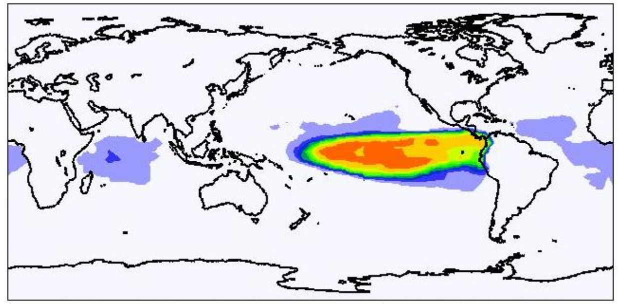

Investigating large-scale climate dynamics by using networks, information theory and symbolic analysis

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30 Years of Nonlinear Dynamics in Geosciences
Rhodes, Greece, July 2016

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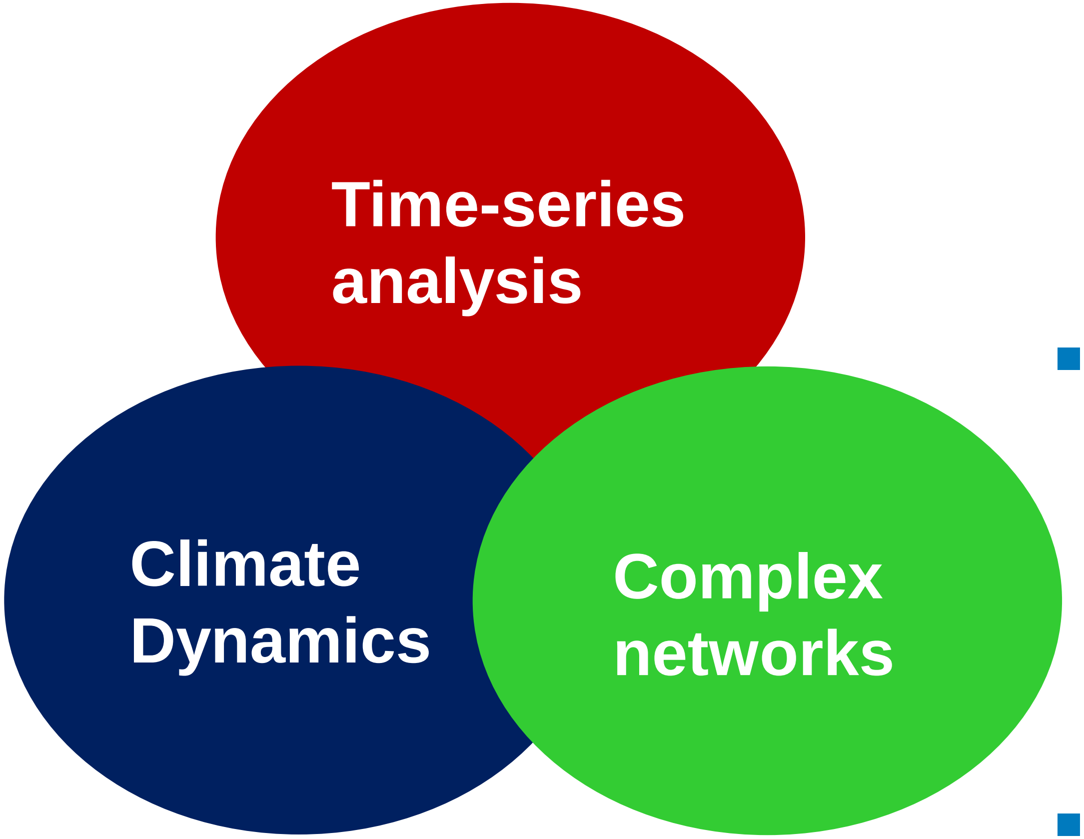
Outline



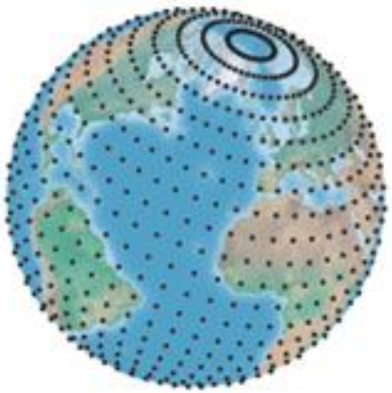
- Introduction
  - Climate networks
  - Symbolic method of time-series analysis
- Results
  - Inferring the network connectivity
  - Inferring climate communities
- Summary

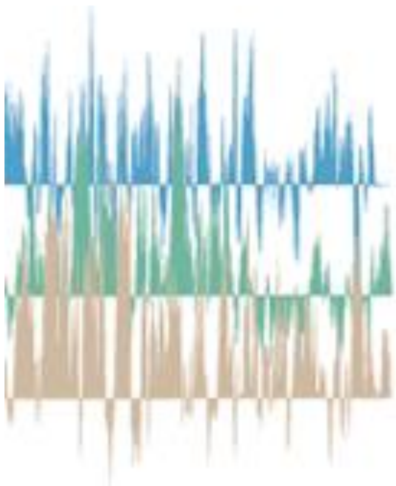
WHAT DO NETWORKS HAVE TO DO WITH CLIMATE?

BY ANASTASIOS A. TSONIS, KYLE L. SWANSON, AND PAUL J. ROEBBER

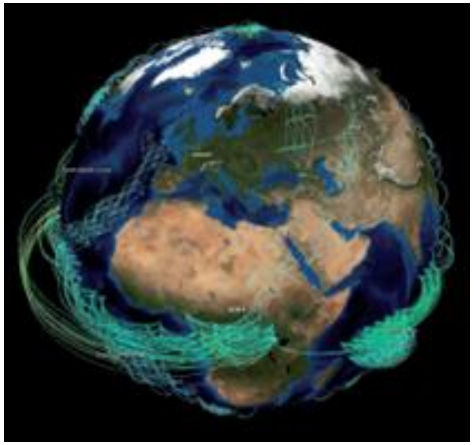
Advances in understanding coupling in complex networks offer new ways of studying the collective behavior of interactive systems and already have yielded new insights in many areas of science.

