Midlatitude Ocean-Atmosphere Model: Decadal Variability and Dynamics

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Plan of the Presentation

(1) Statement of the problem and background

(2) Midlatitude ocean-atmosphere model

(3) Low-frequency variability patterns

(4) Role of the oceanic eddies

Papers

Berloff, P., S. Kravtsov,, W. Dewar, and J. McWilliams, 2006: Ocean eddy dynamics in a coupled ocean-atmosphere model. *J. Phys. Oceanogr.*, submitted.

Kravtsov, S., P. Berloff, W. Dewar, M. Ghil, and J. McWilliams, 2006b: A highly nonlinear coupled mode of decadal-to-interdecadal variability in a mid-latitude ocean-atmosphere model. Part II: Dynamics. *J. Climate*, submitted.

Kravtsov, S., W. Dewar, P. Berloff, J. McWilliams, and M. Ghil, 2006a: A highly nonlinear coupled mode of decadal-to-interdecadal variability in a mid-latitude ocean-atmosphere model. Part I: Phenomenology. *J. Climate*, submitted.

Statement of the Problem

- The **central hypothesis** is:

In the midlatitudes, the ocean-atmosphere system generates a *coupled* low-frequency variability (LFV) mode.

- The **main questions** are:

(1) What is the generic LFV pattern?

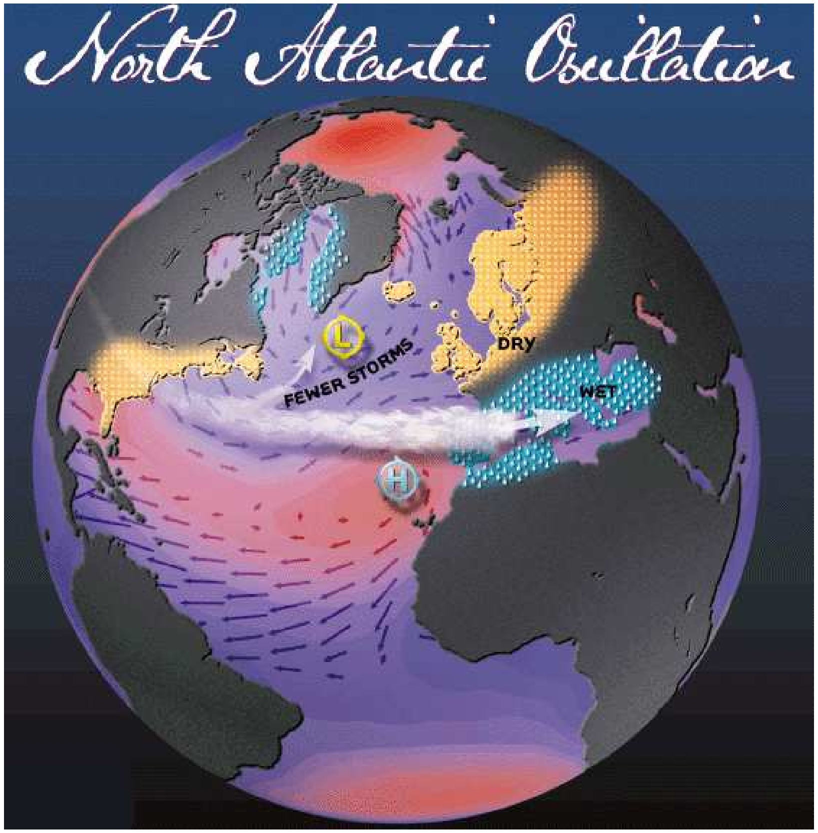
(2) What is the underlying dynamical mechanism?

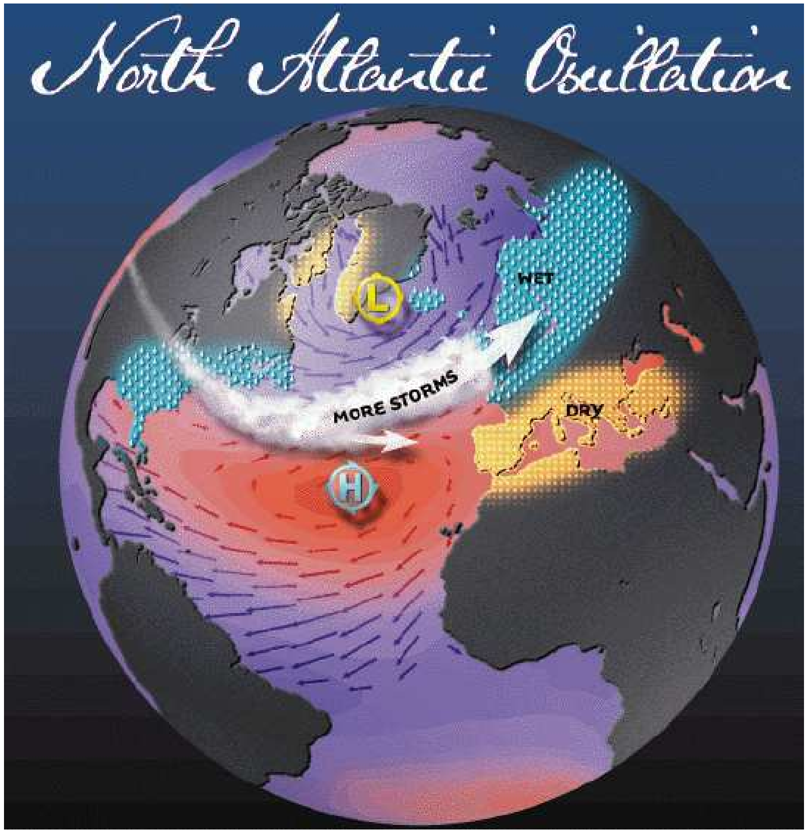
(3) What is the effect of the mesoscale oceanic eddies and how to parameterize it?

1. Background: Observations

• In the equatorial ocean, there is a well-known coupled interannual oscillation: *El Nino*.

• In the North Pacific and North Atlantic, *decadal variability is observed* both in the ocean and atmosphere (*below, opposite phases of the NAO pattern are shown*).





2. Background

- Dynamical mechanism of the decadal LFV in middle latitudes remains a mystery, and it can be explained as:

  (i) Intrinsic *atmospheric*,

  (ii) Intrinsic *oceanic*,

  (iii) *Coupled ocean-atmosphere* mechanism.

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

  (a) Dynamics in GCMs is rather difficult to analyze;

  (b) Oceanic mesoscale eddies in GCMs are not properly resolved and, instead, are inaccurately parameterized.

- *Idealized coupled models* are the analytical tool of choice, but their hierarchy is so far incomplete and poorly studied.

3. **Background:** Intrinsic Variability Studies

• *Atmospheric*, intrinsic decadal LFV is a poorly understood phenomenon:

— It can be related to bimodality of the atmosphere (Kravtsov et al. 2005).

• *Oceanic*, intrinsic decadal LFV is understood much better (in the context of steady atmospheric forcing!), and there are 2 classes of the dynamical mechanisms proposed:

— The "linear" school of thought explains this variability in terms of the linear unstable eigenmodes and early bifurcations of the underlying nonlinear steady state (e.g., *works by Drs Michael Ghil, Henk Dijkstra and their collaborators*);

— An alternative idea is that the LFV is a fundamentally turbulent phenomenon that invokes (1) energetic mesoscale eddies and (2) inhibited (i.e., non-diffusive) eddy transport between the oceanic gyres (e.g., *Berloff et al. 2006*).

This talk focuses on the COUPLED ocean-atmosphere case...

4. Background: Coupled Models

• In the coupled ocean-atmosphere models, imposed spatial resolution of the ocean is a major problem (i.e., *the atmosphere is always over-resolved compare to the ocean*):

— The typical, $4°\times 4°$, ocean resolution is equivalent to 4×4 points resolution of the atmosphere;

— The adequate resolution constraint can be relaxed by using an idealized ocean dynamics.

