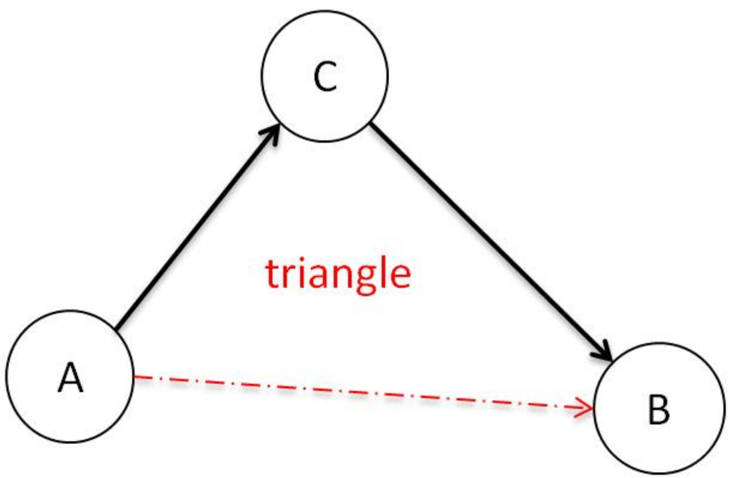
High modularity indicates presence of well formed communities



t-Core decomposition

t = 0

t = 1



T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)

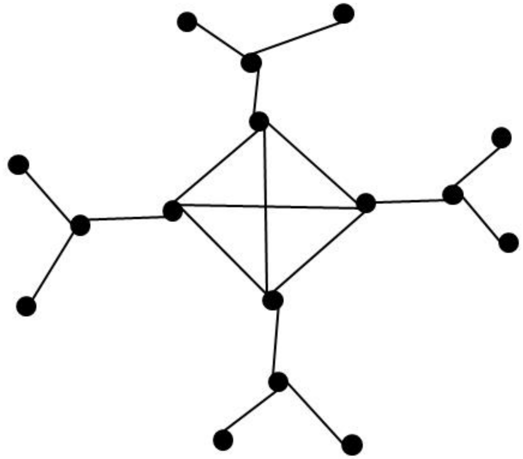
t-Core decomposition

● 8.5% fall out of the cluster

Highly redundant connections

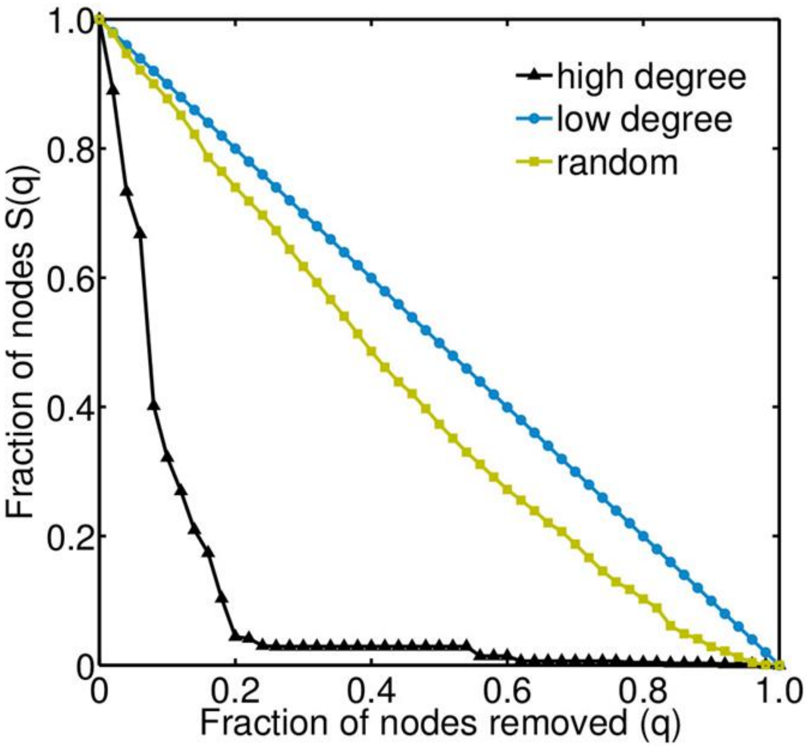
T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)

Disruptions



Global Connectivity – S(q)

