Detecting amplitude and frequency synchronization in global surface air temperature data

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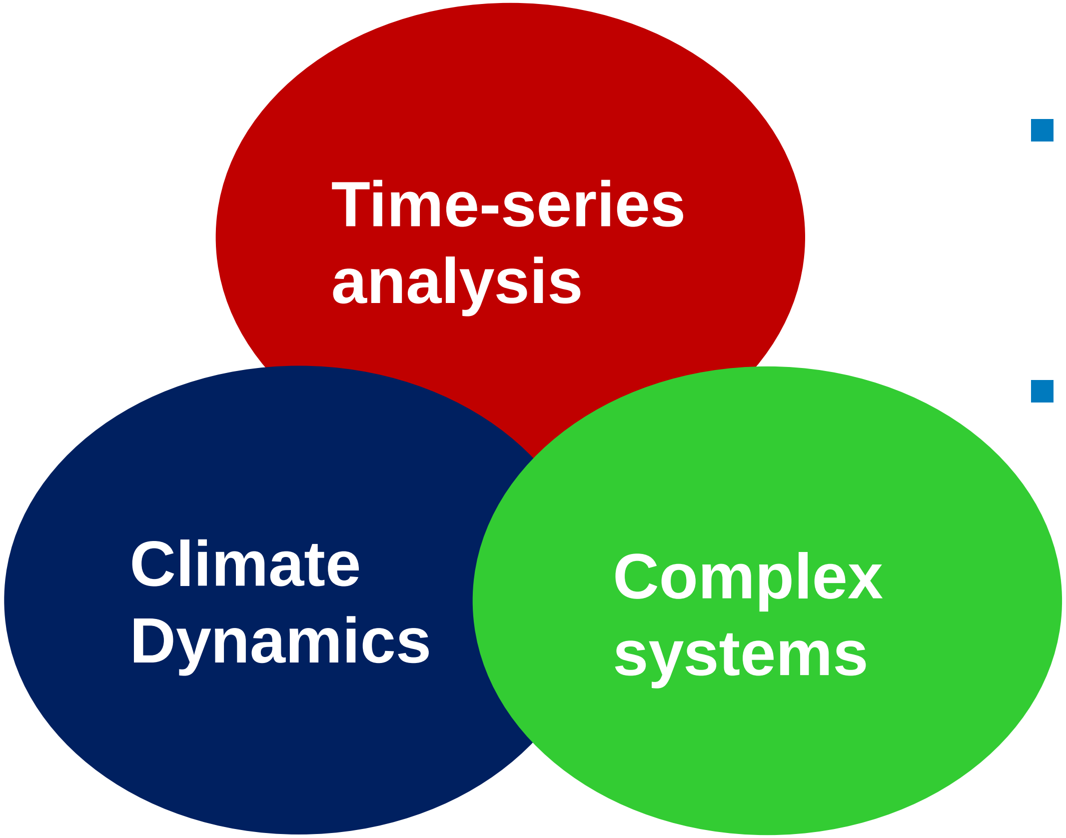
LANET
Puebla, Mexico, September 2017

ICREA

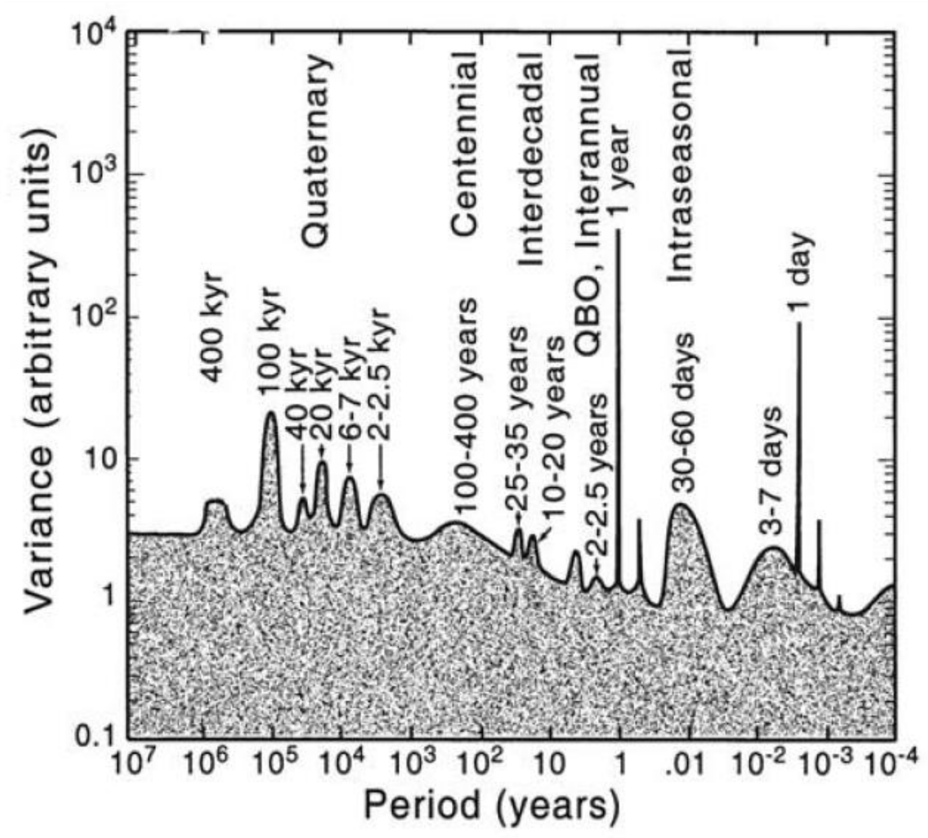
GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Outline

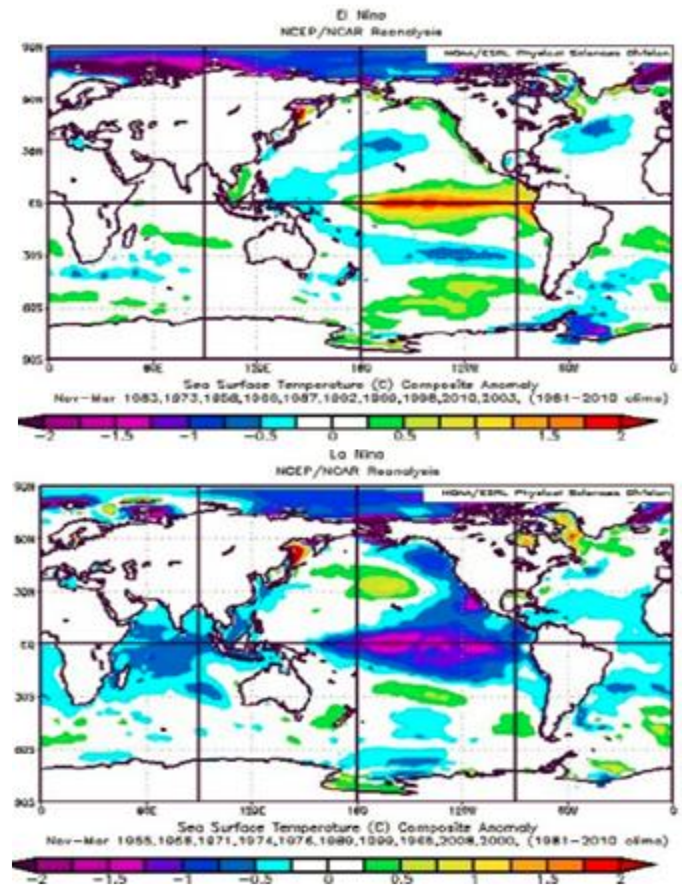


- Motivation
- Data and Hilbert method
- Results
  - Univariate analysis
  - Bivariate analysis
  - Inter-decadal variations
- Summary

Our climate: a complex system with a wide range of temporal scales and spatial modes of variability

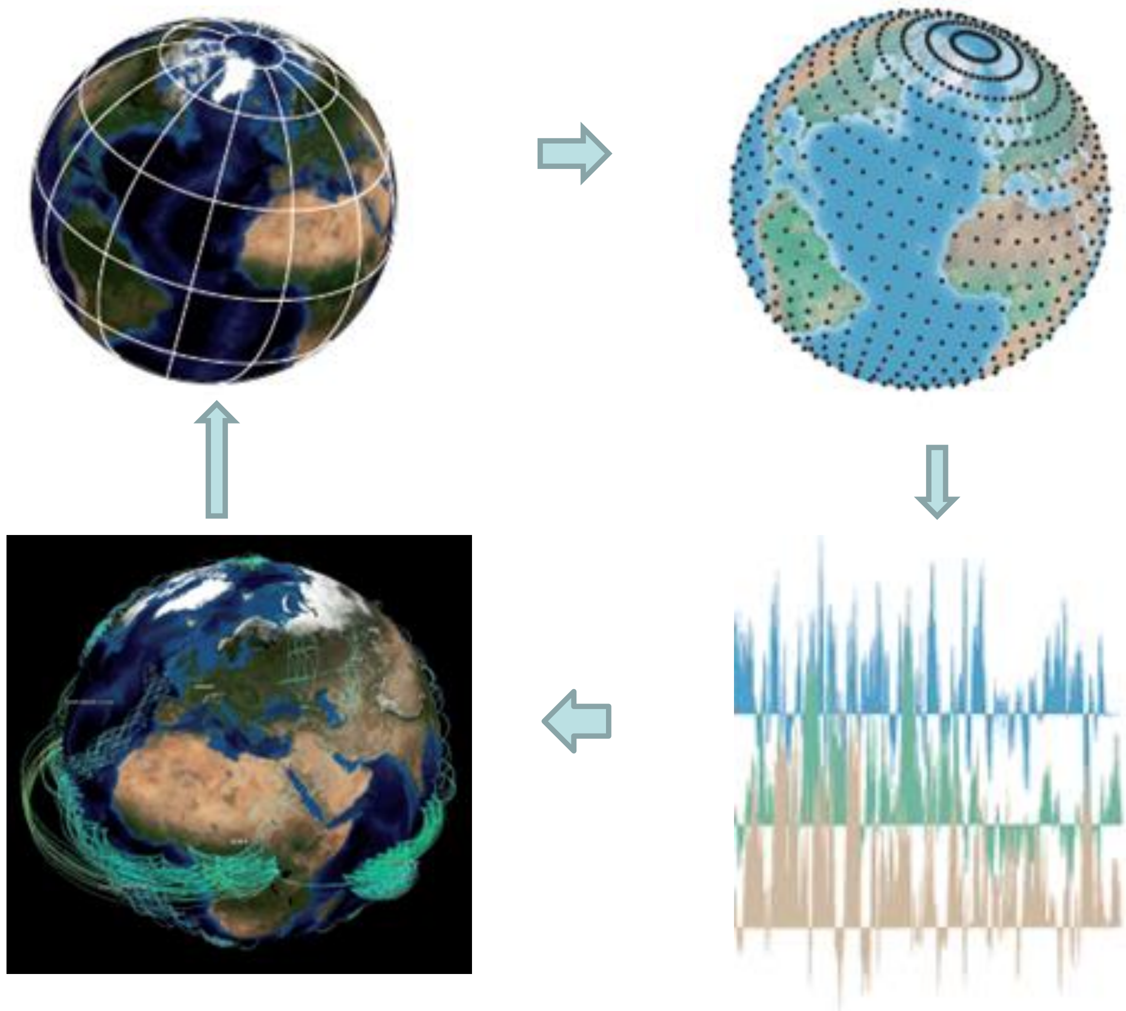


An "artist's representation" of the power spectrum of climate variability (Ghil 2002).



And also, Indian Ocean Dipole,
the Madden–Julian oscillation,
the North Atlantic oscillation, etc, etc

Complex network representation



Donges et al,
Chaos 2015

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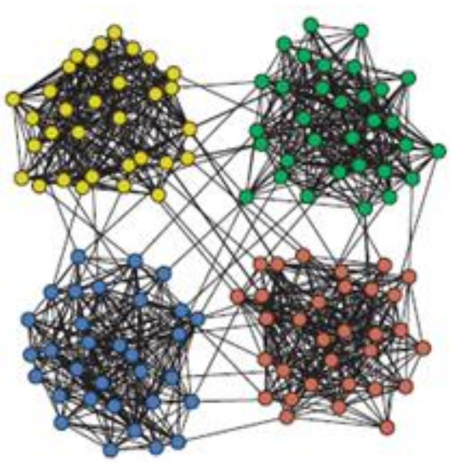
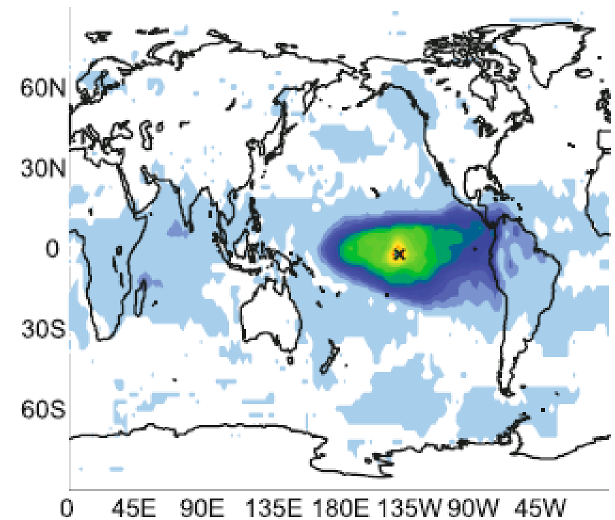
How to identify geographical regions with similar climate?

- A first solution: construct the climate network and run a community detection algorithm.
- Regions with similar climate (rainforests, dry and arid regions, maritime regions, etc.) should belong to the same "community".



