Is ocean surface wind stress key in the long term predictability of the atmosphere?

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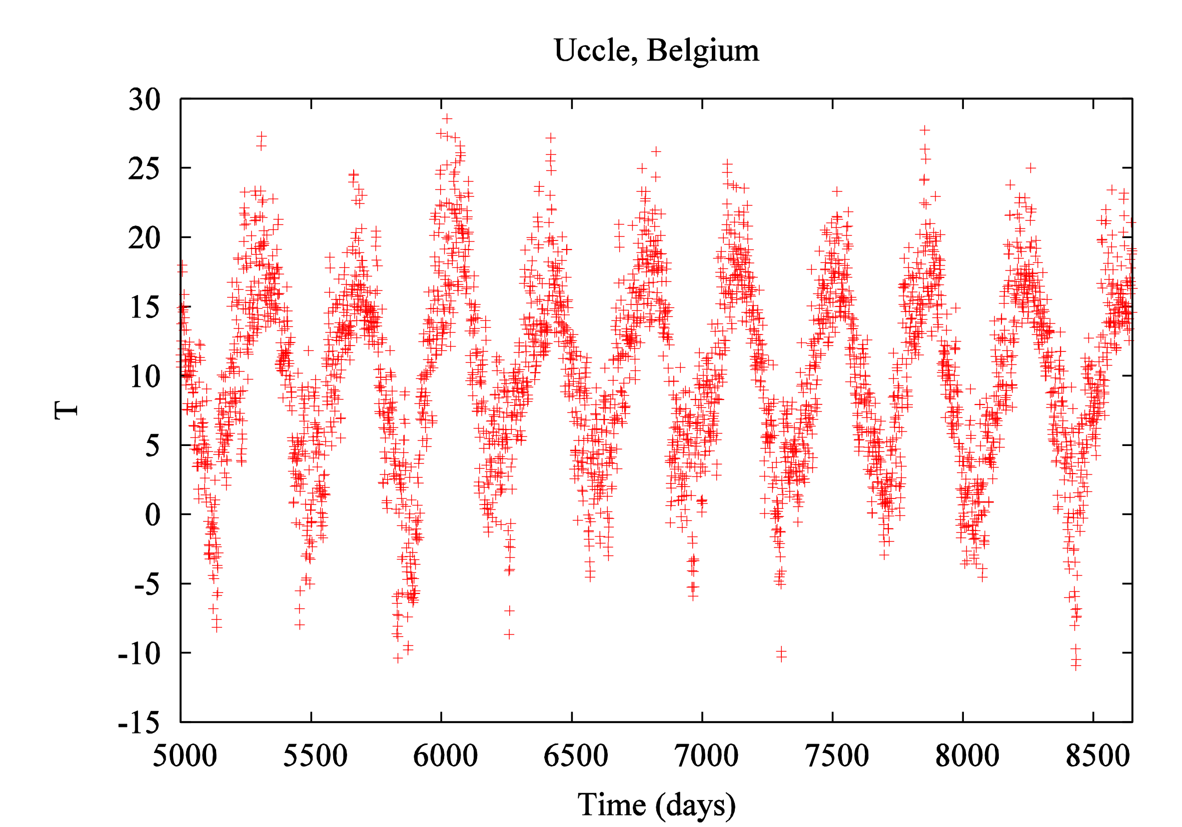
Introduction

Weather variability

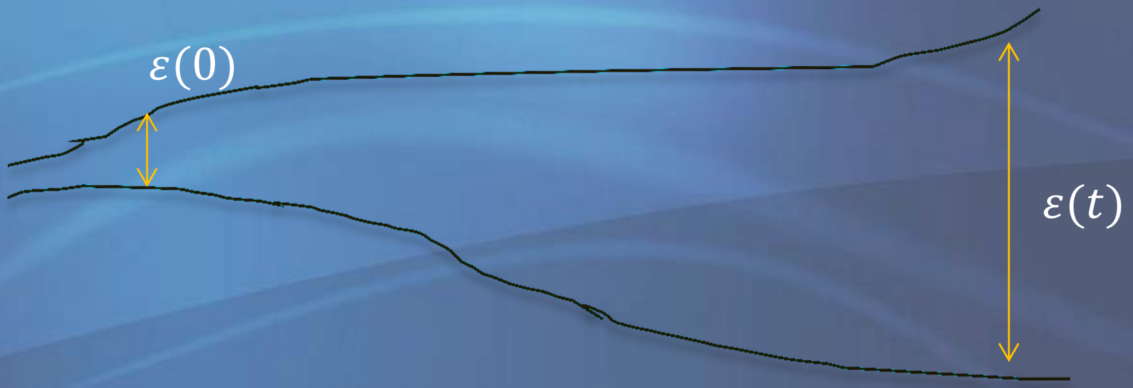


Predictability

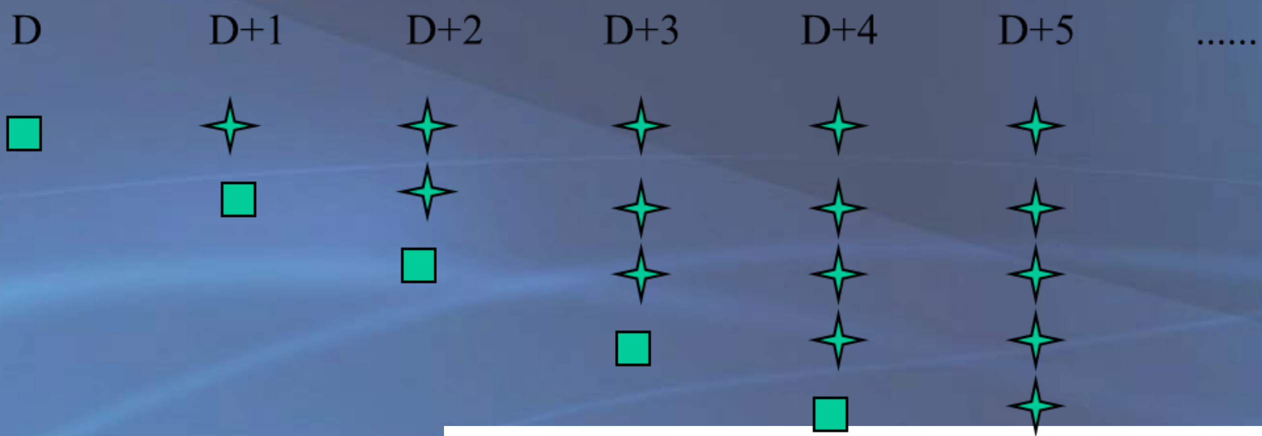
The property of sensitivity to initial (and model) uncertainties at the origin of the degradation of the quality of forecasts of atmospheric flows

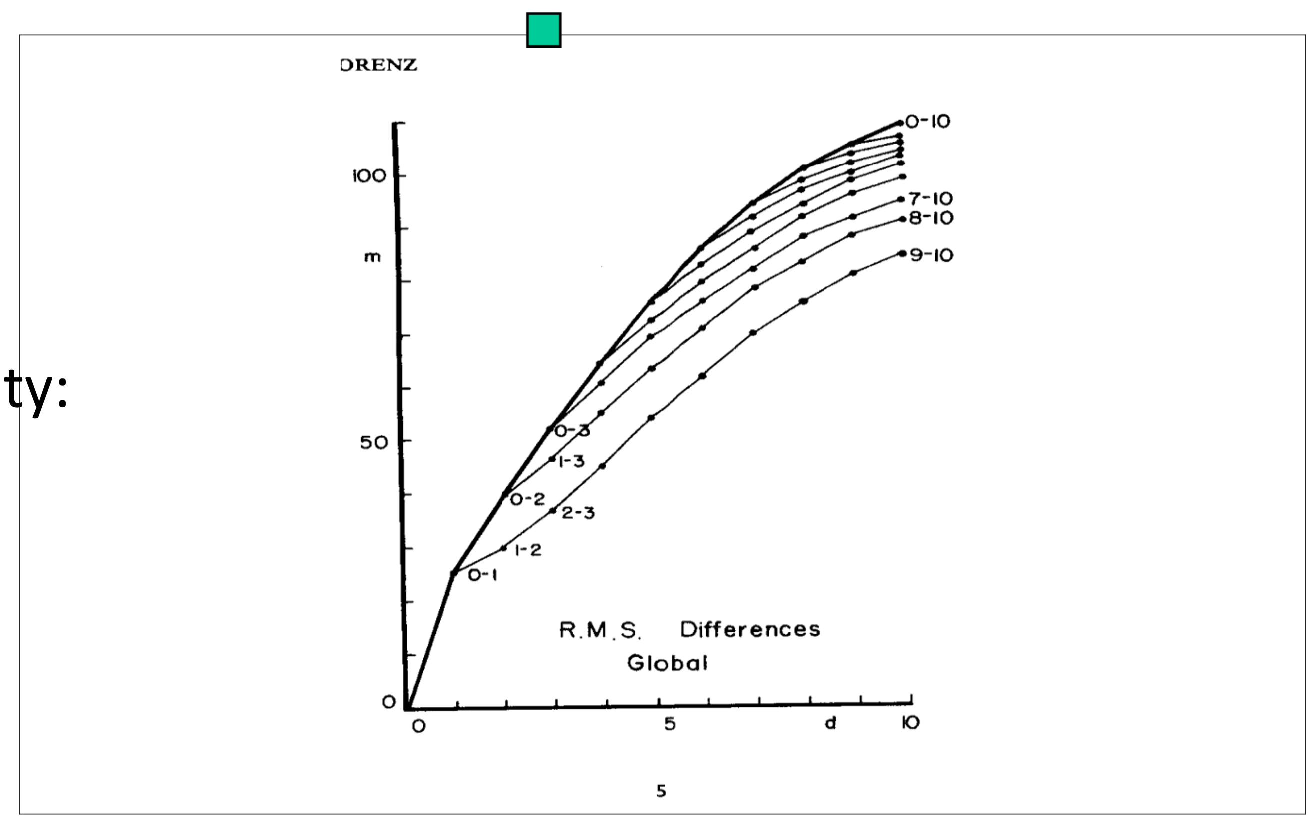
Property already recognized by
Thompson (1957, Tellus, 9) and Lorenz (1963)

From a mathematical point of view: Poincaré (1888; 1908, Science et méthode)



Lorenz 1982 (Tellus, 24)

