

LFV in a mid-latitude coupled model: Gulf Stream influence on the NAO

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Low-frequency variability in the ocean

- Interannual variability in the mid-latitude oceans arises from a “gyre-mode” of period **7–8 y** — theory and simple models.
- Robust relaxation oscillation of eastward oceanic jets (Jiang et al., JPO, 1995; Chang et al., JPO, 2001; Simonnet & Dijkstra, JPO, 2002; Simonnet et al., JPO, 2003a,b; Simonnet, JPO, 2005).
- Period and surface features of this mode agree with the spatio-temporal characteristics of the **North Atlantic Oscillation's (NAO)** SST and SLP fields (Moron et al., Clim. Dyn., 1998; Da Costa & Colin de Verdière, QJRMS, 2002; Simonnet et al., JMR, 2005).

Introduction and motivation (II)

Low-frequency variability in the troposphere: observations

- Plaut & Vautard (JAS, 1994): 70-day oscillation over the North Atlantic.
- Downstream anomalies off the Gulf Stream path.

Low-frequency variability in the troposphere: model

- Feliks, Ghil & Simonnet (JAS, 2004, 2007; FGS'04, '07 hereafter) have shown that a strong and narrow SST front can induce a vigorous jet in the atmosphere above, via **Ekman pumping** in the marine **atmospheric boundary layer (ABL)**.
- Intraseasonal (30–200 days) variability in a QG atmosphere with fixed, time-independent SSTs.

What about fully coupled models of the North Atlantic?

Ocean-atmosphere coupling mechanism (I)

Marine ABL

- Wind above an **eastward oceanic jet** blows from north to south giving a well-mixed **marine ABL** of height H_e with potential temperature $\theta(z) \simeq \theta(z=0) \equiv T(x, y)$.
- Hydrostatic approximation yields pressure $p(z) = p(H_e) - g\rho_0(H_e - z)T/T_0$.
Pressure $p(H_e)$ at the top H_e of the **marine ABL** is given by the **geostrophic winds** in the free atmosphere.
- Linear equation of motion in the **marine ABL** with appropriate boundary conditions (B.C.s):

$$\begin{aligned} k_0 \frac{\partial^2}{\partial z^2} u + fv - \frac{1}{\rho_0} \frac{\partial p}{\partial x} &= 0 \\ k_0 \frac{\partial^2}{\partial z^2} v - fu - \frac{1}{\rho_0} \frac{\partial p}{\partial y} &= 0 \end{aligned} \Rightarrow u(z), v(z)$$

- Divergence-free vector field gives vertical velocity (**Ekman pumping**):

$$w(H_e) = - \int_0^{H_e} (\partial_x u + \partial_y v) dz$$

Ocean-atmosphere coupling mechanism (II)

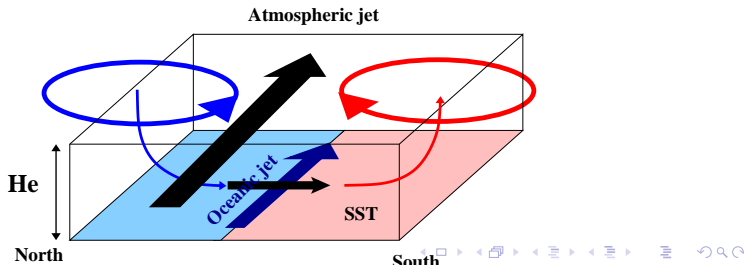
Vertical velocity at the top of the marine ABL

- The nondimensional $w(H_e)$ is given by

$$w(H_e) = \left[\gamma \zeta_g - \alpha \nabla^2 T \right],$$

with $\gamma = c_1(f_0 L/U)(H_e/H_a)$ and $\alpha = c_2(g/T_0 U^2)(H_e^2/H_a)$, where H_a is the layer depth of the free atmosphere (~ 10 km), and ζ_g the atmospheric geostrophic vorticity.

