INFLUENCE OF BOTTOM TOPOGRAPHY ON LARGE-SCALE DECADAL BASIN MODES

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Abstract

The influence of bottom topography on the generic properties of the baroclinic basin modes is investigated through linear stability analysis of a two-layer shallow water ocean model. Various idealized bottom profiles imitating a mid-ocean ridge and continental slopes are implemented in an extratropical β-plane closed basin. The damping rate of the leading baroclinic mode is found to be weakly sensitive to bottom topography while the decadal period is shortened by bottom elevations. The mechanism of modal decay is rationalized through energy and vorticity budgets for the barotropic and baroclinic components, to characterize the energy routes and conversions. For small amplitude topography, the barotropic flow results accurately from the interaction of the flat-bottomed baroclinic motion with the topographic height: it is found to be three times stronger within closed potential vorticity contours than with blocked contours. However, the conversion of energy from the baroclinic to the barotropic mode remains weaker than the frictional processes.

Motivation & Context

The low-frequency ocean circulation is likely a major player, given its large heat capacity and long adjustment. The latter is achieved through the baroclinic planetary waves that cross the Atlantic basin in a few decades at mid-latitude. The baroclinic Rossby basin modes have thus been proposed as a possible explanation for the interdecadal oscillation: they are westward-propagating Rossby waves reinitiated at the eastern boundary through rapid Kelvin wave adjustment (LaCasce 2000) or nonresonant inertia-gravity wave response (Primeau 2002), and owe their existence to mass conservation laws (Cessi and Primeau 2001). However, most of these studies examined the low-frequency large-scale basin modes from a quasigeostrophic point of view. Moreover, all of them considered a flat bottom or a reduced gravity configuration so that the effect of topography could be ignored. It is then natural to wonder what effect the removal of these simplifications (quasigeostrophy, flat-bottom) might have on the structure of the baroclinic basin modes, given the well-known tendency of the large-scale topography to couple the vertical modes. This study is motivated by the desire to pursue these investigations by considering the influence of different topographic features on the generic property of the baroclinic basin modes as well as their damping.

Model & Method

1- Governing equations

The two-layer shallow water equations with bottom topography are:

$$D_t\mathbf{u_i} + f\mathbf{k}\times\mathbf{u_i} = -g\nabla\left(\eta_1 + \delta_{i2}\frac{\rho_2-\rho_1}{\rho_2}\eta_2\right) + \nu\nabla^2\mathbf{u_i}, \qquad (1a)$$

$$\partial_t h_i + \nabla\cdot(h_i\mathbf{u_i}) = 0. \qquad (1b)$$

h_i, $\mathbf{u_i}$ are the thickness and velocity in each layer i, g =9.81 m s^{-2} the acceleration due to gravity and g' =0.02 m s^{-2} the reduced gravity, ν = 10^5 m^2 s^{-1} the lateral eddy viscosity, η_i the free surface and interface elevations with respect to H_i: H_1 =10^3 m, H_2 =3×10^3 m $\rightarrow h_1 = H_1 + \eta_1 - \eta_2$ and $h_2 = H_2 + \eta_2 - b$, $b(x,y)$ the bottom height and $f = f_0 + \beta y$ the Coriolis parameter, f_0 =10^{-4} s^{-1}, β =1.6× 10^{-11} m^{-1} s^{-1}. No-slip boundary conditions are imposed on the lateral solid walls along with mass conservation in each layer.

2- Linear stability analysis

The eigenvalue problem associated with the linearized prognostic equations is:

$$\omega X = JX, \qquad (2)$$

where J is the Jacobian matrix and $X = (h_i, \mathbf{u_i})$ is the state vector. The time evolution of the perturbation follows: $X(t) = e^{\omega_r t}\left[X_r\cos(\omega_i t) - X_i\sin(\omega_i t)\right]$. J is explicitly computed from the finite difference formulation of the equations on an regular Arakawa C-grid with a 60-point standard resolution in each direction. Its leading eigenvalues ω (typically 30) based on the largest real part are computed using Arnoldi's method as provided in ARPACK (Lehouck et al. 1998).

