KMI - IRM

Koninklijk Meteorologisch Instituut

Institut Royal Météorologique

Köninglische Meteorologische Institut

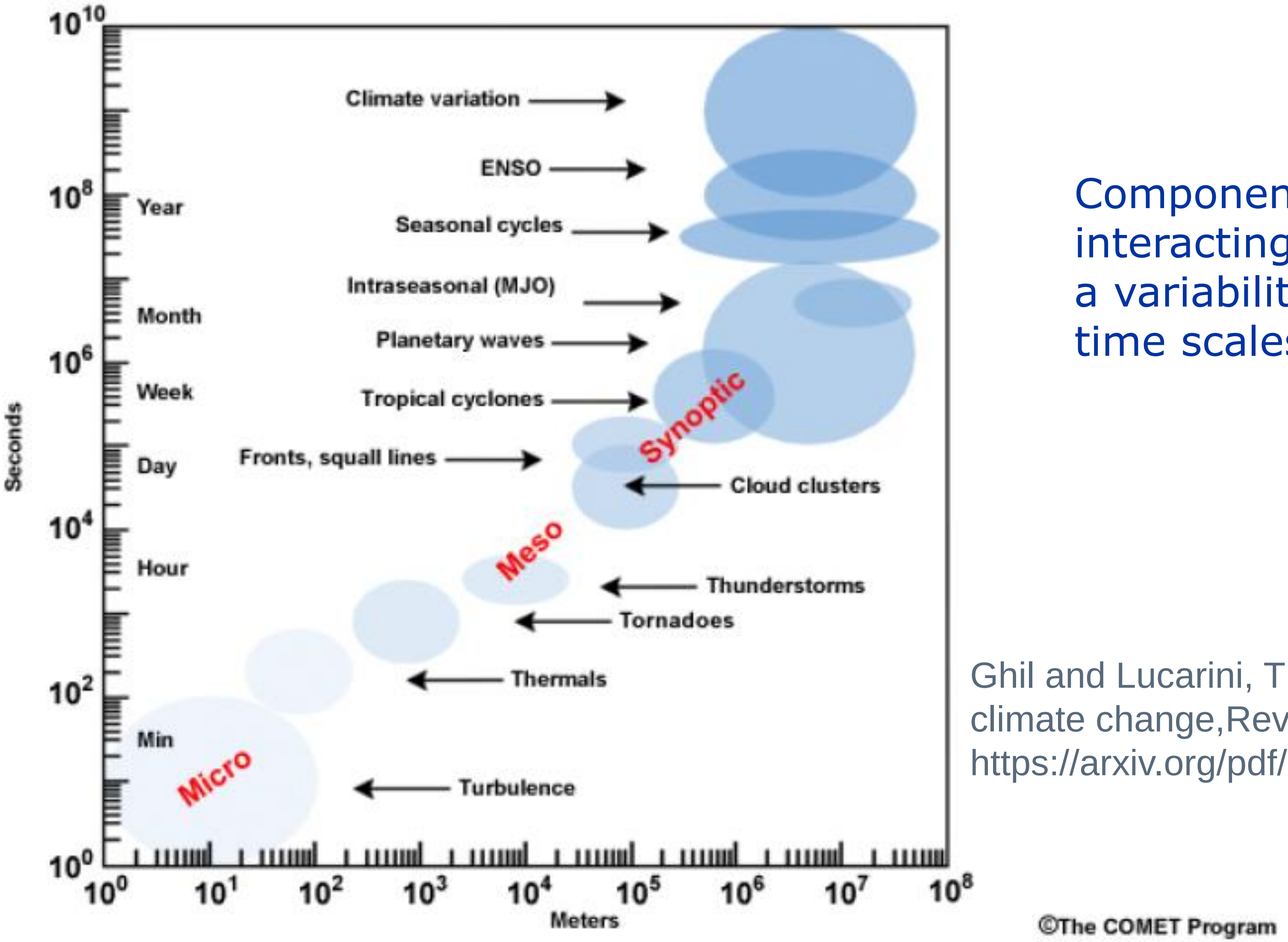
Royal Meteorological Institute

Probabilistic prediction and predictability of the atmosphere at seasonal-to-decadal time scales: A reduced-order model perspective

Stéphane Vannitsem

Collaborations: L. De Cruz, J. Demaeyer, W. Duan, M. Ghil, S. Penny

Introduction: Atmospheric variability



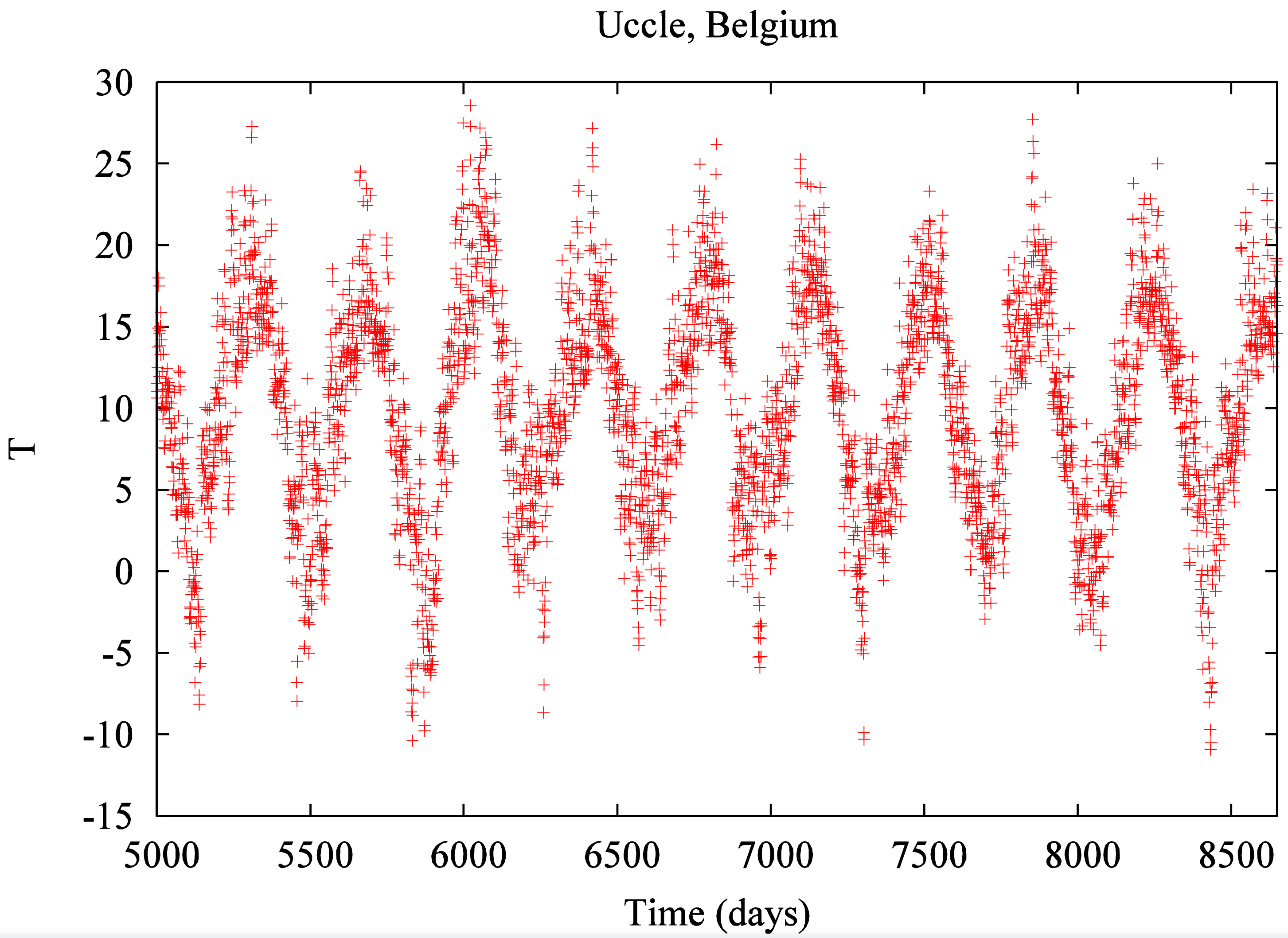
Components of the climate system all interacting with each other and leading to a variability on a wide range of space and time scales

Ghil and Lucarini, The physics of climate variability and climate change,Rev. Mod. Phys. **92**, 035002, 2020 extracted from https://arxiv.org/pdf/1910.00583.pdf

Introduction

Short-term variability

What is the predictability of that variable?

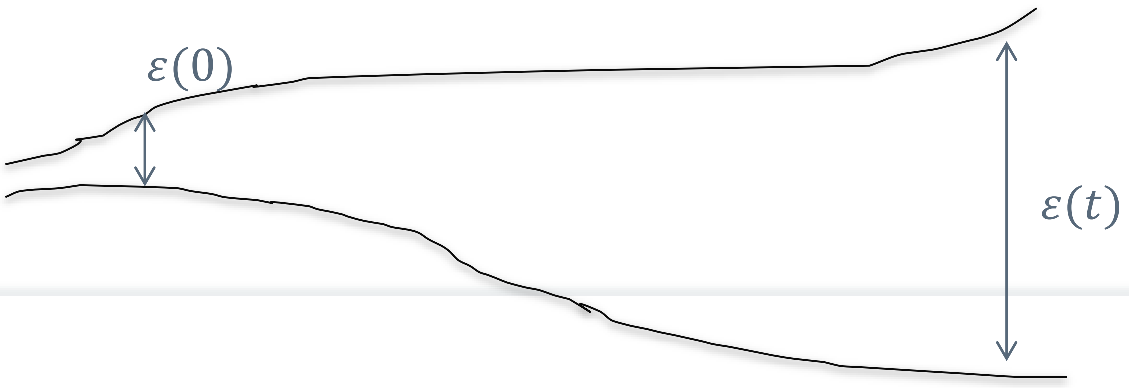


Predictability

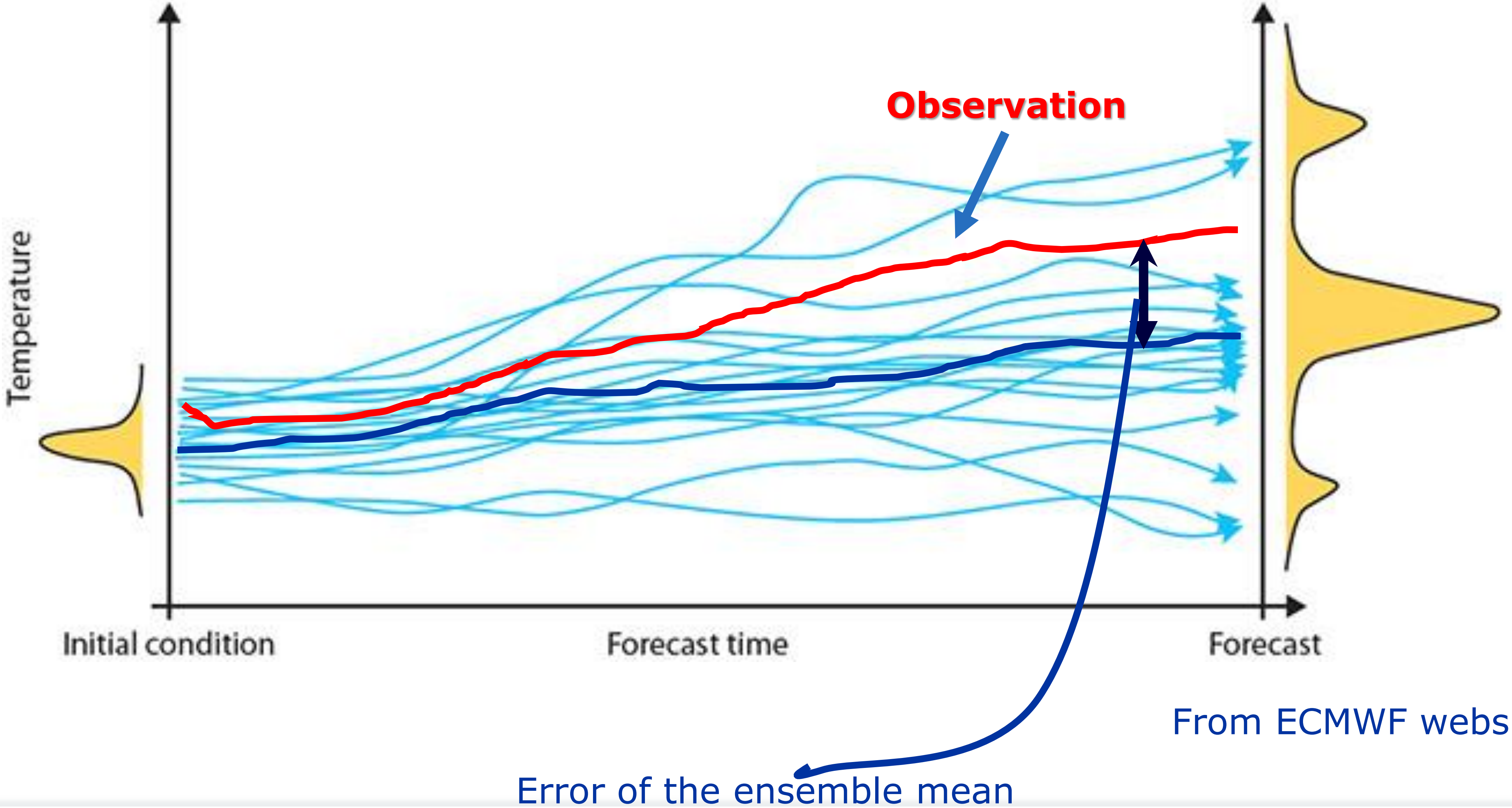
The property of sensitivity to initial (and model) uncertainties at the origin of the degradation of the quality of forecasts of atmospheric flows