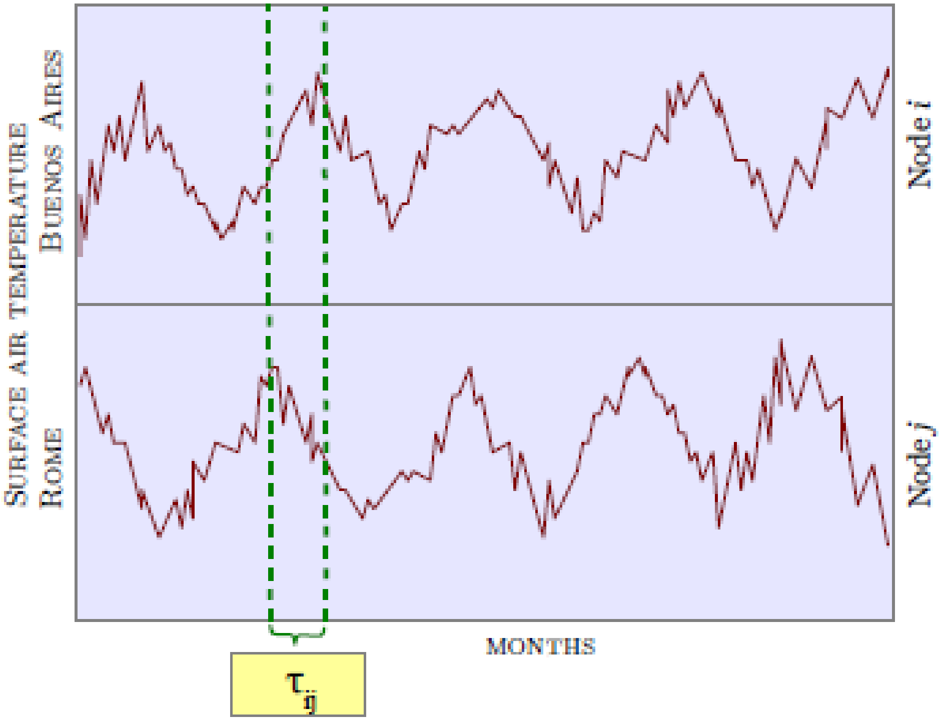
- Problem: with "usual" correlation analysis the north and south hemispheres are only indirectly connected.



Cross correlation of surface air temperature anomalies (seasonal cycle removed)

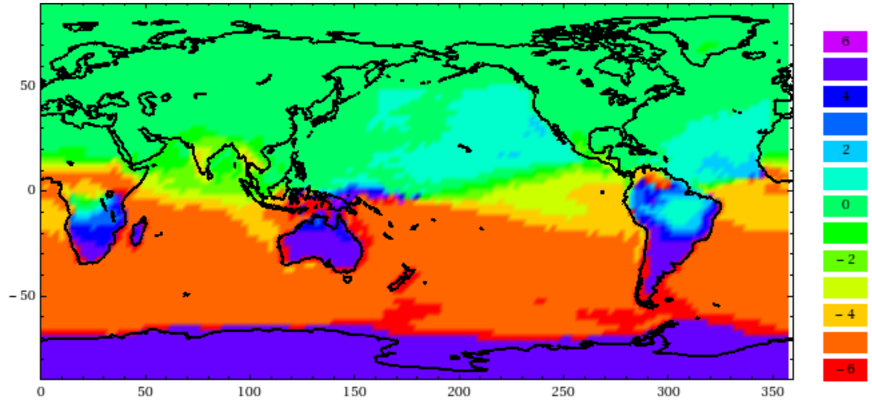
How to identify geographical regions with similar climate?

- Our first approach: lag-times between seasonal cycles (bivariate correlation analysis of Surface Air Temperature)

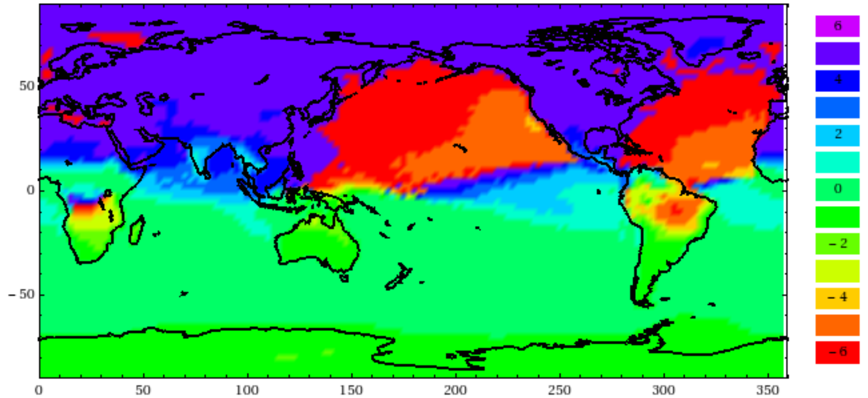


G. Tirabassi and C. Masoller, Sci. Rep. 6:29804 (2016)

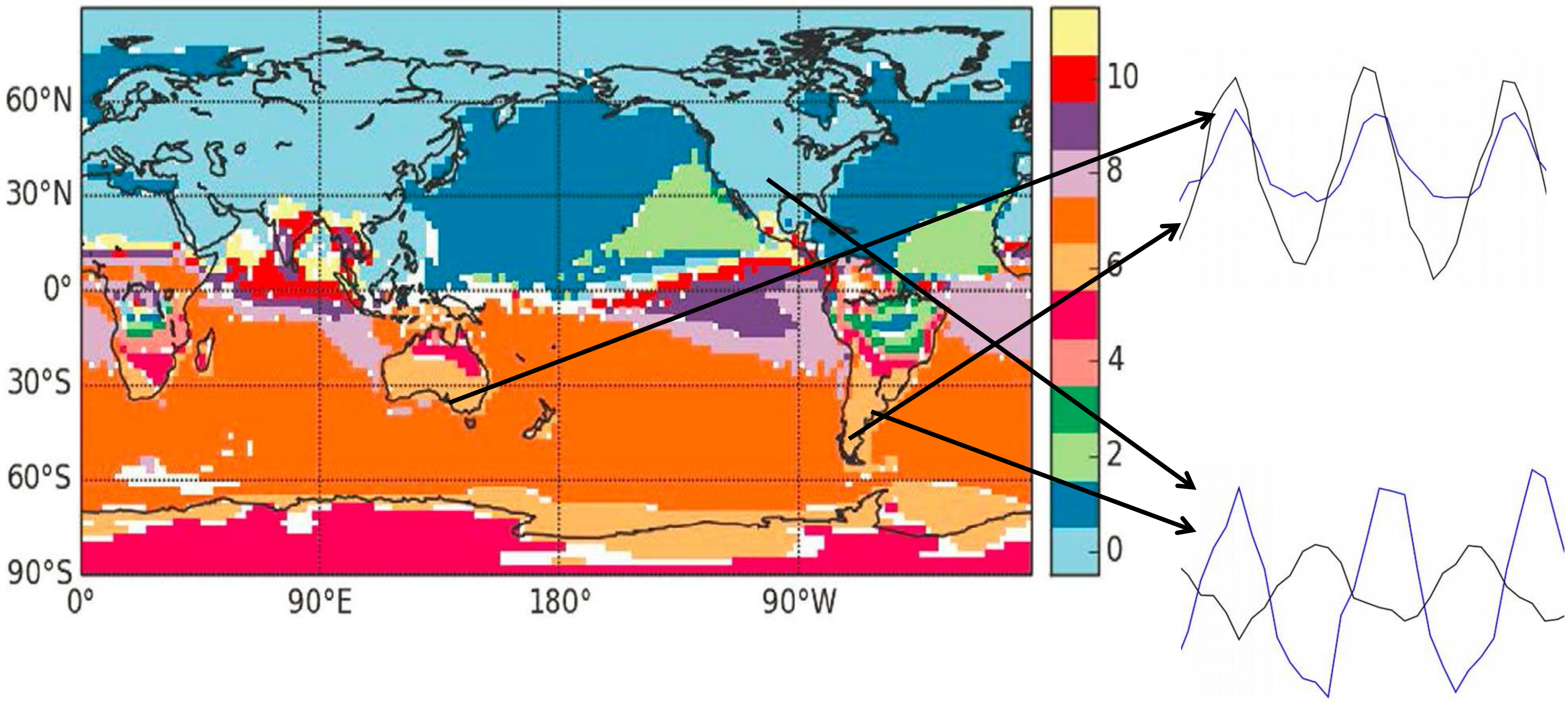
Rome



Buenos Aires



Geographical regions with synchronous (inphase) seasonal cycles

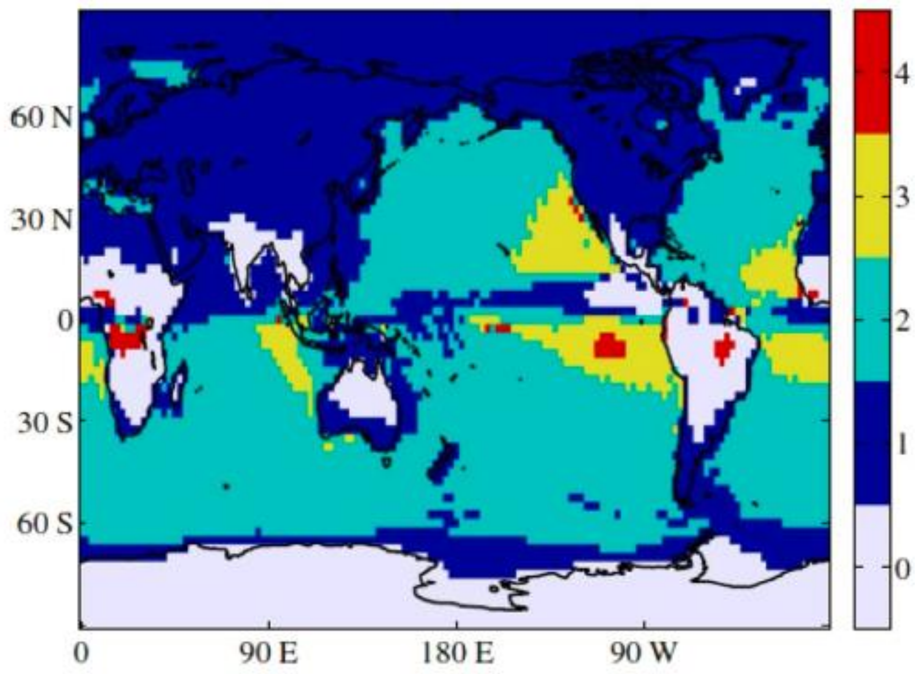


- Six-month lag between the two hemispheres.
- Oceans have a one-month lag with respect to the landmasses

G. Tirabassi and C. Masoller, Sci. Rep. 6:29804 (2016)

Our second approach

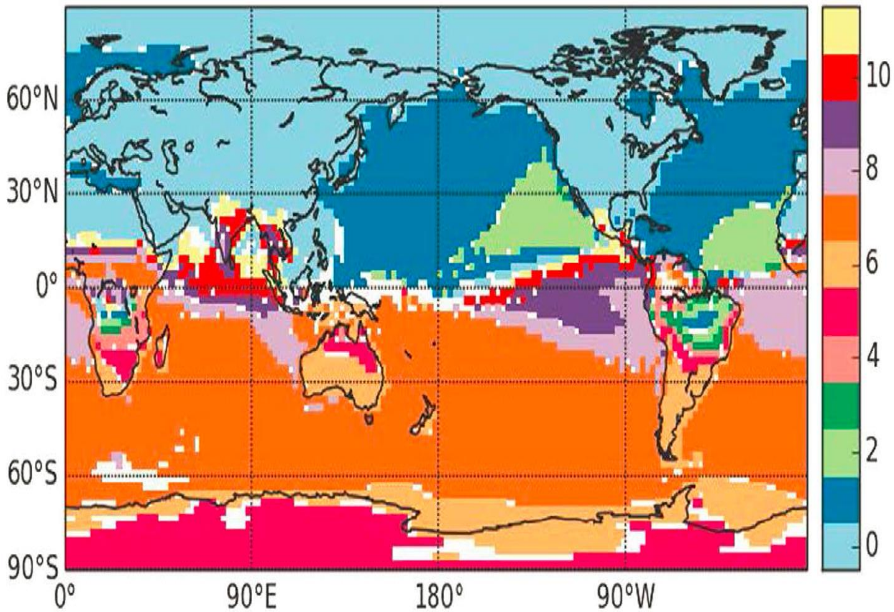
- Lag-time between surface air temperature seasonal cycle and the isolation (local top-of-atmosphere incoming solar radiation)
- computed by minimizing the distance between the time-series.



F. Arismendi, M. Barreiro and C. Masoller, Sci. Rep. 7, 45676 (2017)

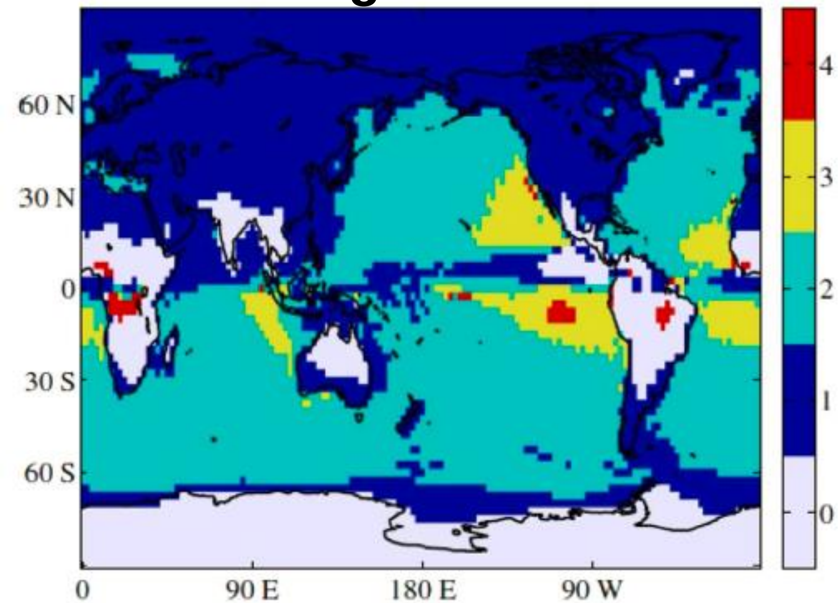
Comparison

Regions with inphase (synchronized) surface air temperature seasonal cycle



G. Tirabassi and C. Masoller, Sci. Rep. 6:29804 (2016)

Lag between surface air temperature seasonal cycle and incoming solar radiation



F. Arismendi, M. Barreiro and C. Masoller, Sci. Rep. 7, 45676 (2017)

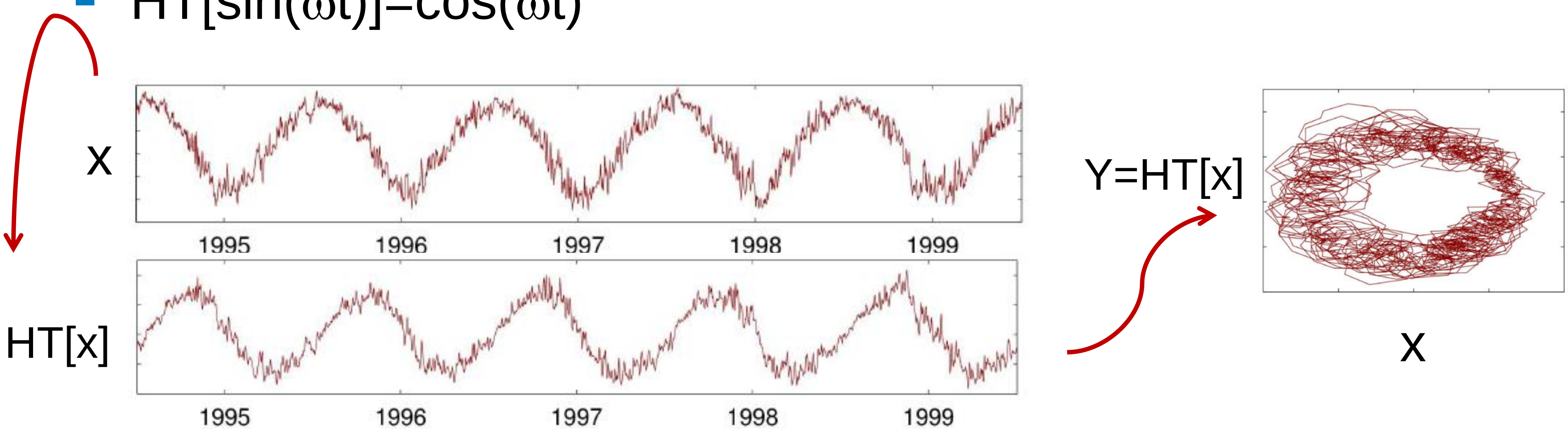
How to identify regions with similar climatic variability?

