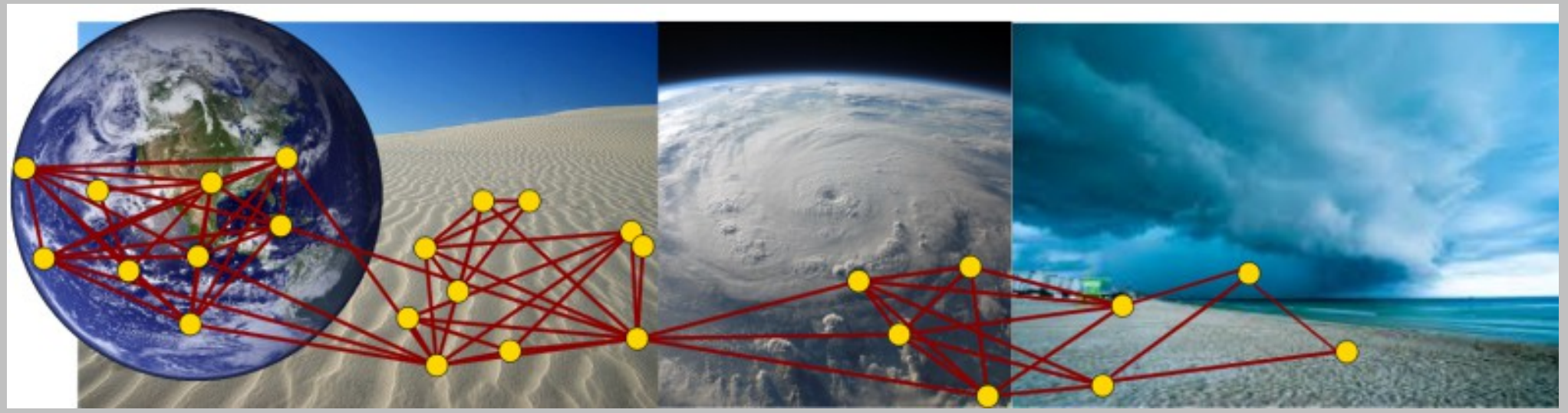
Interacting Networks in Climate



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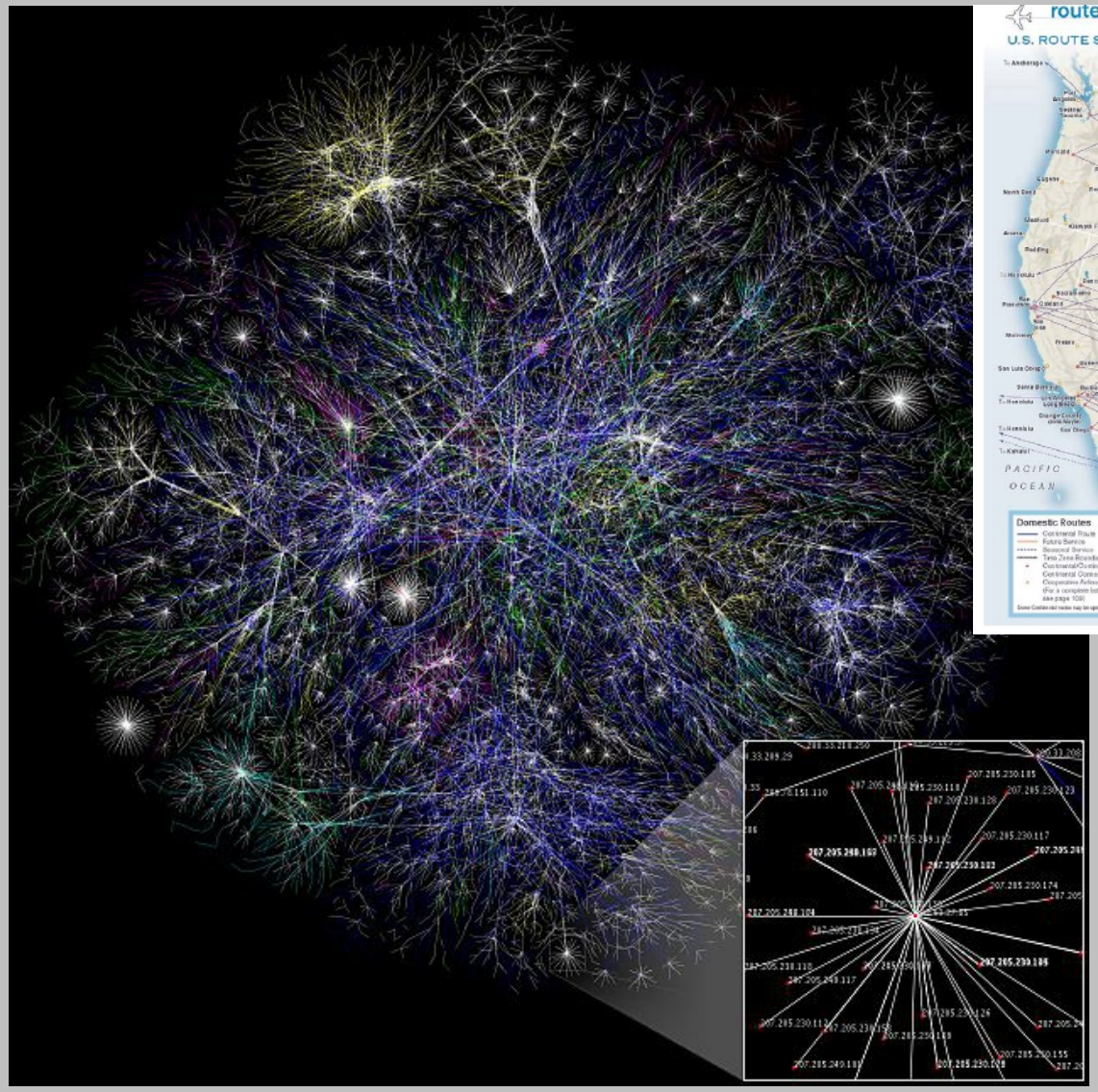
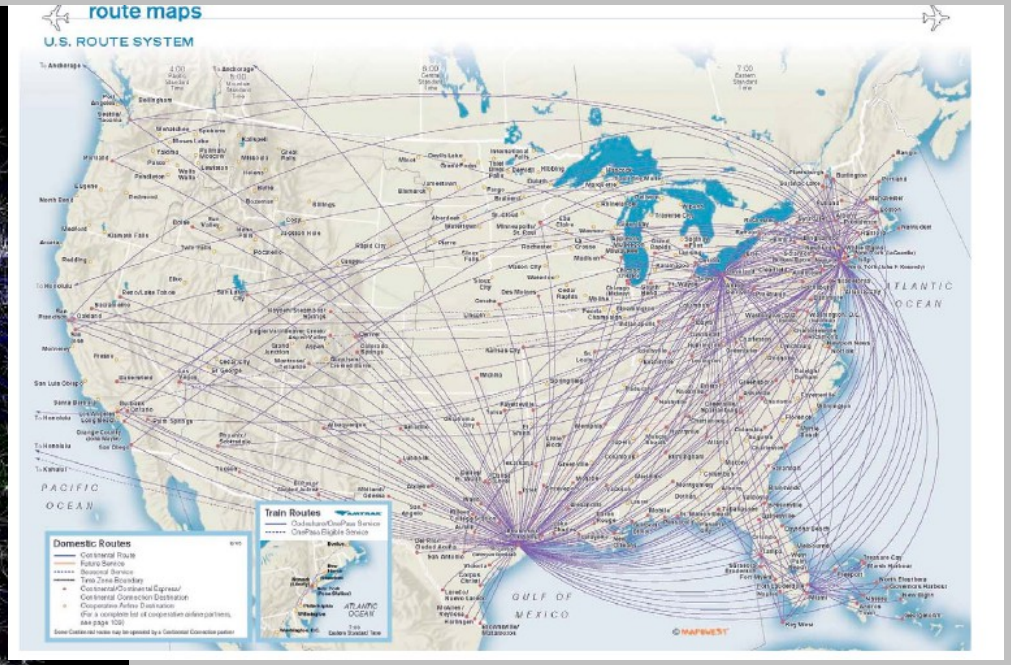
Talk Layout

- Climate (Functional) Network Construction methodology: Similarity
  - Ordinal Patterns
  - Graphical representation
  - Case study: Connectivity monthly mean Surface Air Temperature (SAT) on different time scales
- Climate Network Construction methodology: Directionality
  - Directionality of SAT
  - Case study: Impact on SAT
- Synchronization among different components of the climate system.
  - Case study: Influence of tropical oceans on South America rainfall
- Summary

What are complex (structural) networks?

They are an interacting network of nodes (agents)

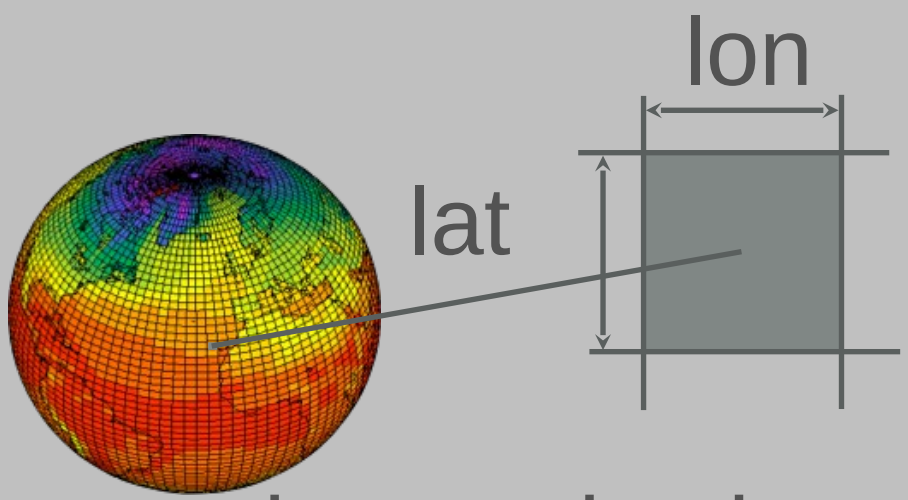




Map Continental Route
(Tsonis et al 2006)

The internet map (Opte Project)
Connection among IPs

Climate networks



time series in each point

- Nodes – grid points $x_i(t)$
- Links – defined using similarity or directionality measures.

Matrices can be huge!

- Very efficient to characterize spatial patterns.
- Properties of temporal series are contained in network topology.
- Framework to validate climate models.

A short story of the field...

- A. Tsonis et al early-2000s → : focus on interaction among climate variability nodes (ENSO, NAO, PDO, etc) and study abrupt climate changes.
- J. Kurths et al mid-2000 → : global climate network construction from grid points and study several network measures. Focus on extremes.
- S. Havlin et al mid-2000s → : study El Niño properties and evolution using complex networks.

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Methodology for climate network construction

Statistical Similarity

Directionality

Statistical similarity between time series

Person Correlation (linear)

$$C_{ij} = |\sum_{t=0}^{N} \frac{(x_i(t) - \overline{x}_i)(x_j(t) - \overline{x}_j)}{\sigma_i \sigma_j}|$$

Mutual Information (nonlinear)

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

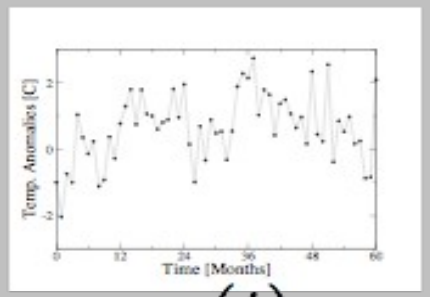
Measures how much information about x_i we get by knowing the evolution of x_j. $P_{i,j}$ are pdfs.

