Hilbert analysis of climatological data uncovers signatures of Rossby waves and large-scale patterns of phase synchronization

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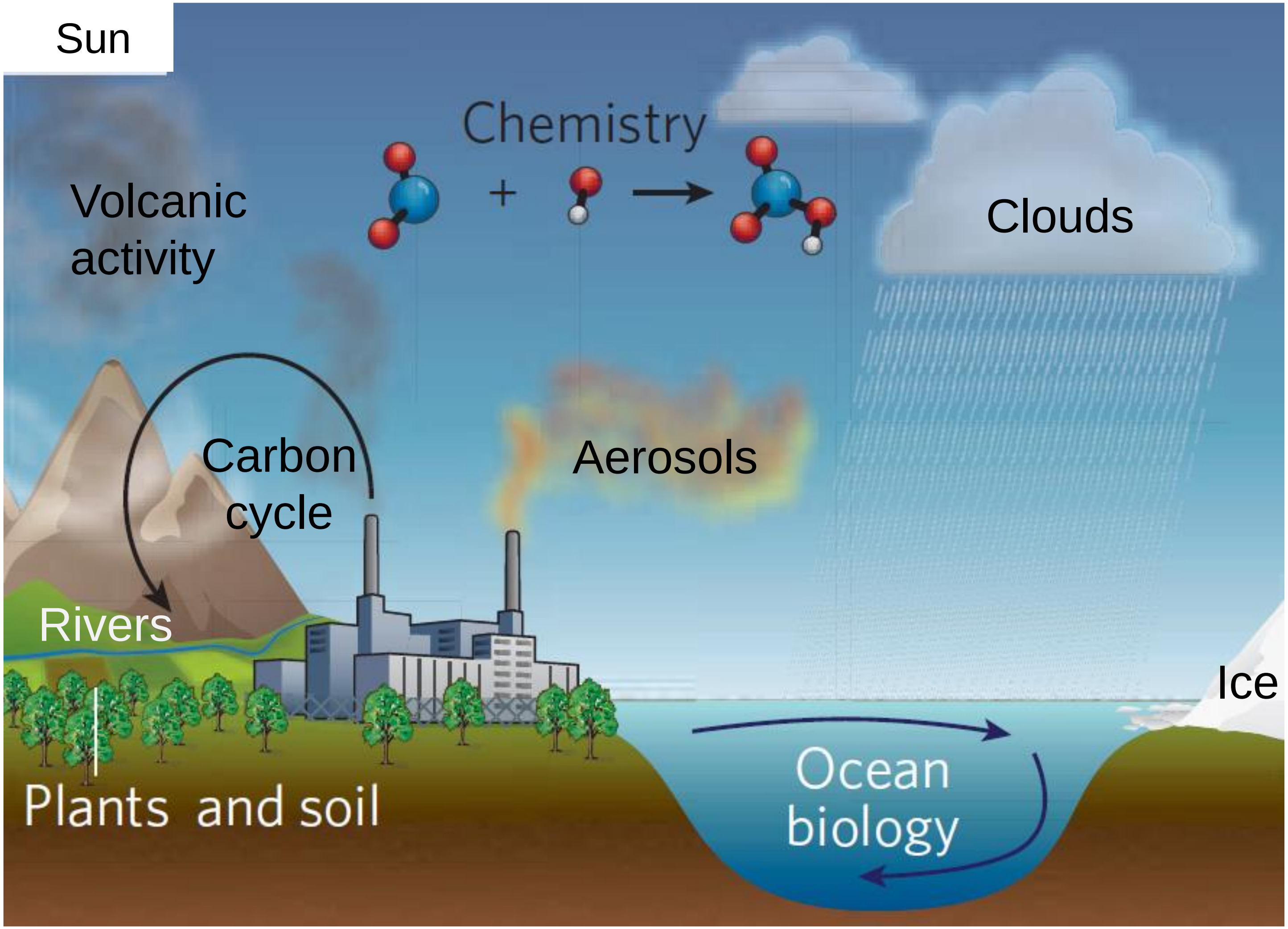
ICREA

The climate system: a very complex system!

- nonlinear subsystems
- nonlinear interactions
- different time-scales
  - hours to days,
  - months to seasons,
  - decades to centuries, etc.



Are weather extremes becoming more frequent? More extreme? Can they be predicted? Anticipation?

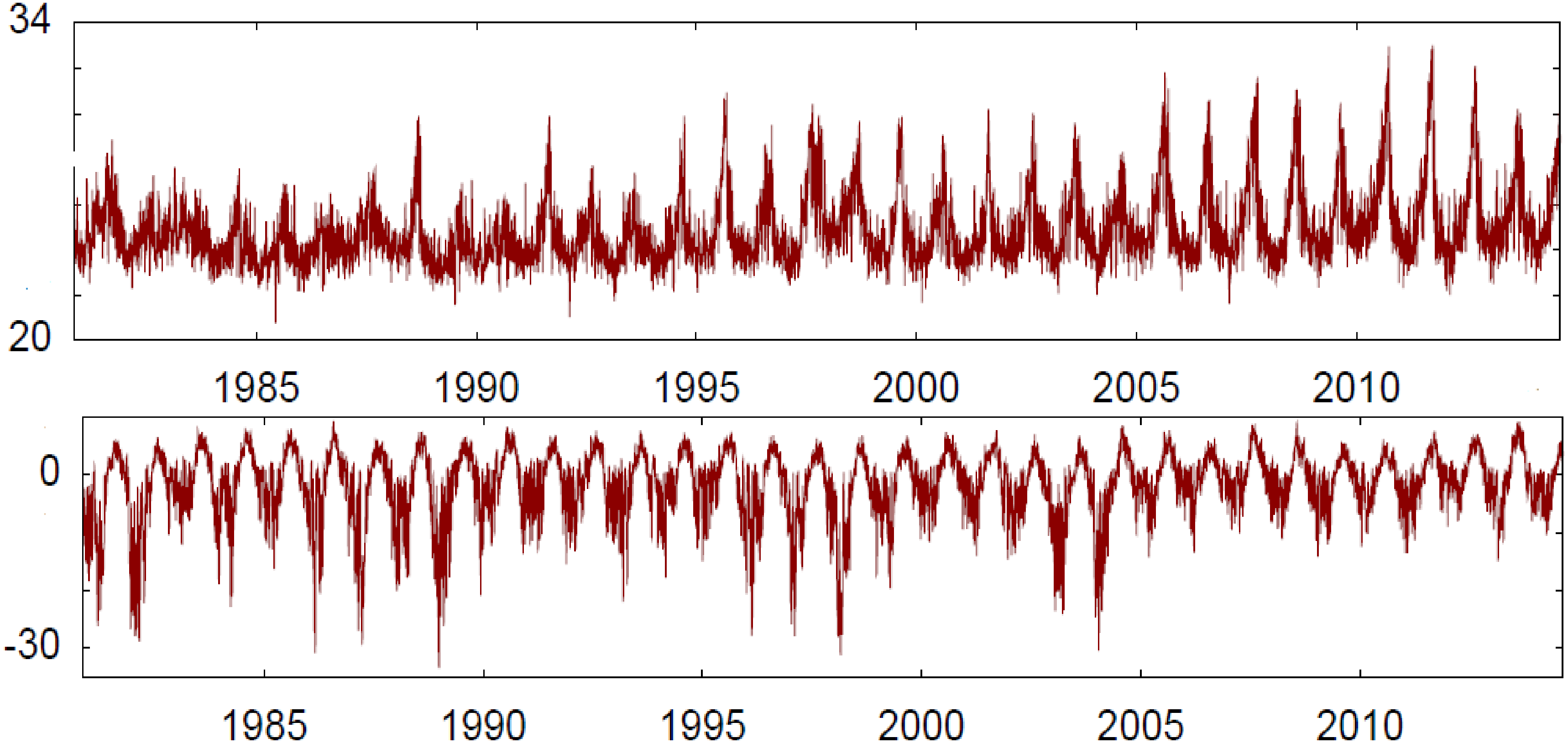
Physics Today, Sep. 2017

ECMWF

Bangladesh, Nature 2014

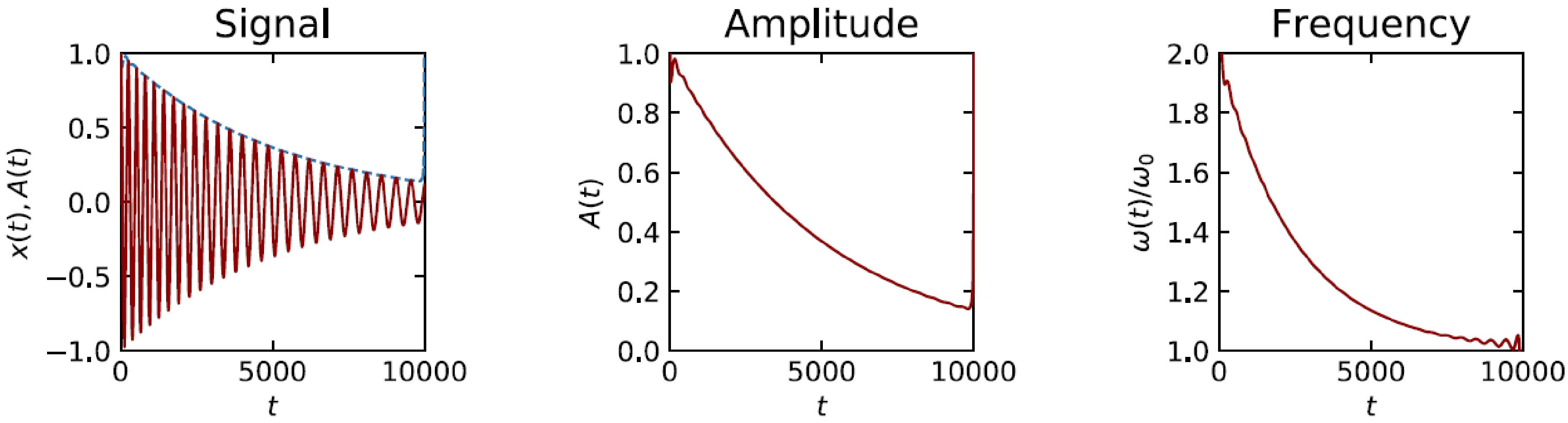
Strong need of reliable data analysis tools