- Our solution: Hilbert Transform of a real **oscillatory** signal.

- Allows to calculate, **for each data point** in the time series, the instantaneous

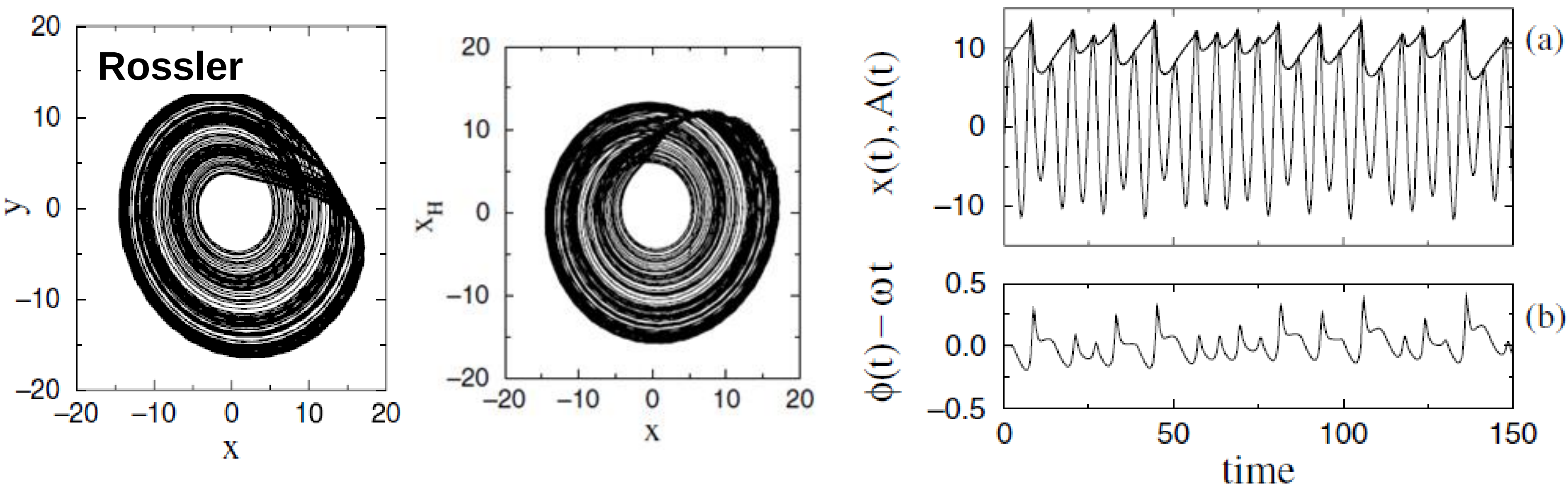
  Amplitude **a(t)** Phase **φ(t)** Frequency **ω(t)=dφ(t)/dt**

- HT[sin(ωt)]=cos(ωt)



Hilbert transform

Extensively used to analyze output signals of complex systems (physiological, neurological, etc.)



Can we use the amplitude, phase, frequency, to investigate:

- synchronization in climate data?
- quantify regional climate changes?

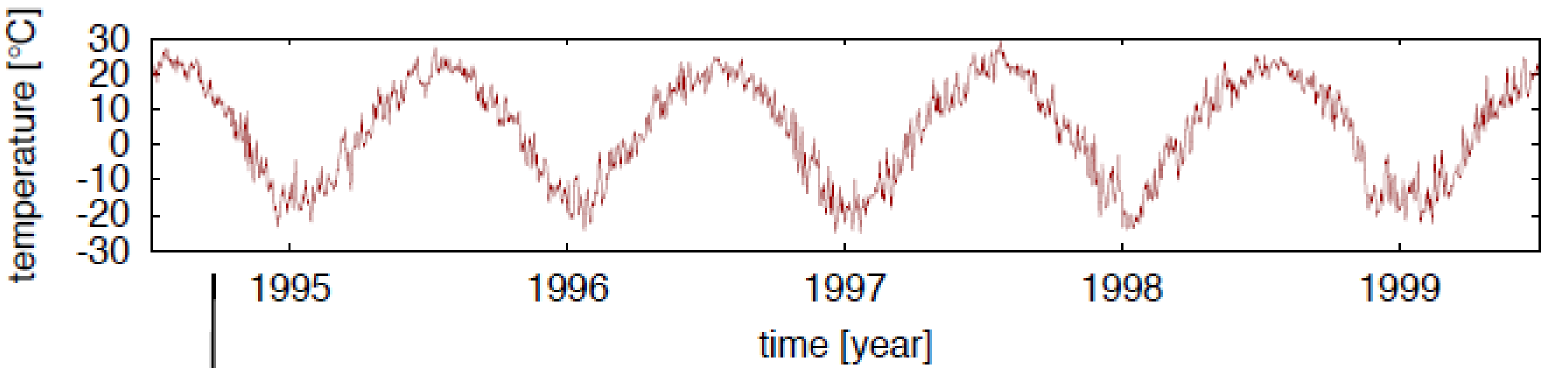
A. Pikovsky, M. Rosenblum and J. Kurths 2001

Surface Air Temperature Datasets

- NCEP/NCAR Reanalysis (from National Centers for Environmental Prediction and National Center for Atmospheric Research)
  - monthly-averaged surface air temperature (SAT)
  - spatial grid resolution of 2.5° (10512 points)
  - January 1958 – May 2012 (773 months)

- ERA-Interim (from European Centre for Medium-Range Weather Forecasts)
  - daily-averaged values of SAT
  - spatial resolution of 2° (16380 nodes)
  - January 1979 – April 2015 (13269 days)

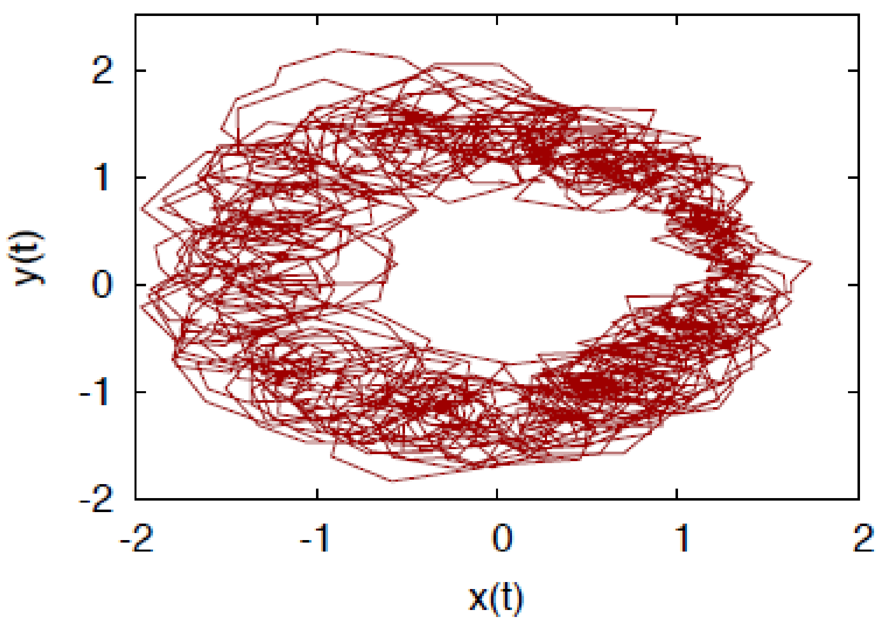
Hilbert analysis of surface air temperature



SAT series of a site in continental east Asia

$x(t)$ detrended and normalised: $\langle x \rangle = 0;\ \sigma_x = 1$

$y(t) = \mathrm{H}[x](t)$



amplitude: $A = \sqrt{x^2 + y^2}$

phase: $\varphi = \mathrm{arctg}\left(\frac{y}{x}\right)$ then unwrap

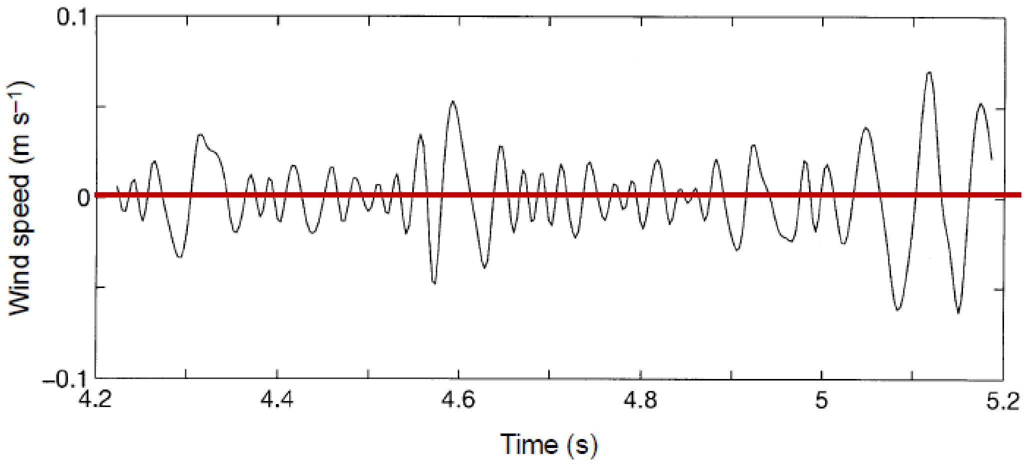
frequency: $\omega = \frac{d\varphi}{dt}$

By construction:

$x(t) = A(t)\cos\varphi(t)$

Restriction

- In order to obtain meaningful instantaneous frequency, the signal has to be 'narrow band'
- For a narrow band signal the number of extrema and the number of zero crossings have to equal.

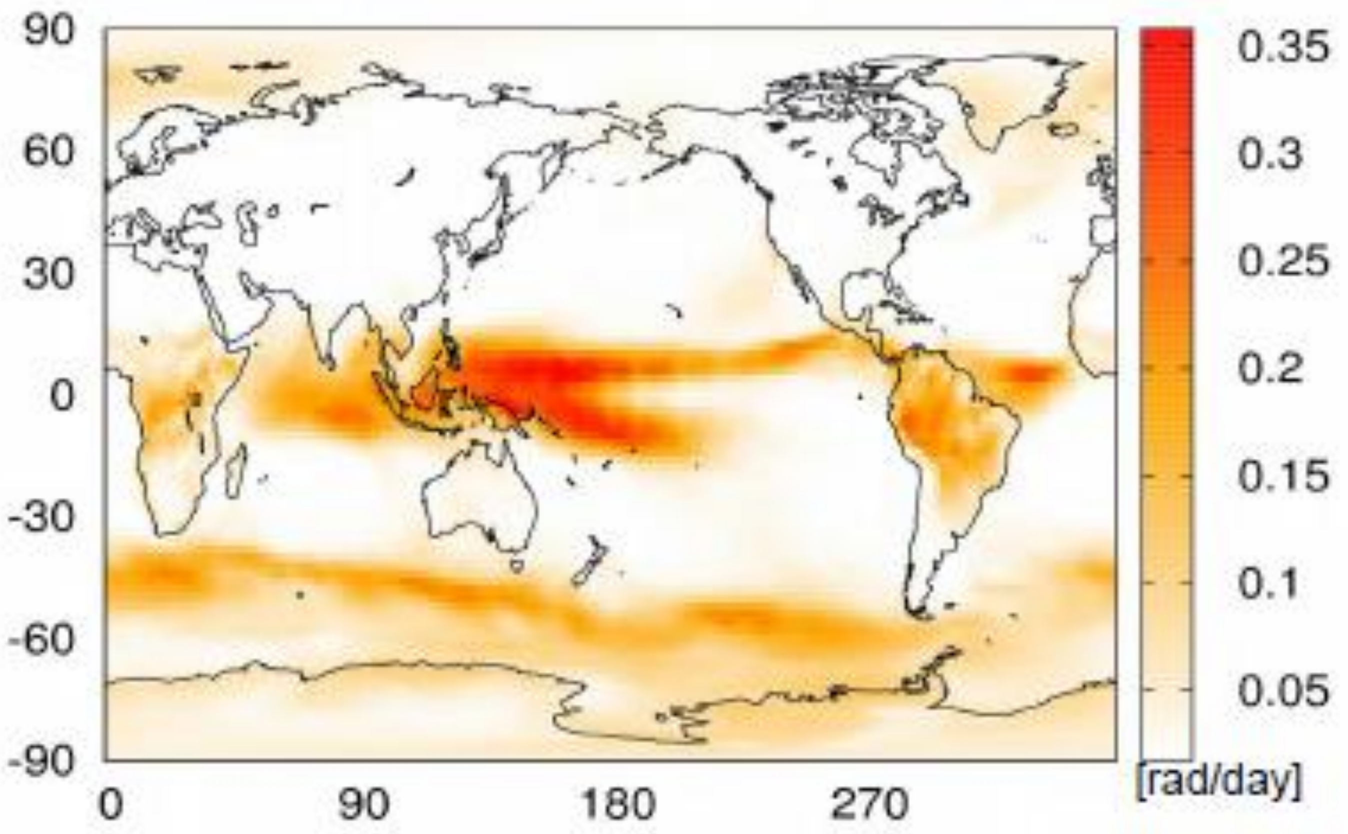


- This condition does not hold to daily SAT time series ("noisy" weather). However…

"*Even in cases where the data do not meet the mathematical or algorithmic requirements …, the results of nonlinear time-series analysis can be helpful in understanding, characterizing, and predicting dynamical systems*."