Other possible measures: transfer entropy (Runge et al 2012) or event synchronization (Malik et al 2012).

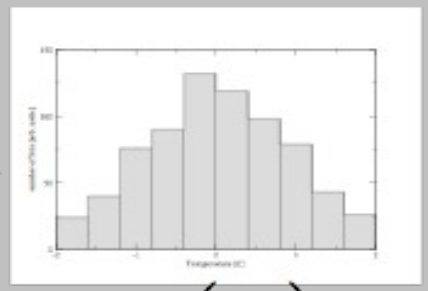
Mutual information: histograms

From time series in i & j we can approximate their pdfs. And their joint distribution.

Barcelona

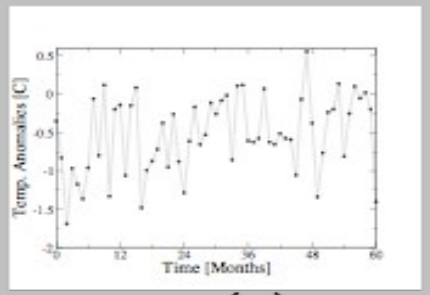


$x_i(t)$

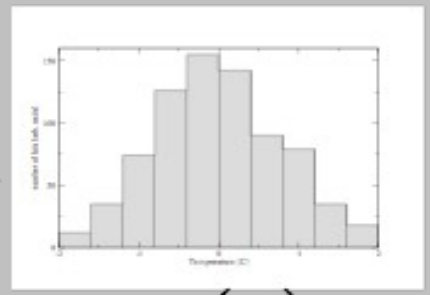


$p_i(m)$

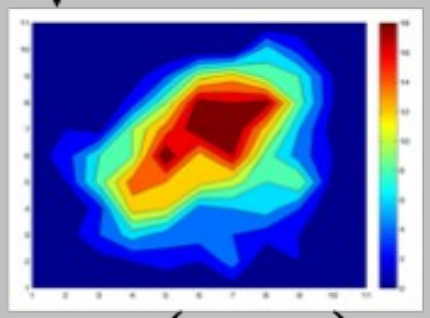
Montevideo



$x_j(t)$



$p_j(n)$



$p_{ij}(m,n)$

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

Adjacency Matrix

$$A_{ij} = \Theta(|S_{ij}| - T) - \delta_{ij}$$

Θ – heavyside function

S_{ij} – similarity measure (Mutual Information)

T – significance threshold: global or for each pair depending on significance criterion. $T \rightarrow 0$ fully connected network / $T \rightarrow 1$ network without links.

The Adjacency matrix defines the network associated to a particular field.

Graphical Representation

1. Local: Connections from or to a node (X).

2. Global: Area Weighted Connectivity (AWC):

$$AWC_i = \frac{\sum_{j=1}^{N} A_{ij} \cos(\theta_j)}{\sum_{j=1}^{N} \cos(\theta_j)}$$

A_{ij} = adjacency matrix

Area to which a node is connected. Maxima in AWC are called supernodes or hubs.

Other measures: e.g. closeness centrality (inverse of mean network distance of node I to all other nodes via shortest paths)

Par@graph - a parallel toolbox for the construction and analysis of large complex climate networks. Ihshaish et al 2015 (Geosci. Mod. Dev.)

Scale separation: Ordinal Patterns

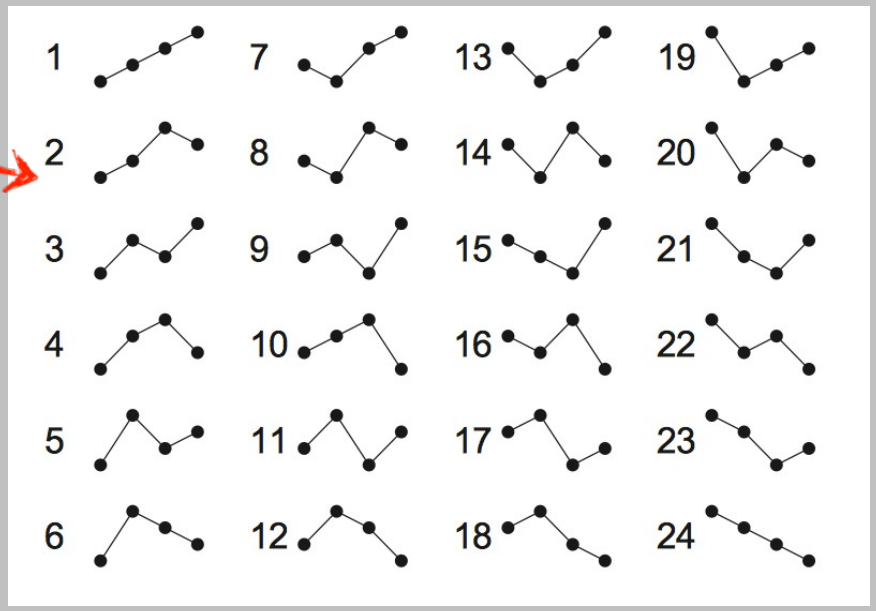
- Consider a time series

$$x_1, x_2, x_3, x_4, \ldots, x_n$$

- Ordinal Patterns (OP) are defined as a way to order the elements of the time series

OP word size 3.

OP word size 4.



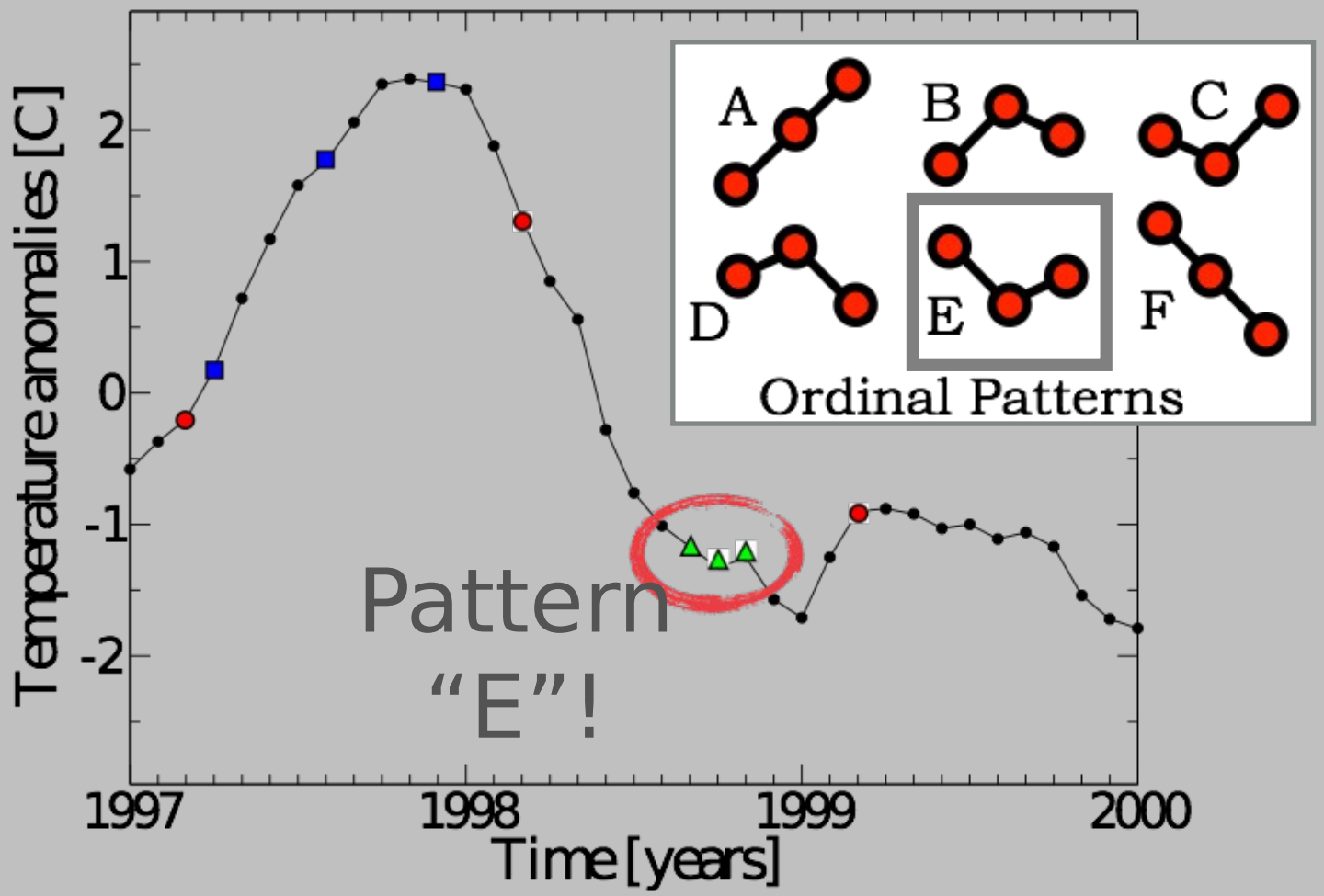
The length of the time series limits the size of the word

OP larger: more resolution

pdfs are calculated counting the number of times that each word appears in the time series.

