Nonlinear tools to extract information from complex signals

(examples from climate, brain, neurons & lasers)

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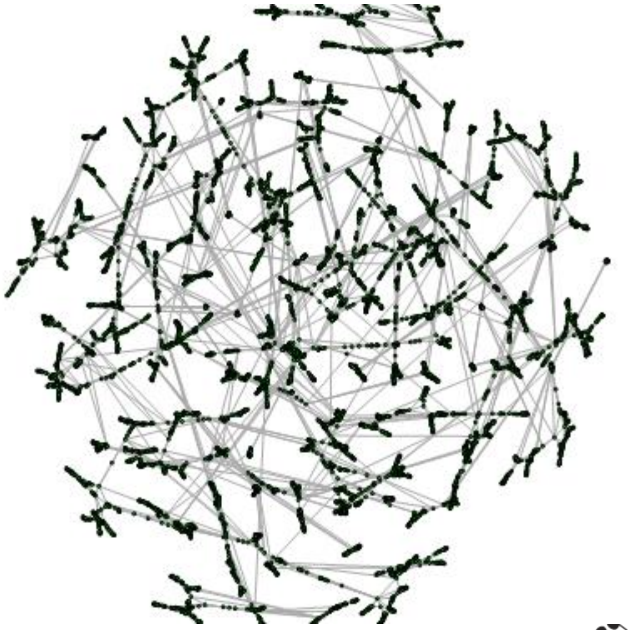
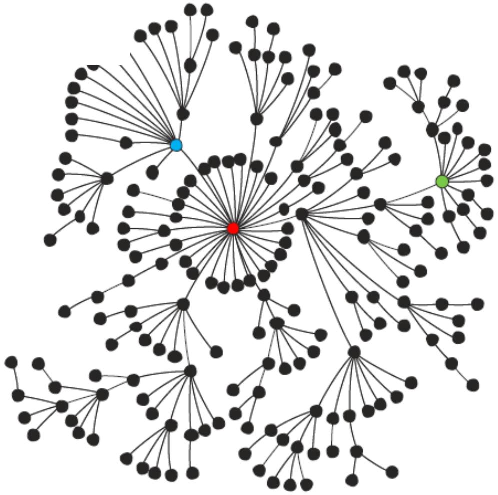
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

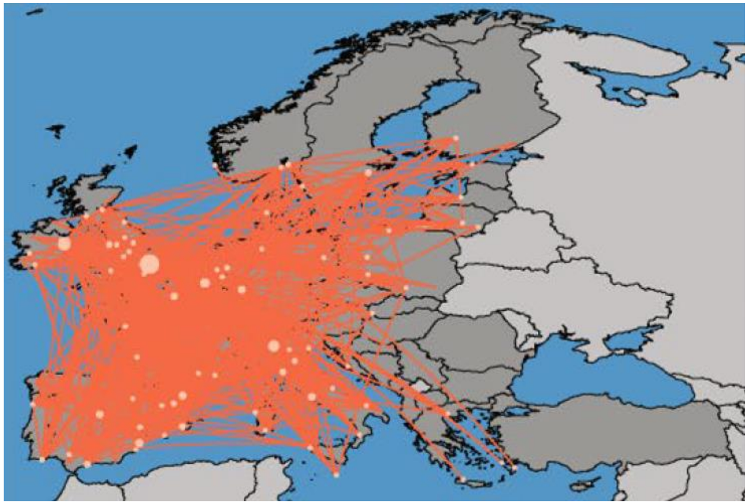
Presentation

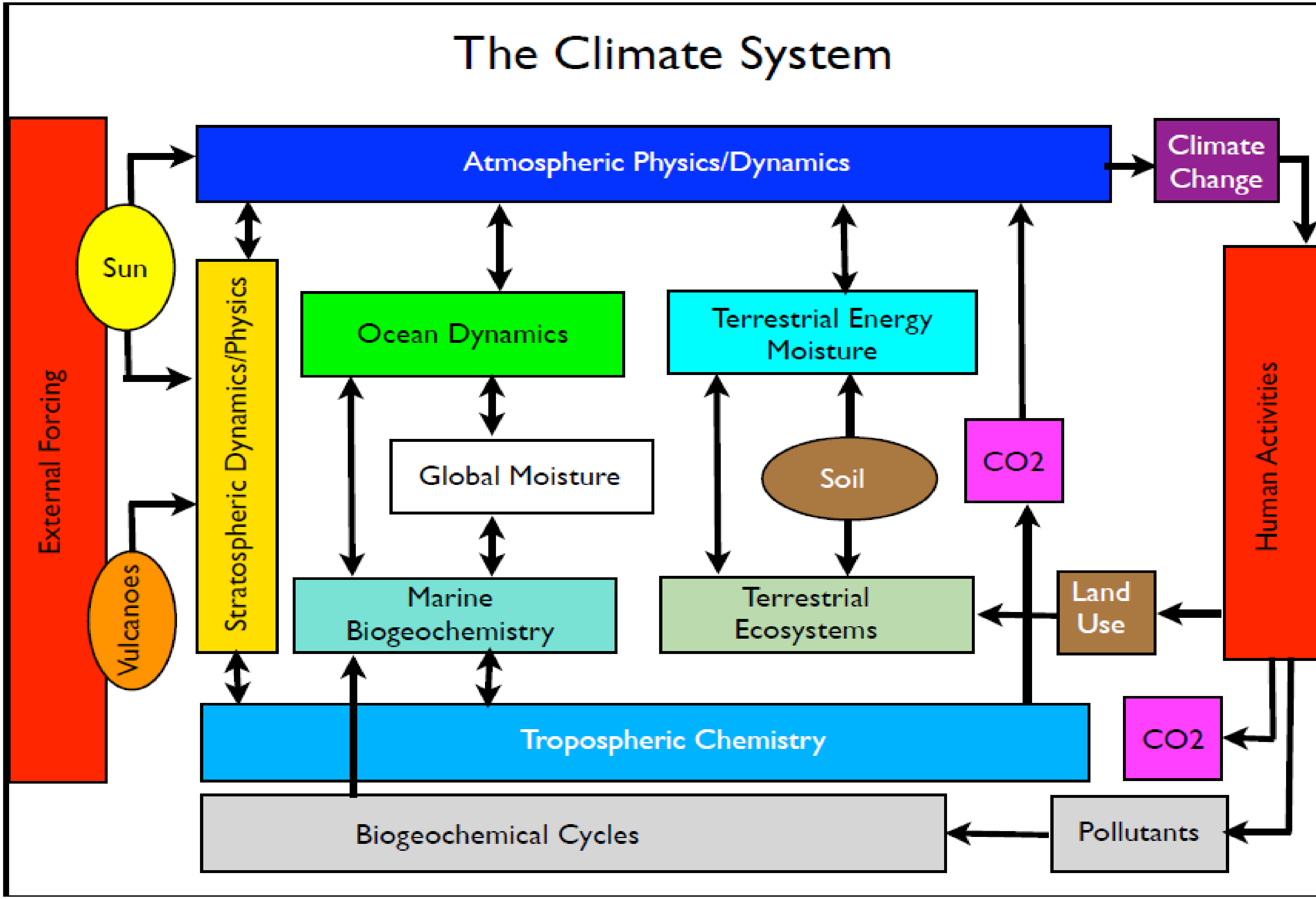
- Originally from Montevideo, Uruguay
- PhD in physics (lasers, Bryn Mawr College, USA)
- Since 2004 @ *Universitat Politecnica de Catalunya.*
- Member of the research group on *Dynamics, Nonlinear Optics and Lasers*.

Complex systems



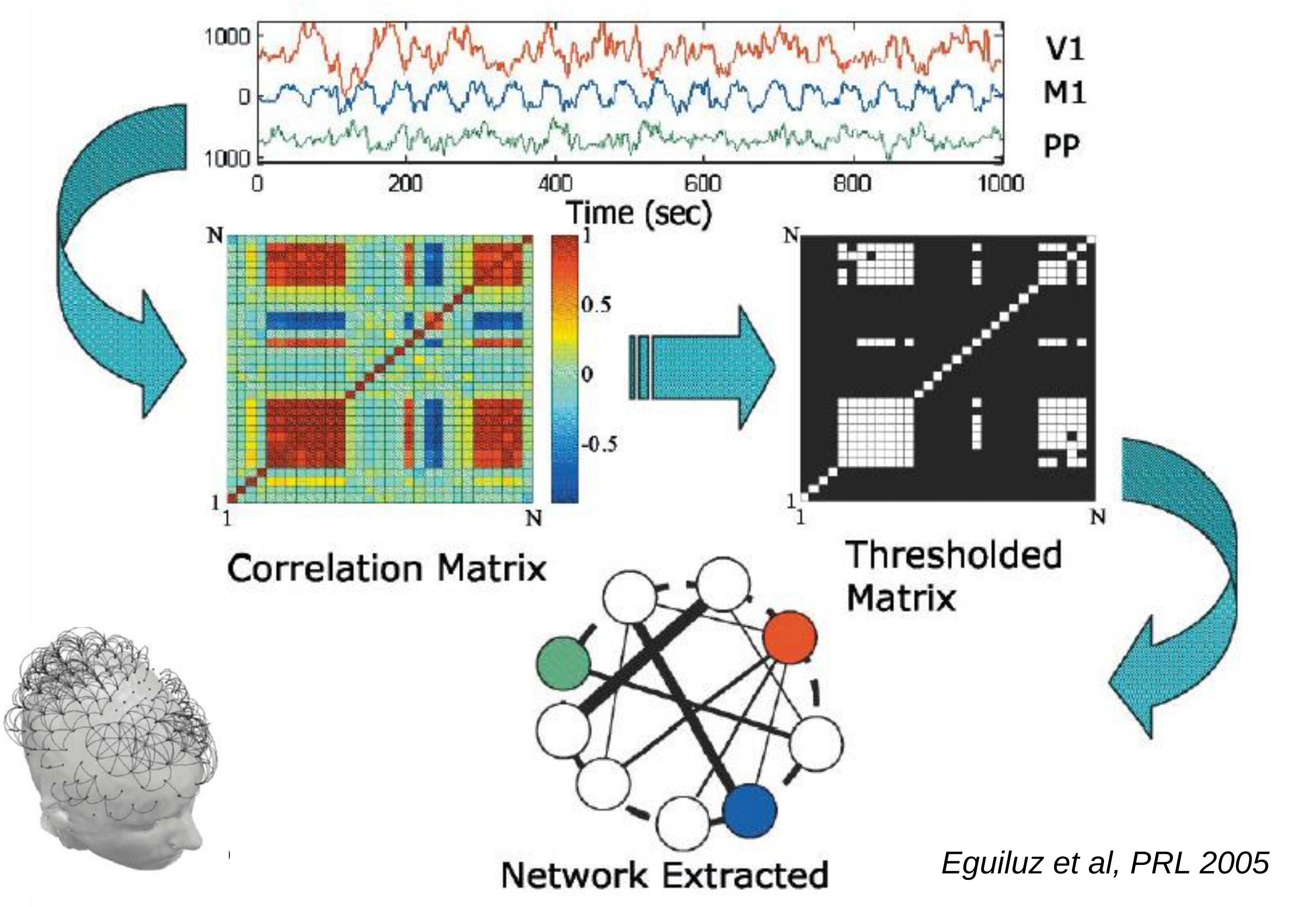






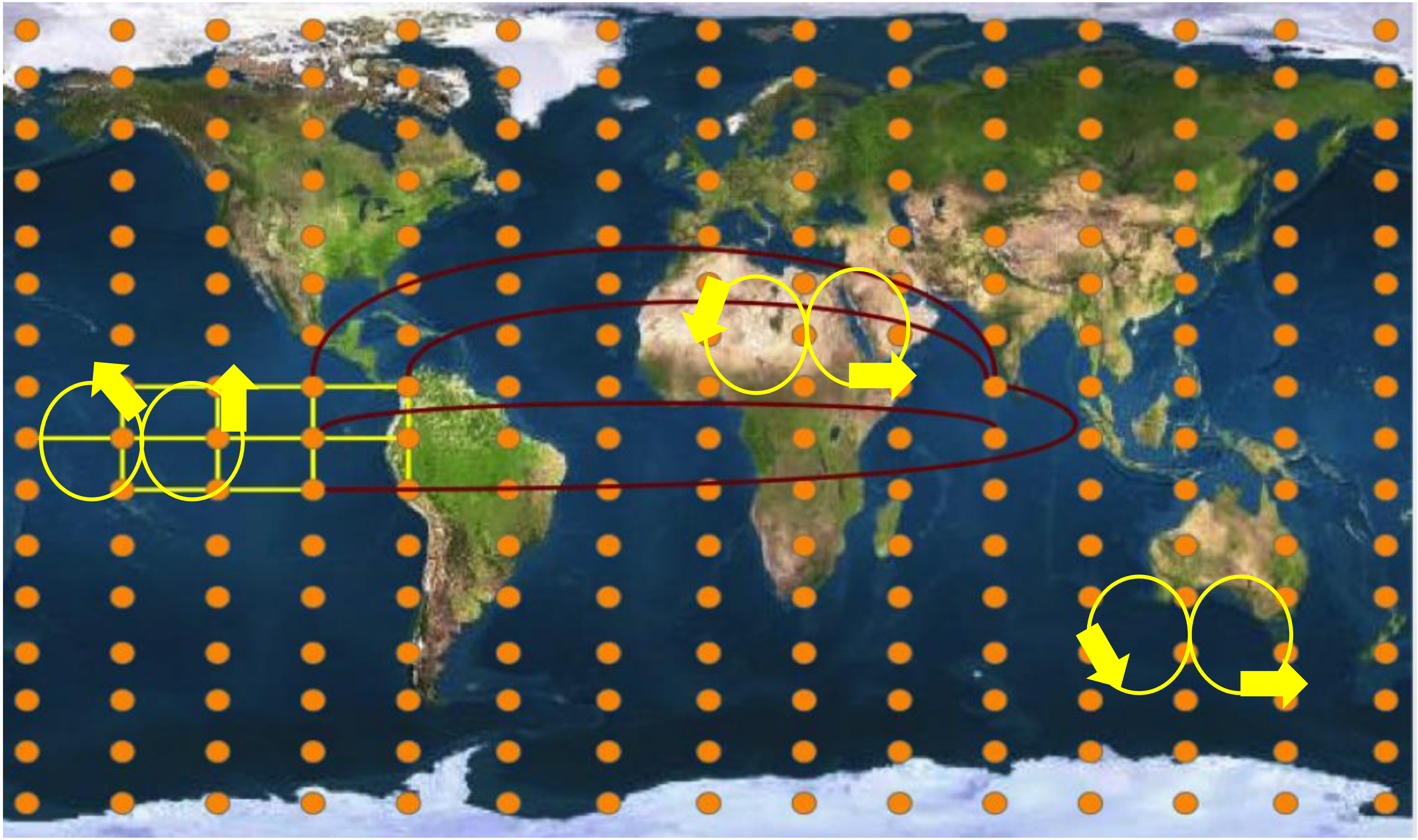
Courtesy of Henk Dijkstra (Ultrech University)

