DECADAL SCALE VARIABILITY AND BAROCLINIC OCEAN BASIN MODES

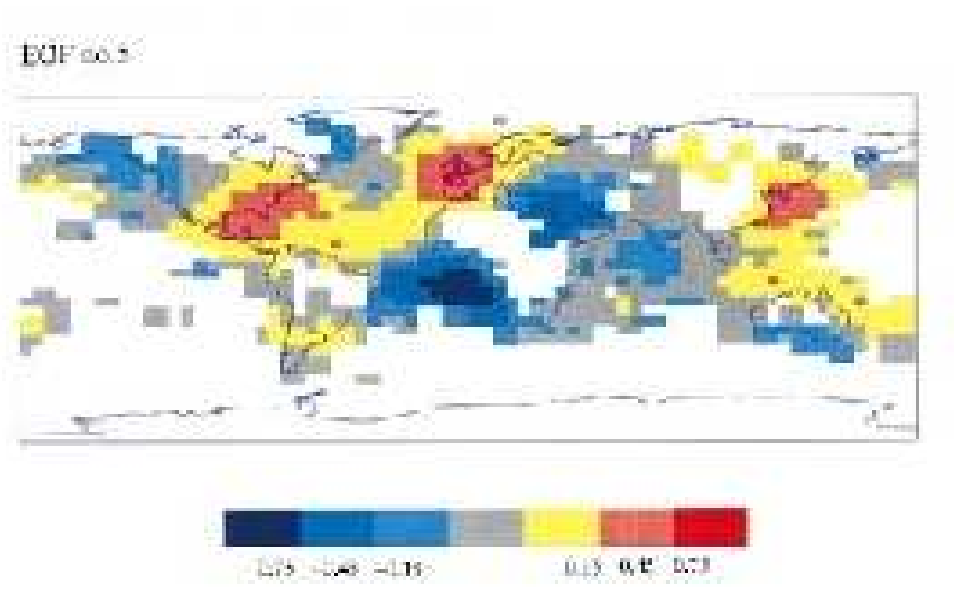
Are there sustained decadal modes in the ocean?

Thierry HUCK <thuck@univ-brest.fr>

Laboratoire de Physique des Océans, CNRS, Brest, France

Mahdi BEN JELLOUL <mjelloul@whoi.edu>

Woods Hole Oceanographic Institution



[Mann *et al.* 1998]

INTRODUCTION

OBSERVATIONS

Atlantic Multidecadal Oscillation may be linked to the thermohaline circulation

[Mann *et al.* 1998, Delworth&Mann 2000]

THEORY

¿ are there unstable ocean "basin modes" with (inter) decadal time scales?

(incidently, this is the timescale of baroclinic Rossby waves propagation across ocean basins)

METHODS

• analytical: $R_d \ll L$, i.e. very small Burger number
$\rightarrow$ **weakly nonlinear expansion** in Bu

• numerical: **linear stability analysis** in a hierarchy of ocean models (quasigeostrophic, shallow-water, planetary geostrophic)

BASIN MODES IN QUASIGEOSTROPHIC DYNAMICS

$$\partial_t(\nabla^2\Psi - Bu^{-1}\Psi) + \beta\partial_x\Psi = \text{Dissipation}$$

- $Bu = (R_d/L)^2 \gg 1 : \omega \propto k^{-1}$ [Pedlosky 1987]