• The following types of the idealized ocean component have been looked at:

— Linear;

— With nonlinear thermohaline circulation;

— With nonlinear horizontal circulation, but not in the turbulent regime;

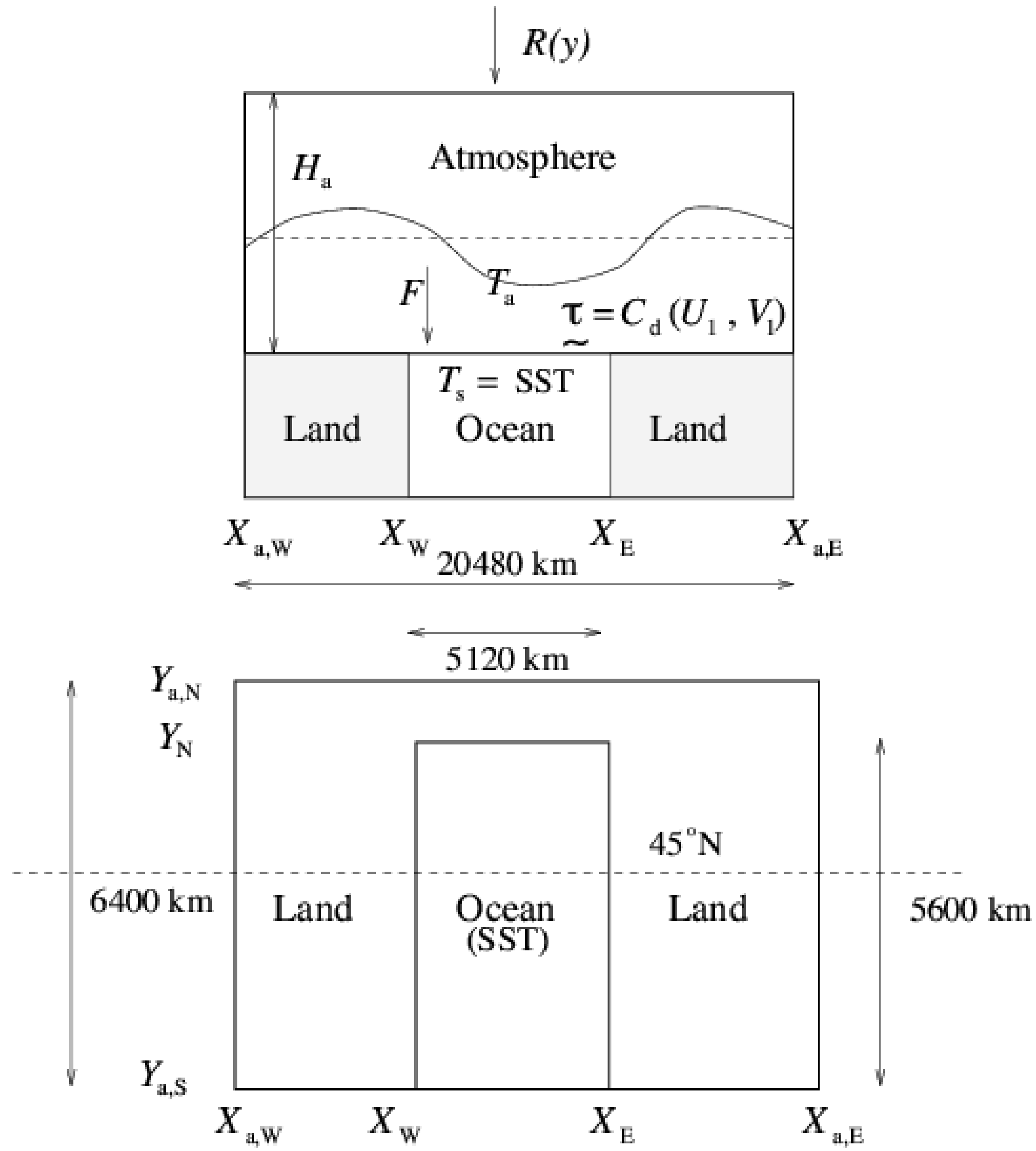
— **Fully turbulent regime** of the horizontal circulation [*this study*].

• For this purpose, quasigeostrophic (QG) coupled models are a very useful tool!

— They have been formulated recently (Kravtsov and Robertson 2002; Hogg et al. 2003), and their analysis is in progress;

— The QG approximation filters out the (unbalanced) fast motions and yields evolution of the (balanced) geostrophic currents.

Model Configuration: Atmosphere, Ocean, and Oceanic Mixed Layer



1. Atmosphere Component: Fluid Dynamics

- The barotropic and baroclinic potential vorticities (ψ and τ are the corresponding velocity streamfunctions; Rd is the Rossby deformation radius) are:

$$q_\psi = \nabla^2\psi + \beta y \,, \qquad q_\tau = \nabla^2\tau - Rd^{-2}\,\tau$$

- The isopycnal-layer velocity streamfunctions (h_1 and h_2 are the layer depths) are:

$$\psi_1 = \psi + h_2\,\tau \,, \qquad \psi_2 = \psi - h_1\,\tau$$

- The governing equations:

$$\frac{\partial q_\psi}{\partial t} + J(\psi, q_\psi) = -h_1 h_2 J(\tau, q_\tau) \quad - k\Big[\nabla^2\psi + h_2\nabla^2\tau\Big] - \sum_{n=1}^{3} k^{(n)}\nabla^2\psi^{(n)} + A_H\nabla^6\psi$$

$$\frac{\partial q_\tau}{\partial t} + (h_2 - h_1)J(\tau, q_\tau) = -\Big[J(\tau, q_\psi) + J(\psi, q_\tau)\Big] \quad + \frac{f_0}{H_a}\frac{1}{h_1 h_2}\,F(\mathbf{x};\psi,\tau)$$
$$-k\left[\frac{h_2}{h_1}\nabla^2\tau + \frac{1}{h_1}\nabla^2\psi\right] - \sum_{n=1}^{3} k^{(n)}\nabla^2\tau^{(n)} + A_H\nabla^6\tau$$

- Re-entrant zonal channel with the no-slip velocity condition on the boundaries.
- Mass and momentum constraints (McWilliams 1977).

2. Atmosphere Component: Radiation and Heat Exchange

- Atmospheric temperature, T_a, is the average temperature of an air column:

$$T_a = T_{eq} - C\,\tau$$

- The atmosphere is transparent to the short-wave solar radiation:

$$R(y) = 190 - 165 \sin\left(\frac{2\,y}{r}\right) \qquad \left[W m^{-2}\right]$$

- The following functions depend on T_a, sea surface temperature (SST), and some parameters:

O — oceanic long-wave radiation (absorbed by the atmosphere);

B — atmospheric back radiation;

H_{SL} — sensible and latent ocean-atmosphere heat exchange (also depends on the sea-level wind speed).

- Over the *ocean*, the atmospheric forcing function is:

$$F \sim O + H_{SL} - 2\,B\,,$$

and over the *land*, it is:

$$F \sim R - B\,.$$

1. Ocean Component

- The isopycnal-layer potential vorticities and streamfunctions are connected as:

$$
\begin{aligned}
Q_1 &= \nabla^2\Psi_1 + \frac{f_0^2}{g_1' D_1}(\Psi_2 - \Psi_1) + \beta y\,, \\
Q_2 &= \nabla^2\Psi_2 - \frac{f_0^2}{g_1' D_2}(\Psi_2 - \Psi_1) + \frac{f_0^2}{g_2' D_2}(\Psi_3 - \Psi_2) + \beta y\,, \\
Q_3 &= \nabla^2\Psi_3 - \frac{f_0^2}{g_2' D_3}(\Psi_3 - \Psi_2) + \beta y\,,
\end{aligned}
$$

where g_i' and D_i are the reduced gravities and the layer thicknesses.