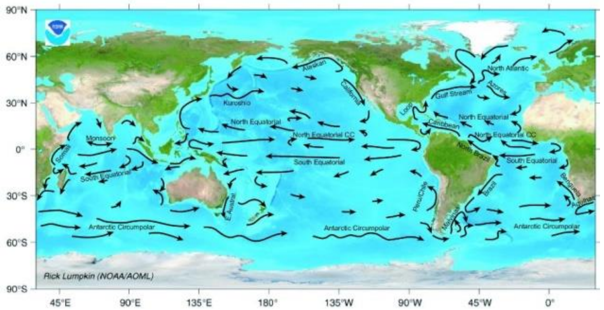
Functional brain network

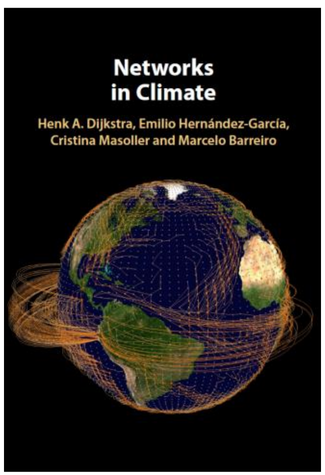


Eguiluz et al, PRL 2005

We can use the same method to construct a climate network

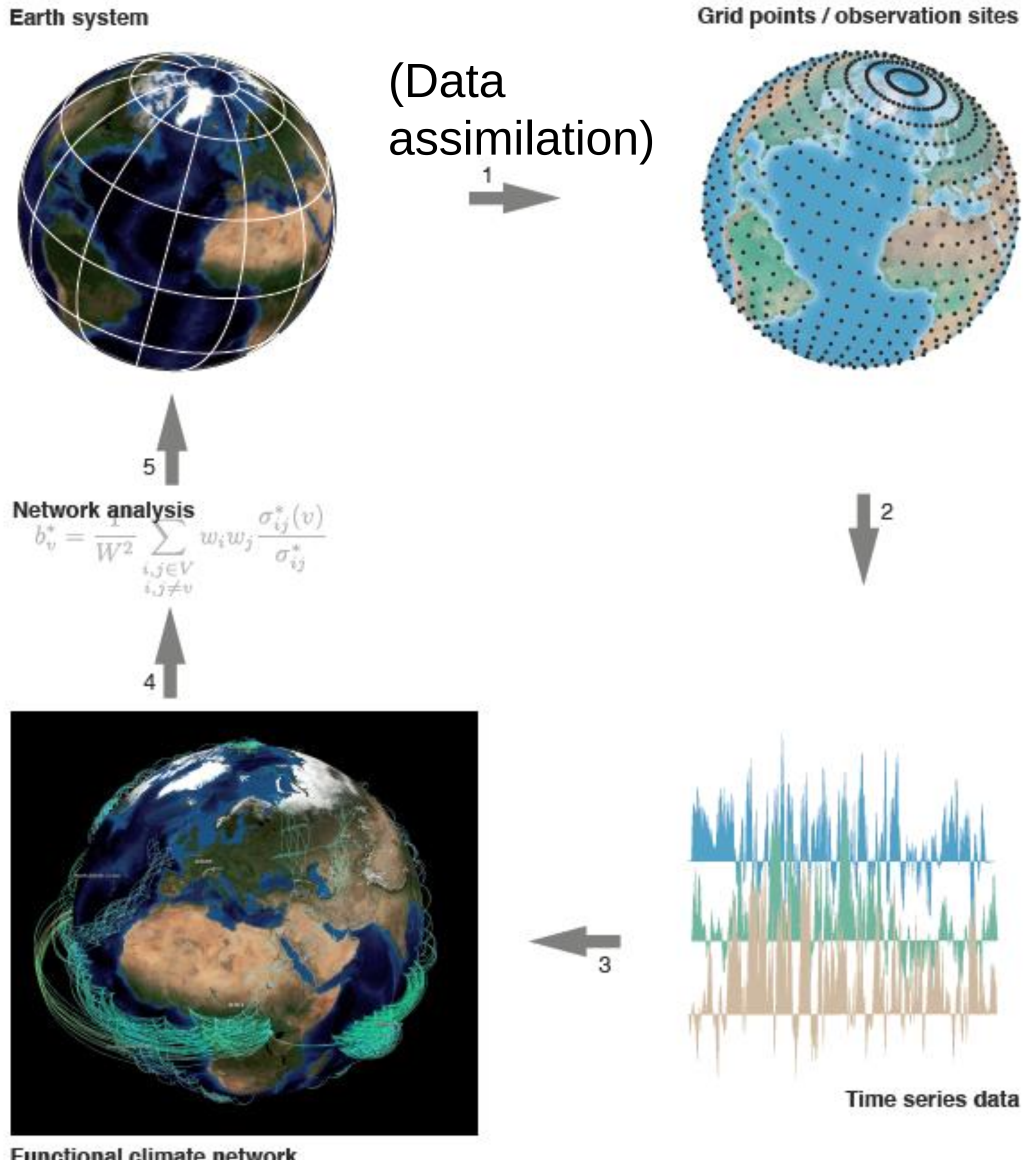






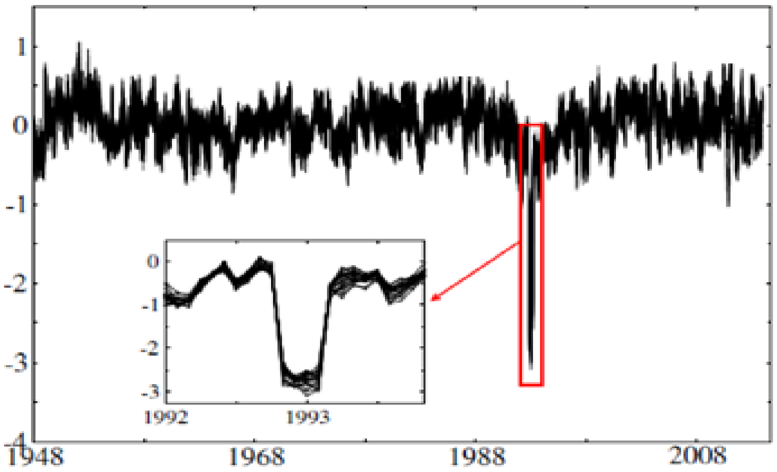
Cambridge University Press 2019

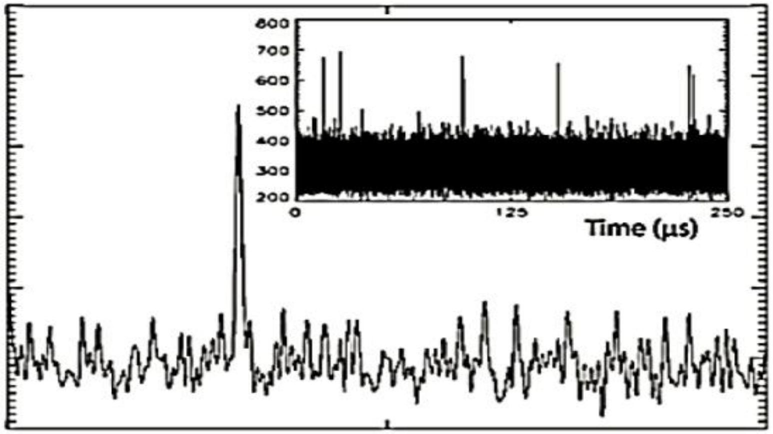
(Data assimilation)



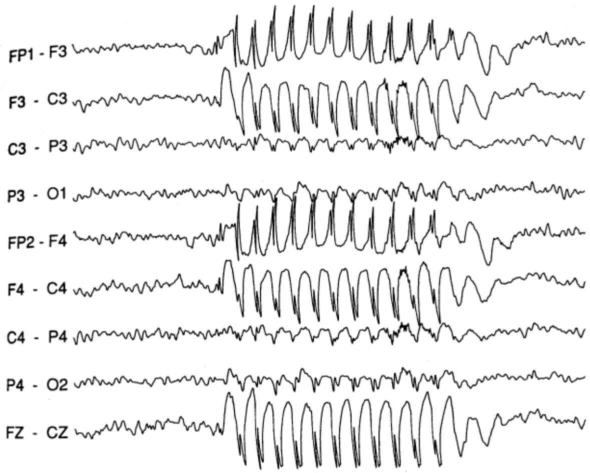
Donges et al, Chaos 2015

Complex systems often display dynamical transitions and/or large fluctuations

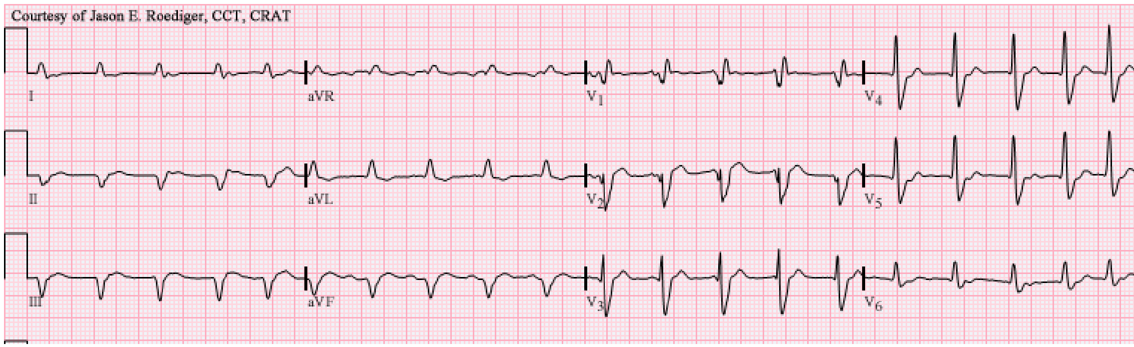




Time



Source: P. Suffczynski



Source: Wikipedia

A main goal is to predict, and also, to try to understand, the dynamical behavior.

Are extreme fluctuations becoming more frequent? More extreme?