- Two components: one **mechanical**, due to the geostrophic flow ζ_g above the marine ABL and one **thermal**, induced by the SST front.

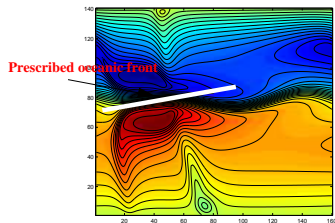


Results in idealized atmospheric models

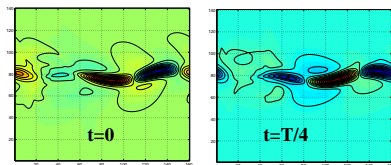
Intraseasonal variability (FGS'04, '07)

- A prescribed, *time-independent*, mid-latitude ocean thermal front forces a barotropic (FGS'04) and baroclinic (FGS'07) QG atmosphere in a periodic β -channel.
- **Rectangular** domain and a tilted, antisymmetric SST front: **multiple equilibria** with (perturbed) symmetry-breaking and Hopf bifurcations.
- Barotropic instabilities with 5–30-day and 70-day periods.
- Baroclinic instabilities with a 9-month period.

Atmospheric streamfunction



70-day barotropic instability



DOWNSTREAM !



A model of the North Atlantic basin (I)

The next step in the modeling hierarchy

- Realistic East Coast contour, at -200 m isobath.
- An oceanic QG baroclinic model with **four layers** and internal Rossby radii from observational dataset (Mercier et al., 1993).
- Climatological, annual-mean COADS wind-stress forcing (1 deg).
- **Realistic bathymetry.**
- Transport equation for the SST relaxed to the climatological SST field.
- **Full coupling** with a QG barotropic atmosphere in a periodic β -channel, with vorticity feedback to the ocean.
- No-slip B.C.s for the ocean at the coasts parametrized following Verron and Blayo (1995); free-slip B.C.s elsewhere.
- Neuman B.C.s for **SST** field, with $\int_{\Omega} \nabla^2 T \, dx = 0$.
- Free-slip and periodic B.C.s for the atmosphere.

A model of the North Atlantic basin (II)

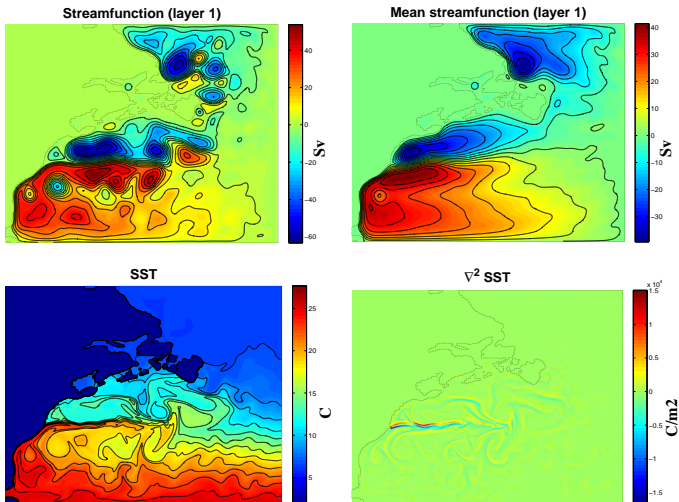
Gulf Stream (GS) separation and WBC instabilities: issues

- Correct no-slip oceanic B.C.s crucial to obtain separation at Cape Hatteras (well-known) \Rightarrow positive vorticity advected into Florida Current.
- Strong inertial flow is necessary to obtain correct GS path (see Chassignet et al., etc.); trade-off between viscosity and wind-stress intensity
 \Rightarrow **sufficiently high resolution is necessary!**
- Model is sensitive to stratification parameters: too strong baroclinic and/or bathymetric instabilities destroy GS path along Florida coast
 \Rightarrow **barotropization of the GS.**
- Occurrence of GS retroflexion: **true bimodality or model artifact?**
- **Correct stratification parameters enhance GS penetration into the ocean interior!**
- Thermal diffusivity is important to insure smoothness of the SST front w.r. to spatial resolution. It also controls the atmospheric jet strength.