Climate networks

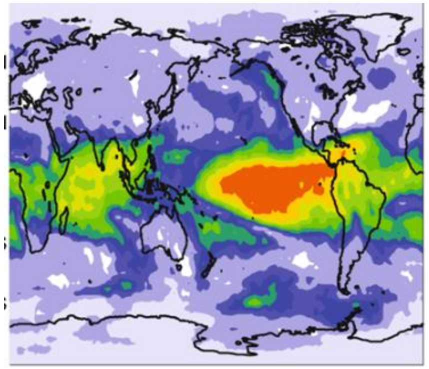




Donges et al,
Chaos 2015



Area-weighted connectivity (weighted degree)



Deza et al,
Chaos 2013

Our analysis: nonlinear in three aspects

- We use a **nonlinear measure** to quantify 'statistical interdependency' between the climate in different regions.

$$M_{ij} = \sum_{m,n} p_{ij}(m,n) \log \frac{p_{ij}(m,n)}{p_i(m)p_j(n)}$$

- We use a **threshold** to select the significant M_{ij} values (contrasting M_{ij} values obtained from original time-series with M_{ij} values obtained from surrogates).

- We use **symbolic** time-series analysis (ordinal patterns) to compute the probabilities.

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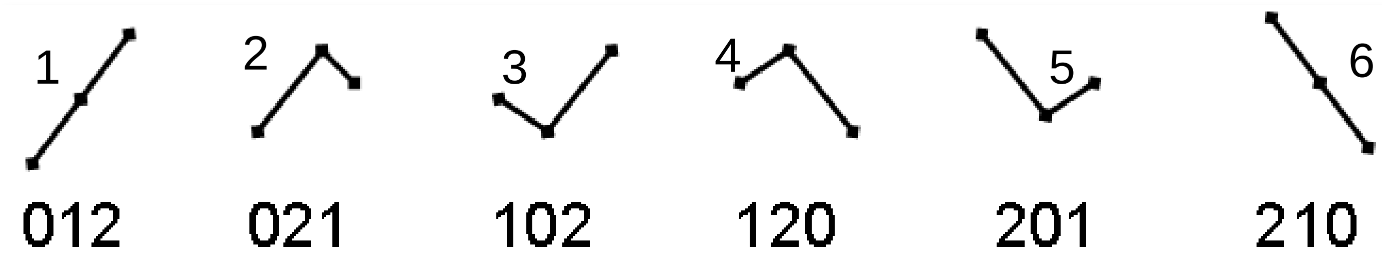
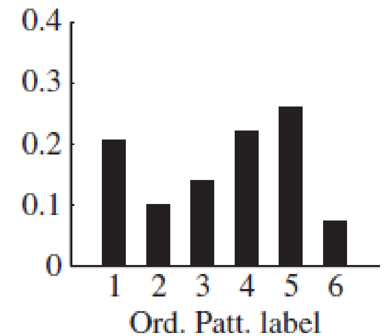
Method of symbolic time-series analysis: ordinal patterns

- $X = \{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)





The OP probabilities allow to identify frequent patterns in the *ordering* of the data points

Random data $\Rightarrow$ OPs are equally probable

– Advantage: the probabilities uncover temporal correlations.

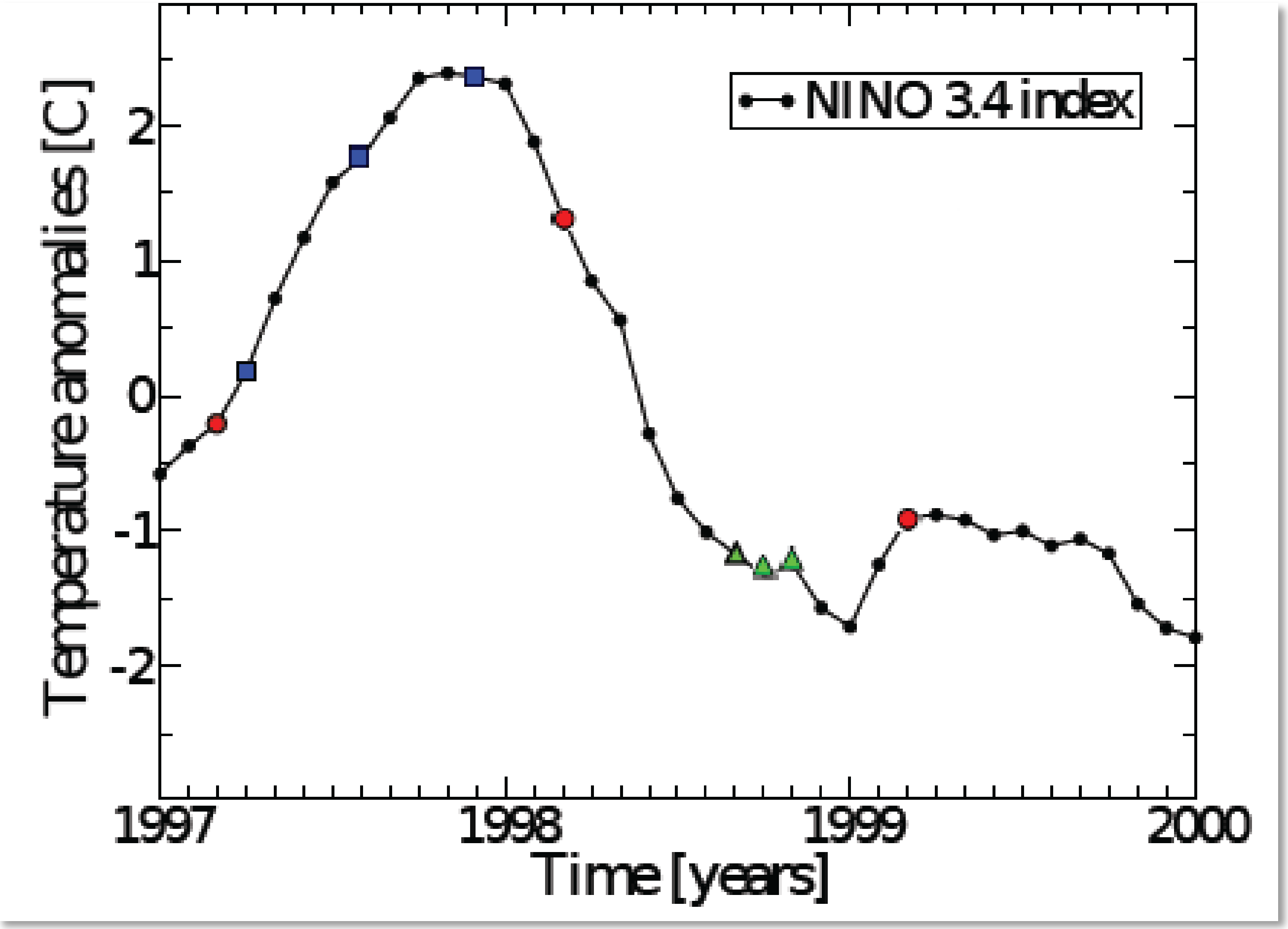
– Drawback: we lose information about the actual values.