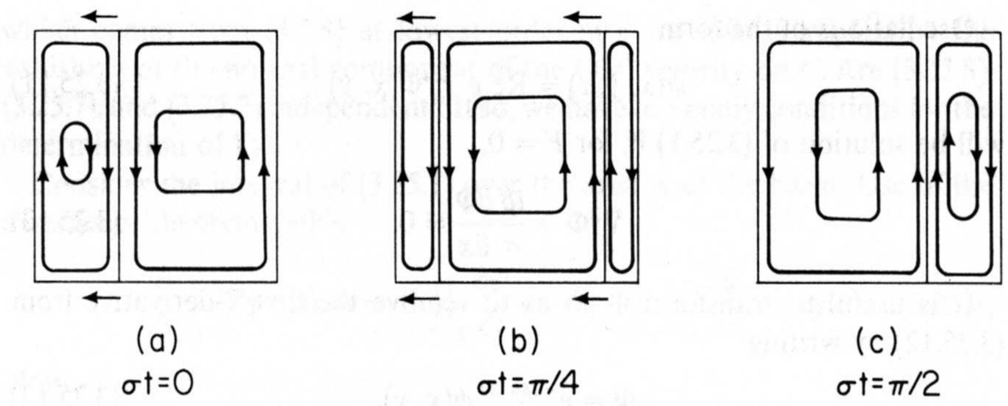


Figure 3.25.3 The first normal mode in a rectangular basin. Note the propagation of phase toward negative x in the pattern of the oscillation.

- $Bu \ll 1 : \omega \propto k$ [Cessi&Primeau 2001]
  - **mass conserving boundary condition** [Flierl 1977]
  - dissipative selection of low-frequency modes
  - excitation by stochastic atmospheric forcing/coupling
  - rectification by the mean circulation

- BASIC PROCESSES
  - baroclinic Rossby wave propagation across the basin
  - resonance through fast boundary wave adjustment

  (resolved or parameterized)

BASIN MODE INTERACTIONS AND SELECTION BY THE MEAN FLOW

FRAMEWORK

- reduced-gravity quasigeostrophic model
- rectangular Cartesian β-plane basin

METHODOLOGY

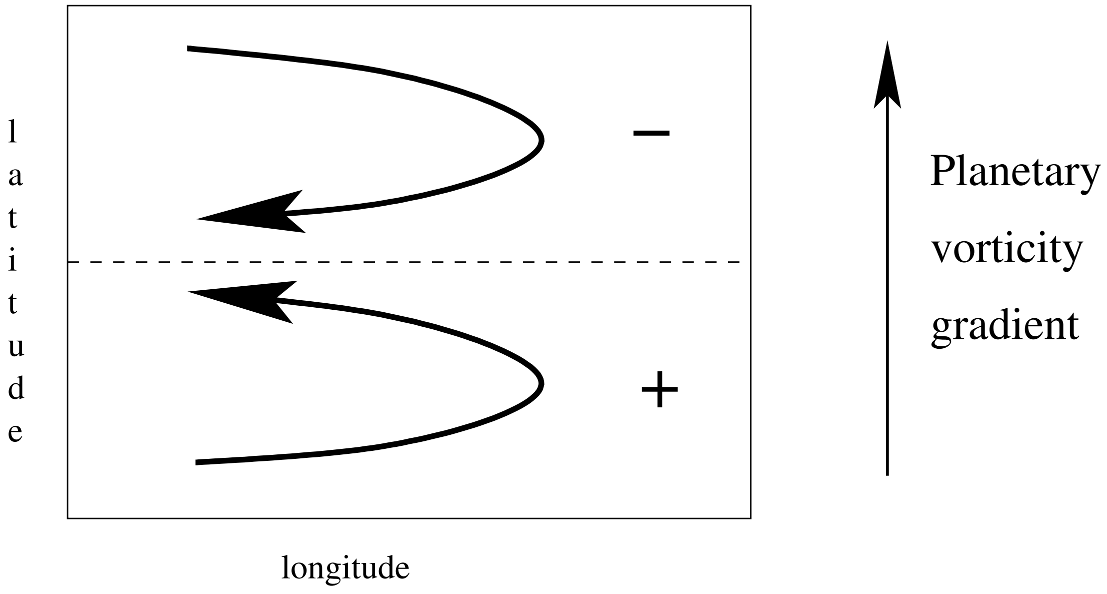
- weakly nonlinear expansion in Burger number
- linear modes and interaction terms are derived:

- analytically (infinite Bu, inviscid case)
- numerically (finite Bu, dissipative case)

RESULTS

$\rightarrow$ mode stability depends on mean gyre configuration:

- single and classic double gyre, all basin modes neutral
- reversed double gyre case, $\exists$ unstable basin modes



