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NP1.5 EDI
The climate model hierarchy: Improving process understanding by bridging the gap between conceptual and earth system models

Simple oceanographic and paleoclimate modeling highlights the same dynamical process: intrinsic variability paced by a deterministic forcing

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Identifying dynamical paradigms is important in the climate sciences

Within the climate model hierarchy, simple, even *very* simple (conceptual) **models** designed to analyze on a conceptual level a specific **climate phenomenon**, can reveal a mechanism -a **dynamical paradigm**- which in principle could have a counterpart in the real climate system

Due to the simplicity of the model approach, that mechanism may have little to do with the actual climate

However, let us suppose that, despite the simplicity of the model, the comparison with observations is encouraging. In such a case that dynamical paradigm could provide a plausible conceptual basis for the explanation of the phenomenon and can, therefore, serve as a reference guideline for climate models at different levels of complexity (up to Earth system models) aimed at analyzing the same climate problem

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In this framework, in this presentation the following cases are discussed:

- **Dynamical paradigm**: *intrinsic variability paced by a deterministic forcing*
- **Climate phenomena**: *1. late Pleistocene glacial terminations*
  2. Kuroshio Extension decadal variability
- **Models**: *1. energy balance model + specific rules parameterizing internal climate feedbacks*
  2. reduced-gravity, nonlinear shallow water equations

The dynamical paradigm

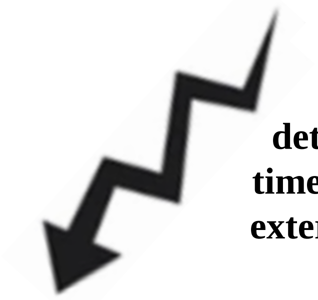
A relaxation oscillation (RO) is a manifestation of the **system's intrinsic variability**, as its very existence is a highly nonlinear feature all internal to the system itself

A RO starts from a basic state (an equilibrium point, a small amplitude limit cycle or even a strange attractor with limited extension in phase space)

A large amplitude, rapid transition leading to an unstable excited state is followed by a slow return to the original state

ROs can be either **self-sustained** or **excitable** depending on the value of some control parameter

The evolution of a RO excited by a suitable external forcing may be almost unaffected by the latter



deterministic
time-dependent
external forcing

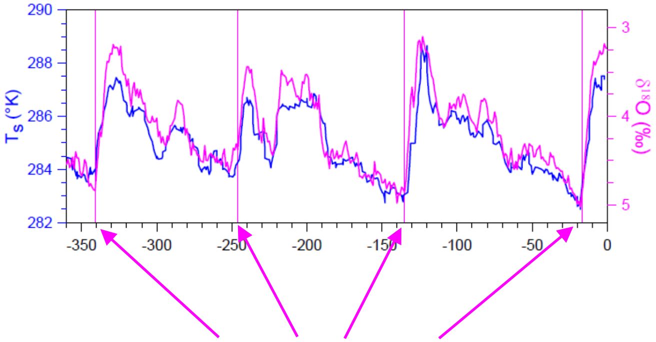
this dissipative nonlinear
dynamical system possesses

relaxation oscillations

and is in an

excitable state

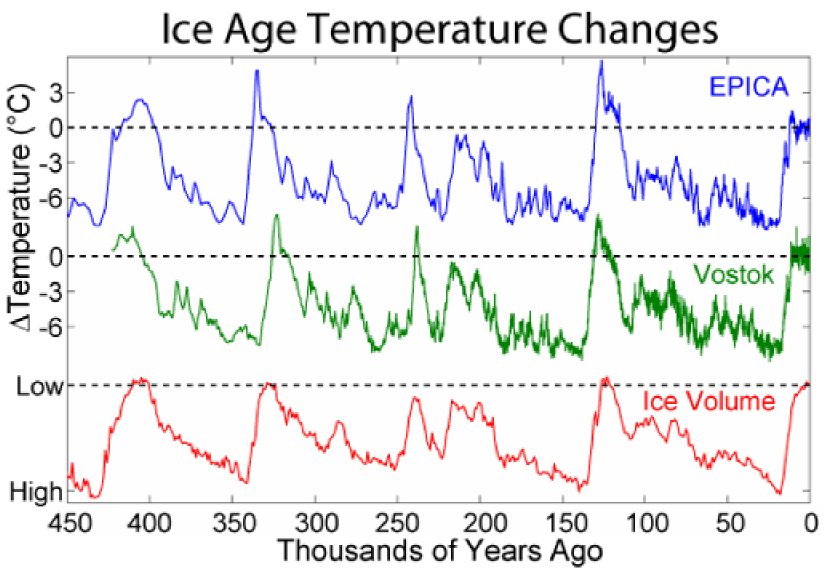
for excitation to occur,
some conditions are required



