The Turbulent Oscillator:

A Mechanism of Low-Frequency Variability of the Wind-Driven Ocean Gyres

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Results are summarized in **Berloff et al. 2007b.**

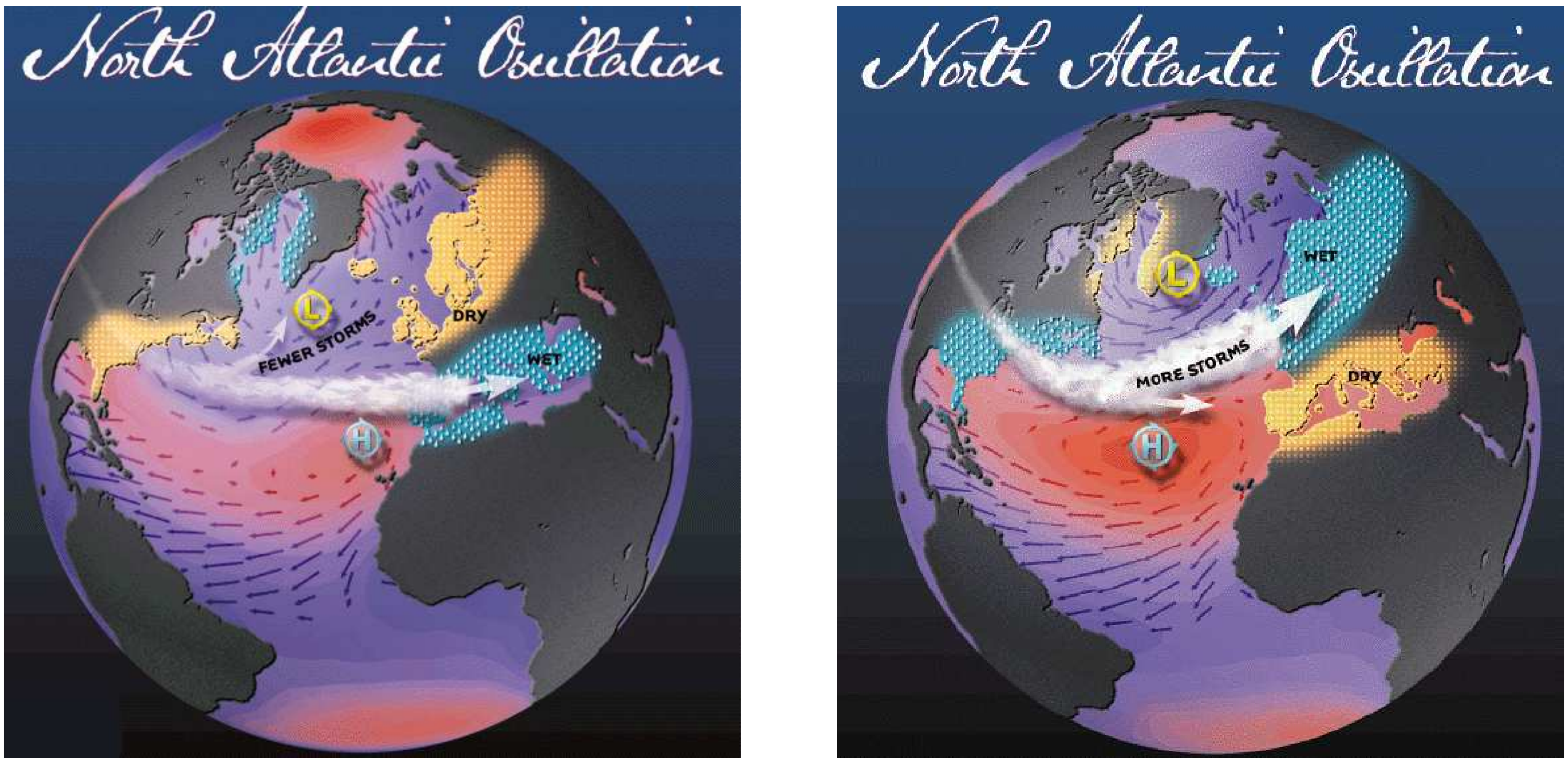
Decadal Climate Variability Phenomenon

(1) In the atmosphere, decadal LFV pattern is well observed;

(2) In the ocean, observations, which are very fragmented, suggest strong LFV;

(3) Mechanism of the LFV is unknown.