ECMWF

Credit: Richard Williams, North Wales, UK

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Science & Environment

Rogue waves occurring less but 'becoming more extreme'

By Rebecca Morelle
Science Correspondent, BBC News

21 March 2019

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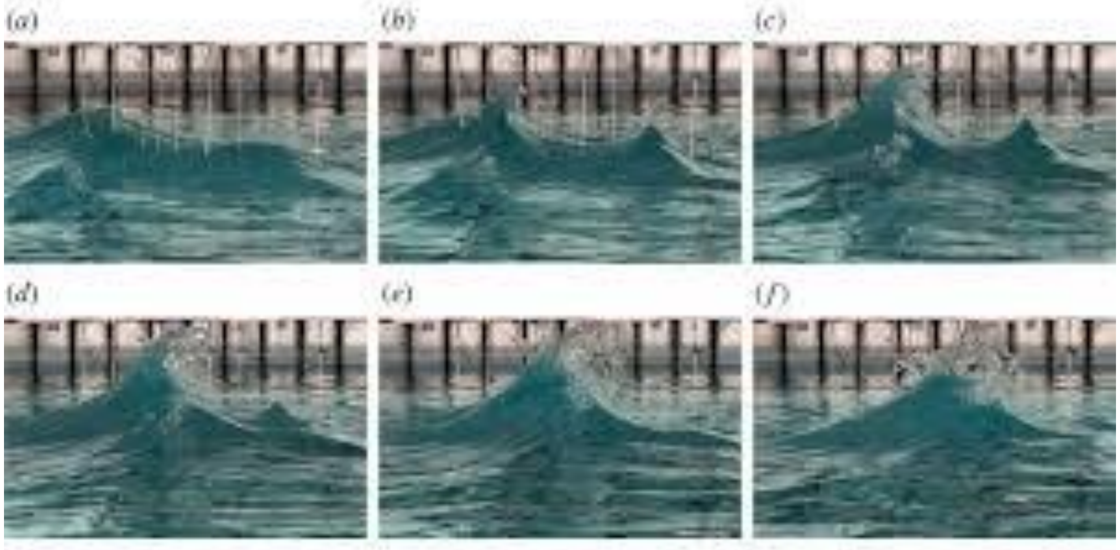
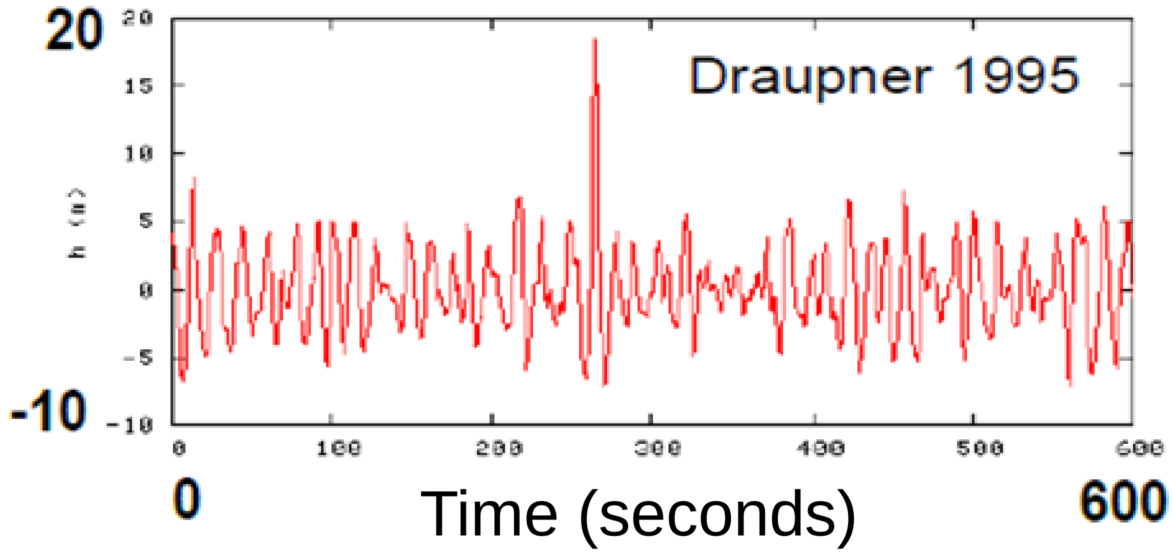
Rogue waves are a growing threat for the global shipping industry

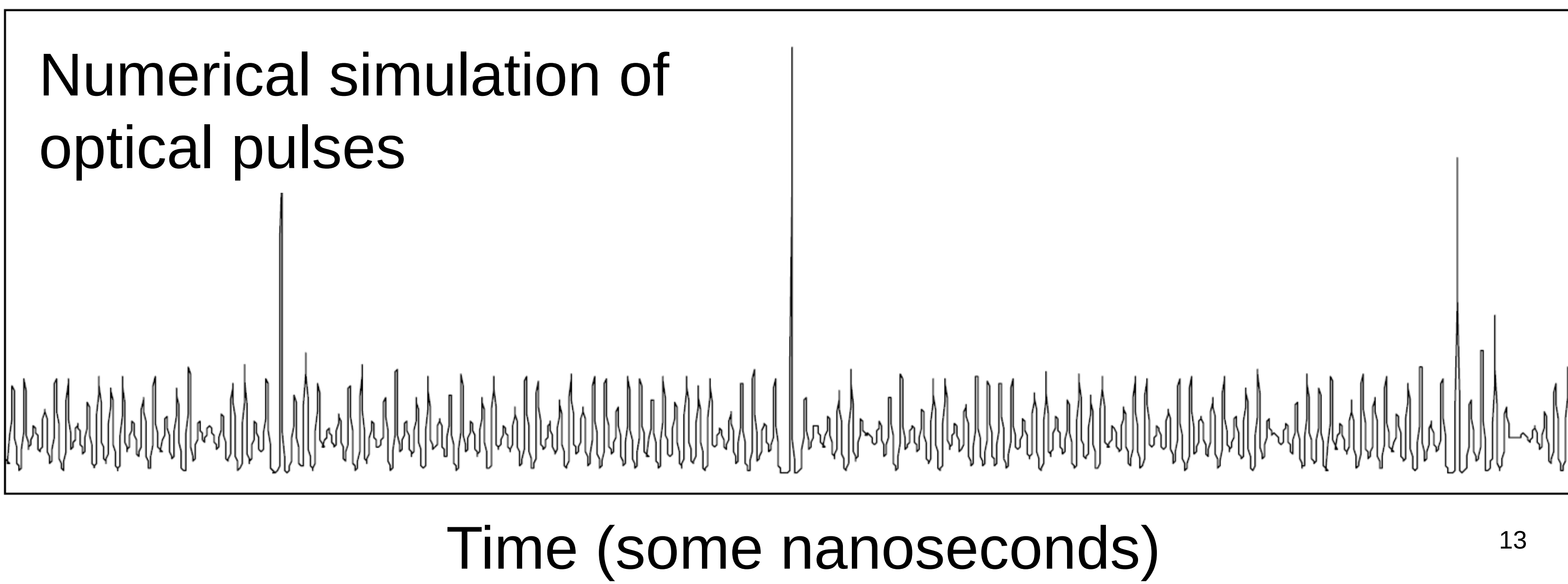


Rogue waves are a huge risk for the global shipping industry.

Are rogue waves in the ocean similar to those in a water tank, or in an optical system?

Ocean rogue waves and optical rogue waves





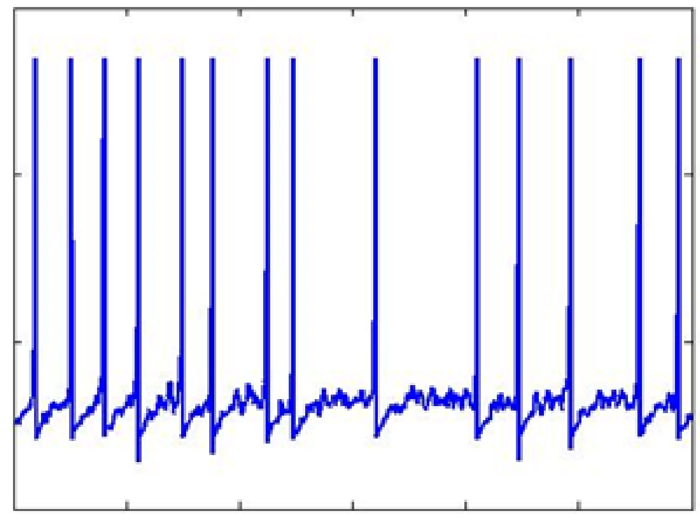
Time series analysis can unveil underlying statistical similarities in very different systems

Laser intensity

Time

10^{-9} s

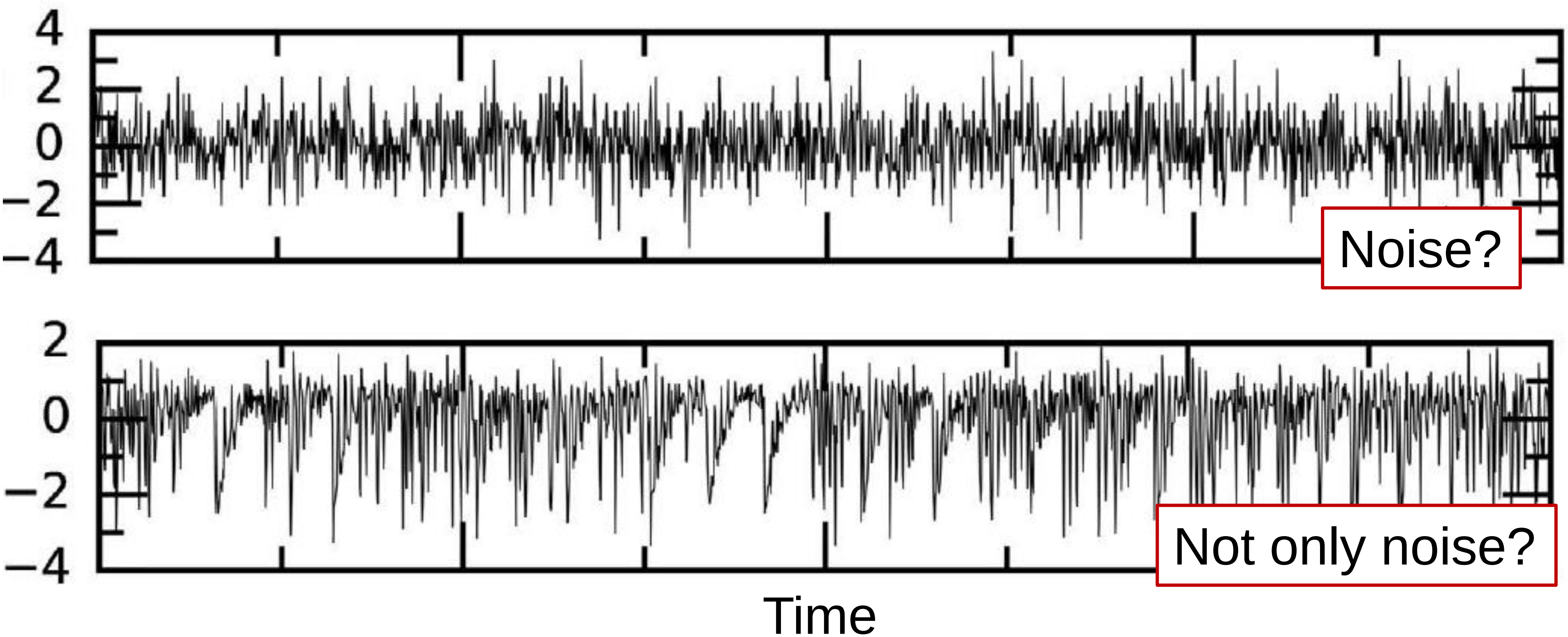
Neuron model



Time

10^{-3} s

Methods of time-series analysis allow to detect and to quantify differences

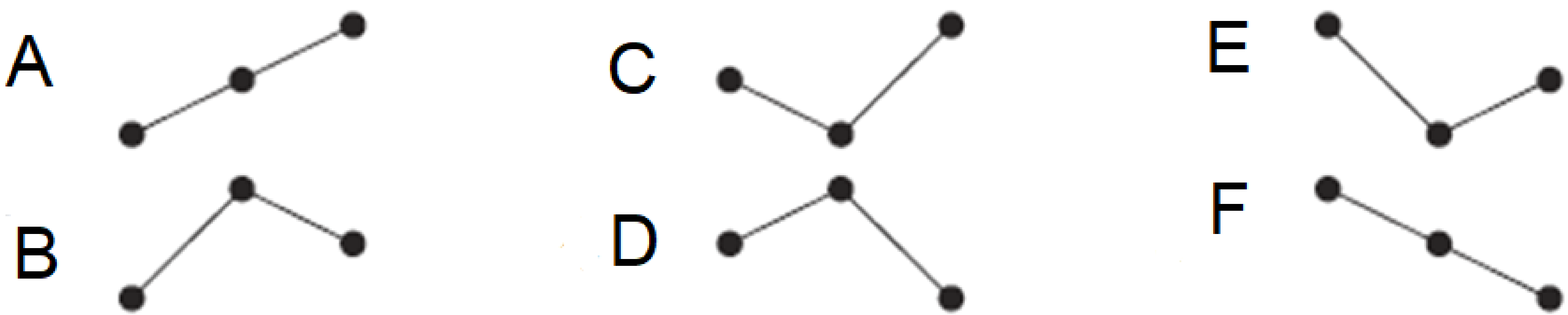


First analysis method: ordinal analysis

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

Possible order relations among three numbers (e.g., 2, 5, 7)