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

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

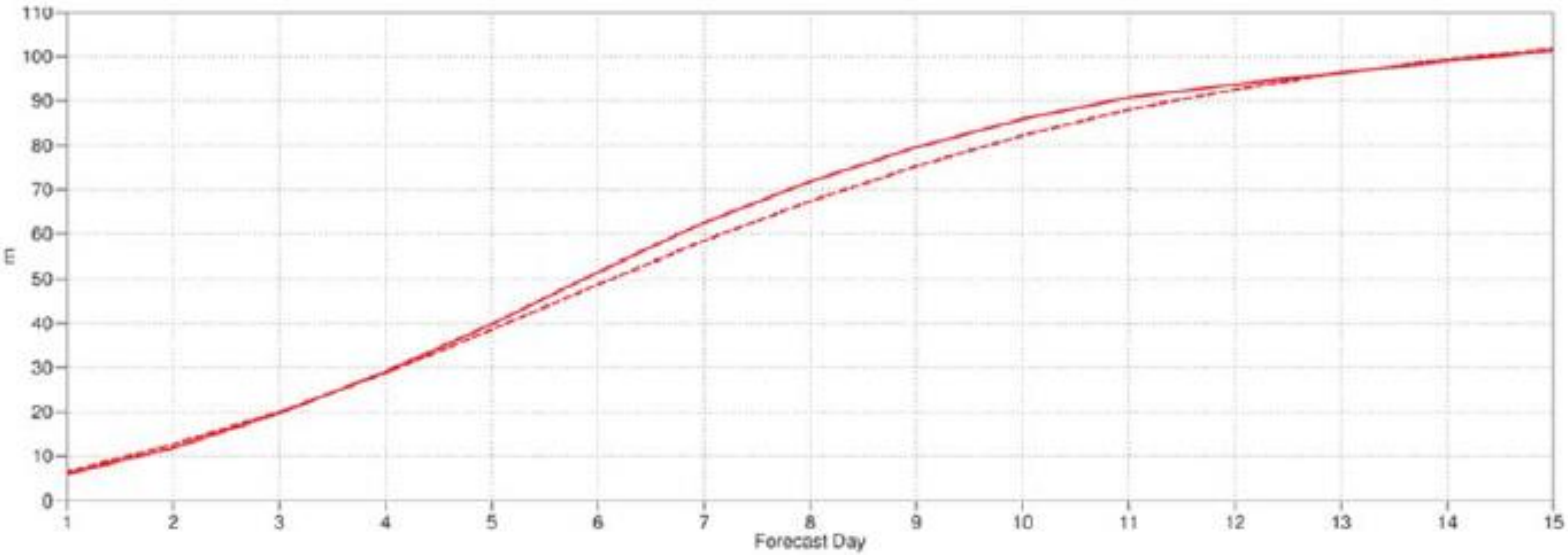


Ensemble forecasts



From ECMWF website

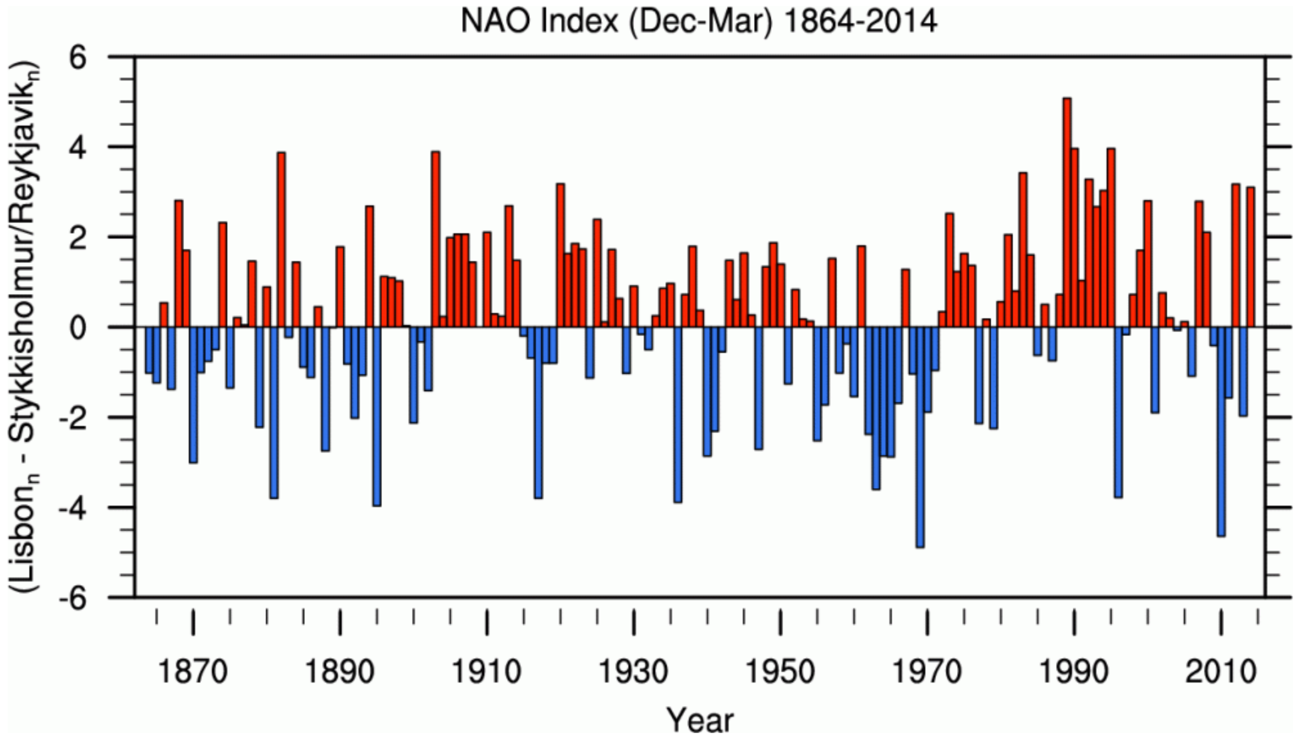
Predictability: Root mean square error evolution for ECMWF forecasts



Haiden T. et al, Evaluation of ECMWF forecasts, including 2014-2015 upgrades, Technical memorandum 765, ECMWF, 2015.

Climate variability: Extratropics

North Atlantic Oscillation (NAO)



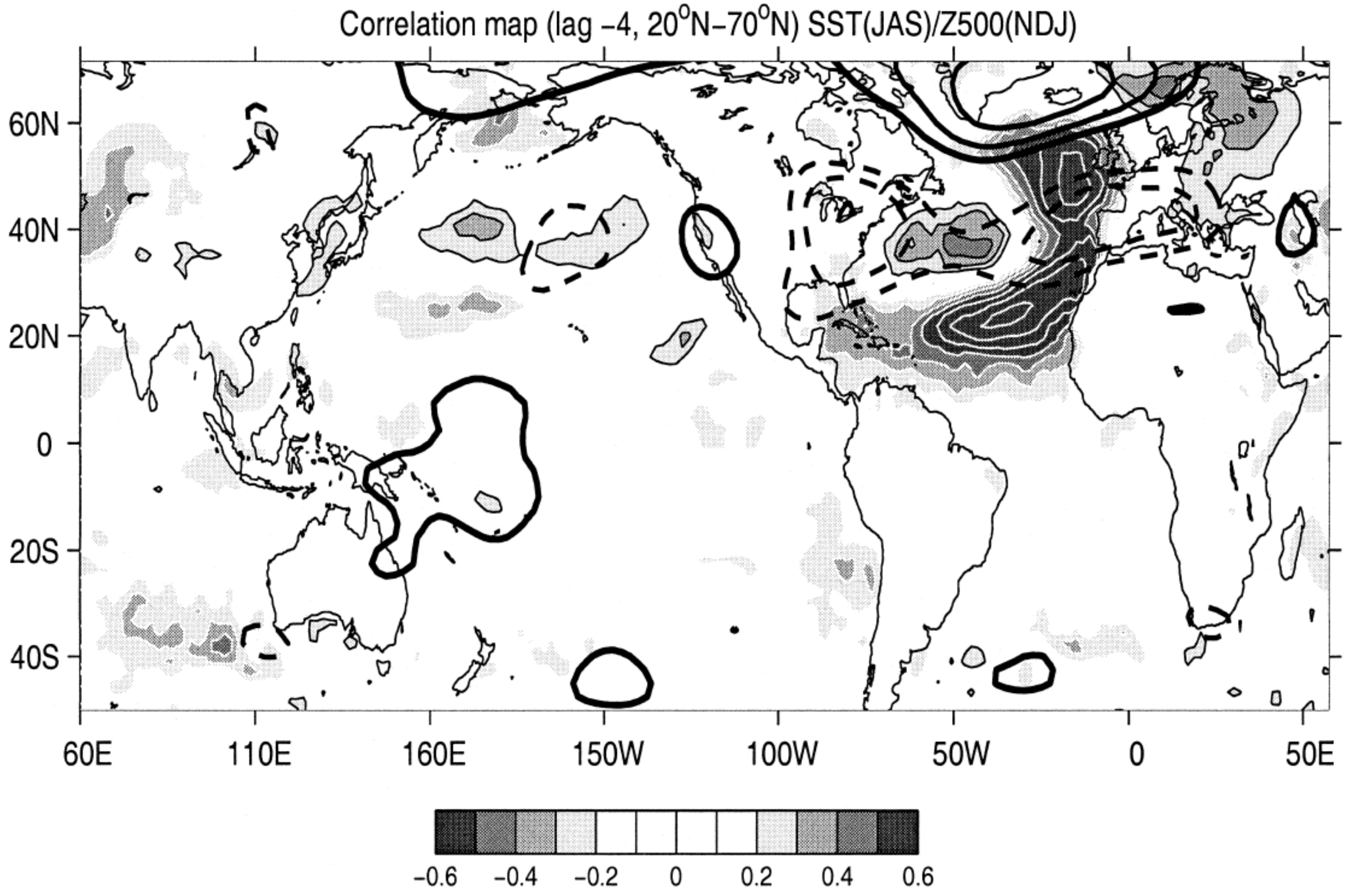
Positive NAO: Larger pressure difference between Lisbon and Reykjavik; Negative NAO: Smaller pressure difference

What is the origin of the low-frequency variability in the extra-tropics?

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

Influence of the ocean?

Correlation between the Ocean and the atmosphere

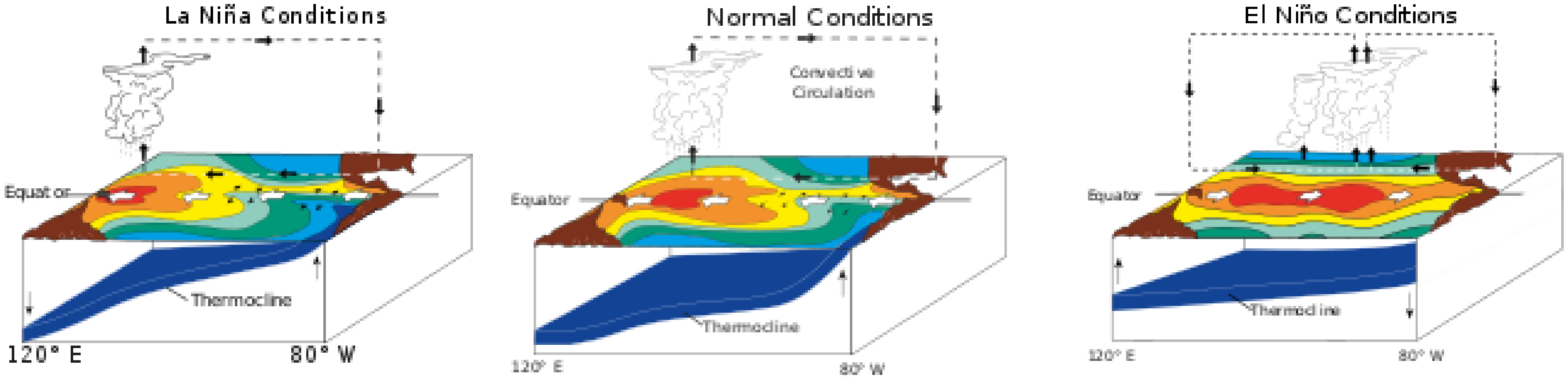


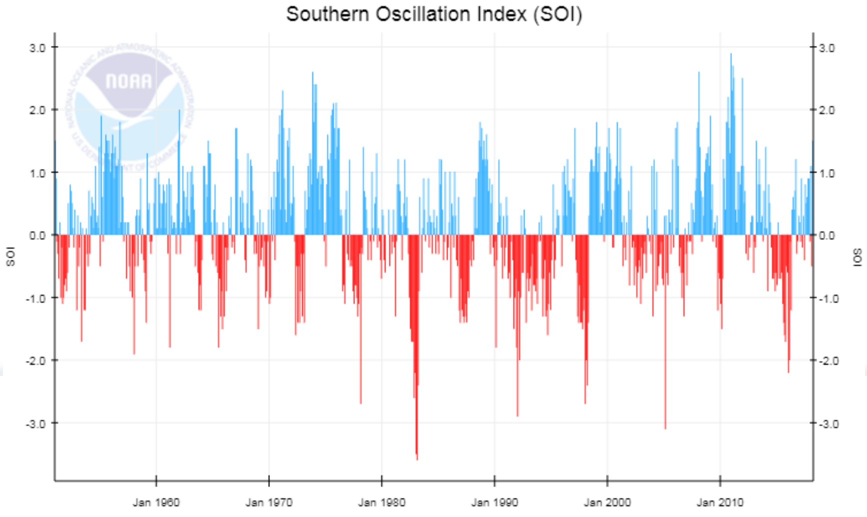
Czaja, A., and C. Frankignoul, 2002: Observed Impact of Atlantic SST Anomalies on the North Atlantic Oscillation. *J. Climate*, **15**, 606–623

Other influences? Stratosphere, remote (ENSO)…?

Remote influence of ENSO?