Elizabeth Bradley and Holger Kantz
Nonlinear time-series analysis revisited
Chaos 2015

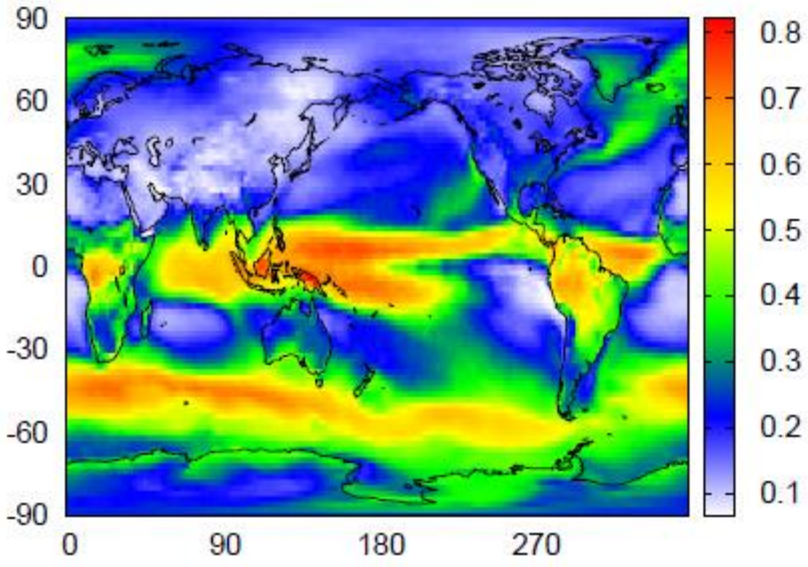
Average frequency



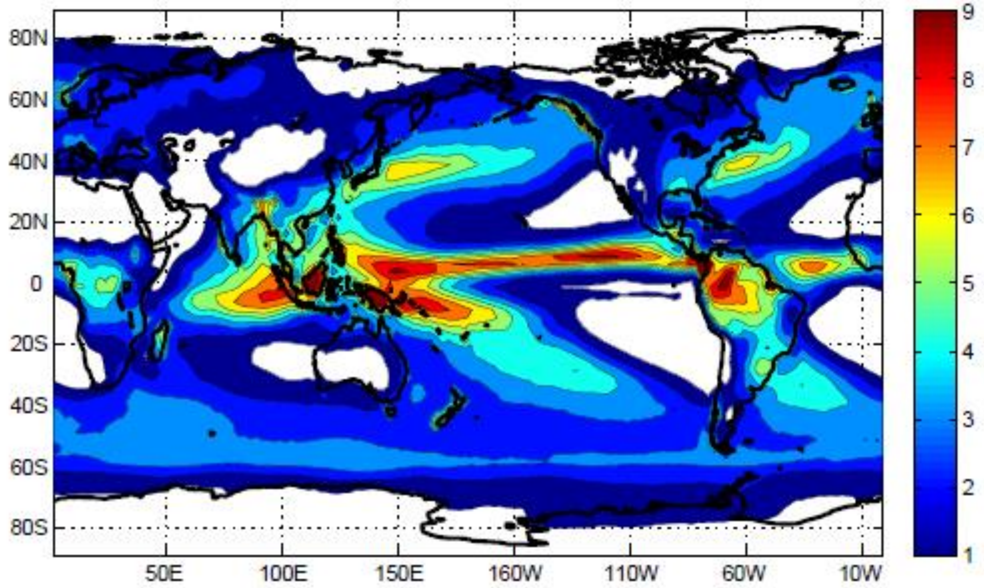
- The expected average frequency (one complete cycle in one year) is 0.017 rad/day

Zappala, Barreiro and Masoller, Entropy 18, 408 (2016)

Standard deviation of frequency fluctuations



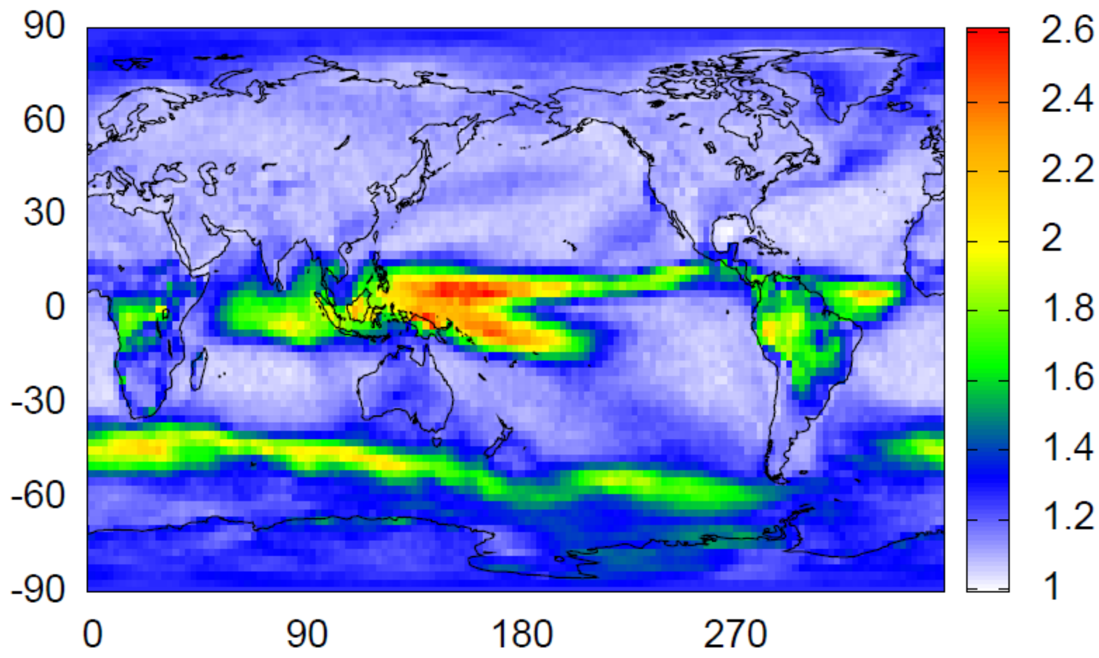
Annual mean precipitation (mm/day)



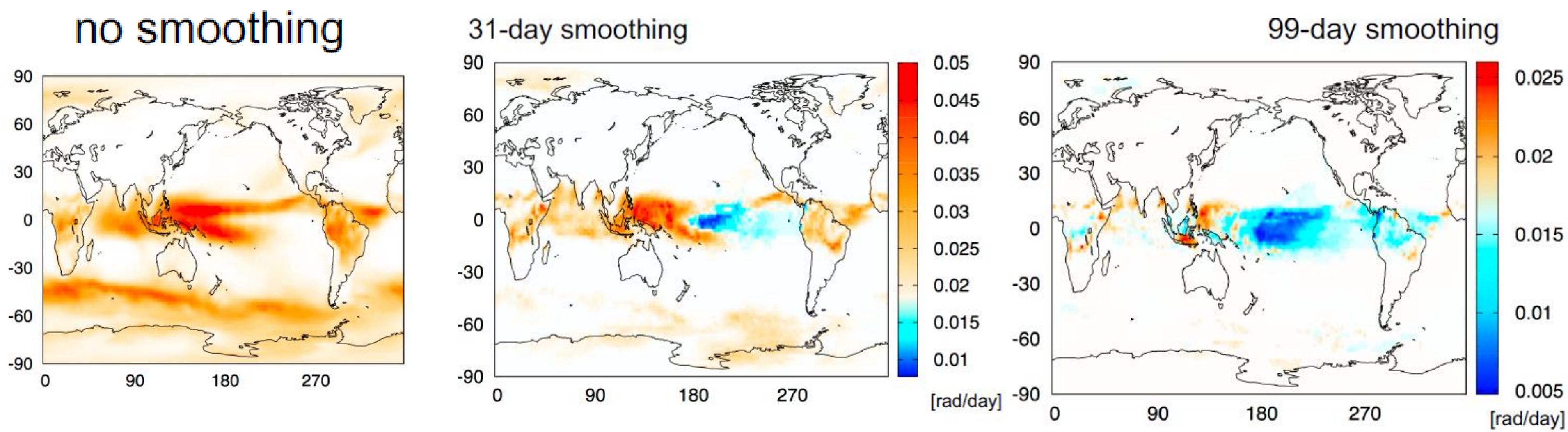
Consistency check

- A real signal has narrow band behavior if relative amplitude variations are very slow when compared with phase variations.

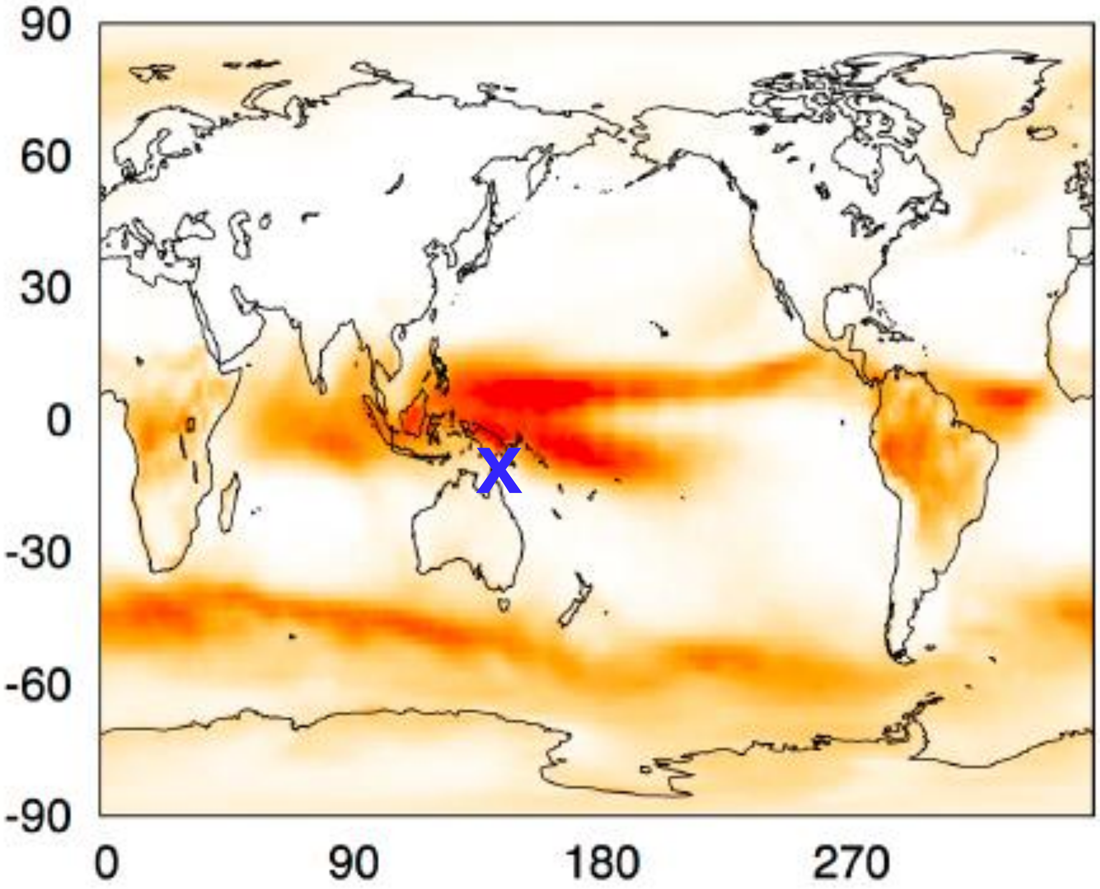
$$\left|\frac{d\varphi}{dt}\right| >> \left|\frac{1}{A}\frac{dA}{dt}\right| \Rightarrow \frac{|\omega|}{|(dA/dt)/A|} >> 1$$



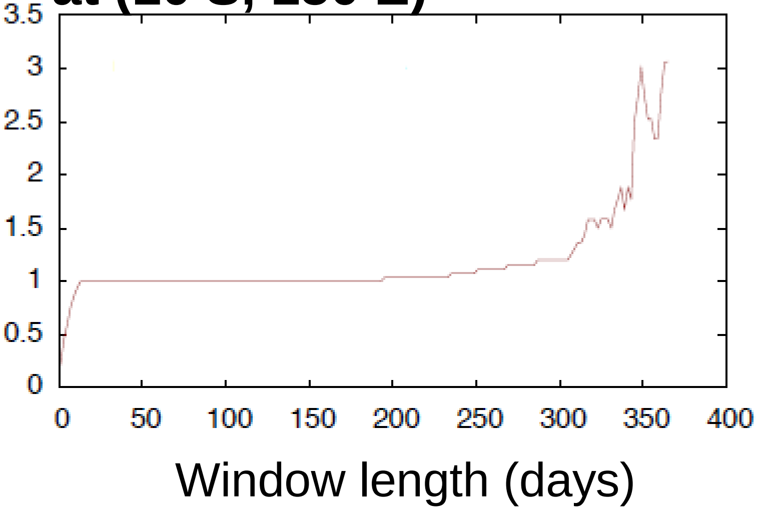
- SAT → average in a window of D days → Hilbert