{…2, 5, 7…} {…5, 2, 7…} {…7, 2, 5 …}

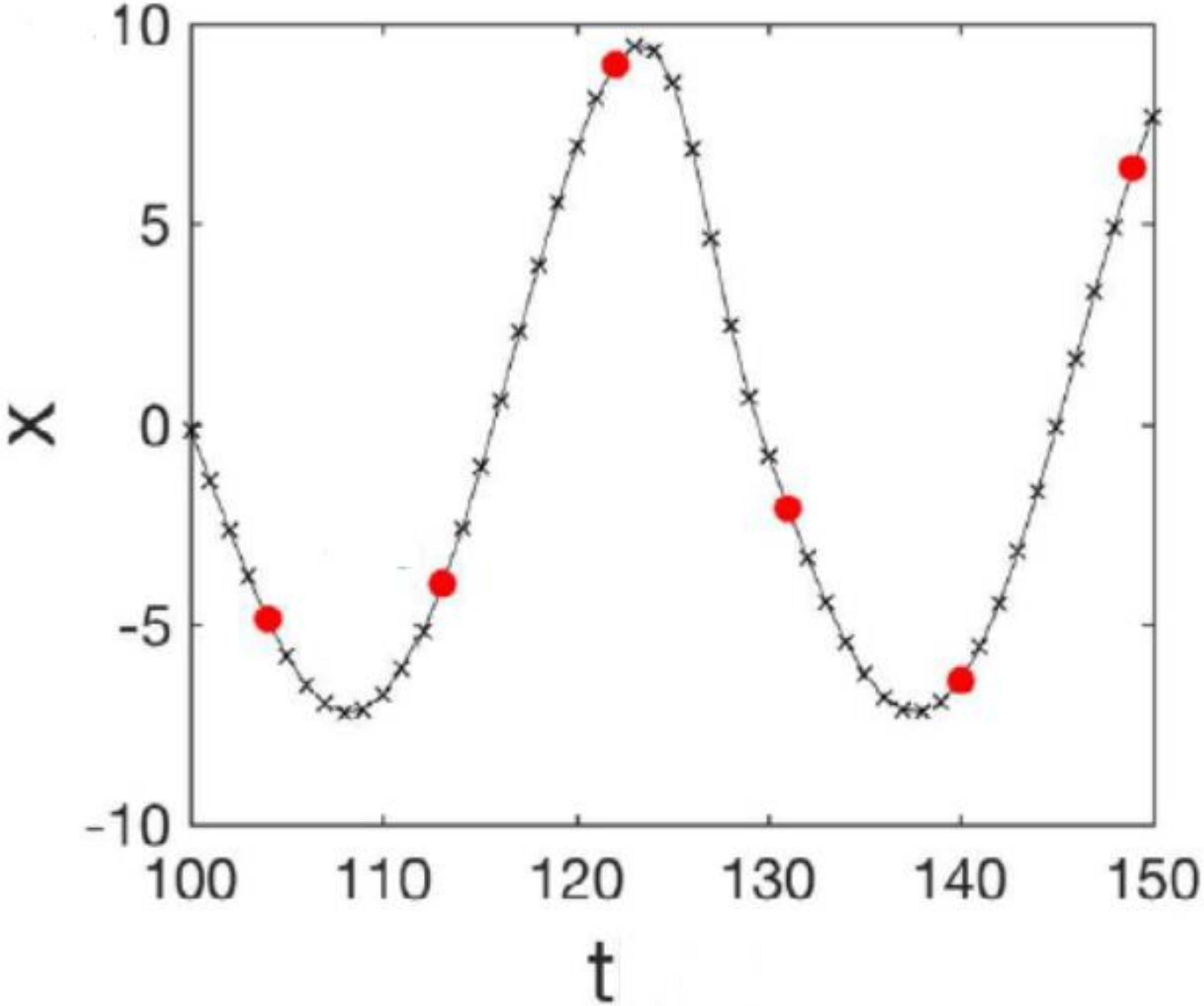


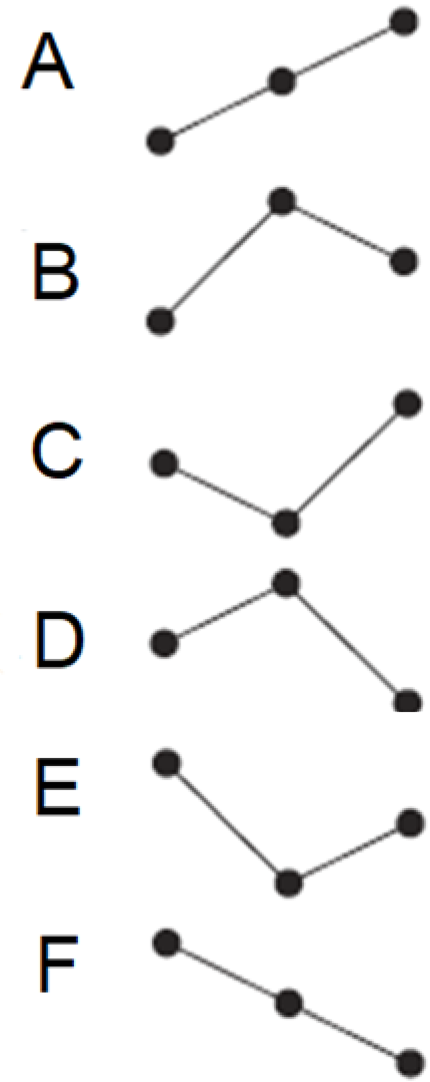
{…2, 7, 5…} {…5, 7, 2…} {…7, 5, 2…}

Bandt and Pompe: Phys. Rev. Lett. 2002

Which is the sequence of "letters" (patterns) defined by the red dots?

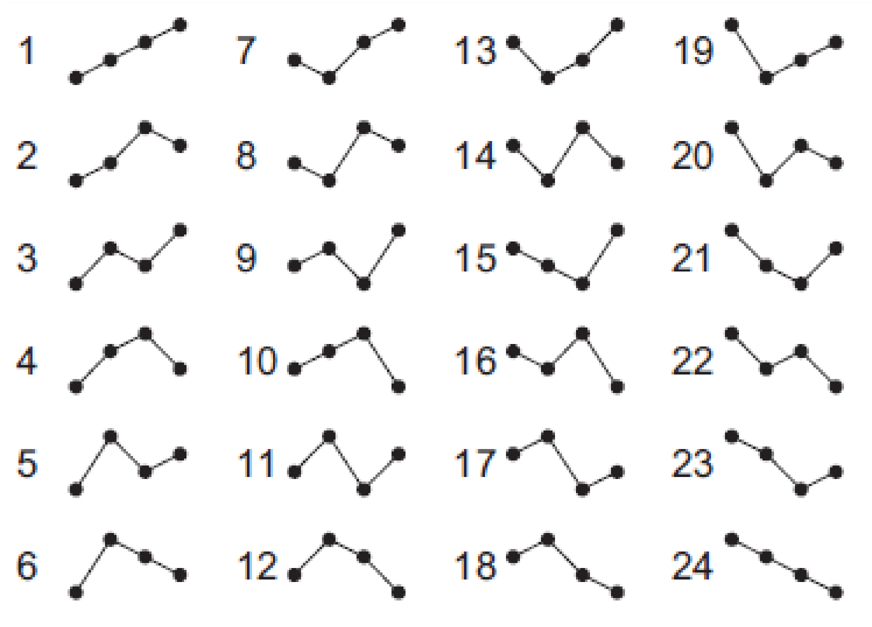
A B F C





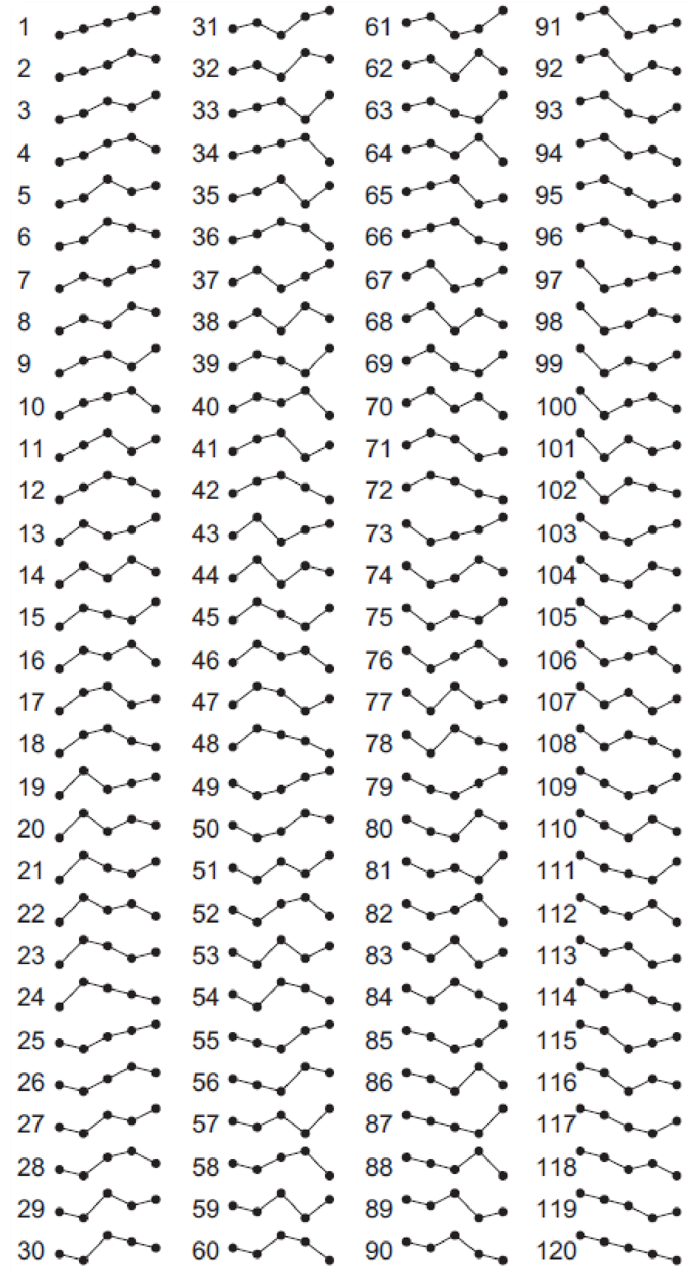
Possible number of patterns increases as D! (D=size of pattern)

$\{\ldots x_i, x_{i+1}, x_{i+2}, x_{i+3} \ldots\}$

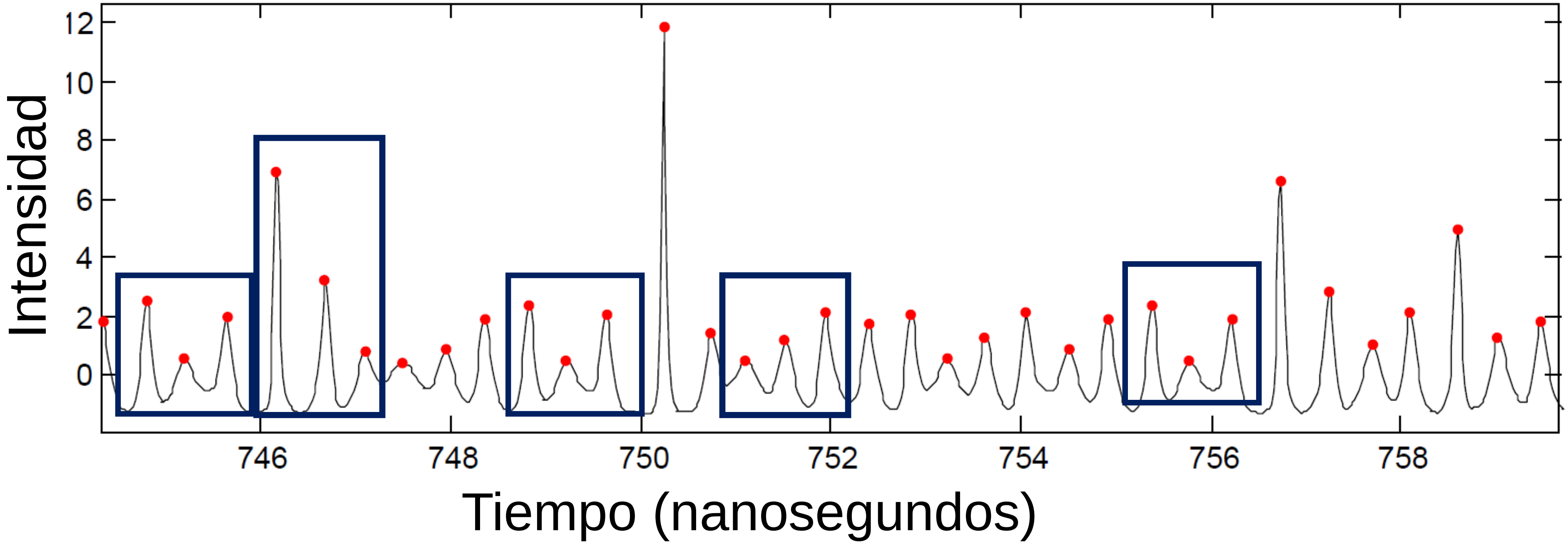


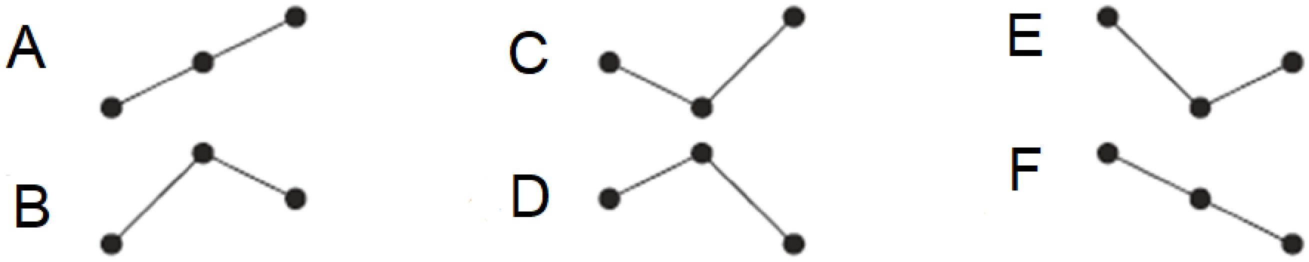
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

$\{\ldots x_i, x_{i+1}, x_{i+2}, x_{i+3}, x_{i+4} \ldots\}$

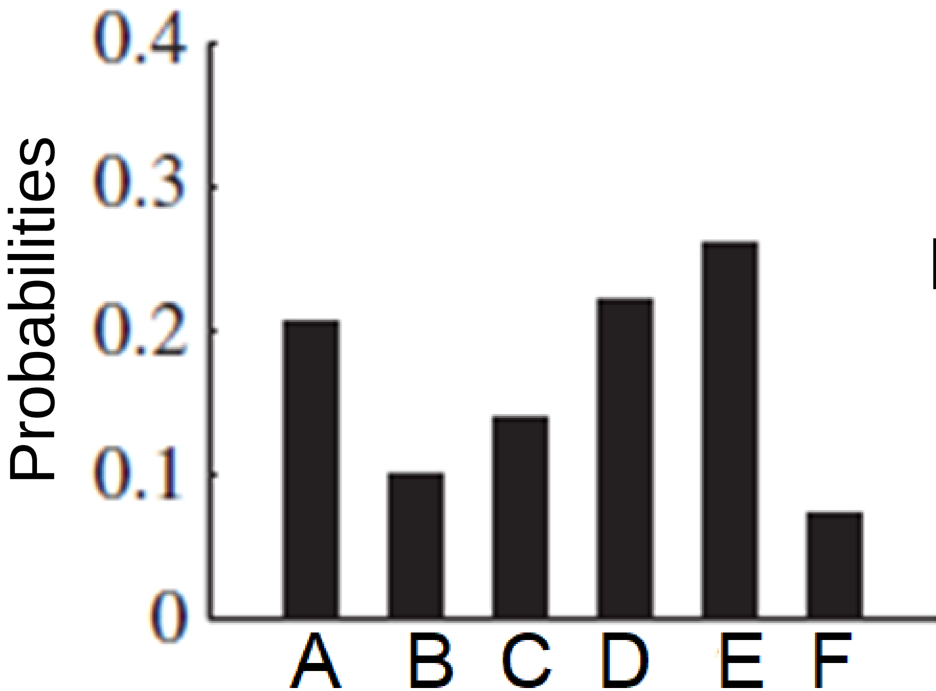


Which pattern occurs before high pulses?