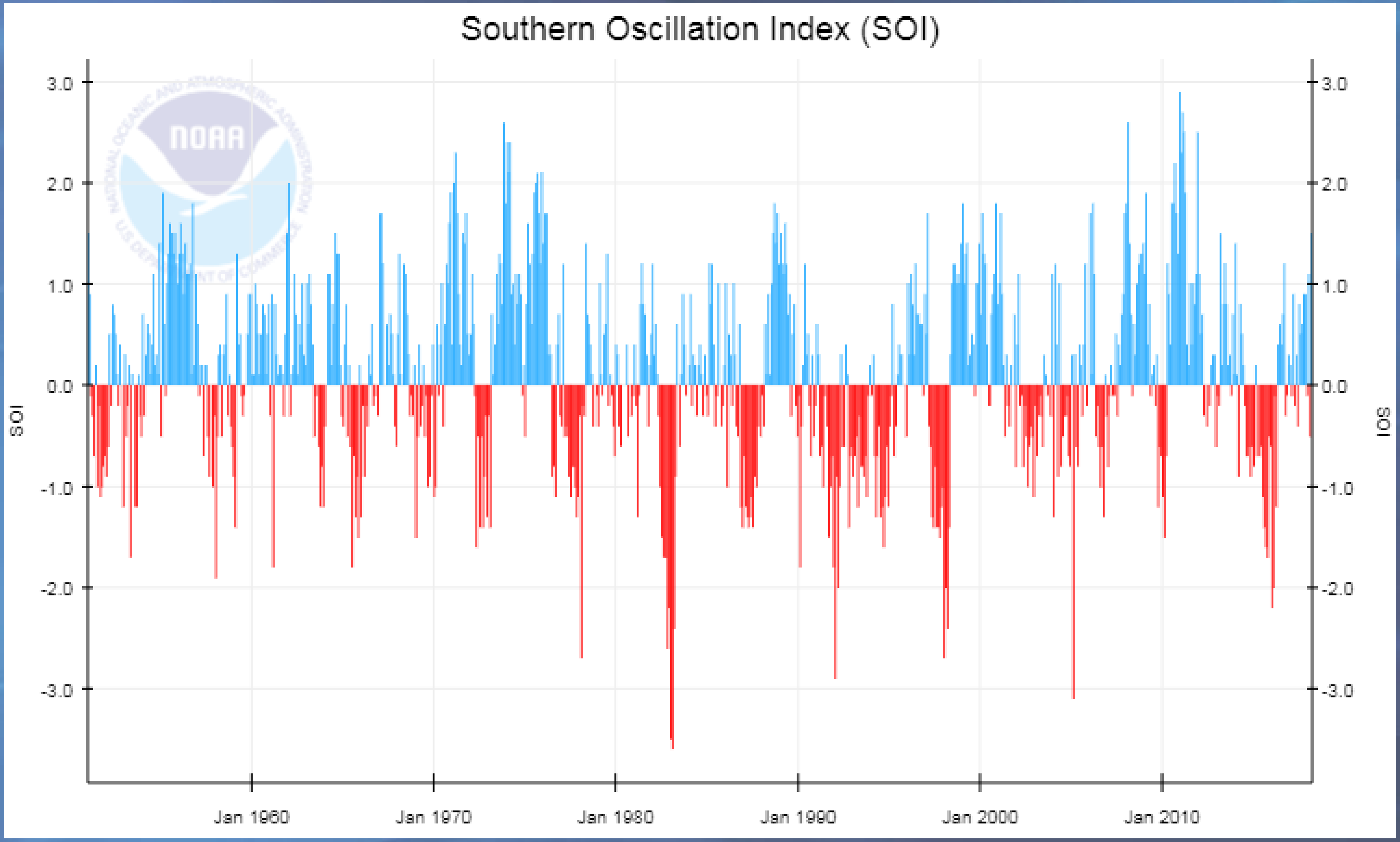




Limited predictability:
about 10-15 days

Climate variability and predictability?

One important signal: Southern Oscillation Index

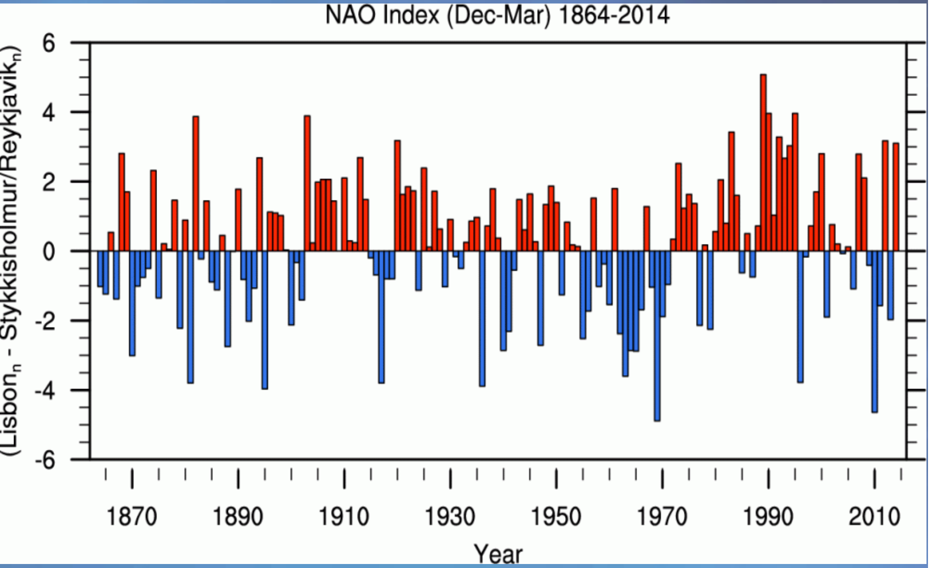


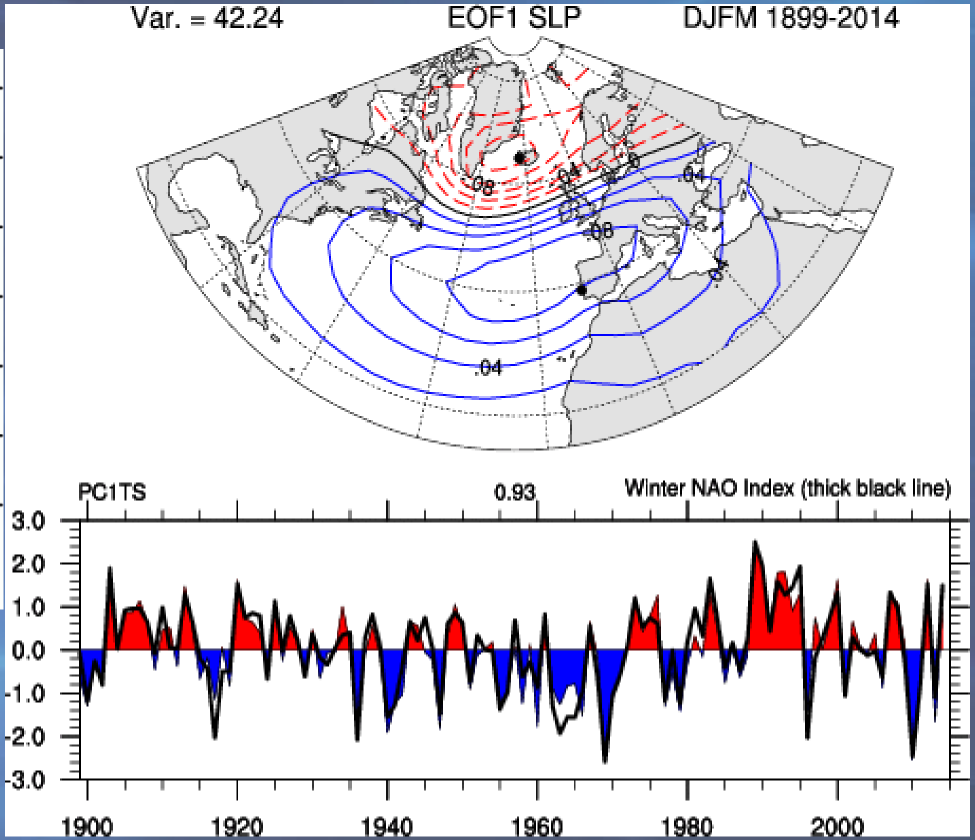
Associated with the development of El-Nino and La-Nina

El-Nino-Southern-Oscillation (ENSO)

Climate variability and predictability?

North Atlantic Oscillation (NAO)





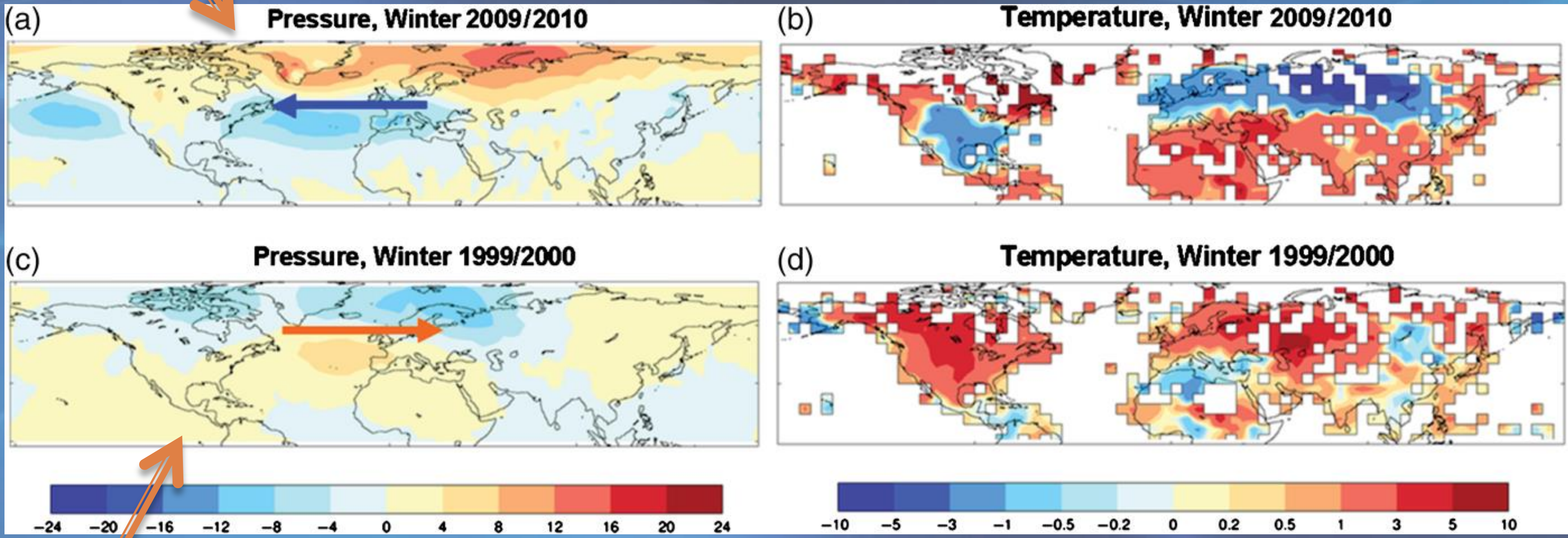
Positive NAO: Larger pressure difference between Lisbon ad Reykjavik
Negative NAO: Smaller pressure difference

Hurrell, 2015, "The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)."

Climate variability and predictability?

Implications?