Ordinal analysis allows selecting the time scale of the analysis

Intra-season 102

Intra-annual 012

Inter-annual 120



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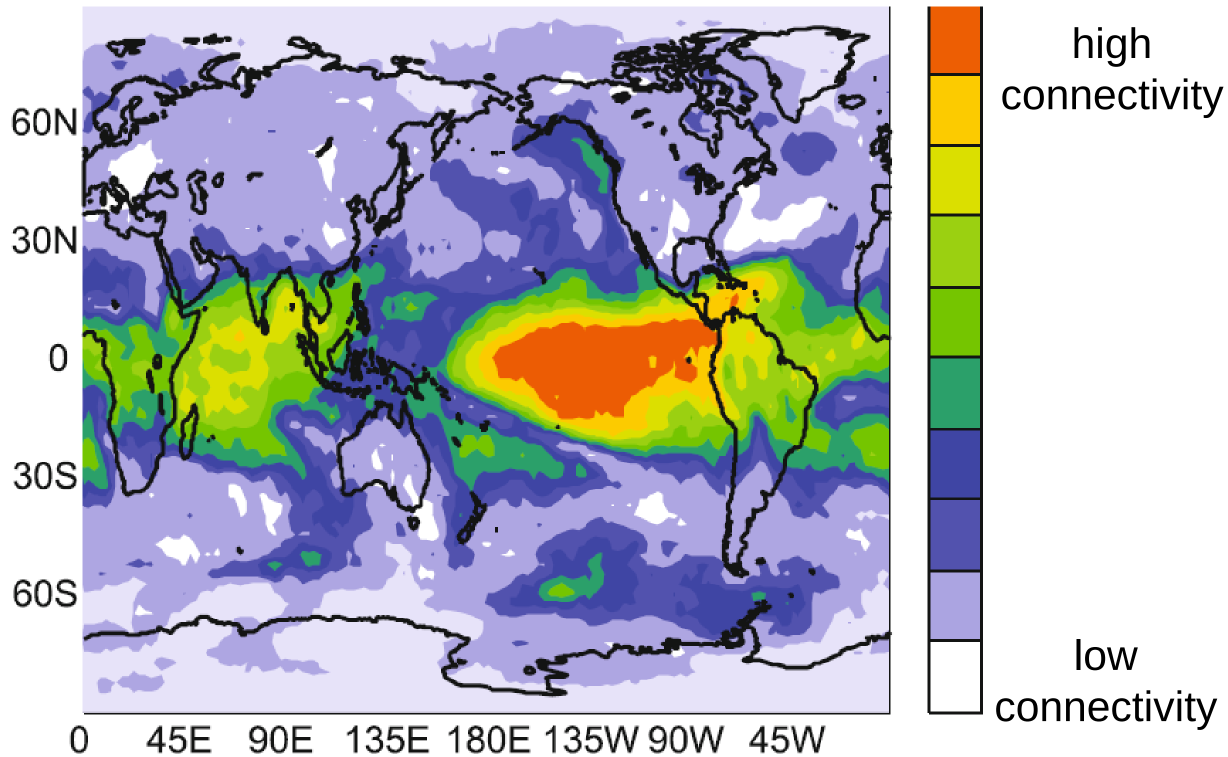
Graphical representation of the climate network

$$\mathrm{AWC}_i = \frac{\sum_j^N A_{ij}\cos(\lambda_j)}{\sum_j^N \cos(\lambda_j)}$$

Network obtained with ordinal analysis using inter-annual time-scale (3 consecutive years). The color-code indicates the Area Weighted Connectivity (weighted degree)

DATA:
Monthly SAT anomalies (NCEP-NCAR reanalysis)

2.5 resolution ⇒ ~10000 nodes
January 1949 to December 2006 ⇒ ~ 700 data points



J. I. Deza, M. Barreiro and C. Masoller, Eur. Phys. J. Special Topics 222, 511 (2013)

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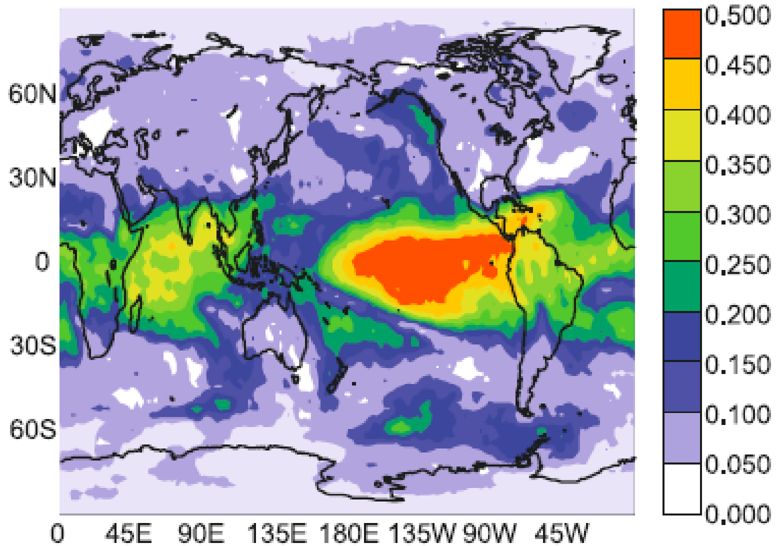
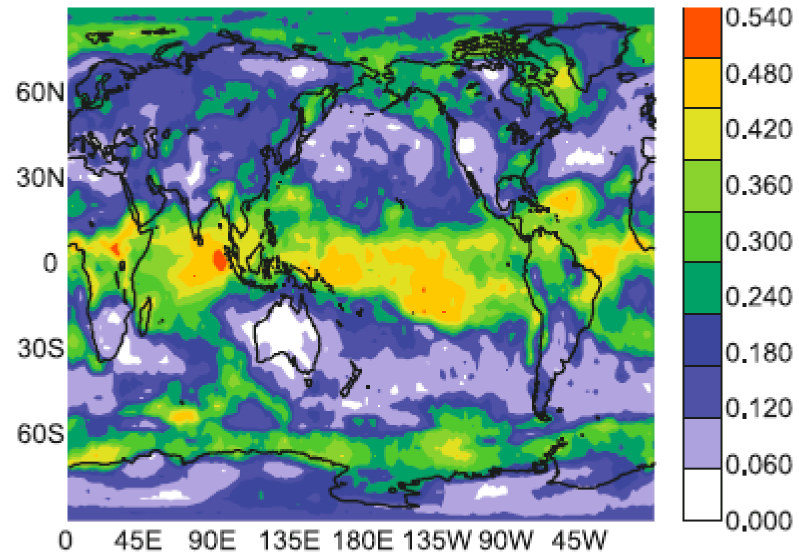
Contrasting two methods for inferring the climate network