For each time series we compute the probabilities of the different patterns



?

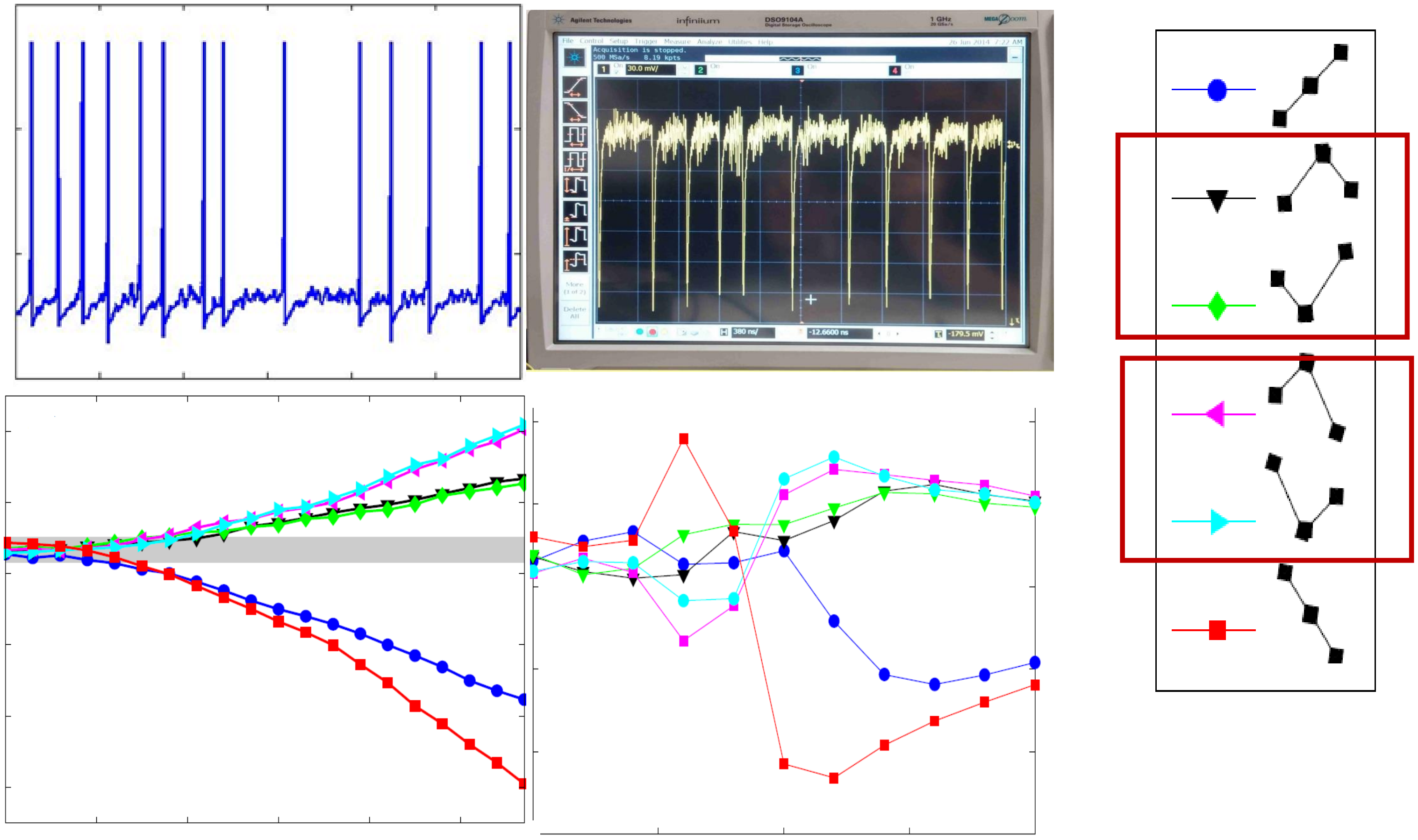
A. Analyze probabilities.

B. Compute information theory measures (entropy, complexity).

A. By analyzing the ordinal probabilities (from inter-spike intervals, ISIs) we uncover laser-neuron similarities

Neuron model **Diode laser with feedback**

Ordinal probabilities

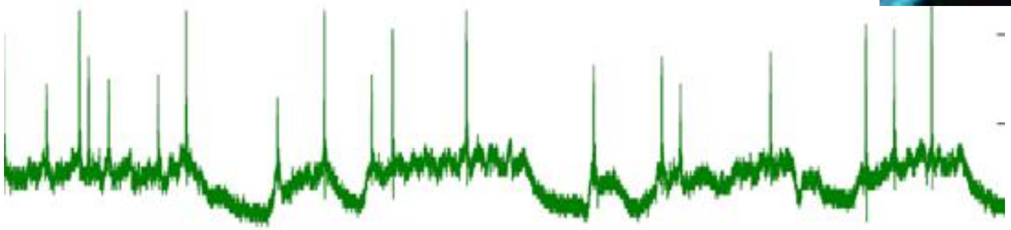


Forcing amplitude Forcing amplitude

J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016) A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)

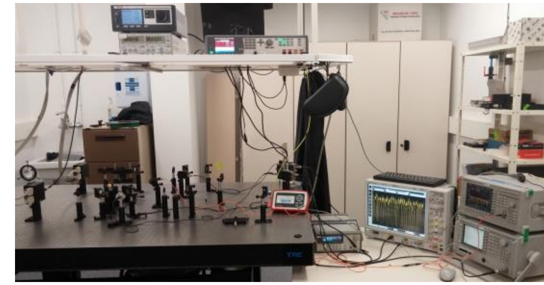
Interesting but useful? Maybe…

- Photonic neurons.
- Diode lasers: very low cost, highly energy efficient.
- Very very fast.
- Main challenge: understand how neurons receive, encode and process information.



How a diode laser and a neuron encode a weak periodic signal?

spike rate code?

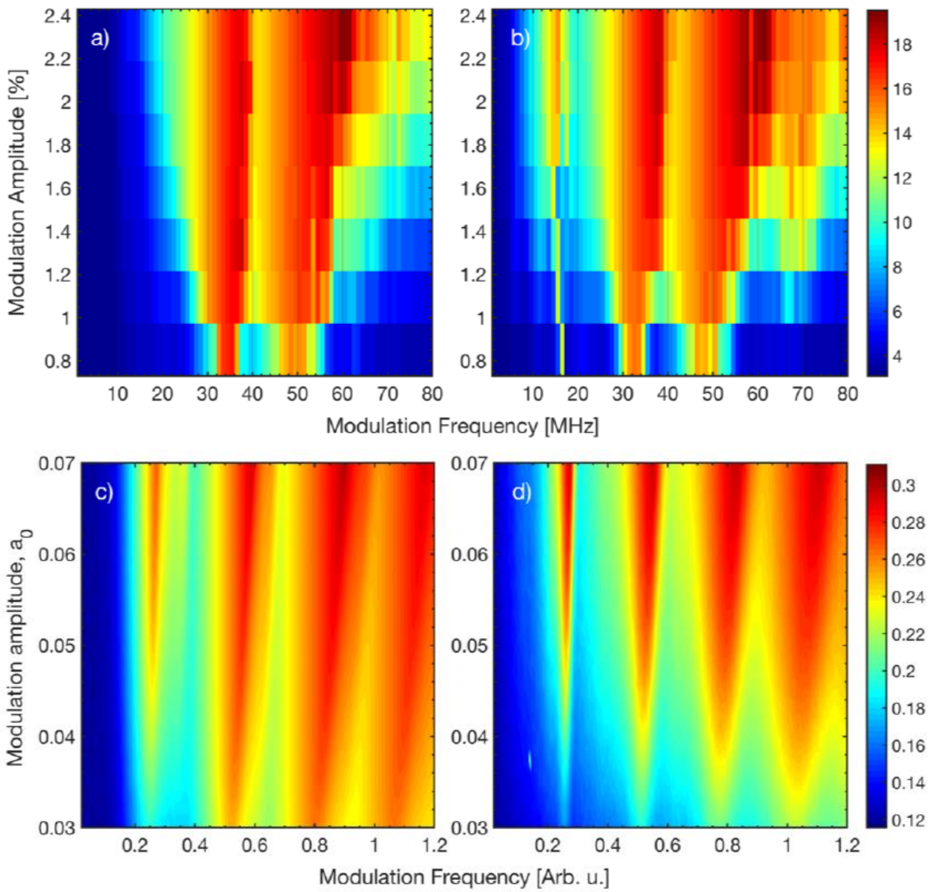


Sinusoidal

Pulsed signal

Diode laser with optical feedback (experiments modulating the laser current)

FitzHugh-Nagumo neuron model (with the same input signal)



Spike rate in color code

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, “*Comparing the dynamics of periodically forced lasers and neurons*”, submitted (2019).

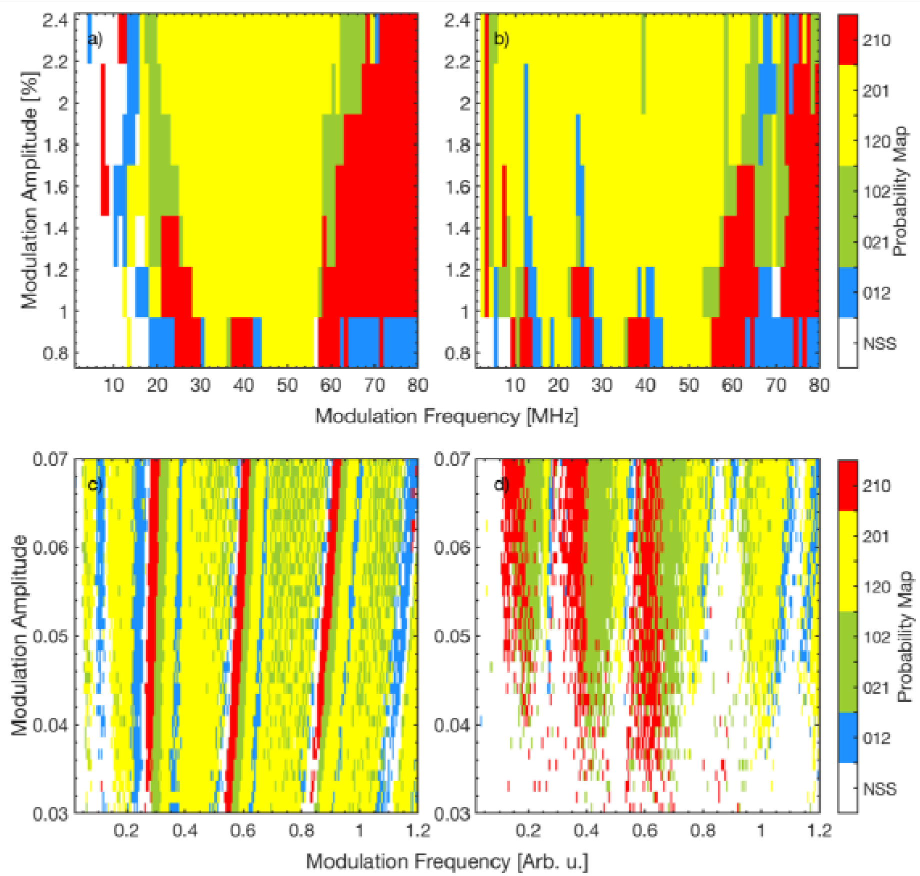
Temporal code?

Ordinal analysis unveils some differences in spike timing.

Sinusoidal   Pulsed signal

Diode laser with optical feedback

FitzHugh-Nagumo model



Most probable pattern in color code

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, "*Comparing the dynamics of periodically forced lasers and neurons*", submitted (2019).

