Chaos in Weather and Climate Science

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EcoClim – Orsay 2018

OUTLINE

1) **What are the implications of chaos in climate dynamics?**

2) **Can we use theoretical physics tools (rather than jut statistics or big climate models) to study climate phenomena?**

3) **What do we know about predictability in climate?**

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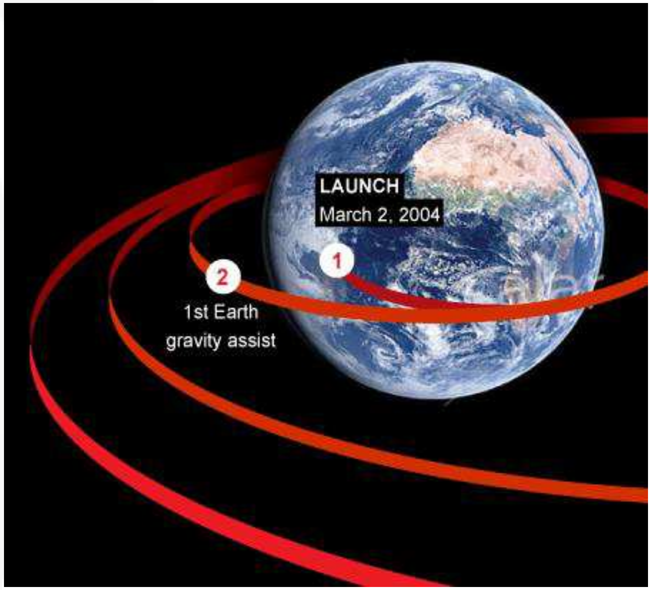
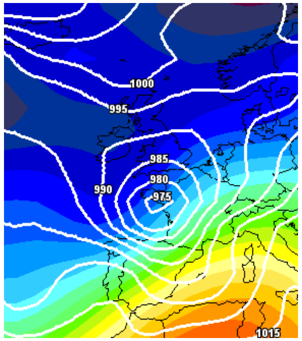
Use of differential equations
to predict the motion (trajectory) of a material point

Foucalt Pendulum

Rosetta Trajectory

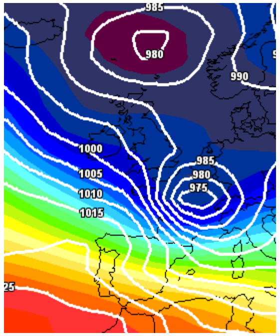


Weather Forecast



TODAY

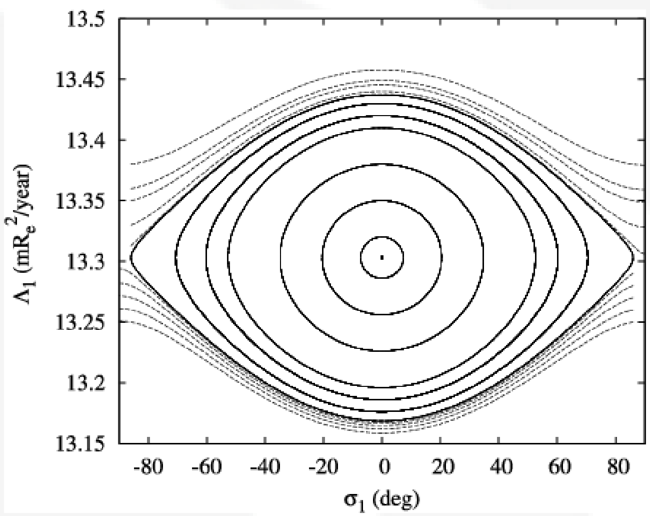
TOMORROW



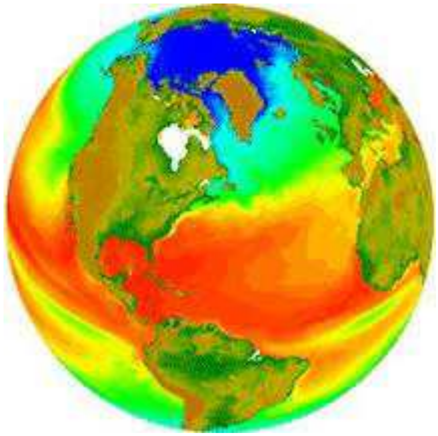
Lagrange - Mécanique analytique (1788),

USES OF DYNAMICAL SYSTEMS THEORY

Reconstruct all the possible configurations of a system, discriminating the most probable ones.



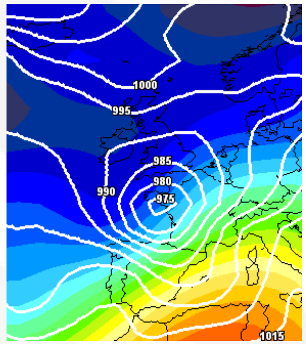
Pendulum Phase Space

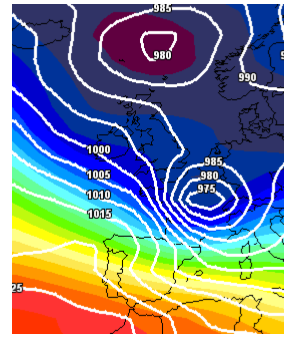


Climate

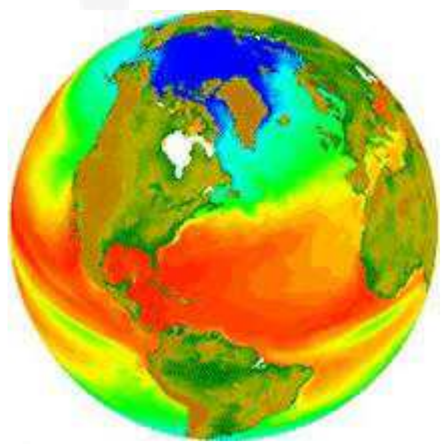
Ludwig Boltzmann, Henri Poincaré, and Willard Gibbs (XIX and XX century)