$$M_{ij} = \sum_{m,n} p_{ij}(m,n) \log \frac{p_{ij}(m,n)}{p_i(m)p_j(n)}$$

Network when the probabilities are computed with ordinal analysis



Network when the probabilities are computed with histogram of values



Who is connected to who?

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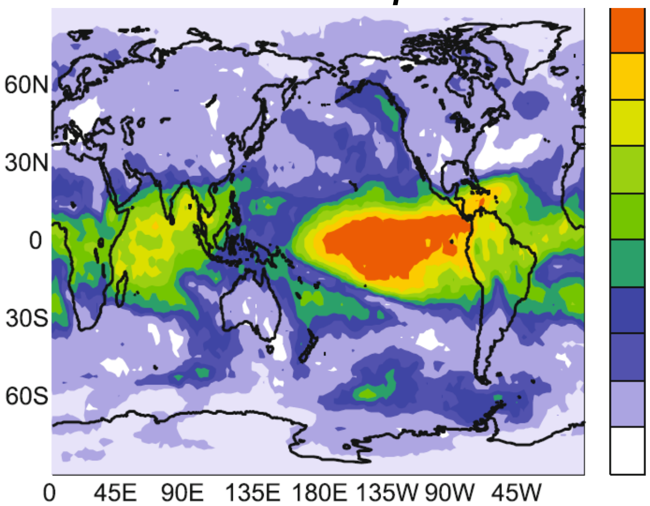
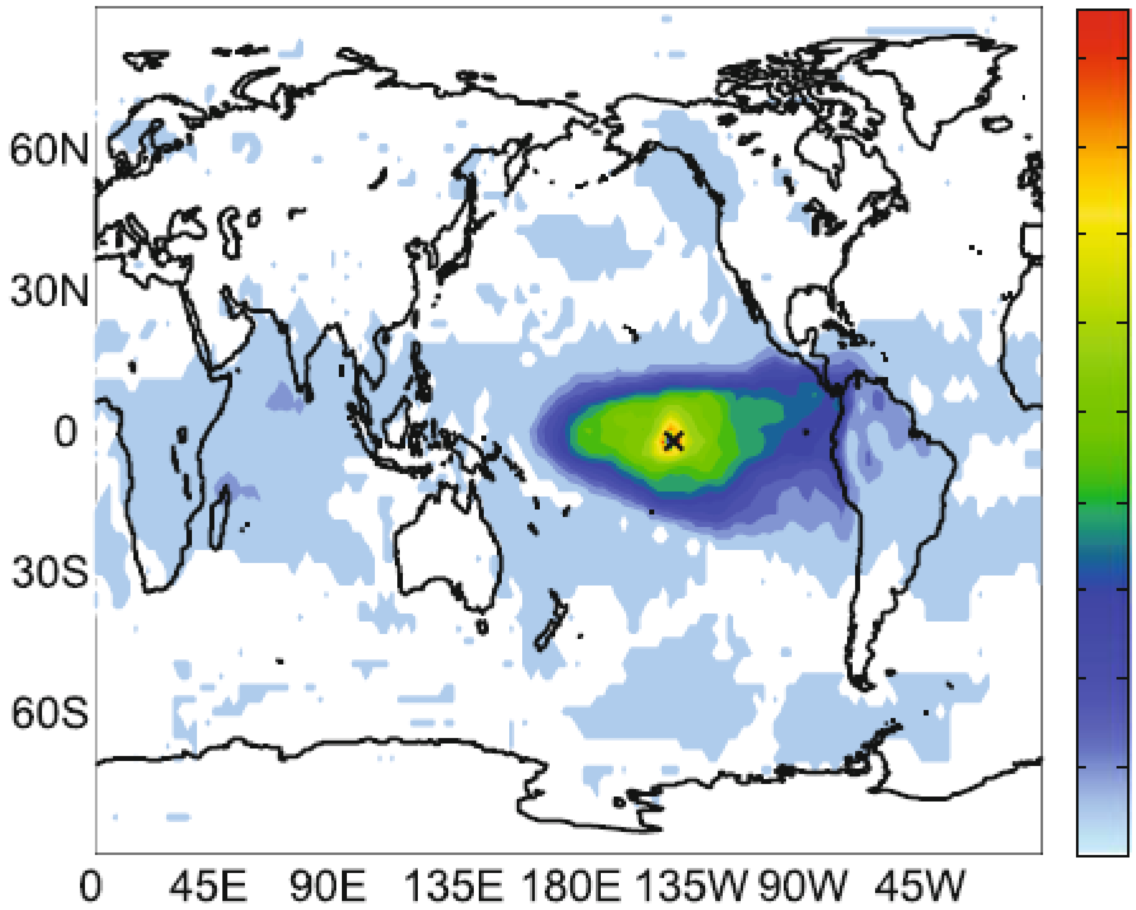
AWC map