Negative NAO



Positive NAO

- **EMBEDDED IN THE NORTH ATLANTIC OCEAN DYNAMICS?**
- **TELECONNECTION WITH THE TROPICAL PACIFIC?**
- **OTHER PROCESSES?**

Smith et al, 2014

General objective

- To characterize the predictability of the atmosphere on seasonal, inter-annual and decadal time scales

Strategy

- Development of reduced-order climate models, and in particular coupled ocean-atmosphere models
- Analysis of the predictability of atmospheric and climate models of various resolutions

Aim of the presentation

Analyze the mechanisms at the origin of the development of long term (potential) predictability of the atmosphere

To this aim, we are using a coupled reduced-order ocean-atmosphere model, under the assumption that the ocean is playing a crucial role on the development of low-frequency variability and long term predictability

More specifically we will use:

- **Version of the MAOOAM model over the Atlantic, called VDDG which was developed in Vannitsem, Demaeyer, De Cruz and Ghil, 2015, Physica D.**

- **New version of the coupled ocean-atmosphere model, called MAO(S)OAM with different boundary conditions**

Low-order modelling

These are simplified models containing:

- Key ingredients of the system's dynamics
- Developed on an appropriate basis at the scale of interest

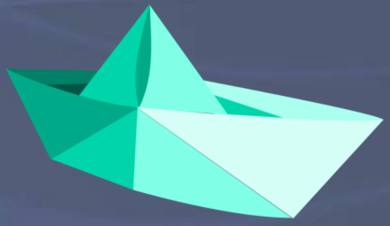
ex: Use of empirical orthogonal functions
Truncated Fourier series

Many models were developed (see e.g. Sprott, 2010)

Procedure

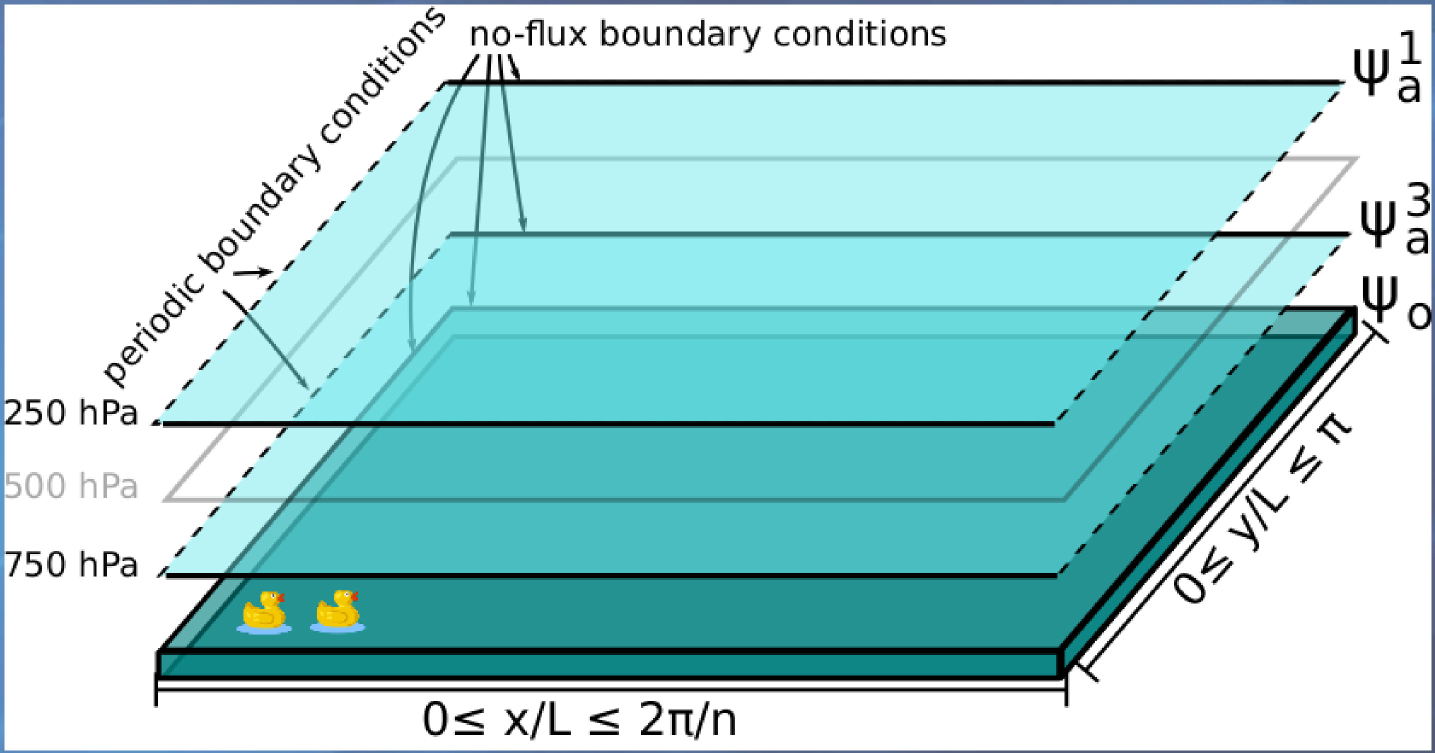
$$\varphi = \sum_{i}^{N} C_i F_i \qquad (f, g) = \iint_{\vartheta} dxdy\, f^* g$$

$$\left(F_i, \frac{\partial \varphi}{\partial t}\right) = (F_i, G(\varphi, \nabla\varphi, \dots))$$



An idealized low-order coupled ocean-atmosphere model

- QG model for both the ocean and the atmosphere



Vannitsem et al, 2015, Physica D, 309, 71-85, 2015, (**VDDG**)
De Cruz et al 2016, Geosci. Model Develop, 9, 2793-2808, 2016. (**MAOOAM**)

Latitudinal dependence of the radiative input

$$R_0 + S_0\sqrt{2}\cos y$$

Surface friction strength

$$\delta = \frac{d}{f_0} = \frac{C}{\rho H f_0}$$

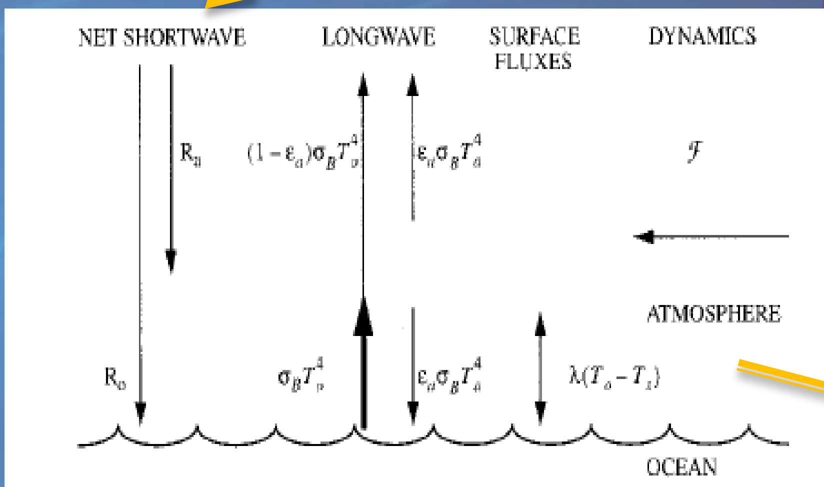
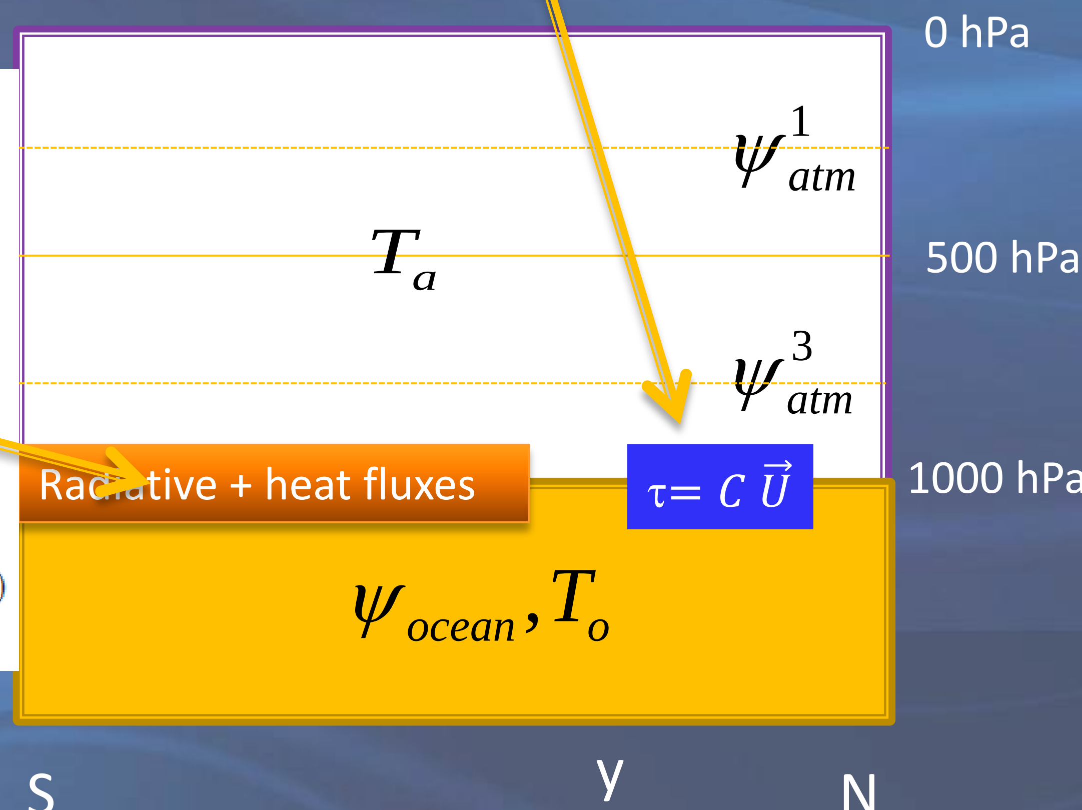


FIG. 2. Diagram of simple energy balance model on which Eqs. (1) and (2) are based. See appendix A for definition of symbols.

Barsugli & Battisti, 1998, JAS



The dynamical equations for the ocean-atmosphere model

For the atmosphere

$$
\begin{aligned}
\frac{\partial}{\partial t}\left(\nabla^2\psi_a^1\right) + J(\psi_a^1, \nabla^2\psi_a^1) + \beta\frac{\partial\psi_a^1}{\partial x} &= -k_d'\nabla^2(\psi^1 - \psi^3) + \frac{f_0}{\Delta p}\omega \\
\frac{\partial}{\partial t}\left(\nabla^2\psi_a^3\right) + J(\psi_a^3, \nabla^2\psi_a^3) + \beta\frac{\partial\psi_a^3}{\partial x} &= +k_d'\nabla^2(\psi_a^1 - \psi_a^3) - \frac{f_0}{\Delta p}\omega \\
& \quad -k_d\nabla^2(\psi_a^3 - \psi_o)
\end{aligned}
$$

Friction on a moving surface

$$\gamma_a\left(\frac{\partial T_a}{\partial t} + J(\psi_a, T_a) - \sigma\omega\frac{p}{R}\right) = -\lambda(T_a - T_o) + E_{a,R}$$

$$E_{a,R} = \epsilon_a\sigma_B T_o^4 - 2\epsilon_a\sigma_B T_a^4 + R_a$$

For the ocean

$$\frac{\partial}{\partial t}\left(\nabla^2\psi_o - \frac{\psi_o}{L_R^2}\right) + J(\psi_o, \nabla^2\psi_o) + \beta\frac{\partial\psi_o}{\partial x} = -r\nabla^2\psi_o + \frac{curl_z\tau}{\rho h}$$