Weather forecast ➔ Single Trajectory

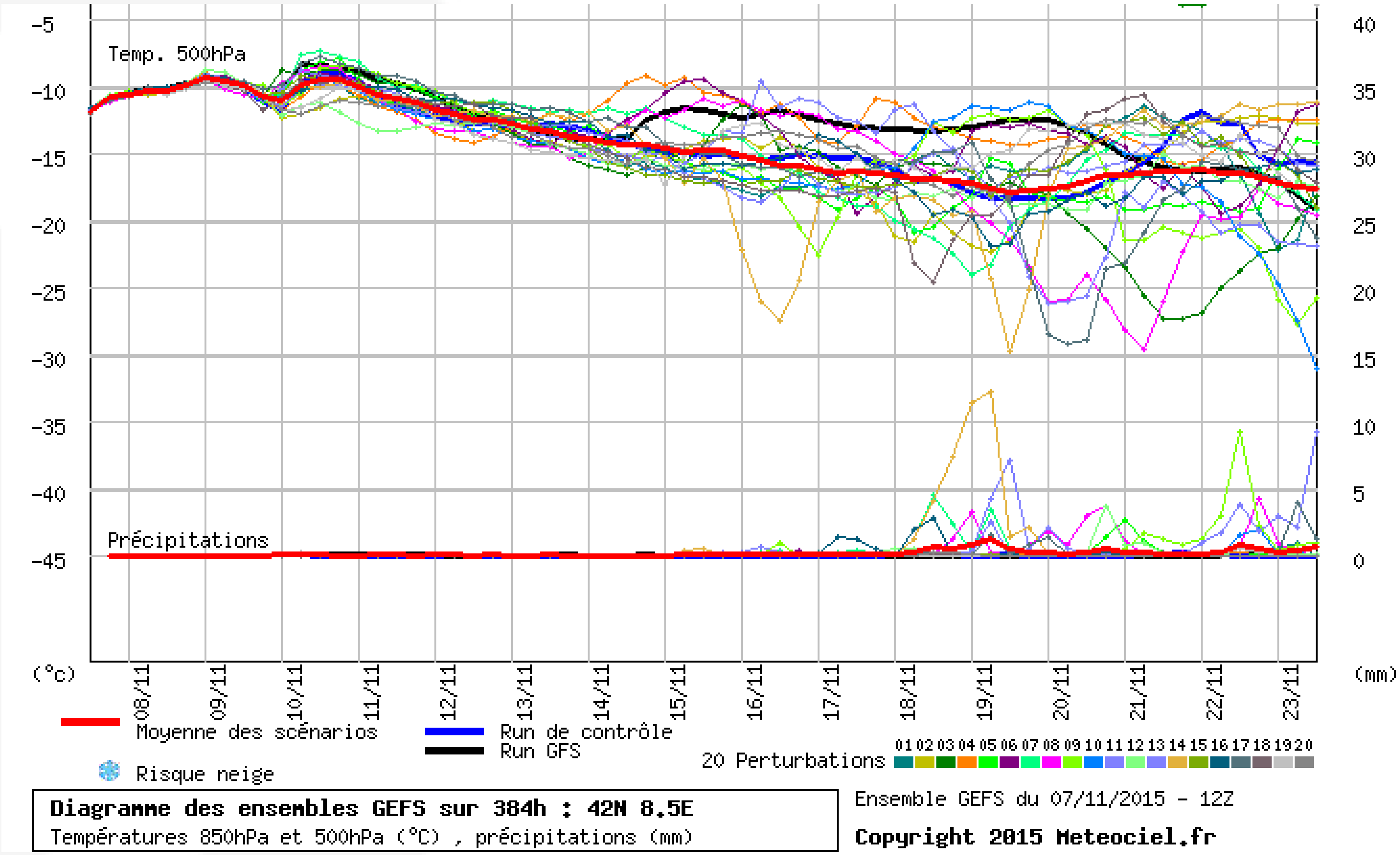




Climate ➔ All possible trajectories

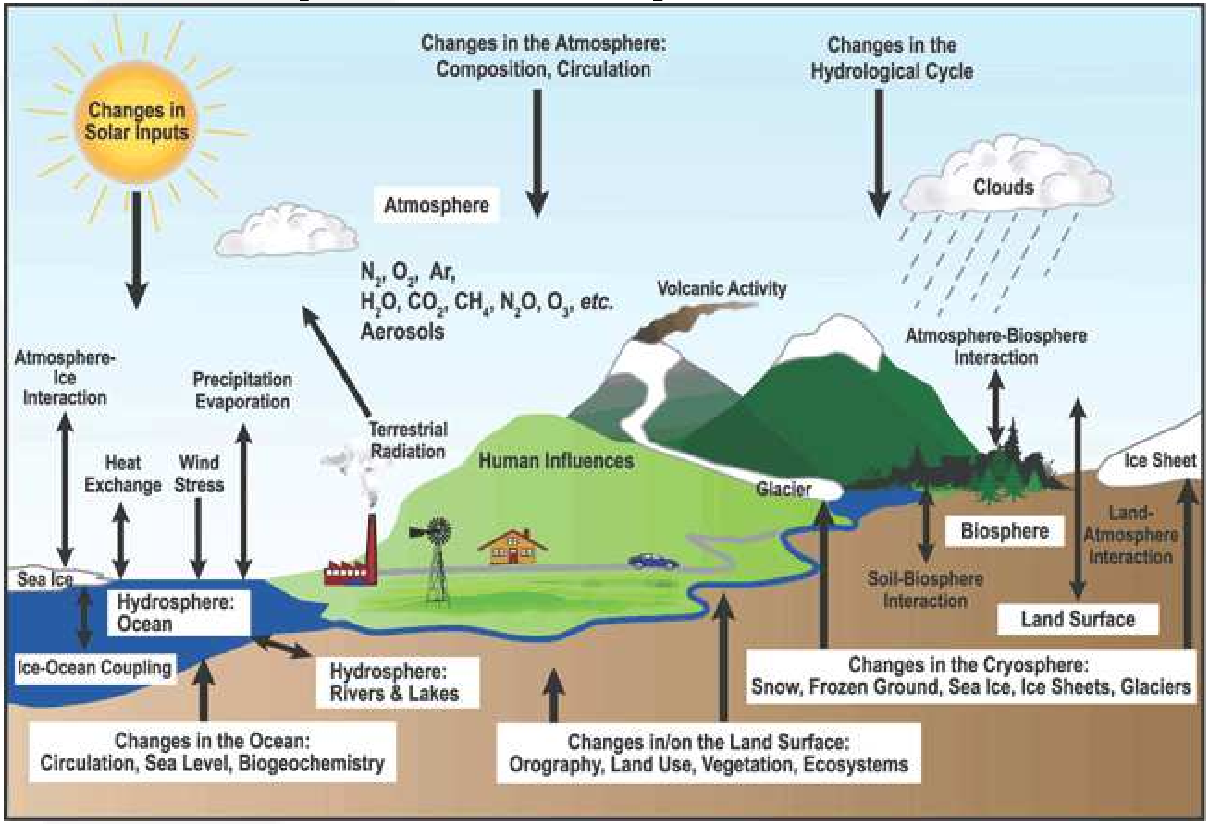


Chaos limits predictability



Lorenz (1963)

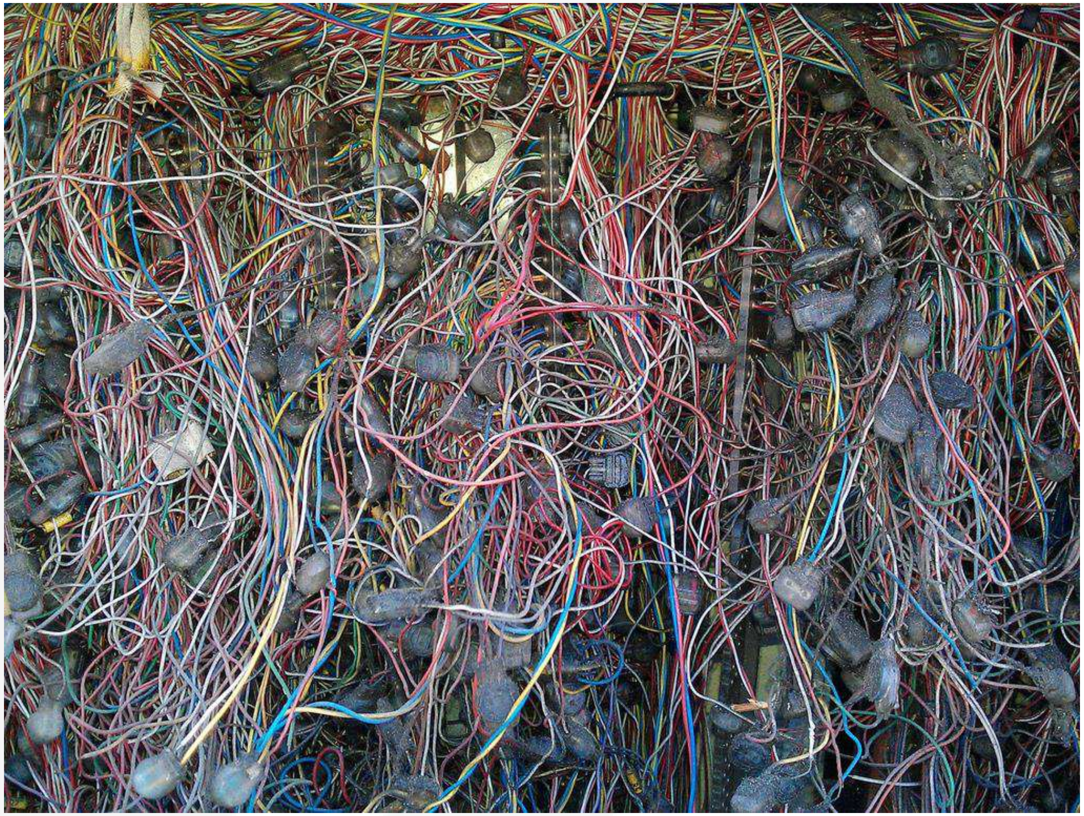
Complexity limits the possibility of reconstruct all possible trajectories



Landau (~1950), Nicolis and Nicolis (1987)