El-Nino – Southern Oscillation (ENSO): Ocean-atmosphere coupled dynamics in the Tropical Pacific





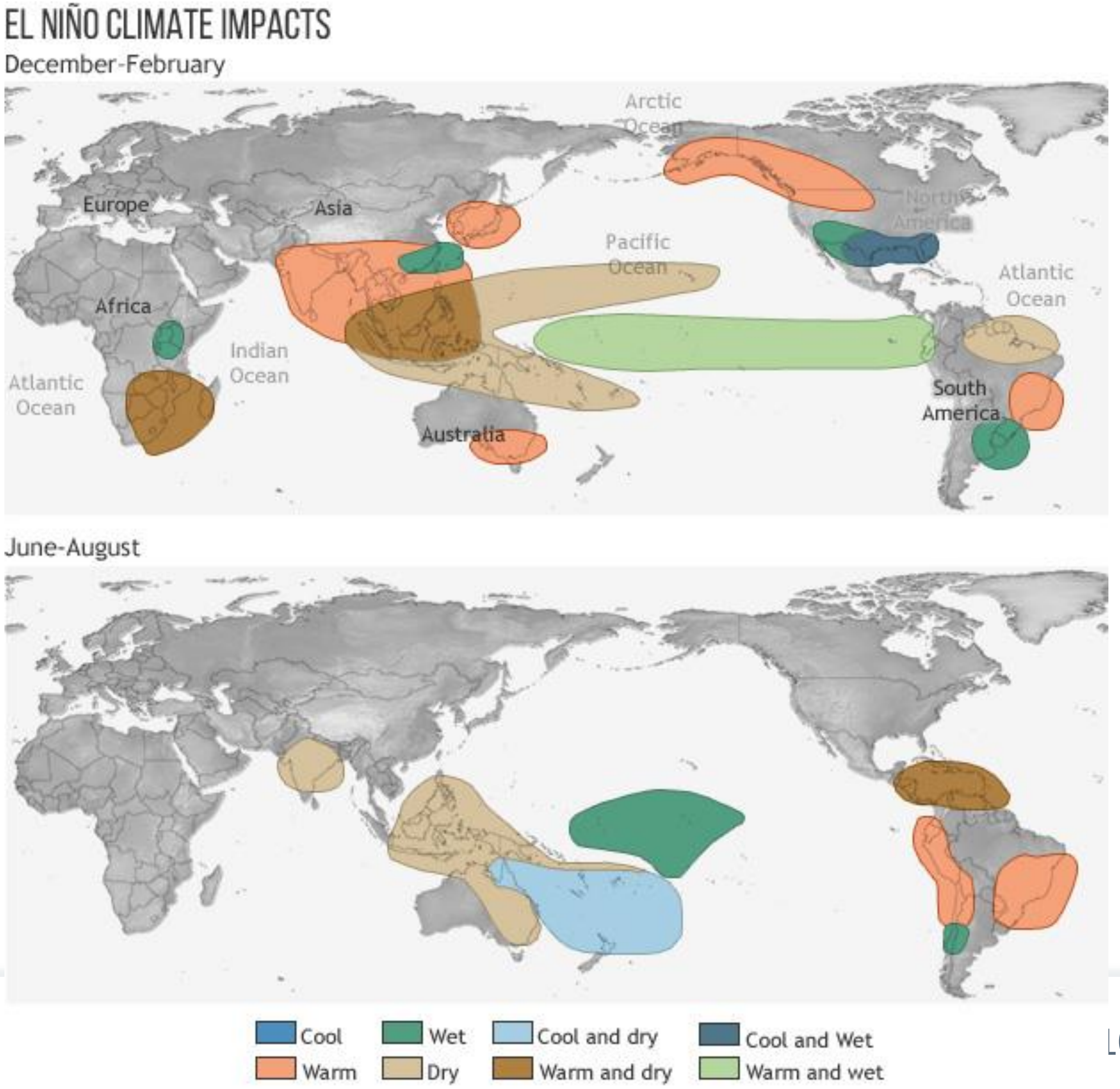
Associated with the development of El-Nino and La-Nina in the Tropical Pacific

Remote influence of ENSO?

Teleconnections with other regions of the globe!

Does ENSO modify the extratropical Dynamics?

Many studies on that aspect



From NOAA
https://www.climate.gov/news-features/featured-images/global-impacts-el-ni%C3%B1o-and-la-ni%C3%B1a

General objective of this research

To characterize the predictability of the atmosphere on seasonal, inter-annual and decadal time scales, and in particular to answer the following questions:

What is the impact of the coupling between the ocean and the atmosphere?

What is the impact of the coupling with the Tropical regions?

What types of pertubation are needed to generate reliable ensemble forecasts?

Strategy

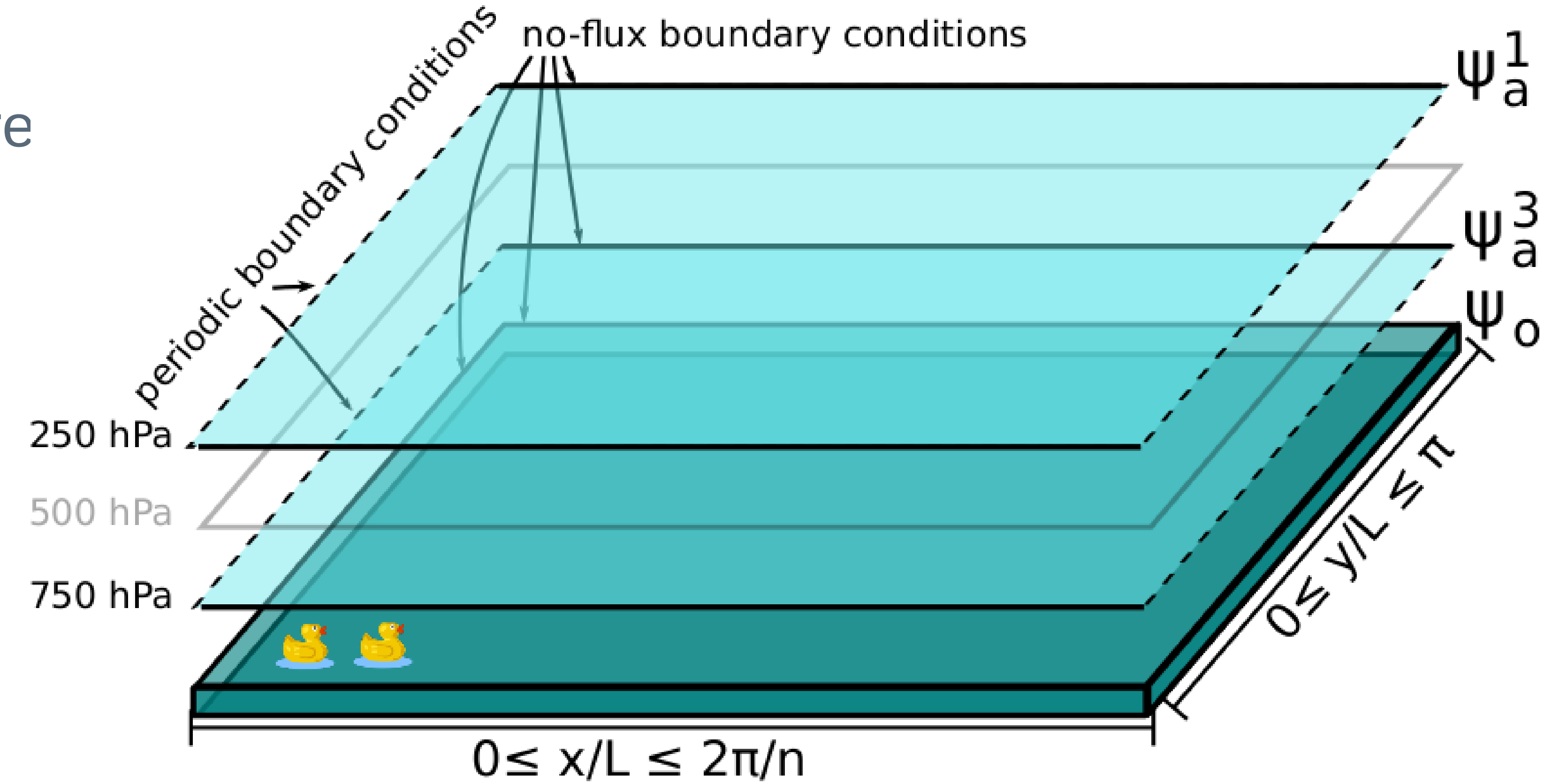
- Development of reduced-order climate models, and in particular coupled ocean-atmosphere models
- Analysis of the predictability of the reduced-order models

The Reduced-order coupled model

- QG model for both the ocean and the atmosphere

Highly truncated model Version:

10 Fourier modes for the Atmosphere
8 Fourier modes for the Ocean



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

Latitudinal dependence
of the radiative input

$R_0 + C_0\sqrt{2}$ cos y

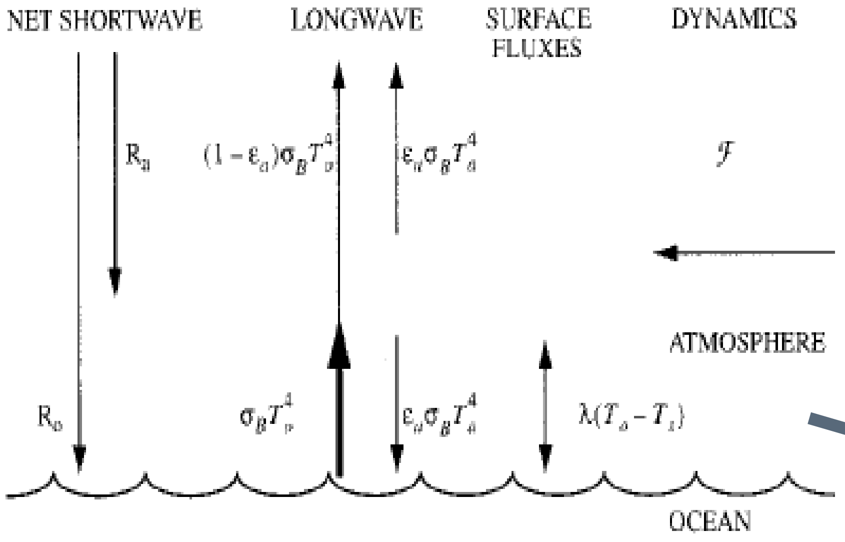
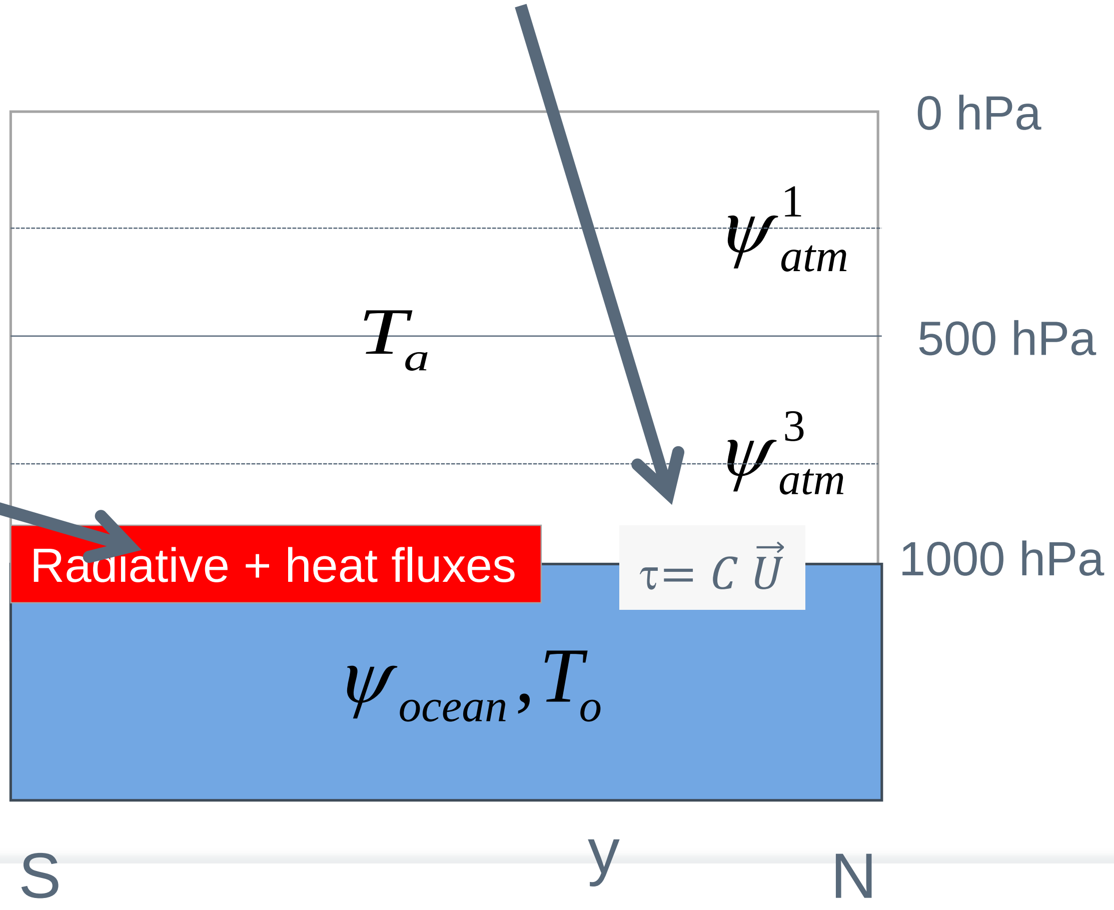


FIG. 2. Diagram of simple energy balance model on which Eqs. (1) and (2) are based. See appendix A for definition of symbols.