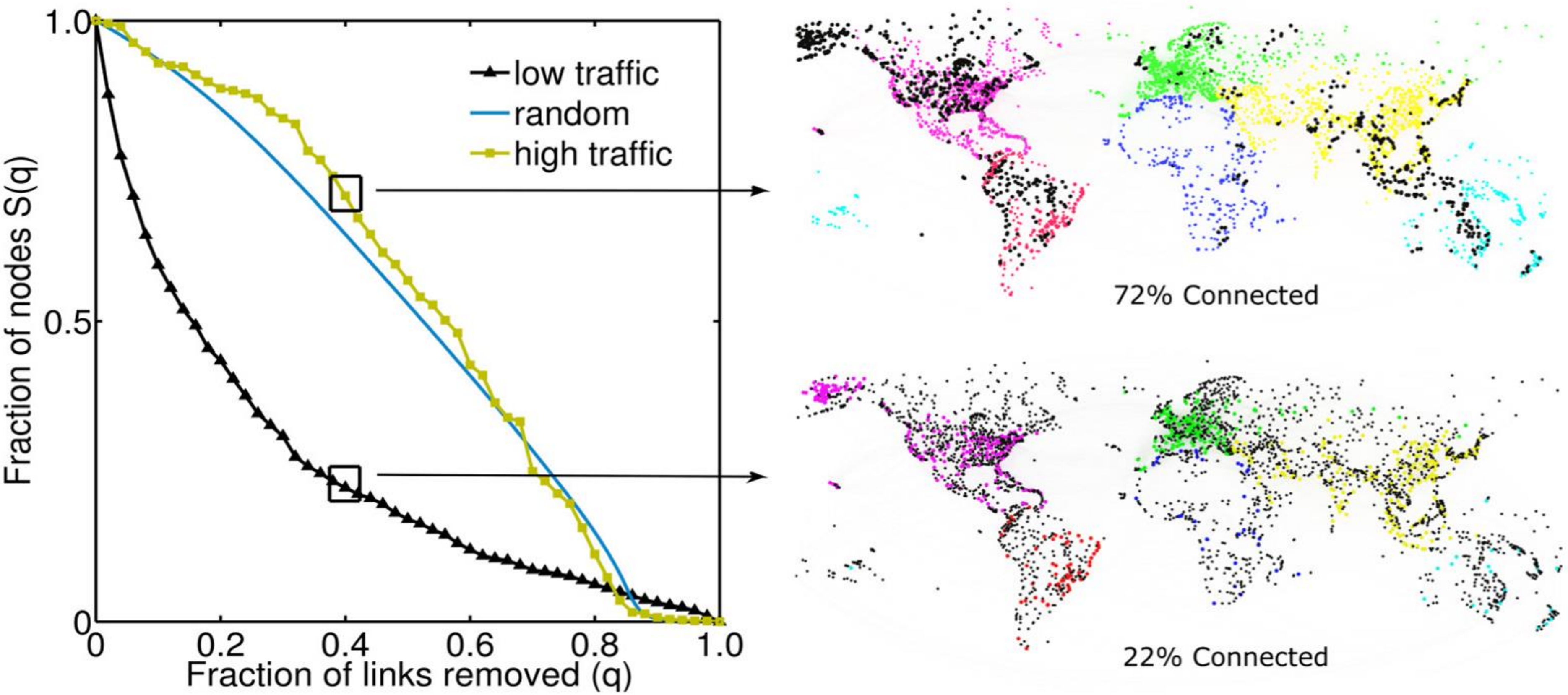
- Fraction of airports in the largest connected cluster
- S(0) = 1, connected WAN
- q : removal of elements
  - Airports (usual behavior)
  - Connections



T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)

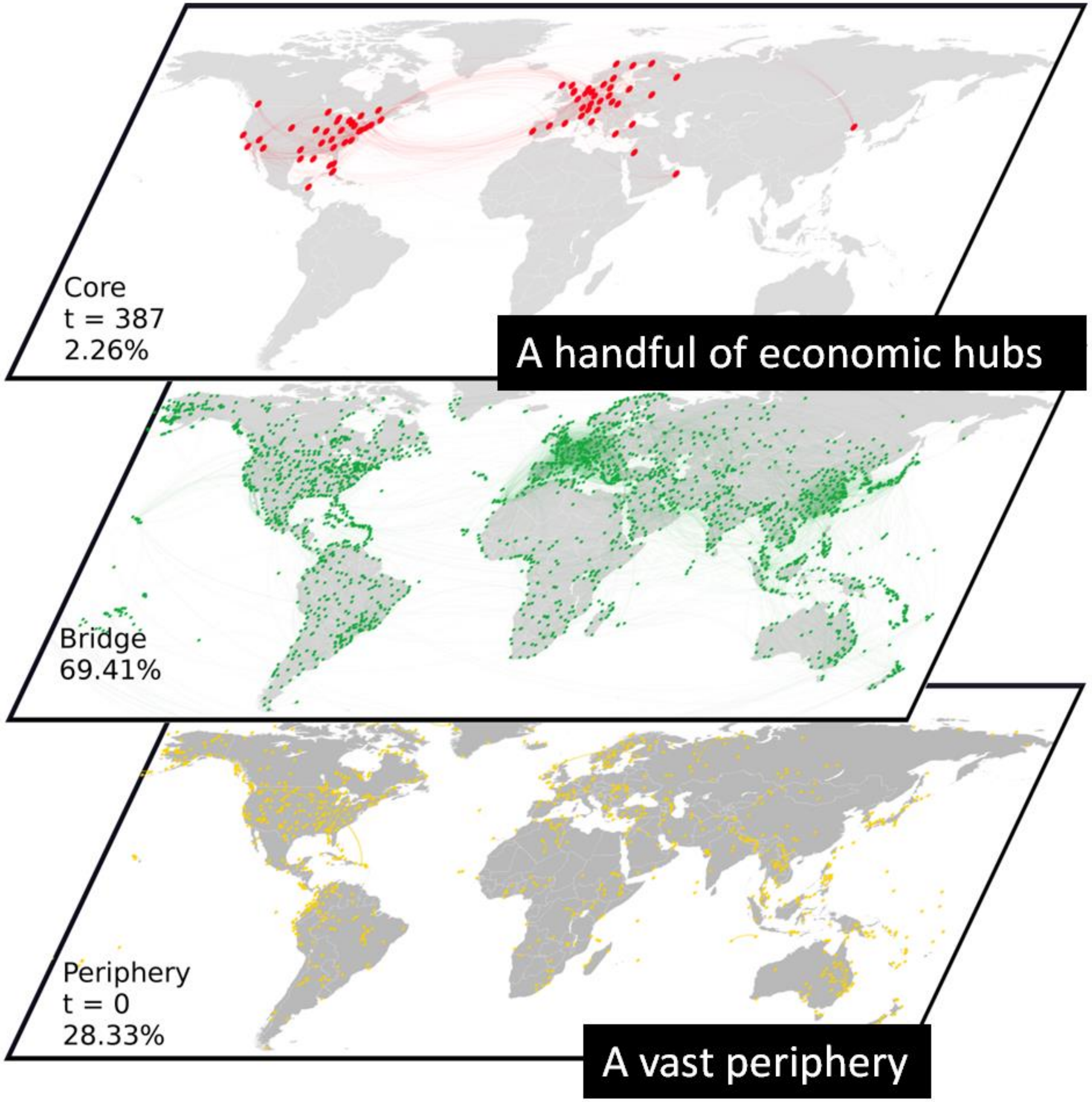
Results

Low Traffic removal causes more damage to the network



T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)