Curl of wind stress

$$\gamma_o\left(\frac{\partial T_o}{\partial t} + J(\psi_o, T_o)\right) = -\lambda(T_o - T_a) + E_R$$

$$E_R = -\sigma_B T_o^4 + \epsilon_a\sigma_B T_a^4 + R_o$$

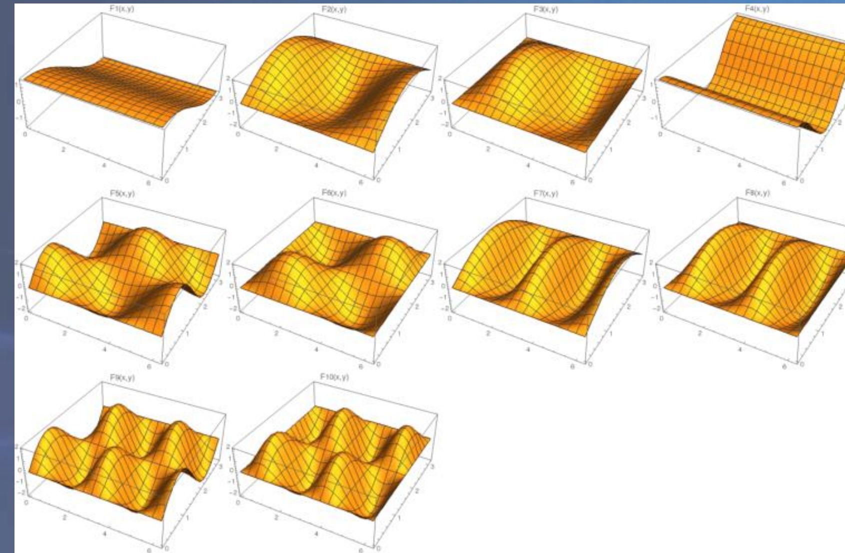
Truncation of Fourier series

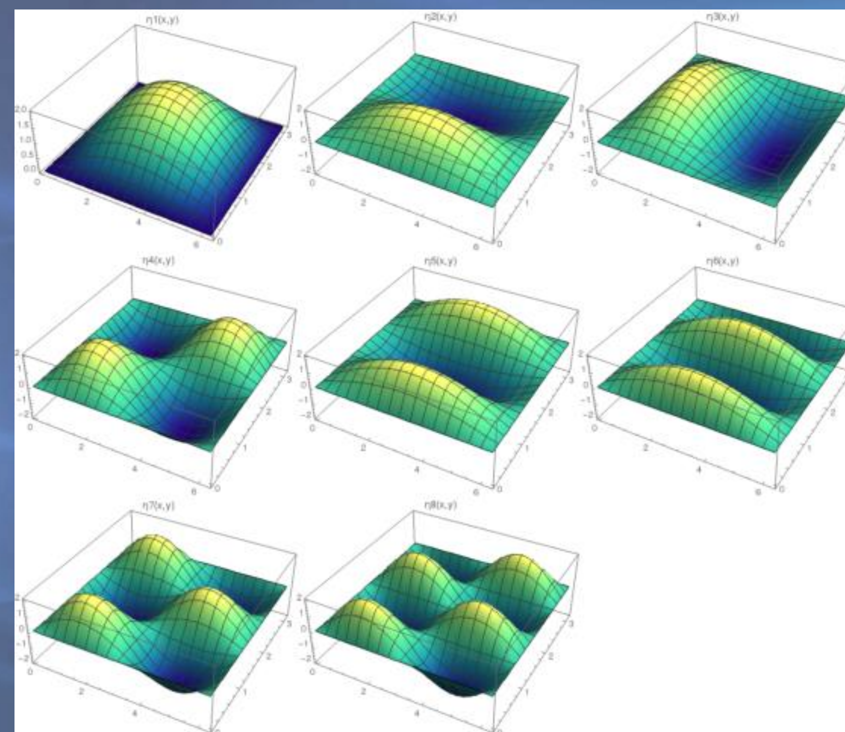
$$\psi = \sum_{k=1}^{K} \psi_k F_k$$

$$\theta = \sum_{k=1}^{K} \theta_k F_k$$

$$\psi_o = \sum_{i=1}^{8} \psi_{o,i}\phi_i, \qquad \delta T_o = \sum_{i=1}^{8} T_{o,i}\phi_i.$$

36-variable model

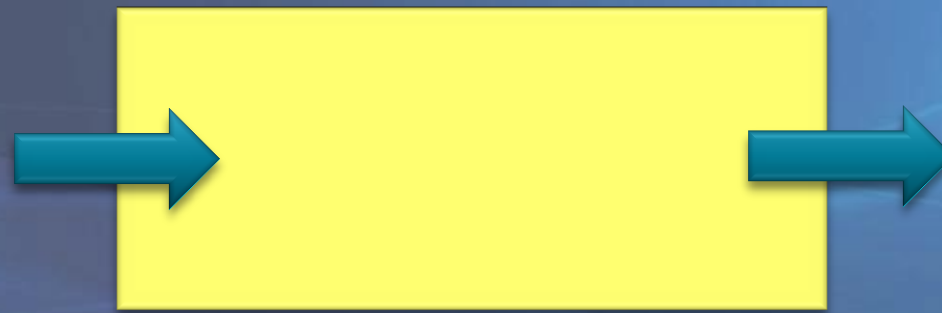


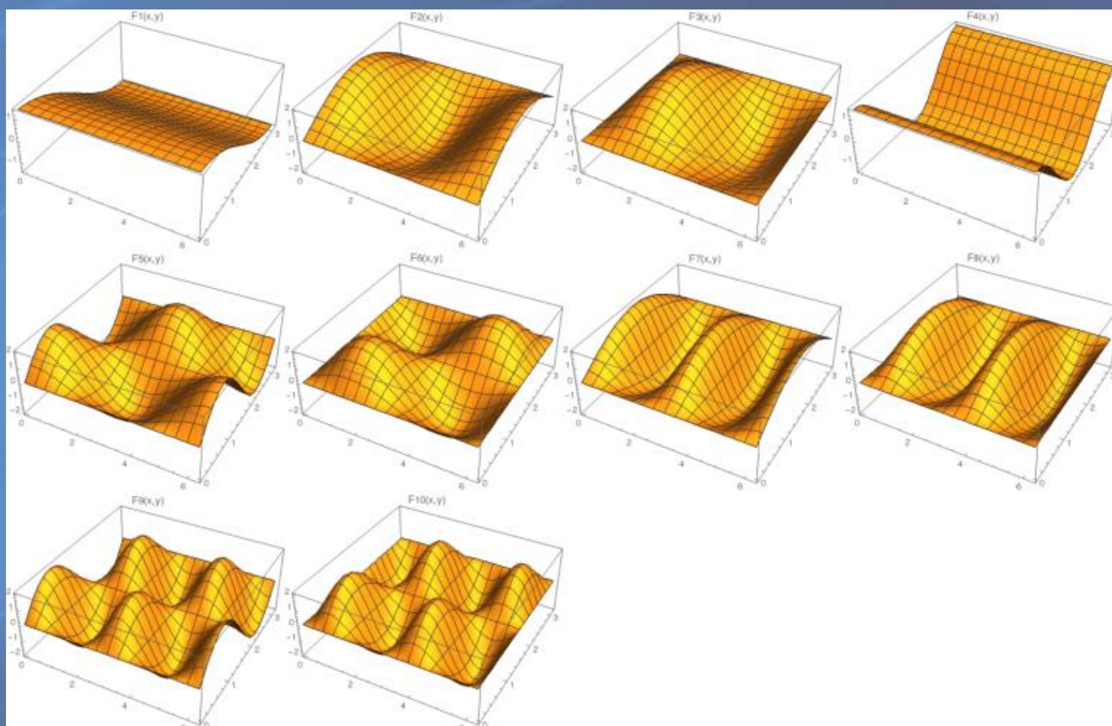


Vannitsem et al, Physica D, 2015

New version of the model: MAOSOAM

Rectangular geometry
Channel flow for the ocean too





Low-order system of 40 variables, 20 for the ocean and 20 for the atmosphere

Parameter values

Table 1. Dimensional Parameters Present in the Coupled Ocean-Atmosphere Models[a]

Dynamic Atmosphere	Dynamic Ocean	Geometry	Coupling
$k_d = gC/\Delta p$ s^{-1}	$L_R = (g'H)^{1/2}/f_0$ m	$L_y = \pi L = 5000$ km	$\epsilon_a = 0.7$
$k'_d = k_d$	$\gamma = 10^{-7}$ s^{-1}	$n = (2L_y)/L_x = 1.5$	$\lambda = c_{p,a}C$ W m^{-2} K^{-1}
$\sigma = 2.16\ 10^{-6}$ J kg^{-1} Pa^{-2}	$\gamma_o = c_{p,o}\rho_o H$ J m^{-2} K^{-1}	$f_0 = 0.0001032$ s^{-1}	$d = C/(\rho_o H)$ s^{-1}
$\gamma_a = 10^7$ J m^{-2} K^{-1}		$\beta = 1.62\ 10^{-11}$ m^{-1} s^{-1}	
		$\Delta p = 500$ hPa	

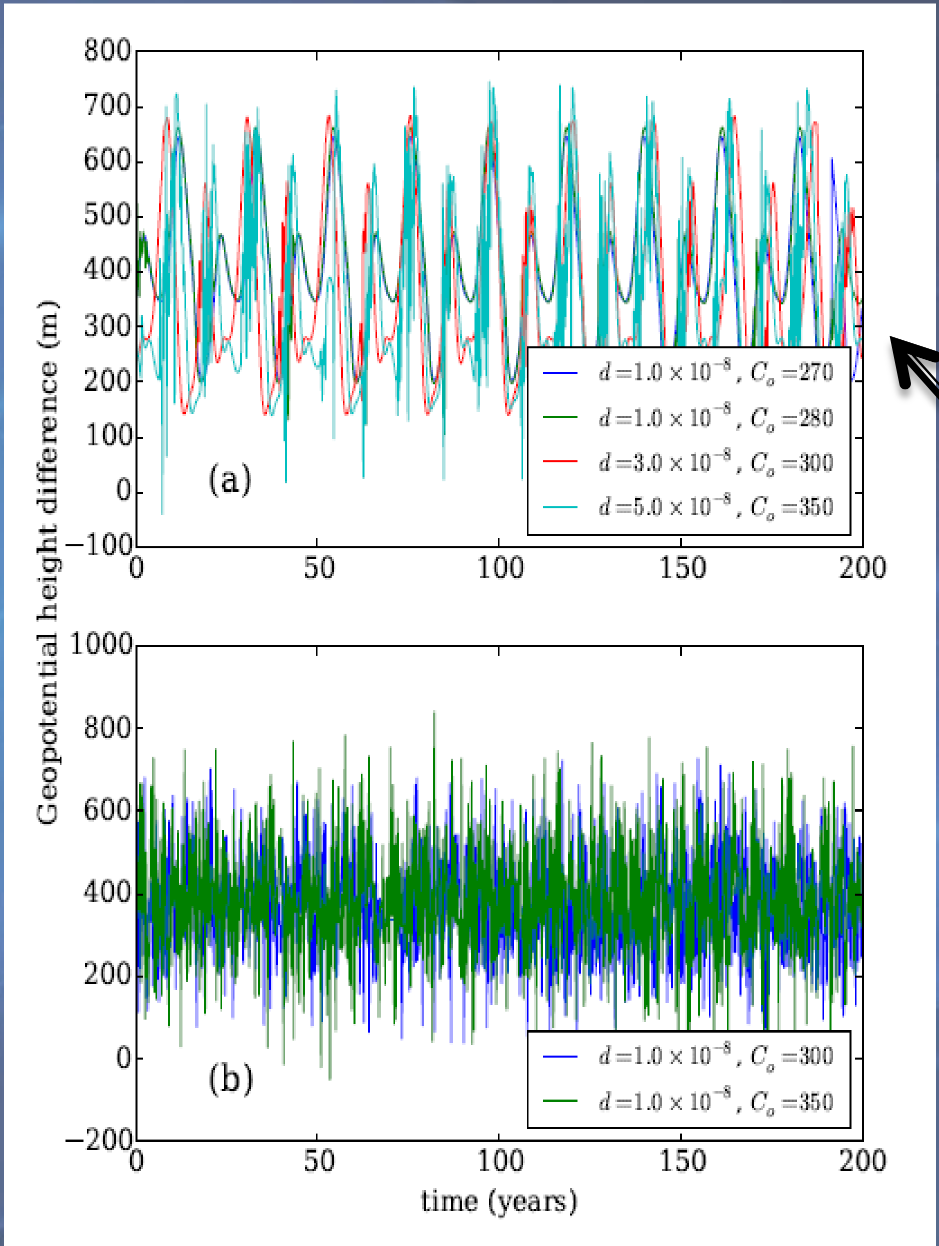
[a] $c_{p,a}$ and σ_B are the usual specific heat at constant pressure of the air and the Stefan-Boltzmann constant, fixed to 1004 J kg^{-1} K^{-1} and 5.6 10^{-8} W m^{-2} K^{-4}, respectively. The density, ρ_o, and the specific heat at constant pressure, $c_{p,o}$, for the ocean layer are fixed to 1000 kg m^{-3} and 4000 J kg^{-1} K^{-1}. g and g' are the gravity and reduced gravity fixed to 10 and 0.031 m s^{-2}, respectively.