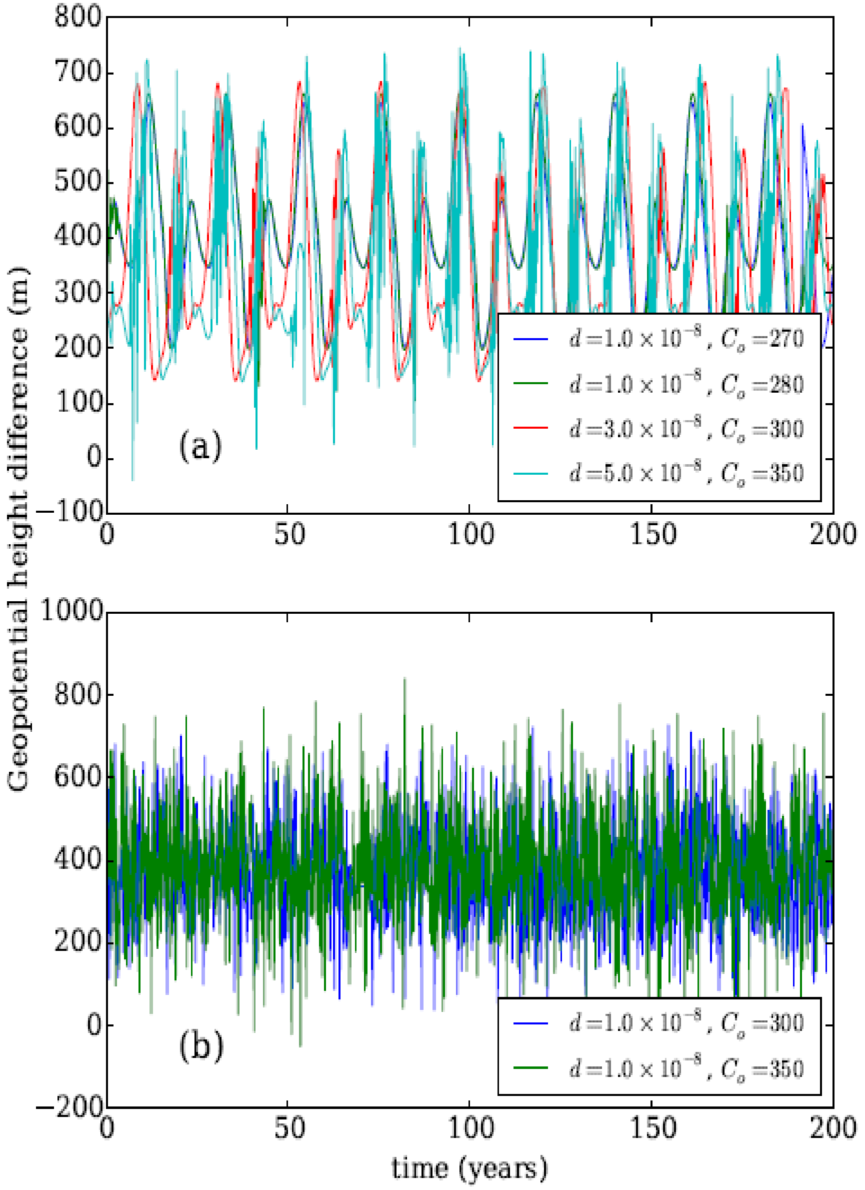
Barsugli & Battisti, 1998, JAS

Surface friction strength

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



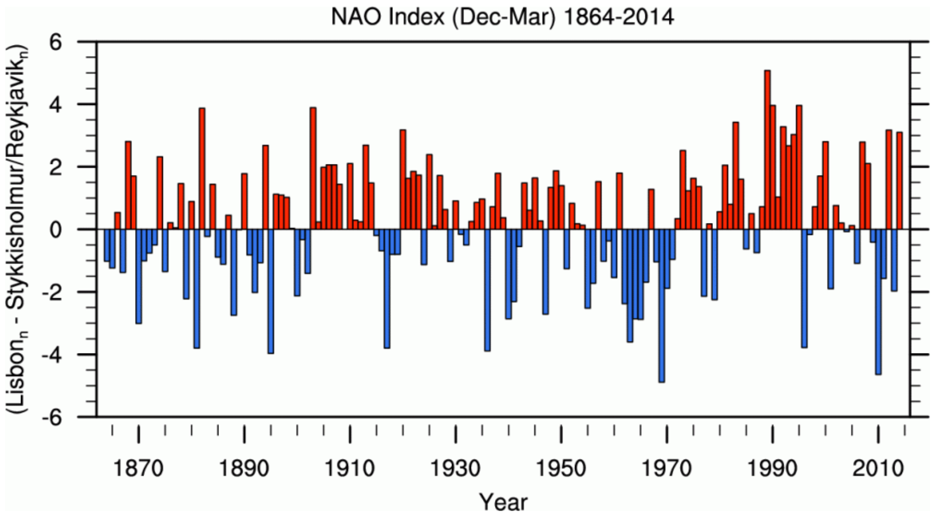
Local coupling: Variability

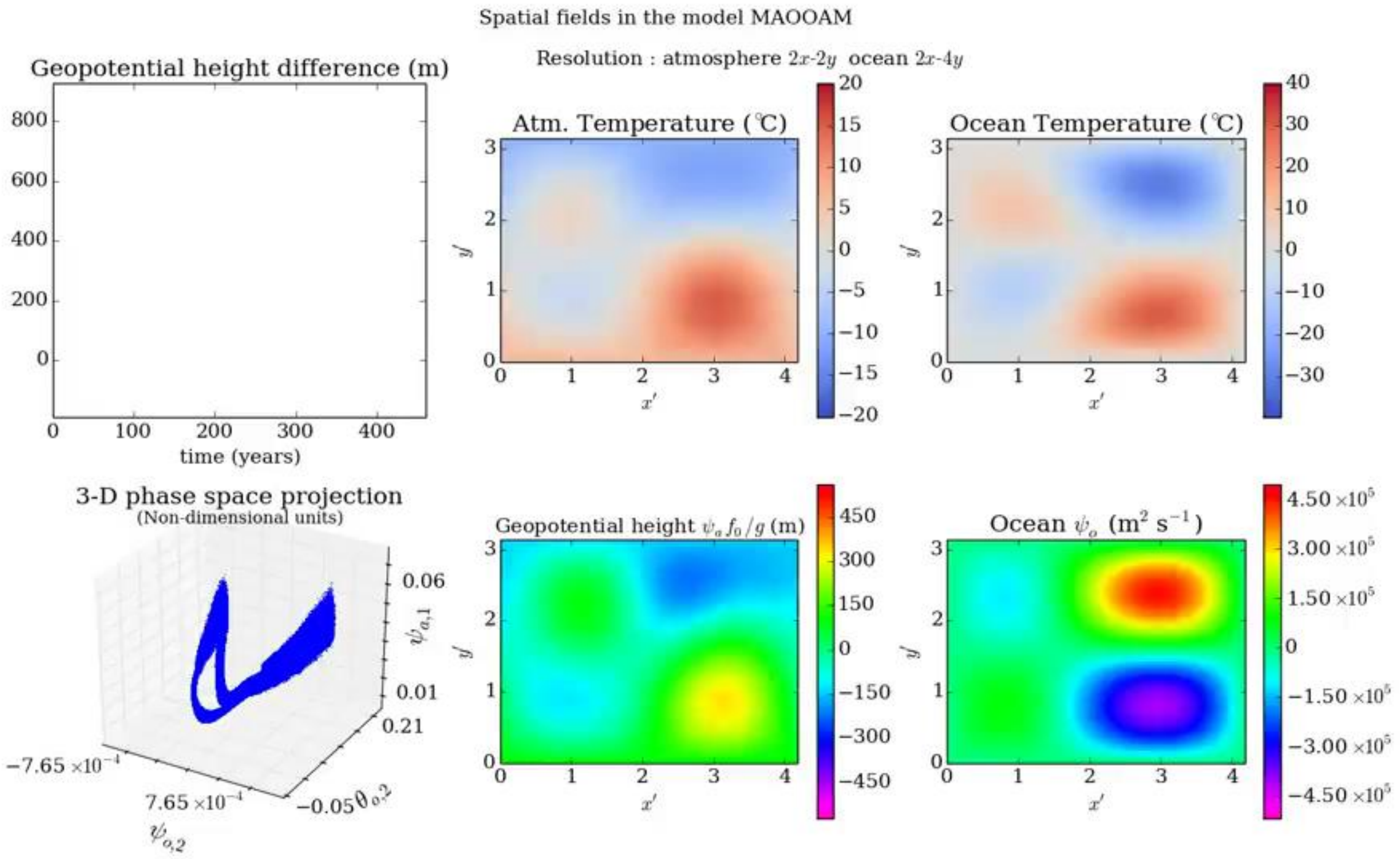


Geop. Height. Diff. between two points from the North and South parts of the domain

Vannitsem et al, 2015, Physica D

Roughly the same decadal variability?





Spatial fields in the model MAOOAM
Resolution : atmosphere 2x-2y ocean 2x-4y
Geopotential height difference (m)
time (years)
Atm. Temperature (℃)
Ocean Temperature (℃)
3-D phase space projection
(Non-dimensional units)
Geopotential height $\psi_a f_0/g$ (m)
Ocean ψ_o ($m^2 s^{-1}$)

Local coupling: Lyapunov exponents

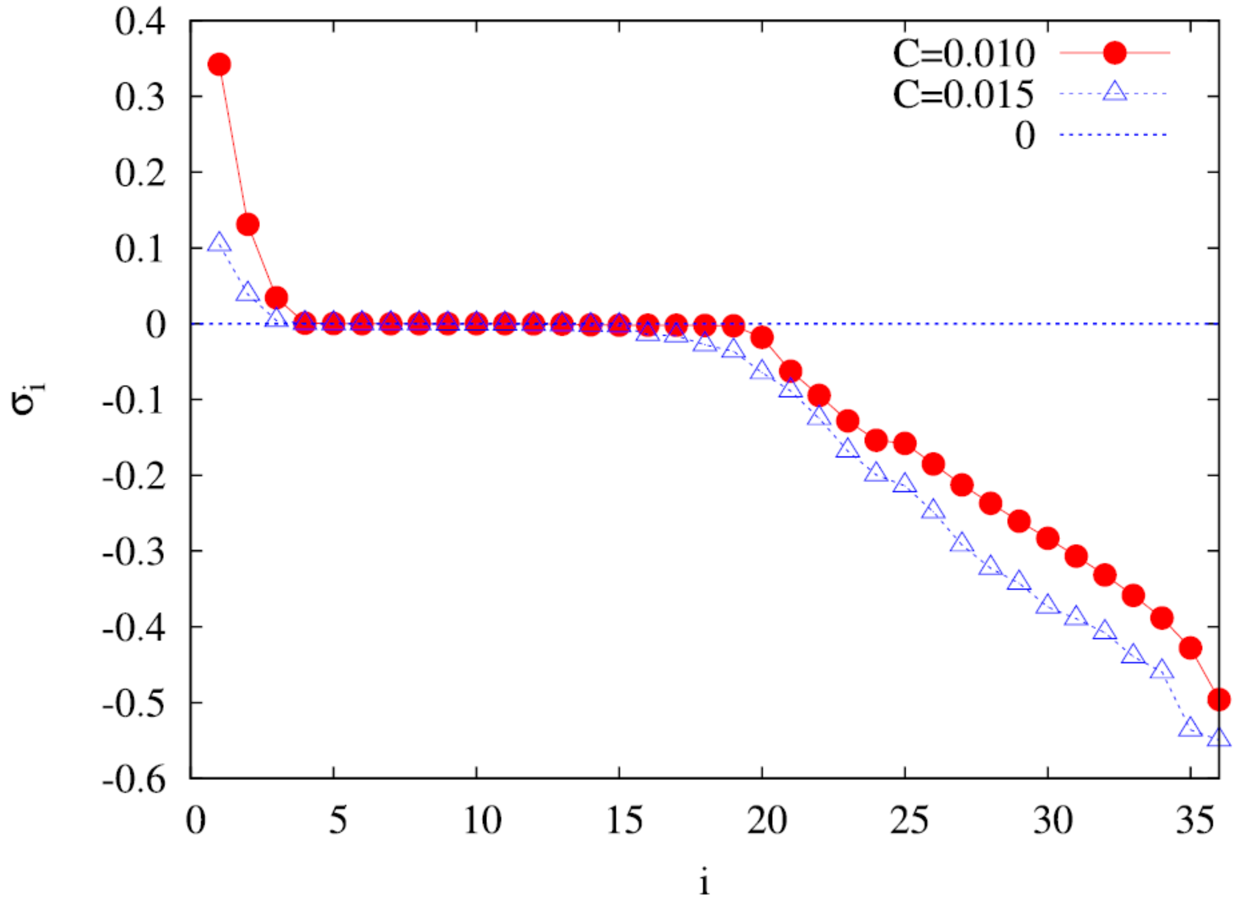
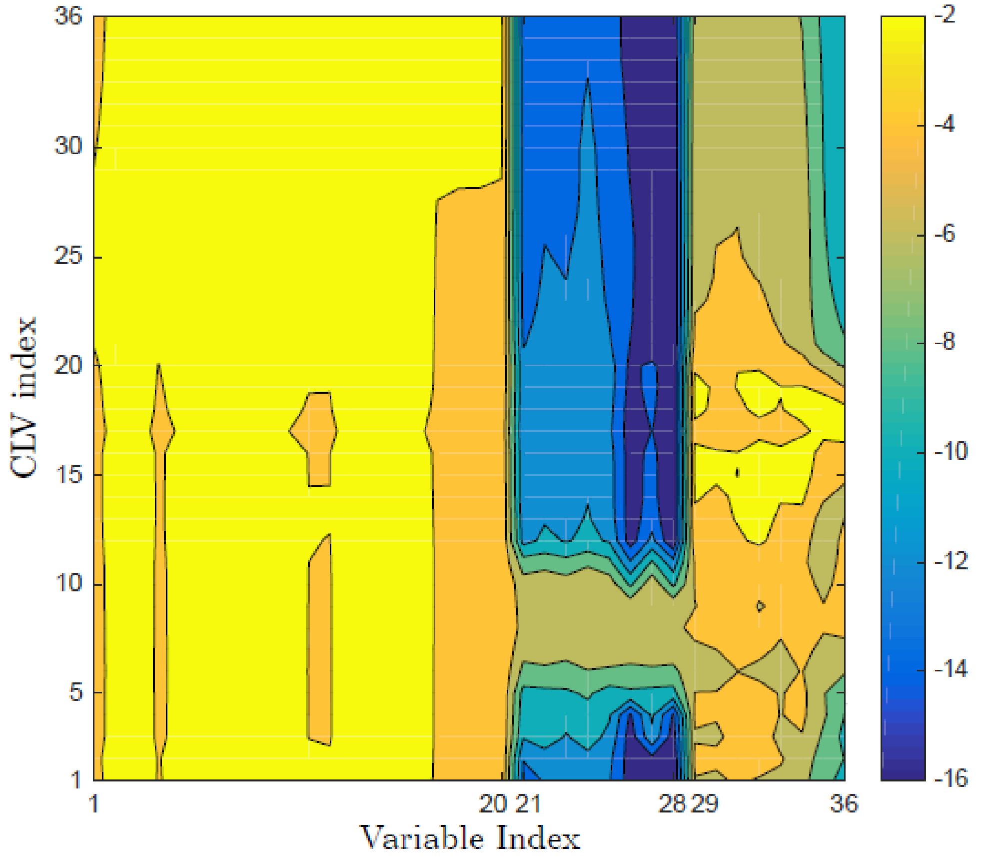


FIG. 9. Lyapunov spectra for the red (red filled circles) and green (blue triangles) attractors displayed in Fig. 8.