**QG modeling is far more difficult than in rectangular basins
but it **works!****

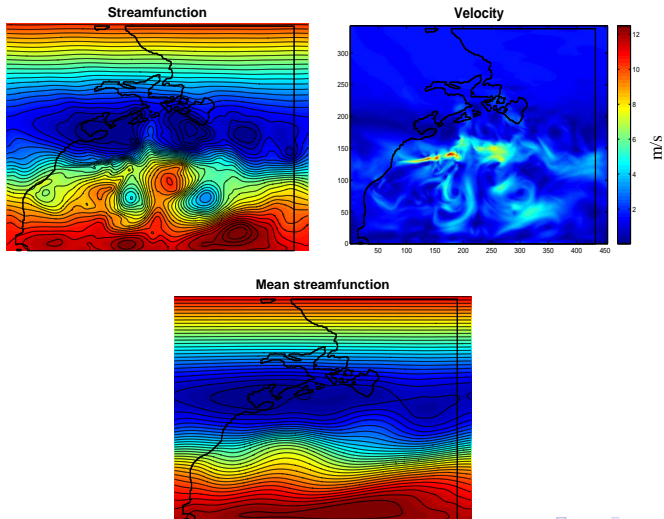
Coupled model results, at (1/9) deg resolution (I)

$$A_h|_{\text{ocean}} = 200 \text{ m}^2/\text{s}, \kappa|_{\text{SST}} = 1200 \text{ m}^2/\text{s}$$



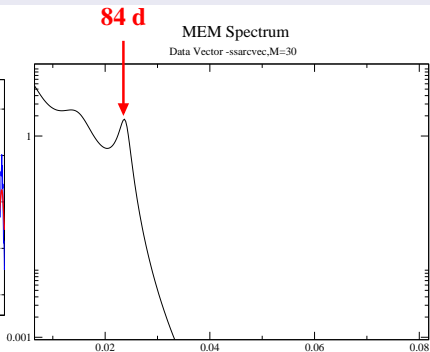
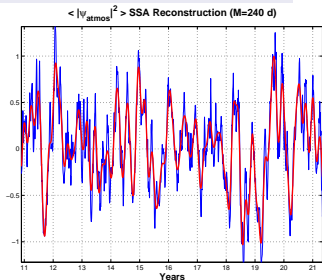
Coupled model results, at (1/9) deg resolution (II)

$$H_e = 800 \text{ m}, A_h|_{\text{atmos}} = 400 \text{ m}^2/\text{s}$$



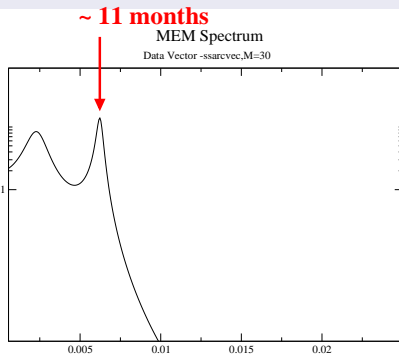
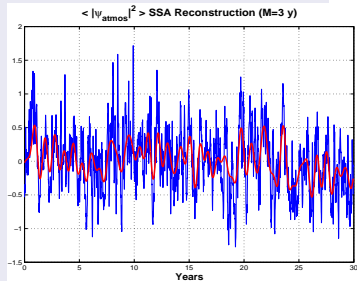
Low-frequency variability of the coupled ocean-atmosphere

Intraseasonal atmospheric variability (I)



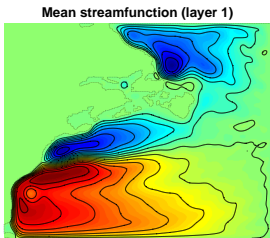
Low-frequency variability of the coupled ocean-atmosphere