A DEFINITION OF COMPLEXITY

Complexity → No suitable definition of material points



Too many variables

Too many spatial scales

Too many time scales

Interaction between time and spatial scales

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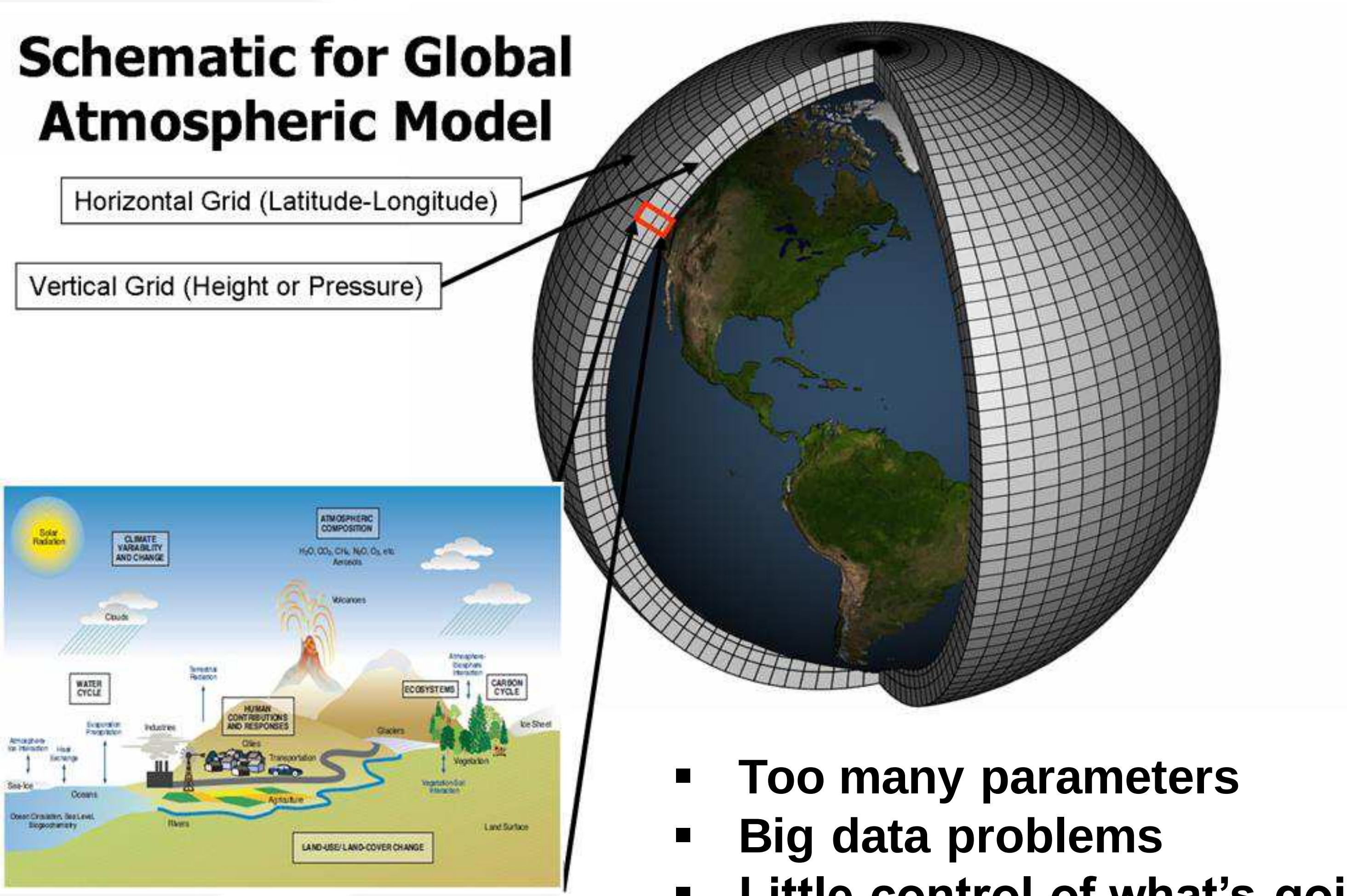
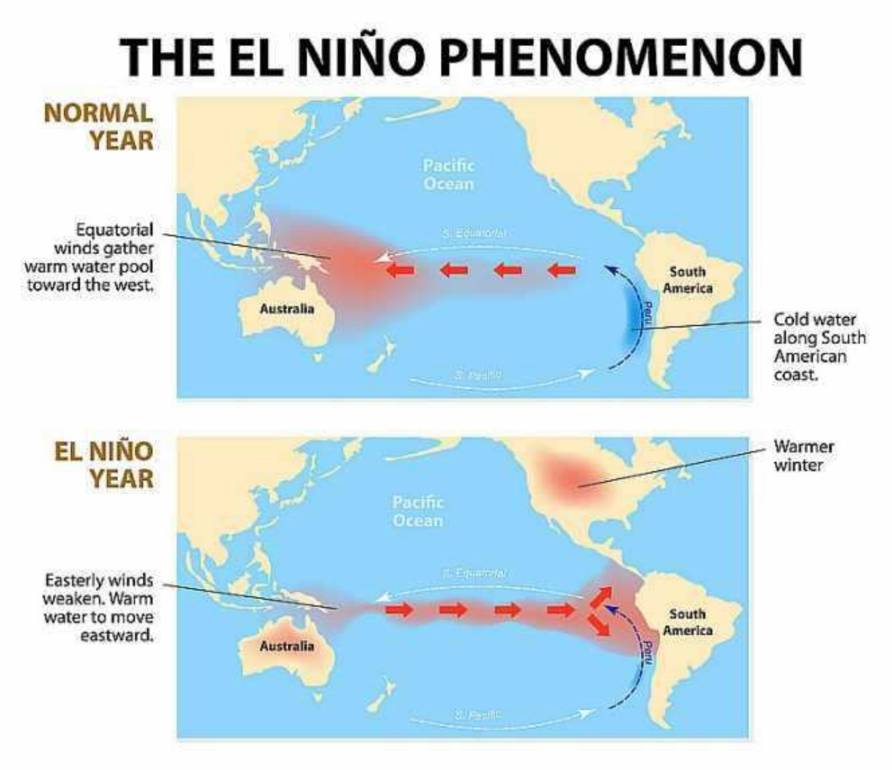
ARE CLIMATE MODELS THE ONLY TOOLS?



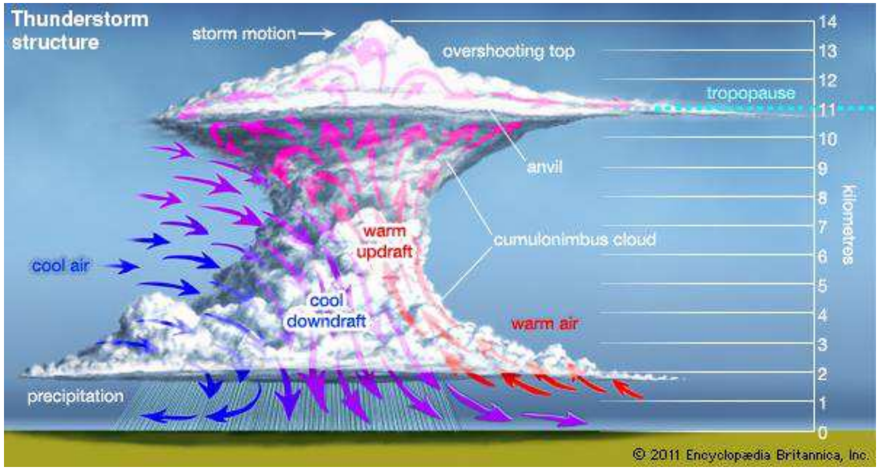
- **Too many parameters**
- **Big data problems**
- **Little control of what's going on**

FOCUS ON « WELL » DEFINED PROBLEMS: EXAMPLES

THE EL NIÑO PHENOMENON



THUNDERSTORM DYNAMICS



- **One phenomenon**
- **Few Variables**
- **One scale**

THE LORENZ 1963 MODEL FOR CONVECTION

1) **Reduce the number of degrees of freedom.**
2) **Find some good order parameters.**

LORENZ 63 system (Rayleigh Bénard convection)

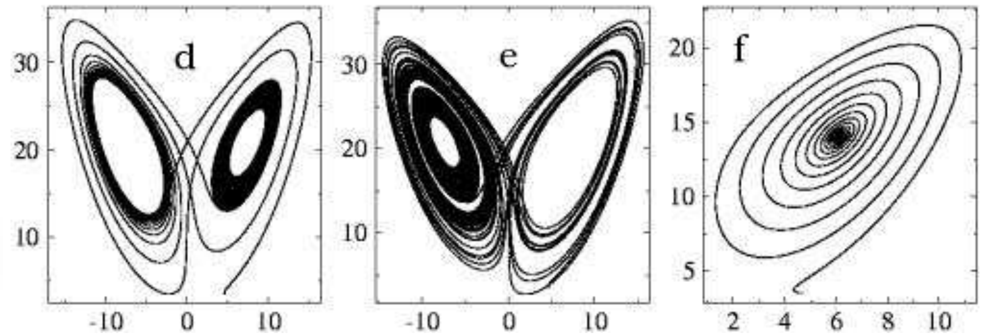
$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = rx - y - xz$$

$$\frac{dz}{dt} = xy - bz$$

Change of σ , r ➔

y

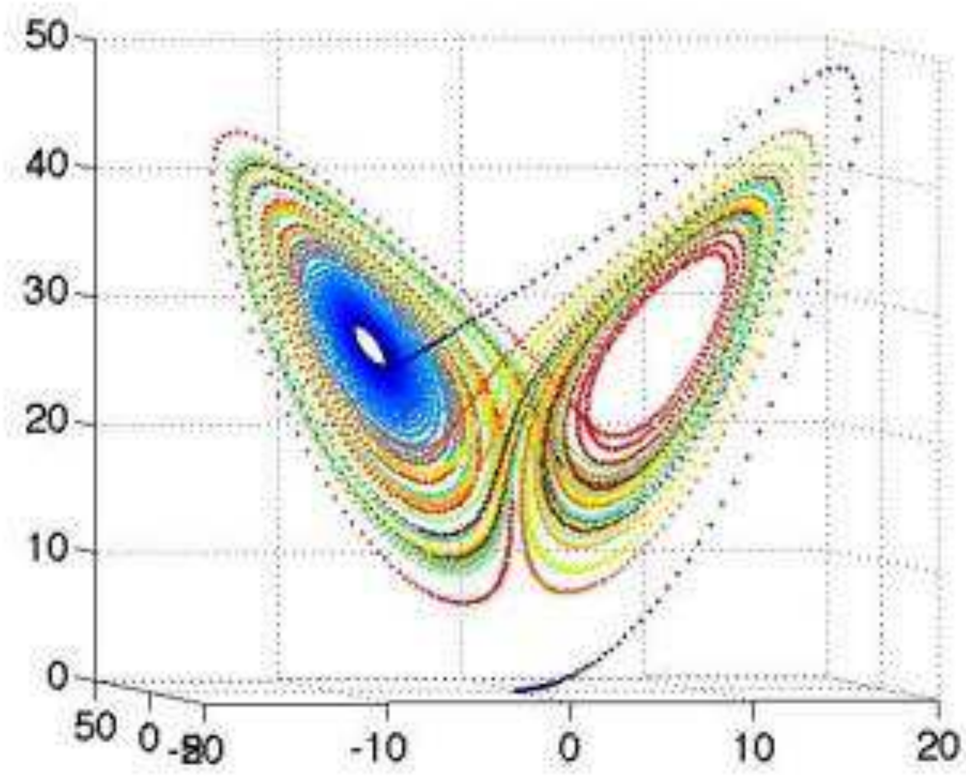


x

σ , r Prandtl and Reyleigh Number, b: ratio of critical parameters
x: convection strength , y: difference of temperature, z: asymmetry