Vannitsem S. & V. Lucarini, *J. Phys. A*, 49, 224001, 2016.

Vannitsem S. Chaos, 27, 032101, 2017,
doi: 10.1063/1.4979042

Ocean-atmosphere coupling: Predictability experiments

Let us now consider the following experiment:

"Perfect model framework"

- Add a random perturbation in the initial conditions of the coupled ocean-atmosphere model, consistent with the initial uncertainty. From a uniform distribution with amplitude 10^{-6}.

Looking at the evolution of the mean square error averaged over 2000 realizations

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

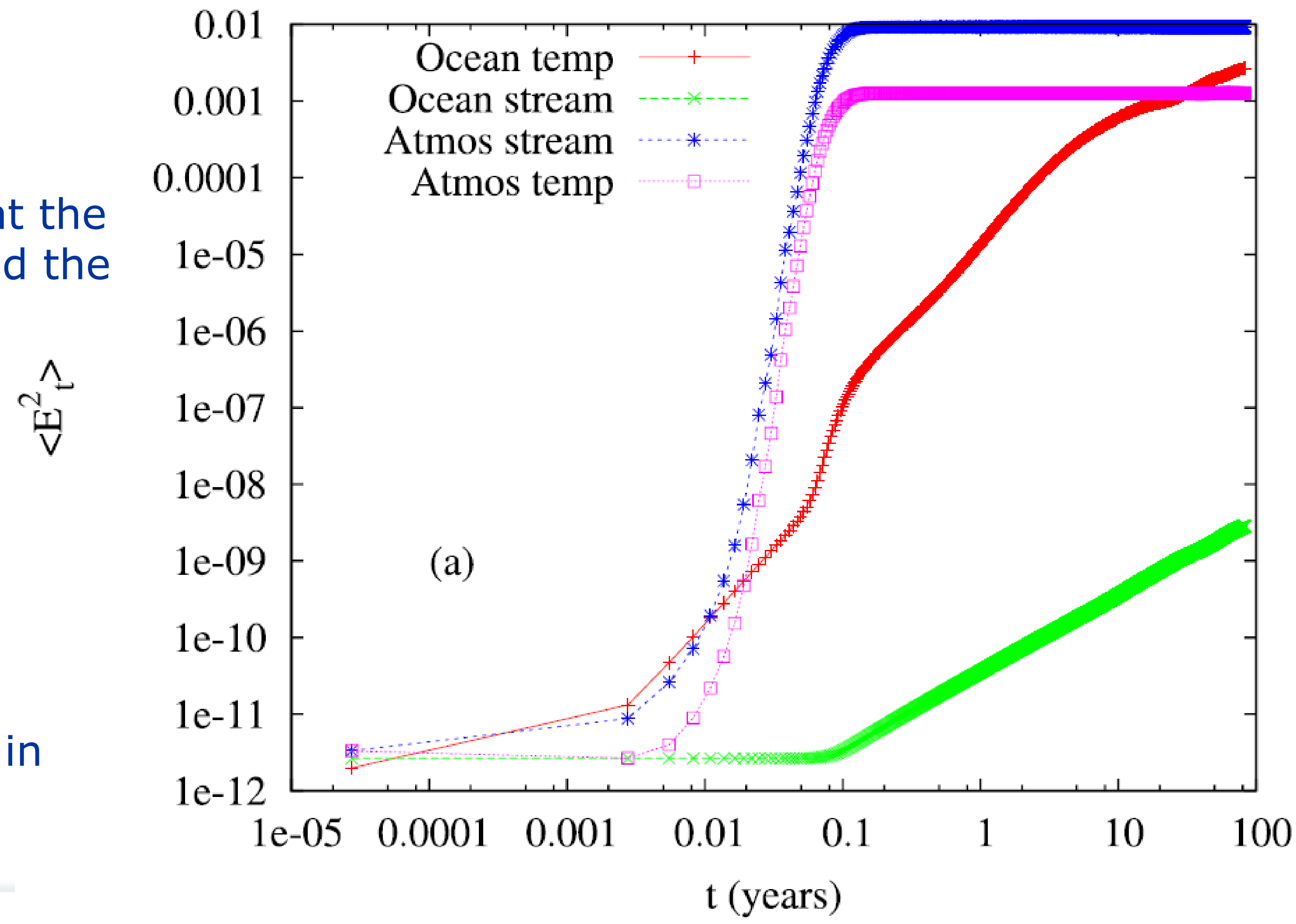
Predictability

Error dynamics

Experiment with small friction at the interface between the ocean and the atmosphere

Small surface friction
C=0.010

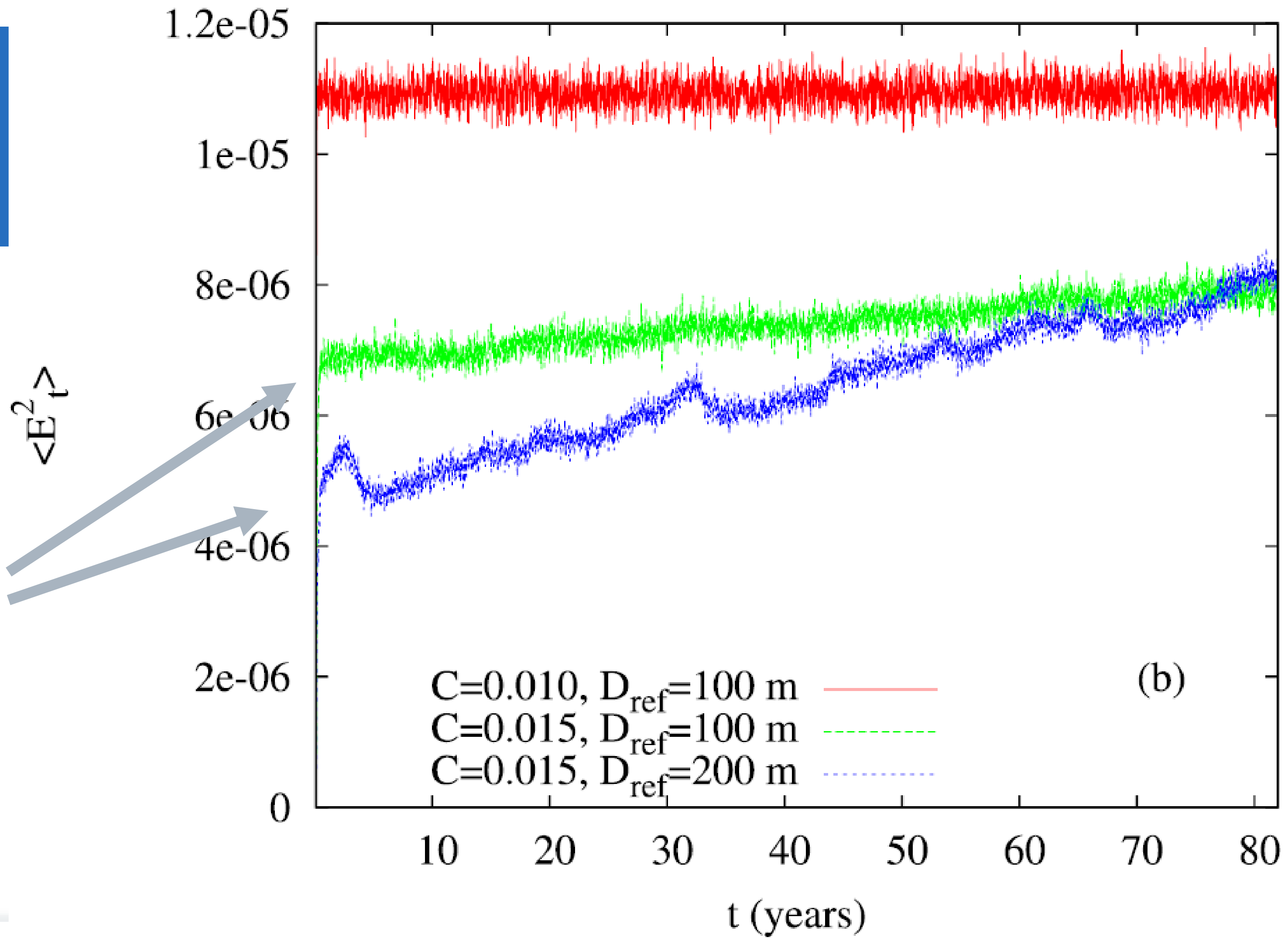
- Complex dynamics in multi-scale systems
- Quick saturation of the error in the atmosphere



Predictability

Error dynamics for the first barotropic mode (zonal flow)

Larger friction experiments



Vannitsem S. Chaos, 27, 032101, 2017,
doi: 10.1063/1.4979042

Influence of “external” forcing

Use of the coupled ocean-atmosphere system forced by the ENSO model of Jin-Timmermann.

Tropical model

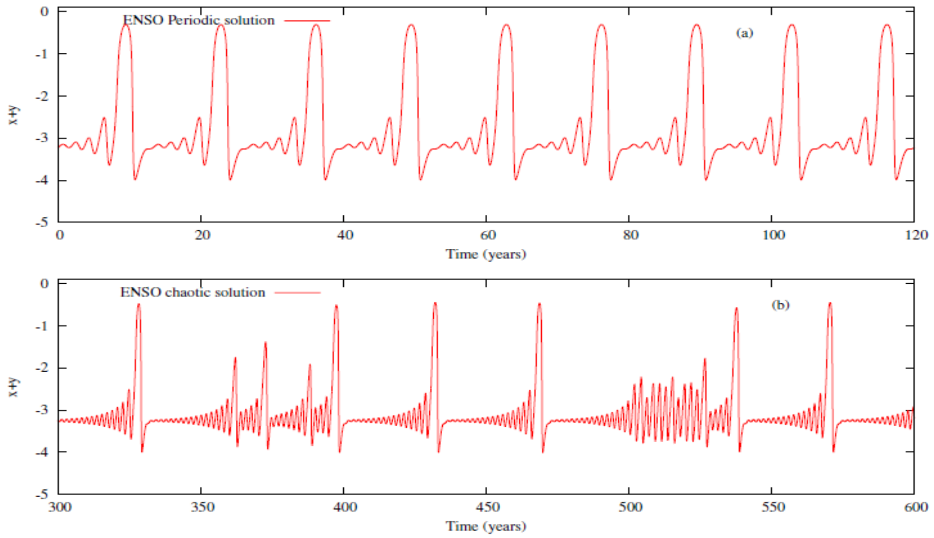
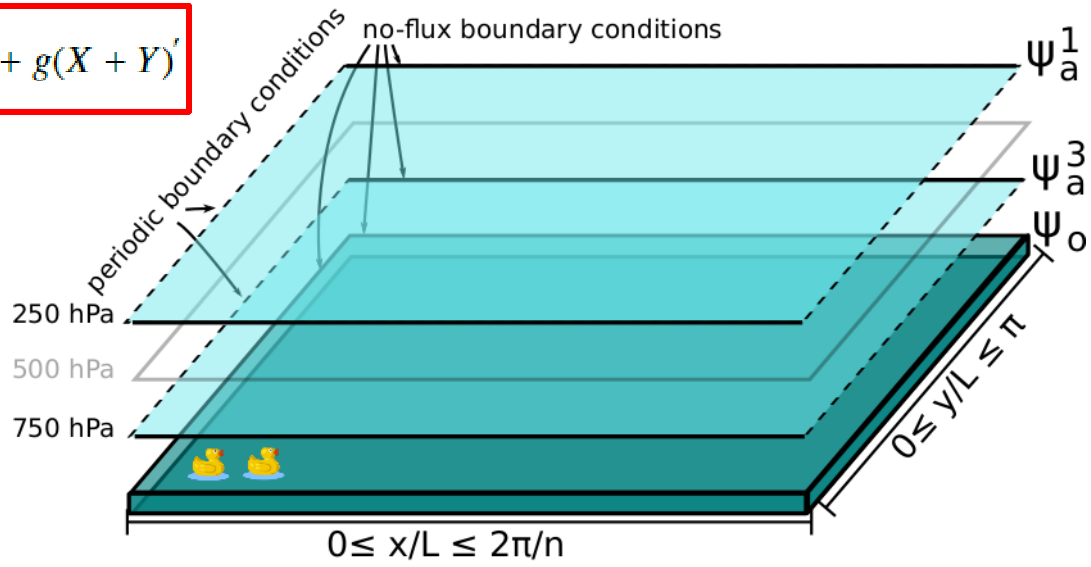