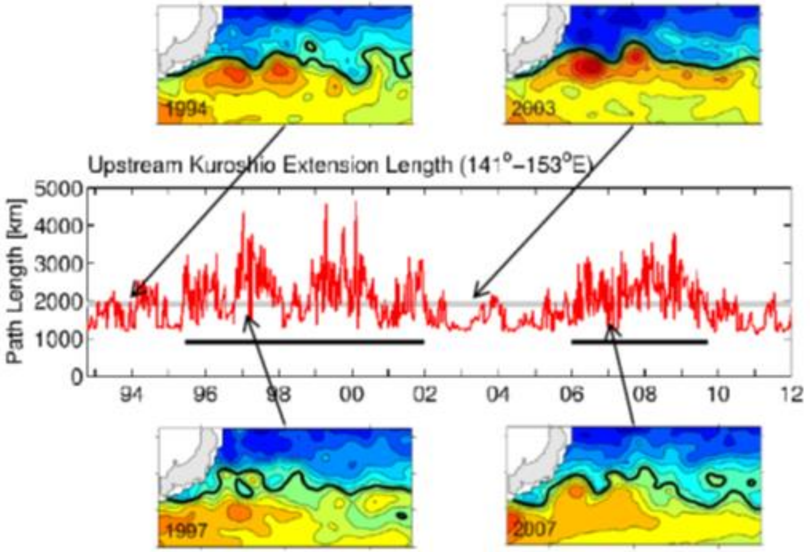
timing of the RO excitation

The climate phenomena

Late Pleistocene Ice ages



Kuroshio Extension decadal variability

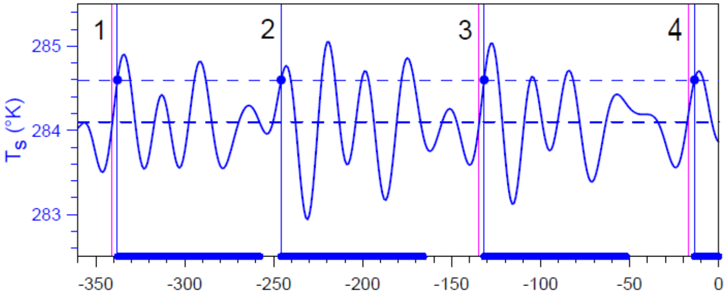


The models

mean daily insolation at 65°N
on summer solstice
(obliquity + climatic precession)

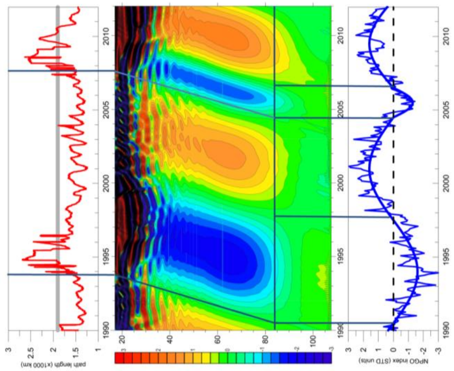
$$C_s \frac{dT_s}{dt} = \frac{S(t)}{4}\,[1 - \alpha\,(T_s)] - \tilde{\epsilon}\sigma\, T_s^4$$