[Ben Jelloul&Huck 2003, JPO, in press]

BASIN MODES IN SHALLOW WATER

- Coriolis parameter varies with latitude$\rightarrow$baroclinic wave celerity $c = \beta R_d^2 \sim \beta N^2 H^2/f^2 \sim N^2 H^2 \cos\theta/(2a\Omega \sin^2\theta)$
- period set at slower poleward boundary
- balance through dissipation in the western boundary

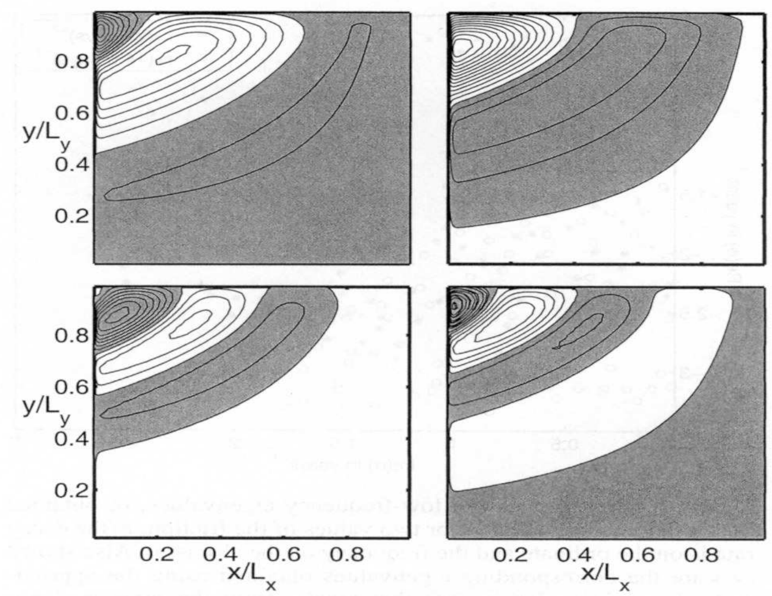
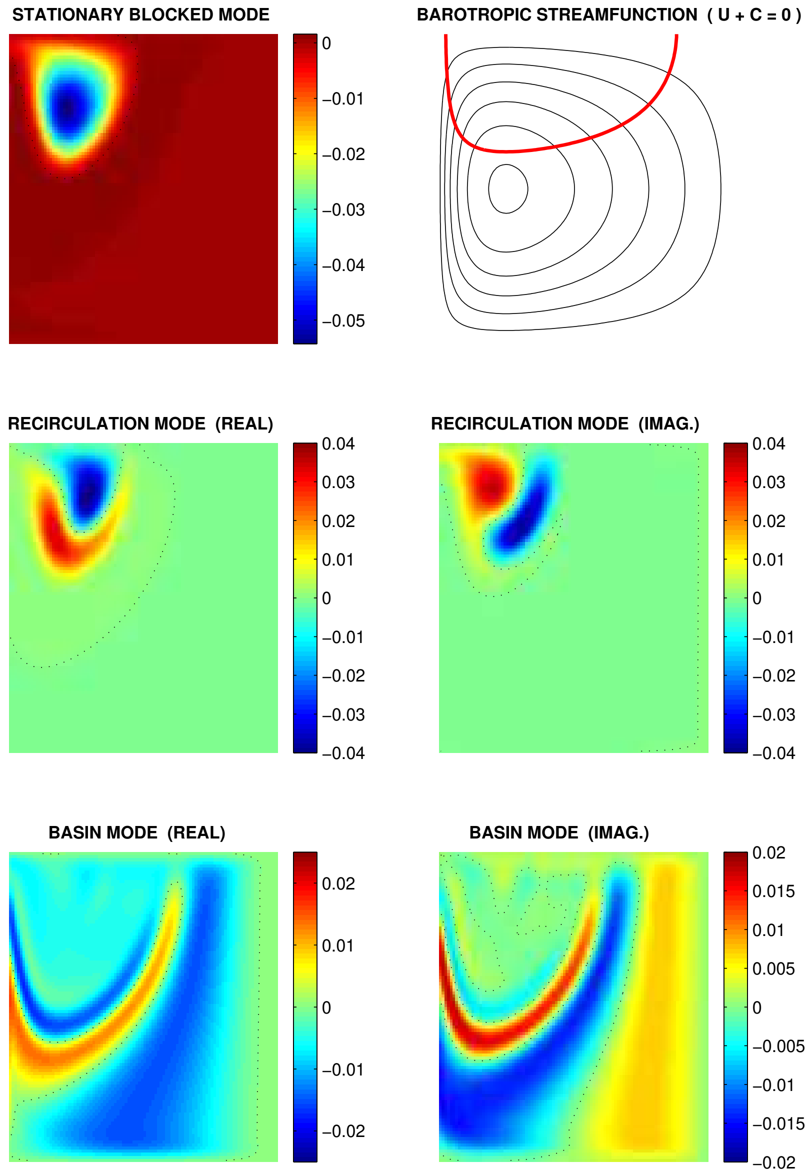