OPPOSITE PHASES OF THE ATMOSPHERIC NAO PATTERN



• *What are the central issues and the main theoretical challenges?*

Background

• The central issue is to pin down the *mechanism* of the mid-latitude LFV in the most general sense. This mechanism must belong to one of the following *categories*:

(1) *Intrinsic atmospheric*,

(2) *Intrinsic oceanic*,

(3) *Coupled oceanic/atmospheric*.

• *Comprehensive* ocean-atmosphere GCMs do not yet discriminate between the above options, because:

(a) On the technical level, dynamics in the GCMs is very difficult to analyze;

(b) On the fundamental level, oceanic mesoscale eddies in the GCMs are not properly resolved and, instead, are often inaccurately "parameterized" $\Longrightarrow$ testing (2) and (3) is problematic.

• Our understanding of the *intrinsic oceanic* LFV is mostly advanced in terms of the single physical idea. This idea heavily relies on the *assumption* that effects of the mesoscale eddies can be approximated by the momentum *diffusion*:

> *The "dynamical systems" school of thought explains the LFV in terms of the early bifurcations of some nonlinear steady states*;

Statement of the Problem

- **Working Hypothesis**:

Mechanism of the midlatitude LFV is *intrinsic oceanic*.

- **Research Tactics**:

To address the LFV with a *turbulent* (i.e., full of mesoscale eddies) but, otherwise, idealized model of the ocean dynamics.

— Diffusive assumption is largely relaxed;

— Standard QG model of oceanic gyres with spatial resolution down to 2-3 km.

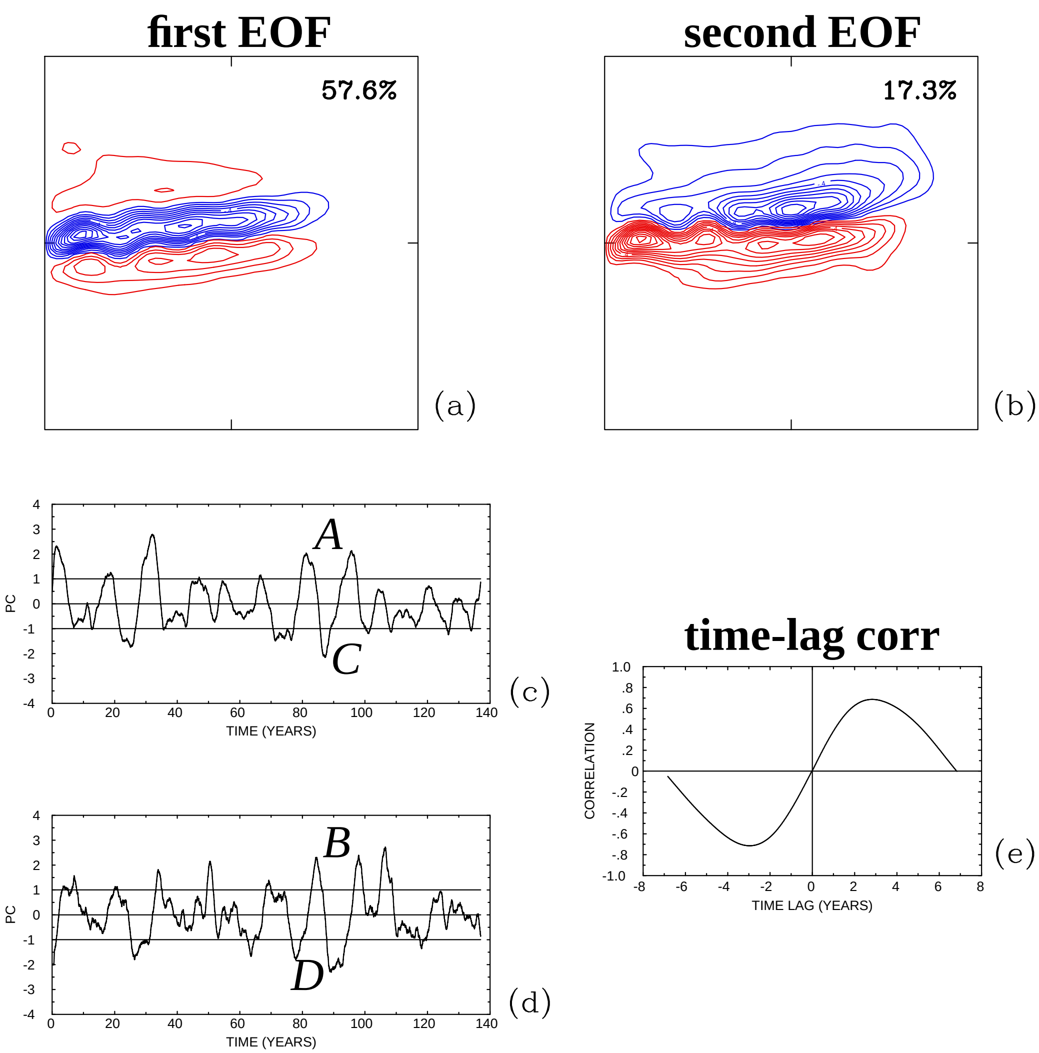
- **Main Questions**:

(1) What is the *generic* LFV pattern?

(2) What is the *dynamical mechanism* that drives it?

- **Precursory Results**: *Berloff and McWilliams (1999).*

Oceanic LFV Pattern



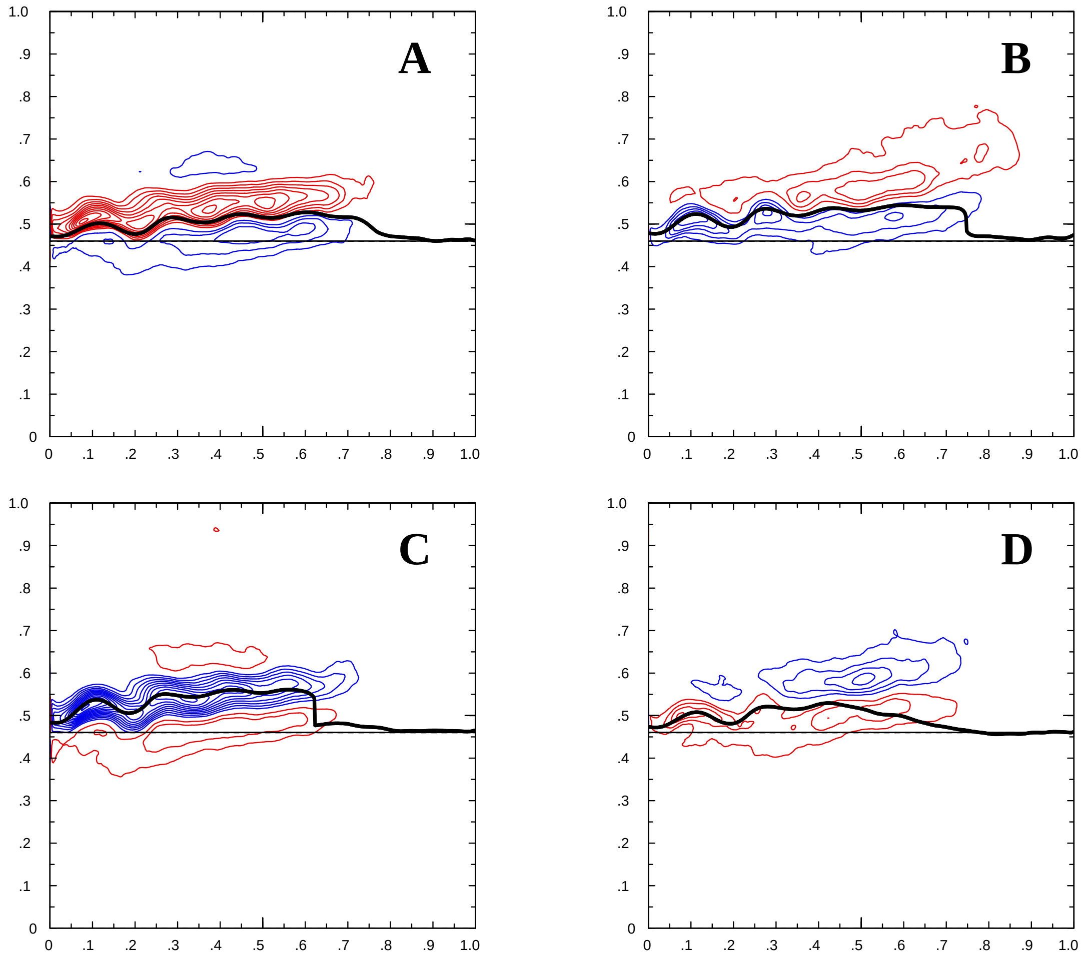
- The leading pair of EOFs is a coherent decadal signal, describing variability of the eastward jet.