specific rules parameterize internal climate feedbacks, which, when activated by the crossing of certain tipping points, excite a RO



climatological +
North Pacific Oscillation
wind stress

$$\left\{\begin{aligned} &\mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{u} + f\,\mathbf{k}\times\mathbf{u} = \\ &= -g'\nabla\tilde{\eta} + \boldsymbol{\tau}/(\rho H) + K_H\nabla^2\mathbf{u} \\ &-\gamma\mathbf{u}|\mathbf{u}| \\ \\ &\tilde{\eta}_t + \nabla(H\mathbf{u}) = 0 \end{aligned}\right.$$



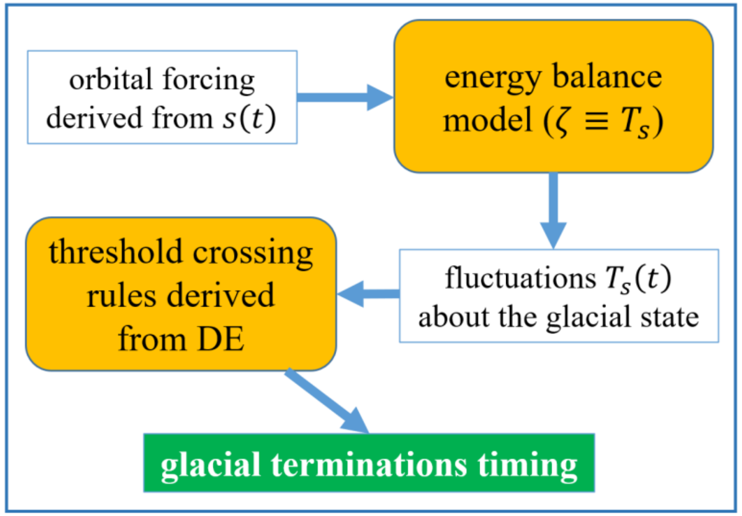
More in detail …

Late Pleistocene ice ages

The *deterministic excitation* paradigm

1. The system is **monostable**, **excitable**, and possesses **relaxation oscillations** (ROs) *
2. In order to be excited, a RO requires that **a given control parameter ζ crosses a given tipping** point $\bar{\zeta}$
3. The **temporal distance between two successive excitations must be greater than the typical time scale of the RO**, τ_{ro}

The conceptual model

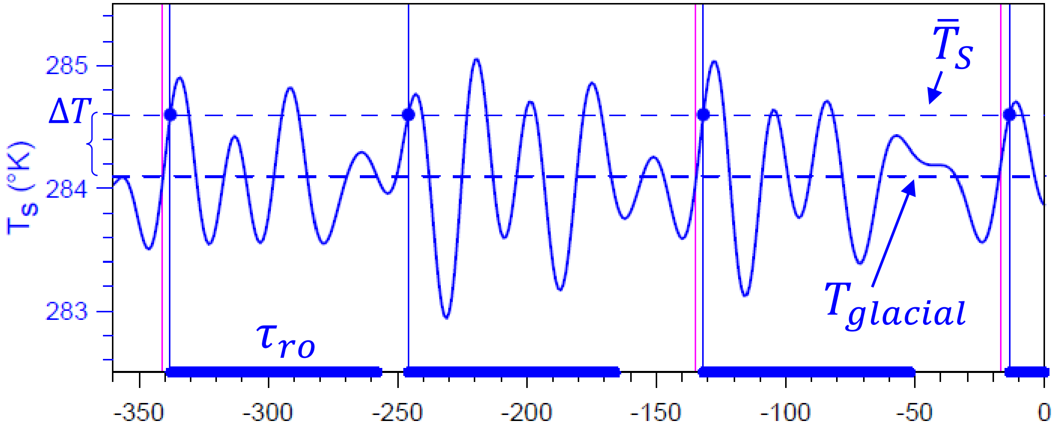

orbital forcing derived from $s(t)$

energy balance model ($\zeta \equiv T_s$)