Time series of surface air temperature in two regions

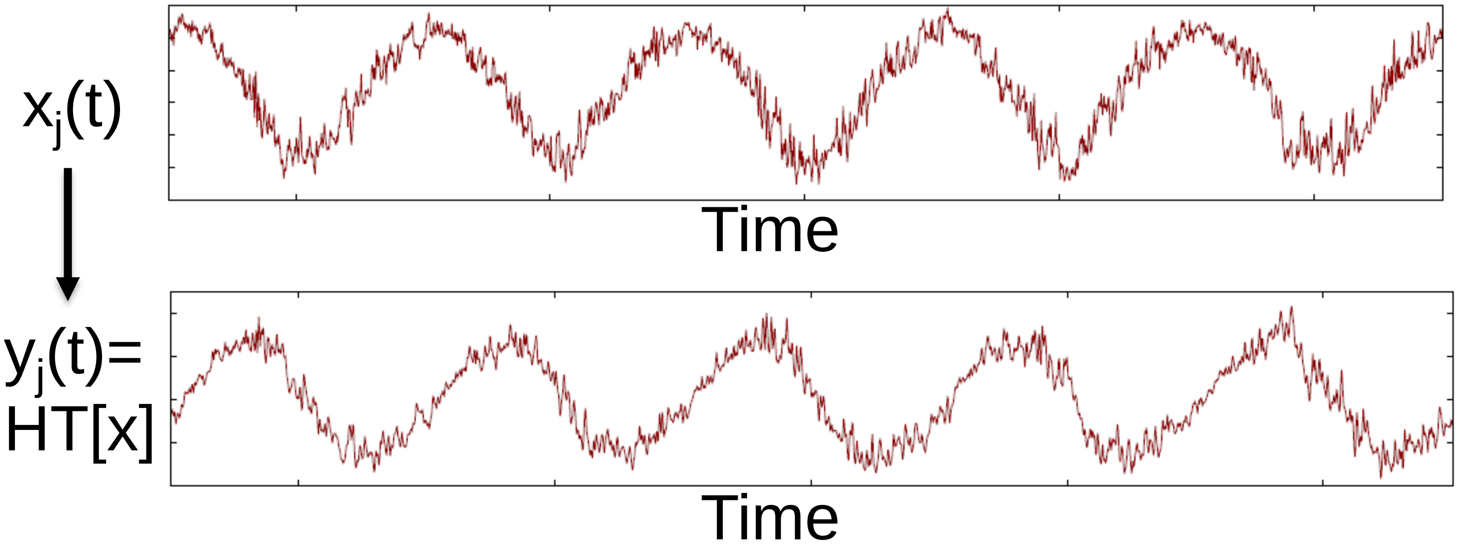


Can gradual changes be quantified? With what reliability?

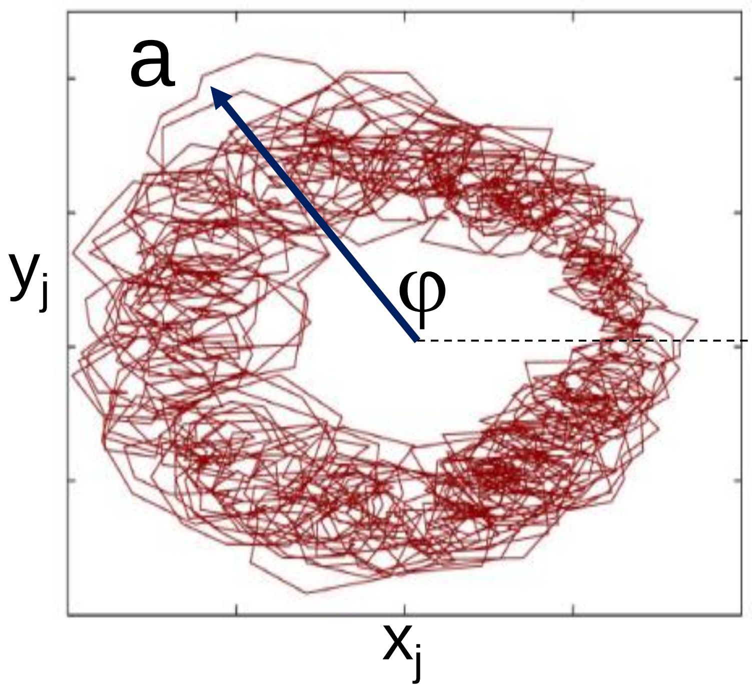
How to obtain amplitude and phase information from a real oscillatory signal?



The Hilbert Transform applied to Surface Air Temperature



HT[cos φ]=sin φ



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

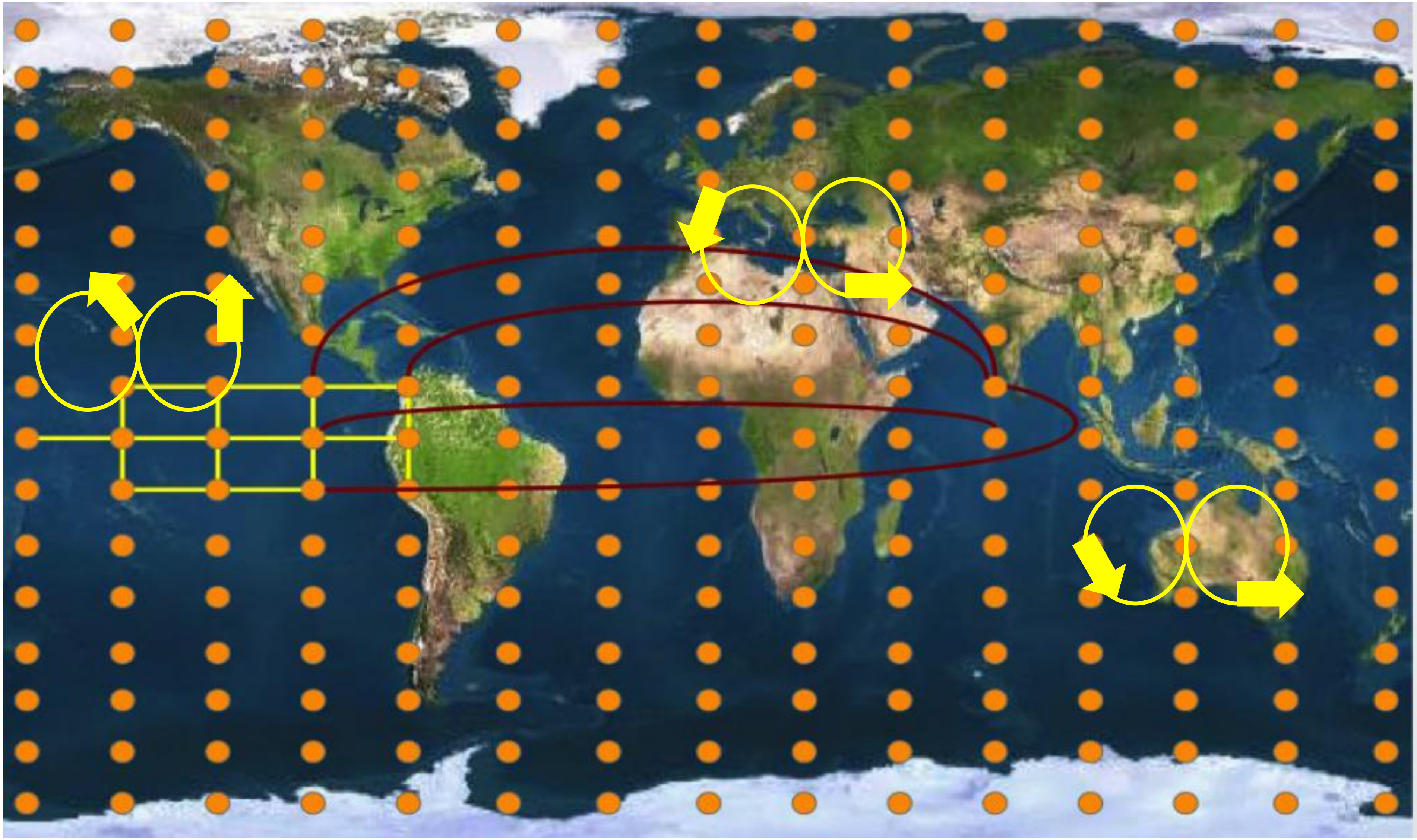
$$\varphi_j(t) = \arctan[y_j(t)/x_j(t)]$$

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

However, here the Hilbert transform is applied to the raw data (no pre-filtering).