Mutual Information: Ordinal Patterns

- A new series of patterns is constructed



Example for a 3 letter word

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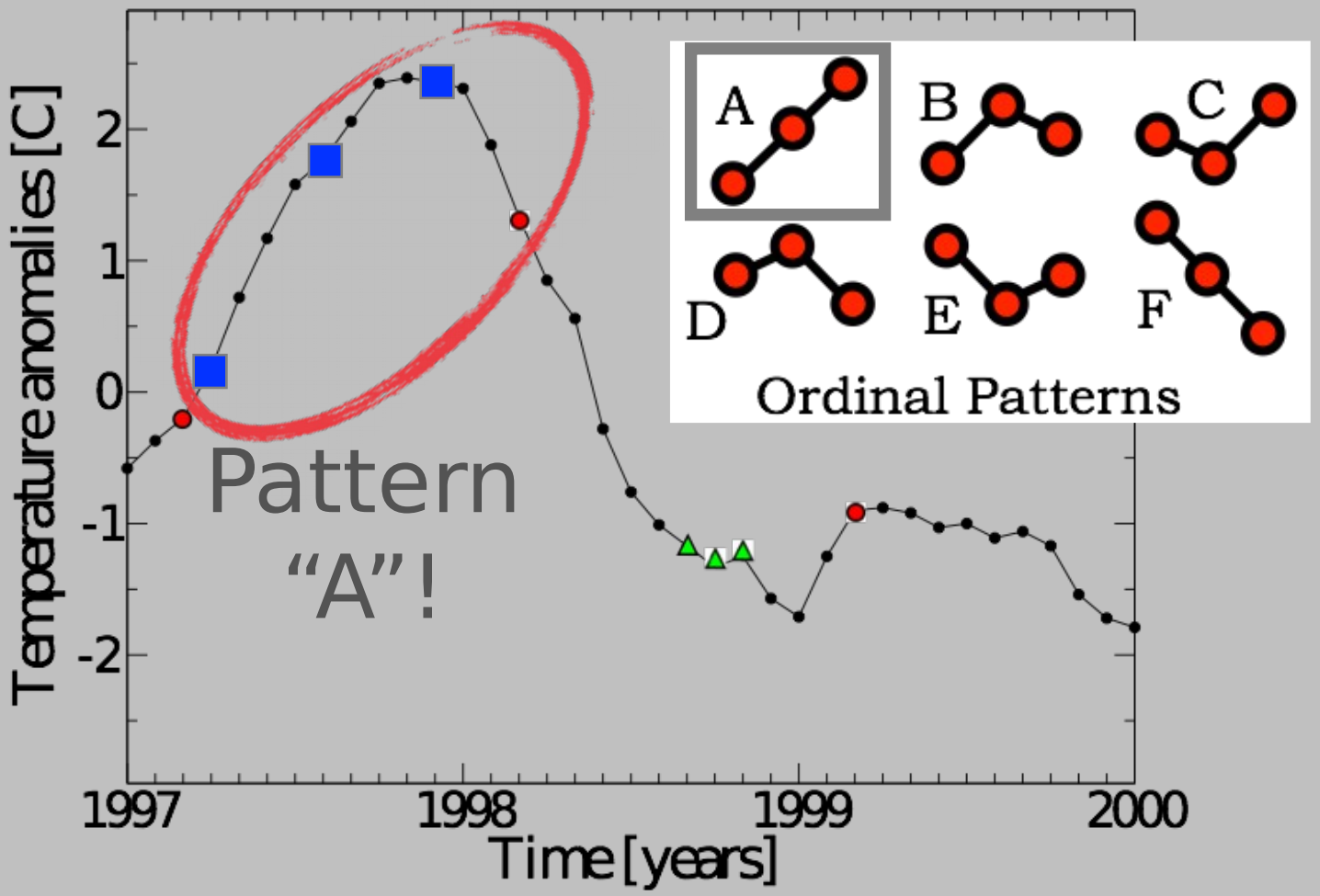
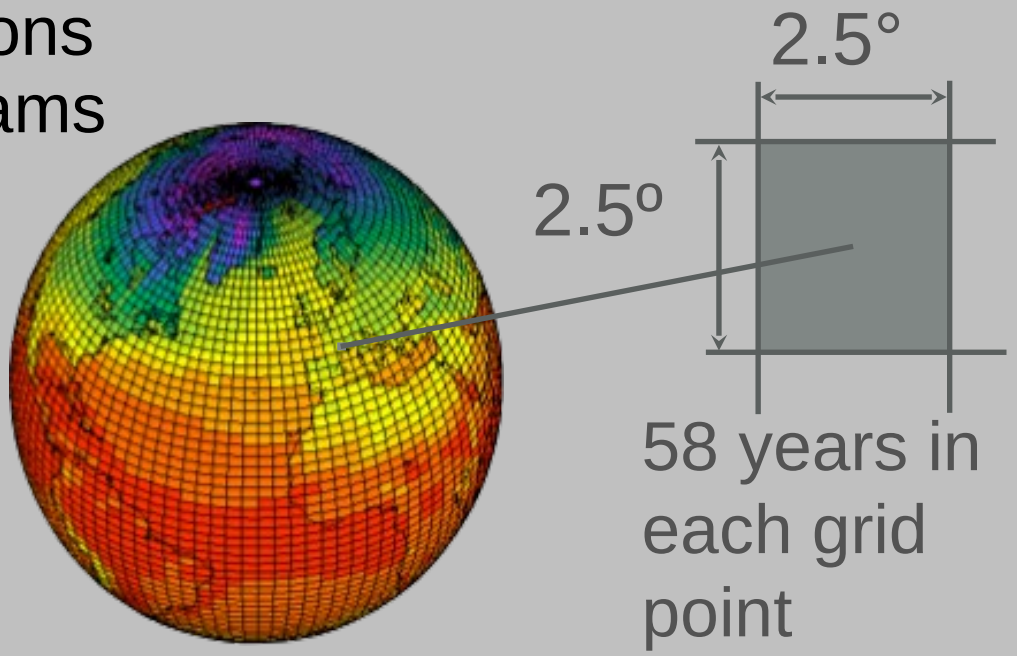
- Points don't need to be contiguous. We can choose time scale of interest.



Connectivity Surface Air Temperature

Objetive

- Study connectivity of SAT on different time scales, i.e. teleconnections
- Construct pdfs using histograms and ordinal patterns.



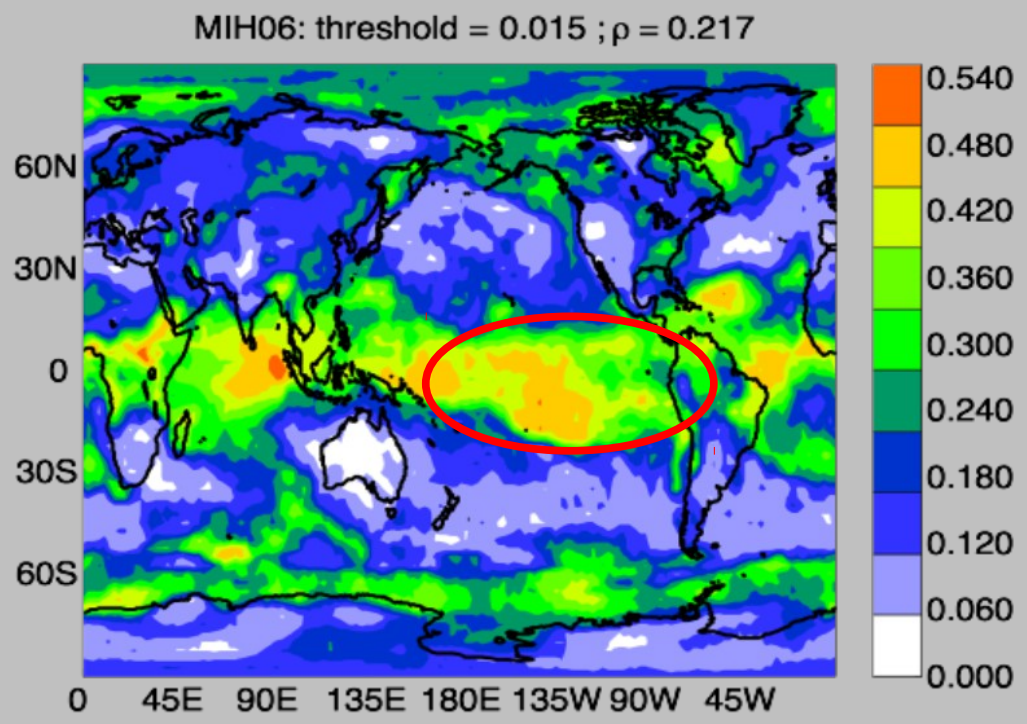
Data

- SAT NCEP-CDAS 1
- ~10.000 nodes
- Monthly mean 1948-2006.

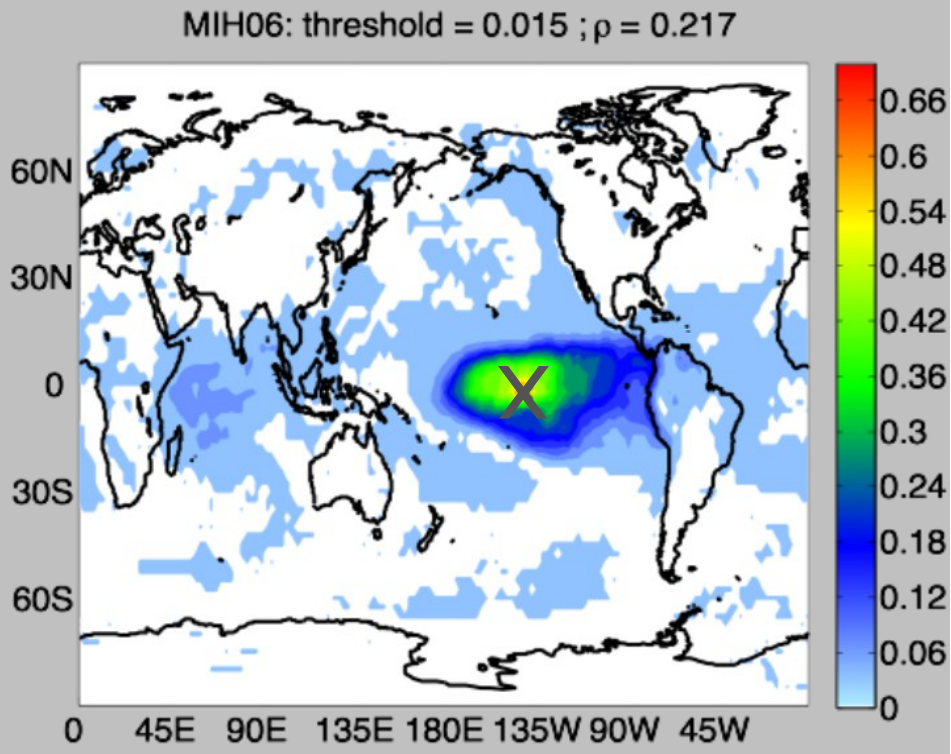
Barreiro et al 2011, Deza et al 2013, Arizmendi et al 2013

SAT – Mutual Information with Histograms

Area Weighted Connectivity



Connectivity of a point



This network contains information on all time scales.

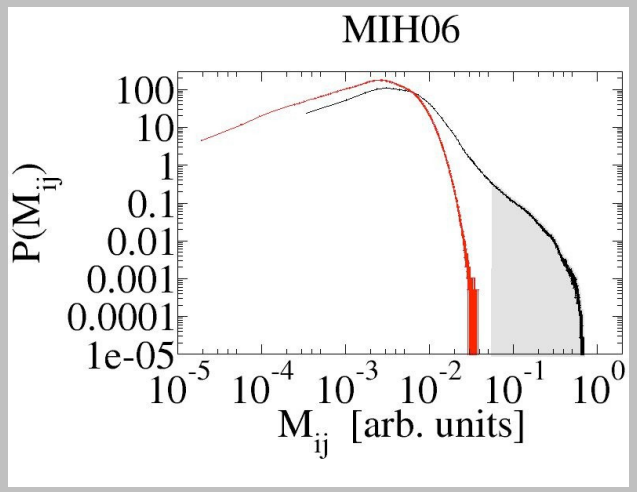
Only significant links are considered.

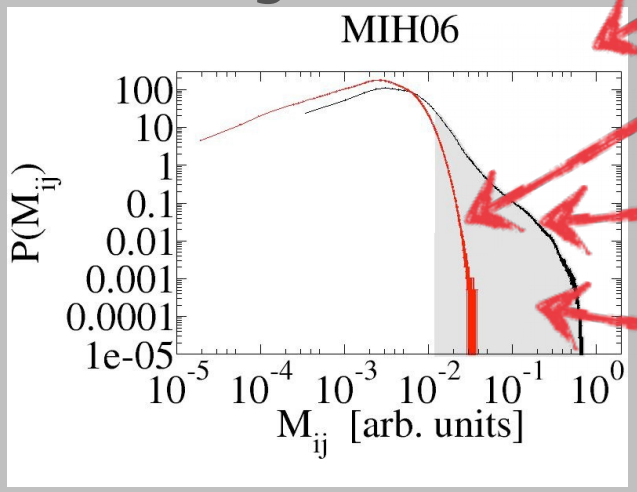
Statistical Significance of MI

Accepted area for fixed density criterion (~2.7% in this case).