- The governing equations are:

$$
\begin{aligned}
\frac{\partial Q_1}{\partial t} + J(\Psi_1, Q_1) &= \frac{f_0}{D_1}(W_E - W_D) + \nu\nabla^4\Psi_1\,, \\
\frac{\partial Q_2}{\partial t} + J(\Psi_2, Q_2) &= \frac{f_0}{D_2}W_D + \nu\nabla^4\Psi_2\,, \\
\frac{\partial Q_3}{\partial t} + J(\Psi_3, Q_3) &= -\gamma\nabla^2\Psi_3 + \nu\nabla^4\Psi_3\,,
\end{aligned}
$$

where the Ekman pumping, W_E, and the entrainment rate, W_D, are both obtained from the mixed-layer dynamics and thermodynamics.

2. Ocean Component

- Rectangular-shape basin and flat bottom.

- Partial-slip lateral boundary condition: $\alpha\,\Psi_{nn} - (1-\alpha/L)\,\Psi_n = 0$

- Mass conservation constraint:

$$\frac{\partial}{\partial t}\iint (\Psi_1 - \Psi_2)\;dx\,dy \;=\; \frac{f_0}{g_1'}\iint W_D\;dx\,dy\,; \qquad \frac{\partial}{\partial t}\iint (\Psi_2 - \Psi_3)\;dx\,dy \;=\; 0$$

(only the first layer interface is affected by the entrainment).

- Lateral eddy diffusivity accounts for dynamically unresolved submesoscale eddies.

Mixed Layer Component

- Surface stress is calculated from the wind: $\tau^{(x)} \sim k\,(U - V)\,, \quad \tau^{(y)} \sim k\,(U + V)$

- Mixed-layer velocity is the sum of the geostrophic and Ekman components:

$$u \;=\; -\frac{\partial \Psi_1}{\partial y} + \frac{1}{\rho_o}\,\frac{\tau^{(y)}}{f_0\,h_{mix}}\,, \qquad v \;=\; \frac{\partial \Psi_1}{\partial x} - \frac{1}{\rho_o}\,\frac{\tau^{(x)}}{f_0\,h_{mix}}$$

- The corresponding Ekman pumping is:

$$W_E \;=\; h_{mix}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

- SST evolves according to:

$$\frac{\partial T_s}{\partial t} + \frac{\partial}{\partial x}(u\,T_s) + \frac{\partial}{\partial y}(v\,T_s) - \frac{1}{h_{mix}}\,W_E\,T_s \;=\; \frac{(F_s + F_{entr})}{\rho_o\,c_{P,o}\,h_{mix}} + K_H \nabla^2 T_s$$

— Surface heat flux, F_s, is a linear function of T_a and T_s;

— Entrainment heat flux through the base of the mixed layer, F_{entr}, is parameterized and $W_D \sim F_{entr}$.

Let's take a close look at the reference ocean-atmosphere solution...

Time-Mean Forcing of the Ocean

- Wind curl imposes the triple-gyre structure.

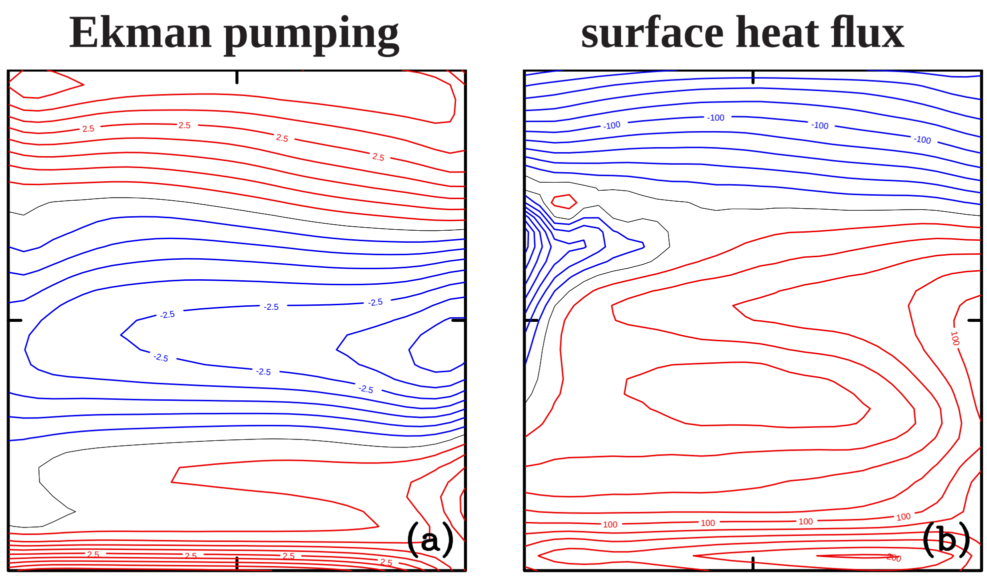
- Sequential drift of solutions is prohibited by imposing:

$$\iint W_D(x, y, t)\, dx\, dy \;=\; 0\,.$$

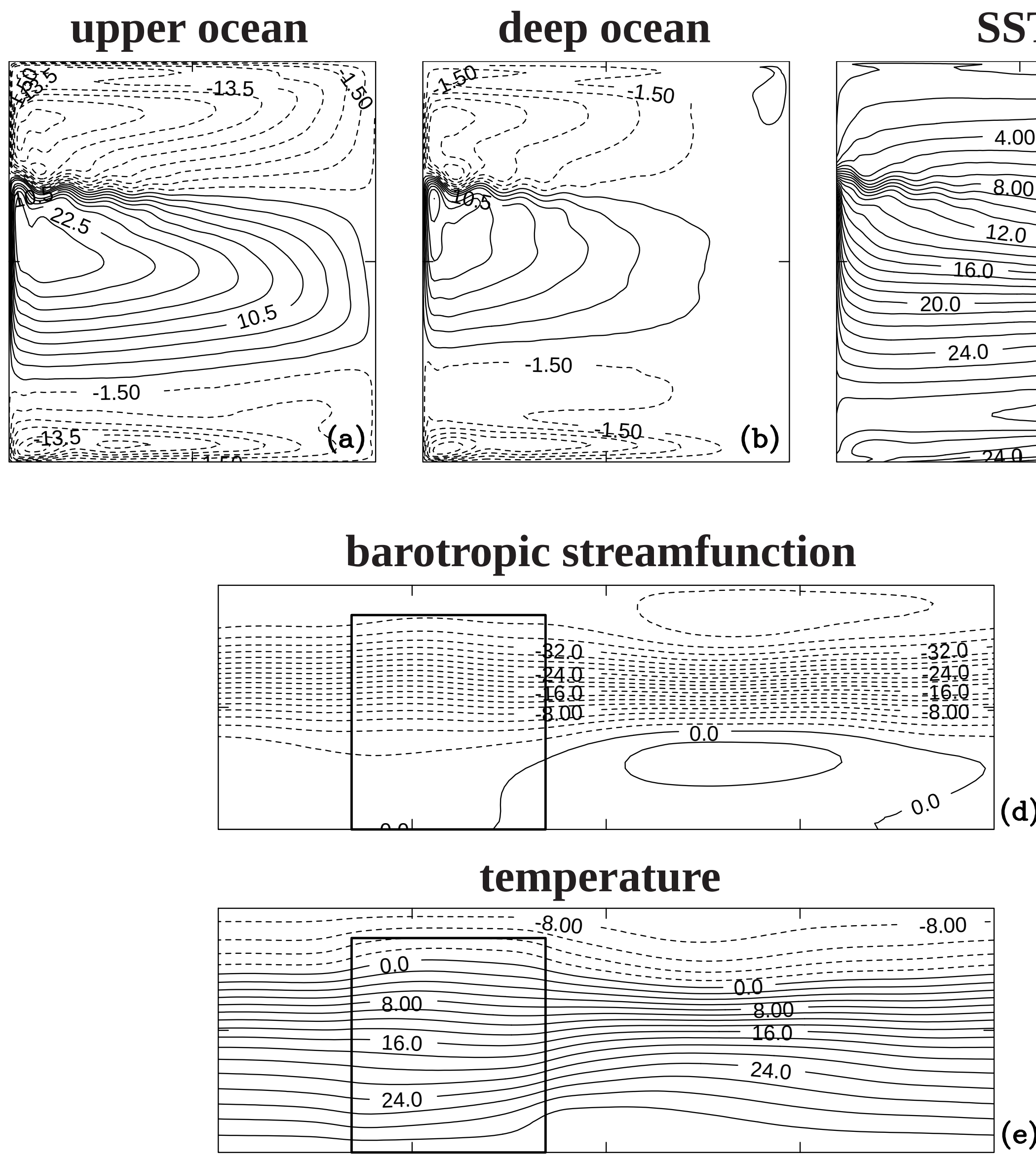
— In the real ocean this is achieved by the thermohaline circulation.