The data: global dataset of Surface Air Temperature

- Spatial resolution $2.5^0 \times 2.5^0 \Rightarrow$ 10226 time series
- Daily resolution 1979 – 2016 $\Rightarrow$ 13700 data points

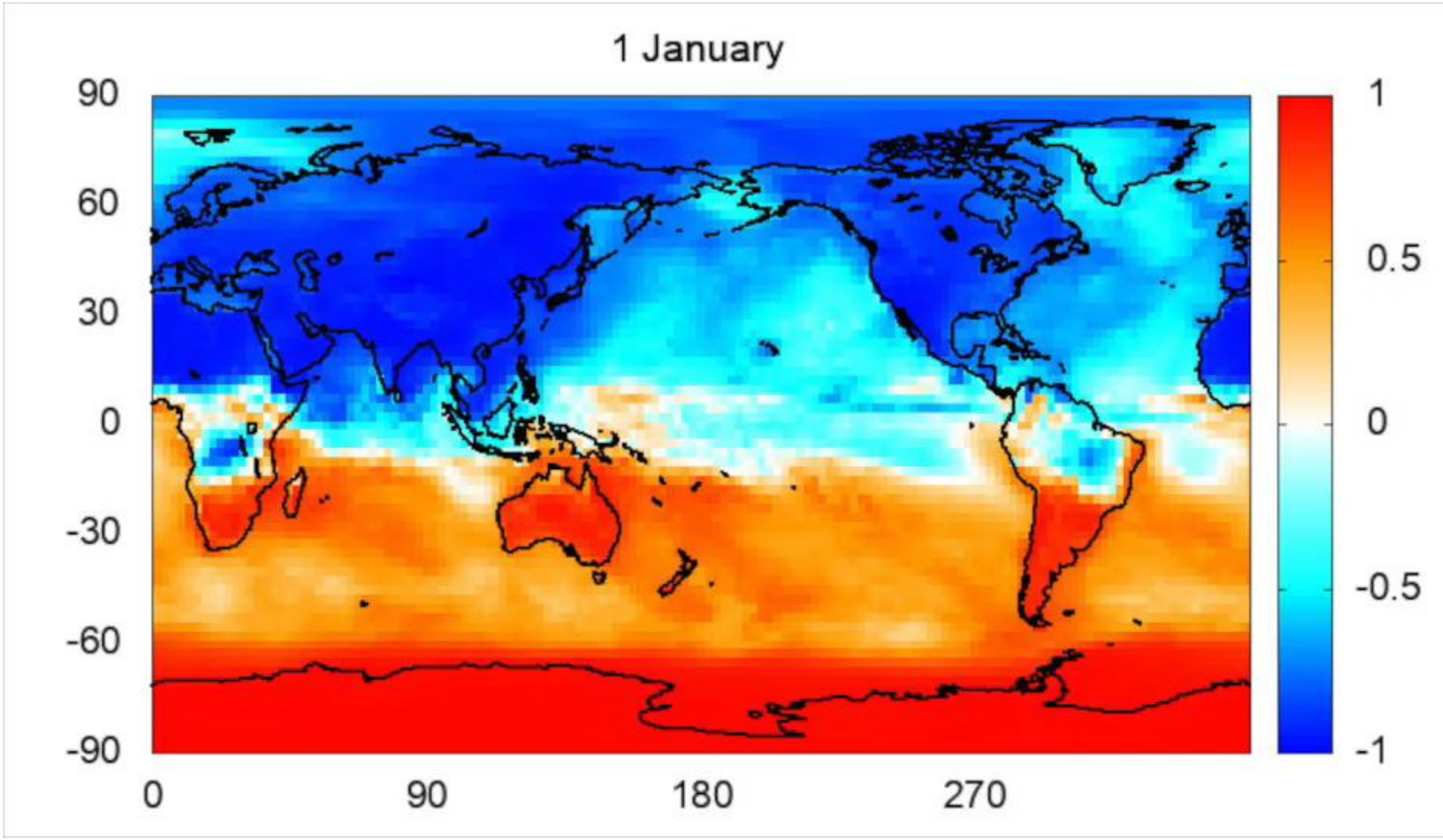


Where does the data come from?

- European Centre for Medium-Range Weather Forecasts (ECMWF, ERA-Interim).
- Freely available.
- Reanalysis = run a sophisticated model of general atmospheric circulation and feed it with the available experimental data, in the different points of the Earth, at their corresponding times.
- This process restricts the solution of the model to one as close to reality as possible in regions where there are data available, and to a solution physically “plausible” in regions where no data is available.

Univariate analysis:
extract information from each time series

Visualization of the seasonal cycle: average annual evolution of the cosine of the Hilbert phase



Changes in Hilbert amplitude detect inter-decadal variations in surface air temperature (SAT)

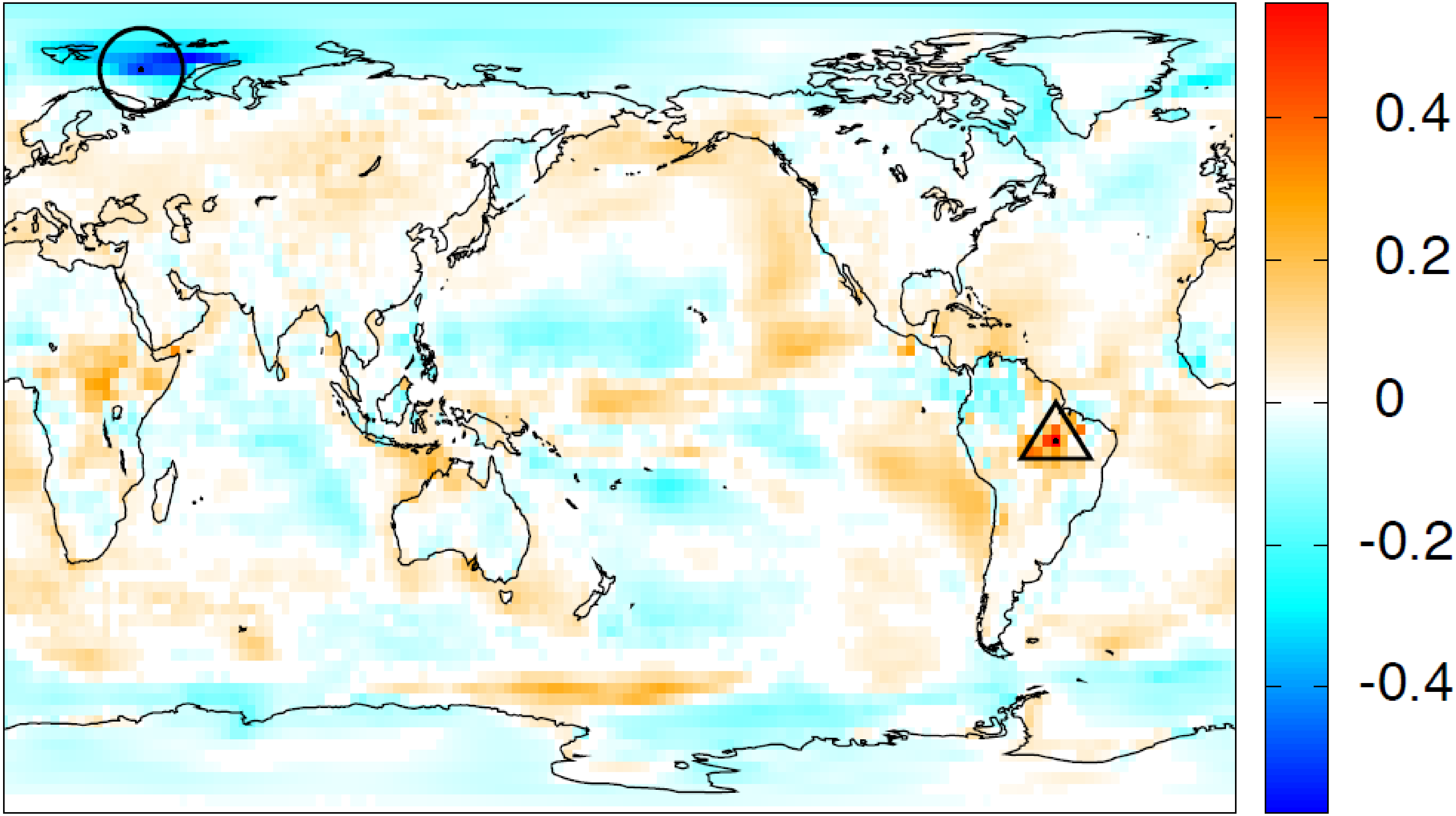
$$\Delta a = \langle a \rangle_{2016-2007} - \langle a \rangle_{1988-1979}$$

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

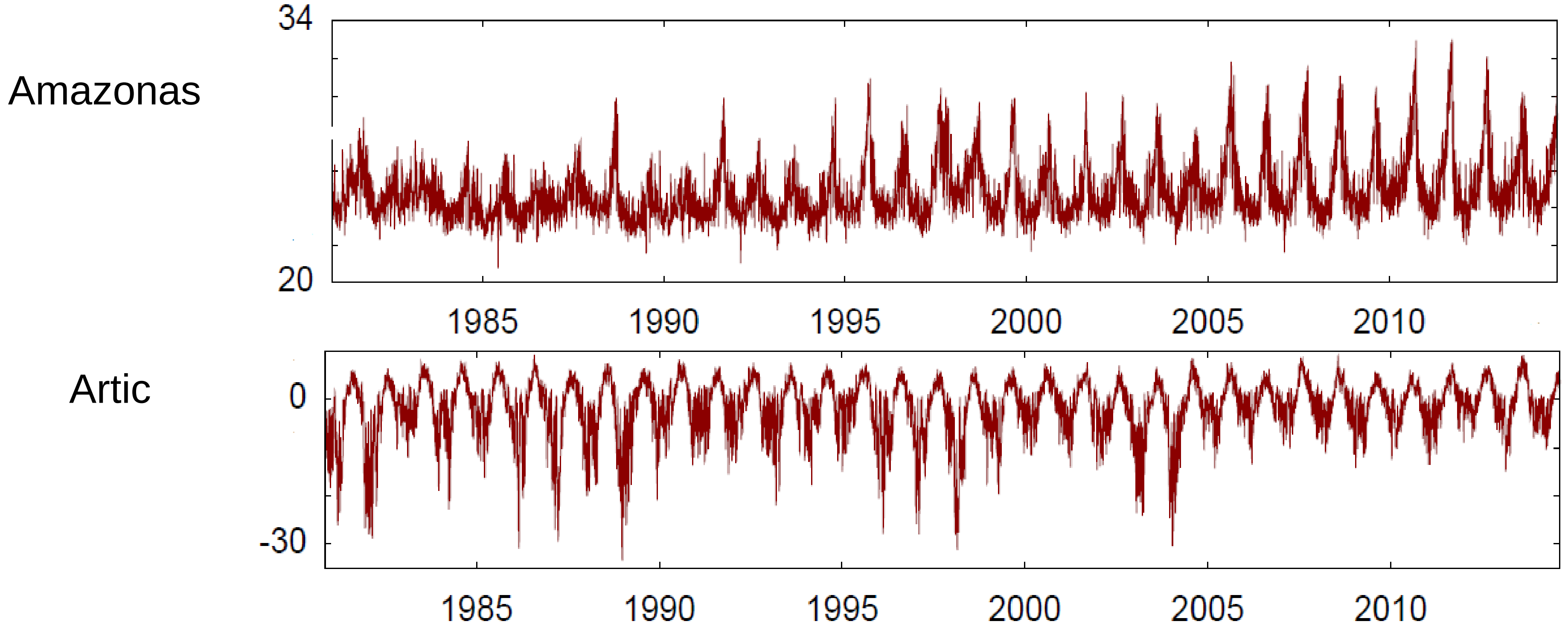
Relative variation is considered significant if:

$$\frac{\Delta a}{\langle a \rangle} \geq \langle . \rangle_s + 2\sigma_s \quad \text{or} \quad \frac{\Delta a}{\langle a \rangle} \leq \langle . \rangle_s - 2\sigma_s$$

100 “block” 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 (2018)



- **Amazonas: decrease of precipitation** (the solar radiation that is not used for evaporation is used to heat the ground).
- **Artic: melting of sea ice** (during winter the air temperature is mitigated by the sea and tends to be more moderated).