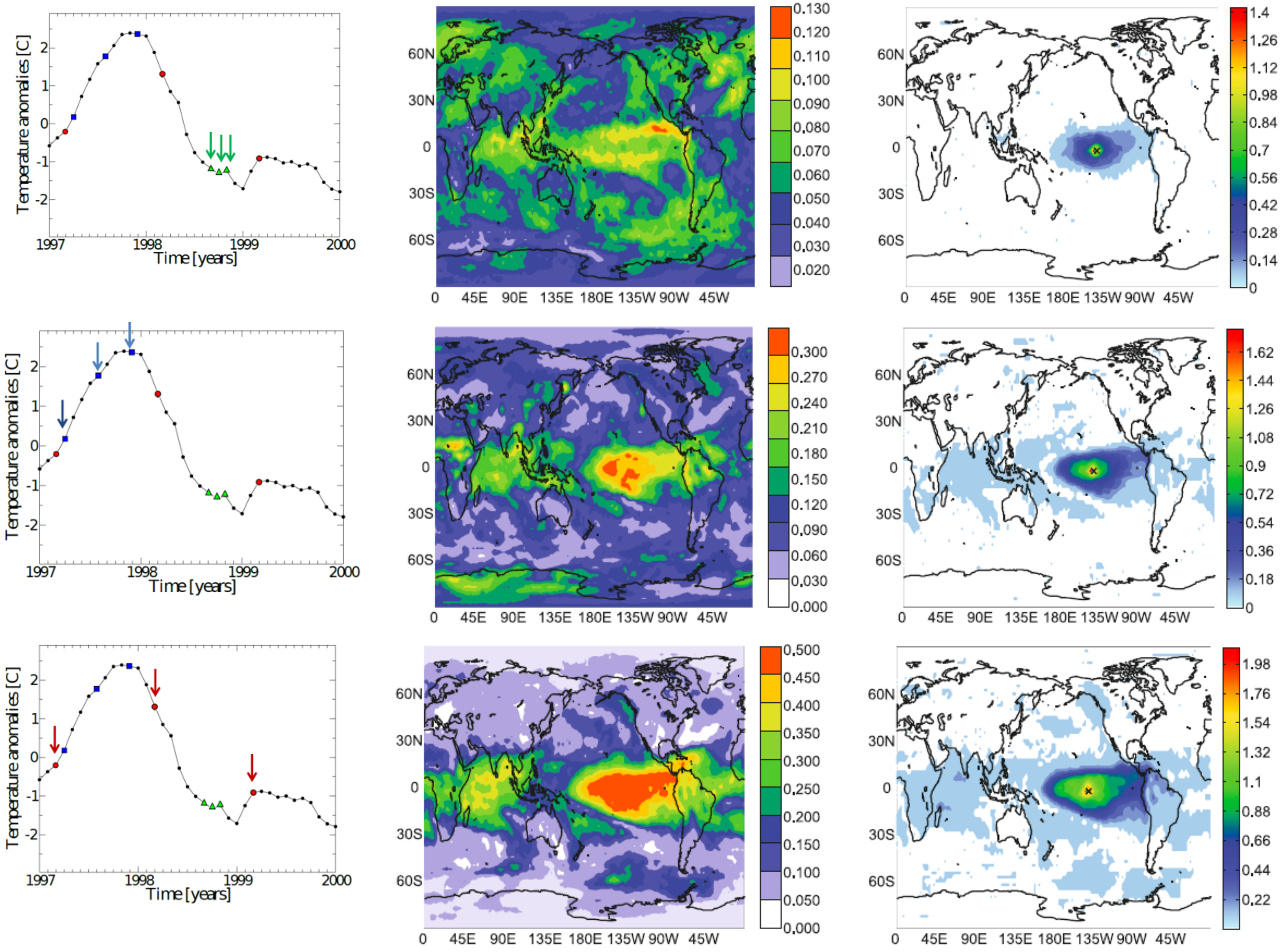


color-code indicates the MI values (only significant values)



J. I. Deza, M. Barreiro, and C. Masoller, Eur. Phys. J. Special Topics 222, 511 (2013)

Influence of the time-scale of the symbolic ordinal pattern



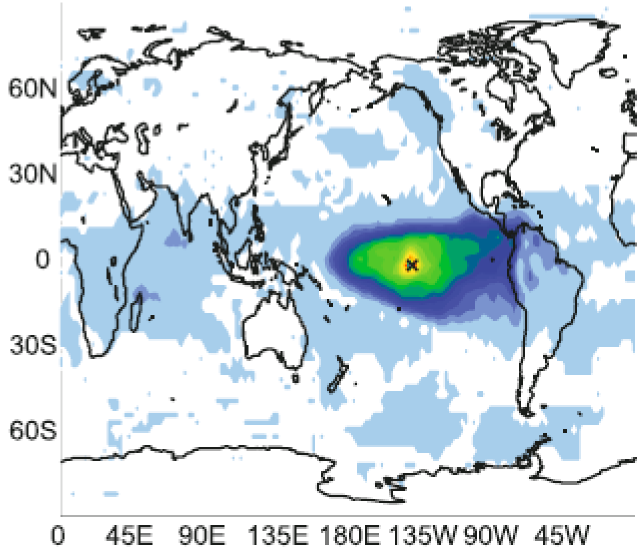
Longer time-scale ⇒ increased connectivity

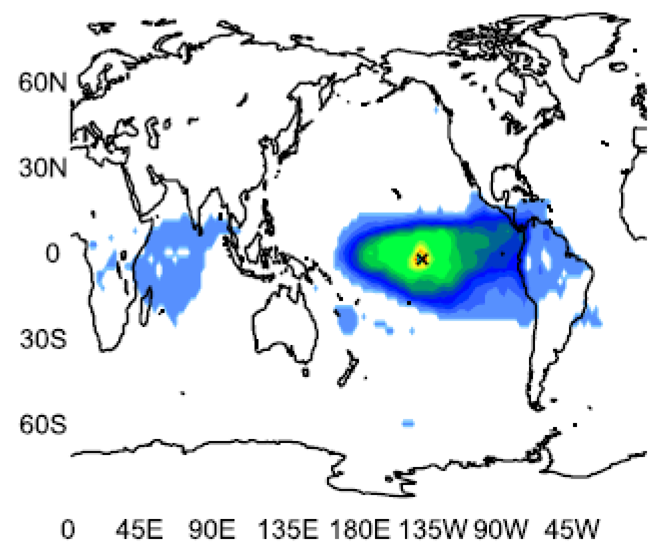
Are the links significant? Influence of the threshold