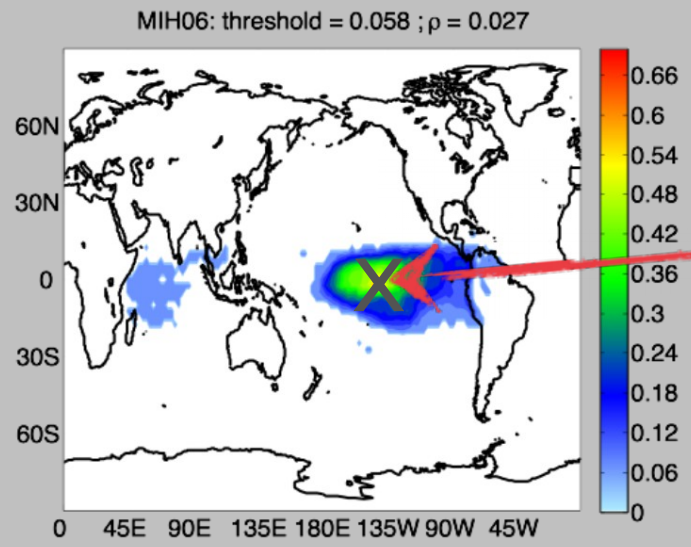
Accepted area for significance μ+3σ bootstrap surrogates (~21%)

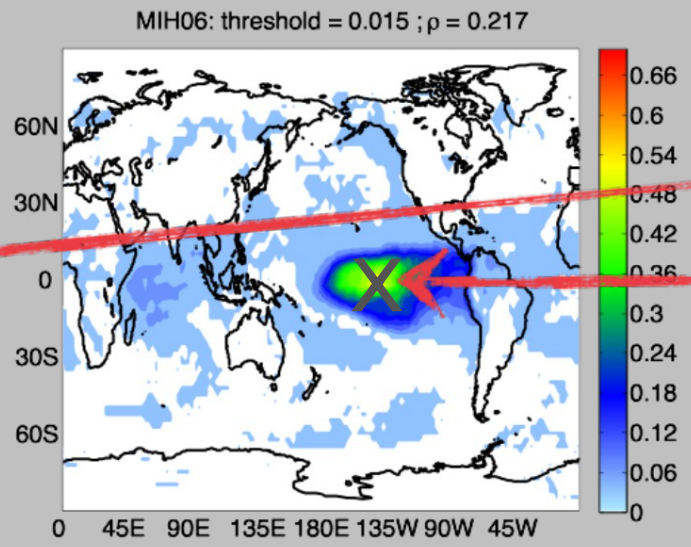
Number of bins for pdf: 6.





- Surrogate data
- Original time series
- Acepted links

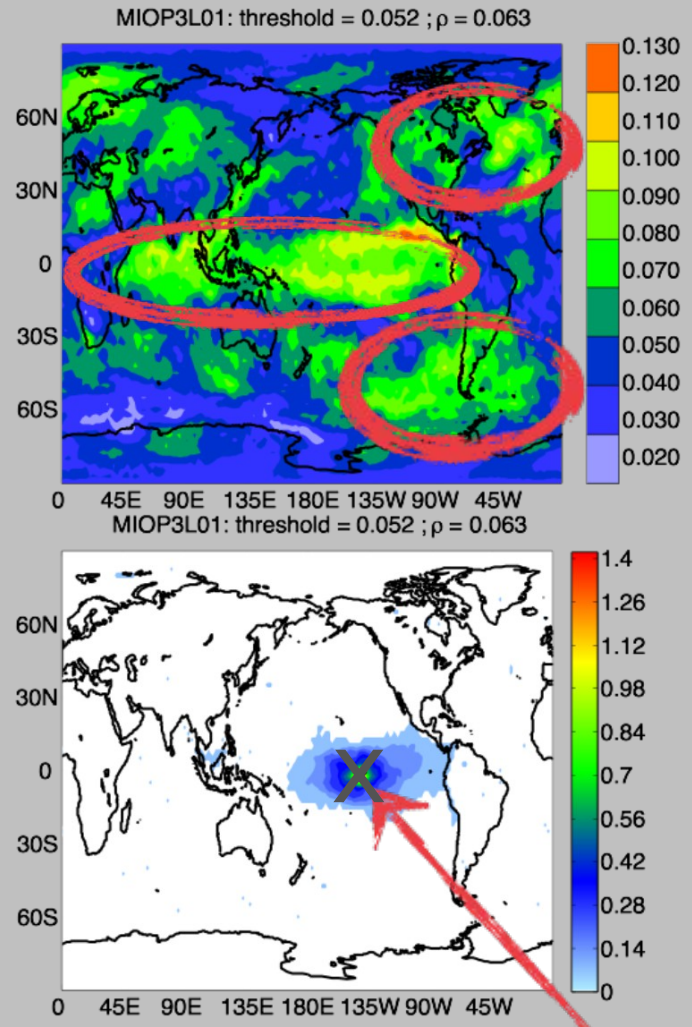




Connections to or from this point depend strongly on threshold.

Ordinal Patterns & networks on different time scales

AWC intra-seasonal



3 consecutive times are used to construct OP of 3 letters.

MI

Connections to/from this point

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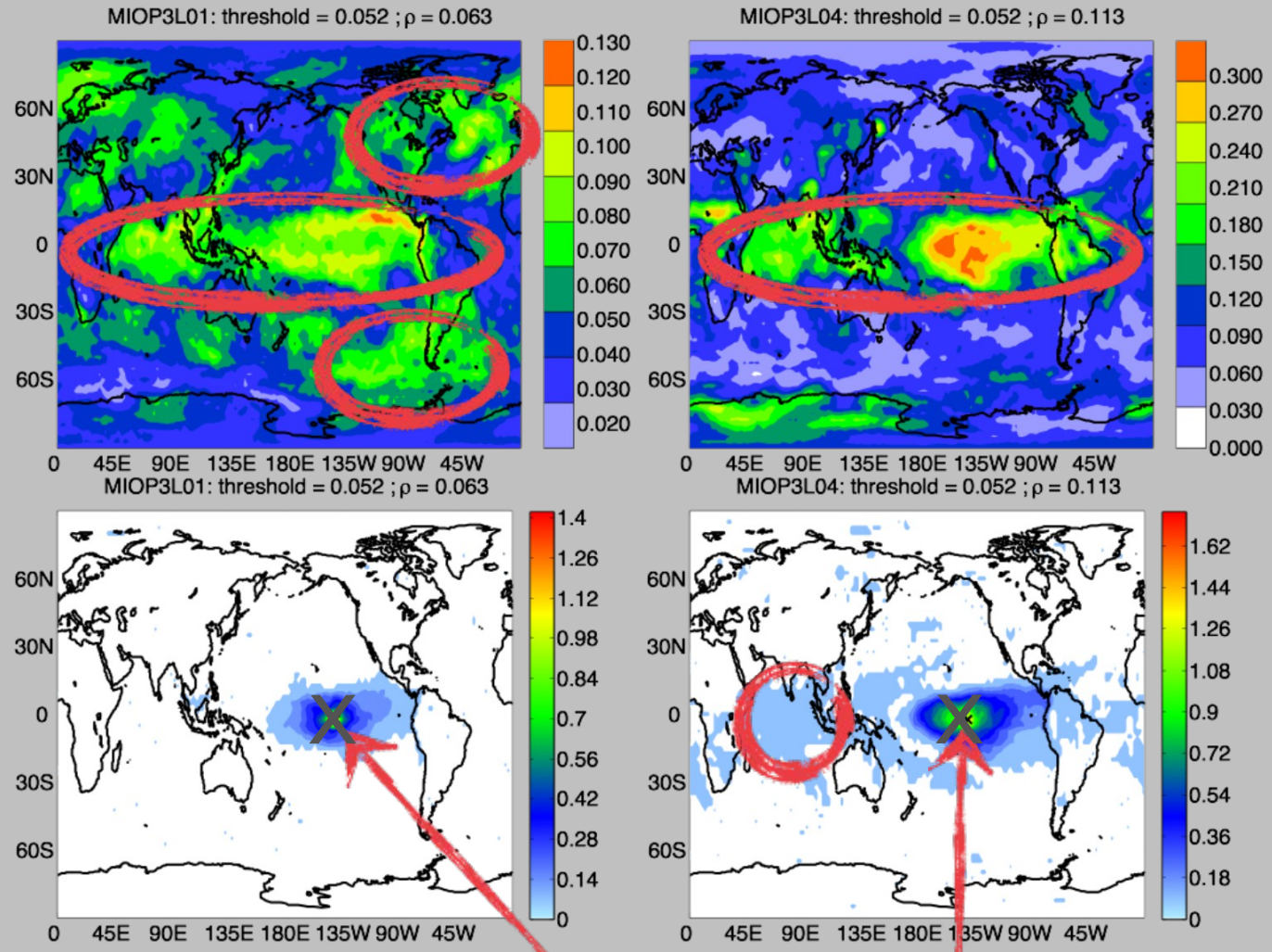
AWC intra-seasonal intra-annual



3 times separated by 4 months are used to construct OP of 3 letters.

MI

Connections to/from this point

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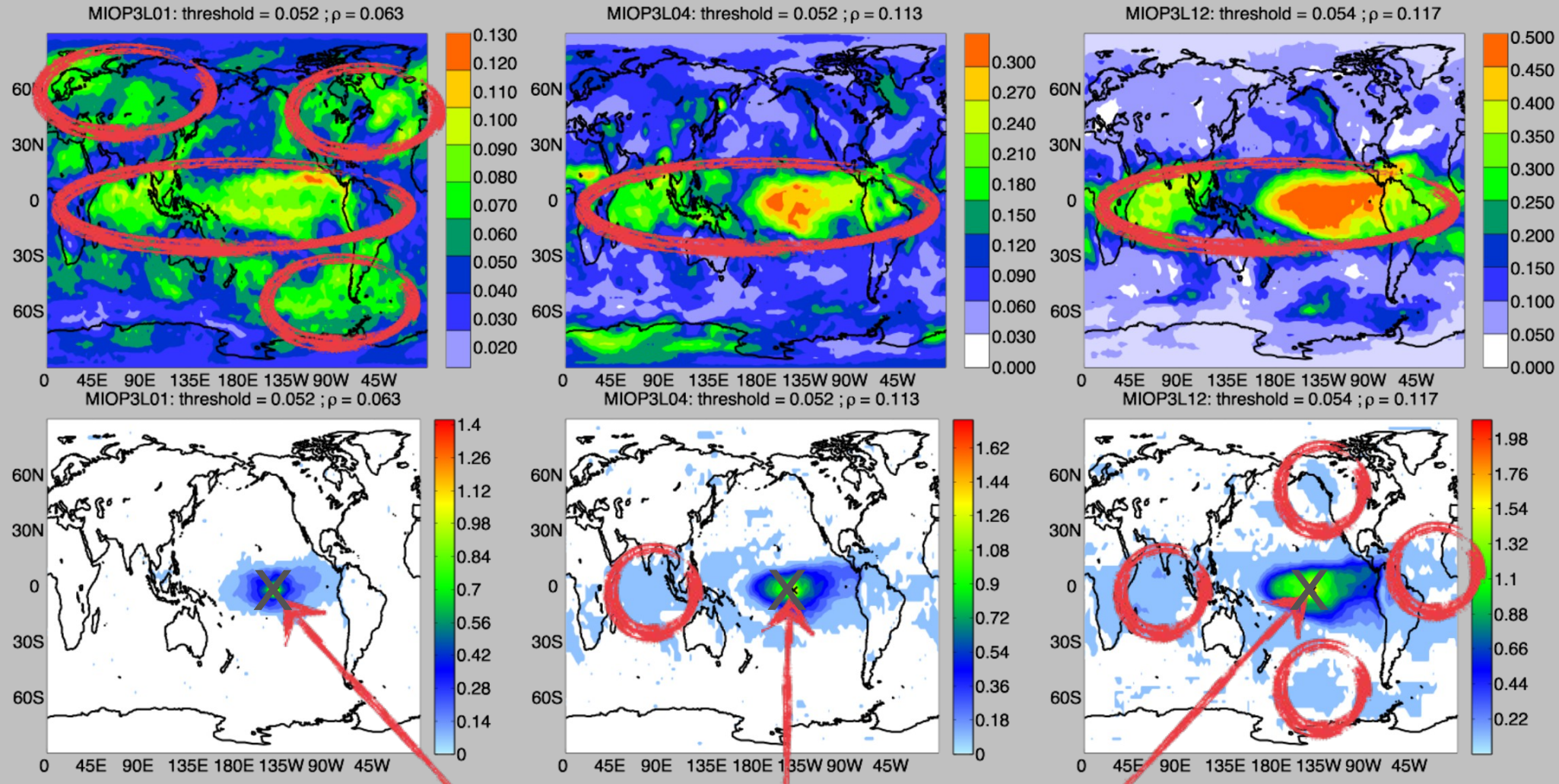
3 times separated by 12 months are used to construct OP.