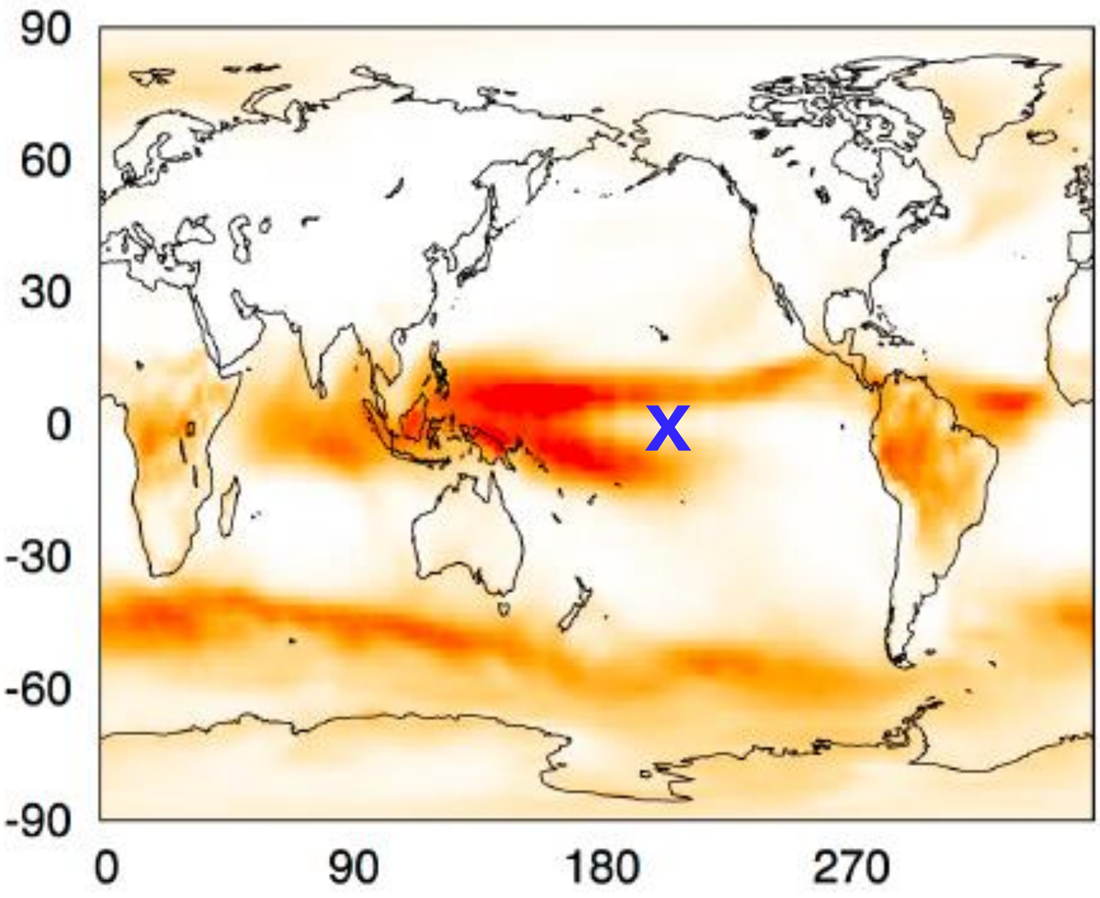


Influence of the length of SAT averaging window

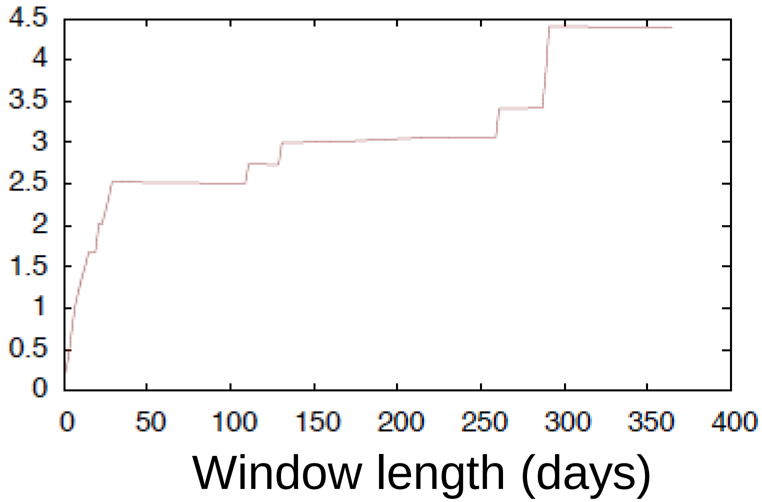


Average Period (years) at (10 S, 150 E)





Average Period (years) at (0, 200 E)



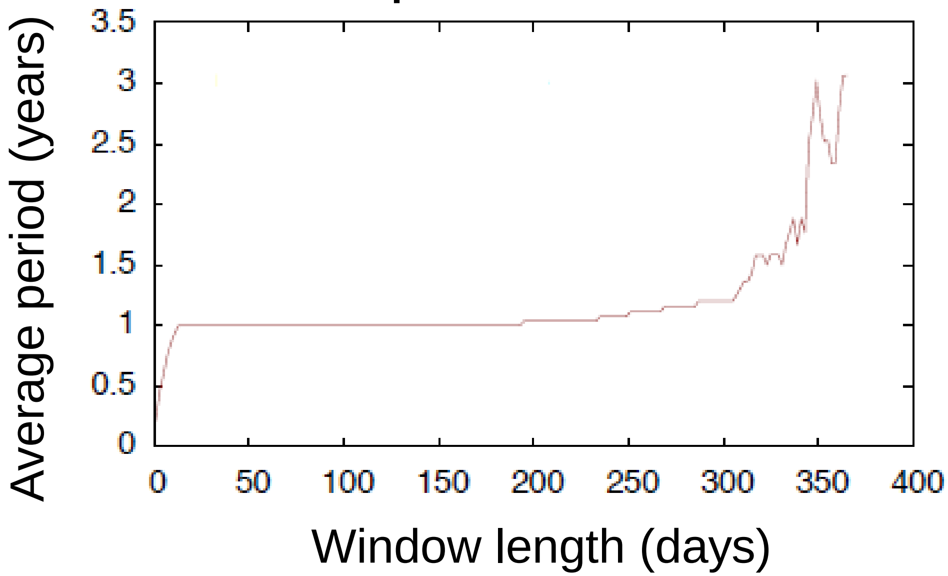
quasi-biennial oscillation (QBO) ?

Comparison with synthetic data

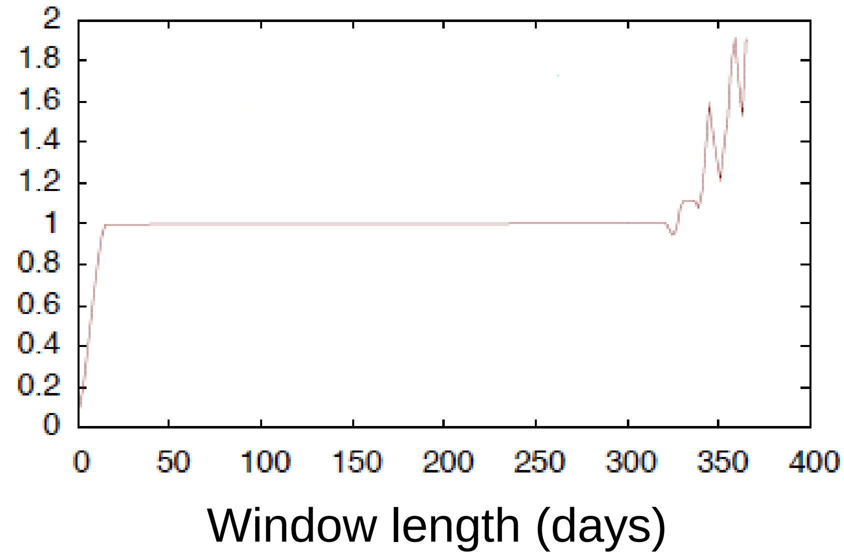
$$S(t) = \sqrt{1-\alpha}\,C\sin(\omega_0 t) + \sqrt{\alpha}\,\xi_{\mathrm{AR}(1)}$$