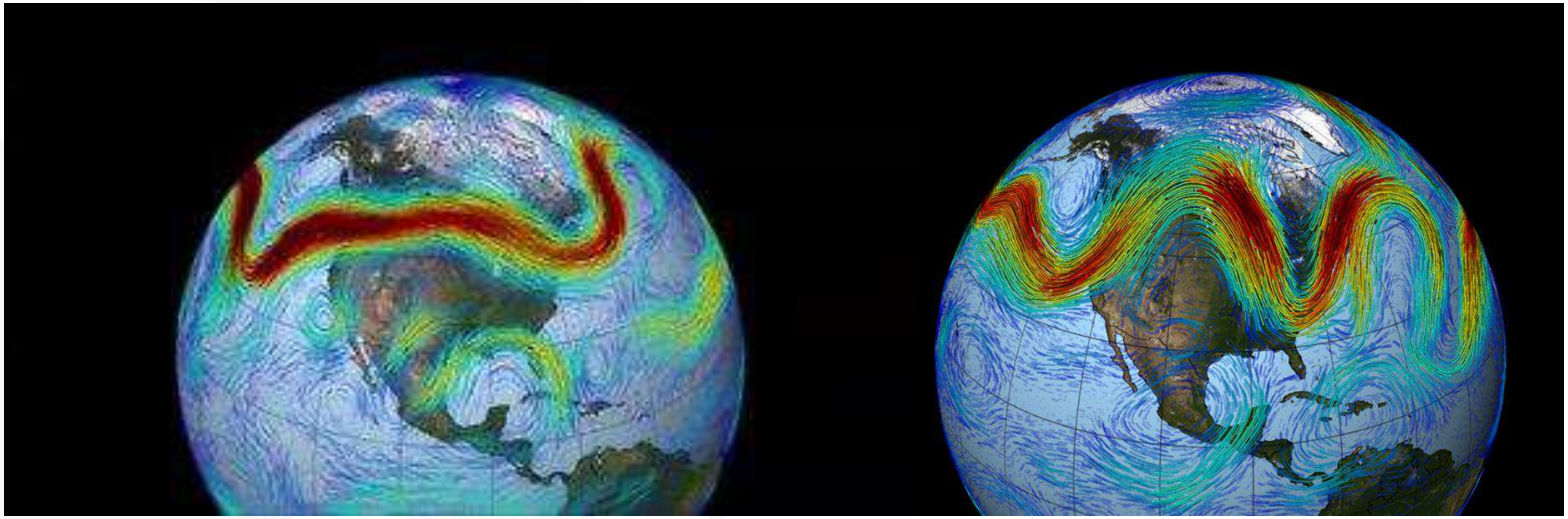
THE LORENZ 1963 MODEL FOR CONVECTION

1) **The motion sets on an attracting set.**
2) **The Lorenz butterfly as a prototype of atmospheric chaos**



METASTABLE STATES IN THE ATMOSPHERIC CIRCULATION?

Picture: Winds at about 10 km height: red >200km/h



Zonal Jet Stream **Wavy Jet Stream**

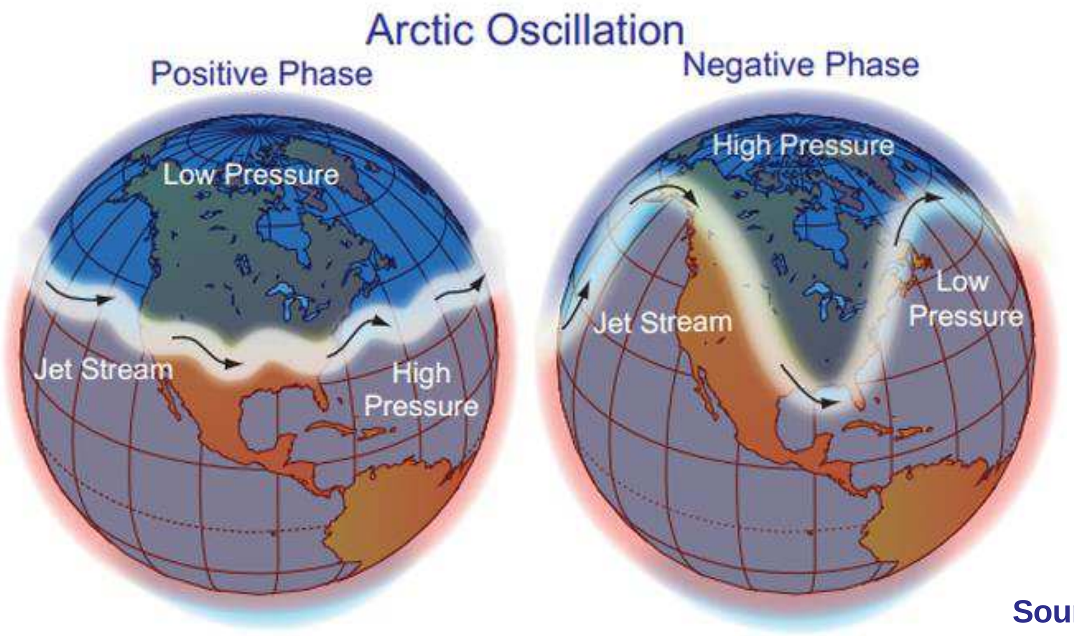
Can we define them as Metastable States?

Landau (~1950), Nicolis and Nicolis (1987)

METASTABLE STATES IN THE ATMOSPHERIC CIRCULATION?

TOOLS: Analysis of local properties of Atmospheric indexes

EXAMPLE : Dynamics of Atmospheric Blocking Phenomena



Source: NOAA website

Zonal flow **Blocking**

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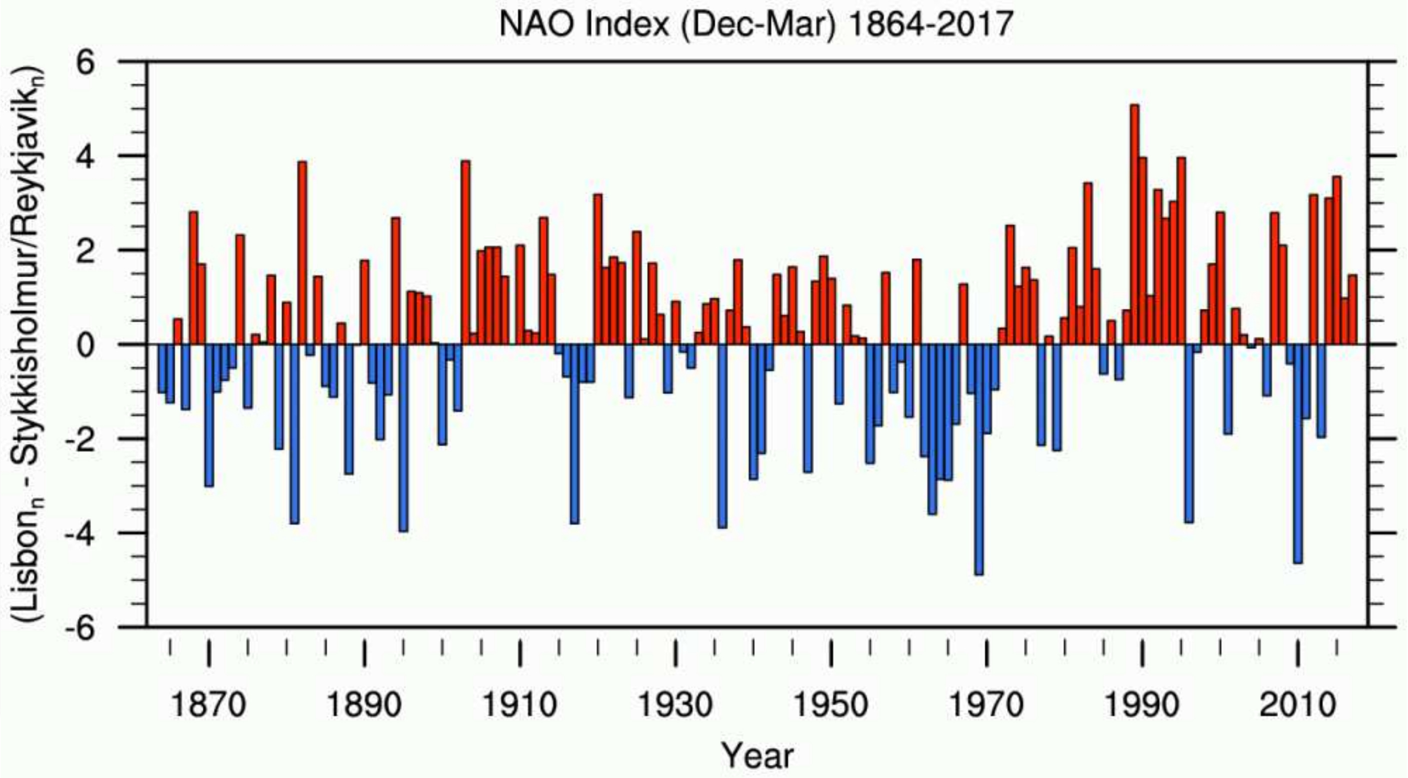
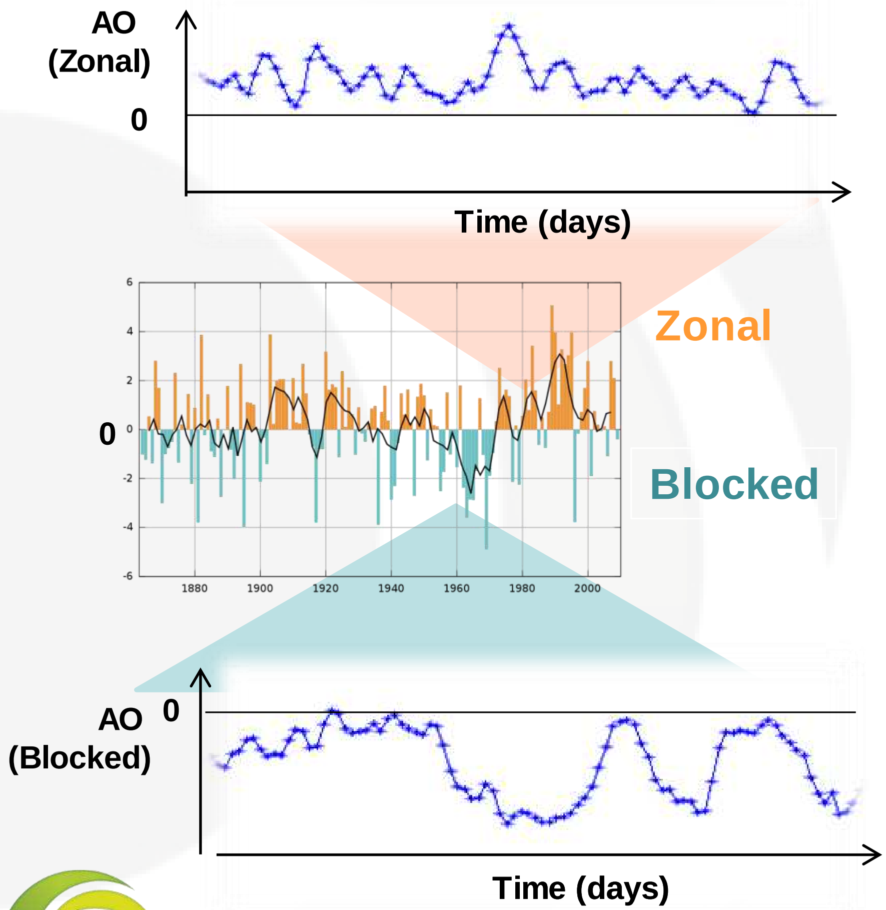