Vannitsem, 2015, Geophys Res Lett

4 important parameters: n, C, H and $C_0 \equiv S_0$

Variability and Lyapunov instability properties of the coupled ocean-atmosphere system

Solution of the VDDG model



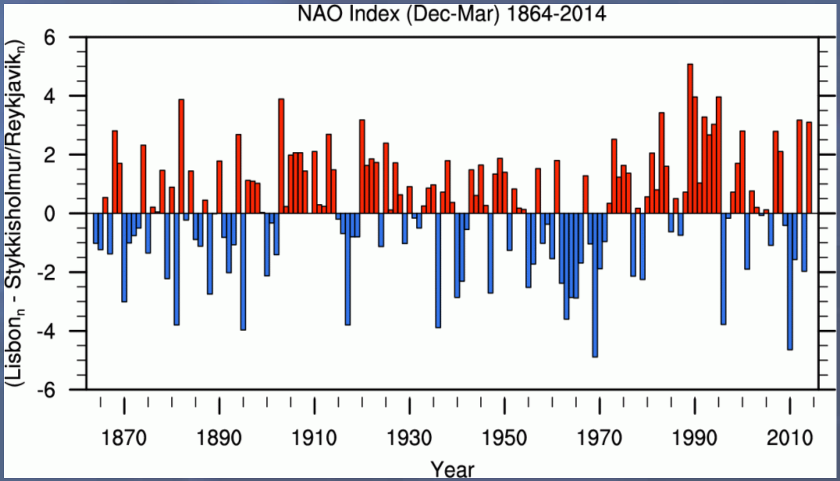
Geop. Height. Diff. between two points from the North and South parts of the domain

Vannitsem et al, 2015, Physica D

n=1.5

H=500 m

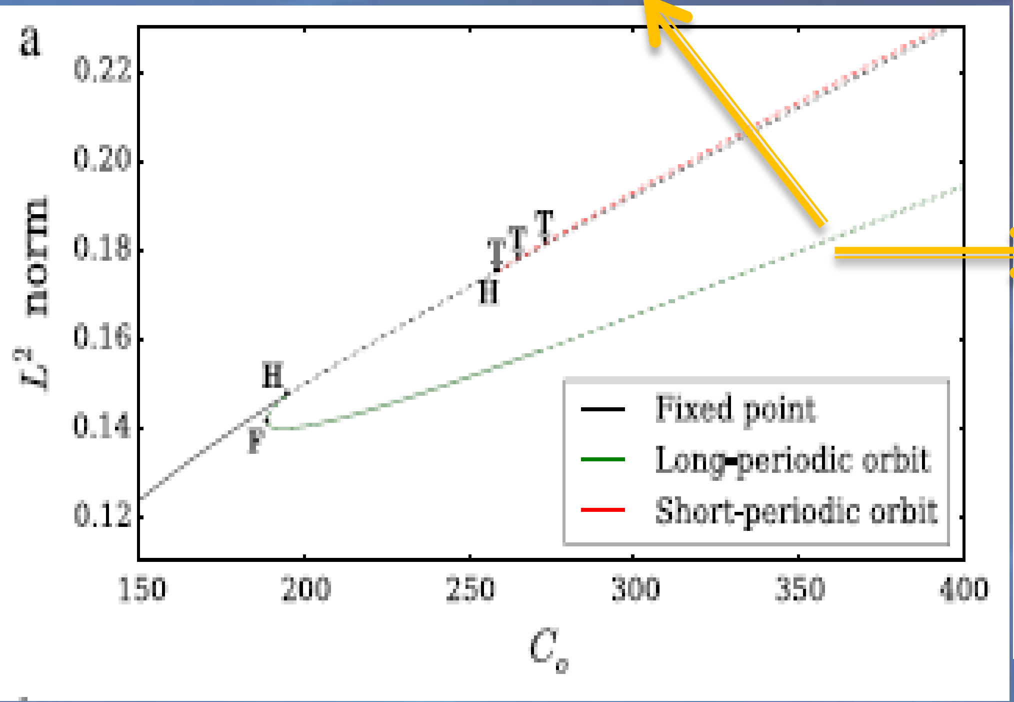
Decadal Variability

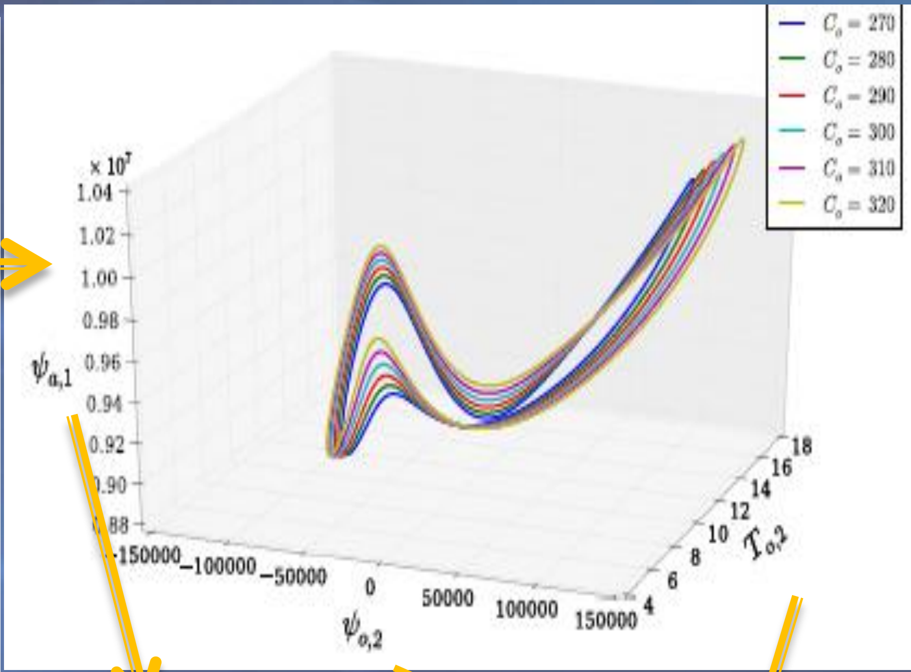


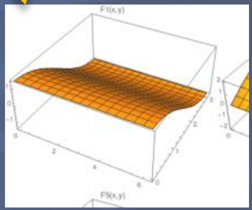
Bifurcation diagram

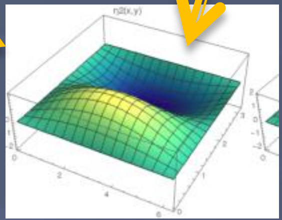
n=1.5
H=500 m
λ=20 W m^{-2} K^{-1}
d=10^{-8}s^{-1}

Slow branch





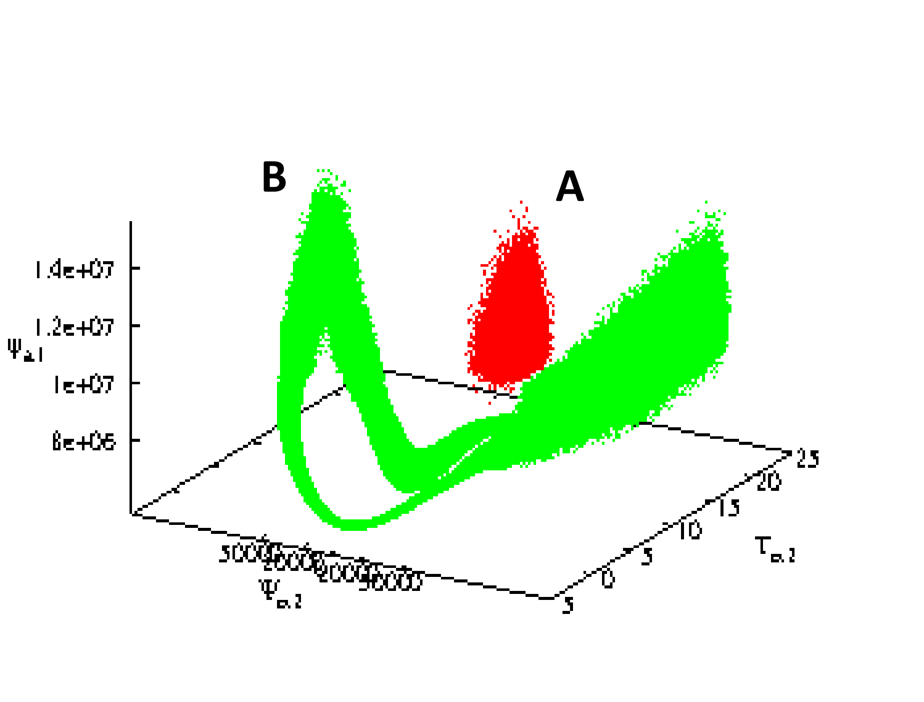




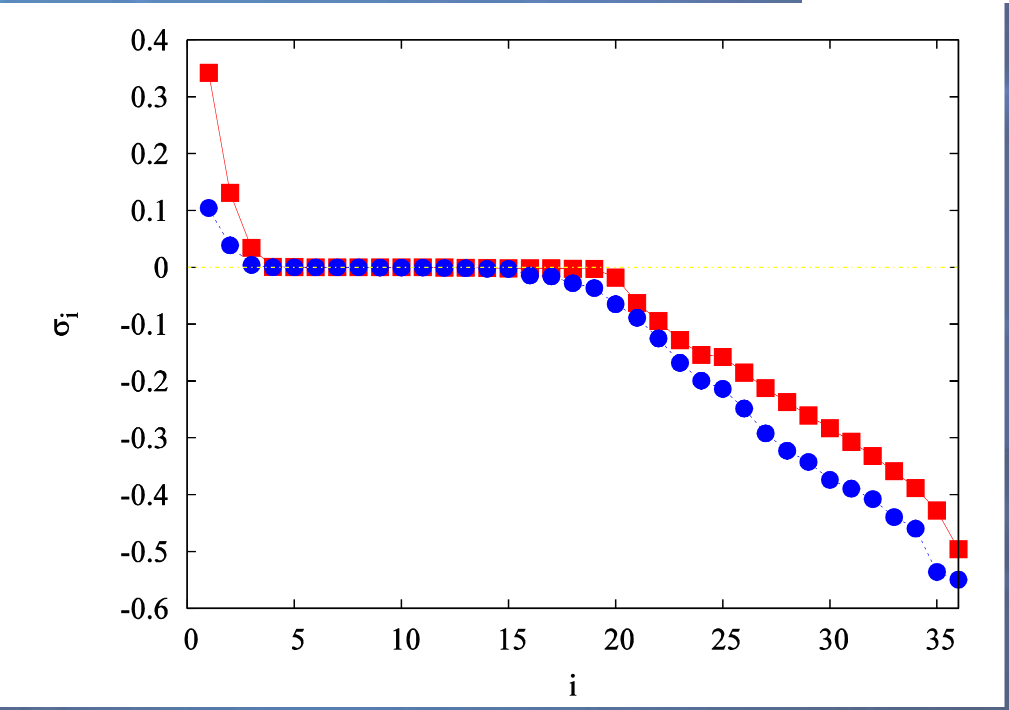
Vannitsem, Demaeyer, De Cruz, Ghil, Physica D, 2015