$\omega_0 = 2\pi/365$
C = norm. factor
β = AR(1) persistence

Empirical data

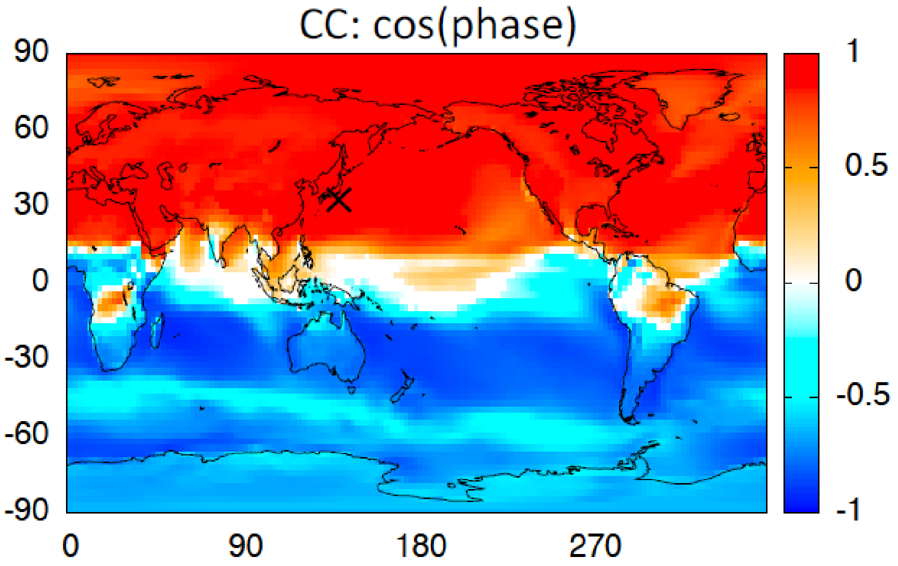


$\alpha=\beta=0.5$

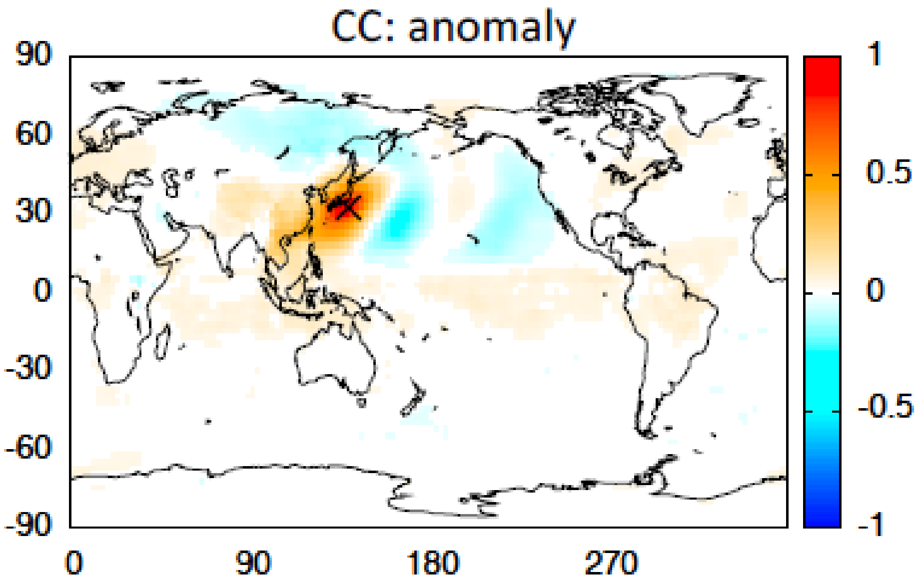


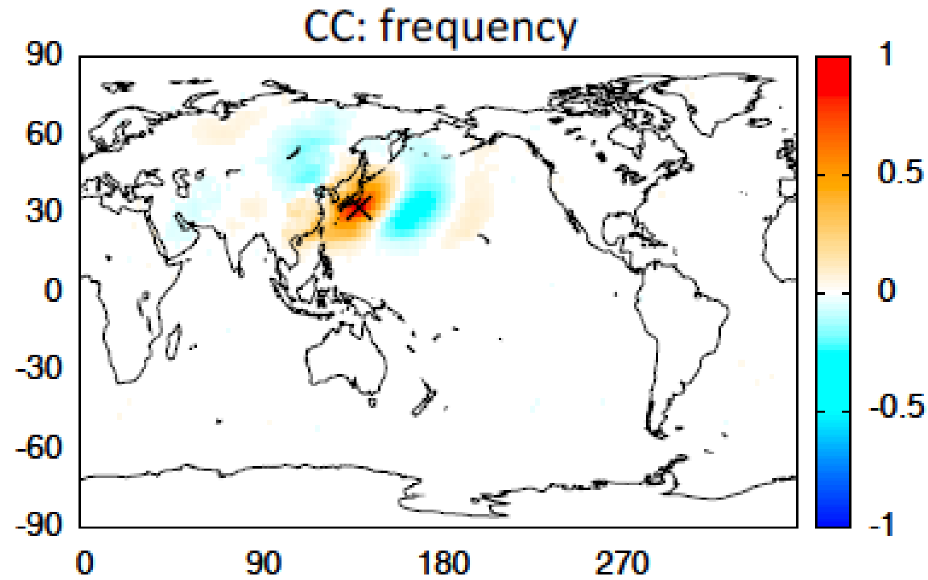
Phase dynamics

- Cos(phase) –typical year
- Cos(phase) –El Niño year
- Cos(phase) –La Niña year

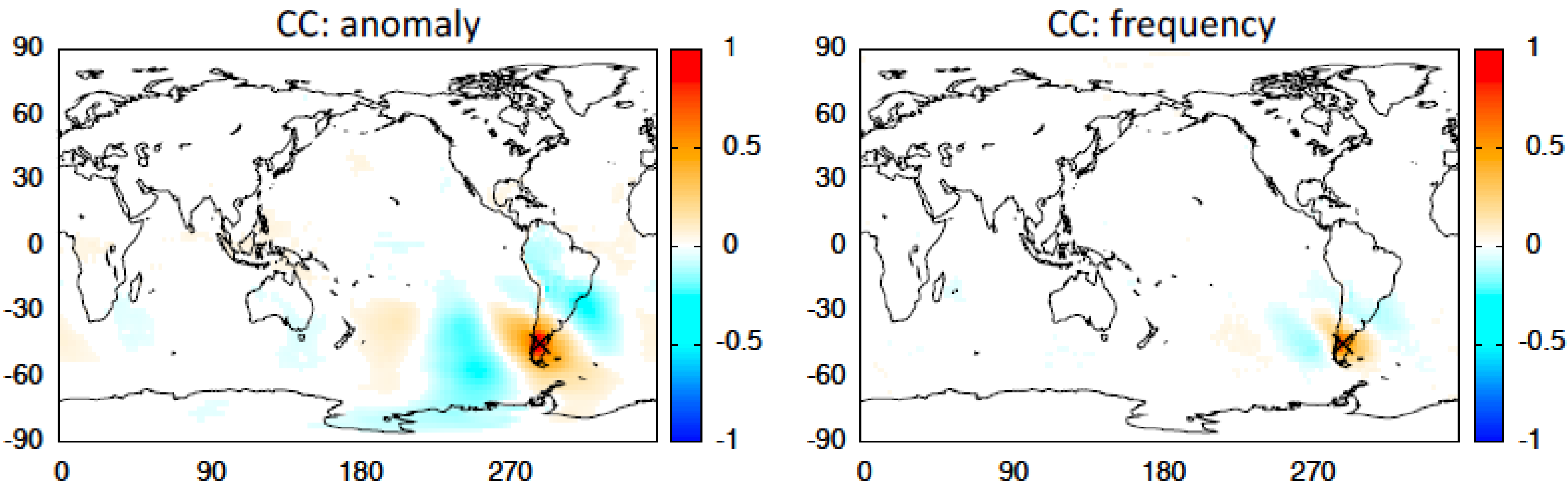


Bivariate analysis: extra-tropics



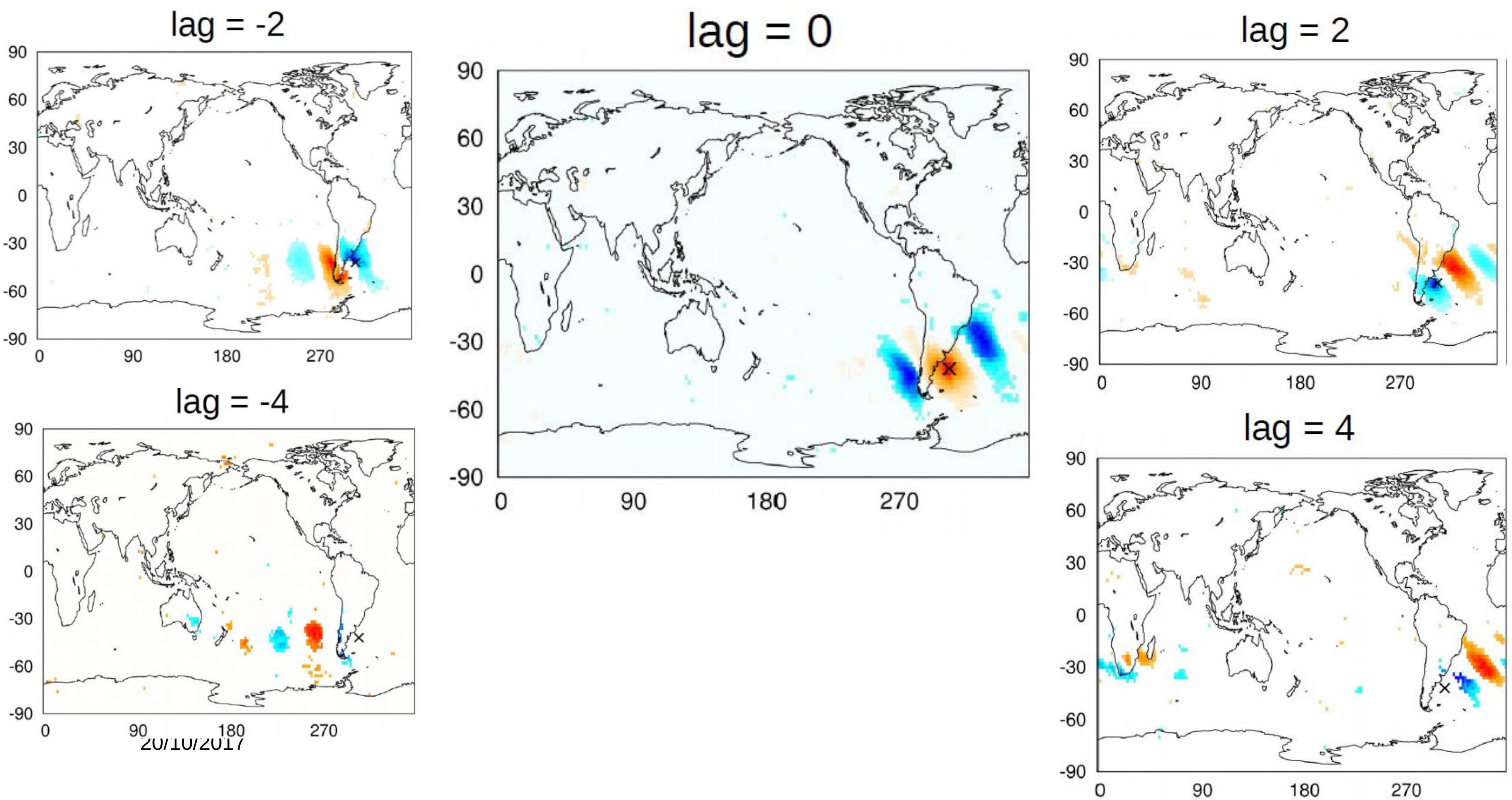


Significance: 100 surrogates (anomaly TS or Hilbert TS), then use 3σ confidence level


CC: anomaly
CC: frequency
90
60
30
0
-30
-60
-90
0
90
180
270
1
0.5
0
-0.5
-1

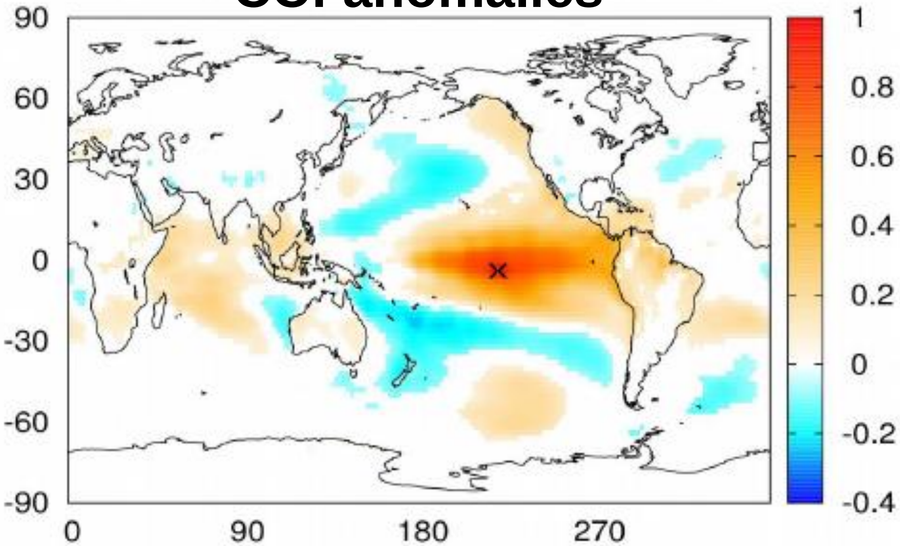
Lagged correlations?

- In the extra-tropics, lag (in days) cross-correlations of Hilbert frequencies.

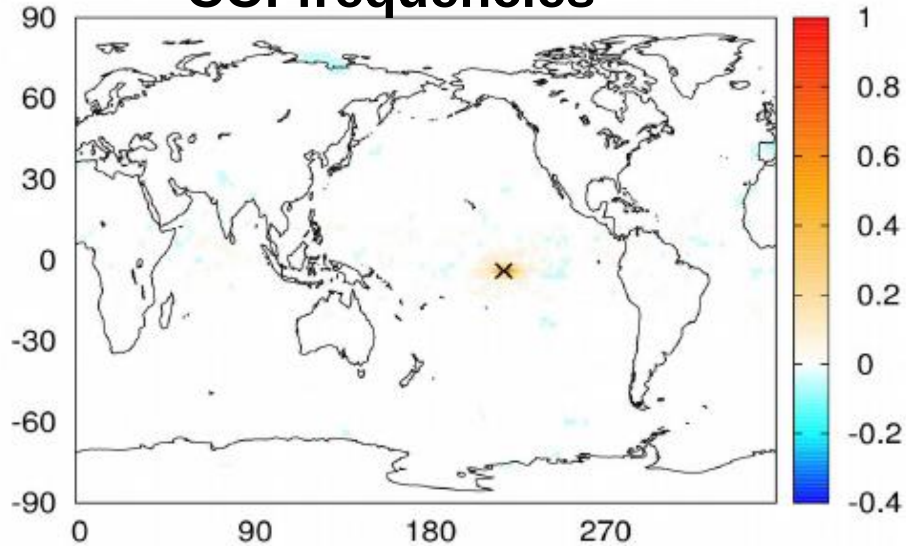


But in the El Niño region

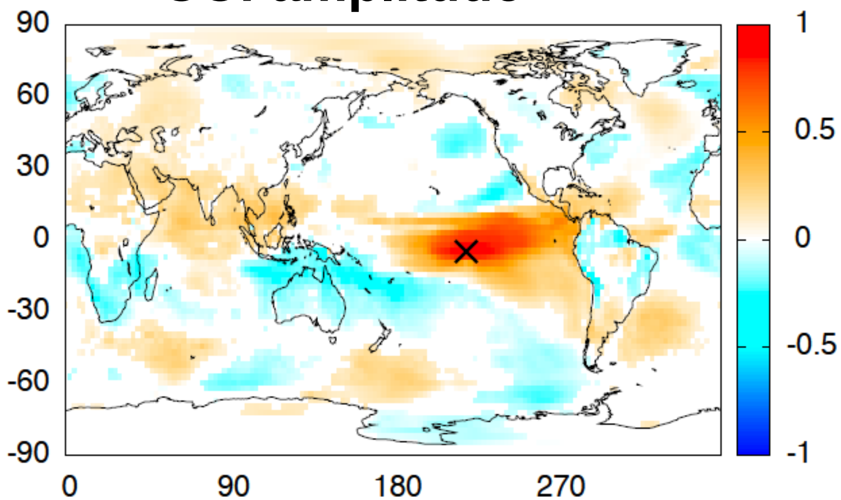
CC: anomalies



CC: frequencies

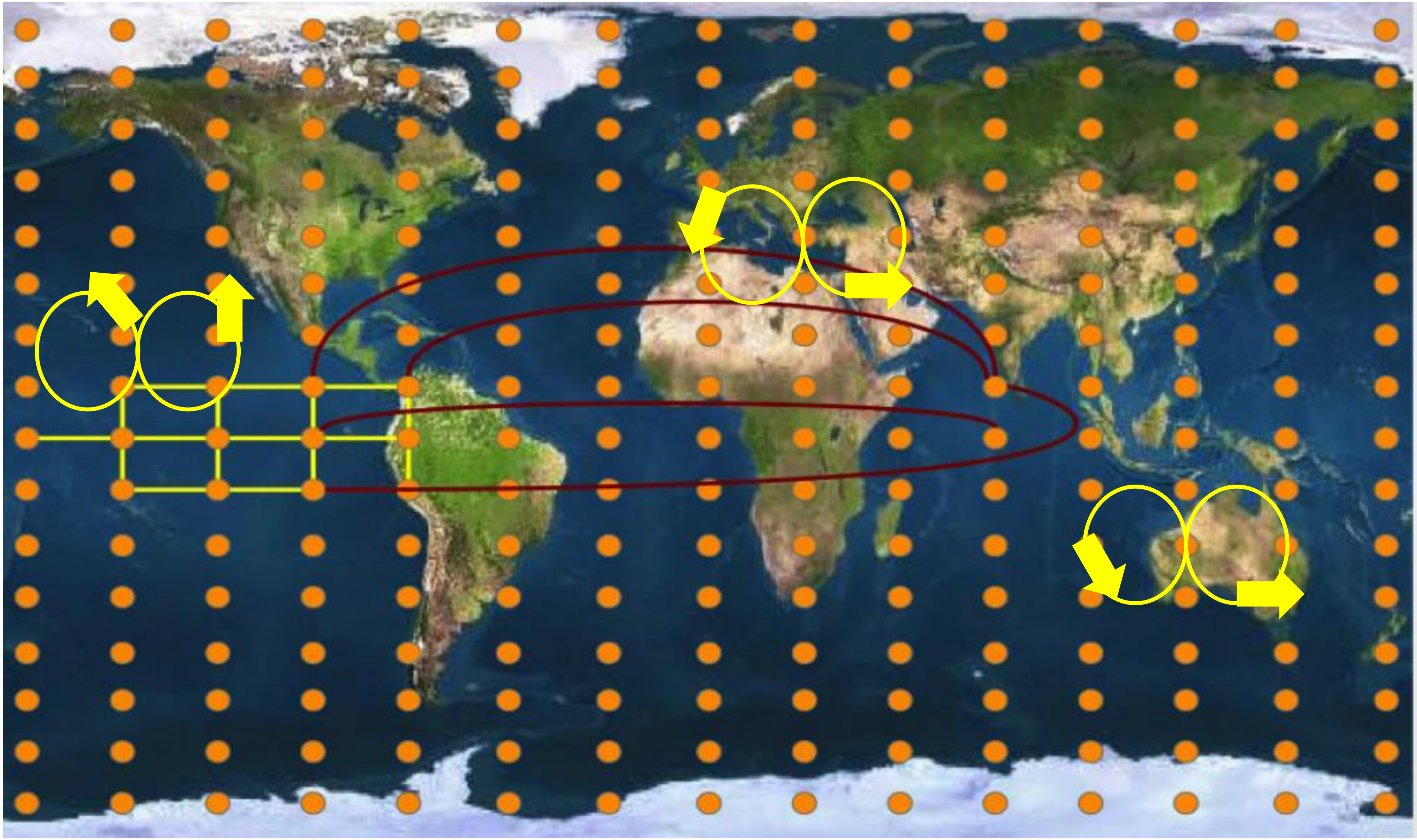


CC: amplitude



$\Rightarrow$ Frequency dynamics in the tropics not synchronized with the extra-tropics