Atmospheric Blocking Index

The Artic Oscillation (AO) index



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Atmospheric Blocking Index

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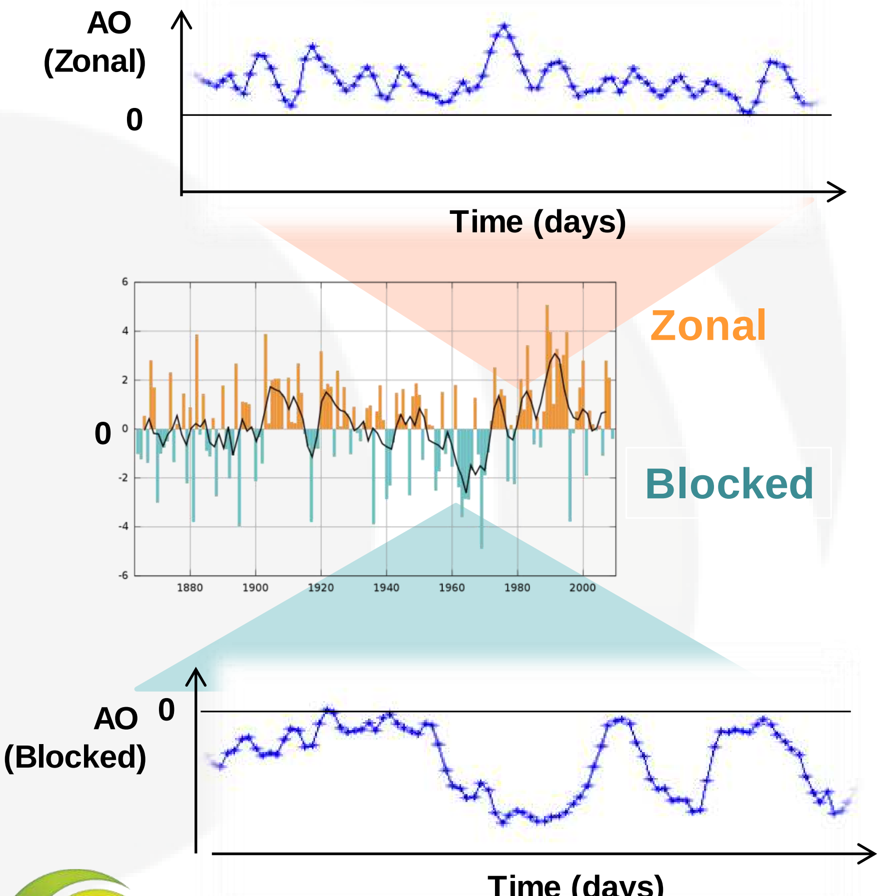
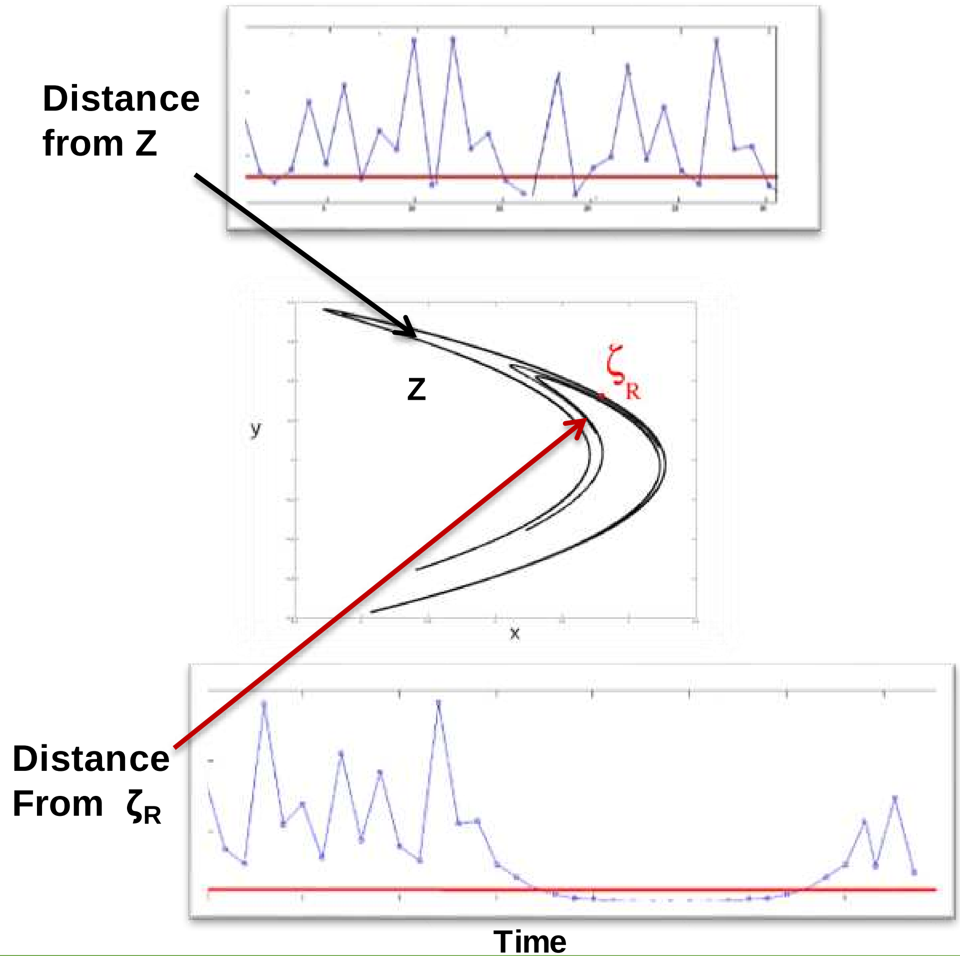


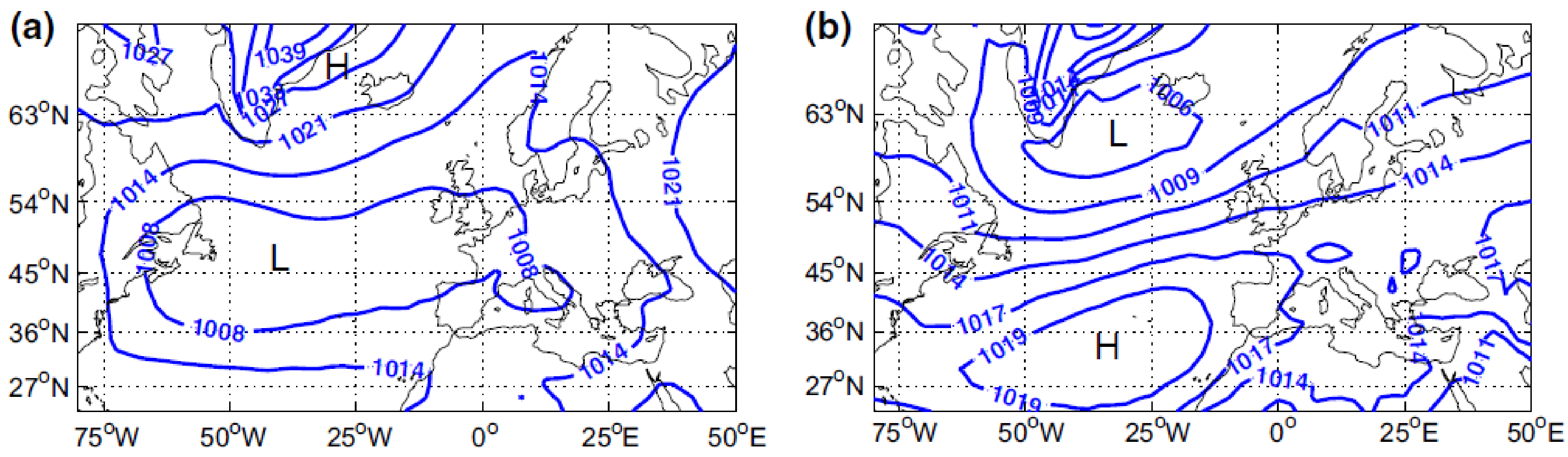
Dynamical Systems

The Hénon Attractor



Metastable state or unstable fixed point?