Figure 1. Trajectory segments of the ENSO model for the eastern Tropical Pacific basin's temperature anomalies $x + y$. (a) Periodic case, and (b) chaotic case; see Eqs. (1) and Table 1 for details. The bursting behavior in both cases, with very large excursions towards more positive values, occurs periodically in panel (a) and irregularly in panel (b). Notice that the total length of the segments is 120 yr in panel (a) and 300 yr in panel (b).

$$\frac{d\psi_{a,1}}{dt} = f_1(\psi_{a,1},\theta_{a,1}) + g(X+Y)'$$

Extratropical model



36-variable reduced-order model

See Timmermann et al (2003, JAS, 60, 152-155)

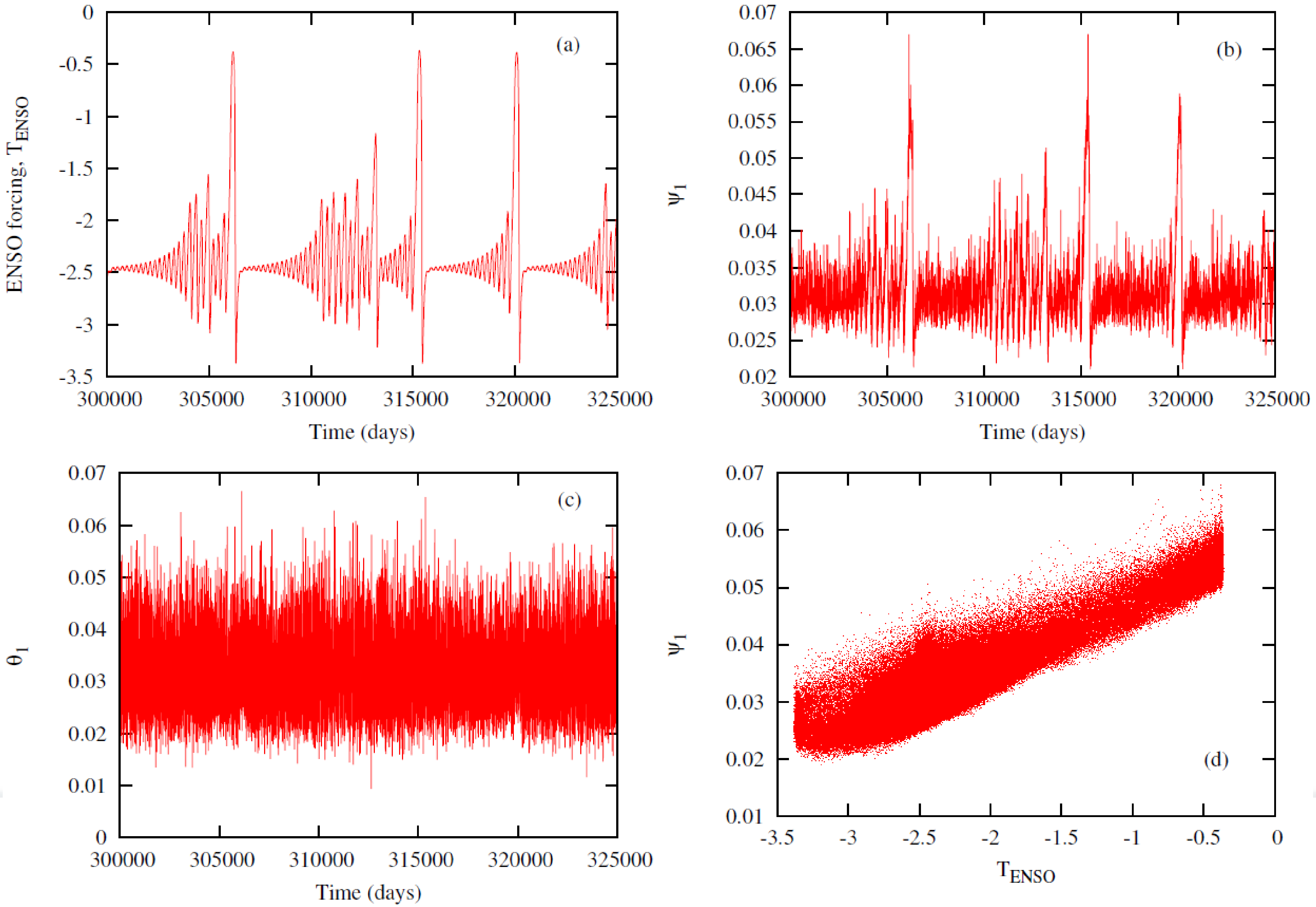
Vannitsem, Demaeyer, Ghil, *JAMES*, *13*, e2021MS002530, 2021.

Remote coupling: Variability

Setup of the experiment:

g=0.002

Lyapunov time of the forcing: 7 years



Remote coupling: Predictability experiment

Let us now consider the following experiment:

"Perfect model framework"

- Add a random perturbation in the initial conditions of the coupled ocean-atmosphere model, consistent with the initial uncertainty. From a uniform distribution with amplitude 10^{-6}.
- Add a random perturbation in the initial conditions of the ensemble for the tropical model, with the same uniform distribution as the initial error. Several amplitudes are considered (0., 0.02, 0.05, 0.1, 0.15). Perturbation amplitudes less than 15 % of the standard deviation of the process!

Use of 2000 different initial states on the attractor of the system

Remote coupling: Perfect predictability

$\psi_{a,1}$ $\theta_{a,1}$

No error in the initial state in the Tropical region.

Initial errors in the extratropics

Without coupling: g=0

With coupling: g=0.002

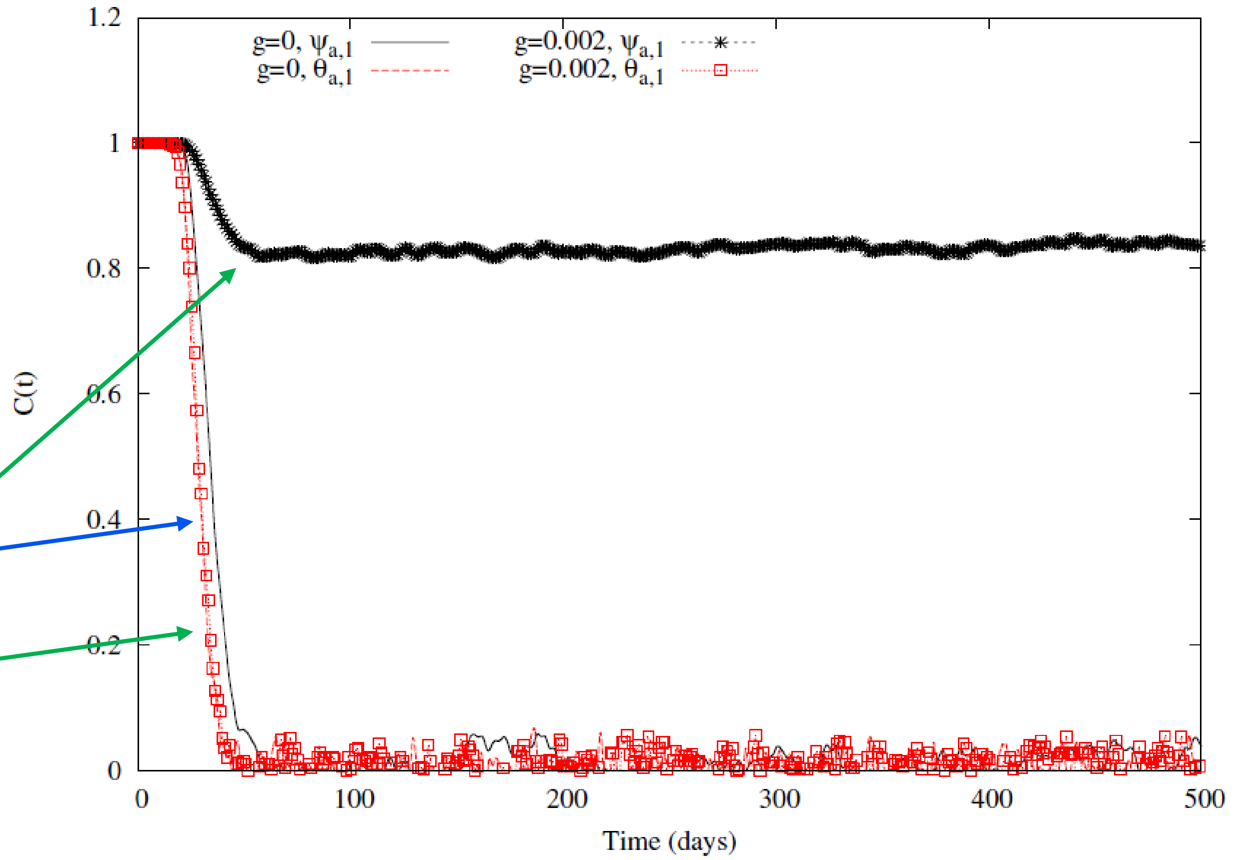


Figure 2. Correlation between the reference integration, viewed as perfect observations, and the ensemble mean of forecasts for variables ψ_1 and θ_1 for $g = 0.$ and $g = 0.002$. The ensemble size is fixed to $M = 1$, hence corresponding to single deterministic forecasts.