- The surface heat flux reaches 150 W m^{-2} (moderate strength).

- *The decadal LFV is associated with strong changes of the Ekman pumping and surface heat flux patterns.*



Time-Mean Fields: Ocean, Mixed Layer, and Atmosphere



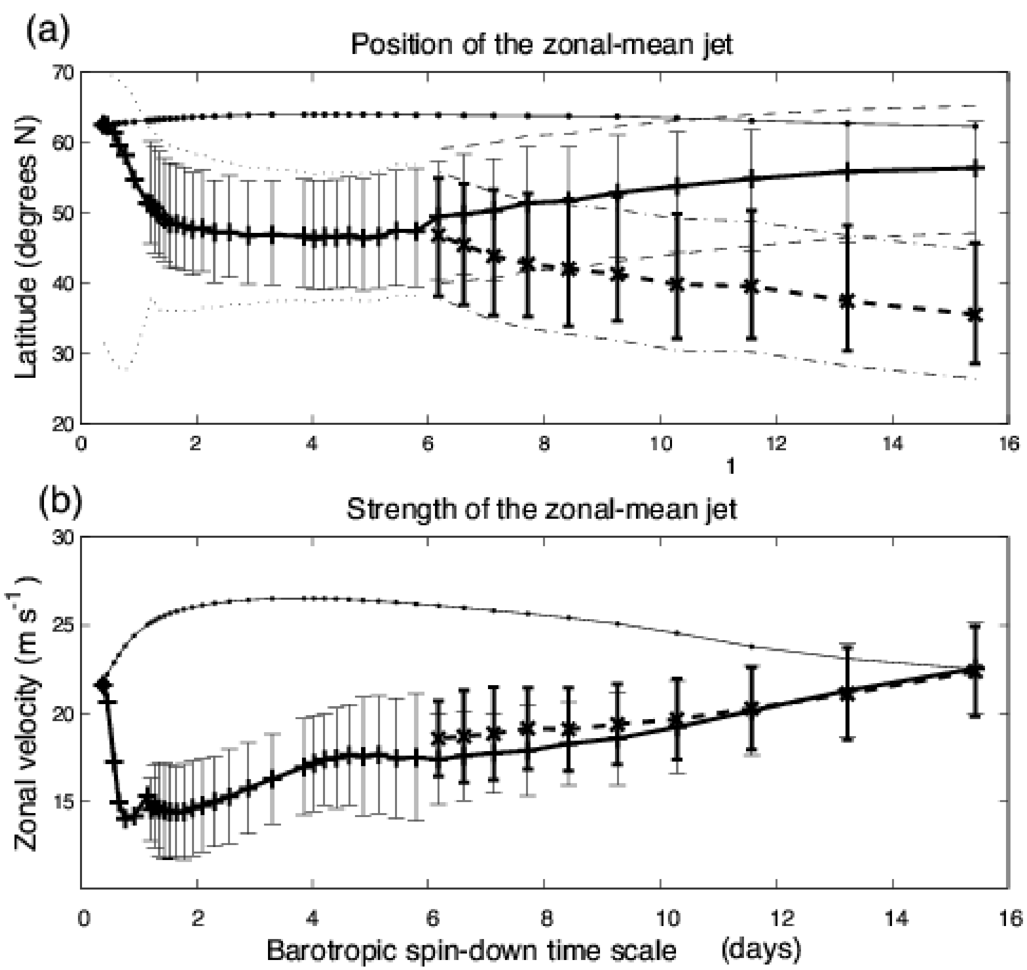
How does the atmosphere behave with the time-mean SST imposed?

Bimodal Atmosphere

• Depending on the surface drag, k, the atmosphere can have two statistically preferred zonal states (Kravtsov et al. 2005):

— There are rare and irregular transitions between these states;

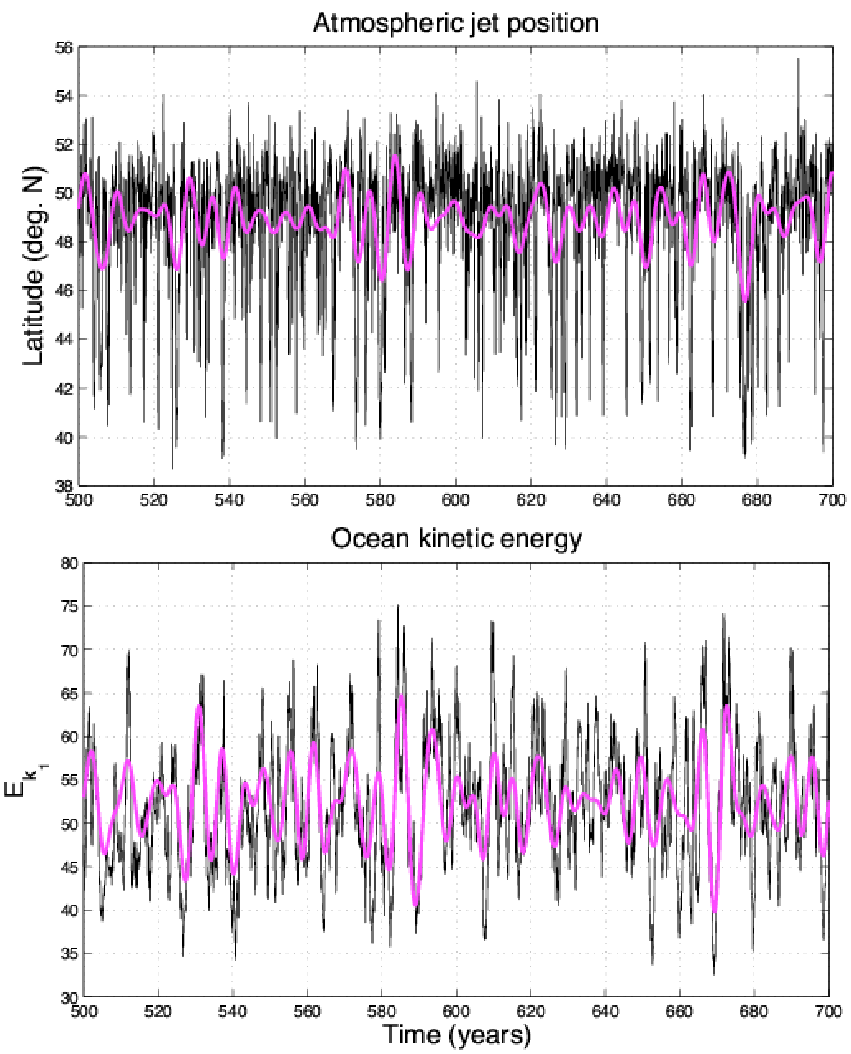
— The underlying unstable steady state is dynamically irrelevant.



1. Temporal Variability: Time Series

• Although, high-latitude (*HL*) state of the atmosphere is more persistent, there are systematic transitions to the low-latitude (*LL*) state.

— Decadal variability is associated with modulation of the frequency of transitions.