Low threshold *(11% link density)*

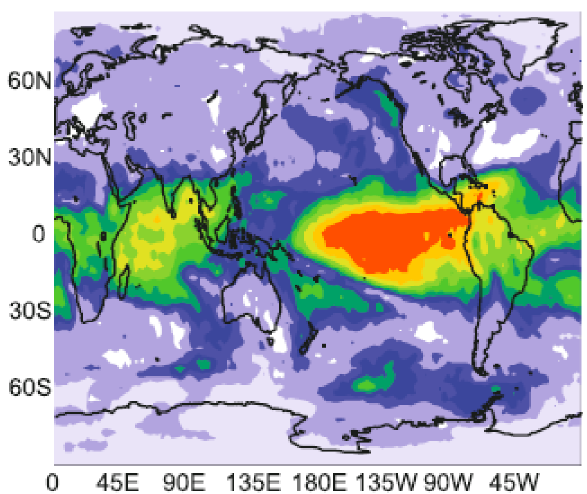
High threshold *(3% link density)*

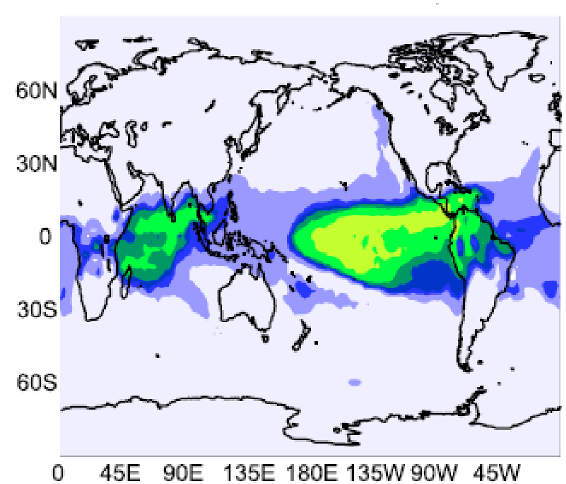
Color code: MI





Color code: AWC





How to improve climate predictability?

Assessing the directionality of the links

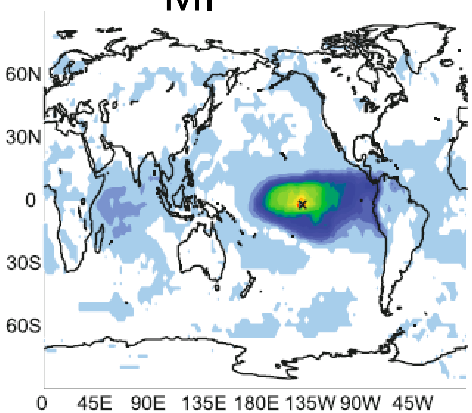
- $I_{xy}(\tau)$: <u>*conditional*</u> mutual information
- τ: *time-scale* of information transfer
- *D*: <u>*net*</u> *direction* of information transfer

$$D_{XY}(\tau) = \frac{I_{XY}(\tau) - I_{YX}(\tau)}{I_{XY}(\tau) + I_{YX}(\tau)}$$

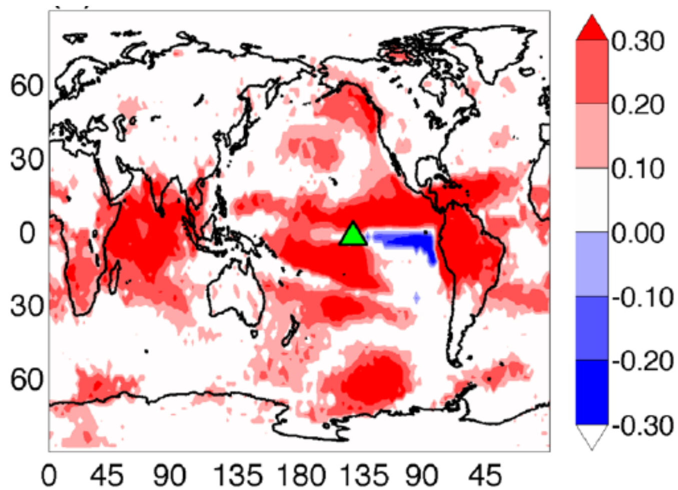
x → y
x → z

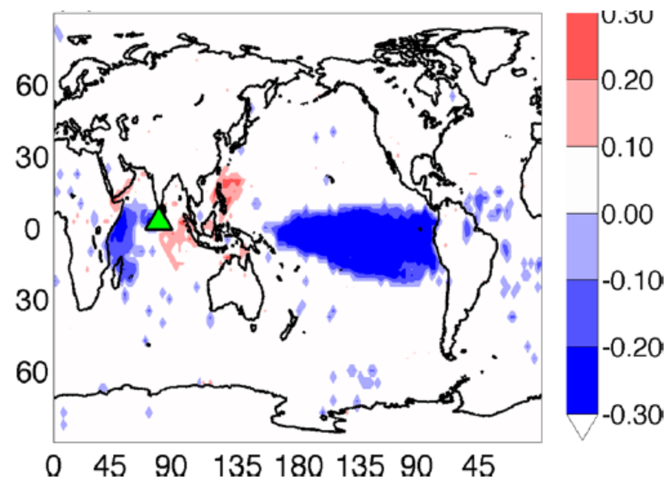
y ↔ z ??

MI



DI





Computed from daily SAT anomalies, PDFs estimated from histograms of values. MI and DI are <u>*both significant*</u> (>3σ, bootstrap surrogates), τ=30 days.