AWC

intra-seasonal

intra-annual

inter-annual



MI

Connections to/from this point

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Methodology for climate network construction

Statistical Similarity

Directionality

Directionality index

- The directionality index can be defined as

$$\mathrm{DI}_{XY}(\tau) = \frac{I_{XY}(\tau) - I_{YX}(\tau)}{I_{XY}(\tau) + I_{YX}(\tau)}$$

Palus (2007)

- where I_{XY} is the Conditional Mutual Information

$I_{XY}(\tau) = I(X; Y|X_\tau)$ quantifies the transfer of info from X to Y: quantity of info shared between X(t) and Y(t) given the influence of X(t-tau) on Y(t).

- $I_{YX}(\tau) = I(Y; X|Y_\tau)$ quantifies the transfer of info from Y to X

- $\tau > 0$ is a parameter chosen to determine the time scale of interest

D_{XY} determines the net direction of information flow.

Other measures like Granger Causality can also be used (Tirabassi et al 2014)

Directed Network of surface air temperature

Objetive

- Study the directionality of SAT using DI

Data

- Daily mean data SAT. NCEP-CDAS1 Reanalysis, 2.5x2.5, 1948-2013.

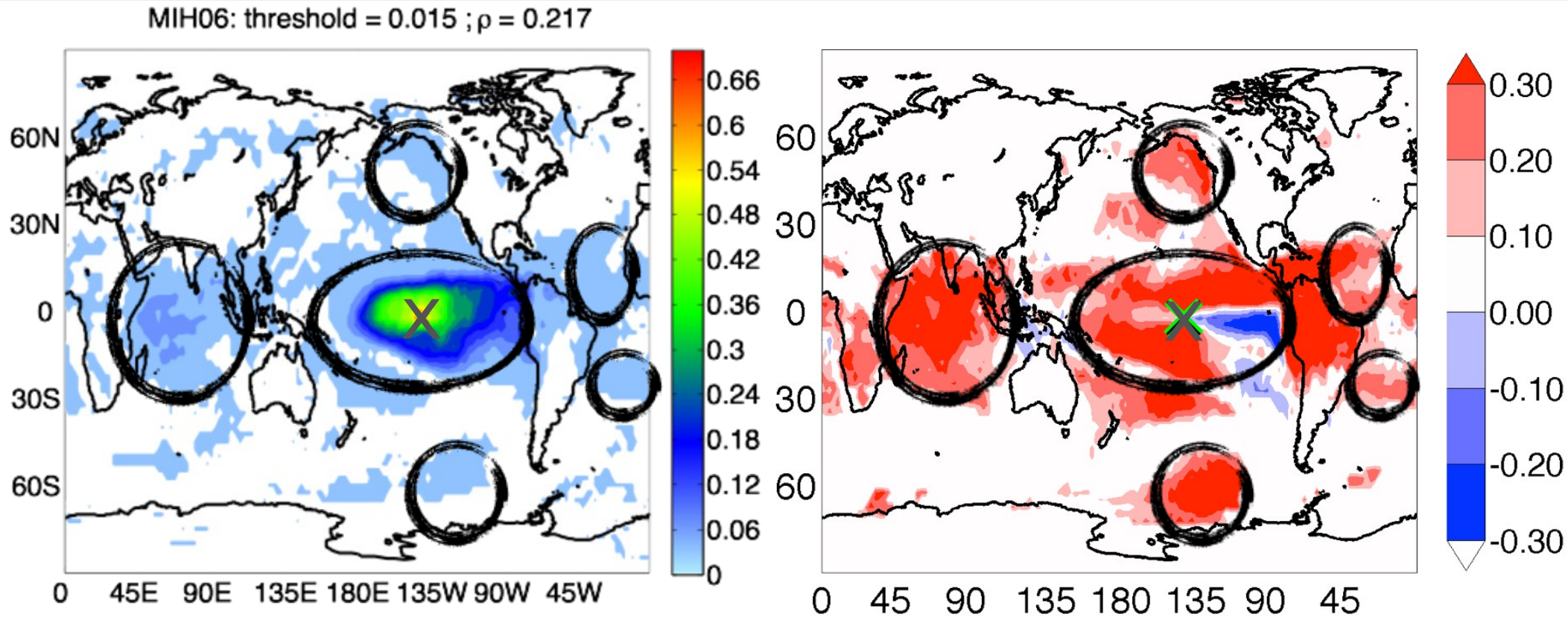
Deza et al (2015)

Tropics – Pacific ocean

Connectivity of eq Pacific - Only MI

Direction

$\tau = 30$ dias



MIH

DIH

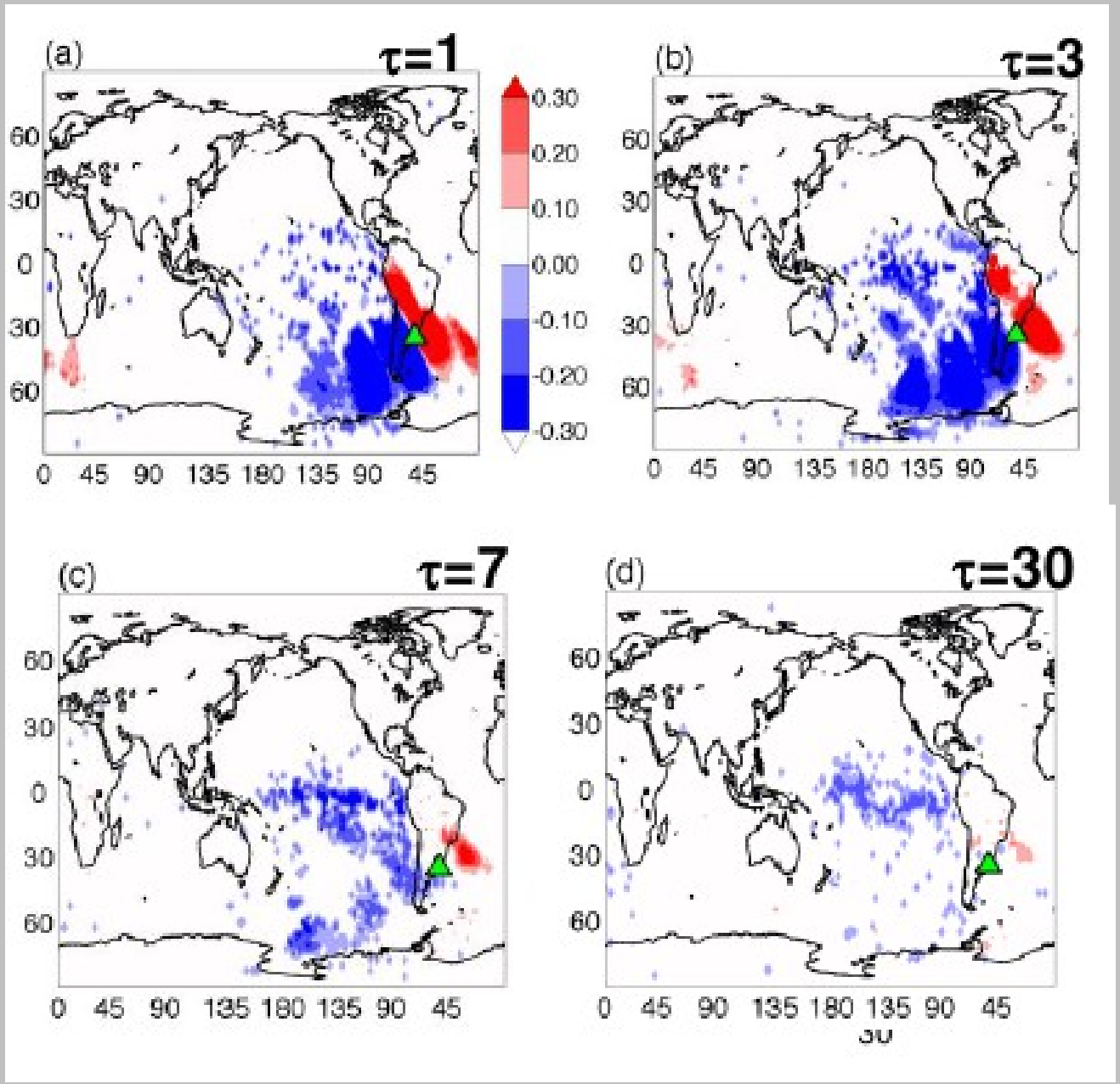
- BLUE incoming links
- RED outgoing links: influenced by eq. Pacific

Extra-tropics

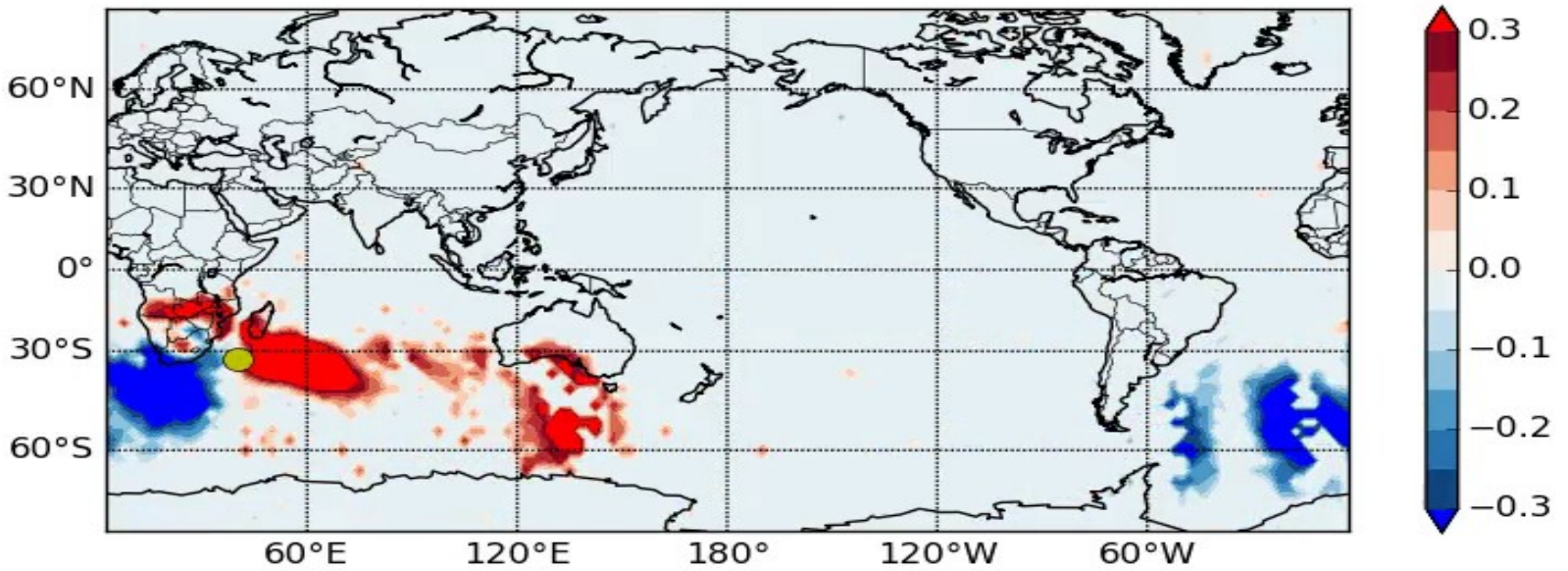
Directionality of a point over Uruguay:

<u>Tau days:</u> shows propagation of synoptic waves & Pacific influence.