fluctuations $T_s(t)$ about the glacial state

threshold crossing rules derived from DE

glacial terminations timing



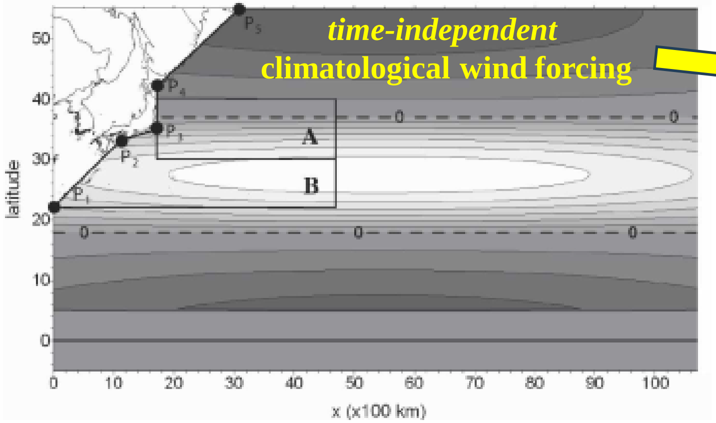
Timing of the simulated glacial terminations (vertical blue lines) vs. timing derived from proxy data (vertical magenta lines). The simulated timing is shown to be **very robust**

The model can be successfully **extended to the last 8 glacial terminations** thanks to a refined definition of the threshold crossing rules (work in progress)

* there are glacial-cycle models that meet these requirements (e.g., Gildor and Tziperman 2001, *JGR, 106, 9117–9133*)

Pierini S., 2023.
Chaos, 33, 033108

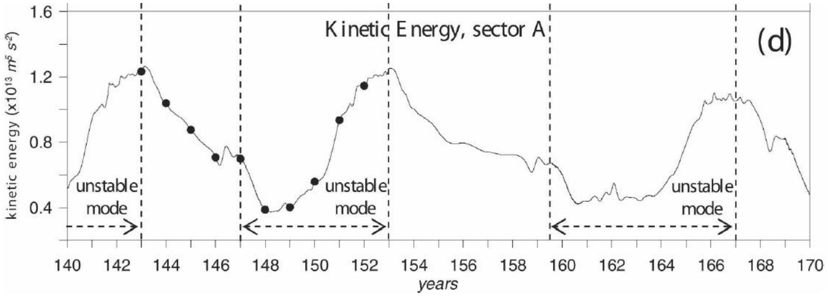
Kuroshio Extension decadal variability

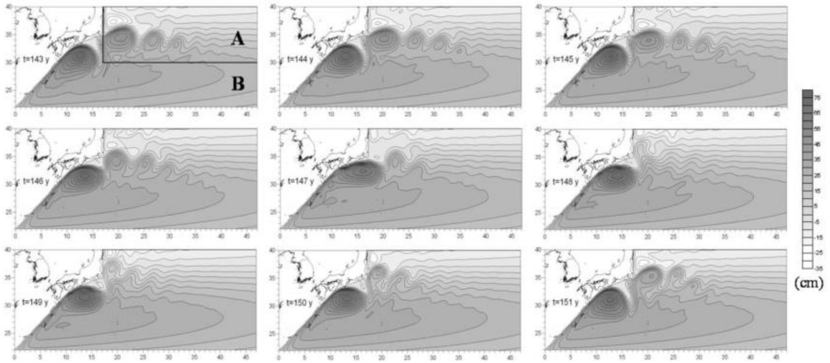


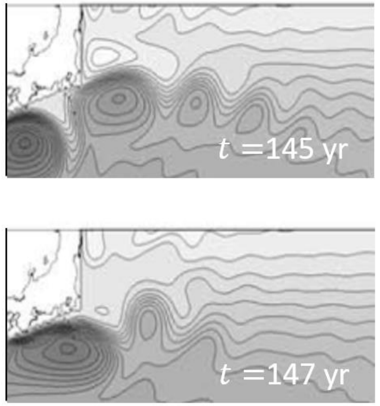
$$\mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{u} + f\mathbf{k}\times\mathbf{u} = -g'\nabla\tilde{\eta} + \boldsymbol{\tau}/(\rho H) + K_H\nabla^2\mathbf{u} - \gamma\mathbf{u}|\mathbf{u}|$$

