Gulf Stream effects on the NAO:
Theory, modeling and observations

M. Ghil [1,2], E. Simonnet [3], Y. Feliks [1,4]

[1]Dept. of Atmospheric and Oceanic Sciences and IGPP, UCLA, USA.
[2]Geosciences Dept. and LMD (CNRS and IPSL), ENS, Paris.
[3]Institut Non-linéaire de Nice, CNRS, France.
[4]Mathematics Department, IIBR, Nes-Ziona, Israel.

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Introduction and motivation (I)

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; Ghil et al., Physica D, 2002; Simonnet & Dijkstra, JPO, 2002; Simonnet et al., JPO, 2003a,b; Dijkstra & Ghil, Rev. Geophys., 2005; 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 vigourous 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):

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

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

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

Ocean-atmosphere coupling mechanism (II)

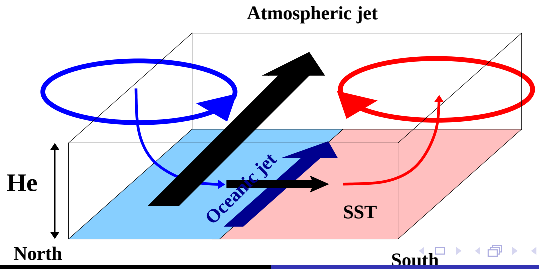
Vertical velocity at the top of the marine ABL

- 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 ($\sim$ 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.

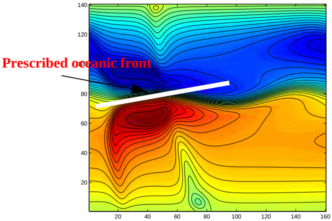


Results in idealized atmospheric models

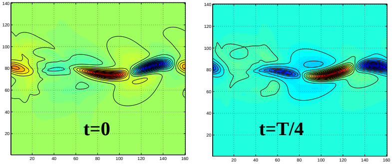
Intraseasonal variability (FGS'04, '07)

- 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 bifucations.
- 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., JPO, 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 (JPO, 1996); free-slip B.C.s elsewhere.
- Neuman B.C.s for SST field, thus ensuring that $\int_\Omega \nabla^2 T \, dx = 0$.
- 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 Hateras (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

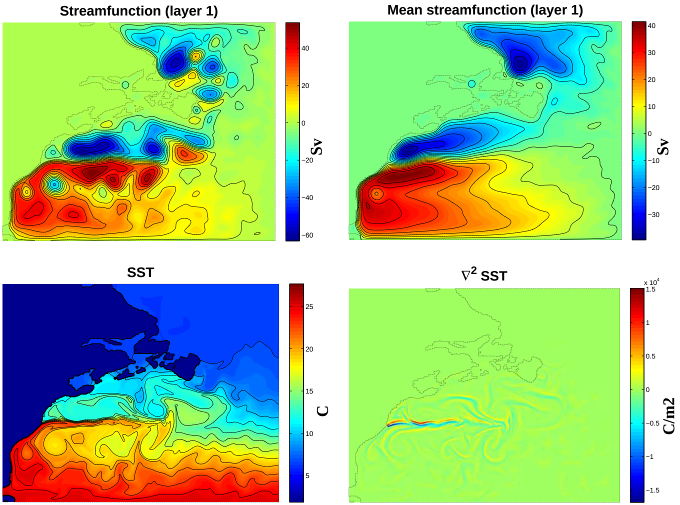
  $\Rightarrow$ barotropization of the GS.
- Occurrence of GS retroflection: true bimodality or model artifact?
- **Correct stratification parameters enhance GS penetration into the ocean interior!**
- Thermal diffusivity is important to insure smoothness of the SST front w.r. to spatial resolution. It 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)

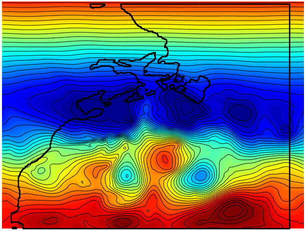
$A_h|_{\text{ocean}} = 200\ \text{m}^2/\text{s},\ \kappa|_{\text{SST}} = 1200\ \text{m}^2/\text{s}$



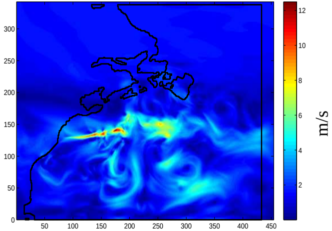
Coupled model results, at (1/9) deg resolution (II)