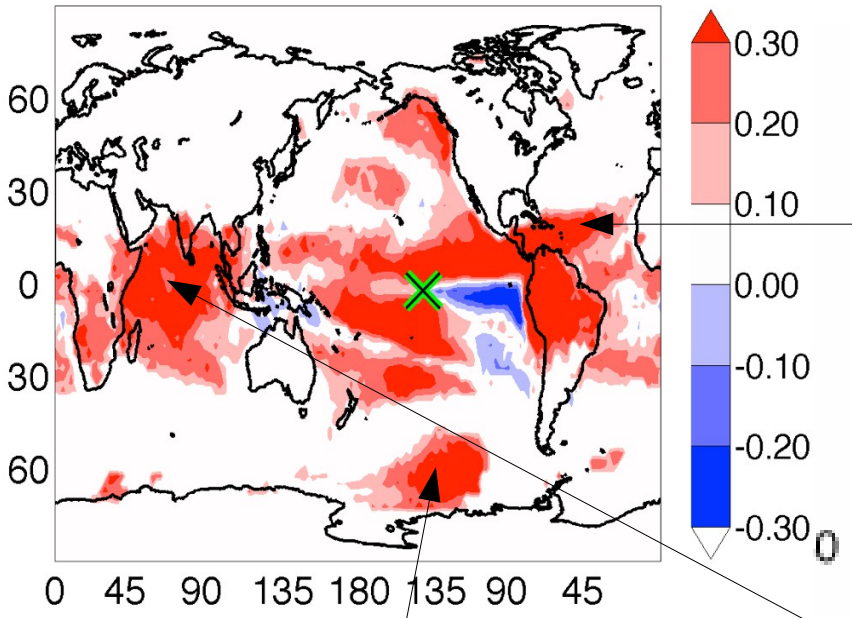
<u>Tau monthly:</u> only remains Pacific influence

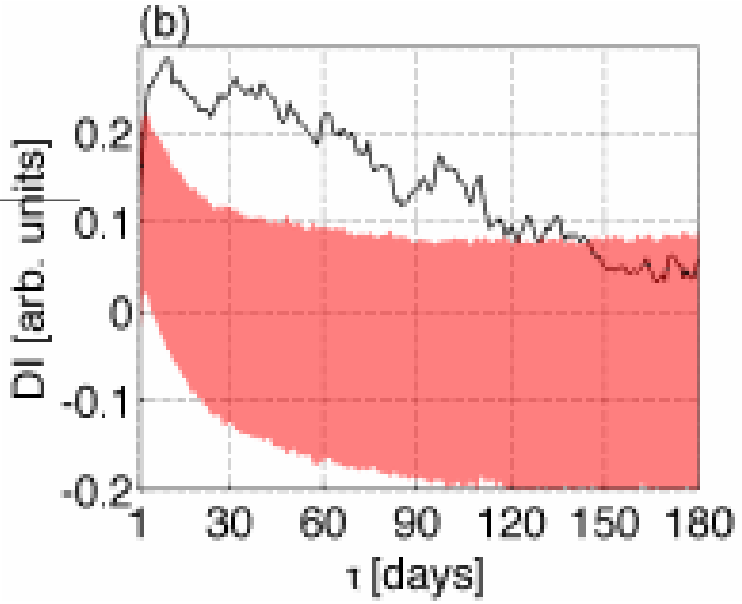


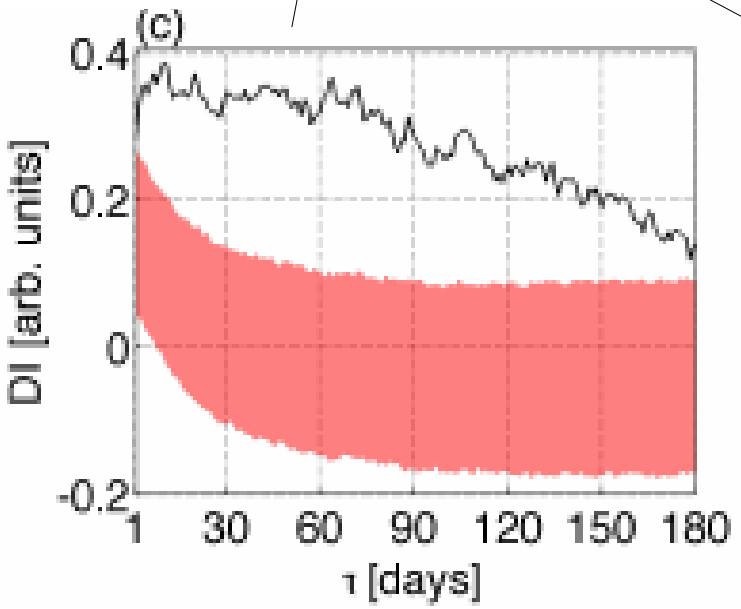
Movie – tau=3 days for different points in 30S.

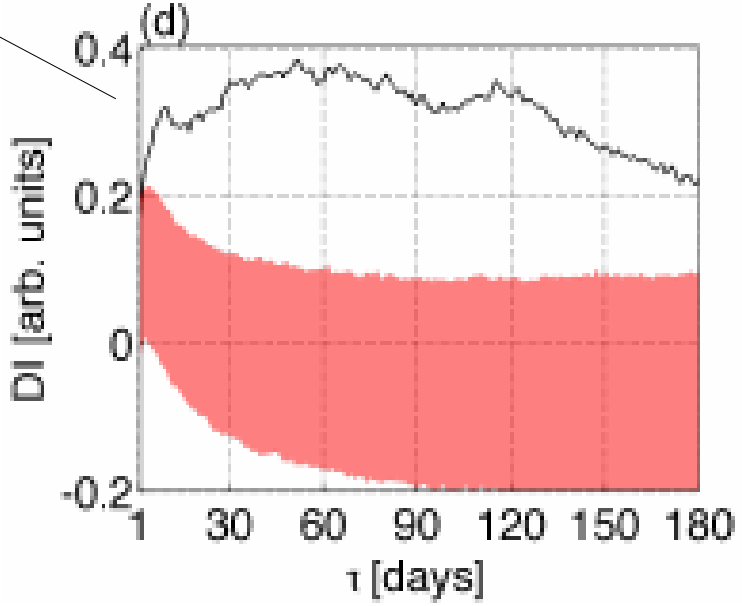


Dependence of DI on τ
- shows time scale of remote connections.







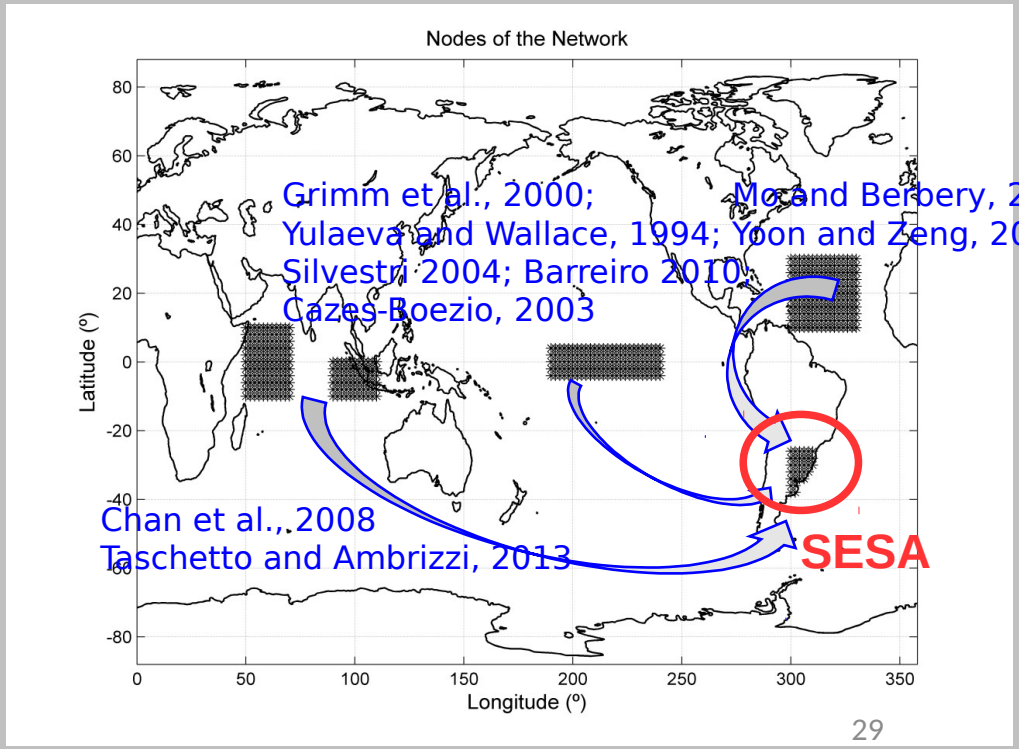


Fast Time Scale ~ 10 days + a longer time scale that depends on air-sea Interaction in each basin

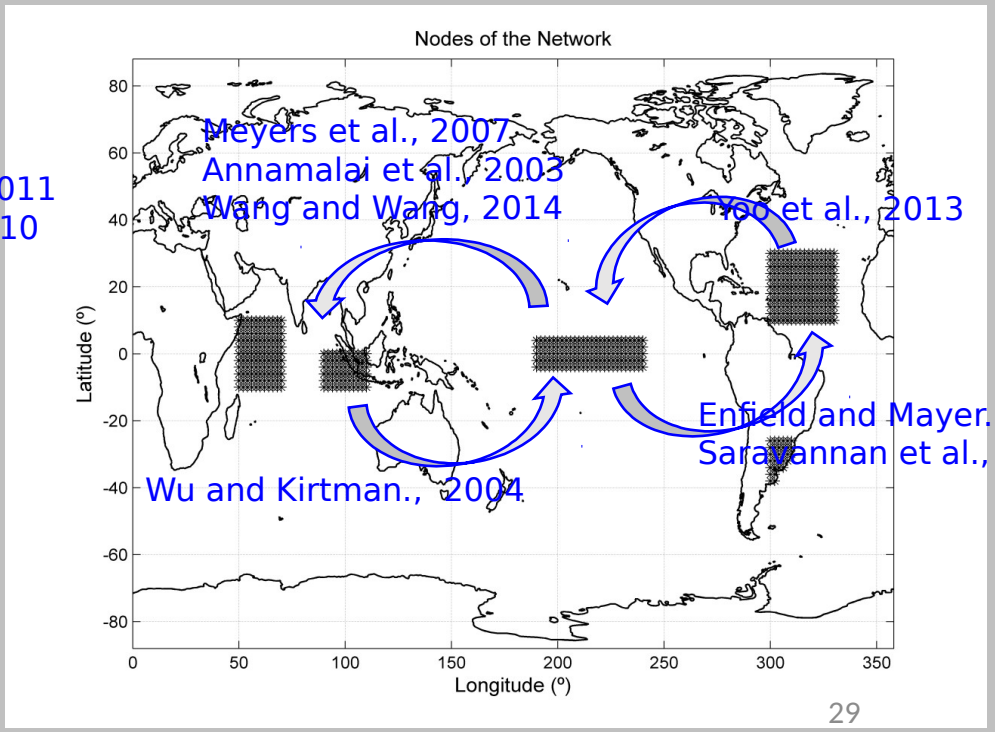
Analize the variability of the collective connectivity of the three tropical oceans and precipitation over Southeastern South America during the 20th century