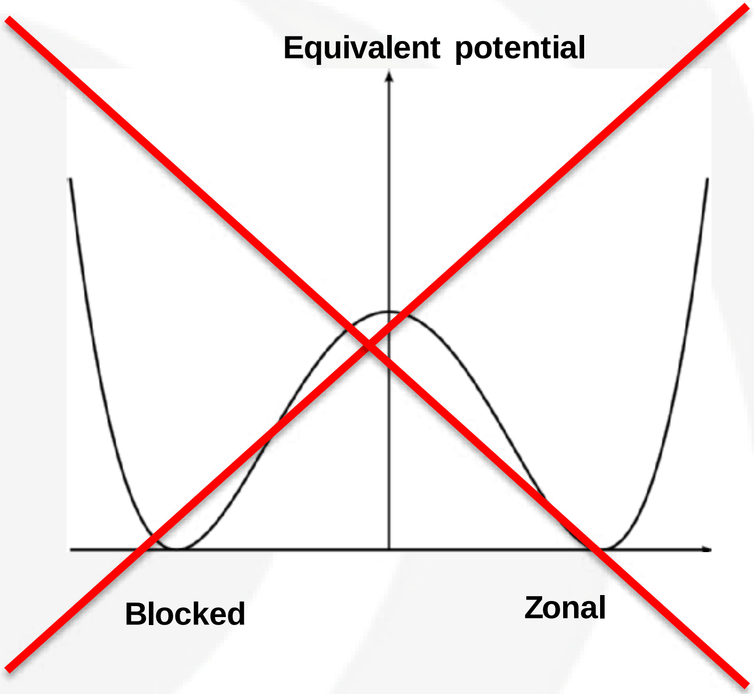
In DF et al 2015 (Climate Dynamics) we detect unstable fixed points in the AO time series from data in the period 1979-2018.

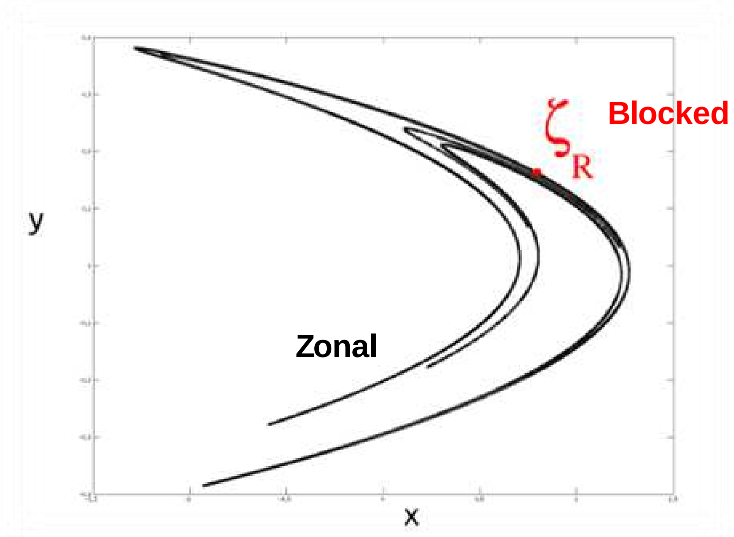


Averaging on unstable fixed points give panel (a) whereas the rest give (b)

METASTABLE STATES IN THE ATMOSPHERIC CIRCULATION?

Our study suggests that there are not proper metastable states but rather a single basin chaotic attractor with unstable fixed point (Like Henon)





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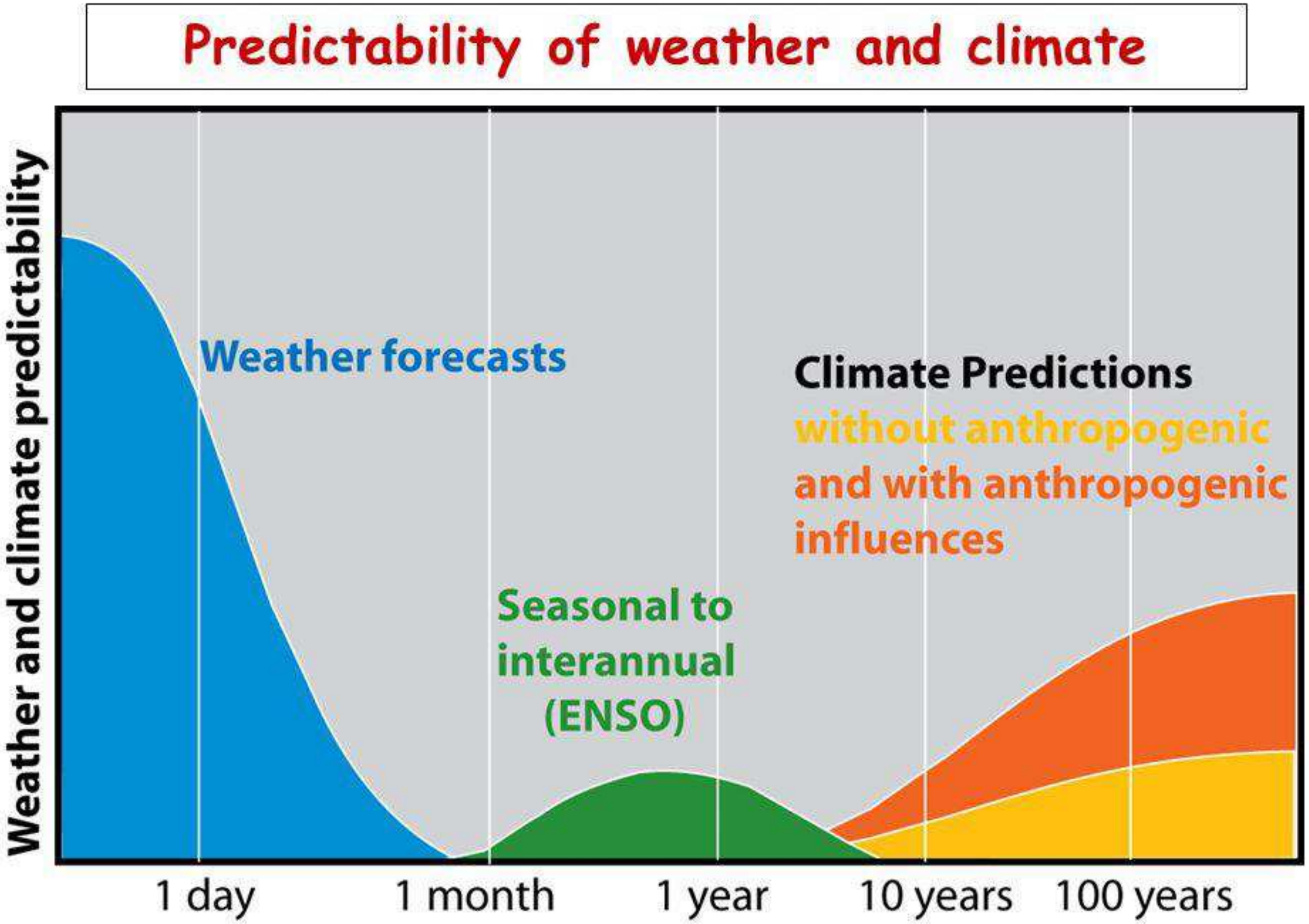
FEW CONCEPTS ABOUT PREDICTABILITY



Source: NCAR

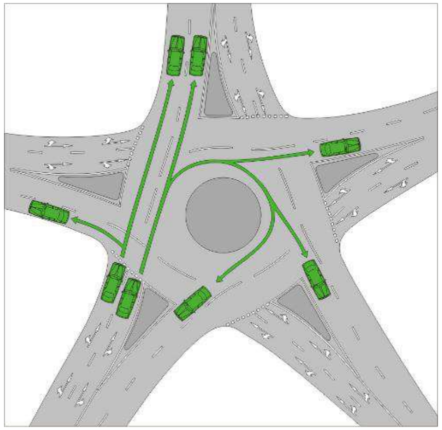
HOW TO MEASURE PREDICTABILTY?

In DF et al 2017 (Scientific Reports) we compute Dynamical Systems metrics to characterize atmospheric states, verifying that a long series of observations sample the underlying attractor.

THE LOCAL DIMENSION: d

It is proportional to the number of possible configurations (**number of degrees of freedom**) originating and resulting from the atmospheric field analyzed.