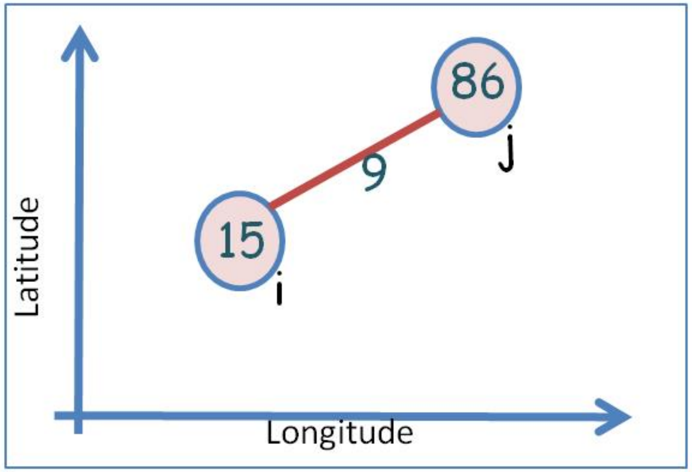
The structure of the World Airline Network



T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)

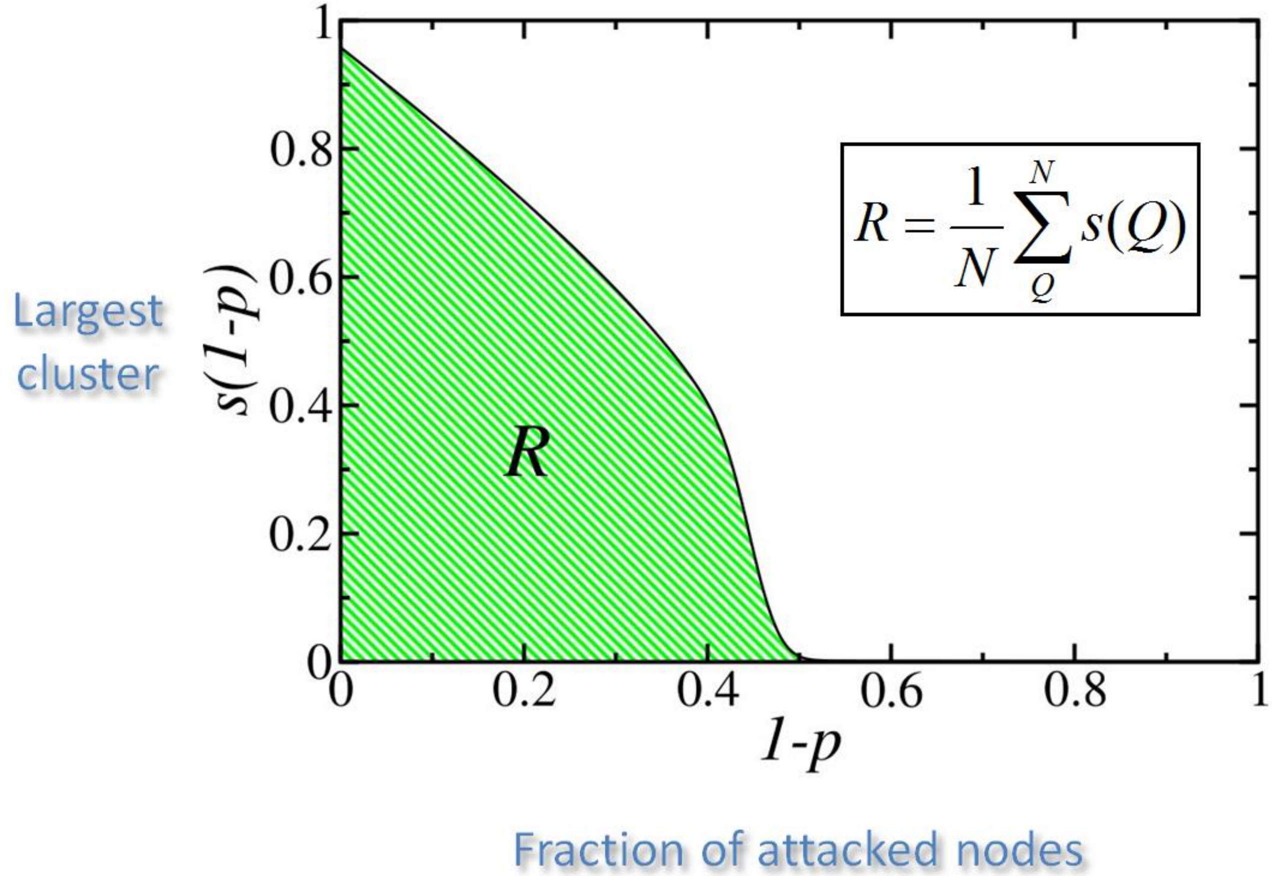
Improve the resilience

- Nodes are airports;
- Node weight is the number of passengers;
- Edge weight is the number of flights;
- We have geographical coordinates.