Southeastern South America (SESA) is known to be influenced by all tropical oceans, and the tropical oceans are known to influence each other

The tropical oceans influence rainfall over SESA



The tropical oceans interact among each other



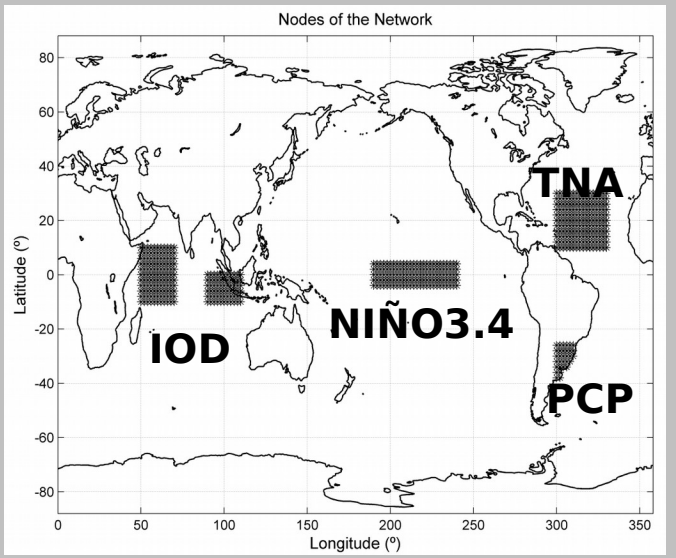
How does evolve the collective behavior of oceans and rainfall over SESA?

Martin & Barreiro (2016)

Network construction

a) Nodes definition: 4 nodes (NIÑO3.4, TNA, IOD, PCP)

- Indices:
  - Seasonal means of monthly SSTa (for the case of the oceanic indices)
  - Seasonal means of monthly rainfall (PCP) in SESA.
  - Focus on austral spring



b) Data

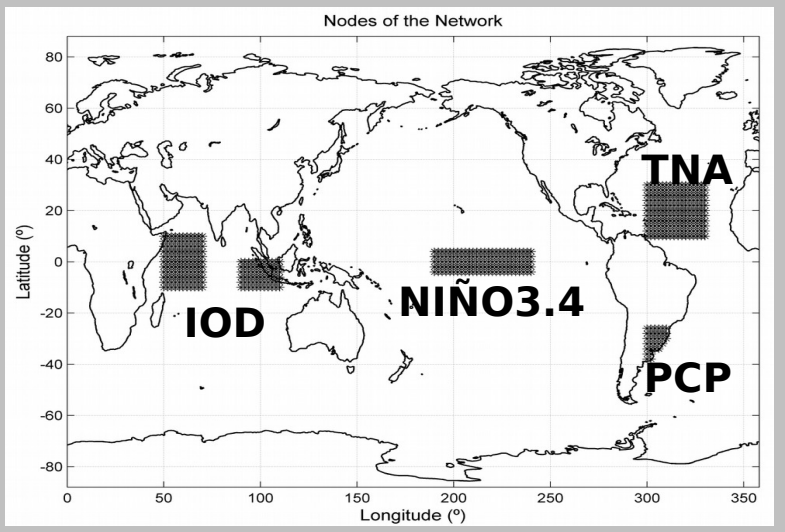
- SST – ERSSTv3b (Smith et al 2008)
- PCP – GPCCv5 (Schneider et al 2011)

- Atmospheric Model: ICTP AGCM (Moltine et al 2003) 10-member ensemble forced with historical SST.

Mean degree of collective interaction among the nodes

c) Mean network distance (Tsonis et al., 2007):

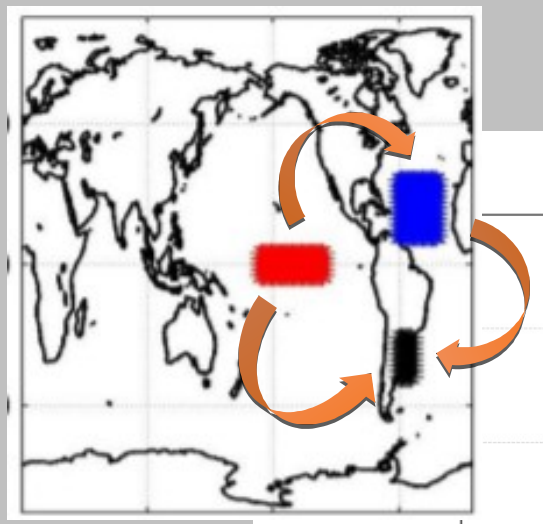
$$d(t) = \frac{2}{N(N-1)} \sum_{i<j} \sqrt{2\left(1 - \left|\rho_{ij}^{t}\right|\right)}$$

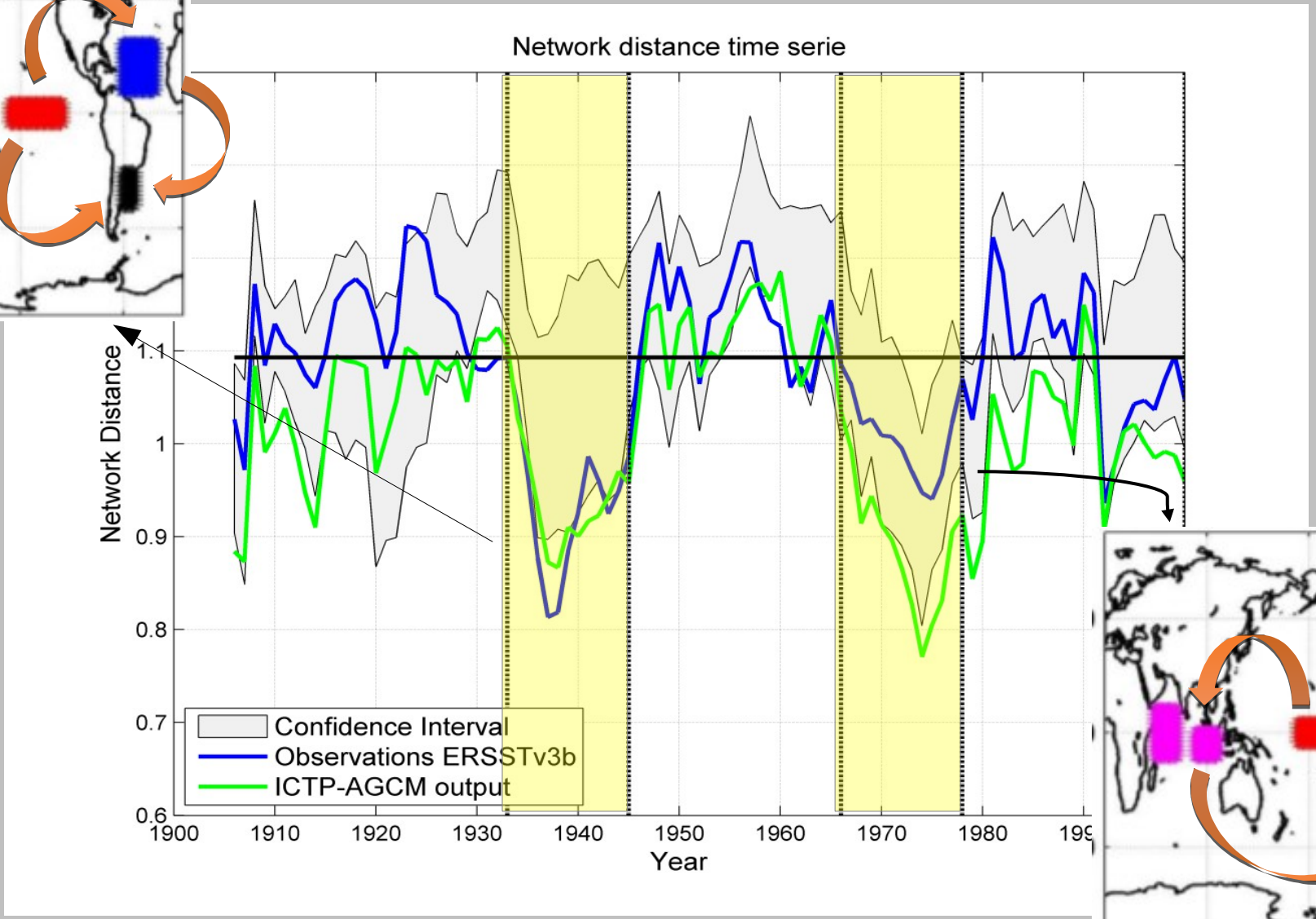


- ρ_{ij}^{t} Pearson correlation coefficient
- Sliding window of 11 years
- $\left|\rho_{ij}^{t}\right|$ intensity of interaction
- N: number of networks' nodes
- Max(d)=sqrt(2) $\leftrightarrow \rho_{ij}^{t} = 0$ (completely disconnected network)
- Min(d)=0 $\leftrightarrow \rho_{ij}^{t} = 1$ (completely connected network)

Evolution of connectivity during the 20th century

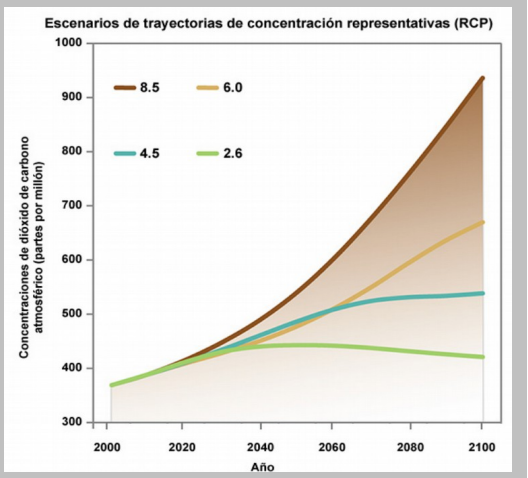
- Two periods of synchronization between the oceans and rainfall over SESA detected in reanalysis and simulations.
- Different oceans influenced SESA in these two periods.





How will this collective interaction change under anthropogenic forcing?