D. A. Zappala et al., Earth Syst. Dynam. **9**, 383 (2018)


15:49 lavanguardia.com 43 %

Terrassa - Vallès

DE LA UPC

Un investigador descubre "otra perspectiva" para estudiar el cambio climático

- El experto ha examinado la frecuencia y la amplitud de las oscilaciones de temperaturas reflejados en los vaivenes del termómetro

El Ártico es una de las zonas del planeta más


el Periódico

BARCELONA > TERRASSA

Un investigador de la UPC de Terrassa detecta nous patrons en el canvi climàtic

L'oscil·lació tèrmica és menor a l'Àrtic, amb menys pics de temperatures fredes, i major a l'Amazònia, amb pics d'altes temperatures

0

Efe

Terrassa - Diumenge, 10/06/2018 | Actualitzada 11/06/2018 - 11:45


15:52 antena3.com 40 %

Noticias Tiempo previsión

ATRES player Suscríbete

Universidad Politécnica de Cataluña /

Descubren un nuevo patrón del cambio climático al hallar anomalías en las temperaturas del Ártico y la Amazonía

La amplitud térmica ha caído

CUMBRE DEL CLIMA MADRID: Greta Thunber...

DIRECTO ÚLTIMAS

D. A. Zappala et al., Earth Syst. Dynam. **9**, 383 (2018)

Troben un patró de ca[...] climàtic en temperatu[...] a l'Àrtic i l'Amazònia

▶L'estudi l'investigador de la Universitat Politècnica de Catalu[...]
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Hallan un nuevo patrón de[...] en temperaturas del Árti[...]

AGENCIAS
BARCELONA

■■■ El investigador de la Universidad Politécnica de Cataluña Dario Zappalà descubrió un nuevo patrón del cambio climático al hallar grandes anomalías en las oscilaciones de las temperaturas cerca del Polo Norte y en la Amazonía.

[...]rededor de un 50% y los picos de temperatura muy baja se han reducido muy significativamente durante los últimos 10 años debido a la fundición de los hielos polares.

En cuanto a la zona de la Amazonía ha comprobado que la amplitud de la oscilación de temperatura ha aumentado un 50 % debido a la[...]

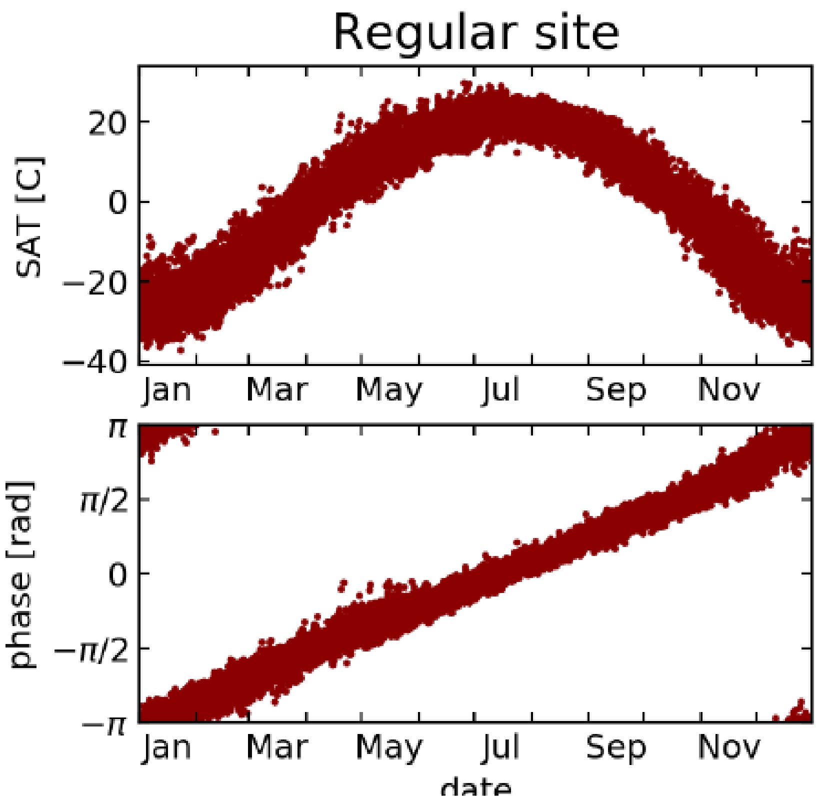
LA INVES[...]
CONFIRM[...]
GRANDES[...]
DETERMI[...]
QUE PODRÍAN AFECTAR AL EQUILIBRIO DEL CLIMA

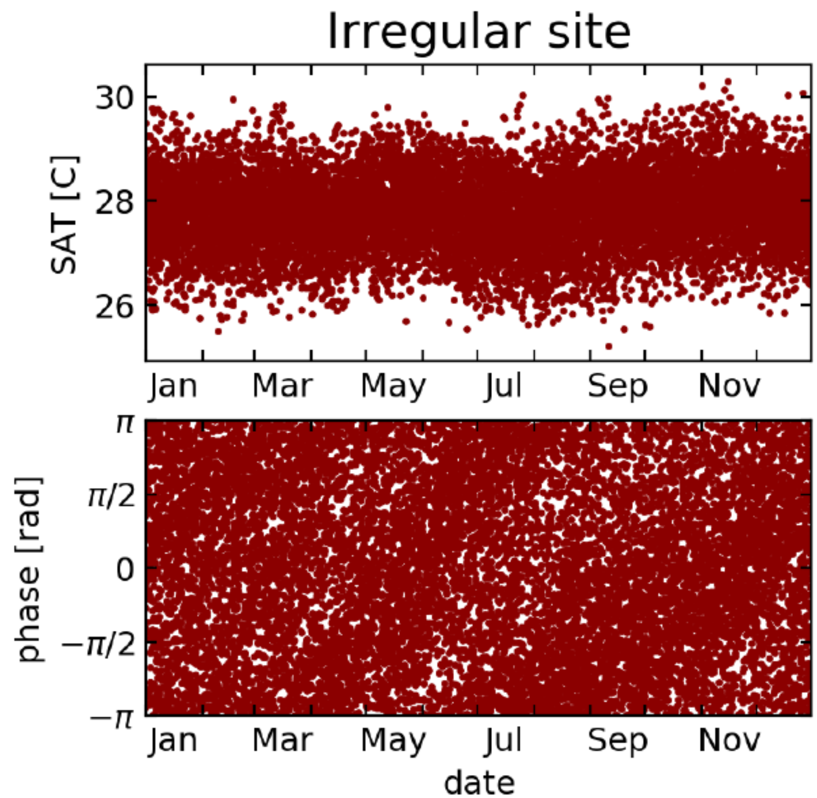
[...]que
[...]m-
[...] de
[...]bio
confirma, más allá del incremento de temperatura ya conocido, grandes cambios en determinadas regiones que podrían afectar[...]

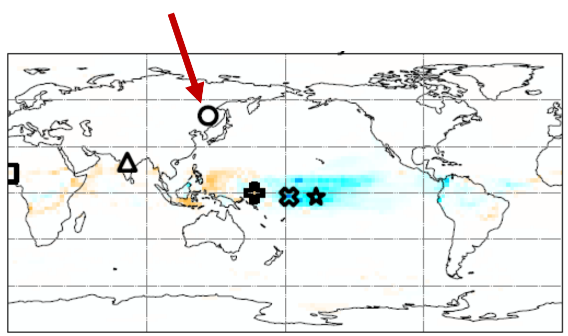
Un investigador de la UPC descriu un nou patró en el canvi climàtic

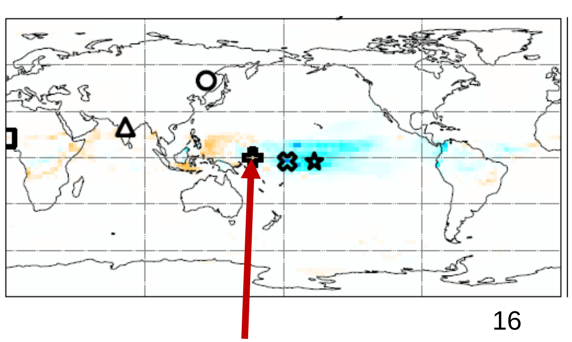
▸▸ **L'investigador de la Universitat Politècnica de Catalunya (UPC) Dario Zappalà ha descobert un nou patró del canvi climàtic al trobar grans anomalies en les oscil·lacions de les temperatures a prop del pol Nord, on l'amplitud tèrmica ha caigut un 50% des del 1979, i a l'Amazònia, on ha augmentat un 50% en una dècada.**