Deza, Barreiro and Masoller, Chaos 25, 033105 (2015)

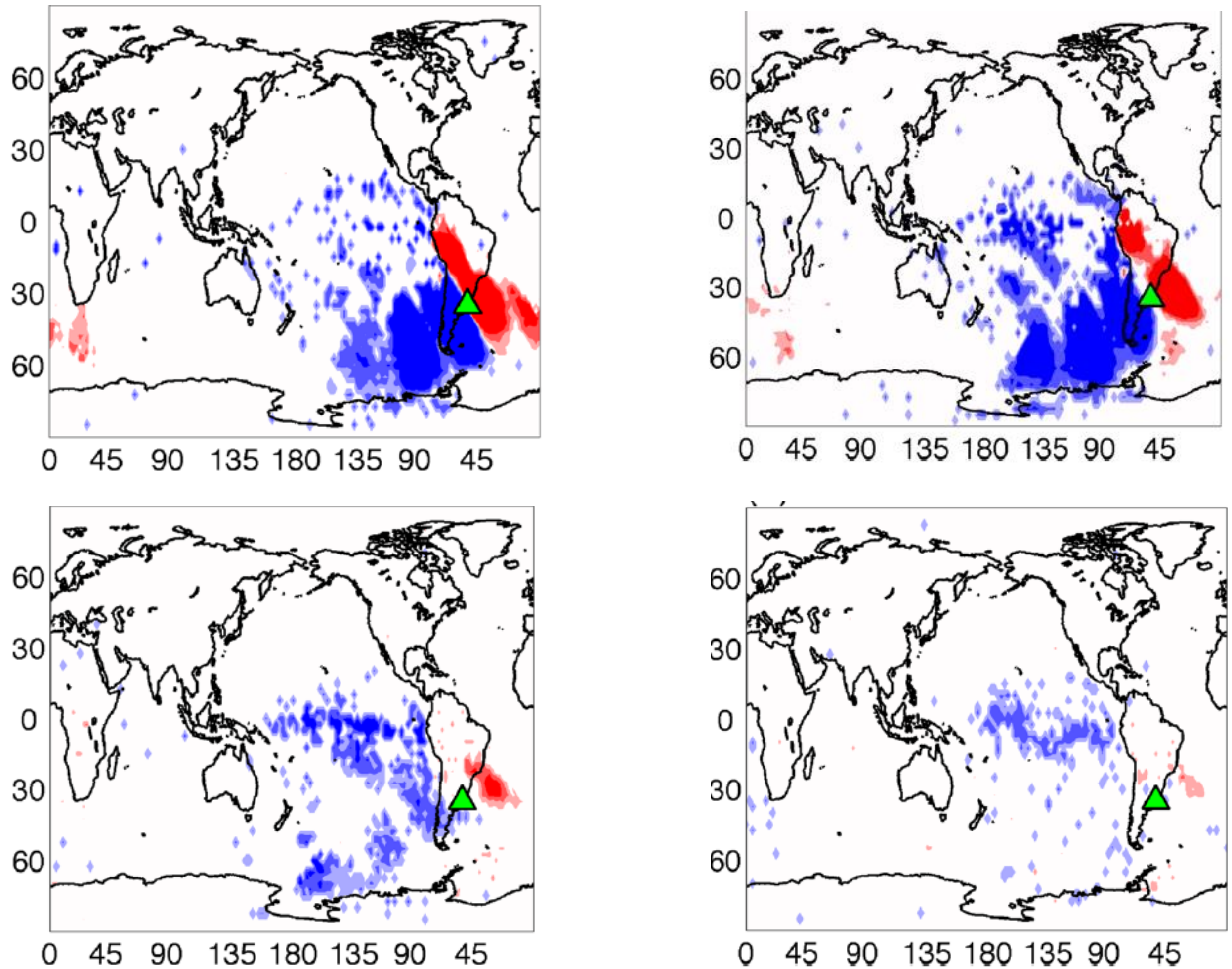
Time-scale of interactions

τ=1 day

τ=3 days

τ=7 days

τ=30 days



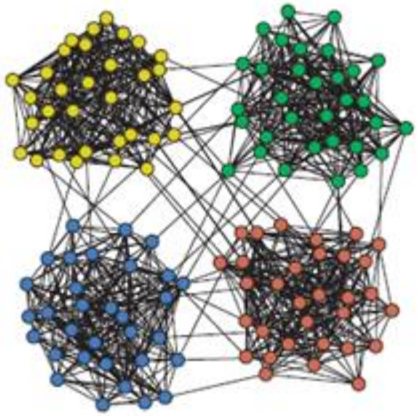
Link directionality reveals wave trains propagating from west to east

Deza, Barreiro and Masoller, Chaos 25, 033105 (2015)

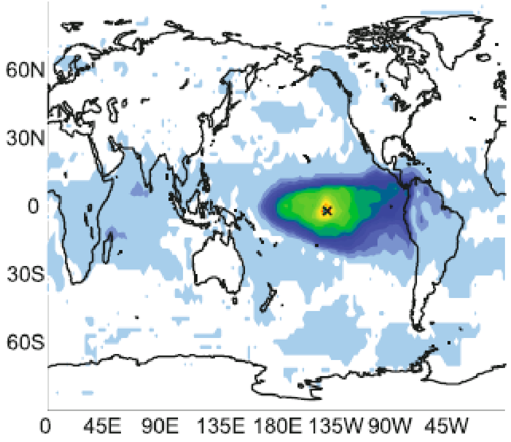
Climate "communities"

How to identify regions with similar climate?

- Goal: to construct a network in which regions with similar climate (e.g., continental) are in the same "community".



- Problem: not possible with the "usual" method to construct the network because NH and SH are only indirectly connected.