(Martin & Barreiro 2017)



CMIP5-Model	Runs	Ensemble size
BCC-CSM1.1	HISTORICAL	3
	RCP4.5	1
	RCP8.5	1
CCSM4	HISTORICAL	5
	RCP4.5	5
	RCP8.5	6
CSIRO-Mk3.6.0	HISTORICAL	9
	RCP4.5	10
	RCP8.5	9
GFDL-CM3	HISTORICAL	5
	RCP4.5	1
	RCP8.5	1
HadGEM2-ES	HISTORICAL	4
	RCP4.5	4
	RCP8.5	4
IPSL-CM5A-LR	HISTORICAL	6
	RCP4.5	4
	RCP8.5	4
MPI-ESM-LR	HISTORICAL	3
	RCP4.5	3
	RCP8.5	3

HISTORICAL RUN: (1901 - 2005)

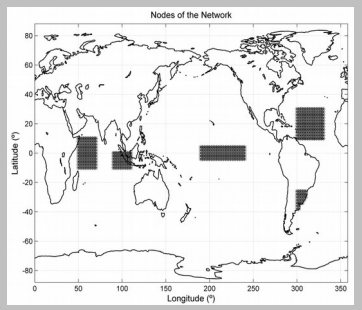
RCP4.5 y RCP8.5: (2005 - 2100)

SST

PCP

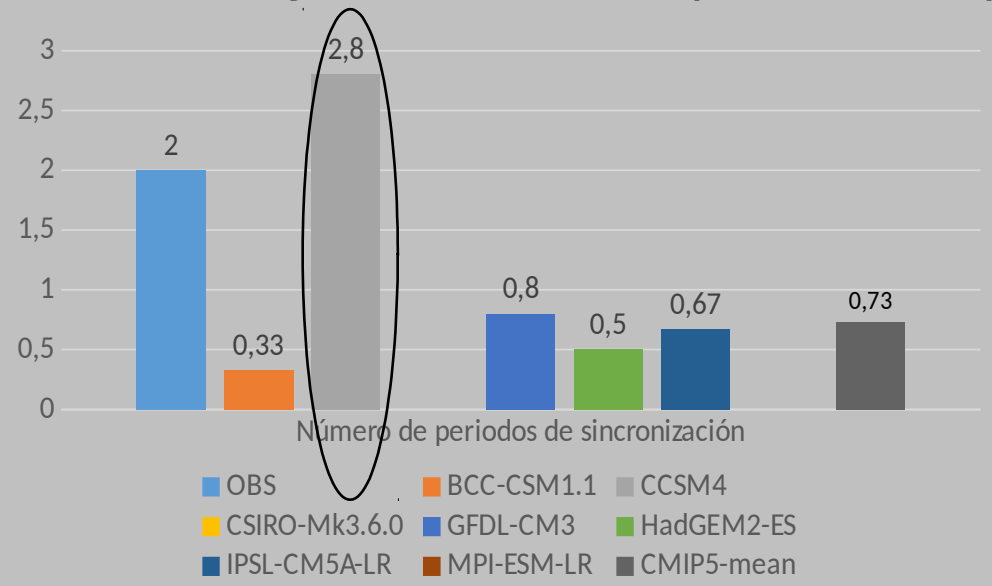
Nodos

$$d(t) = \frac{2}{N(N-1)} \sum_{i<j} \sqrt{2\left(1 - \left|\rho_{ij}^{t}\right|\right)}$$

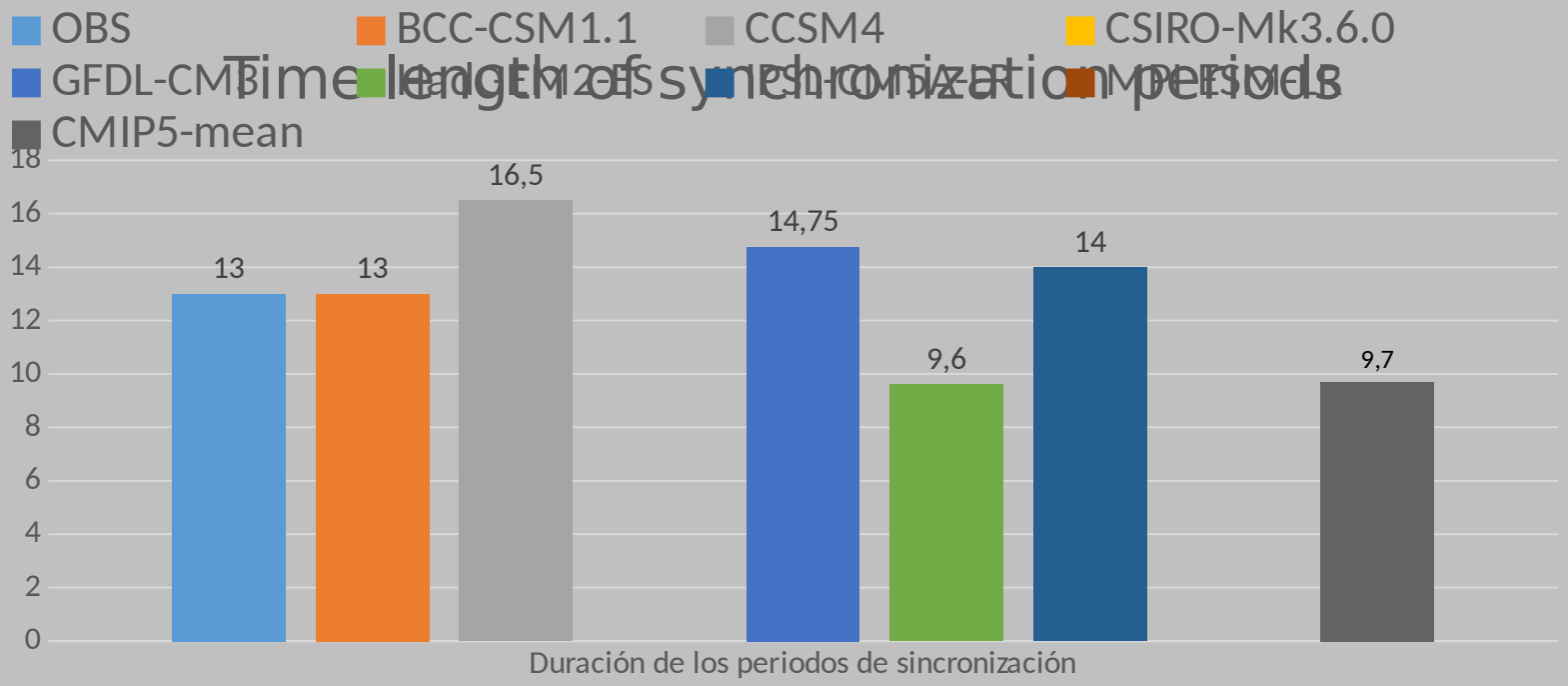


- Maximum y minimum value de d(t)
- Number of synchronization periods
- Time length
- Nodes connectivity

1) CMIP5 models validation



- CMIP5 models subestimate nsp, except CCSM4
- Model closer to observations: CCSM4
- CSIRO-Mk3.6.0 y MPI-ESM-LR: present limitation to reproduce atmospheric teleconnections



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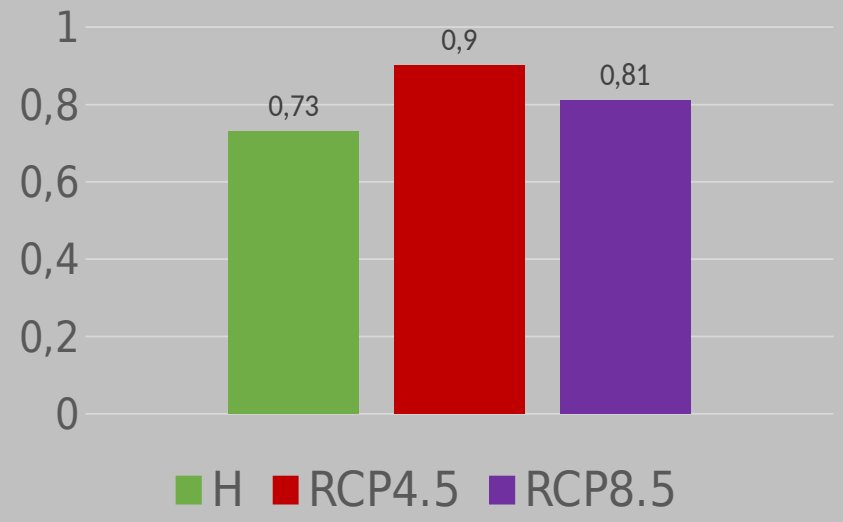
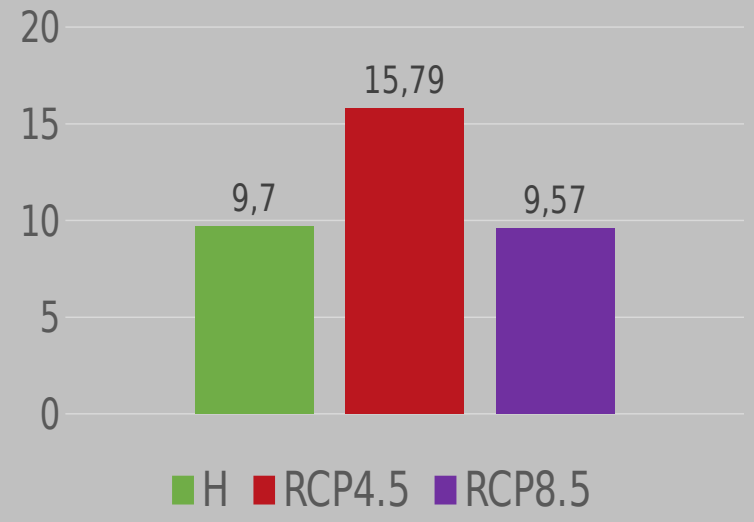
2) Evaluation of 21st century changes

Nonlinear response to GHG forcing.

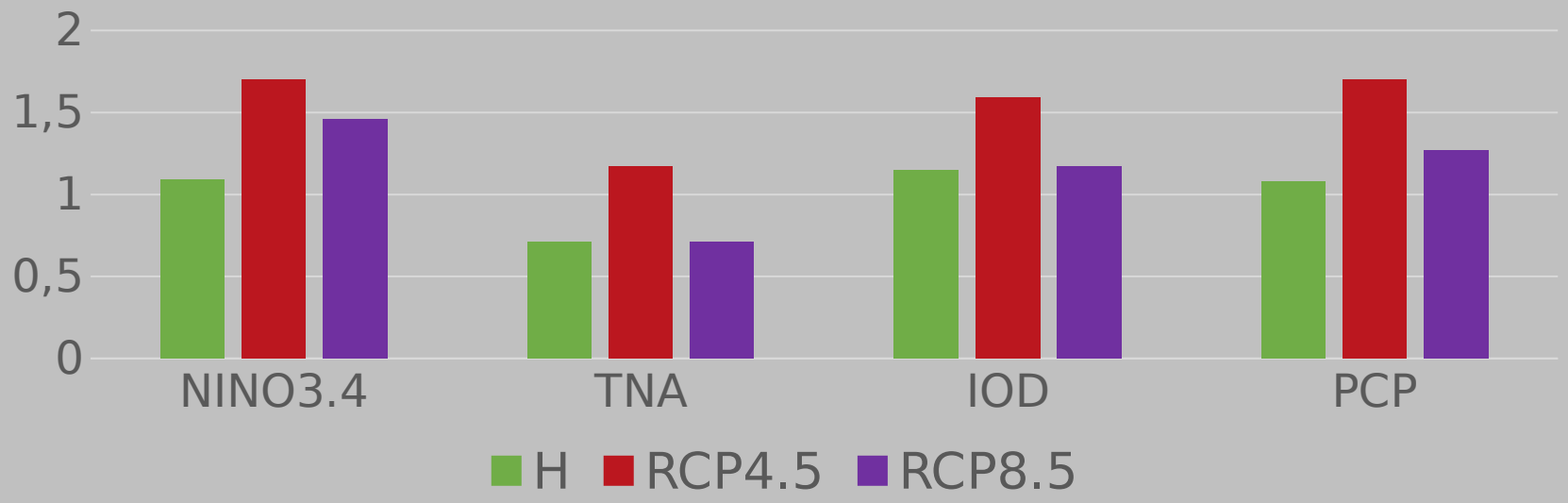
Number of synchronization periods



Time – length of the synchronization periods



Nodes connectivity



Final remarks

- Tools from complex networks and information theory provide a new methodology for analysis of (big) climate data.
- AWC likely adds to standard EOF analysis when there is no dominant mode of variability and the field shows spatial coherence (Dongues et al 2015).
- Multivariate (interacting) networks imply computation of very large matrices. Need to implement codes to construct such networks.