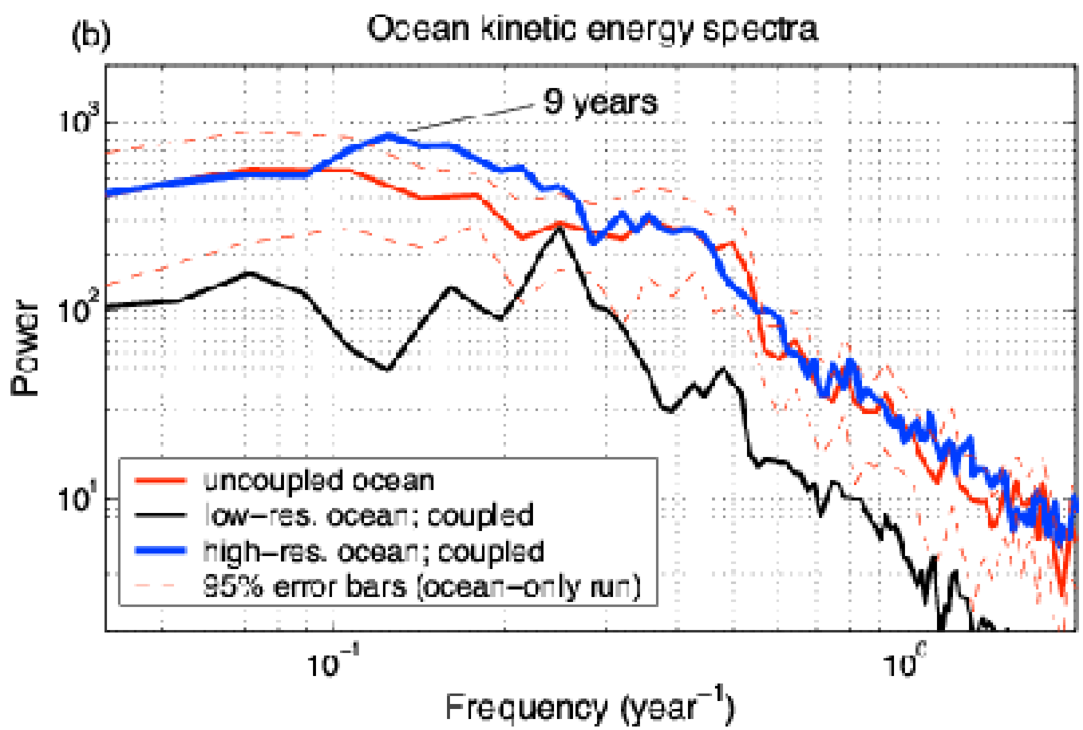


Is this variability coupled?

Is it a large-Re phenomenon?

2. Temporal Variability: Power Spectra

- Significant fraction of decadal variability has both **coupled** and **large-Re** origins.

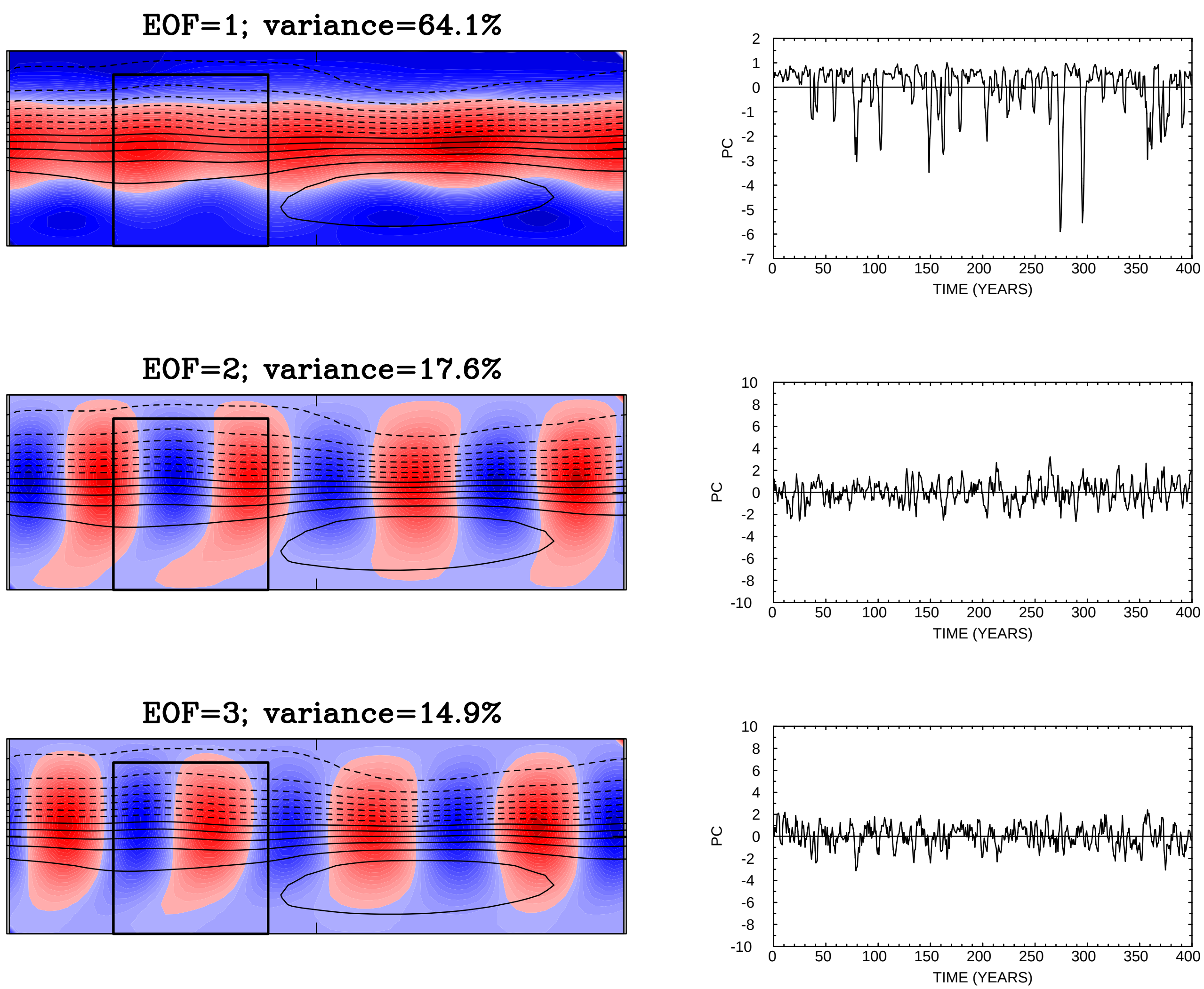


How do the atmosphere and ocean LFV patterns look like?

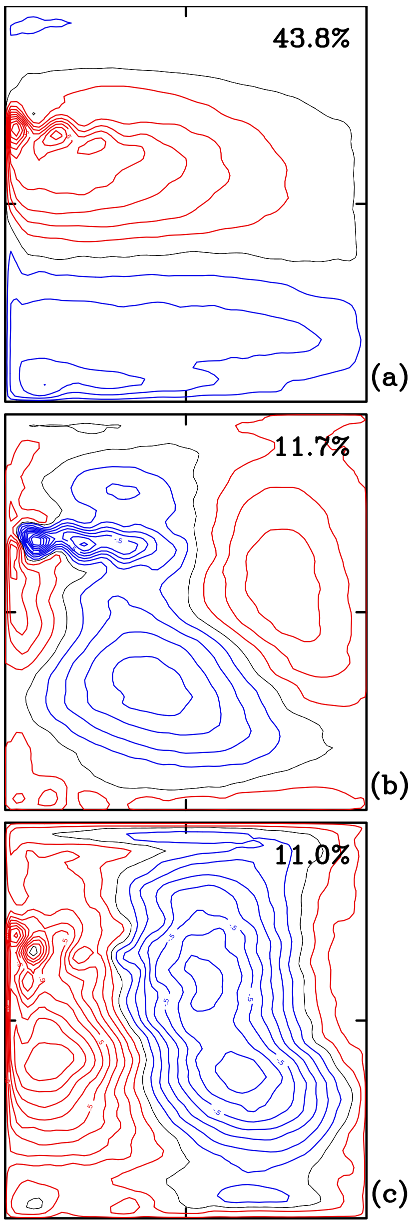
Atmosphere Variability Patterns

• Empirical Orthogonal Functions (EOFs) and their principal components show that most of the atmospheric LFV is due to **decadal meridional shifts** of the mean jet stream.