Phase-date relationship

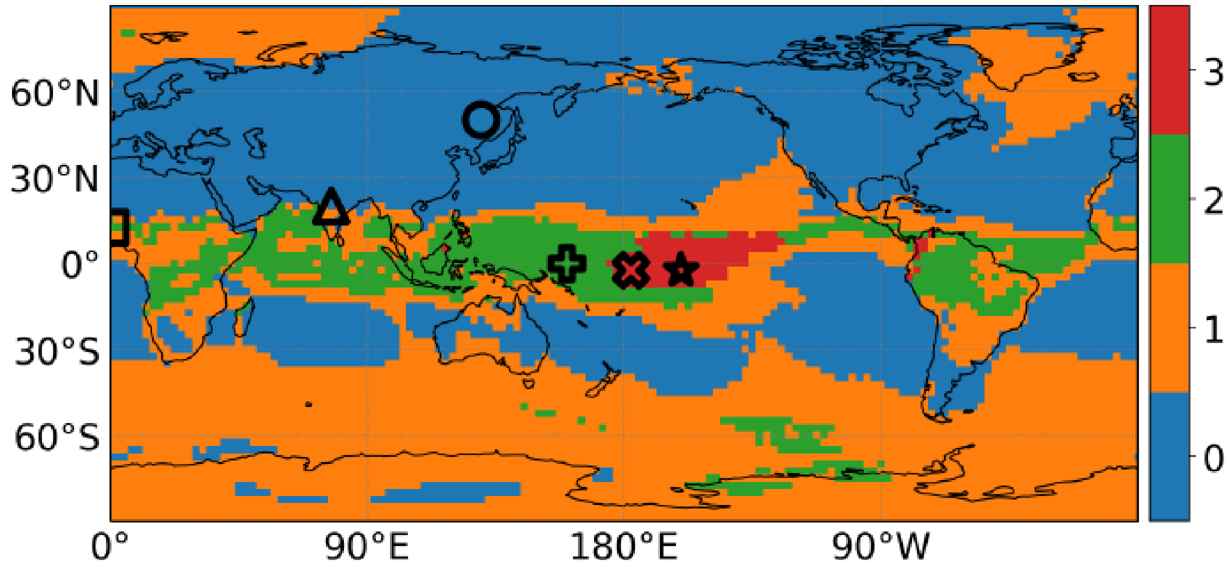








Classification of SAT dynamics using *k-means clustering*



- **Blue cluster**: regions dominated by the seasonal cycle and large temperature variations
- **Orange cluster**: regions with fast dynamics that reveal the annual cycle only after smoothing over segments of more than 20 days, which may reflect the importance of subseasonal variability
- **Green cluster**: spatial structure is closely related to the mean rainfall pattern, temperature variability is to convection
- **Red cluster**: relatively weak annual cycle + influence of El Niño results in slow dynamics

D. A. Zappala, M. Barreiro, and C. Masoller, "Uncovering underlying regularities in climatological data through Hilbert phase analysis", Chaos 29, 051101 (2019).

Bivariate analysis

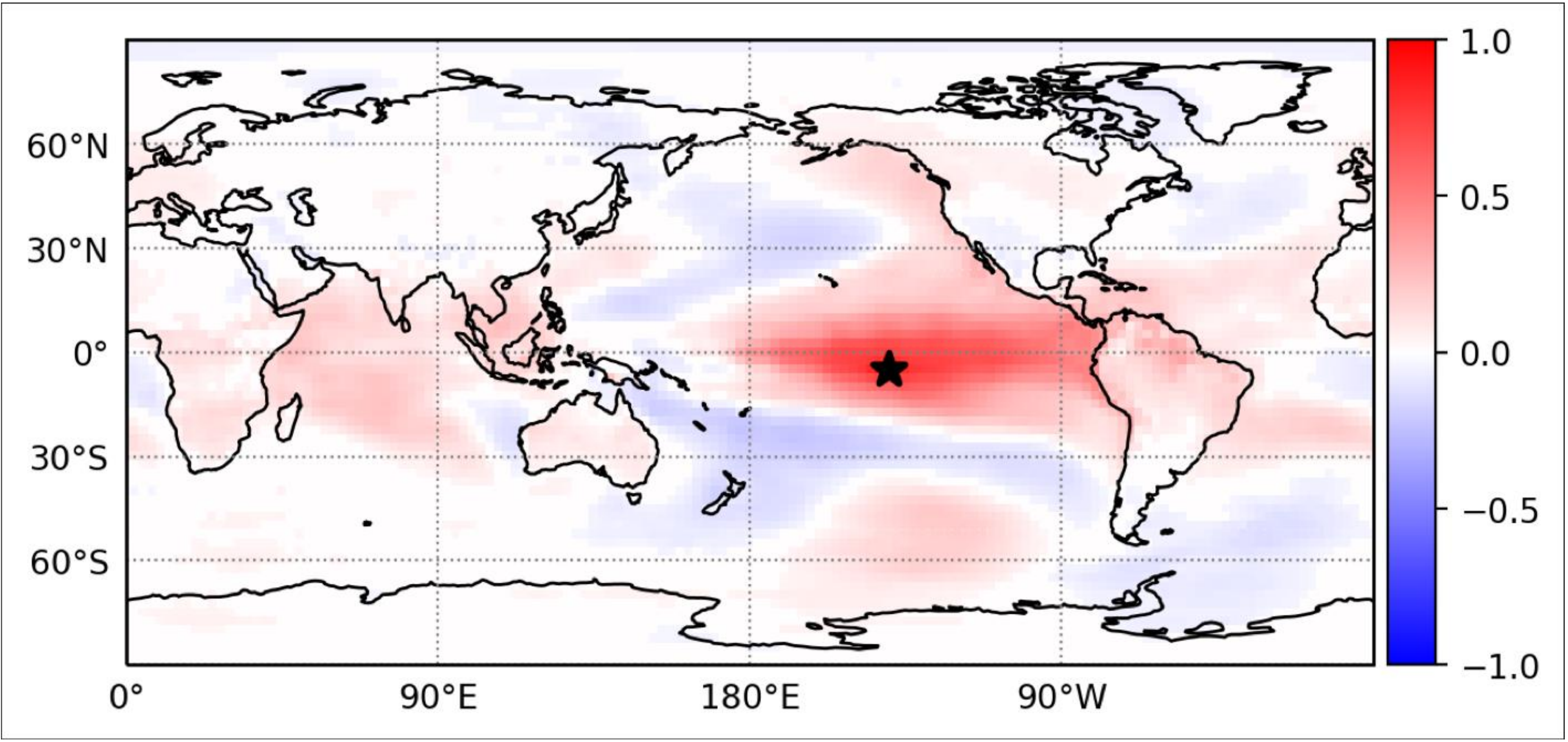
Cross-correlation: X,Y time series in different locations

$$C_{xy}(\tau) = \frac{1}{N-\tau}\sum_{k=1}^{N-\tau} x(k+\tau)y(k)$$

the two time series are normalized to zero-mean **μ=0** and unit variance, **σ=1**

- $-1 \leq C_{X,Y} \leq 1$
- $C_{X,Y} = C_{Y,X}$
- The maximum of $C_{X,Y}(\tau)$ indicates the **lag** that renders the time series *X* and *Y* best aligned.
- Pearson coefficient: $\rho = C_{X,Y}(0)$

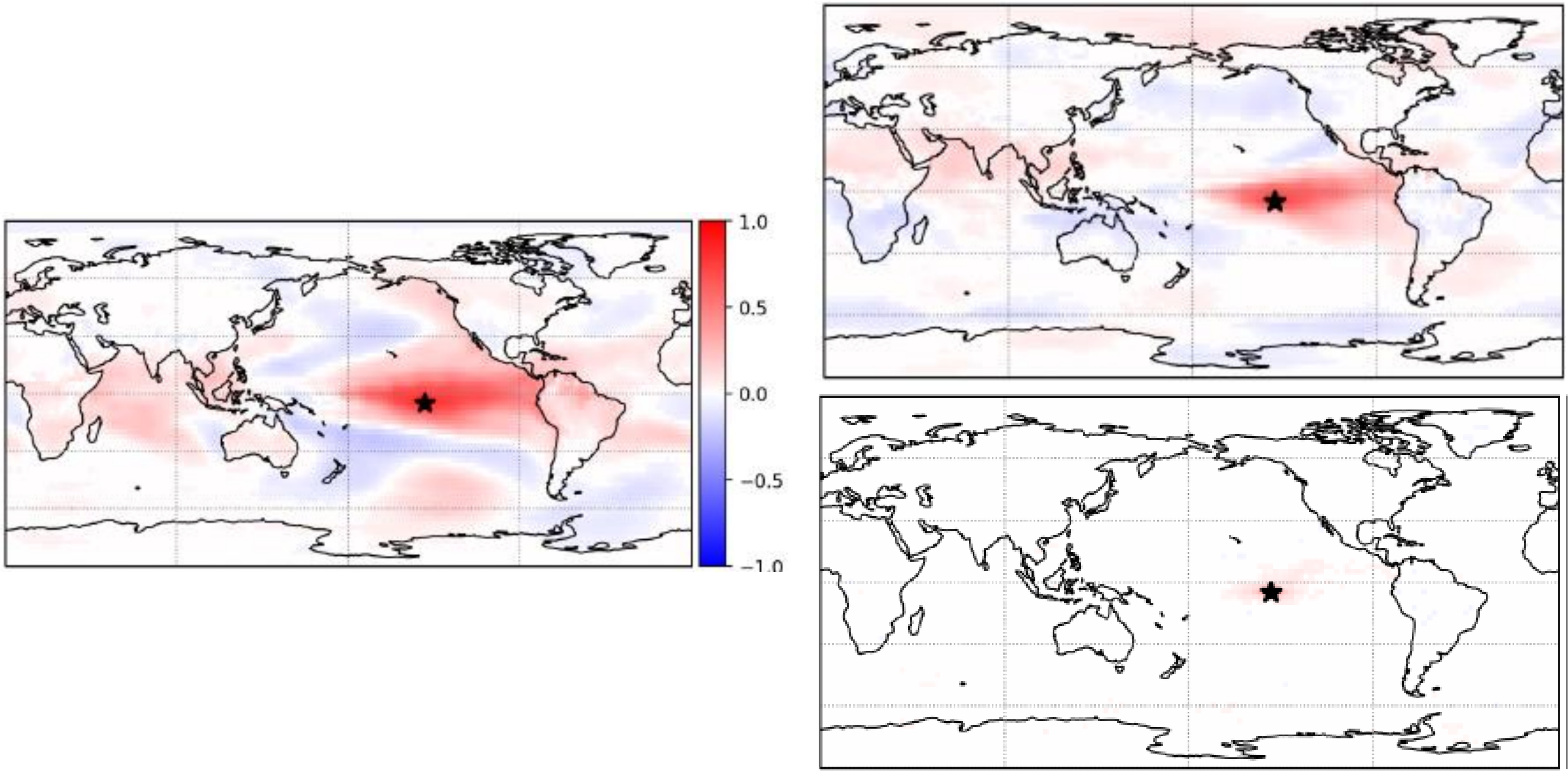
Example of cross correlation map computed from surface air temperature (SAT) anomalies