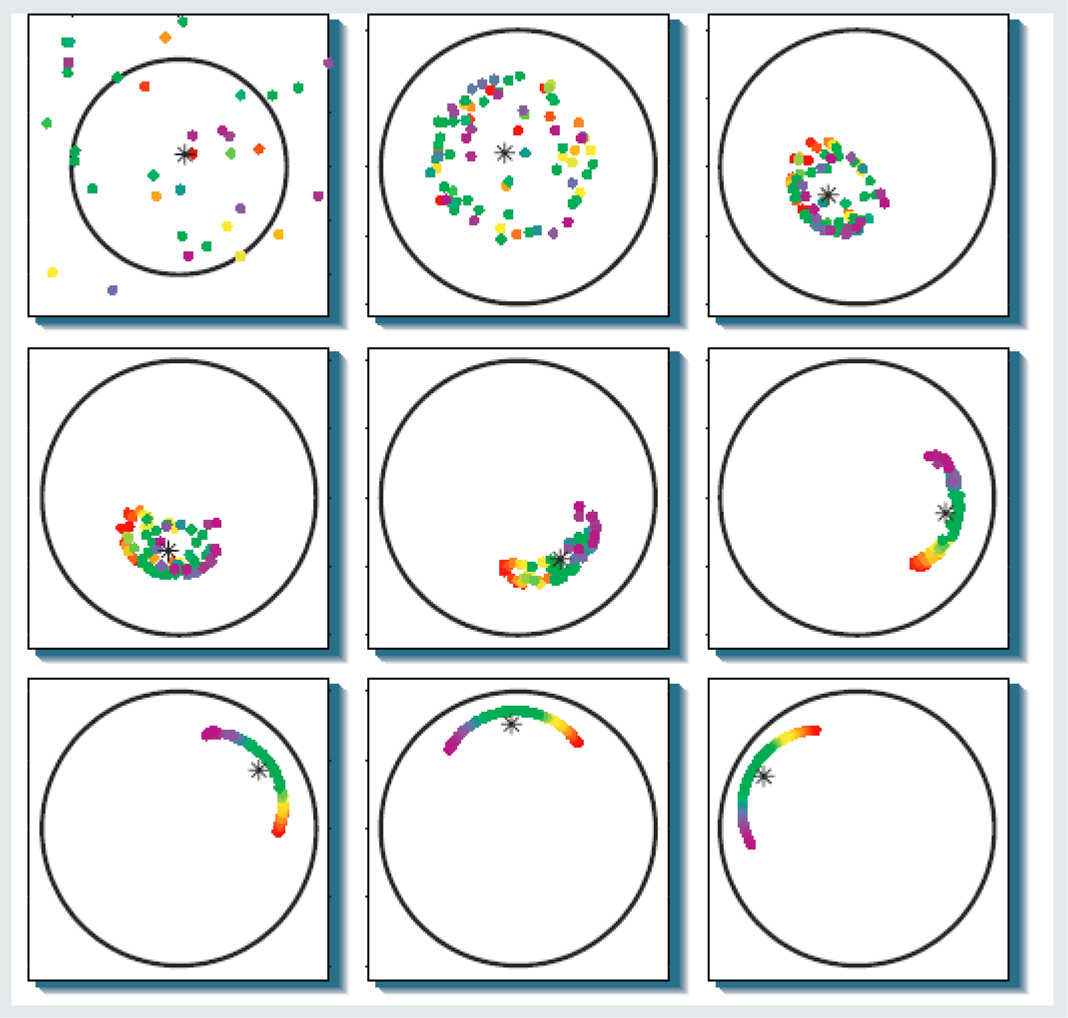
Network of individual oscillators



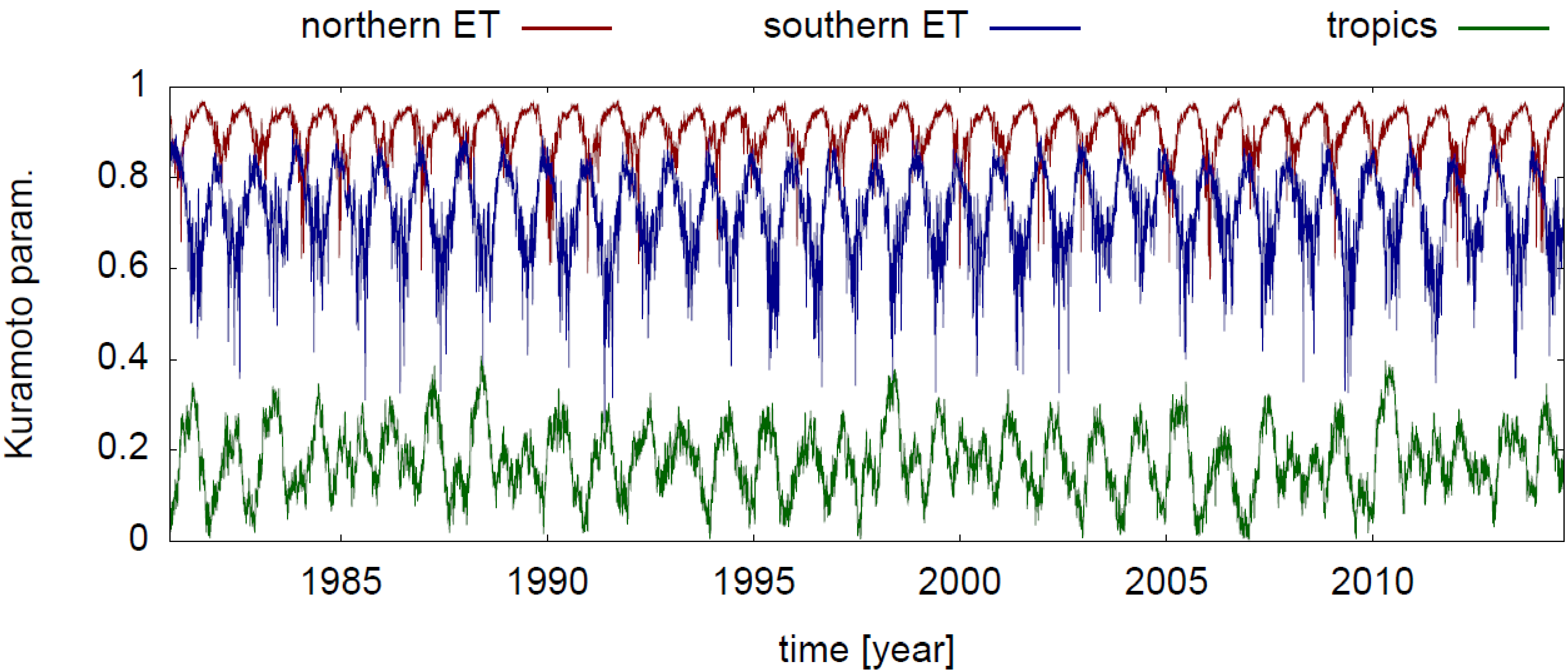
Quantifying phase synchronization

- Kuramoto order parameter

$$r(t) = \left| \frac{1}{N} \sum_{j=1}^{N} e^{i\theta_j(t)} \right|$$



Steven H. Strogatz, Nature 2001


northern ET
southern ET
tropics
Kuramoto param.
1
0.8
0.6
0.4
0.2
0
1985
1990
1995
2000
2005
2010
time [year]

Unveiling inter-decadal changes

-can amplitude and frequency variations be used as a quantitative measure of regional climate change?

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Relative inter-decadal variation (ERA-Interim, 37 years)

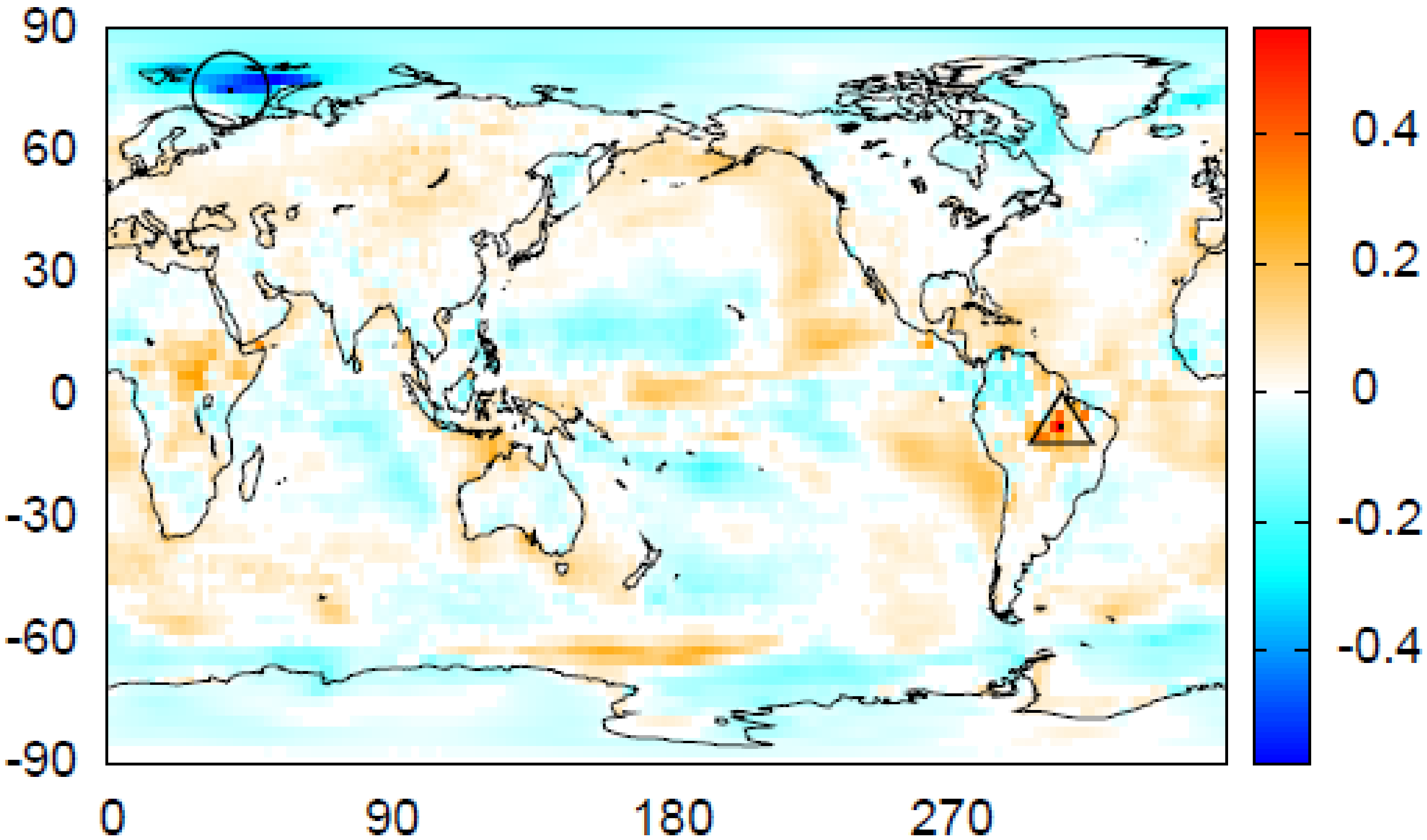
$$\Delta a = \langle a \rangle_{2016-2007} - \langle a \rangle_{1988-1979}$$

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

Significance analysis: For each amplitude time series 100 shuffle surrogates were generated, and the relative change is significant if:

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

Relative change of time-averaged Hilbert amplitude

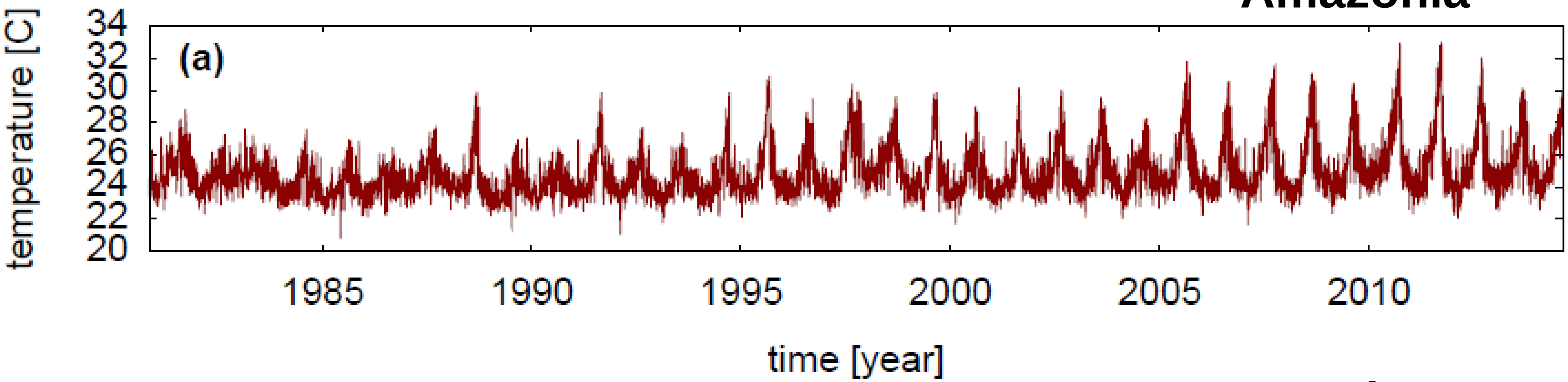


Melting of sea ice: during winter the air temperature is mitigated by the sea and tends to have more moderated values

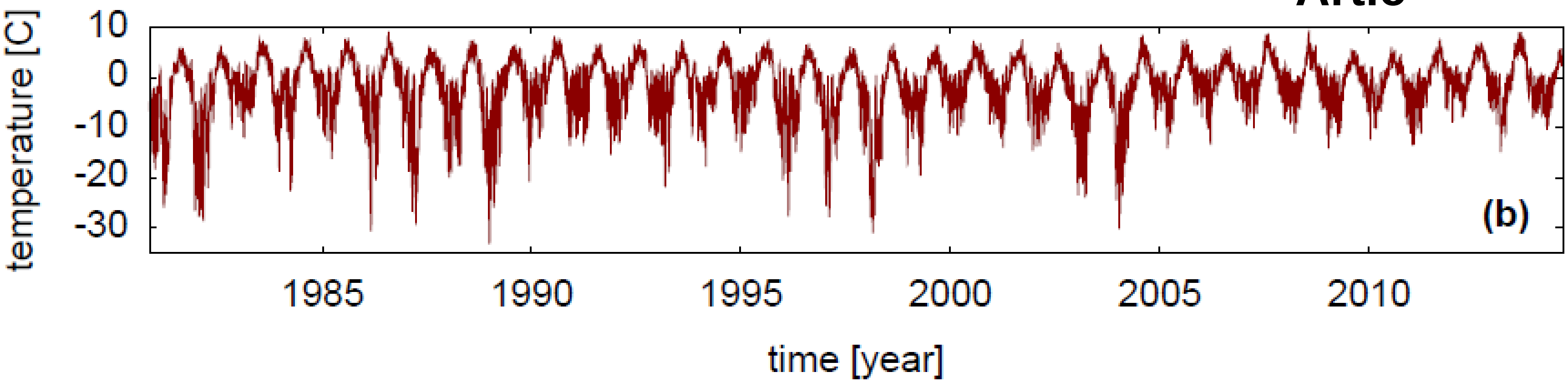
Decrease of precipitation: the solar radiation that is not used for evaporation is used to heat the ground.