Linear vorticity balance

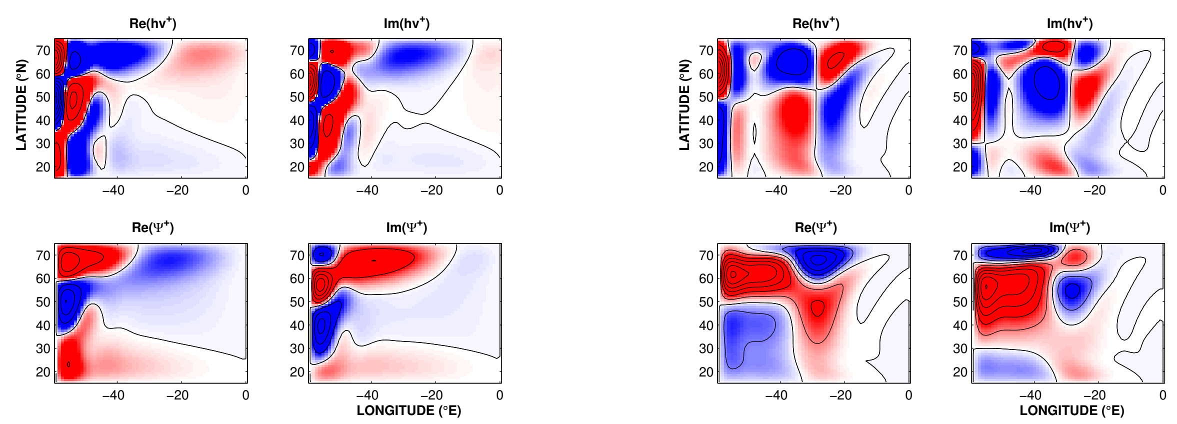
For each variable, we note $X^+/hX^+ = H_1X_1 + h_2X_2$ the vertically averaged (barotropic) component and $X^- = X_1 - X_2$ its baroclinic counterpart.

$$* \text{ Large-scale SW: } \partial_t\zeta^+ = f\partial_t\eta_1 - \beta h v^+ - f\mathbf{u}^+\nabla b + \frac{H_1}{h}J(p^-,b) + \mathbf{k}\cdot\nabla\times F$$

$$* \text{ PG} \rightarrow \mathbf{k}\times\nabla\psi^+ = h\mathbf{u}^+: \quad J\left(\psi^+, \frac{f}{h}\right) = \frac{H_1}{h^2}J(p^-,b)$$

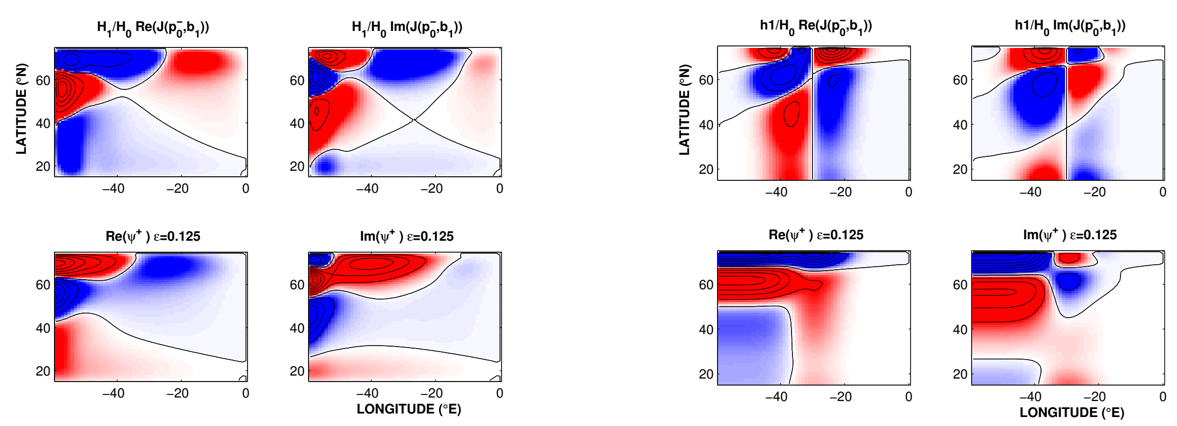
$$* \ \epsilon = \frac{b}{H_0} \ll O(1): \quad \beta\partial_x\psi_1^+ = \frac{H_1}{H_0}J(p_0^-,b_1)$$