Color code represents the zero-lag cross-correlation of ∗ with all the world

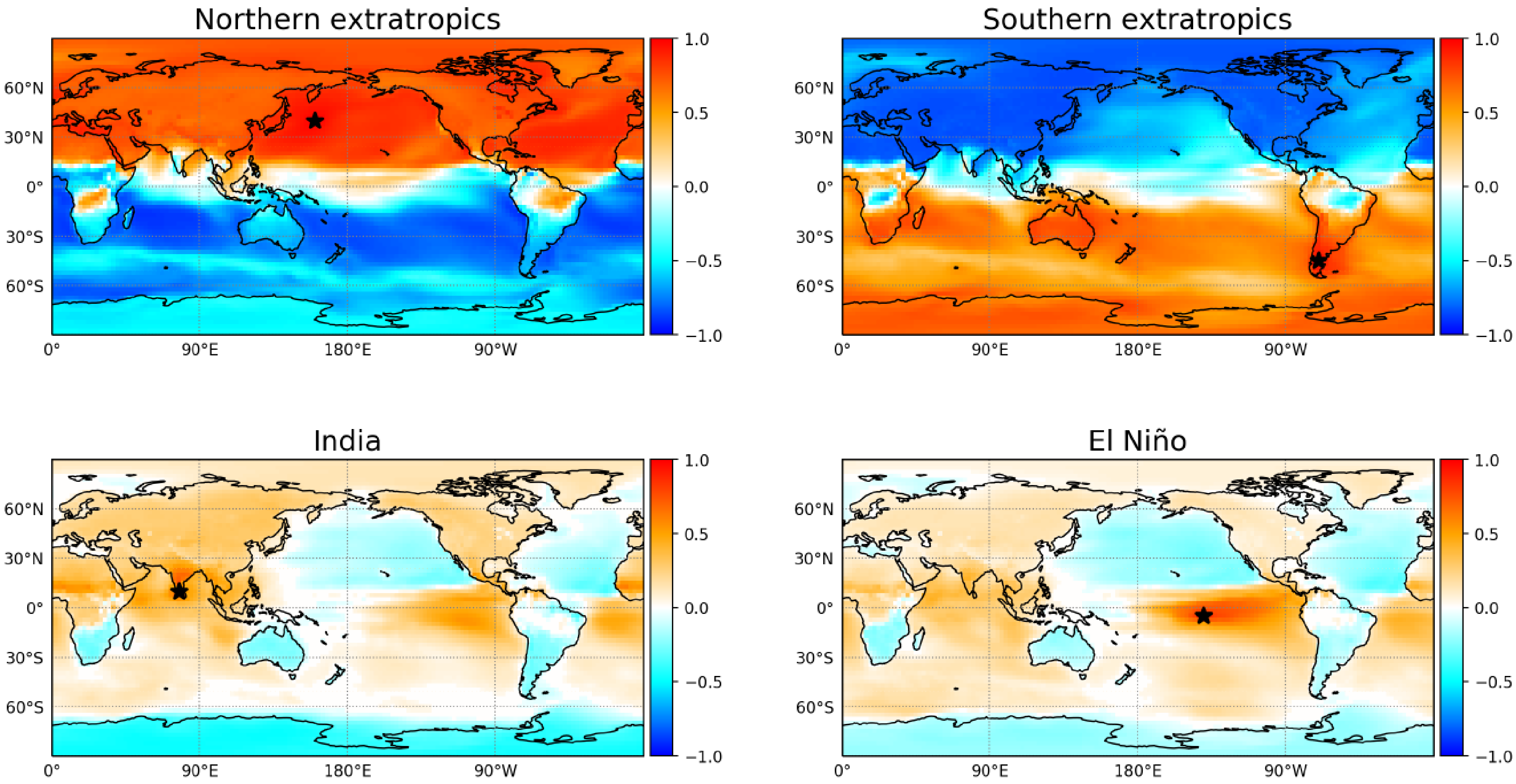
Comparison

Correlations of SAT anomalies vs. amplitude and frequencies



Cross-correlation of the cosine of Hilbert phases

$$\rho_{ij}(\tau) = \langle \cos\phi_i(t), \cos\phi_j(t) \rangle$$

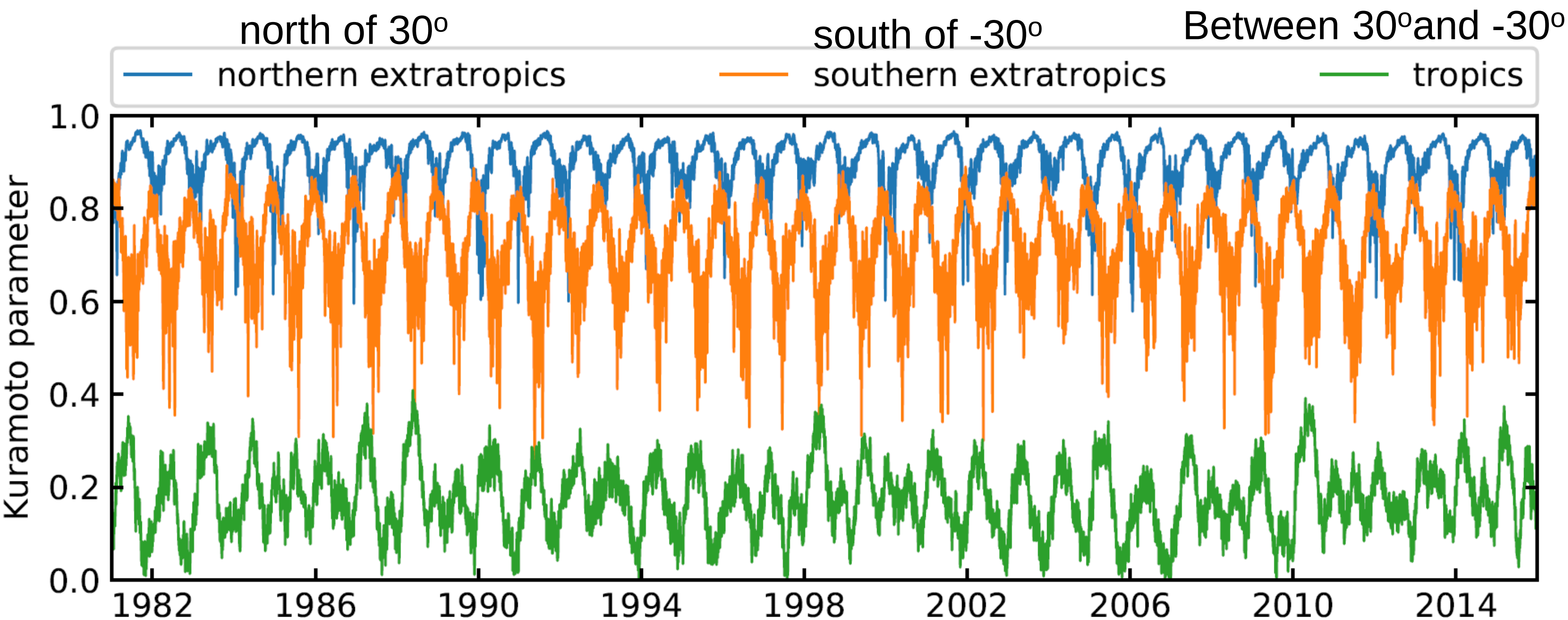


How to quantify the degree of synchronization?