Hotspots

Amazonia



Artic



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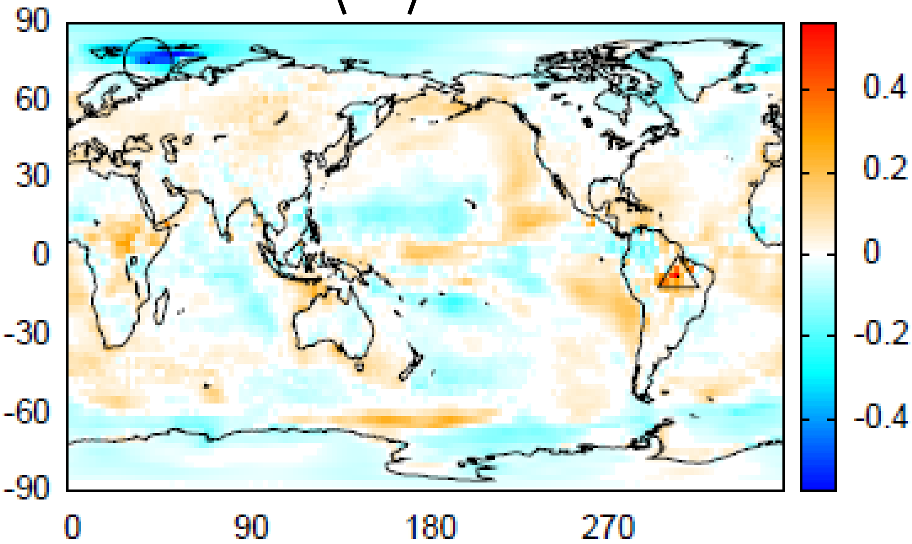
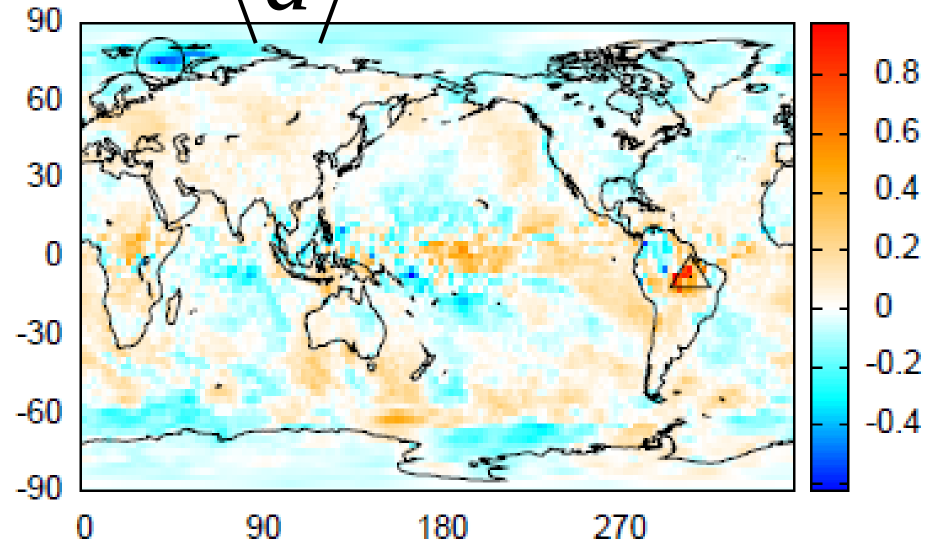
Hilbert amplitude variation consistent with climatology variation

$$\frac{\Delta a}{\langle a \rangle} \qquad \frac{\Delta a^{c\lim}}{\langle a \rangle^{c\lim}}$$





$$a_j^{(\mathrm{clim})}(I) = \max[c_j^I(t)] - \min[c_j^I(t)]$$

I = time interval (2016—2007; 1988—1979; 2016—1979)

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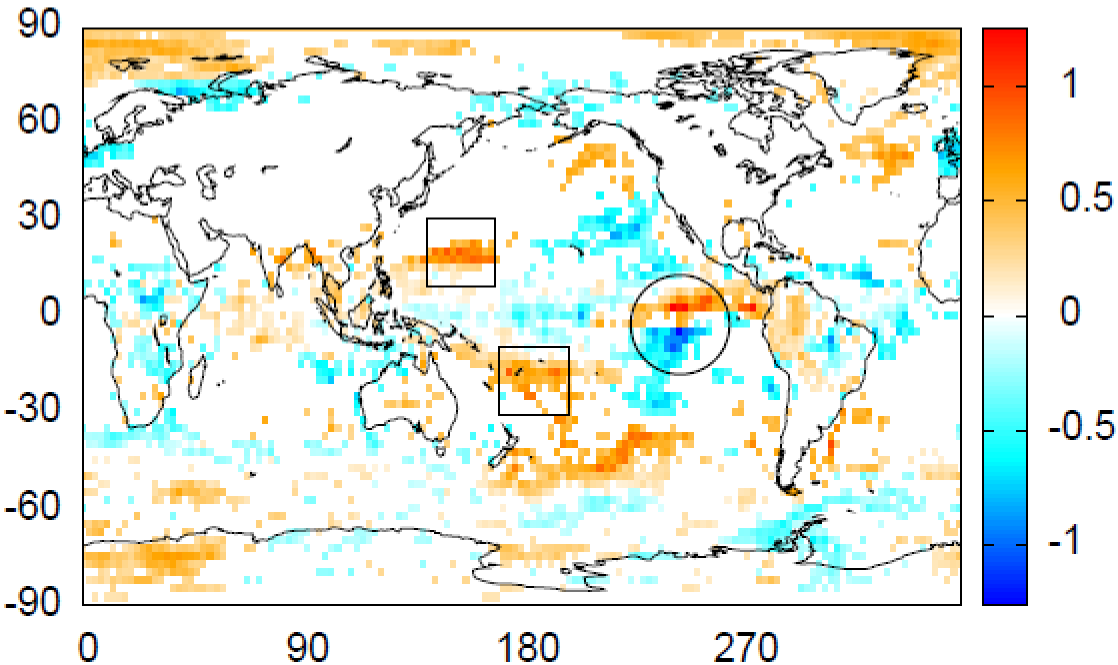
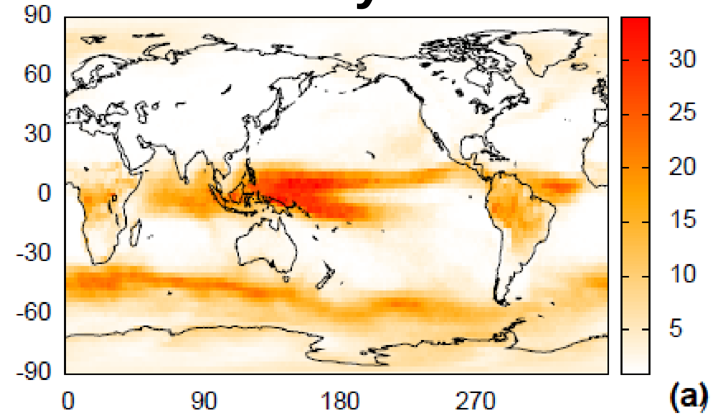
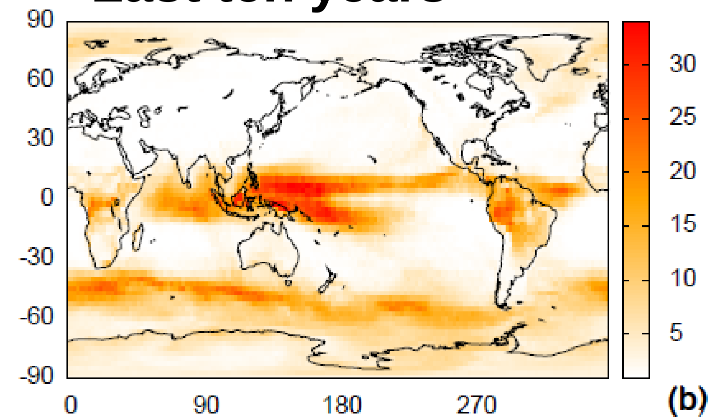
Relative change of time-averaged Hilbert frequency



First ten years



Last ten years



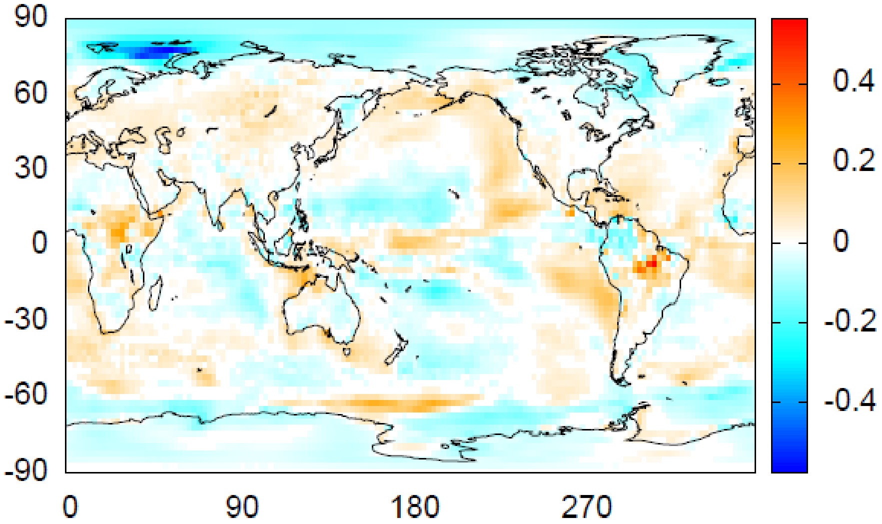
⇒ Consistent with a **shift towards north and a widening of the ITCZ**

⇒ Consistent with variation in the number of zero-crossings

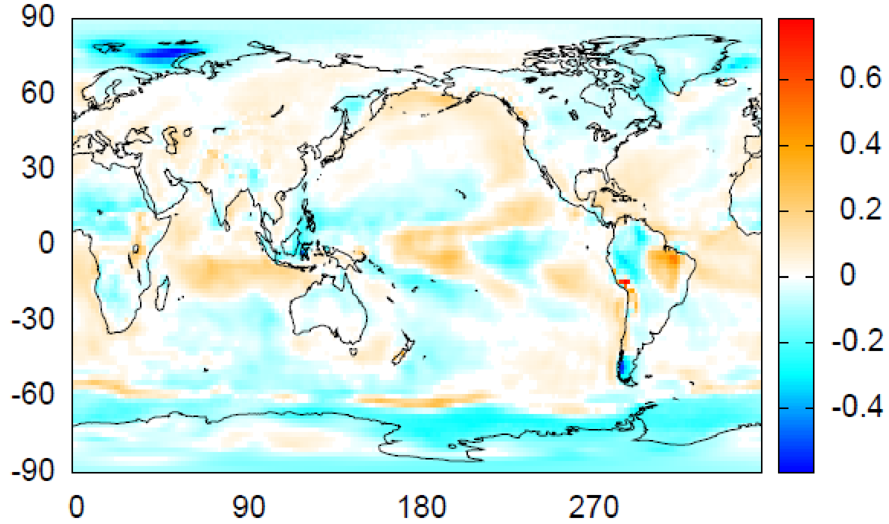
Model inter-comparison (same temporal period and resolution)

Average amplitude inter-decadal variation

ERA-Interim



NCEP-DOE



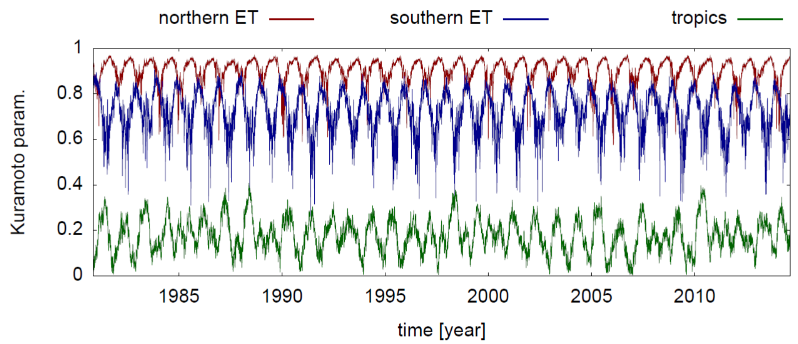
Good qualitative agreement (also in the maps of variations of average frequency the uncover ITCZ migration) but some differences are detected in certain regions.

Conclusions

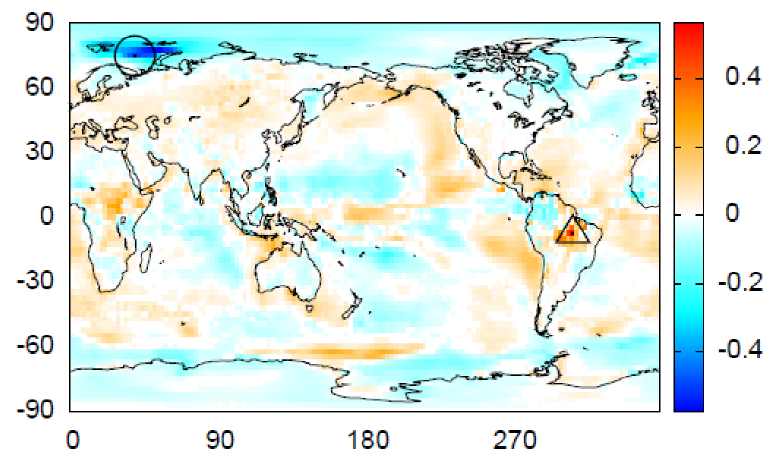
What did we learn?

- Hilbert analysis applied to **raw** climatic data can be useful for investigating synchronization and regional climate changes.

- High phase synchronization in the NH, lower in the SH, and even lower in the tropics.



- Large variations of Hilbert amplitude interpreted as due to ice melting (Arctic) or precipitation decrease (in Amazonia).
- Ongoing work: predictive power?



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G. Tirabassi and C. Masoller, "*Unravelling the community structure of the climate system by using lags and symbolic time-series analysis*", Sci. Rep. 6, 29804 (2016).

F. Arizmendi, M. Barreiro, C. Masoller, "*Identifying large-scale patterns of unpredictability and response to insolation in atmospheric data*", Sci. Rep. 7, 45676 (2017).

D. A. Zappala, M. Barreiro, and C. Masoller, "*Global atmospheric dynamics investigated by using Hilbert frequency analysis*", Entropy 18, 408 (2016).

D. A. Zappala, M. Barreiro, and C. Masoller, "*Quantifying interdecadal changes in large-scale patterns of surface air temperature variability*", submitted (2017).