⇒ The barotropic mode is accurately diagnosed through the interaction of the flat-bottomed baroclinic mode with the imposed topography elevation.



(a) ψ from the transport

(b) ψ from the transport



(c) ψ from the JEBAR in the CR experiment

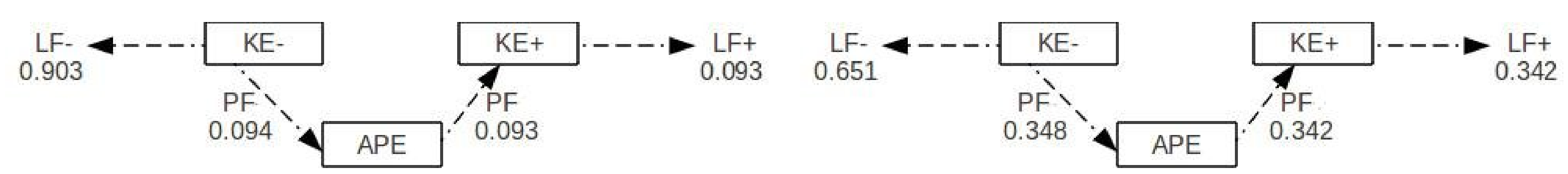
(d) ψ from the JEBAR in the MOR experiment

Figure 1: Real (left) and imaginary (right) parts of the barotropic transport streamfunction: (a) as obtained from the vertically integrated horizontal transport (upper panel) and (b) diagnostically calculated using the JEBAR term (bottom panel). A weak topography amplitude ϵ = 0.125 is used.

Mechanims of modal decay

$$\frac{1}{2}h\partial_t|\mathbf{u}^+|^2 + \frac{1}{2}g\partial_t\eta_1^2 = -\nabla\cdot(h\,p^+\mathbf{u}^+) + \frac{h_2}{h}p^-\partial_t\eta_1 + p^-\mathbf{u}^+\frac{H_1}{h}\nabla b + LF^+, \qquad (3a)$$

$$\frac{1}{2}h^*\partial_t|\mathbf{u}^-|^2 + \frac{1}{2}g'\partial_t\eta_2^2 = -\nabla\cdot(h^*p^-\mathbf{u}^-) - \frac{h_2}{h}p^-\partial_t\eta_1 - p^-\mathbf{u}^+\frac{H_1}{h}\nabla b + LF^-. \qquad (3b)$$



(a) 1500 m-MOR; Dissipation time-scale τ= 3.83 yr

(b) 1500 m-CR; τ=3.93 yr

Figure 2: Perturbation energy box diagram showing the baroclinic total-drag energy route for the least damped basin mode. Energy budgets are evaluated after taking the volume integral in the global domain.