V. H. P. Louzada, N. A. M. Araujo, T. Verma, F. Daolio, H. J. Herrmann, and M. Tomassini. *PLoS One* **10**, e0118635 (2015)

Network *Robustness*



$$R = \frac{1}{N}\sum_{Q}^{N} s(Q)$$

C. M. Schneider, A. A. Moreira, J. S. Andrade Jr., S. Havlin, and H. J. Herrmann. *PNAS* **108**, 3838 (2011)

Robust networks attend to many passengers even in face of a threat

Deleting the node with highest degree

People in the largest connected component

$$Robustness = \frac{1}{\Pi(0)} \sum_{i=1}^{N} \Pi(i)$$

Delete the highest connected node (the hub), calculate the number of ~~nodes~~ passengers in the largest connected component, find the new hub, and repeat.

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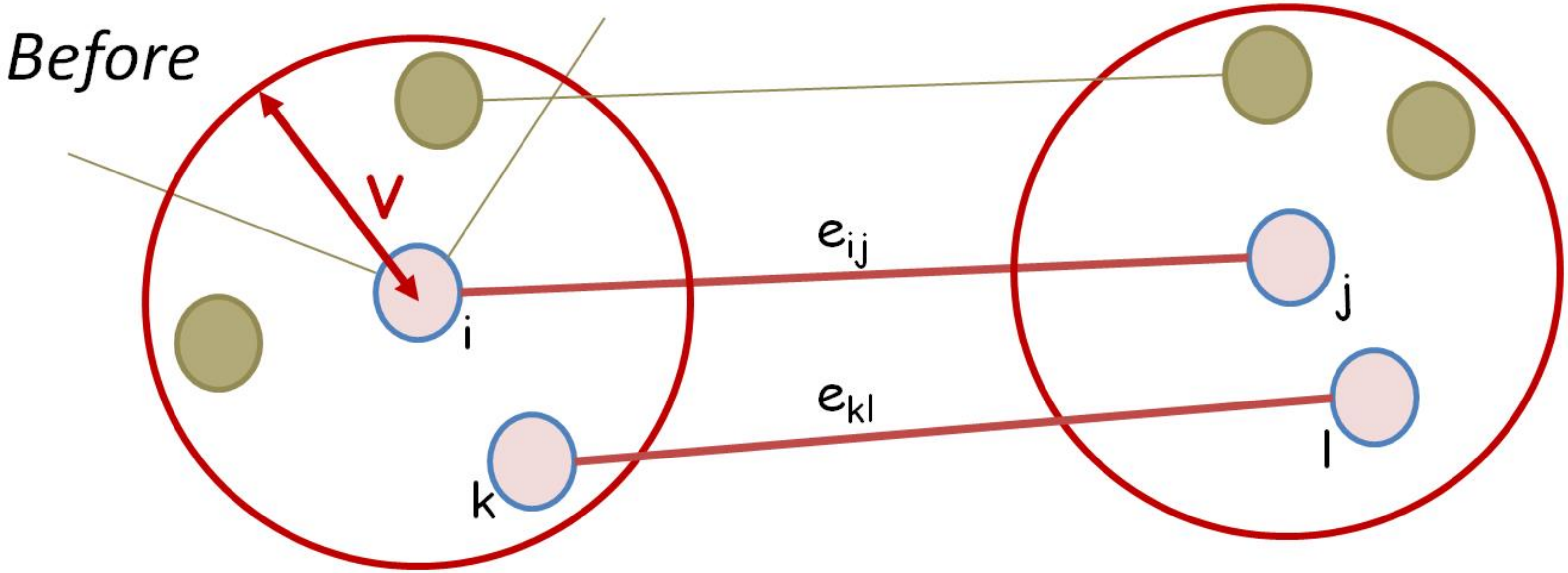
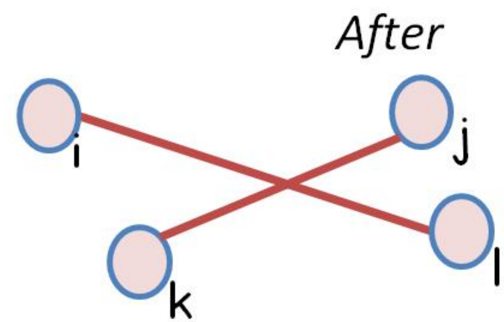


$$P(e_{ij}) \propto \frac{1}{weight(e_{ij})} \qquad P(e_{kl}) \propto \frac{1}{weight(e_{kl})}$$



- If $R_{after} > R_{before}$, keep it. Otherwise, unswap.