Consider 2 different attractors
(obtained with different parameters)

n=1.5
H=164 m
C_0=S_0=310 W/m^2

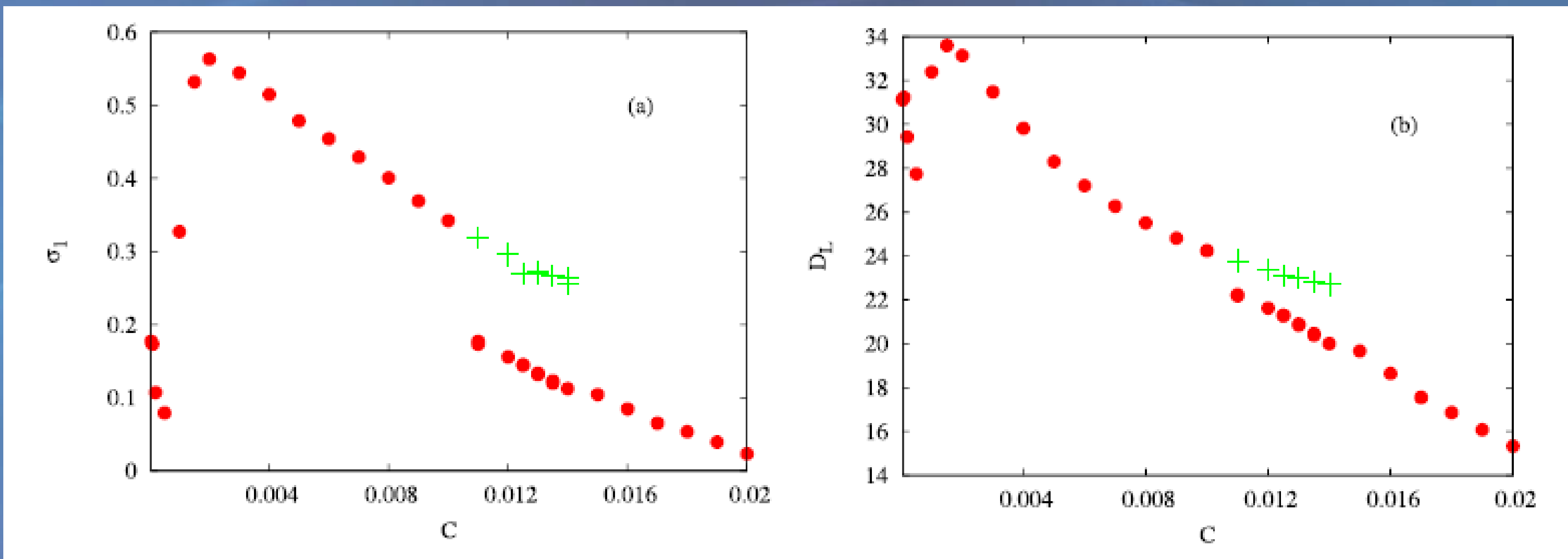


Lyapunov spectra



Vannitsem, 2017, Chaos, 27, 032101

Changes of the Lyapunov instability as a function of friction



Vannitsem, 2017, Chaos, 27, 032101

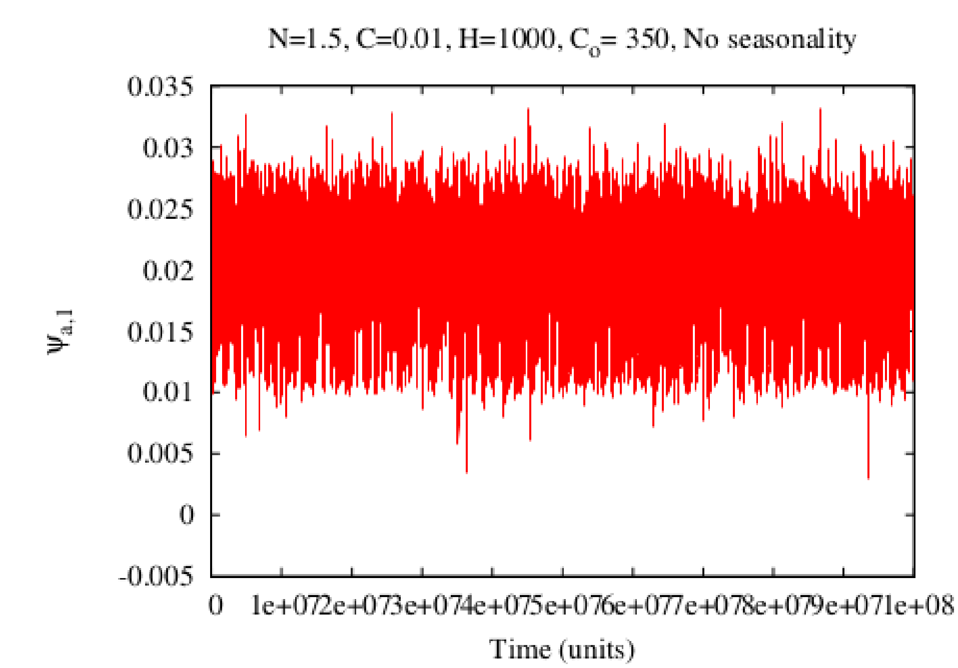
n=1.5

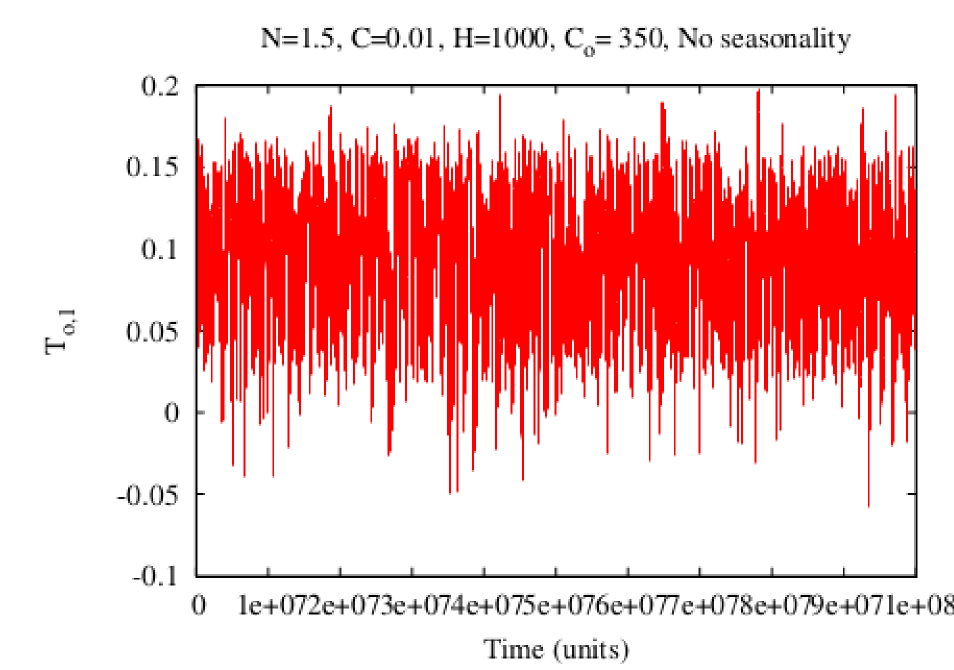
H=164 m

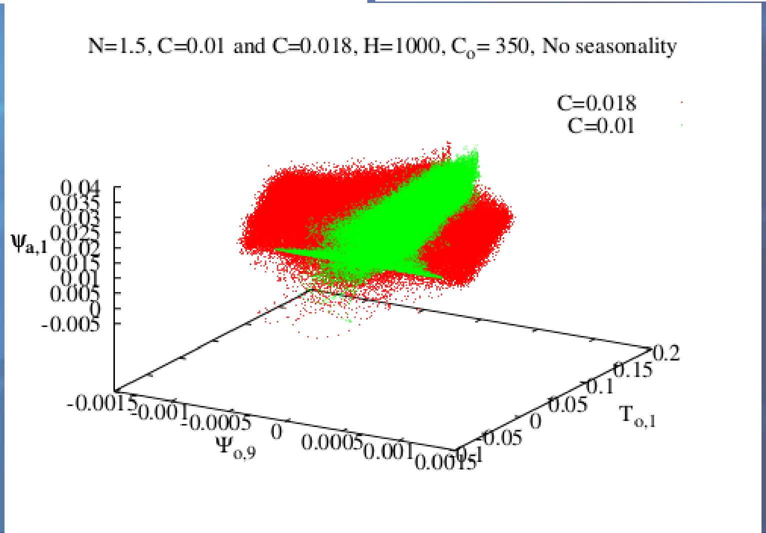
C_0=S_0=310 W/m^2

Results with the new version of the model, MAOSOAM

Depth of the ocean= 1000 m, S_o = 350 W/m^2 $\quad n = 2\ L_y/L_x$ =1.5





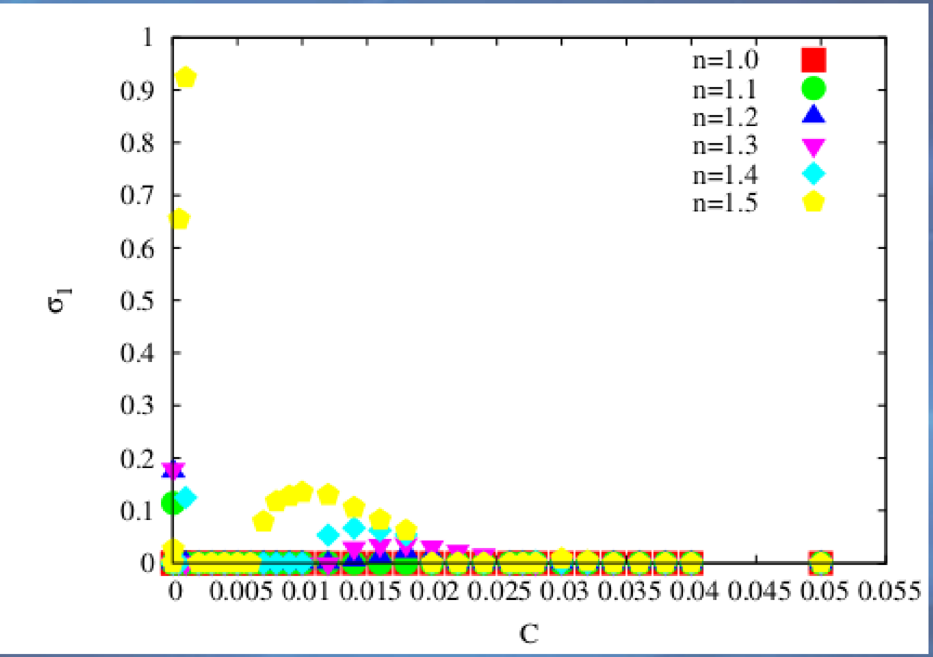


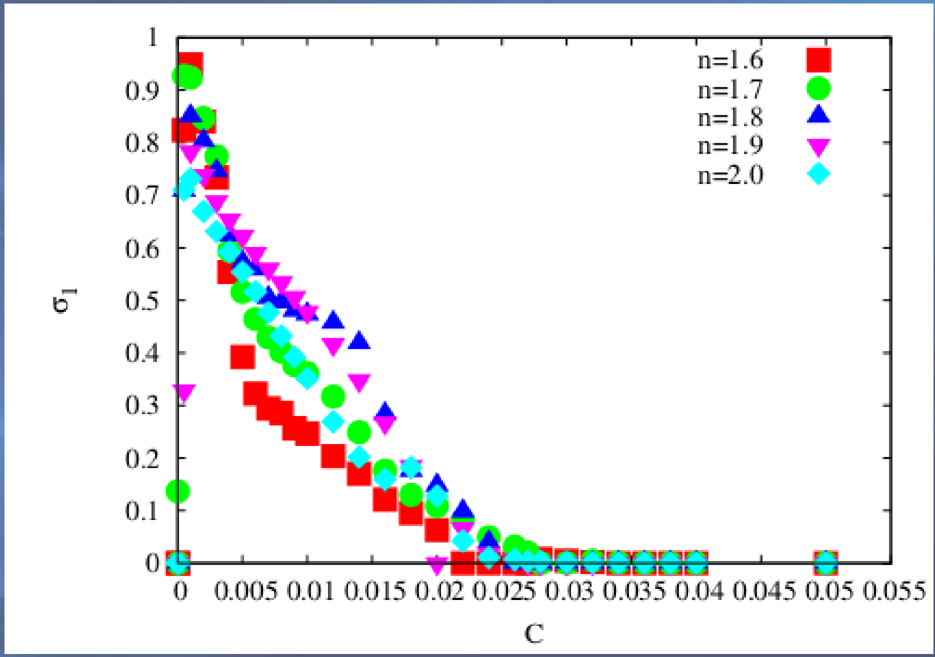
Results with the new version of the model, MAOSOAM