~Number of possible exits in a roundabout

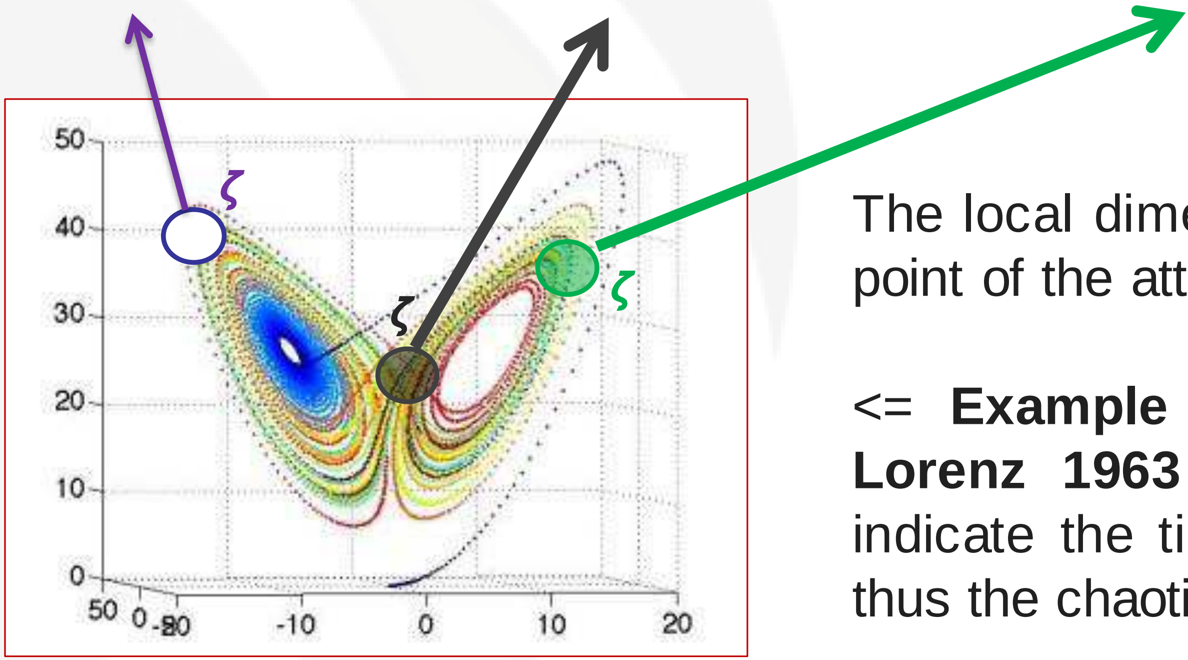


LOCAL DIMENSIONS IN THE LORENZ 1963

Line: d(ζ)=1

Patch: d(ζ)=2

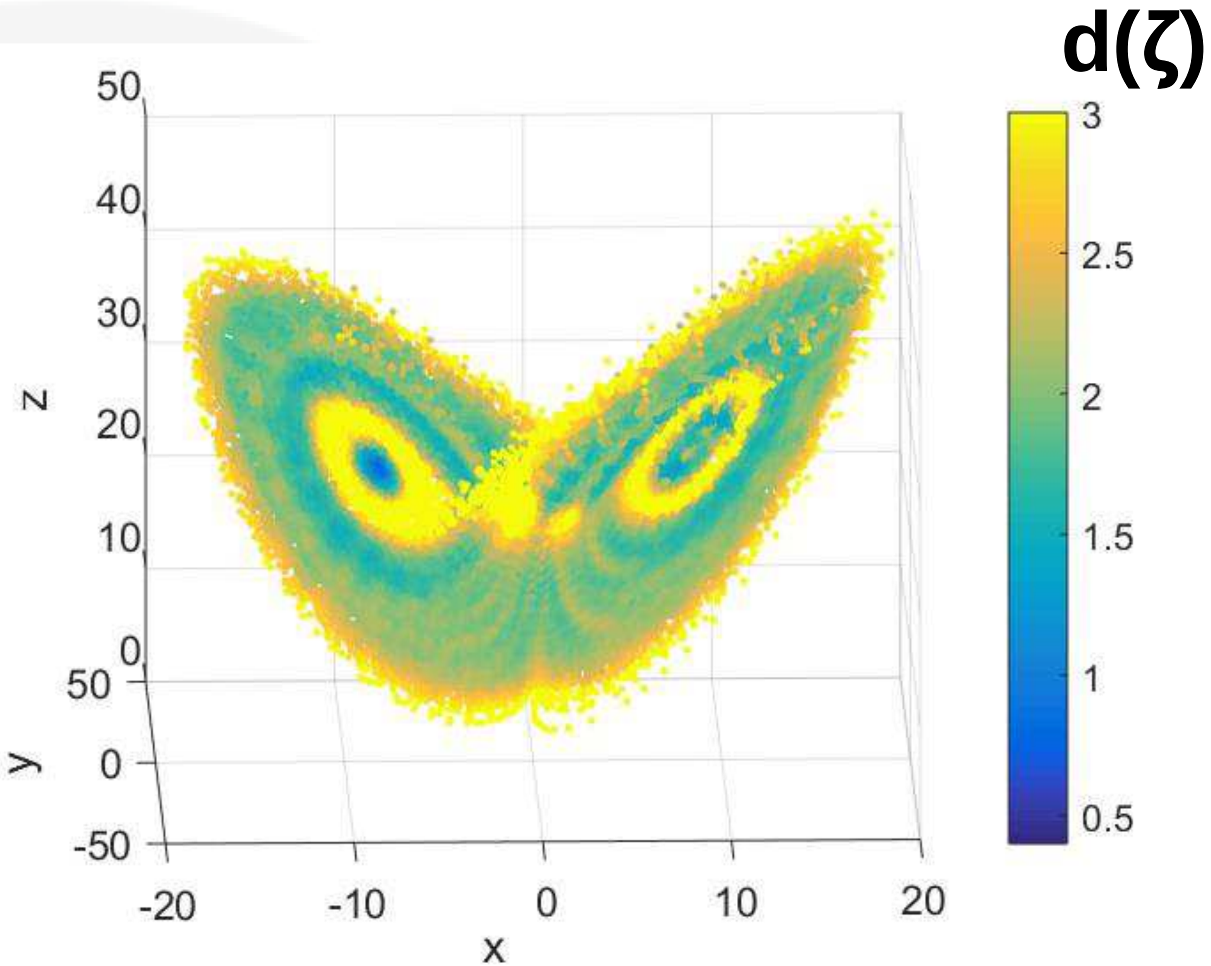
Fractal:1 < d(ζ) < 2



The local dimension depends on the point of the attractor considered

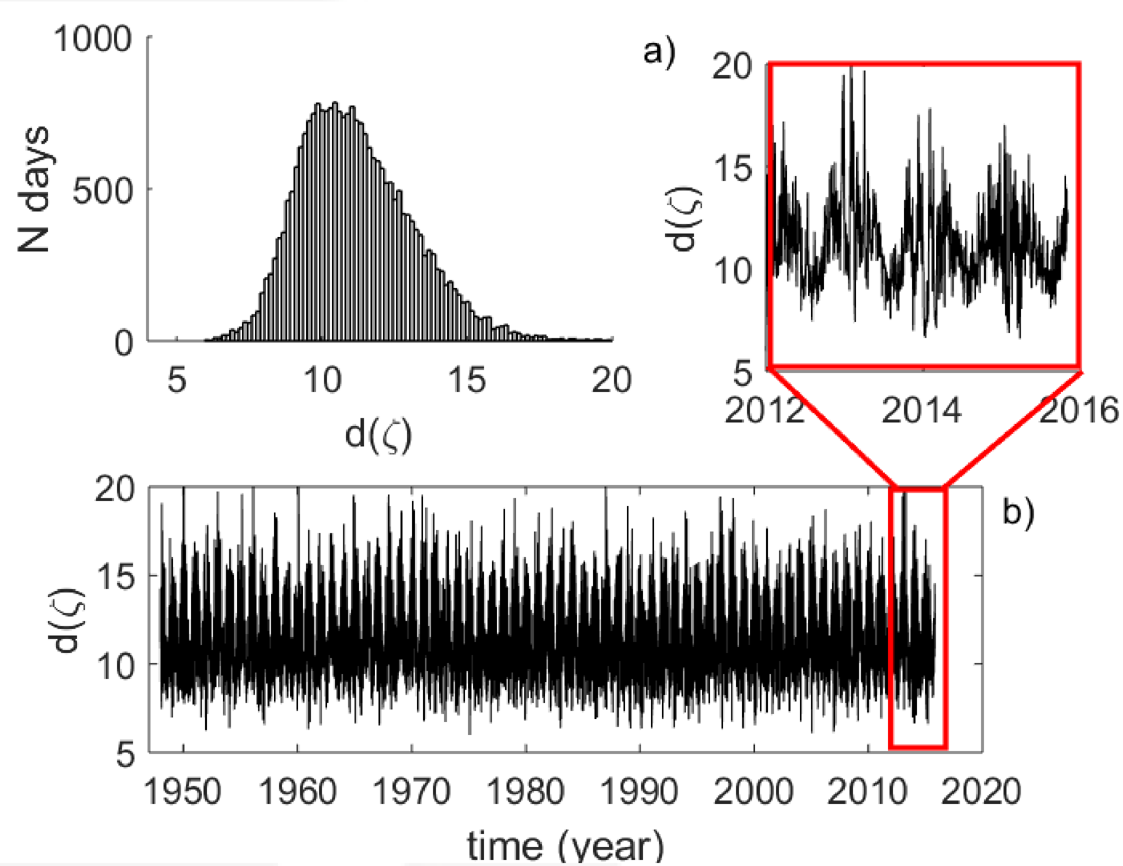
<= **Example of trajectory in the Lorenz 1963 attractor**, the colors indicate the time of the simulations, thus the chaotic behavior