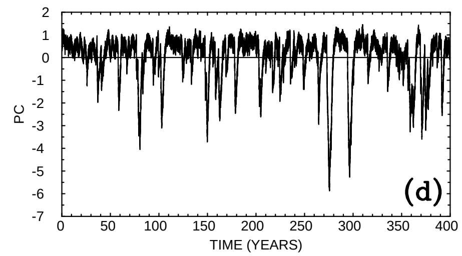
— The rest of the signal is dominated by the 4-year propagating mode.



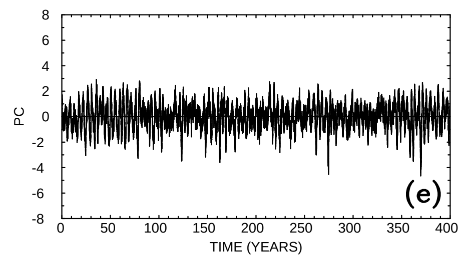
Ocean Variability Patterns



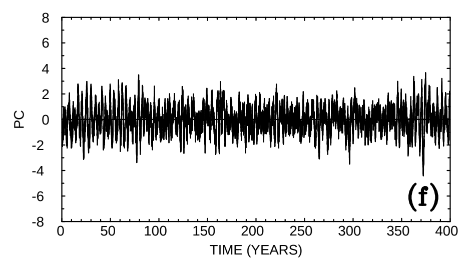
EOF=1: shifting mode



EOF=2: basin mode



EOF=3: basin mode



- Variability of the atmosphere projects on variability of the ocean forcing.
  - — Ekman pumping, W_E, reshapes the main gyres (*active* role);
  - — Entrainment rate, W_D, tends to spin the gyres down (*passive* role).

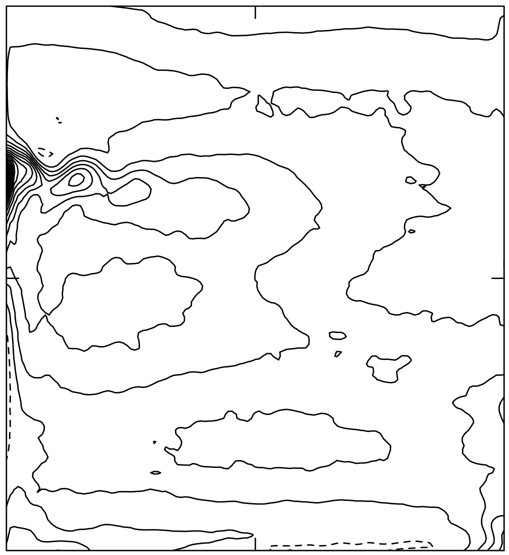
- Ocean variability is dominated by **decadal shifts** and 4-year basin mode.
  - — The latter is a linear coupled phenomenon (Goodman & Marshall 1999).

Is the decadal shifting mode coupled?

SST Variability and Its Effect on the Atmosphere

• Ocean shift from the HL to LL state is associated with substantial cooling of the mixed layer.

SST anomaly [*CI=1°C*]



The key question:

Does the OCEANIC contribution to this SST anomaly have an effect on the atmosphere?

• The answer is given by solving for the Atmosphere/Mixed-Layer ($A{+}ML$) combined system which is decoupled from the underlying ocean. For this purpose:

— Conditionally-averaged ocean states are found for several phases of the shifting mode;

— These states are kept fixed below the mixed layer;

— The corresponding $A{+}ML$ solutions are found.

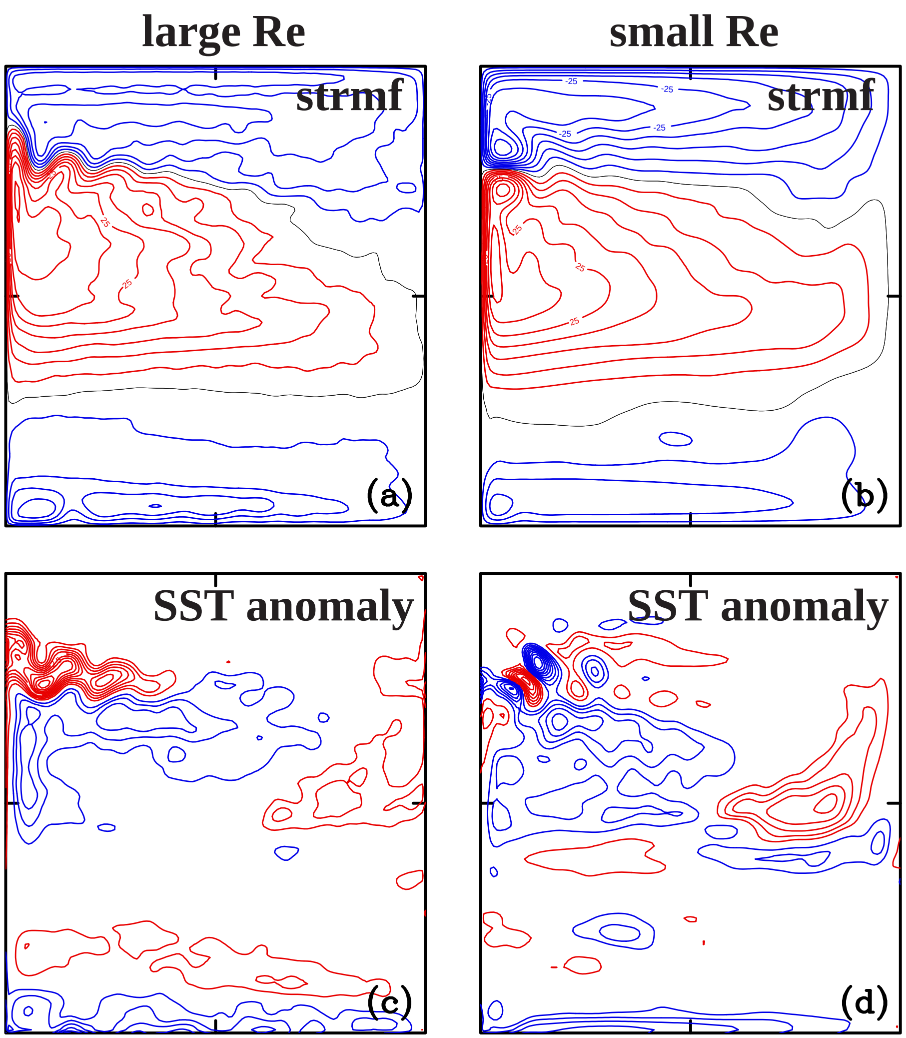
• For different phases of the ocean, probability of the atmospheric transitions between the HL to LL states varies by 10%.

By changing this probability, ocean always tends to push atmosphere to the opposite state.

Oceanic Nonlinear Adjustment sets decadal timescale of the LFV (Dewar 2003).

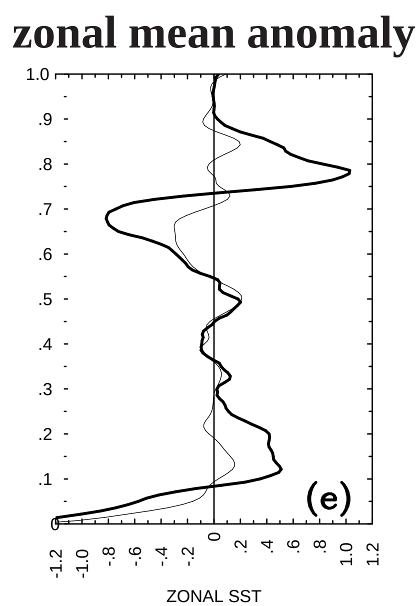
Ensemble-averaged ocean states that are nearly adjusted to the HL *state are shown below.*

- If the eddies are not resolved, adjustment is different and effect on the atmosphere is lost:



— Adjustment to each state yields *long-term SST anomalies*;

— These anomalies force atmosphere toward the opposite state only in the large-Re case.