Dominant Lyapunov exponent for different values of C, for different aspect ratios n,

$$n = 2\, L_y / L_x$$

Depth of the ocean= 1000 m, S_o = 350 W/m^2





The interaction with the ocean induces chaos

The interaction with the ocean reduces chaos

Error dynamics of atmospheric and climate flows

Typical evolution of the averaged Error

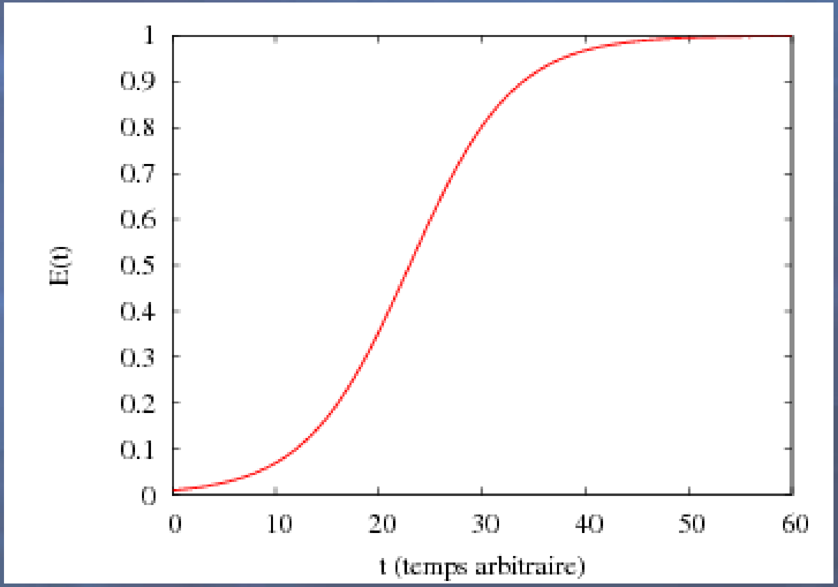
A lot of discussions on the shape of the mean square error evolution

$$\langle E_t^2 \rangle = \int \mathrm{d}\mathbf{x}_0 \, \rho(\mathbf{x}_0) \{ \mathbf{y}(t; \mathbf{x}_0 + \boldsymbol{\varepsilon}) - \mathbf{x}(t; \mathbf{x}_0) \}^2$$

Idealized shape of the evolution of the error :

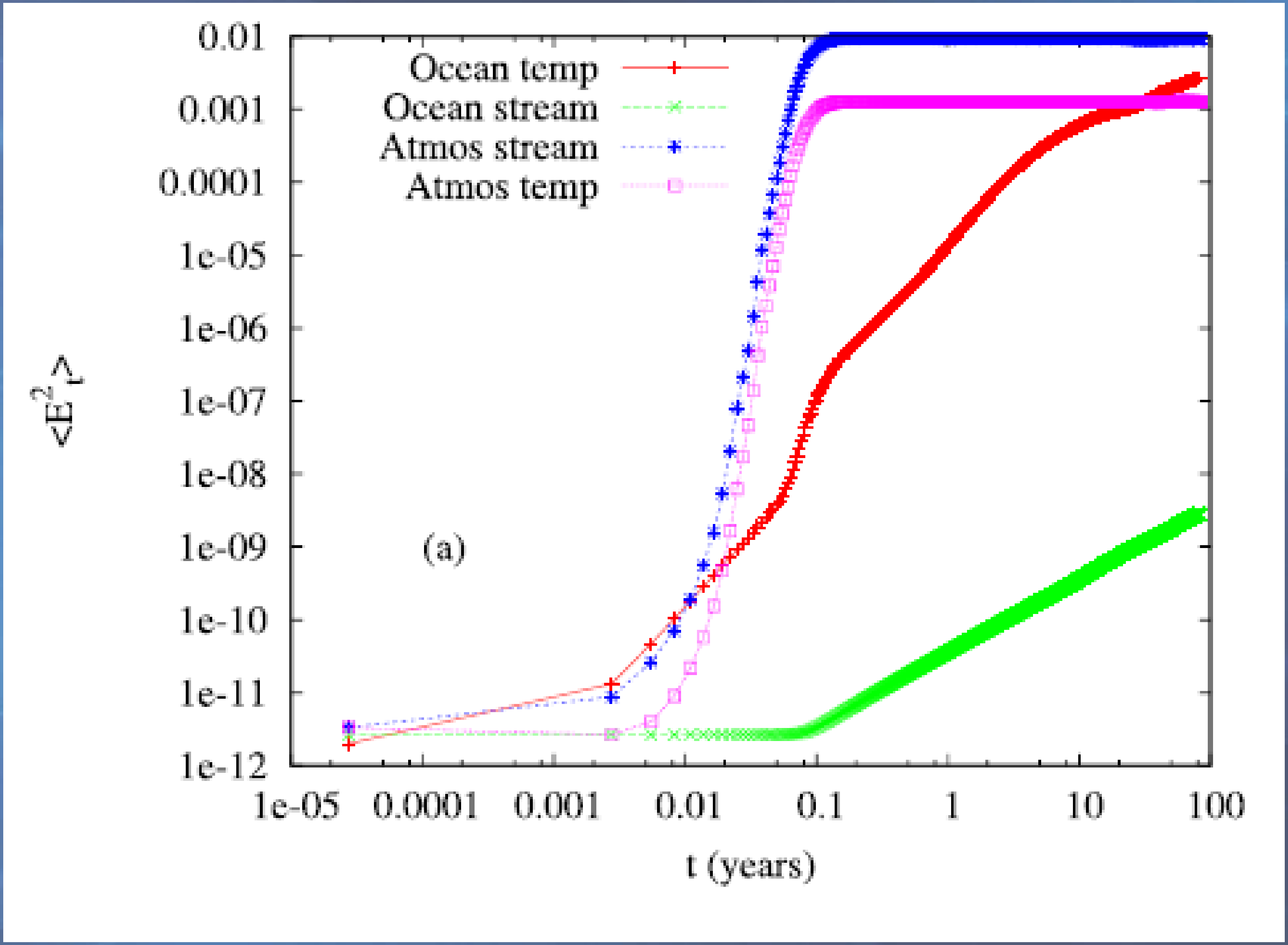
$$\frac{dE}{dt} = aE - bE^2$$

Lorenz (1969, Tellus, 21)
Trevisan et al (1992, JAS, 49)
Nicolis (1992, QJRMS, 118)