Kuramoto order parameter: $re^{i\psi} = \frac{1}{N}\sum_{j=1}^{N} e^{i\phi_j}$

r =0 incoherent state (oscillators scattered in the unit circle)

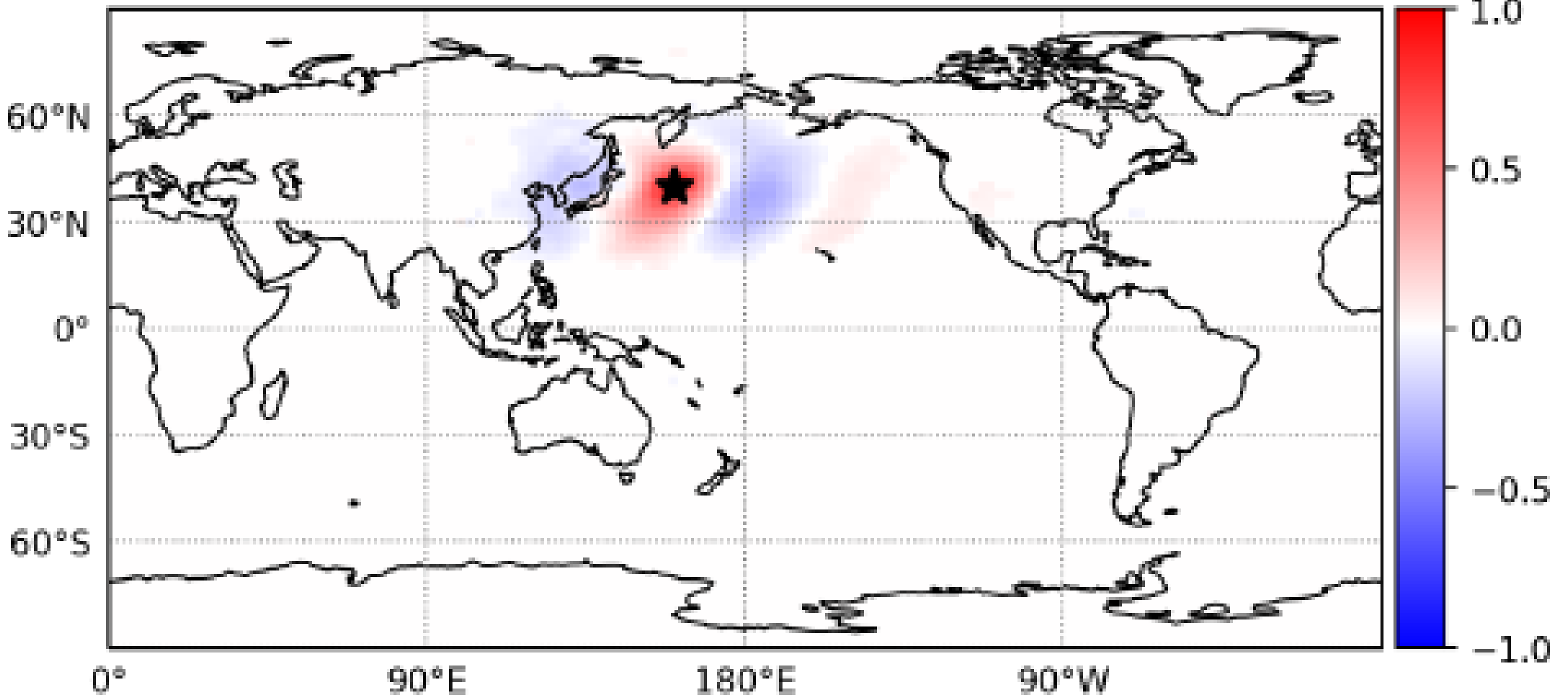
r =1 all oscillators are in phase ($\theta_i = \theta_j\ \forall$ i,j)



Correlations of frequencies identifies Rossby waves

$$\rho_{ij} = \langle d\phi_i/dt,\ d\phi_j/dt \rangle$$

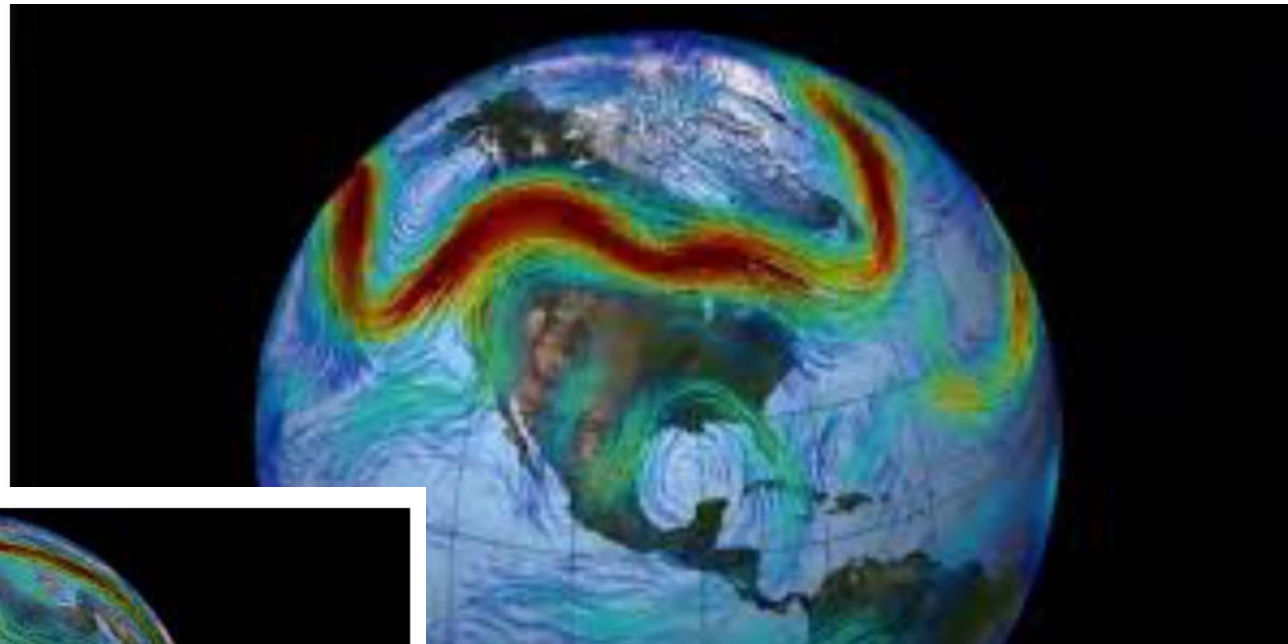
Cross-correlation in color code

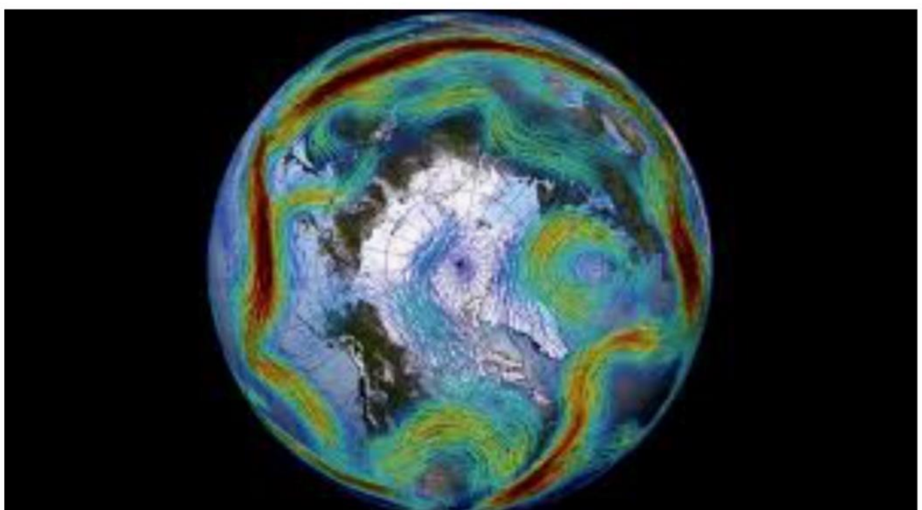


D. A. Zappala, M. Barreiro and C. Masoller, "*Quantifying phase synchronization and unveiling Rossby wave patterns in surface air temperature dynamics*", submitted (2019)

Rossby waves

Observed in the atmosphere and oceans due to the rotation of the planet. They have a major influence on weather.

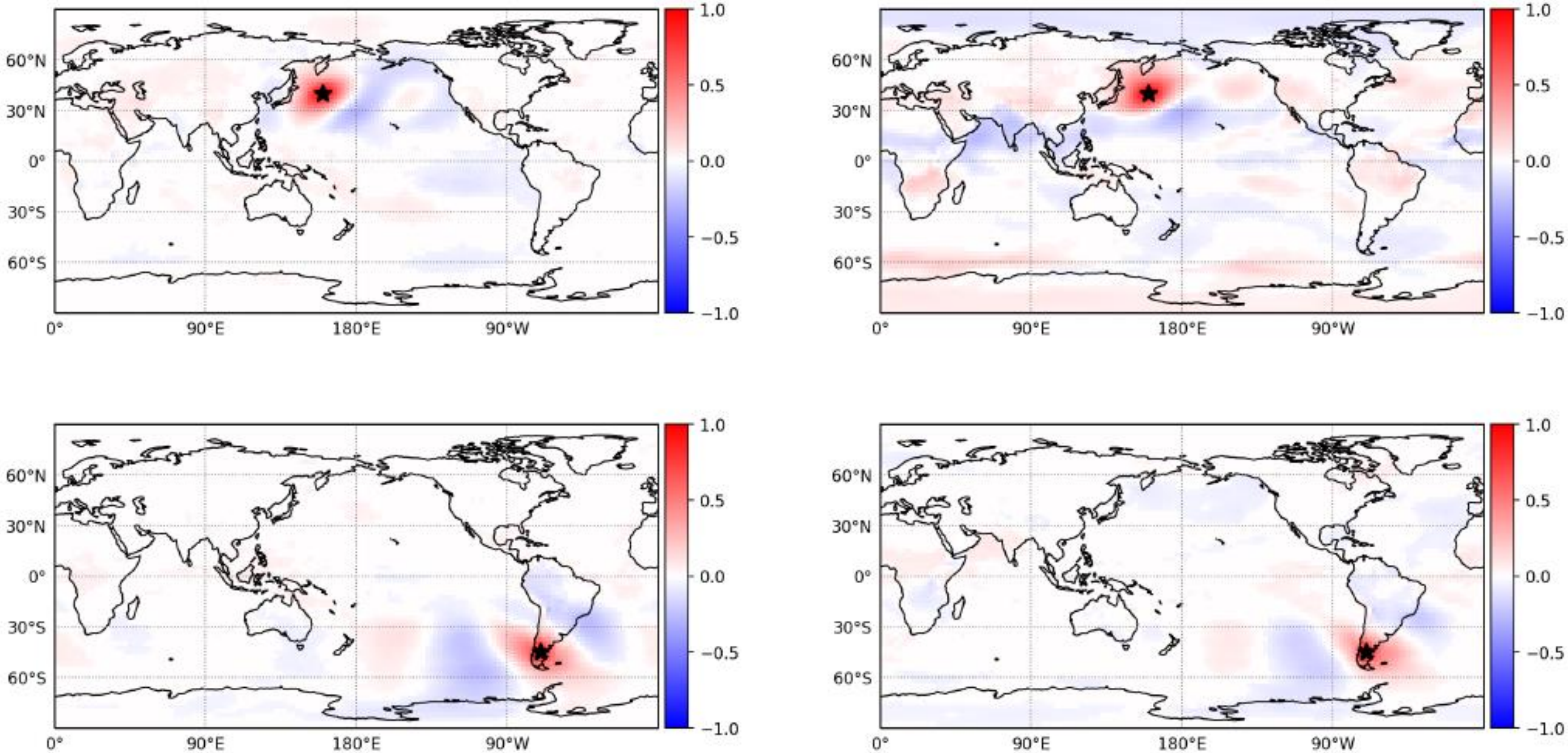




Clean wave pattern not observed with anomalies or amplitudes (likely due to seasonality or other slow phenomena)

Cross-correlation in color code.