FIG. 2. (left) Real and (right) imaginary parts of the eigenfunctions, $\hat{h}$, associated with the (top) smallest and (bottom) next-to-smallest eigenvalues of Fig. 1 for $r = 8 \times 10^{-7}\ \mathrm{s}^{-1}$ (14.5 days)$^{-1}$. (top) For mode 1 the eigenvalue is $\sigma = -0.1658 + i0.2504$ in yr^{-1}, corresponding to a period of 25.1 yr. (bottom) For mode 2 the eigenvalue is $\sigma = -0.2366 + i0.4998$ in yr^{-1}, corresponding to a period of 12.6 yr. Negative contours are shaded.

[Cessi&Louazel 2001]

BAROTROPIC FLOW – BAROCLINIC BASIN MODES INTERACTION



basin modes westward propagation arrested by mean flow

$\rightarrow$ slow modes trapped in the recirculation gyre

QG dynamics [Ben Jelloul&Huck 2003, JPO, in preparation]

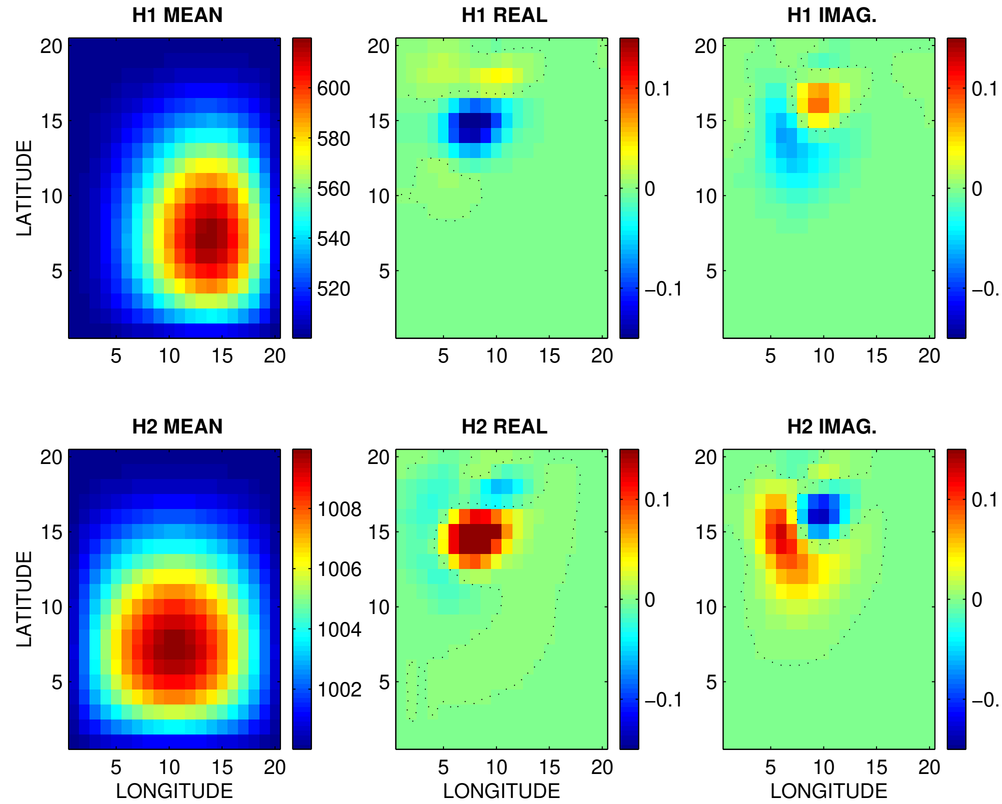
UNSTABLE BASIN MODES REQUIRE ACTIVE BAROCLINIC INSTABILITY