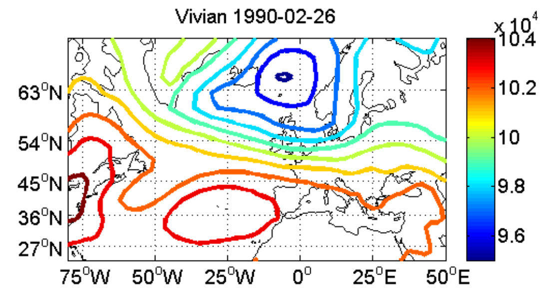
LOCAL DIMENSIONS IN THE LORENZ 1963



The average dimension $< d(\zeta) >_\zeta = 2.06$ is the same as classical estimates

LOCAL DIMENSIONS IN THE NORTH ATLANTIC CIRCULATION

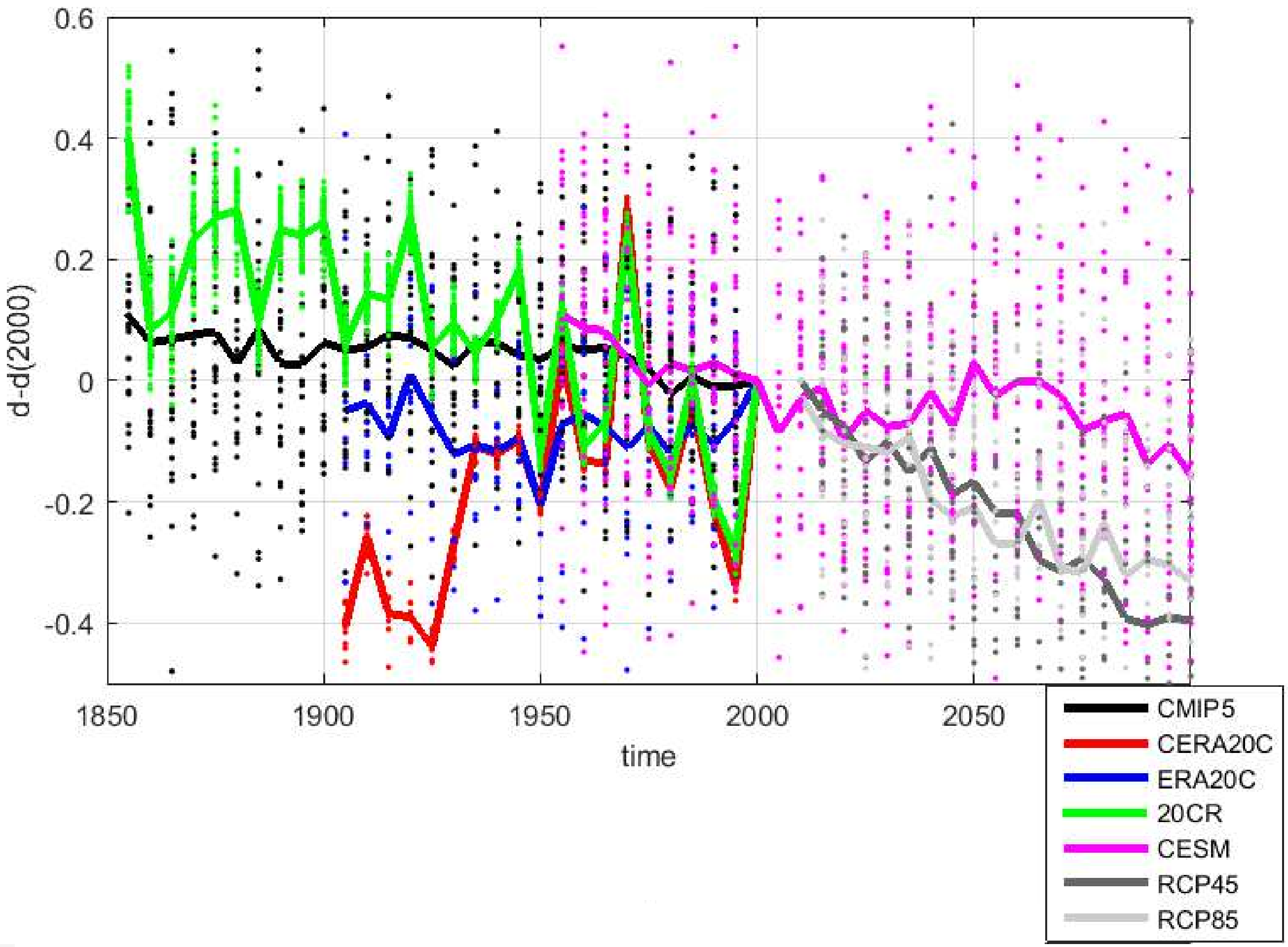




Dataset: daily matrices of sea level pressure over the North Atlantic (NCEP reanalysis)

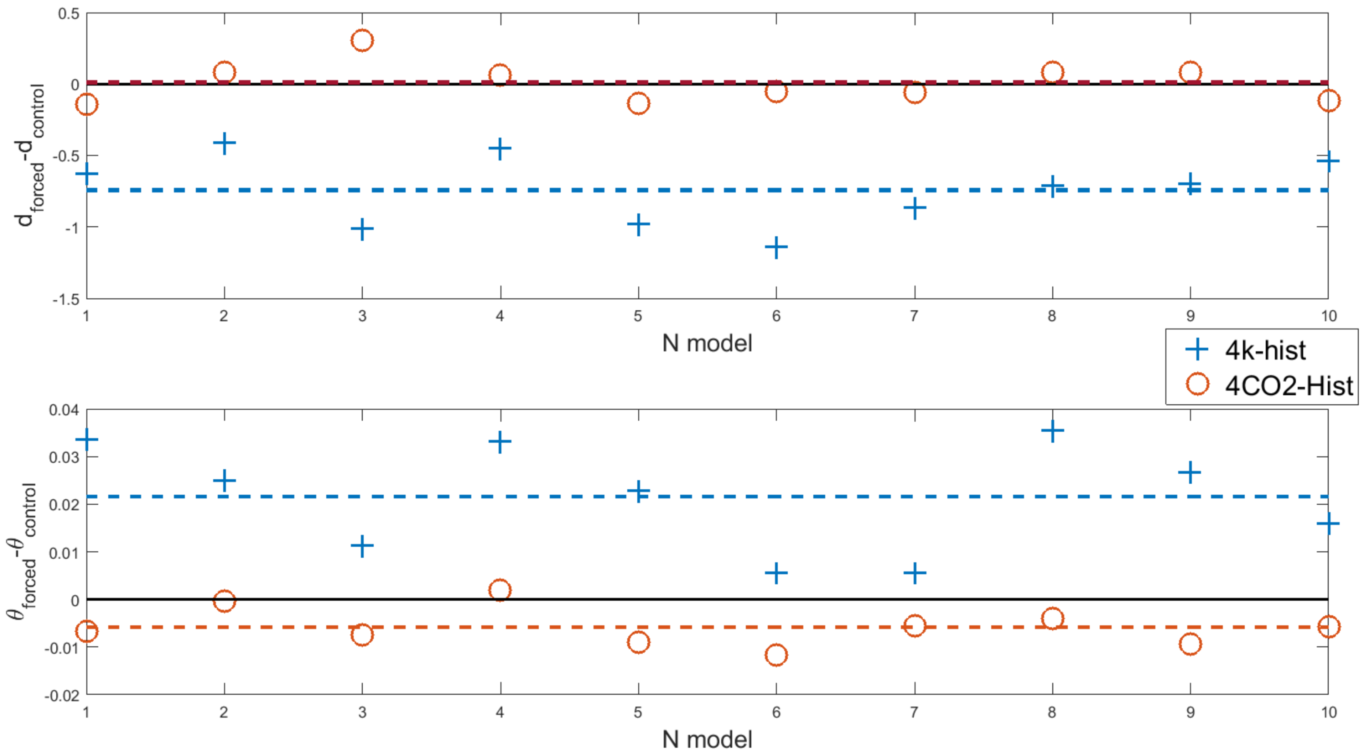
The instantaneous dimensions d (y-axis) versus the years of the database shows an interesting seasonal cycle. Extremes are found in wintertime, where sharp transitions occur between maxima and minima.

LOCAL DIMENSIONS IN MODELS FOR THE NORTH ATLANTIC



5 years averaged values of local dimensions d

EXPLANATION OF THE TRENDS



Ocean's inertia effects reduce the dimension of North Atlantic circulation when ocean temperature is increased

CONCLUSIONS

- **Climate dynamics is chaotic,** predictability depends on the scale of the motion

- The **theoretical physics** approach to understand climate is to focus on specific problems and **build low dimensional models**

- **Dynamical systems theory** has several tools to understand features of atmospheric motions:
  1) Atmospheric dynamics is like a connected attractor with unstable regions
  2) Predictability will change in the future as an effect of the ocean dynamics retroaction on the atmosphere

REFERENCES

[1] Davide Faranda, Gabriele Messori and Pascal Yiou. Dynamical proxies of North Atlantic predictability and extremes**. Scientific Reports**, 7-41278, **2017**.

[2] Davide Faranda, Giacomo Masato, Nicholas Moloney, Yuzuru Sato, Berengere Dubrulle, Francois Daviaud, and Pascal Yiou. The switching between zonal and blocked mid-latitude atmospheric circulation from a dynamical systems perspective. **Climate Dynamics, 1-13, 2015**.

[3] David Rodrigues, M Carmen Alvarez-Castro, Gabriele Messori, Pascal Yiou, Yoann Robin , Davide Faranda. Changes in the dynamical properties of the North Atlantic atmospheric circulation in the past 150 years. Accepted in **Journal of Climate, 2018**