Anomalies | **Hilbert amplitudes**

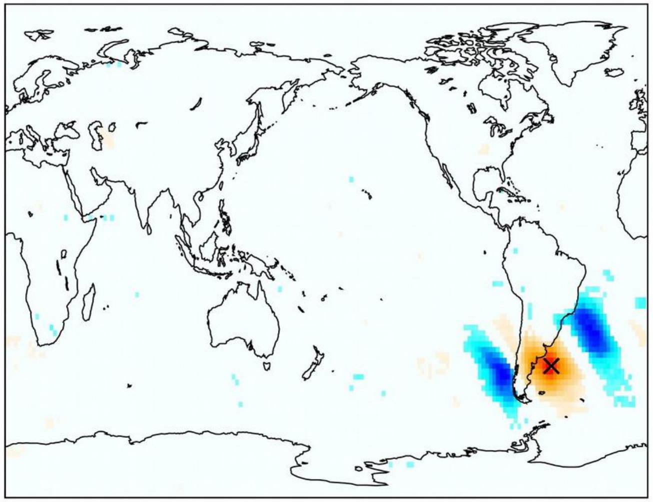


D. A. Zappala, M. Barreiro,C. Masoller, "*Mapping atmospheric waves and unveiling large scale synchronization patterns in global air temperature datasets*", submitted (2019)

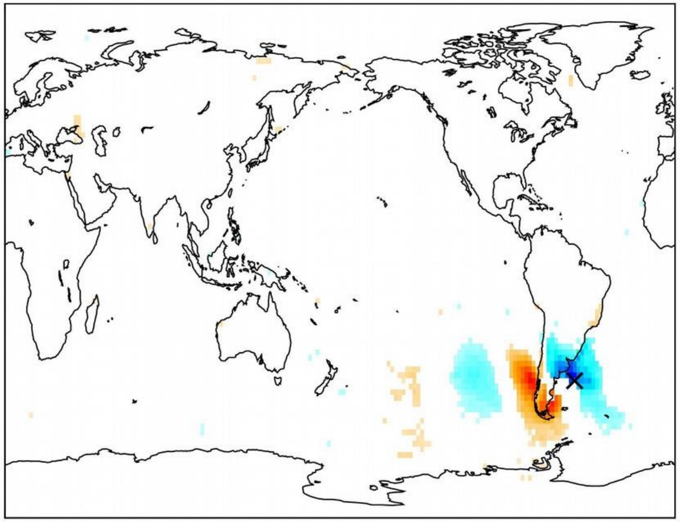
Lagged-cross correlation

$$\rho_{ij}(\tau) = \langle d\phi_i/dt, d\phi_j(t+\tau)/dt \rangle$$

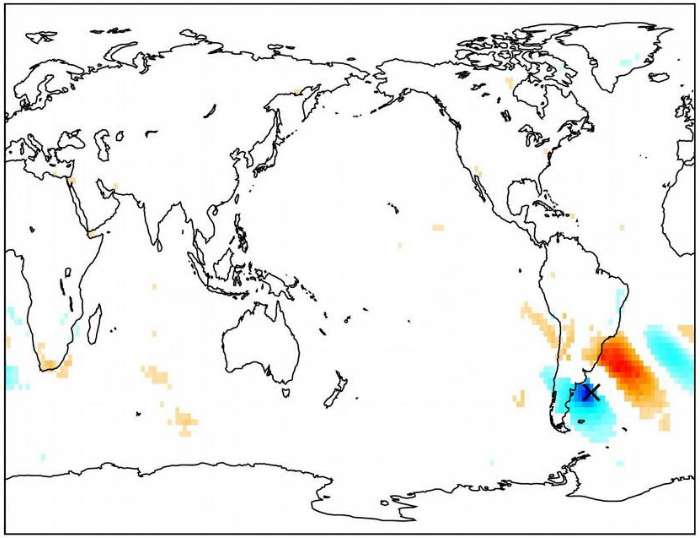
$\tau=0$



$\tau = -2$ days



$\tau = +2$ days



As expected, the wave pattern moves towards east

Summary

We used the Hilbert transform to obtain instantaneous amplitude and phase of “raw” oscillatory signals (surface air temperature).

Then, we used the amplitude and phase time series:

- To detect significant changes occurred in the last 30 years.
- To uncover climate similarities in different regions.
- To quantify phase synchronization (stronger in the north hemisphere due to the presence of large continents).
- To identify Rossby waves that propagate across the planet.

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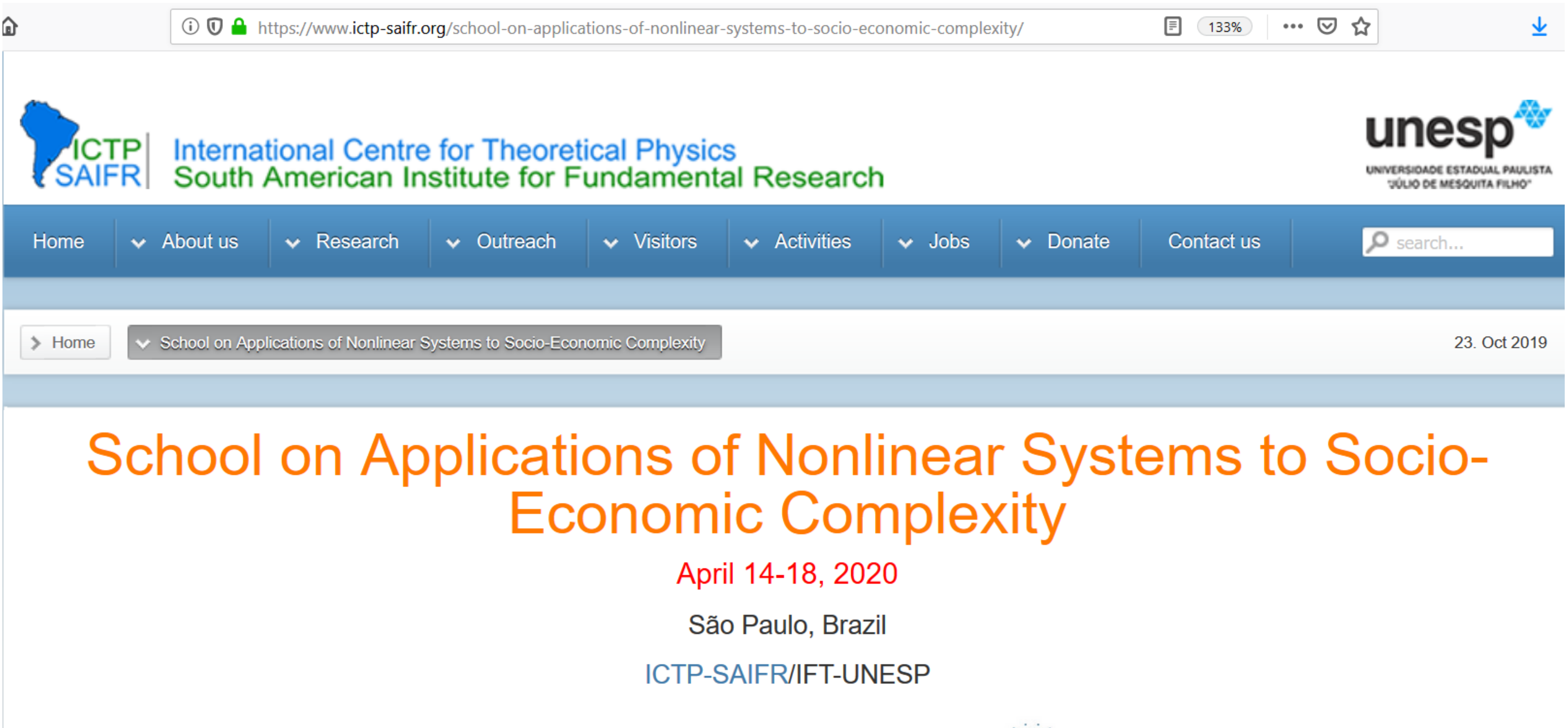

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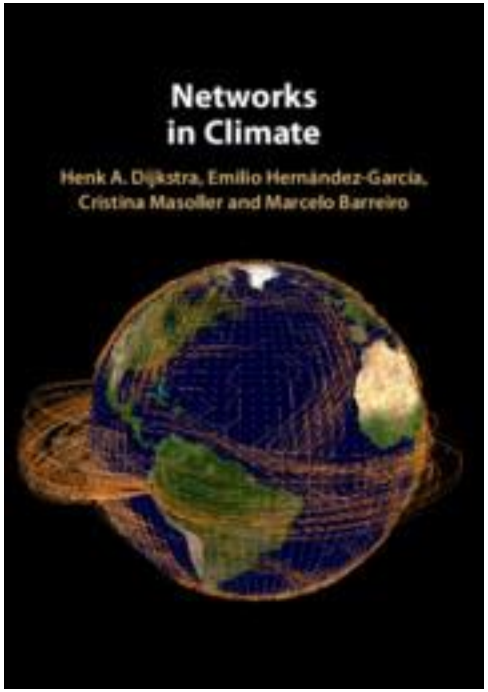

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