- The decadal cycle can be described by transitions between the 4 key states: $A \longrightarrow B \longrightarrow C \longrightarrow D$, corresponding to the extreme values of the leading principle components.

What are the key dynamical ingredients of the underlying LFV mechanism?

Response to PV Anomalies

POTENTIAL VORTICITY ANOMALIES OF THE KEY STATES

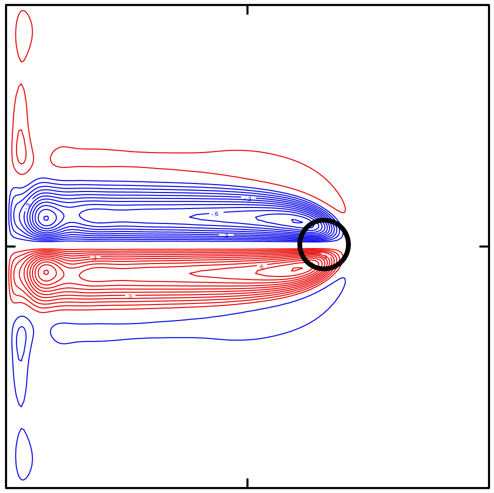


★ Response to PV anomaly is part of the underlying LFV mechanism:

— PV anomaly of the same sign as the gyre causes this gyre to shrink $\Longrightarrow$ meridional shift of the eastward jet.

Response to Localized Transient Forcing (a.k.a. Oceanic Eddy Backscatter)

Let's consider "rectified" (i.e., time-mean) response to a localized "plunger" (oscillating forcing) with zero mean. The transient response is dominated by resolved eddies...



• Both *nonlinearity* and *beta effect* are necessary for the flow rectification.

• Rectification can be driven by fluctuations of the internal *eddy forcing*:

$$F(t,\mathbf{x}) = \nabla \cdot \left(\mathbf{u}'q' + \overline{\mathbf{u}}q' + \mathbf{u}'\overline{q} \right)$$

★ In the eddy-resolving ocean model, ensemble of "plungers" (generated by flow instabilities) is diagnozed and quantified over the LFV cycle.

— More efficient $F(t,\mathbf{x})$ drives stronger eastward jet, as in key state B.

Other Physical Ingredients:

• As suggested by the PV analysis, LFV is dominated by

(1) *Eddy inter-gyre flux*,

(2) *Geometric wind effect*: correlation between size of the gyre and PV wind forcing.

• *Variability of the eddy inter-gyre flux is anti-diffusive*: strong inter-gyre PV contrast is associated with the inhibited PV flux.

— This is because the oceanic eastward jet is a partial *transport barrier*;