Remote coupling: Predictability

Correlation skill for

$$\psi_{a,1}$$

g=0.002

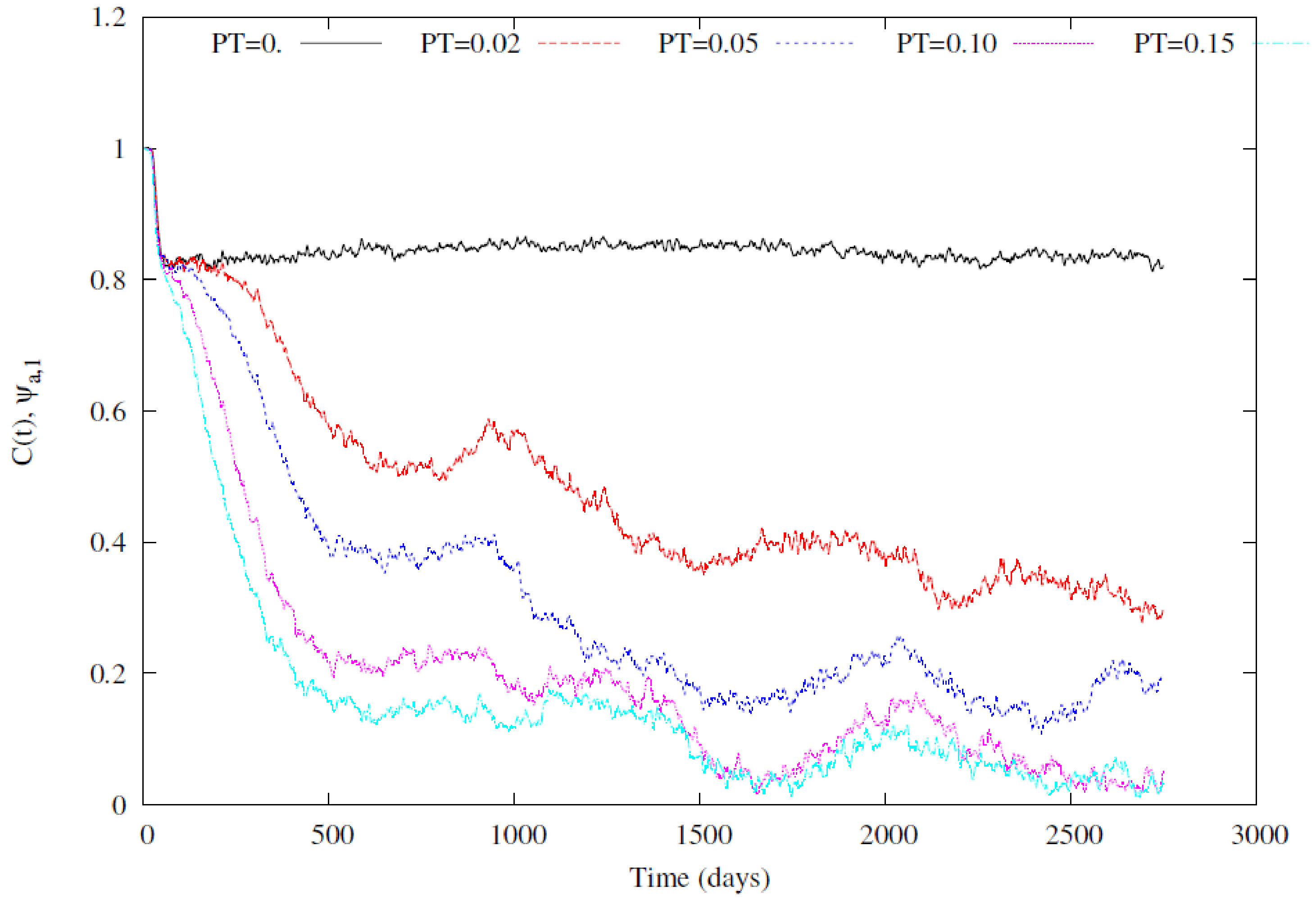


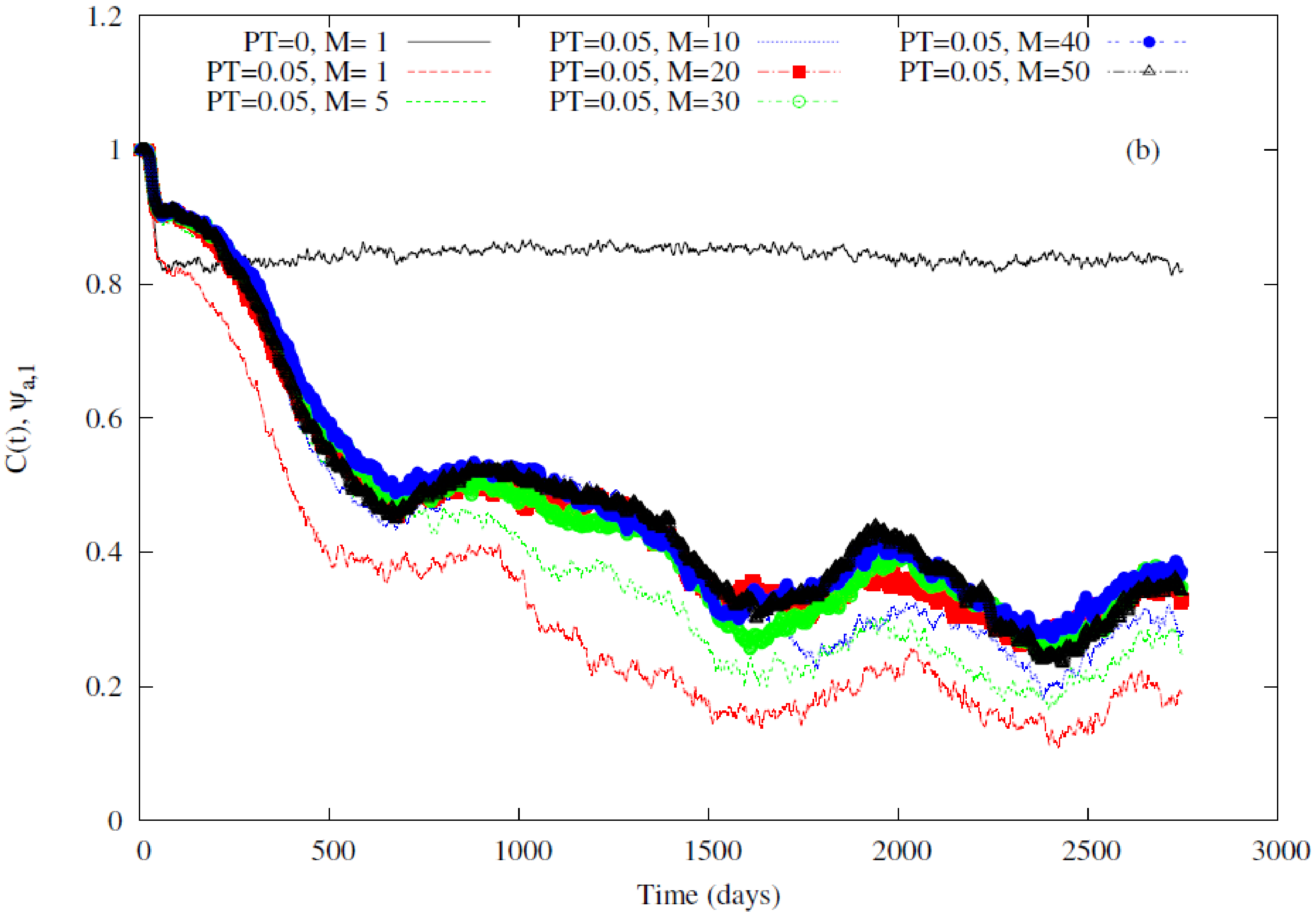
Figure 4. Evolution of the correlation skill for $M = 1$ for different amplitudes of the errors introduced in the initial conditions of the tropical model.

Remote coupling: Ensembles

Correlation skill for the ensemble mean

Different sizes of ensembles are considered.

Already with 5-10 ensemble members, one extracts all the information.



Remote coupling: temporal averages

Correlation skill for the ensemble mean of temporal averages

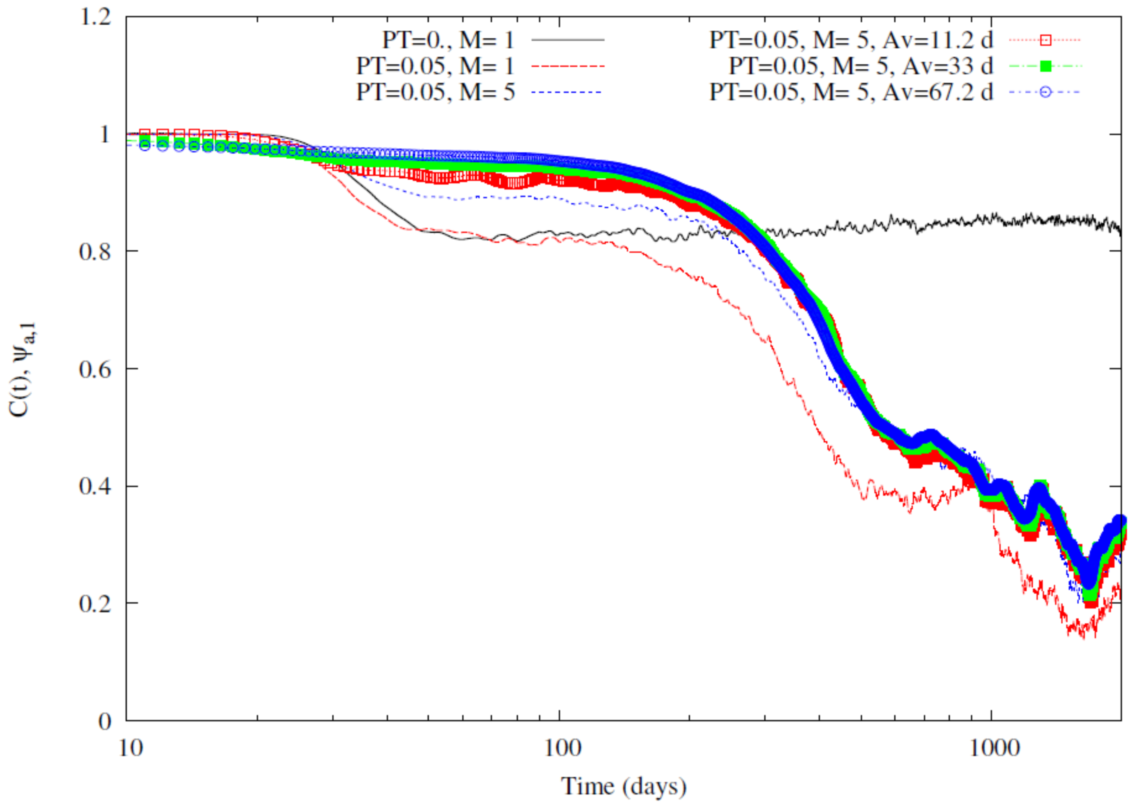


Figure 11. Evolution of the corrrelation skill for $\psi_{a,1}$ for various combinations of averaging (ensemble and/or in time).

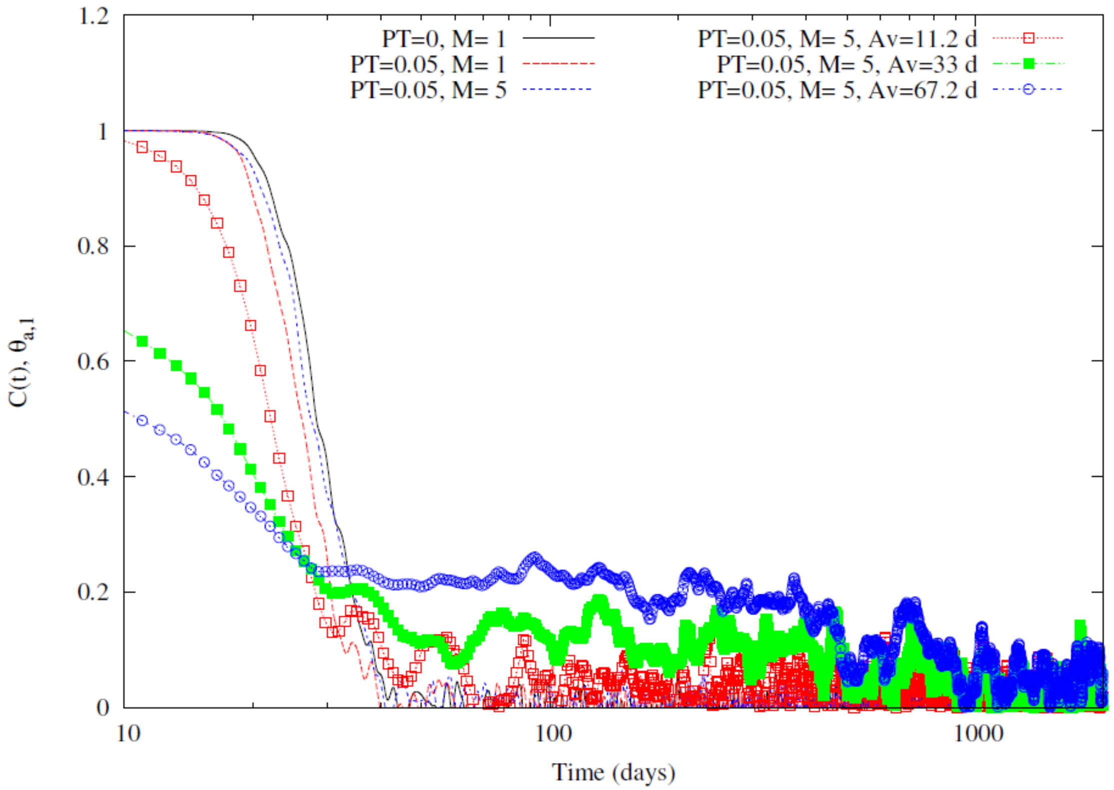


Figure 12. Evolution of the corrrelation skill for $\theta_{a,1}$ for various combinations of averaging (ensemble and/or in time).

Some conclusions on long-term predictability

- The coupling between the ocean and the atmosphere leads to the development of a low-frequency variability (LFV) driving (and driven by) both the ocean and the atmosphere

  Key ingredients: Surface friction and heat transfer between the two components

- The LFV associated with the interaction between the ocean and the atmosphere induces a long term predictability of the atmosphere on decadal time scales

- The remote forcing from the Tropics and the associated teleconnections may provide some hope for long term predictability as the forcing has long-term memory, but …

- Initial Condition (IC) errors in the Tropics induce a rapid degradation of the long term predictability in the extratropics, implying that accurate knowledge of the IC of the forcing is necessary for decadal predictions in order to make full use of teleconnections

Ensemble forecasts: How to perturb?

- S2S predictions is beyond atmosphere predictability limit
  - Coupled Earth system models must be used
- Usually done with ensemble:
  - How to initialize them consistently to obtain reliable results?
- Already tested, use of the:
  - Bred vectors (Peña & Kalnay, 2004; Yang et al., 2008; O'Kane et al., 2019)
  - EOFs (e.g. Polkova et l, 2019)
  - Climatological anomalies…

In the current presentation, we investigate the projections of the initial conditions on the Backward Lyapunov vectors and other structures (Vannitsem and Duan, Climate Dynamics, 2020)

Ensemble forecasts: How to perturb?

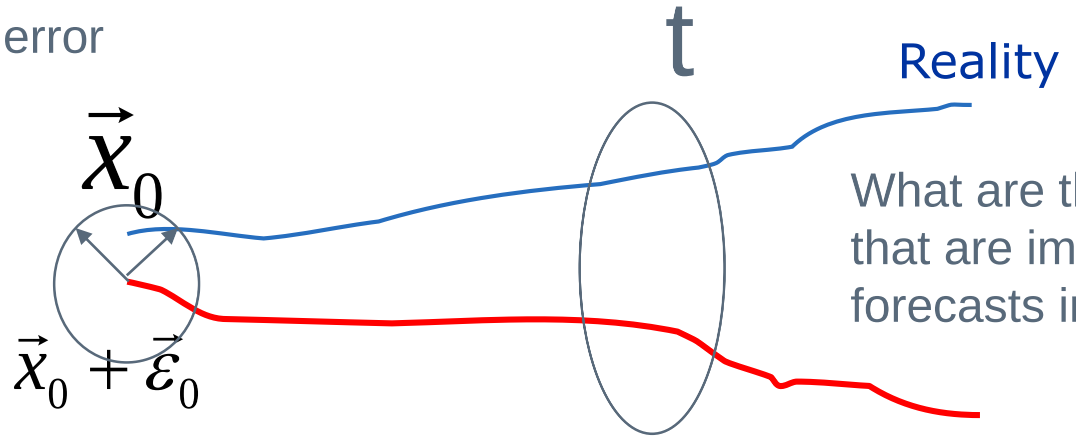
Experimental setup

Initial error: Random

Number of ensemble members: 20

Number of realizations on the attractor of the system: 1000

No model error



What are the (un)stable directions that are important for ensemble forecasts in multiscale systems?

Use of the Backward Lyapunov vectors to perturb the initial state

Ensemble forecasts: How to perturb?