$$\tilde{\eta}_t + \nabla(H\mathbf{u}) = 0.$$

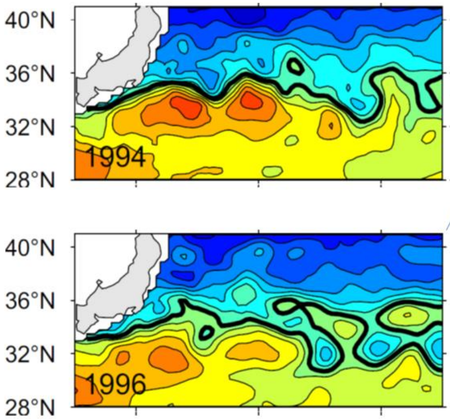
Transitions are self-sustained:
the system is a chaotic
relaxation oscillator



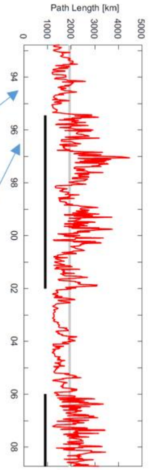




model results
(*Pierini* 2006)



altimeter data
(*Qiu and Chen* 2005)



This is a case of **intrinsic oceanic variability**

Pierini S., *J. Phys. Oceanogr.*,
2006, 36, 1605-1625
2008, 38, 1327-1333
2010, 40, 238-248