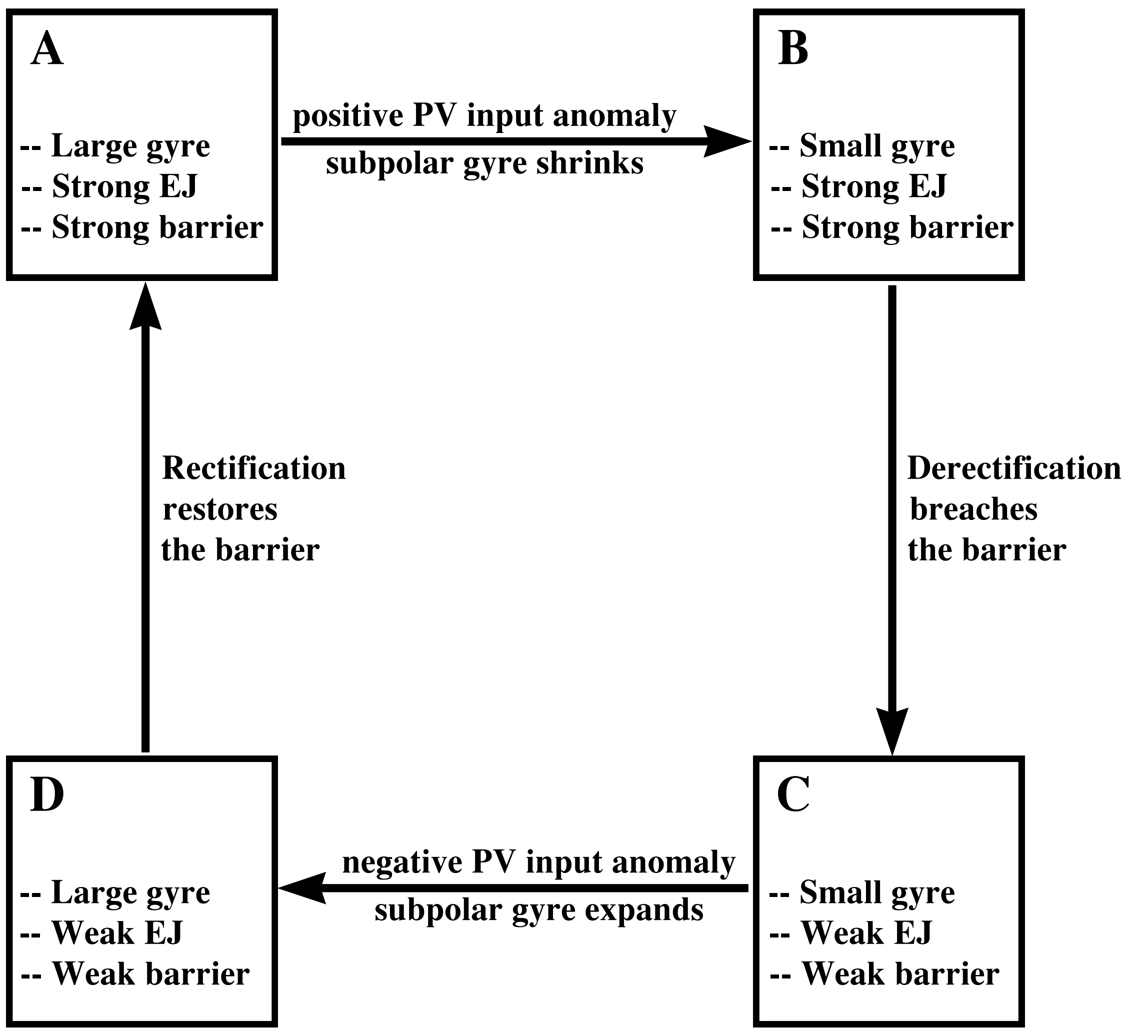
— Permeability of the barrier is controlled by the rectification process.

• Over the LFV cycle, flow either has positive/negative PV anomaly, or it is over/under rectified with respect to the wind forcing input.

Now, let's combine all of the identified physical ingredients in the unified LFV mechanism...

Schematic Diagram of the Low-Frequency Variability Mechanism

• *"Turbulent Oscillator": The LF variability is a turbulent phenomenon driven by the competition between the eddy rectification process and the PV anomalies induced by changes in the inter-gyre transport barrier.*



• *Physical ingredients*:

(1) Rectification maintains the eastward jet;

(2) Eastward jet is a transport barrier;

(3) Rectification controls permeability of the barrier;

(4) Geometric wind effect;

(5) PV anomalies accumulated near the barrier tend to reshape the gyres;

(6) Nonlinear adjustment of the gyres (Dewar 2003).

Parameter Sensitivity Study (Re, boundary condition, wind forcing):

• Turbulent oscillator is a very *robust* phenomenon:

Intense eddy activity $\Longrightarrow$ developed eastward jet $\Longrightarrow$ *Turbulent Oscillator*

LFV with Eddies Replaced by Momentum Diffusion:

• At small Re, the LFV pattern is *qualitatively different* from that of the turbulent oscillator:

(1) *Interannual* time scale instead of the decadal;

(2) *Multi-cell* spatial pattern instead of the asymmetric tripole;

(3) *No coherence* between the EOFs.

• More importantly, the dynamical mechanism is *fundamentally different*, because inter-gyre PV gradient and eddy flux are positively correlated.

Summary

• Very robust pattern of the decadal oceanic variability is found in a turbulent, but otherwise idealized, ocean model;

• Underlying dynamical mechanism—-the *turbulent oscillator*—-is understood.

★ This study suggests to shift the whole research on the oceanic LFV towards models that properly account for the eddy dynamics.

Further Questions about the *Turbulent Oscillator*:

(1) How is it affected by the *seasonal cycle*?

(2) Can it *couple to the atmosphere*?

(3) How will it operate in a *comprehensive, eddy-resolving GCM*?

(4) What do we have to *observe* in the real ocean, in order to test whether it operates there?