Dependence of the LFV on the Model Parameters

• Weaker oceanic **bottom friction** yields longer oceanic adjustment timescale and, therefore, slower LVF.

— The variability can be even *interdecadal*;

— The dynamical mechanism remains the same.

• **Atmospheric surface drag** must be in the intermediate range:

— *Weak* surface drag makes atmospheric bimodality too intermittent (i.e., probability of atmospheric transition to the opposite state becomes too small), therefore oceanic feedback on the atmosphere becomes inefficient;

— *Strong* surface drag makes the atmosphere unimodal—-this degrades sensitivity of the atmosphere to the SST anomalies.

• **Reynolds number** must be large (unless eddy effects are accurately parameterized).

How do the oceanic eddies drive the coupled mode?
Let's isolate the eddies and their effects...

1. Eddy Diagnostics

• Coarse-grained ocean solution can be decomposed into the large-scale and eddy components,

$$\mathbf{u} \;=\; \overline{\mathbf{u}} + \mathbf{u}' \qquad q \;=\; \overline{q} + q' ,$$

in the *dynamically consistent* way (Berloff 2005), in order to analyze eddy effects.

• For this purpose:

(1) Governing equations are re-written on a coarse grid;

(2) Solution of the coarse-grid model defines $\overline{\mathbf{u}}$, and the eddies, $\mathbf{u}'$, are found as the residual;

(3) The coarse-grid model is driven by both the *atmospheric forcing* history and the *eddy-forcing* correction;

(4) The eddy-forcing correction is calculated interactively as the difference between the coarse-grid predicted and true nonlinearities;

(5) In terms of the flow components, the eddy forcing can be found as

$$f(t, \mathbf{x}) \;=\; -\nabla\left(\overline{\mathbf{u}}\, q' + \mathbf{u}'\, \overline{q} + \mathbf{u}' q'\right) ,$$

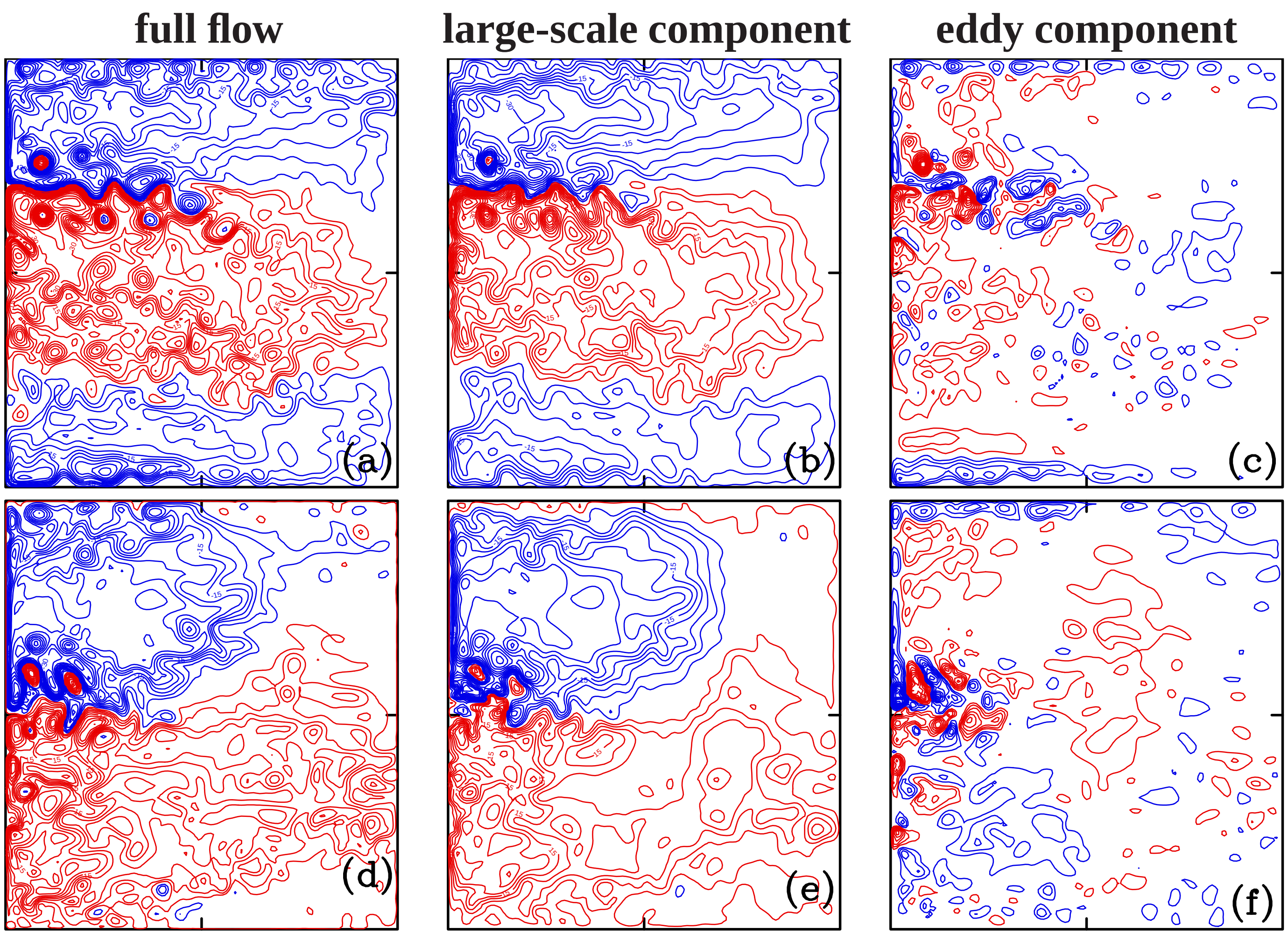
where ∇ is the coarse-grid operator and state variables are taken on the coarse grid.

• Eddy forcing consists of the relative-vorticity and stretching components associated with:

$$q \;=\; R + B\,; \qquad R = \nabla^2 \psi\,, \qquad B = \frac{\partial}{\partial z}\, S\, \frac{\partial \psi}{\partial z}$$

2. Eddy Diagnostics: Illustration

• The algorithm ensures that coarse-grid solution approximates the full solution (*typical flow snapshots are shown below*).



Upper row:
HL-state.

Lower row:
LL-state.