2.5 LAYER SHALLOW WATER EQUATIONS

$$\left.\begin{array}{l} \partial_t h_i + \nabla \cdot (h_i \boldsymbol{u_i}) = F_i \\ \partial_t \boldsymbol{u_i} - f\boldsymbol{k} \times \boldsymbol{u_i} = -\gamma_i \nabla h_1 - \gamma_{i+1} \nabla h_2 - r\boldsymbol{u_i} \\ \boldsymbol{u_i} \cdot \boldsymbol{n} = 0 \text{ on boundaries} \end{array}\right| \quad i = 1, 2$$

$$\gamma_1 = g(\rho_3 - \rho_1)/\rho_0 \;;\; \gamma_2 = g(\rho_3 - \rho_2)/\rho_0 \;;\; \gamma_3 = g(\rho_3 - \rho_2)/\rho_0$$

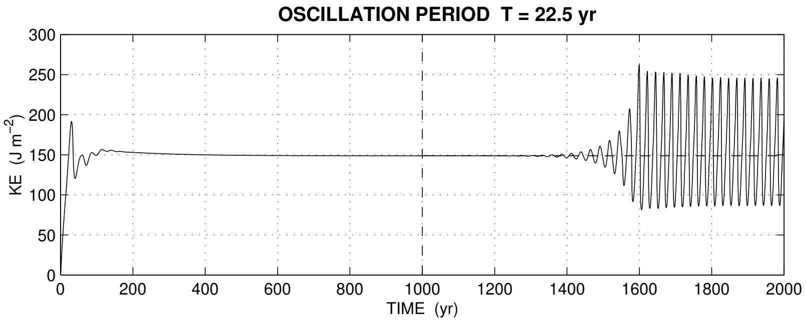
- finite-difference formulation on C-grid
- linearization for prescribed $H_i(x, y)$
- eigen-analysis function of upper layer deviation amplitude

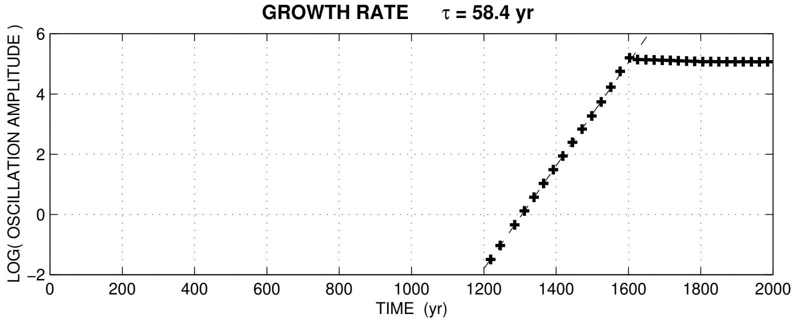


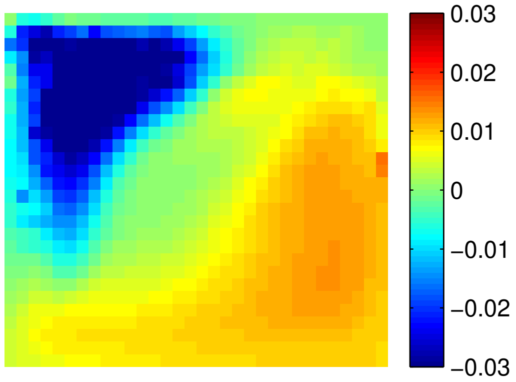
Hopf bifurcation → unstable mode T=38yr growthrate=$(22\text{yr})^{-1}$