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

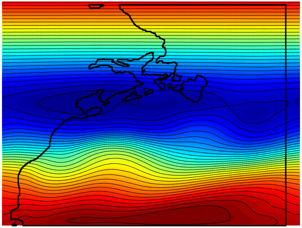
Streamfunction



Velocity

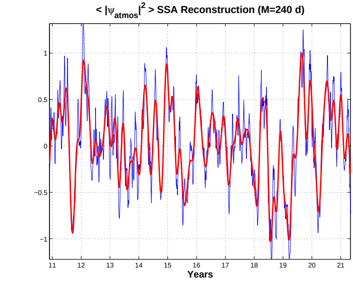


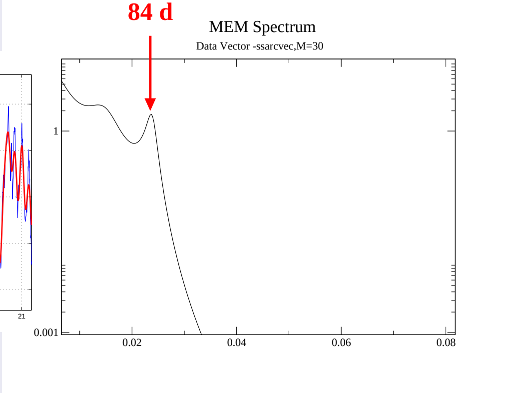
Mean streamfunction



Low-frequency variability of the coupled ocean-atmosphere

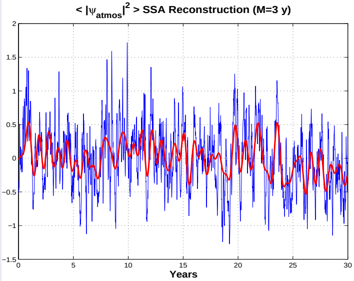
Intraseasonal atmospheric variability (I)

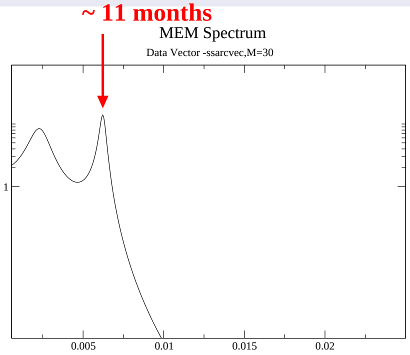




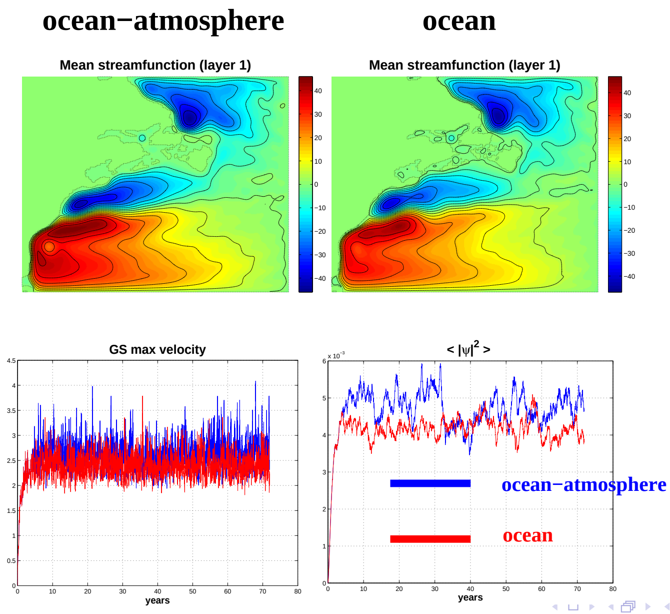
Low-frequency variability of the coupled ocean-atmosphere

Intraseasonal atmospheric variability (II)



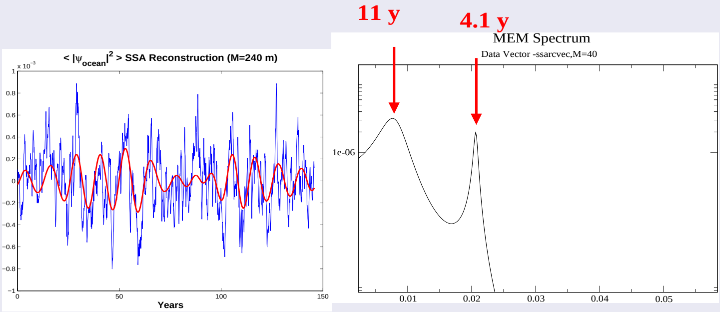


Effect of the coupling on the ocean



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 ($\sim$ 10 y) and, probably, atmosphere as well.

Concluding remarks

Summary

- We have a realistic coupled ocean-atmosphere QG model of the North Atlantic basin; 700 000 grid-point variables (ocean + SST + atmos.).
- 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 ($i = 1, 4$)

$$\partial_t q_i + J(\psi_i, q_i) + \beta \partial_x \psi_i = \nu_i \nabla^4 \psi_i + \delta_{i1} \left(\sigma \gamma \nabla^2 \psi_a + \nabla \times \mathcal{H}(x, y) \right),$$

$$q_i = \nabla^2 \psi_i - S_{ii+1}(\psi_i - \psi_{i+1}) - S_{ii-1}(\psi_i - \psi_{i-1}) + \delta_{i4} c_b \mathcal{B}(x, y)$$

SST equation

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

Atmospheric QG equation

$$\partial_t q_a + J(\psi_a, q_a) + \beta \partial_x \psi_a = \nu_a \nabla^4 \psi_a - \gamma \nabla^2 \psi_a + \alpha \nabla^2 T.$$