Kuroshio Extension decadal variability

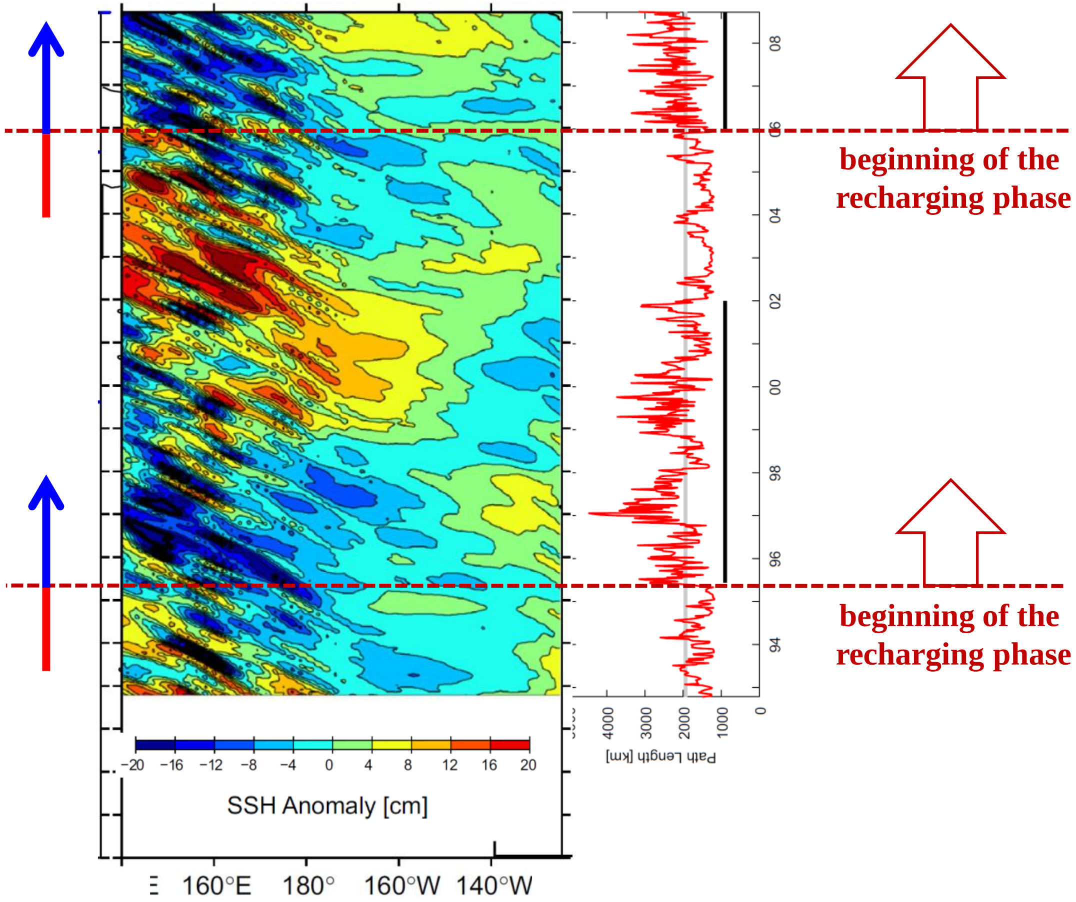
However …

The first two dominant decadal time-scale modes of the sea level pressure variability in the North Pacific drive the **Pacific Decadal Oscillation** and **North Pacific Gyre Oscillation**

Linear vorticity models have been used to show that **Rossby waves** propagate the PDO/NPGO signatures from the central and eastern North Pacific into the Kuroshio Extension region

This leads to the synchronization of the KE bimodal decadal variability with those modes (*Qiu and Chen* 2005, 2010; *Ceballos* et al. 2009)

(adapted from *Qiu and Chen 2010, JPO*)

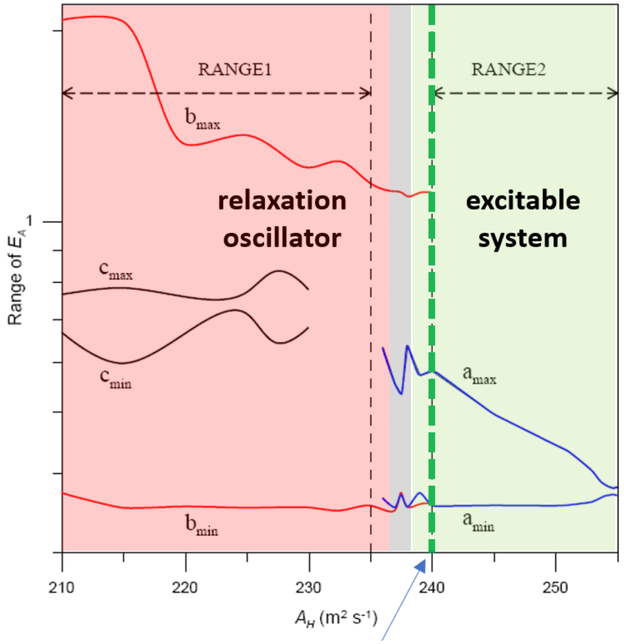


beginning of the recharging phase

beginning of the recharging phase

Ceballos L. I., et al., 2009. *J. Climate*, 22, 5163–5174
Qiu B. and S. Chen, 2005. J. Phys. Oceanogr., 35, 2090–2103
Qiu B. and S. Chen, 2010. *Deep-Sea Res. II*, 57, 1098–1110