Network construction based on similar symbolic dynamics

- Step 1: transform SAT anomalies in each node in a sequence of symbols (we use ordinal patterns)

  $s_i = \{012, 102, 210, 012\ldots\}$ $s_j = \{201, 210, 210, 012, \ldots\}$

- Step 2: in each node compute the transition probabilities

  $TP^{i}_{\alpha\beta} = \#(\alpha \rightarrow \beta)/N$

- Step 3: define the weights $w_{ij} = \dfrac{1}{\sum_{\alpha\beta}\left(TP^{i}_{\alpha\beta} - TP^{j}_{\alpha\beta}\right)^2}$

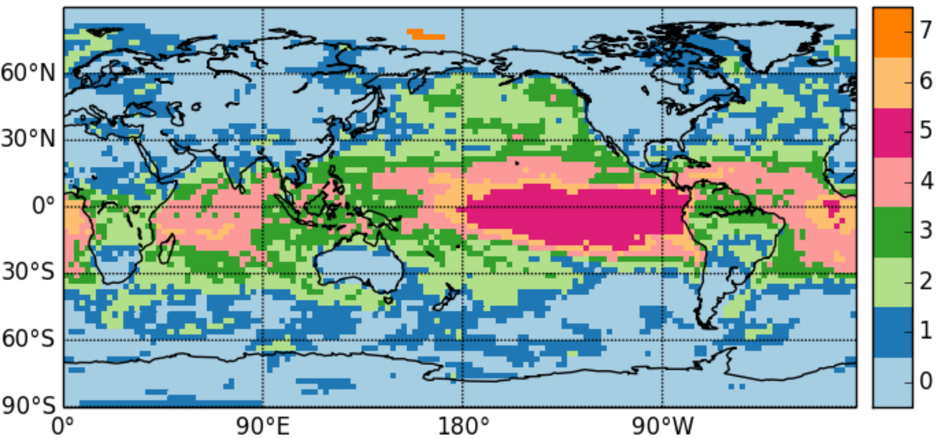
High weight if similar symbolic "language"

- Step 4: threshold w_{ij} to obtain the adjacency matrix.

- Step 5: run a community detection algorithm (Infomap).

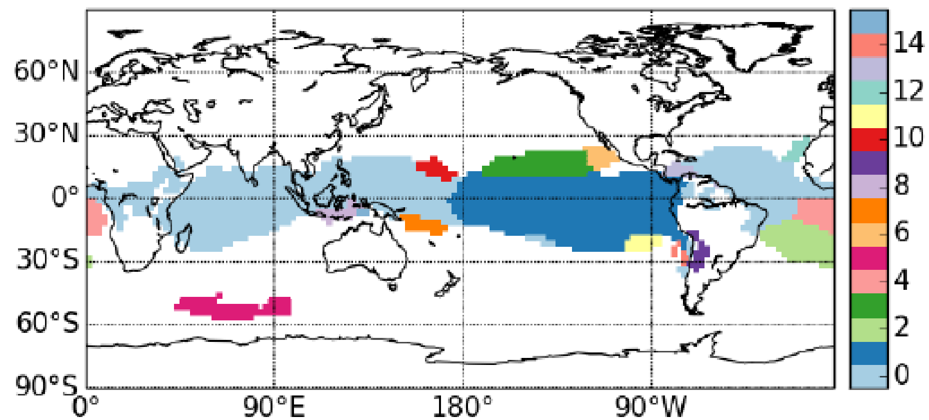
Results

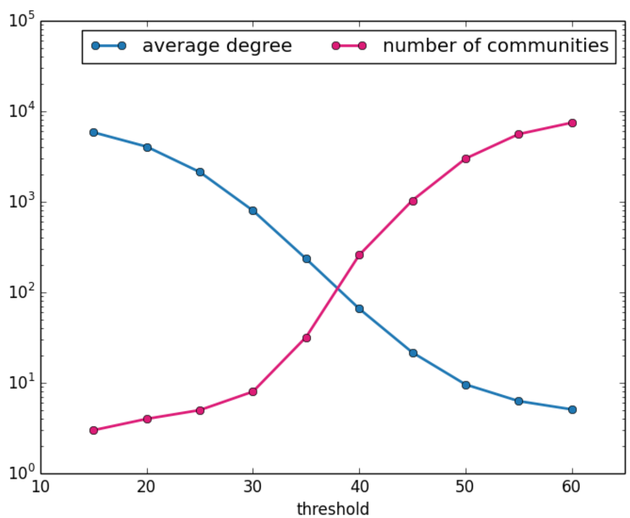
TP Network

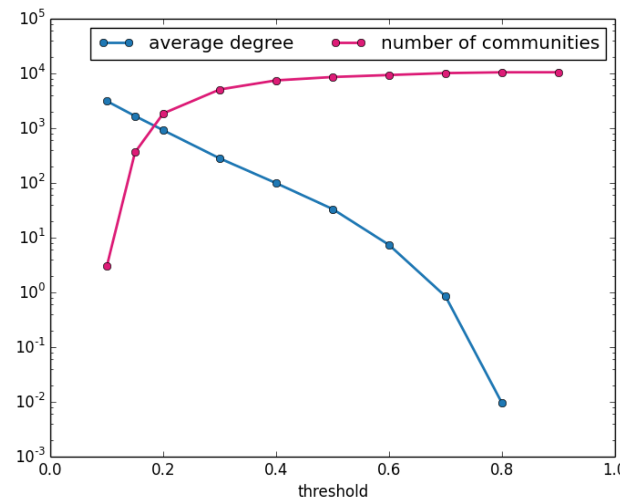


CC Network

(only the largest 16)







G. Tirabassi and C. Masoller, Sci. Rep. in press (2016)

Outline

- Introduction
- Results
- **Summary**

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What did we learn?

- Take home message:
  - The network approach provides an opportunity for improving our understanding of climate phenomena.
  - The challenge: use networks to advance predictability

- A few specific conclusions:
  - Ordinal analysis allows identifying climate communities and time-scales of climate interactions.
  - Conditional mutual information allows identifying net direction of climate interactions.

- Ongoing work:
  - Potential of Hilbert transform to gain more information from climate data? (***Dario Zappala's talk: Wednesday, July 6***)

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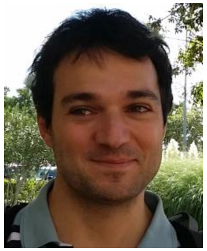
Collaborators & funding

- Ignacio Deza
- Giulio Tirabassi
- Dario Zappala
- Marcelo Barreiro
  (Universidad de la República, Uruguay)



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- M. Barreiro et al, Chaos 21, 013101 (2011).
- J. I. Deza et al, Eur. Phys. J. Special Topics 222, 511 (2013).
- J. I. Deza, M. Barreiro and C. Masoller, Chaos 25, 033105 (2015).
- G. Tirabassi and C. Masoller, Sci. Rep. in press (2016).