Experimental setup

There are 36 Backward Lyapunov Vectors that can be considered

Experiments of ensemble forecasts with a set of Backward Lyapunov Vectors:

10 dominant ones

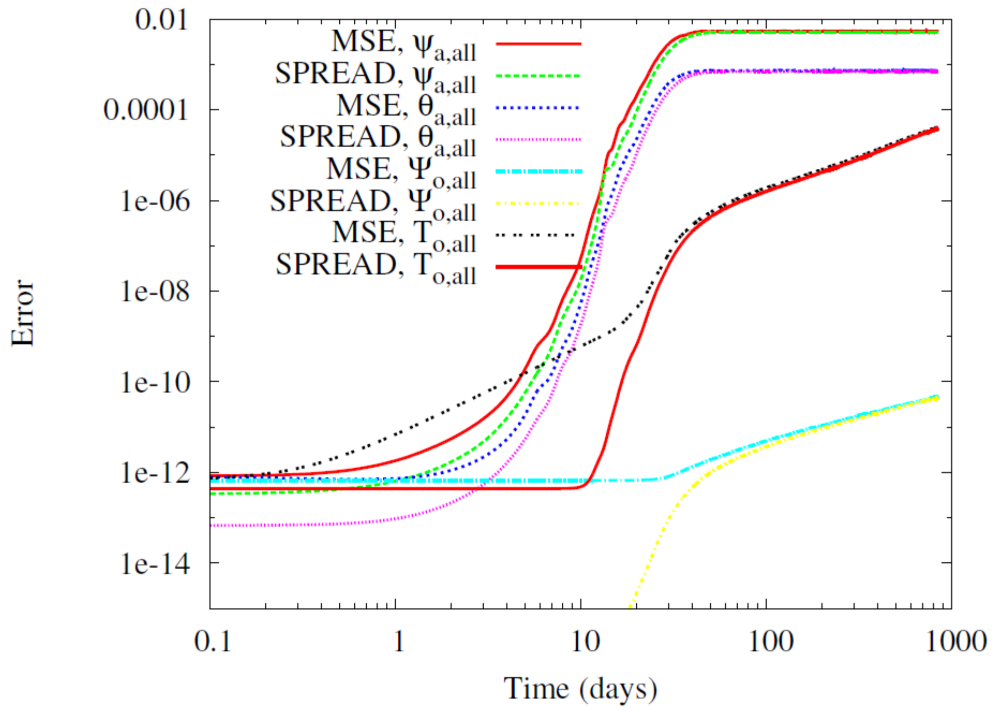
11 to 20

21 to 30

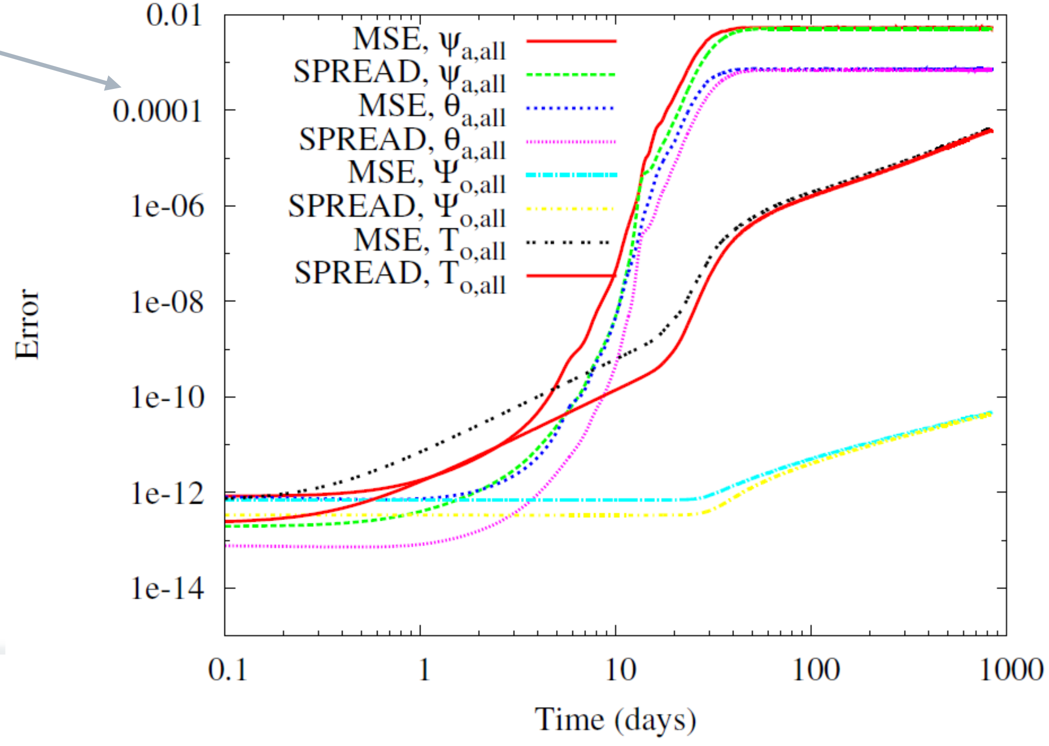
→ Random errors projected on these vectors

36 : The reference experiment since it is equivalent to the full reliable ensemble

Perturbations based on the 10 first Lyapunov vectors

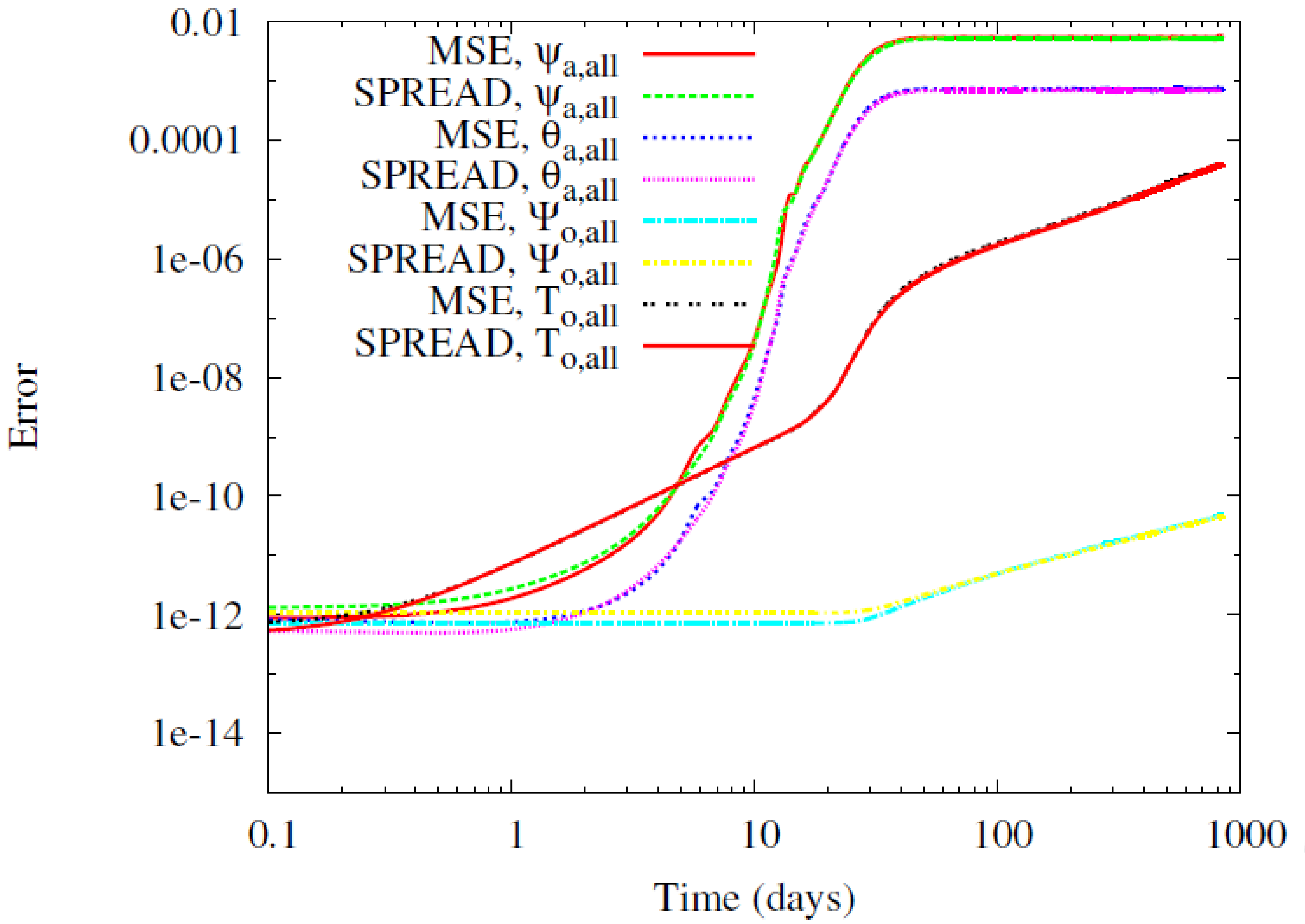


Perturbations based on the 11 to 20 Lyapunov vectors



Better performance if perturbations are introduced along the near-neutral unstable modes, even for the atmosphere

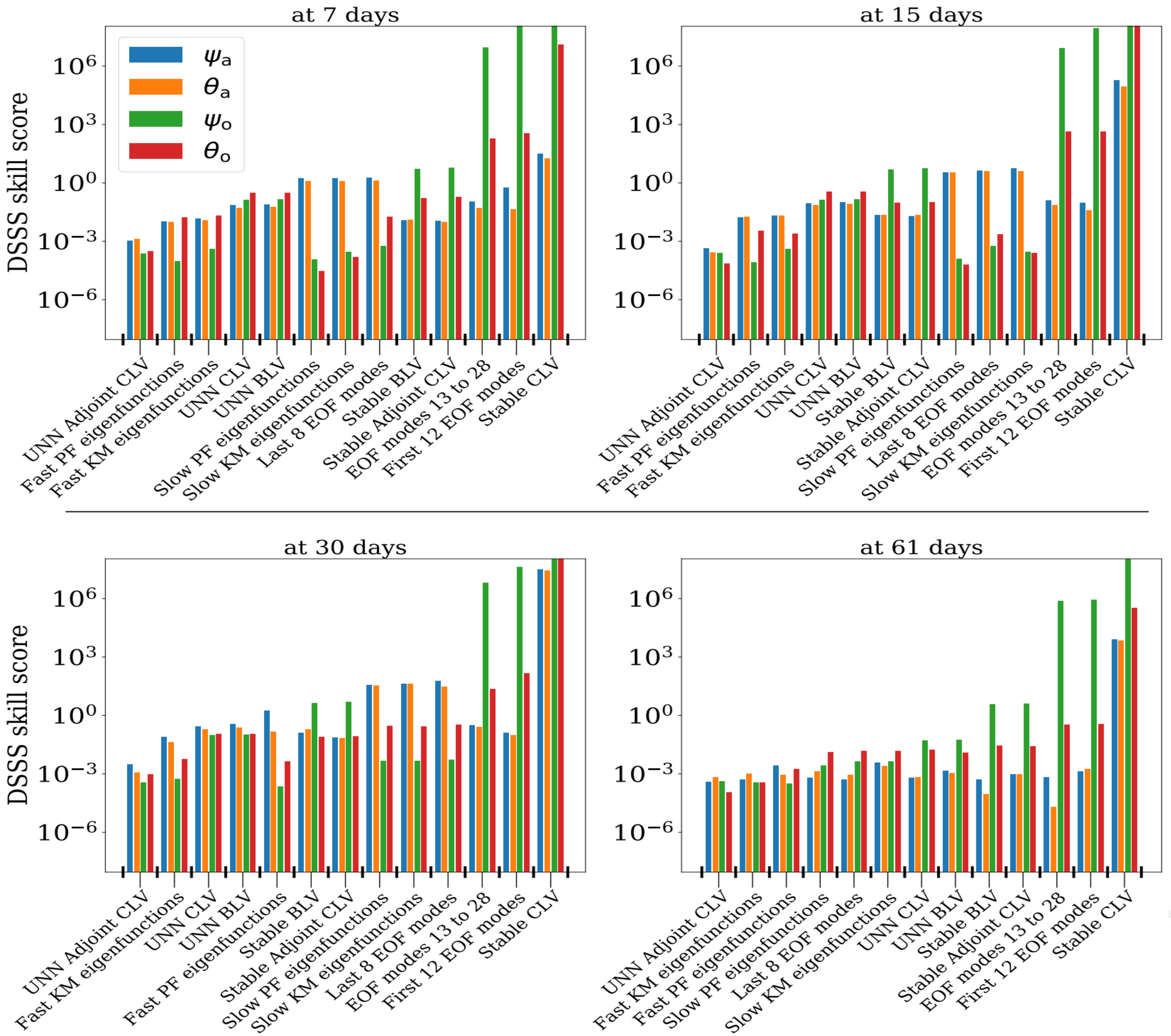
A bit more tuning by changing the amplitude of the perturbations for the 11-20 LVs?



Ensemble forecasts: Other approaches?

In Demaeyer et al (2022):

- Backward Lyapunov vectors
- Covariant Lyapunov vectors and their adjoints
- Perron-Frobenius modes
- Koopman Modes



Demaeyer, J., Penny, S. G., & Vannitsem, S. (2022). Identifying efficient ensemble perturbations for initializing subseasonalto-seasonal prediction. *Journal of Advances in Modeling Earth Systems*, *14*, e2021MS002828. https://doi. org/10.1029/2021MS002828

Additional conclusions

- The choice of appropriate perturbations for long range forecasts should not necessarily be based on the dominant instability properties of the flow in multiscale systems

- An appropriate choice should be made based on the modes affecting substantially both components of the system

- Here Backward LVs have been used but more appropriate choices should be envisaged like the adjoint CLVs and the approximations of the Perron-Frobenius modes. The latter have the advantage to be defined on the past evolution of the system (as the EOFs) but related to the underlying structure of the attractor of the system through the Koopman and Perron-Frobenius operators.

Useful references

Demaeyer J., L. De Cruz & S. Vannitsem, **qgs: A flexible Python framework of reduced-order multiscale climate models**. *Journal of Open Source Software*, 5(56), 2597, 2020.

Demaeyer, J., Penny, S. G., & Vannitsem. **Identifying efficient ensemble perturbations for initializing subseasonal-to-seasonal prediction**. *Journal of Advances in Modeling Earth Systems*, *14*, e2021MS002828, 2022.

Vannitsem S. **Predictability of large-scale atmospheric motions: Lyapunov exponents and error dynamics**, Chaos, 27, 032101, 2017, doi: 10.1063/1.4979042

Vannitsem, S., Demaeyer, J., & Ghil, M. **Extratropical low-frequency variability with ENSO forcing: A reduced-order coupled model study.** *Journal of Advances in Modeling Earth Systems*, *13*, e2021MS002530, 2021.

Vannitsem S. & W. Duan, **On the use of near-neutral backward Lyapunov vectors to get reliable ensemble forecasts in coupled ocean-atmosphere systems**. *Climate Dynamics*, 55, 1125-1139, 2020.

Vannitsem S., **Impact of tropical teleconnections on the long-range predictability of the atmosphere at midlatitudes: A reduced-order multi-scale model perspective**, submitted to J. Phys: Complexity. May 24, 2023