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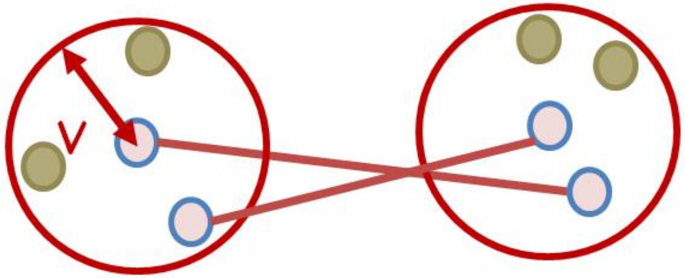
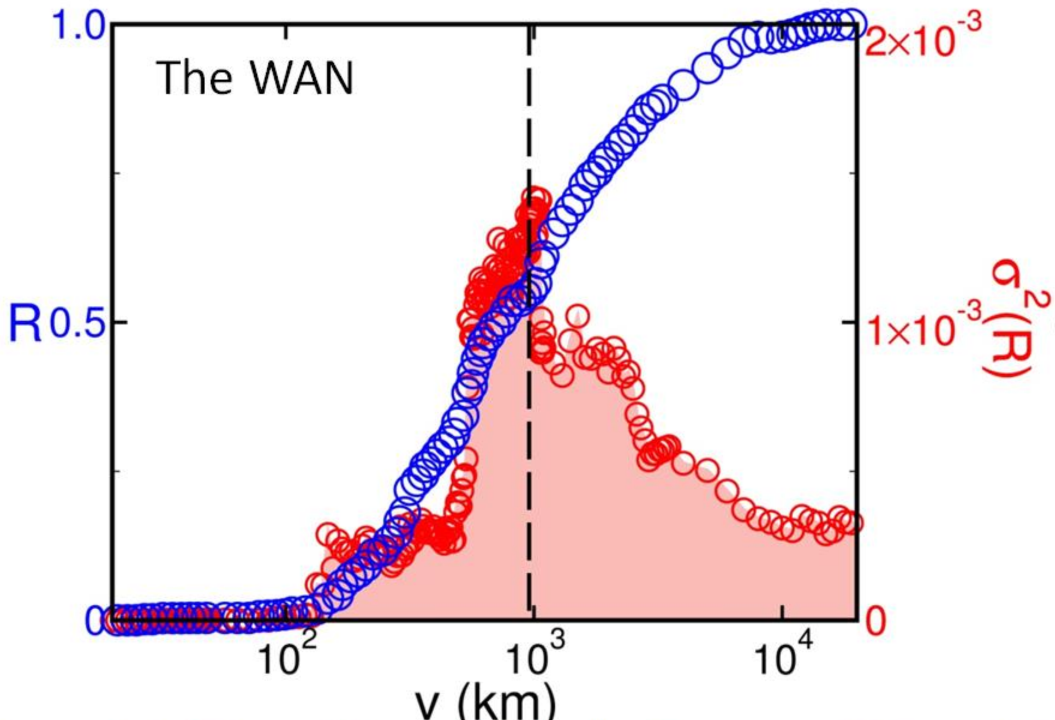
• Once you land in a different airport, take a car to the original destination;



• The cooperation range v should be small in Europe, but large in South America;



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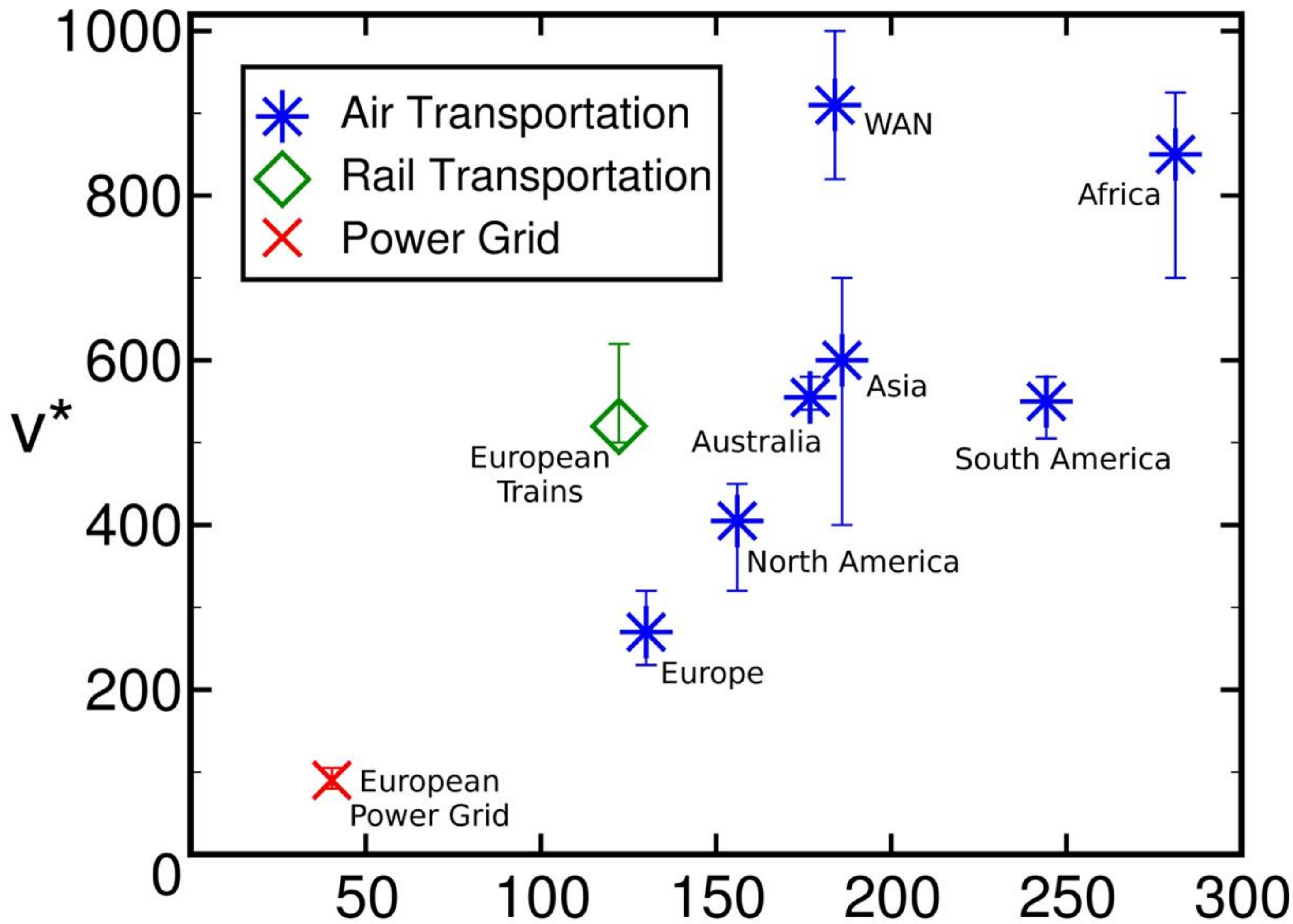