Intraseasonal atmospheric variability (II)

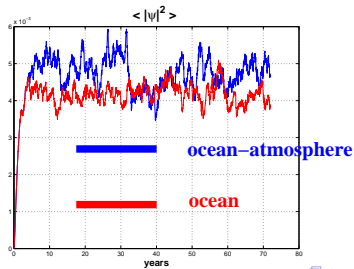
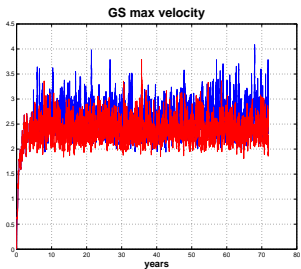
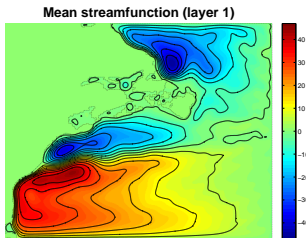


Effect of the coupling on the ocean

ocean–atmosphere

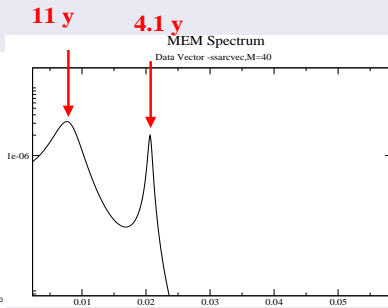
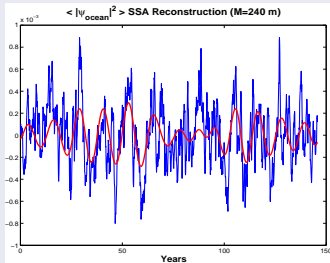


ocean



Interannual variability

Ocean alone



Coupled ocean and atmosphere

- Ongoing (80-y run)...
- Preliminary results indicate a 3–4-y peak in the ocean.
- Longer periods in the ocean (~ 10 y) and, probably, atmosphere as well.

Concluding remarks

Summary

- We have a realistic **coupled** ocean-atmosphere **QG** model of the North Atlantic basin.
- Coupling mechanism is through Ekman pumping in the **marine ABL**.
- Persistent, **eastward atmospheric jet** $\sim 10m/s$ in the troposphere.
- Atmospheric oscillations with periods of **80 days** and 11 months.
- Interannual oscillations in the ocean and atmosphere.

Ongoing work

- Robustness of intraseasonal and interannual oscillations in the model.
- Spatio-temporal structure of the 80-day intraseasonal oscillation.
- Interannual variability in the coupled ocean-atmosphere \simeq NAO?
- Bimodality of the Gulf Stream?
- Baroclinic atmosphere.
- Finer spatial resolution: effects on the Gulf Stream and troposphere.

Appendix. Model equations

Oceanic QG equations ($i = 1, 4$)

$$\partial_t \mathbf{q}_i + \mathbf{J}(\psi_i, \mathbf{q}_i) + \beta \partial_x \psi_i = \nu_i \nabla^4 \psi_i + \delta_{i1} (\sigma \gamma \psi_a + \nabla \times \mathcal{H}(x, y)),$$

$$\mathbf{q}_i = \nabla^2 \psi_i - \mathbf{S}_{ii+1}(\psi_i - \psi_{i+1}) - \mathbf{S}_{ii-1}(\psi_i - \psi_{i-1}) + \delta_{i4} \mathbf{c}_b \mathcal{B}(x, y)$$

SST equation

$$\partial_t T + \mathbf{J}(\psi_1, T) = \kappa \nabla^2 T + \chi(\bar{T} - T)$$

Atmospheric QG equation

$$\partial_t \mathbf{q}_a + \mathbf{J}(\psi_a, \mathbf{q}_a) + \beta \partial_x \psi_a = \nu_a \nabla^4 \psi_a - \gamma \nabla^2 \psi_a + \alpha \nabla^2 T.$$