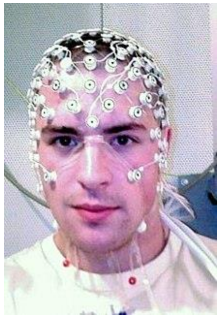
B. By computing information theory measures (entropy, complexity) we can characterize dynamical transitions

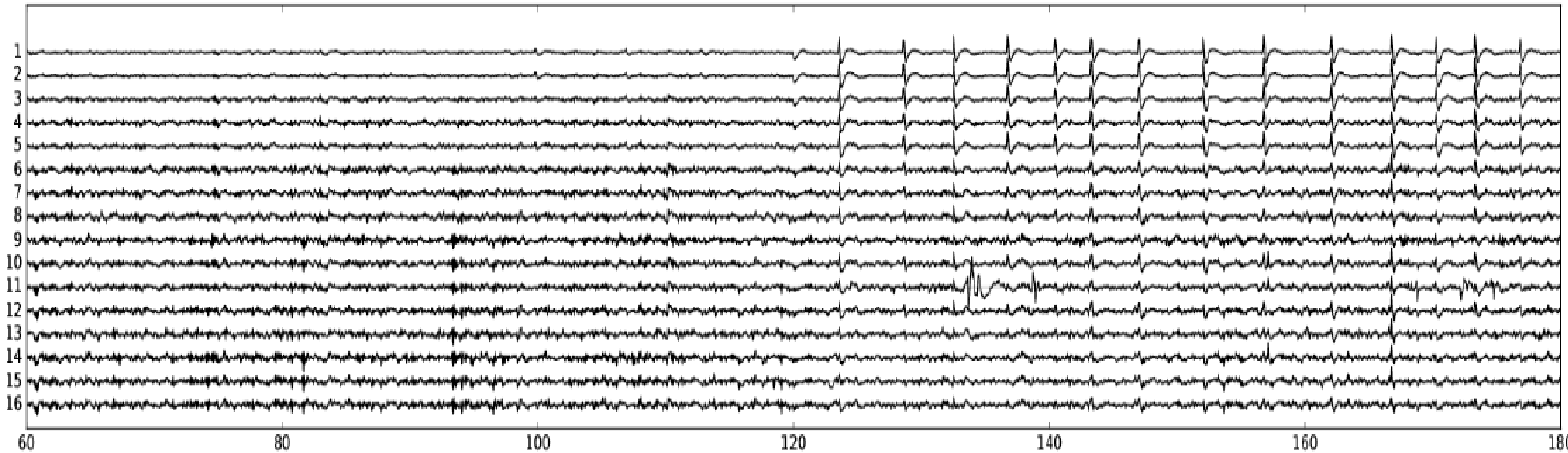
- The time-series is described by a set of probabilities $\sum_{i=1}^{N} p_i = 1$
- **Shannon** entropy: $H = -\sum_i p_i \log_2 p_i$
- Interpretation: "*quantity of* ***surprise*** *one should feel upon reading the result of a measurement*"

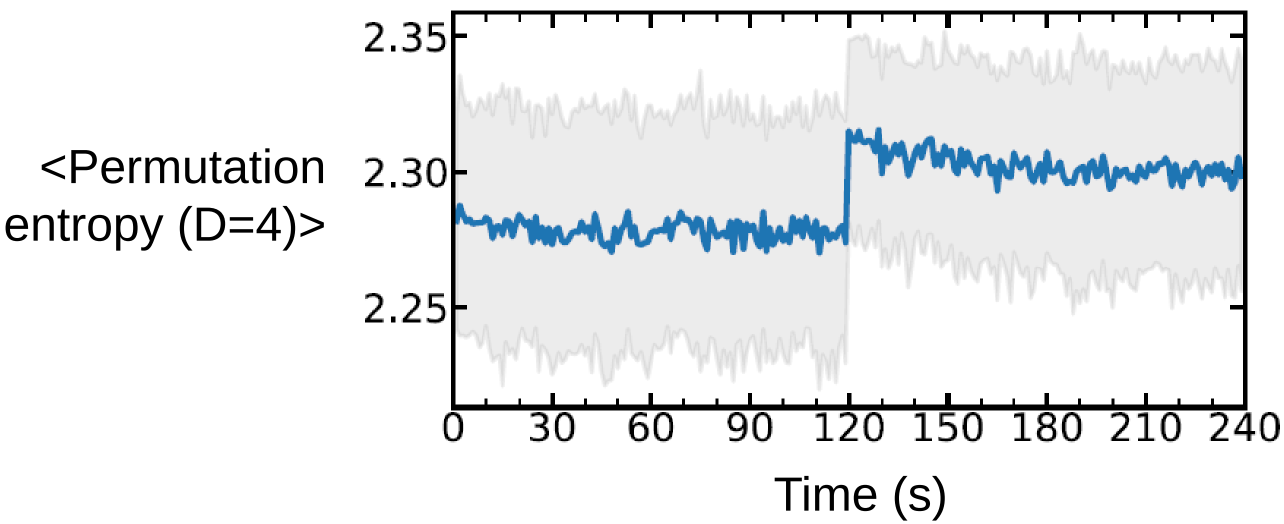
  K. Hlavackova-Schindler et al, Physics Reports 441 (2007)

- The entropy computed from the ordinal probabilities is known as **permutation entropy**.

Eyes closed Eyes open

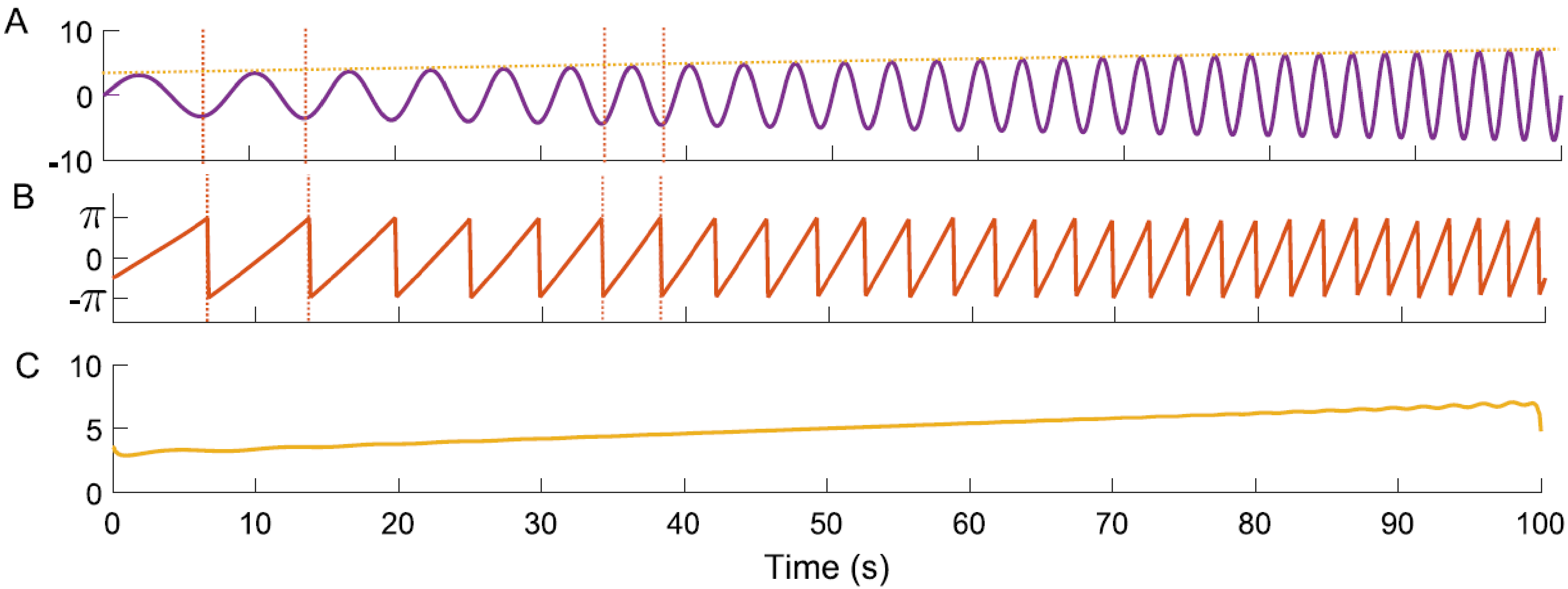






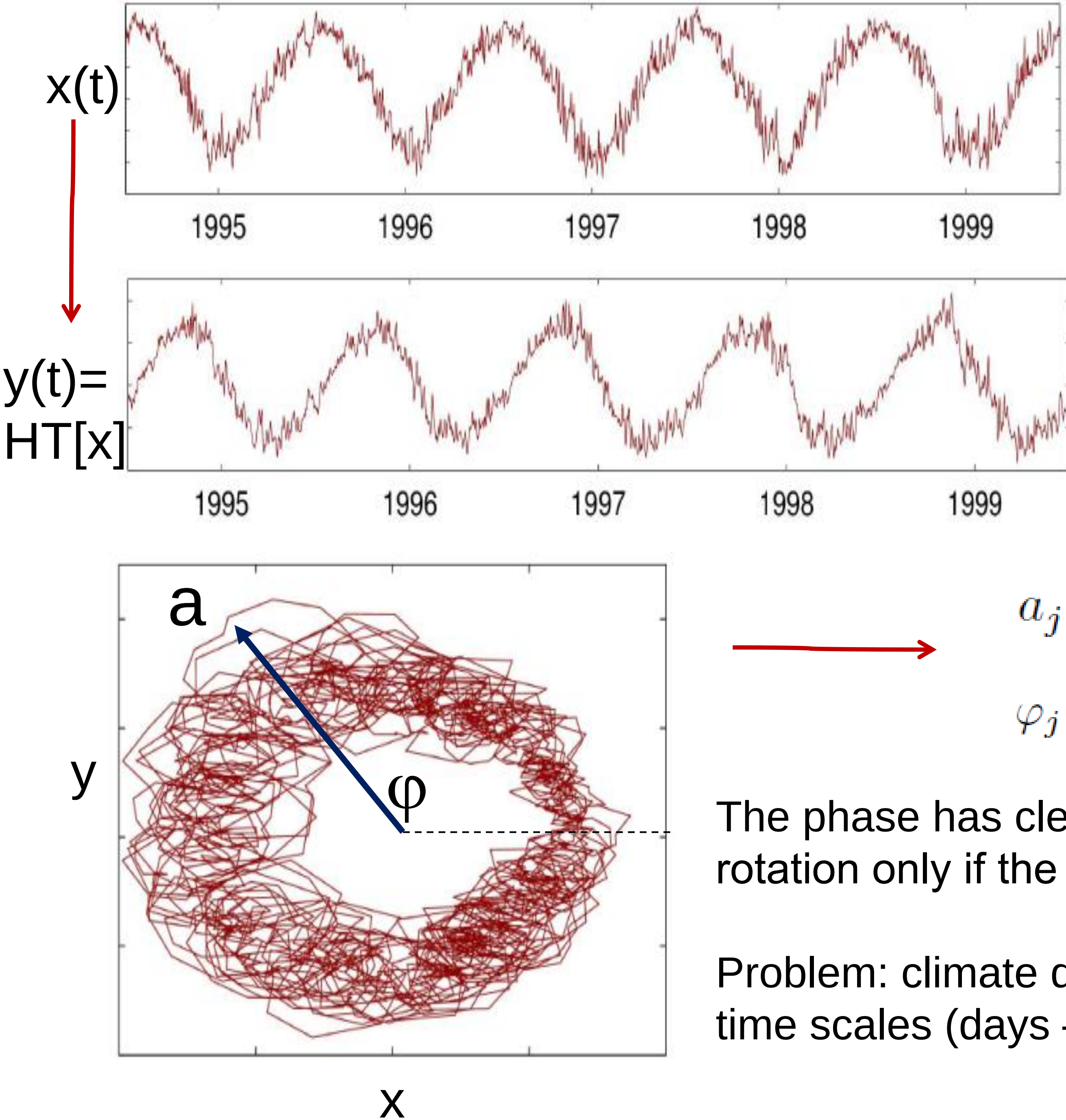
C. Quintero-Quiroz et al, “*Differentiating resting brain states using ordinal symbolic analysis*”, Chaos 28, 106307 (2018).

Second analysis method: The Hilbert transform



- (A) The original signal. (B) The instantaneous phase extracted using the Hilbert transform. (C) The instantaneous amplitude.
- A = C cos(B).
- How to calculate the instantaneous amplitude and phase?