$$\sqrt{\frac{\text{area of the continent}}{\text{number of airports}}}$$

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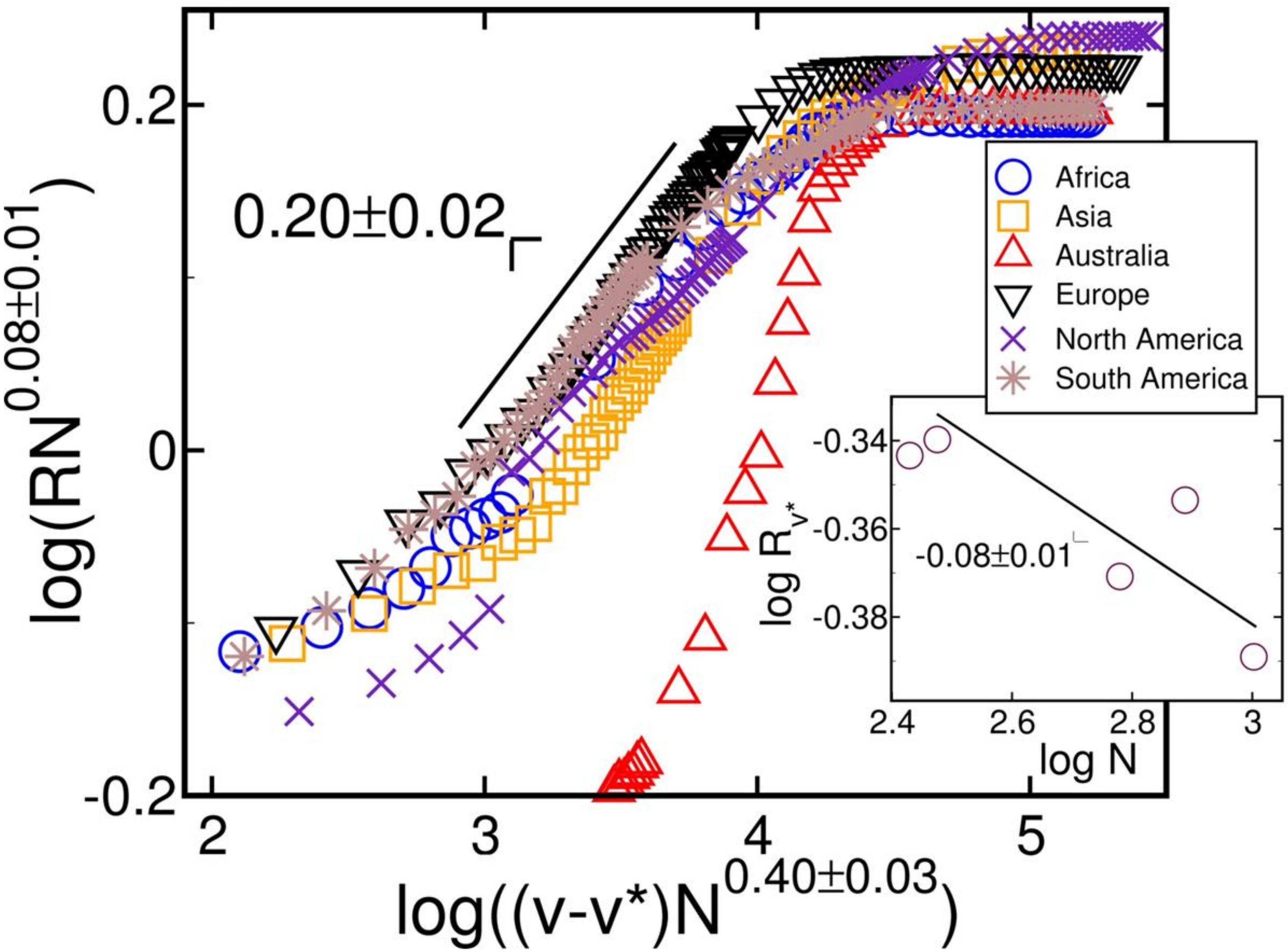
All continents

data collapse «works»