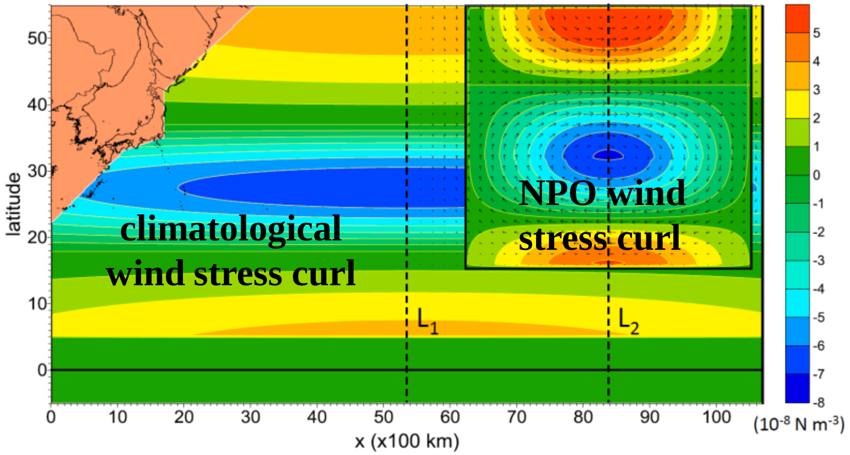
Kuroshio Extension decadal variability

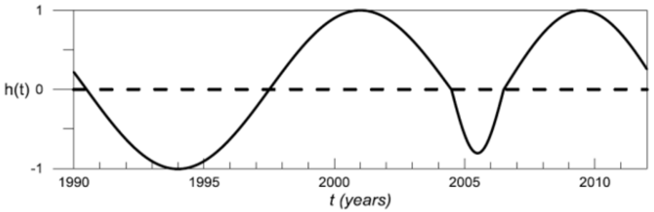


lateral eddy viscosity
used in the simulation

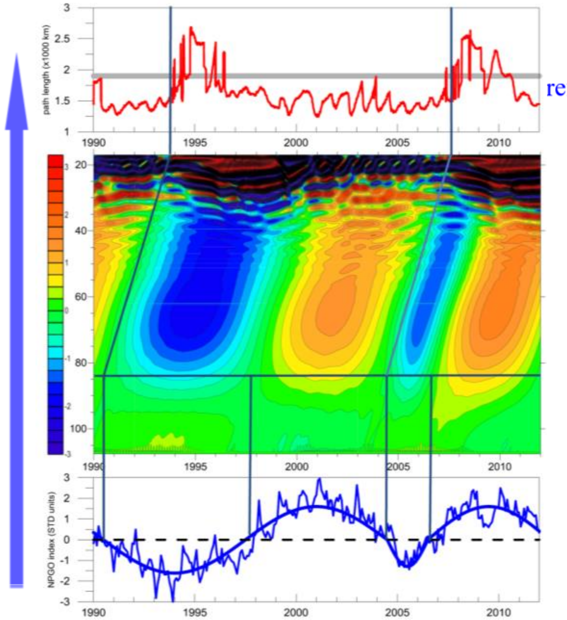
Here a time-dependent deterministic
componentent is added to the forcing

$$\boxed{\boldsymbol{\tau}(\mathbf{x},t) = \boldsymbol{\tau}_0(\mathbf{x}) + \alpha h(t)\boldsymbol{\tau}_{NPO}(\mathbf{x})}$$





time dependence *h(t)* of the NPO forcing



modeled L_{KE} for the
reference simulation (α=0.15)

Hovmoller diagram of the
SSH anomaly at 35°N

NPGO index

This is a case of **intrinsic oceanic variability** ***paced by external forcing***

Pierini S., 2014.
J. Climate, 27,
448-454

Conclusions

The same dynamical systems paradigm, **deterministic excitation**, has emerged from two completely different climate phenomena:

1. the late Pleistocene glacial terminations
2. Kuroshio Extension decadal variability

Two simple models of different level of complexity have been used:

1. an energy balance model + specific rules parameterizing internal climate feedbacks
2. reduced-gravity, nonlinear shallow water equations

In both cases, despite the simplicity of the models, a significant agreement is found between the simulated and observed timing. Furthermore, in case 2, several other realistic dynamical features are also obtained

It is worth noting that:

- the systems **do not need to be multistable**; they must be excitable, a metastable state is needed
- the time-dependent forcing used is **deterministic**. The alternative *stochastic resonance* mechanism invoked in case 1, for which noise plays a decisive role, turns out to be simply inapplicable to the glacial-interglacial variability problem

In conclusion, these results show how simple modeling approaches of different complexity advance process understanding and can, therefore, provide theoretical guidelines for interpreting state-of-the-art ESM results