G. Lancaster et al, Physics Reports 748 (2018) 1–60



Surface air temperature

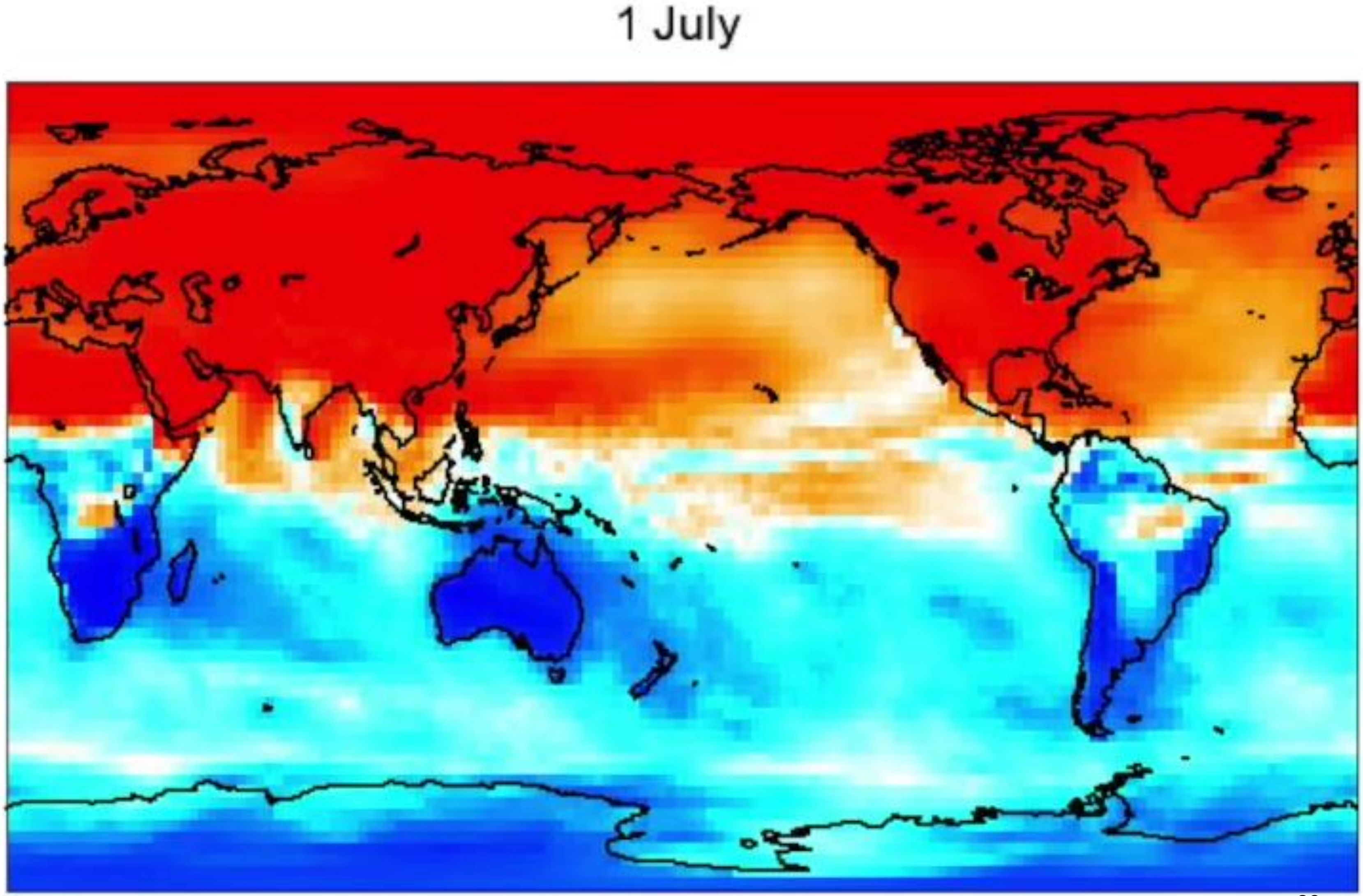
$$a_j(t) = \sqrt{x_j^2(t) + y_j^2(t)}$$

$$\varphi_j(t) = \arctan[y_j(t)/x_j(t)]$$

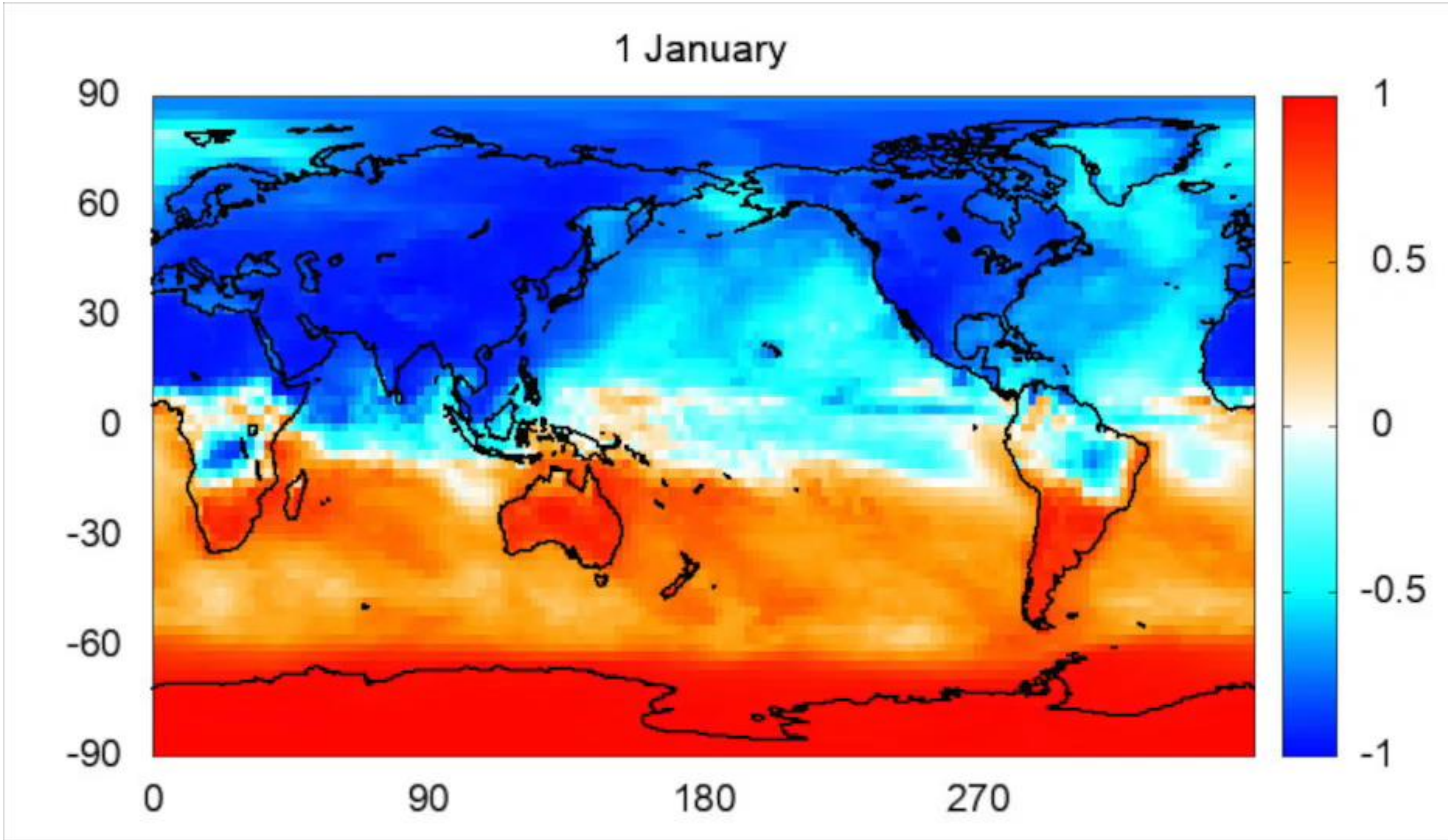
The phase has clear physical meaning of rotation only if the signal is “narrow band”.

Problem: climate dynamics involves many time scales (days – decades).

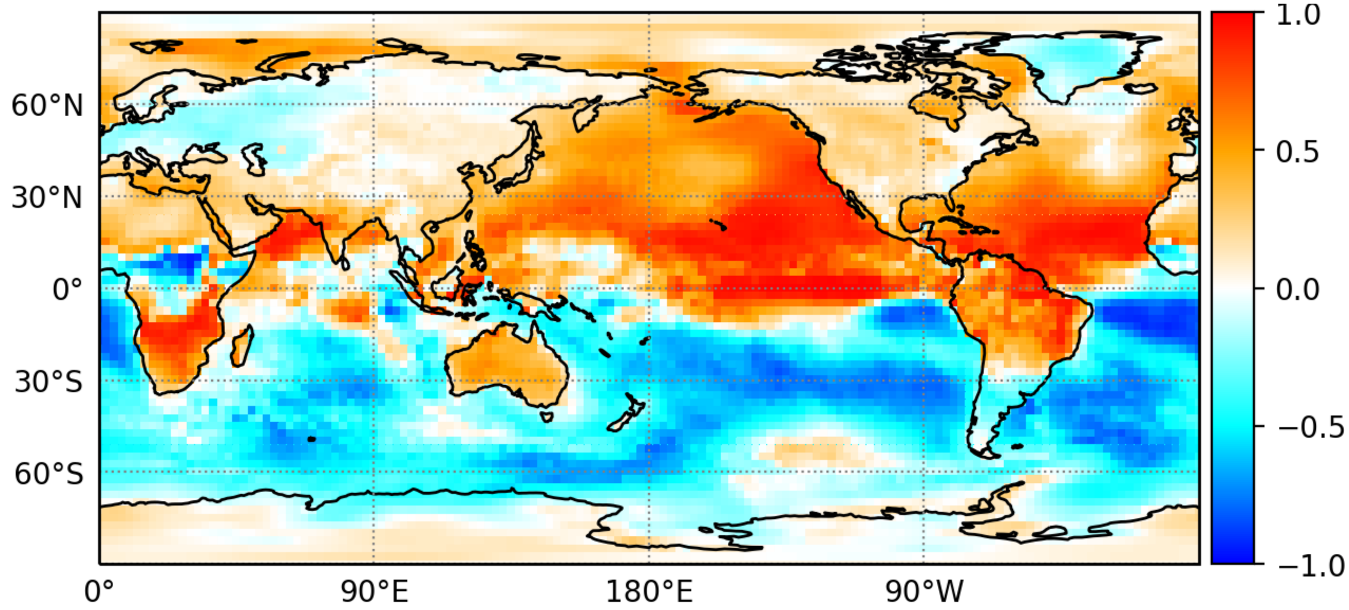
Cosine of the Hilbert phase in color code.
Where the data comes from? Daily reanalysis, 1979 to 2017



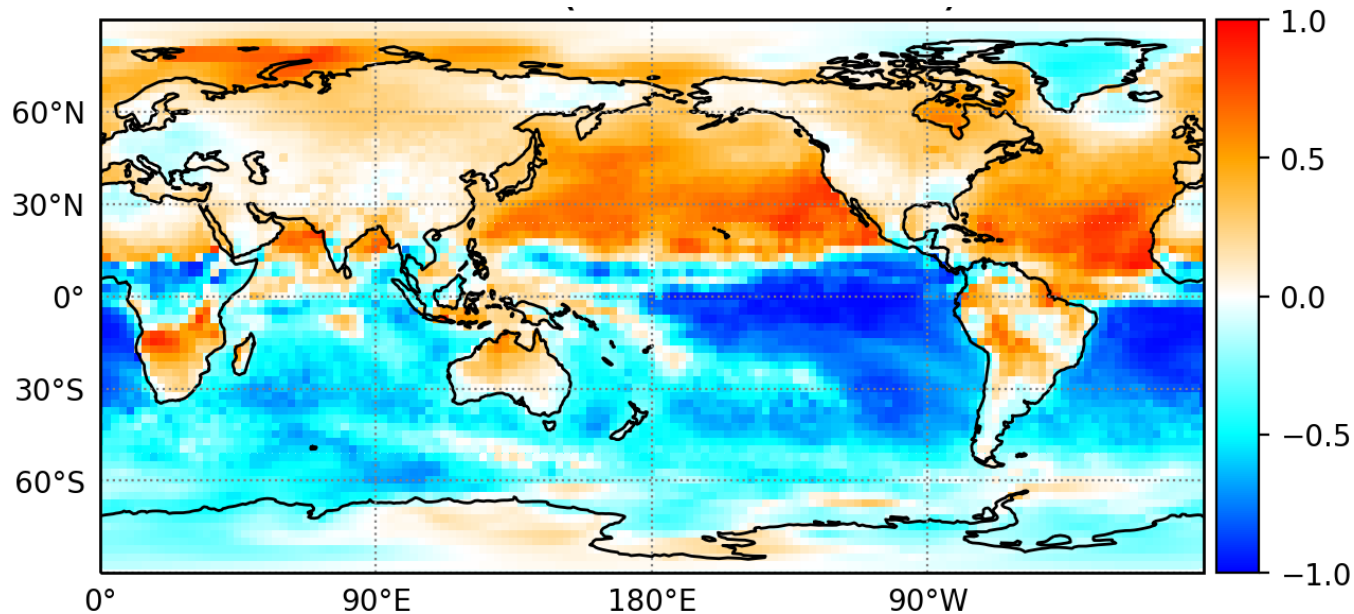
Hilbert visualization of the seasons: temporal evolution of the cosine of the phase



El Niño period
(October 2015)



La Niña period
(Octubre 2011)