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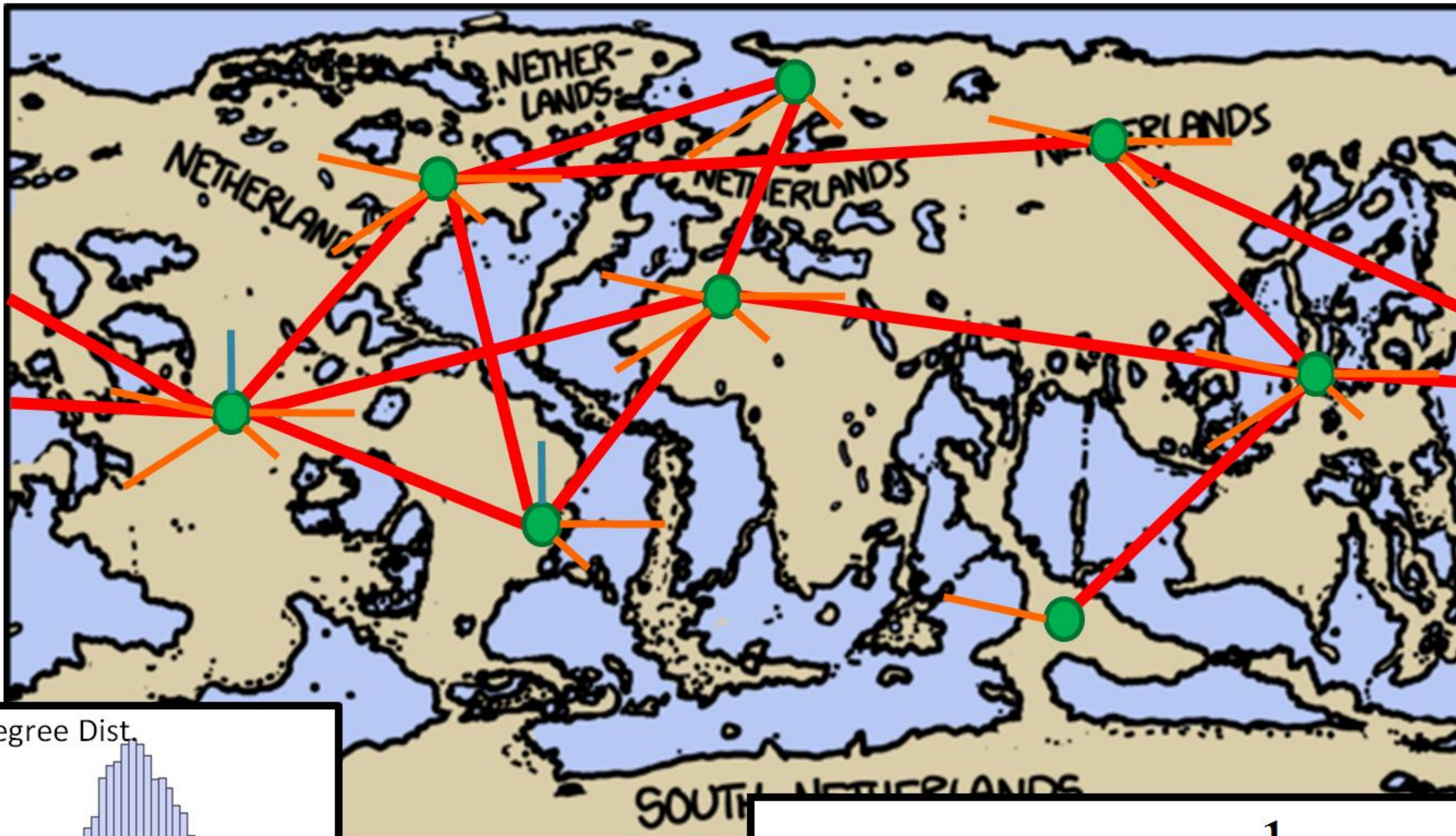
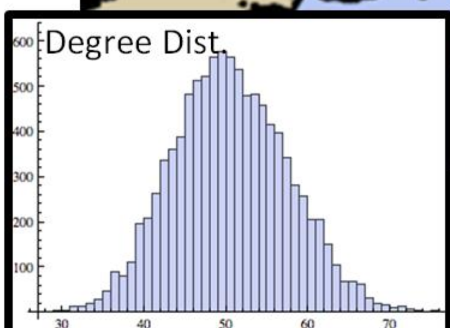
It turns out that a random model like this:

A random world created if the oceans were drained 5km





$$P(i, j) \propto \frac{1}{(\text{distance}(i, j))^{\alpha}}$$

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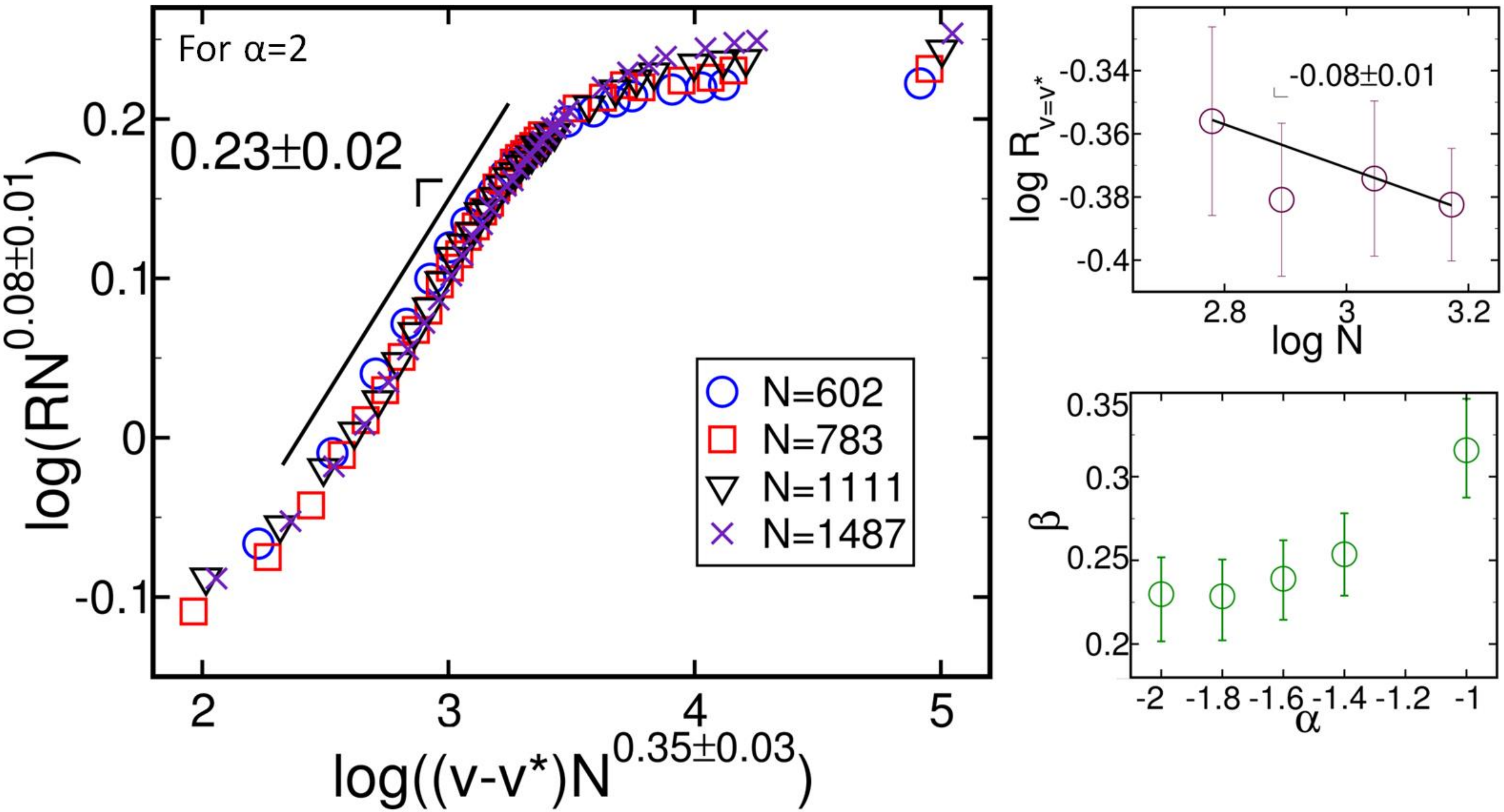
Artificial WAN



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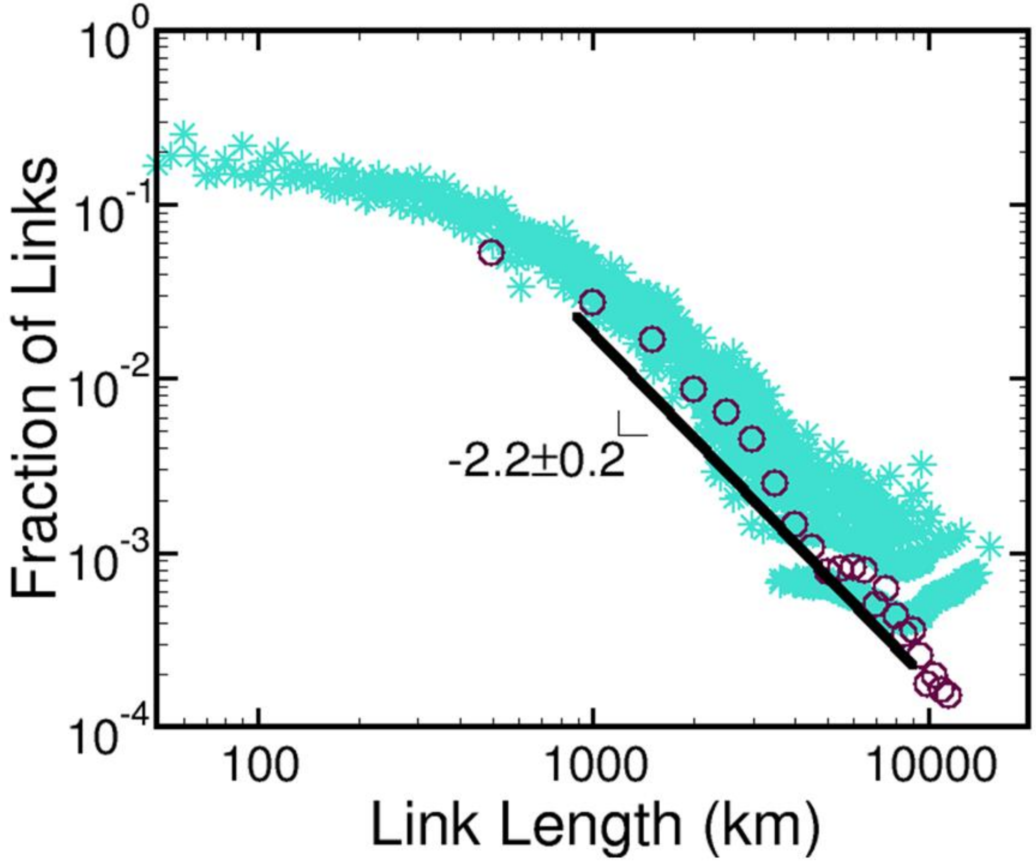
α=2: as we also find in the WAN



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Summary

- A small core resilient structure (guarantees intercontinental connections) and many peripheral connections;
- There is a critical cooperation range for effective improvement;
- Swaps are an effective and economically viable way of improving it.

T. Verma, N. A. M. Araujo, and H. J. Herrmann. *Sci. Rep.* **4**, 5495 (2014)
V. H. P. Louzada, N. A. M. Araujo, T. Verma, F. Daolio, H. J. Herrmann, and M. Tomassini. *PLoS One* **10**, e0118635 (2015)