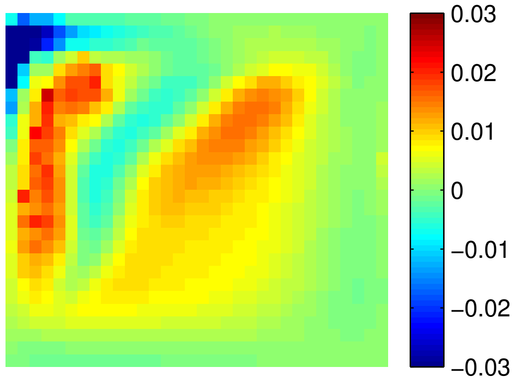
BASIN MODES IN PLANETARY GEOSTROPHIC DYNAMICS

- low resolution ocean models forced by surface **restoring** boundary conditions → **steady-state**
- switch to **fixed surface flux** → decadal **oscillations**
- linear stability analysis of the **steady state** → **linear unstable mode**









T=22.5yr τ=47.4yr

[Huck&Vallis 2001, Tellus]

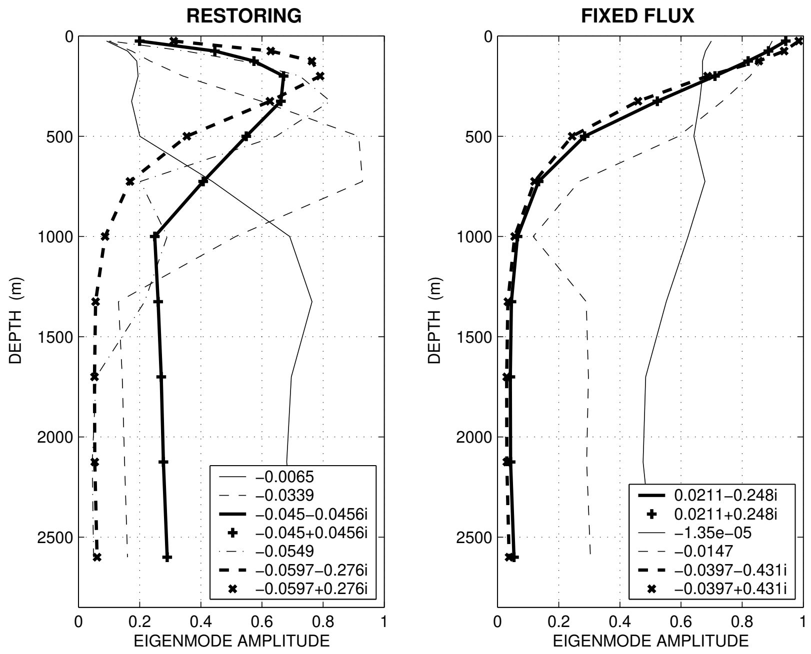
DISCUSSION

• Dissipation not required to fullfill boundary conditions
→ dispersion rather than dissipation may select modes
→ basin scale modes may have small scale structures that can interact with small scale mean flow structure (WBC...)
[LaCasce&Pedlosky 2002, Ben Jelloul&Huck 2003]

• realistic setting and forcing may lead to more damping, i.e. through interaction with large-scale topography...

• atmospheric (simple) coupling better than restoring or mixed surface boundary conditions [te Raa&Dijkstra 2003]

Vertical structure of the eigenmodes



Left is unrealistic since heat capacity lies **in the ocean**

CONCLUSION

Basin modes:
- slow westward propagation (Rossby wave)
- resonance through fast boundary waves adjustment
- rectification by the mean flow (closed PV contours)
- growth through large scale baroclinic instability
- damping through boundary interactions

Whether or not these are sustained (positive growth rate) or weakly damped, such oceanic decadal-scale modes may be excited by stochastic atmospheric forcing

[Delworth&Greatbatch 2000]

→ These modes provide a potential framework for long-term climate prediction

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