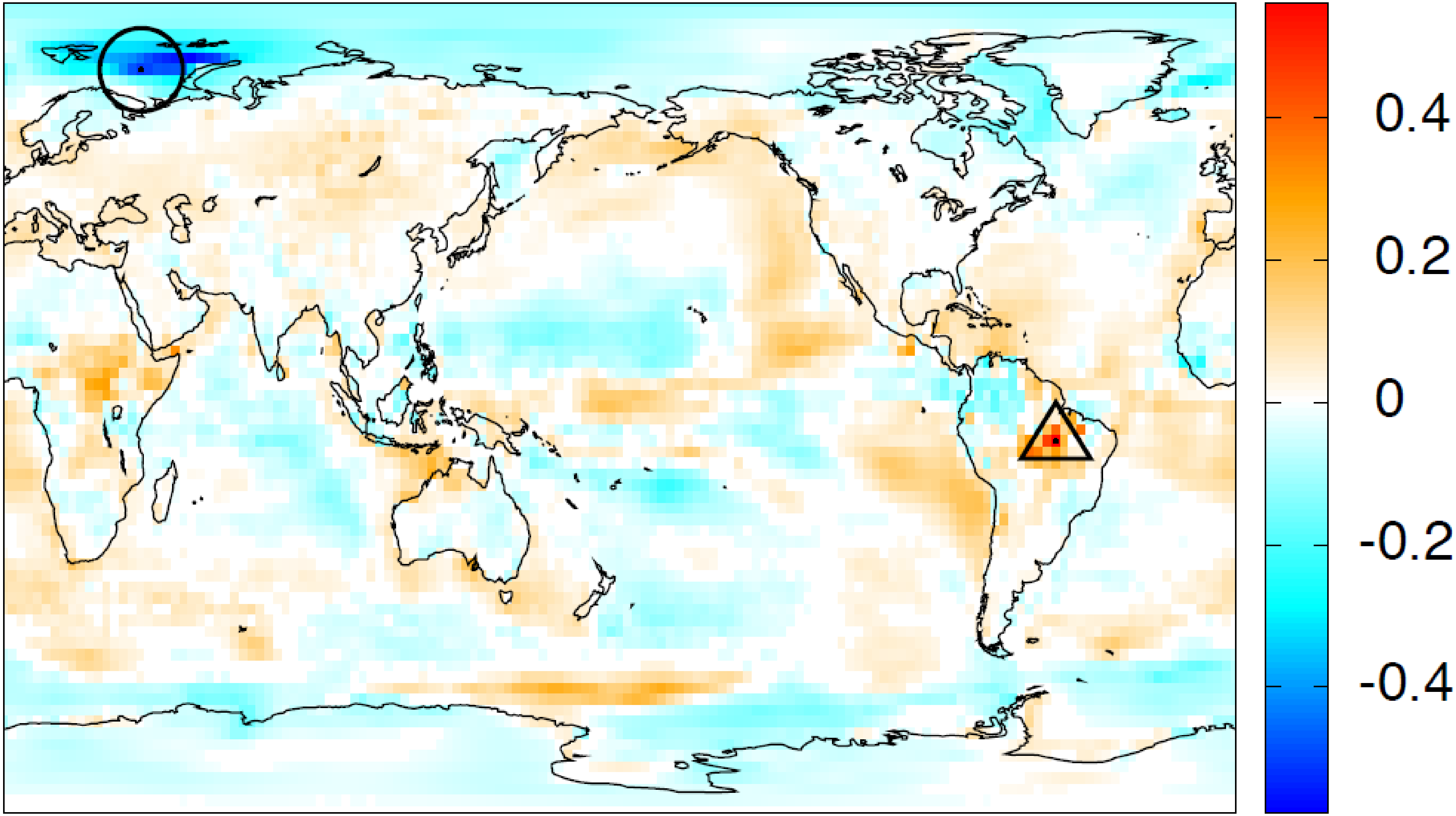
How to detect significant changes in the last 30 years?

$$\Delta a = \langle a \rangle_{2016-2007} - \langle a \rangle_{1988-1979}$$

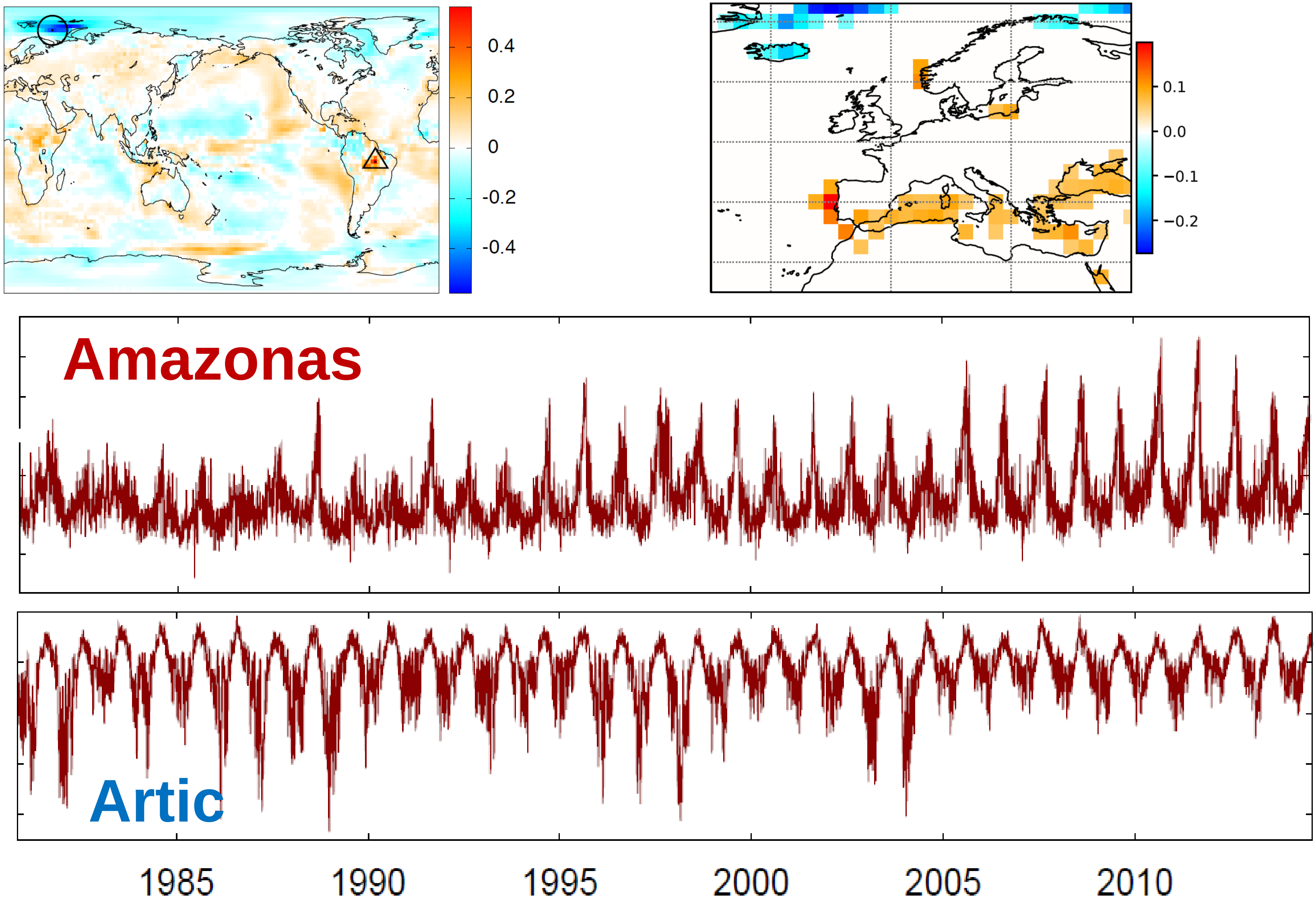
$$\frac{\Delta a}{\langle a \rangle_{2016-1979}}$$

Significant if $\frac{\Delta a}{\langle a \rangle} \geq \langle . \rangle_s + 2\sigma_s$ o $\frac{\Delta a}{\langle a \rangle} \leq \langle . \rangle_s - 2\sigma_s$

Average over 100 “surrogates”



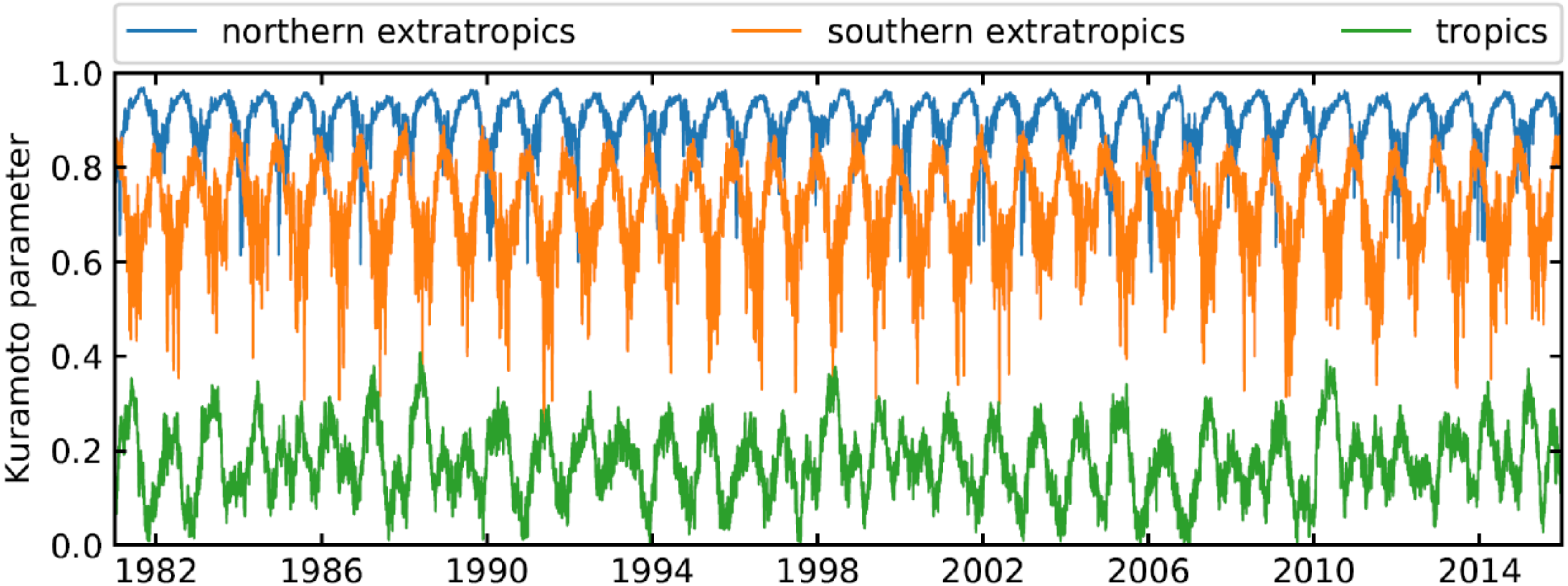
D. A. Zappala, M. Barreiro, and C. Masoller, "*Quantifying changes in spatial patterns of surface air temperature dynamics over several decades*", Earth Syst. Dynam. **9**, 383–391 (2018).



D. A. Zappala, M. Barreiro, and C. Masoller, “*Quantifying changes in spatial patterns of surface air temperature dynamics over several decades*”, Earth Syst. Dynam. **9**, 383–391 (2018).

Quantification of phase synchronization

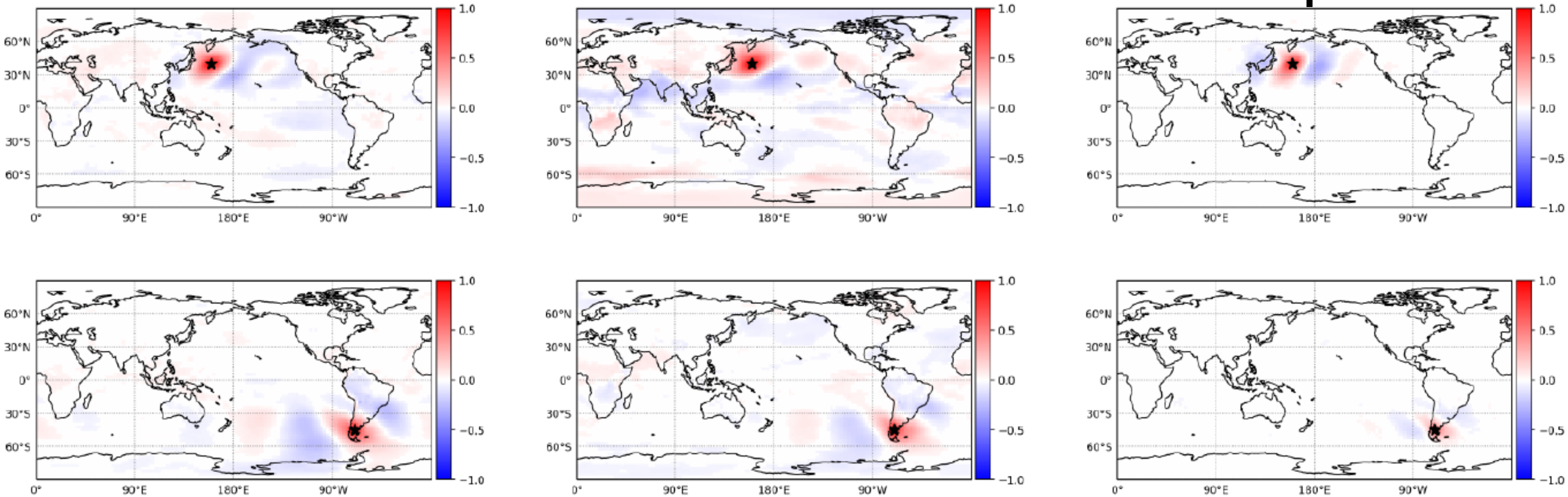
area-weighted Kuramoto parameter: $r(t) = \left| \frac{\sum_{j \in S} w_j \exp[i\varphi_j(t)]}{\sum_{j \in S} w_j} \right|$



D. A. Zappala, M. Barreiro and C. Masoller, "*Quantifying phase synchronization and unveiling Rossby wave patterns in surface air temperature dynamics*", in preparation.

Identification of Rossby waves

Anomalies **Inst. amplitudes** **Inst. frequencies**



Cross-correlation in color code.

D. A. Zappala, M. Barreiro and C. Masoller, "*Quantifying phase synchronization and unveiling Rossby wave patterns in surface air temperature dynamics*", in preparation.

Take home message

- Time series analysis allows to understand, predict, or classify dynamical behaviors of complex systems.
- Even when the data does not meet the mathematical or algorithmic requirements, the results can give useful insights.
- Many interdisciplinary applications.

Thanks to:
Jordi Tiana (UPC)
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Marcelo Barreiro (Uruguay)

Thank you for your attention!

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