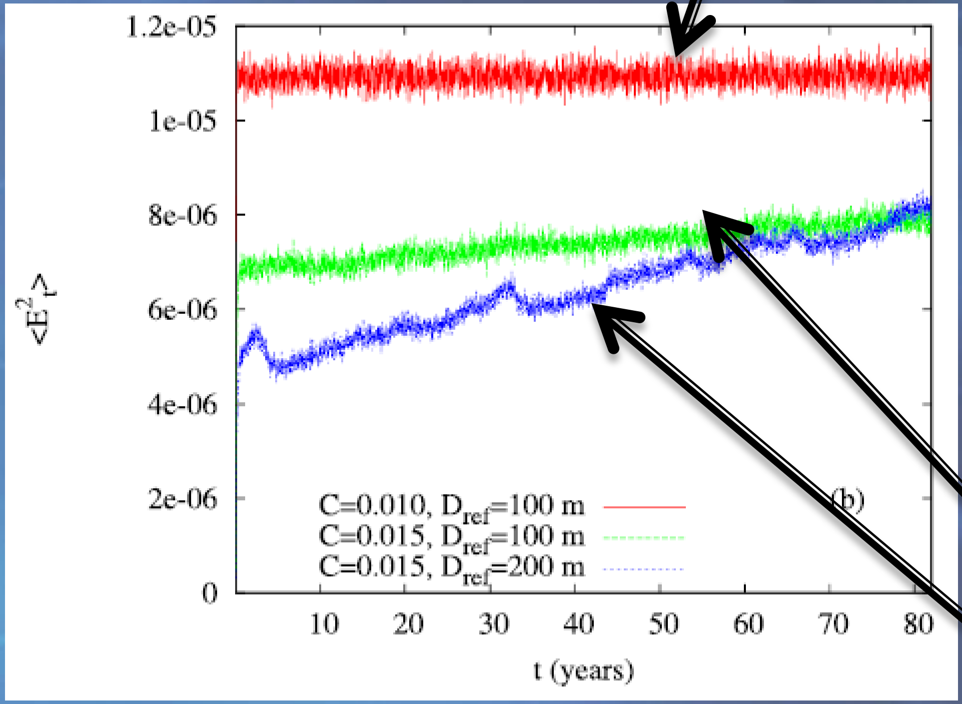
Error dynamics in the VDDG model

Attractor A



Error dynamics in VDDG model

No LFV



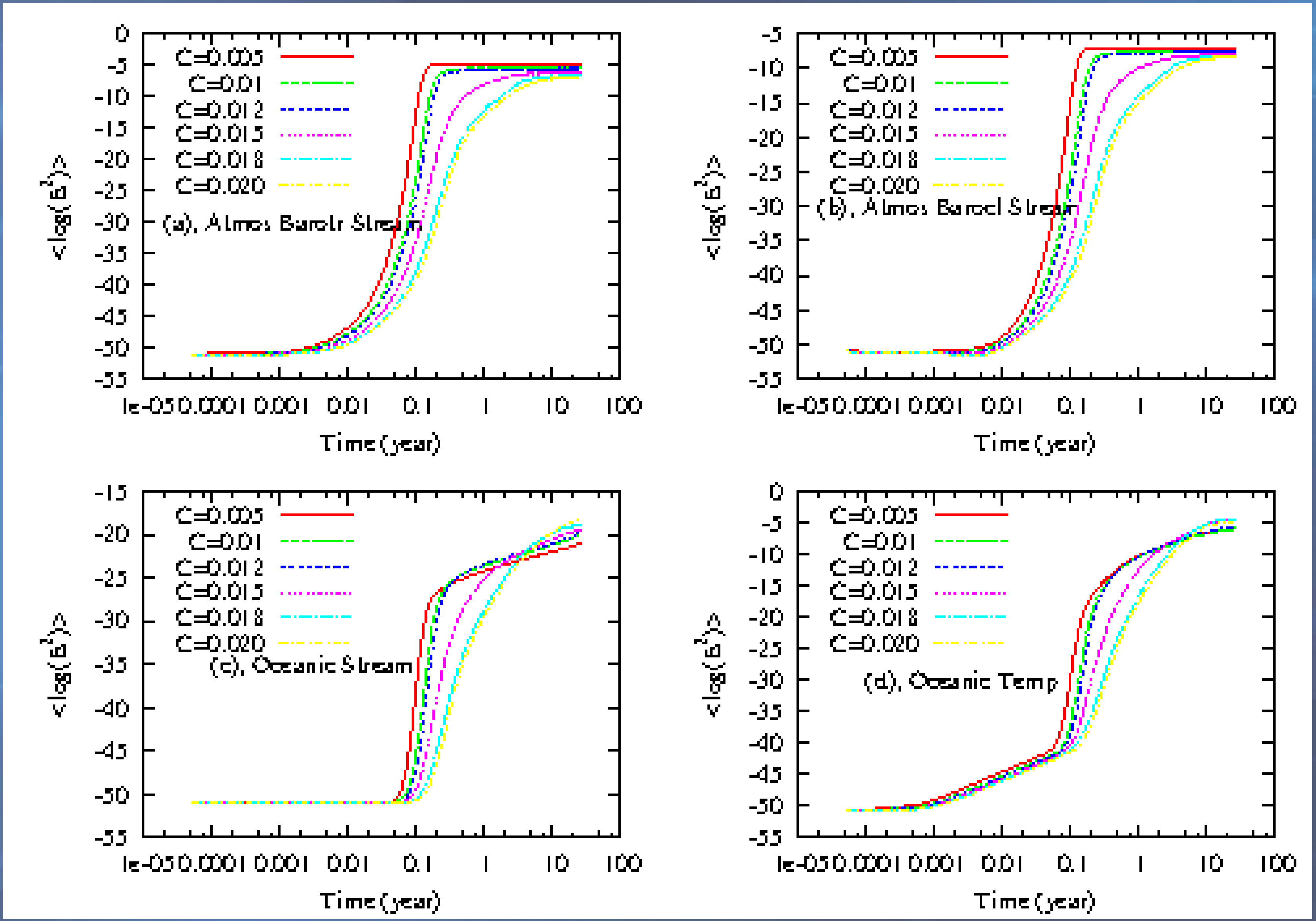
$\psi_{a,1}$

With LFV

Vannitsem, 2017, Chaos, 27, 032101

Results with the new version of the model, MAOSOAM

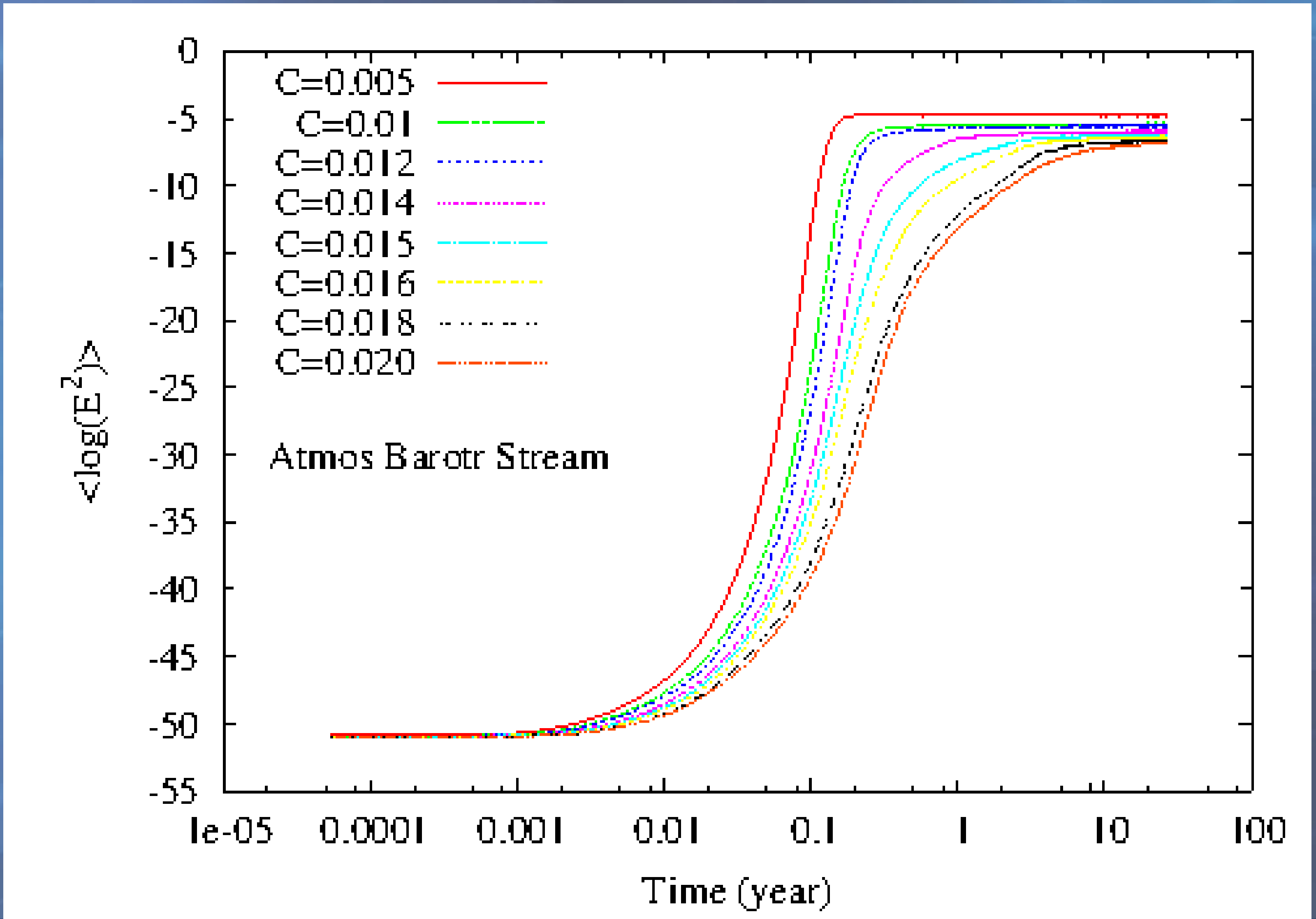
Depth of the ocean= 1000 m, S_o = 350 W/m^2 $n = 2$ L_y/L_x = 1.7



Results with the new version of the model, MAOSOAM

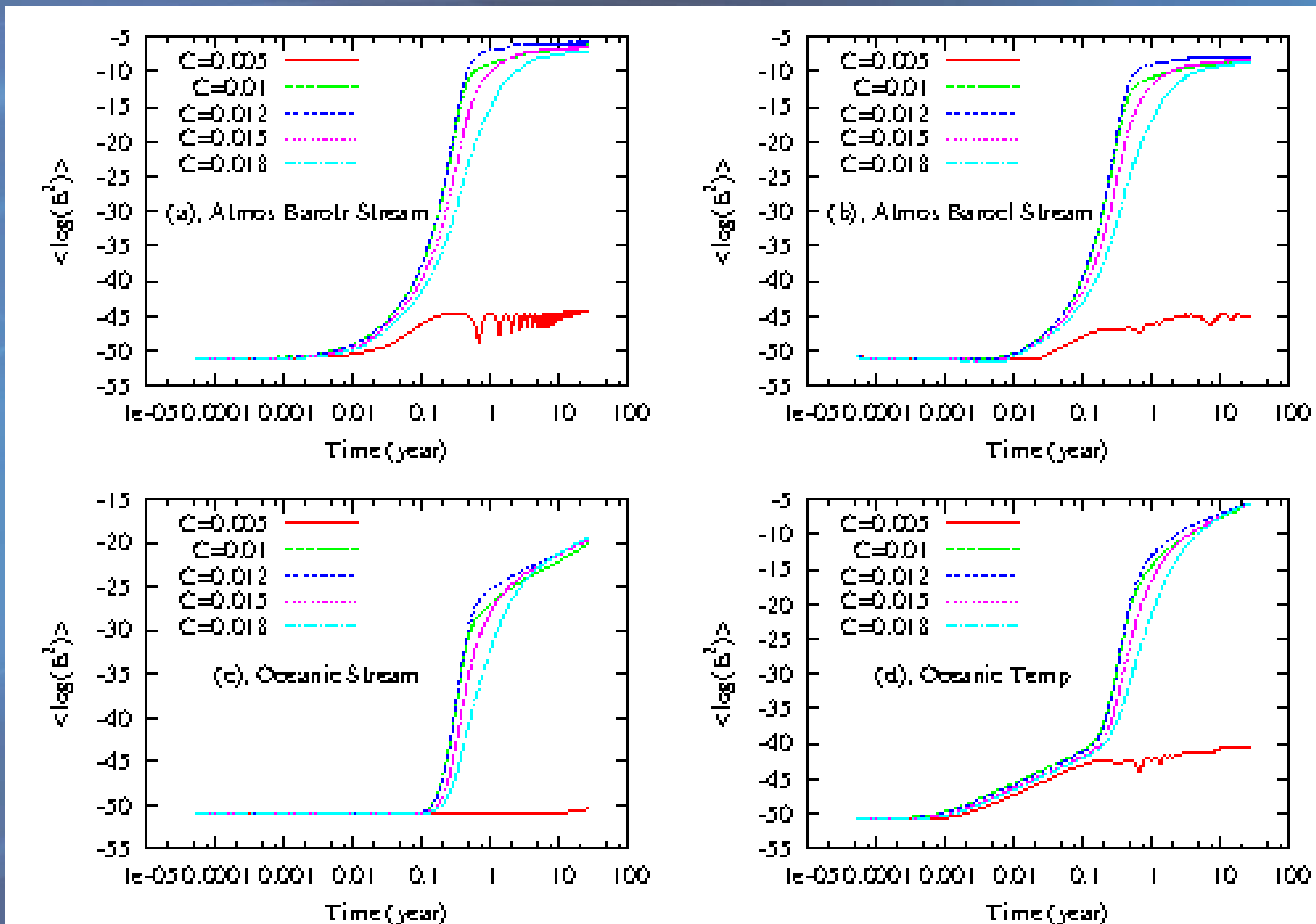
Depth of the ocean= 1000 m, S_o = 350 W/m^2

$n = 2\ L_y/L_x$ = 1.7



Results with the new version of the model, MAOSOAM

Depth of the ocean= 1000 m, S_o = 350 W/m^2 $n = 2\ L_y/L_x$ = 1.5



Some conclusions

In the model version with closed boundaries in the ocean (VDDG or MAOOAM, n=1.5):

- Friction is tempering chaos.
- The long term predictability of the atmosphere is related to the strong coupling between the ocean and the atmosphere (in the Low-order O-A model), i.e. a coupled mode should be present

In the new model version with channel flow:

- The influence of friction depends on the aspect ratio, n, with a chaos-induced dynamics for small aspect ratio and a chaos-tempered dynamics for large aspect ratio
- The long term predictability of the atmosphere depends on the proximity to bifurcation points? (Still work to be done to clarify this feature)

Future investigations

- Analysis of a higher order coupled ocean-atmosphere system
- Coupling with other components of the climate system

Some references

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