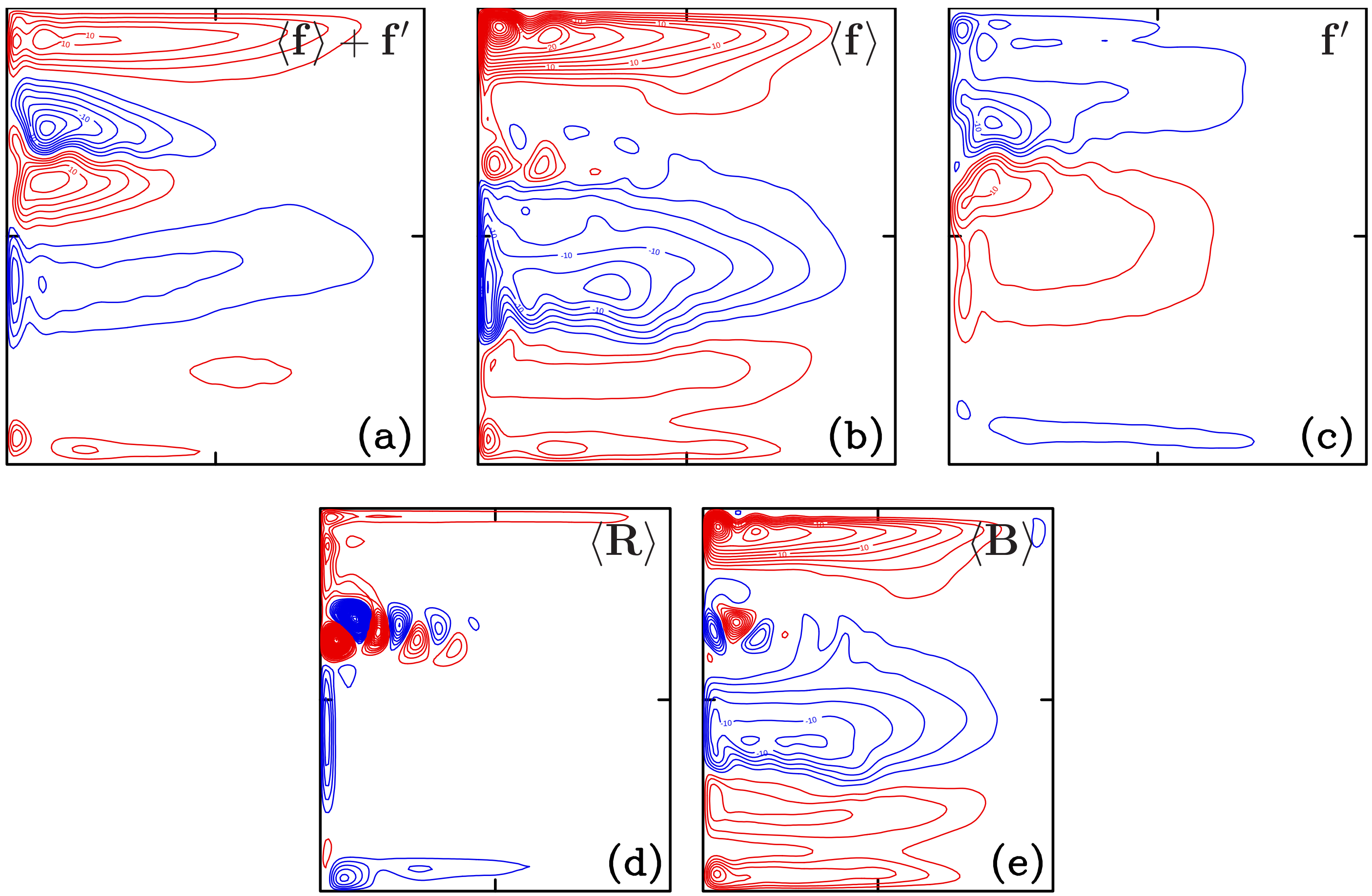
What is the dynamical role of the eddy forcing? Which components of it are important?

Dynamical Response to the Eddy Forcing

• The eddy forcing, $f(t,\mathbf{x}) = \langle f(\mathbf{x})\rangle + f'(t,\mathbf{x})$, weakens the upper-ocean gyres and enhances the eastward jet:

— The former effect is due to the $\langle B\rangle$-forcing [*baroclinic instability*];

— The latter effect [*rectification*], which is fundamentally important for the coupled variability, is due to the f'-forcing (mostly its R' component).



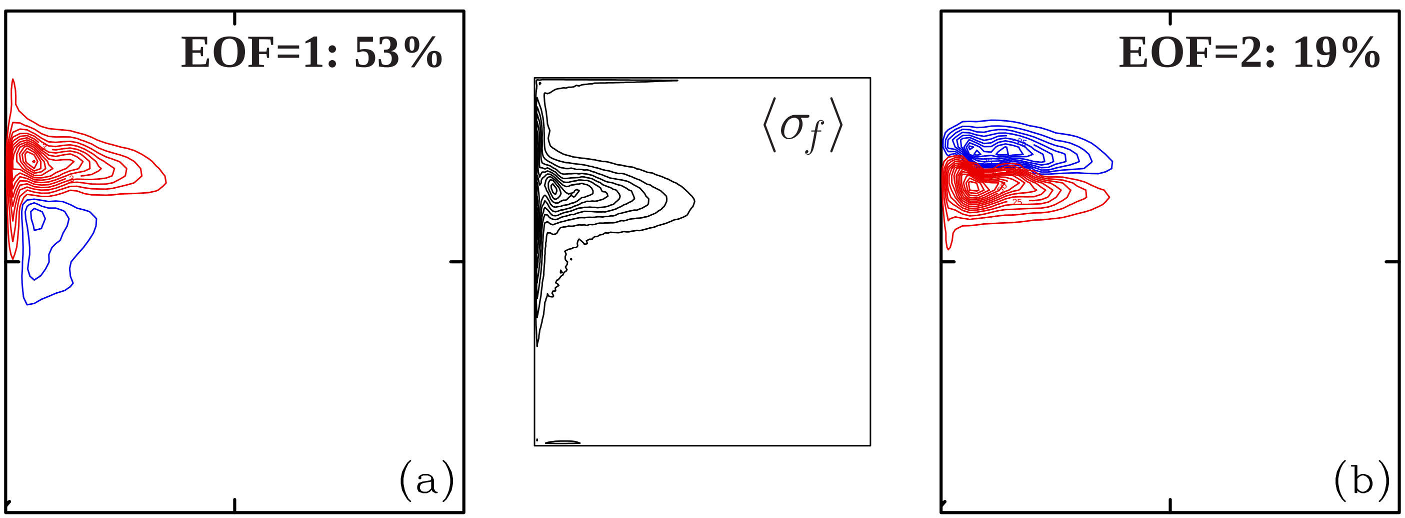
Variance of the Eddy Forcing

The f'-forcing is characterized by its variance...

- This variance, $\sigma_f(t, \mathbf{x})$, is *non-stationary*, and its variability is recovered by splitting eddy forcing into the low- and high-passed frequency components.

- Contribution of the leading EOF of $\sigma_f(t, \mathbf{x})$ is highly correlated with the coupled shifting mode (*the two leading EOFs and the time-mean pattern are shown below*).

— It is an essential part of the LFV, because it controls adjustments of the eastward jet.



Let's summarize what we've learned so far about the LFV mechanism...

Mechanism of the Coupled Variability

★ *Essential aspects*:

(**i**) **Bimodality** of the atmosphere allows for natural transitions between the preferred zonal states.

(**ii**) Oceanic **mesoscale eddies** maintain the eastward jet through the anti-diffusive nonlinear rectification process.

★ The LFV cycle involves the following:

(**1**) Changes of the frequency of atmospheric transitions can induce an oceanic transition from one preferred state to the other.

(**2**) This transition is a slow nonlinear adjustment process involving complex interaction between the eastward jet and mesoscale eddies — it sets decadal-to-interdecadal timescale of the variability.

(**3**) SST anomalies associated with the oceanic adjustment modulate frequency of atmospheric transitions and reverse the cycle.

Is there a simple mathematical model for the effect of the eddies?

Coupled Ocean-Atmosphere Model with Random Eddies

• We model the eddy effects in a non-eddy-resolving model in terms of space-time correlated **random** forcing fields (Berloff 2005).

— The random forcing, like the actual eddies, induces rectification of the oceanic eastward jet.

• Non-stationary variance of the random forcing is *required*, otherwise ocean solutions are trapped in the more preferred *HL* state.

• We found a simple **parameter closure**: the non-stationary random-forcing variance is related to the oceanic baroclinicity index,

$$I_{BC} \;=\; \iint (\Psi_1 - \Psi_2)\, dx\, dy\,,$$

which is integrated over the area surrounding the eastward jet.

★ The randomly forced coupled model generates correct low-frequency coupled variability although it does not resolve the eddies —- **MODELLING SUCCESS!**

Summary

(**0**) Coupled quasigeostrophic ocean-atmosphere model has astonishingly rich dynamics—-it is a powerful tool for analysis of interactions between climate variability and turbulence.
Use it!

(**1**) Solutions of the turbulent ocean-atmosphere model are analyzed and decadal coupled variability is found for a wide range of physical parameters.

(**2**) Both the variability mechanism and the fundamental role of the oceanic eddies are understood in terms of the basic fluid mechanics.

(**3**) The eddy effects are modeled (parameterized) in terms of non-stationary stochastic process with parameters related to the large-scale flow pattern.