Sensitivity analysis

1)- to dissipation:

2)- to R_d resolution

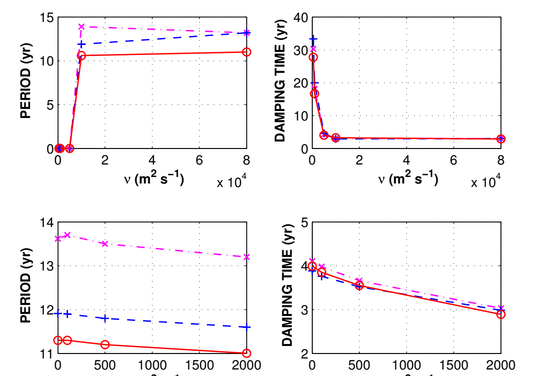


Figure 3: Sensitivity of the (left) oscillation period and (right) decay time (in years) to (top) horizontal viscosity ν for a fixed value of diffusivity $\lambda = 2\times10^3$ m^{2}s^{-1}, (bottom) horizontal diffusivity λ for a fixed viscosity $\nu = 10^4$ m^{2}s^{-1}, in the flat bottom (dash-dot cross line), the 1500 m-MOR (solid plus sign line) and the 1500 m-CR (solid circle line).

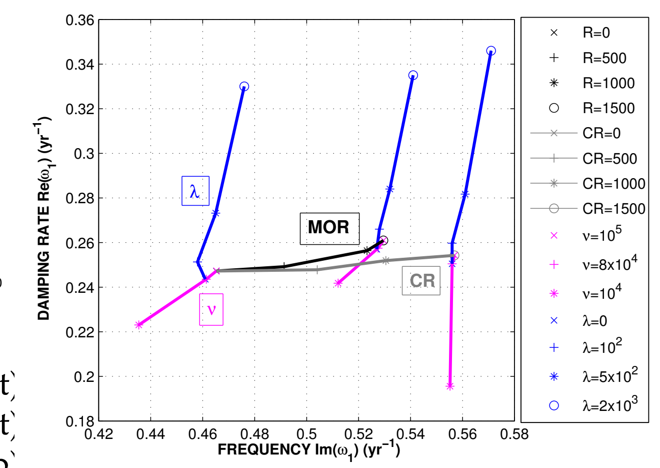


Figure 4: Sensitivity diagram in the $\omega_r - \omega_i$ plane for the least damped oscillation mode under different prescribed forms and amplitudes of topography and dissipation.

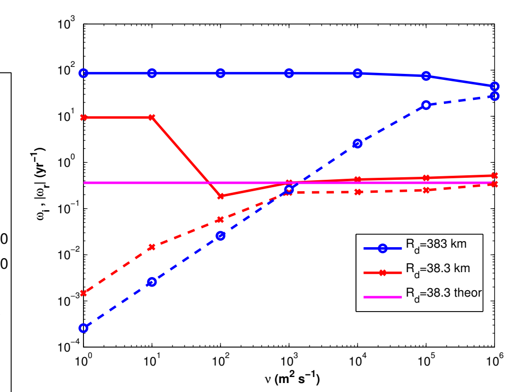


Figure 5: Least damped eigenmode frequency (solid line) and decay rate (dashed line) (yr^{-1}) as function of ν in the flat bottom experiment. The red (blue) curve indicates the realistic (unrealistic) stratification experiment. The magenta line corresponds to the theoretical frequency $2\pi/T_N$ of the realistic stratification experiment.

⇒ The diffusion appears more likely to affect the decay rate while the friction strongly controls the oscillation period of the variability. The diagram confirms the weak effect of the topography with respect to frictional and diffusive processes.

Discussion & Conclusion

The large-scale basin modes with decadal periods are promoted through eddy viscosity at coarse resolution. The period for the gravest basin mode is slightly shortened suggesting a net acceleration of long Rossby waves by bottom heights as pointed out by Tailleux and McWilliams (2000). Changes in horizontal diffusion do not have a crucial influence on the gravest baroclinic mode of ocean variability. However, varying both amplitudes of viscous momentum dissipation and bottom topography exerted a leading damping role upon the baroclinic large-scale circulation. We conjecture that large-scale stationary mean flow forcing (either by winds or heat fluxes) may well act to sustain the decadal mode, thus contributing to the decadal band of climate variability.

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