Models and observations of North Atlantic atmospheric circulation and oscillatory climate modes induced by the Gulf Stream front

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Outline

• spectral analyses of the SODA reanalysis SST field in two regions along the Gulf Stream front, 1958-2007
  ‣ prominent and statistically significant interannual oscillations

• mechanistic model of atmospheric response to SST fronts
  ‣ marine ABL + QG free atmosphere

• atmospheric model response to SODA monthly history
  ‣ two extreme states of the atmospheric simulations
    • eastward extension of the westerly jet associated with the front
    • quiescent state of very weak flow
  ‣ similar interannual periodicities to those found in SST
The North Atlantic Oscillation and our weather ...

... and hopes for “near-term” decadal climate prediction?
Simple models of the ocean gyres and eddies

Ghil, Checkroun, Simonnet (2008)
Jiang, Jin and Ghil (1995)

Simonnet, Ghil, Dijkstra (2005)

... could the ocean be driving the NAO through oscillations in the Gulf Stream SST front?
spectral analyses of the SODA

- SST (−5m), 1958-2007, monthly, 0.5° (SODA v2.0.2-4), Cape Hatteras and Great Banks regions analyzed separately

- annual cycle removed using 12-month running average

- multi-channel singular spectrum analysis (MSSA) of gridded SST

- statistical significance assessed against red noise null-hypothesis

Fig. 1: Mean SST in the North Atlantic between 15N-65N and 85W-0W. The heavy lines are the land boundaries.

Fig. 2: Mean SSH in the North Atlantic between 15N-65N and 85W-0W. CHR: 34N-43.50N, 75W-60W GBR: 42N-50N, 55W-35W
Cape Hatteras SST Spectrum

Fig. 1: Mean SST in the North Atlantic between 15°N - 65°N and 85°W - 0°W. The heavy lines are the land boundaries.

Fig. 2: Mean SSH in the North Atlantic between 15°N - 65°N and 85°W - 0°W.

Fig. 5: Spectral analysis of the SST time series, in CHR, of Monte Carlo MSSA (MC-MSSA) spectrum computed with a window width of M = 150 months; the variance of each mode in the data is in black square, while lower and upper ticks on the error bars indicate the 5th and 95th percentiles of a red noise process constructed from a surrogate data ensemble of 100 series, each with the same variance and lag-one autocorrelation as the original record. The surrogate time series (Allen and Smith, 1996) were produced by projecting the first 10 principal components of the MSSA analysis onto the basis vectors of a red noise process, with M = 150 years.

Fig. 6: The reconstructed 8.5-year oscillatory mode as a function of time, at the point (74°W, 37°N) where its amplitude in CHR is maximal; raw data shown as the solid line, and RC(3,4), which captures the oscillation, as the dashed line.

MSSA Power spectrum

8.5-yr compt at (74W, 37N)

(M = 150 months)
Phase composites of 8.5-yr mode Cape Hatteras SST

![Composite images showing the 8.5-year mode of SST in CHR.](image)

- Large scale meander of front
- 5.2 and 3.8-yr modes exhibit similar structure
Grand Banks Region SST spectrum

Fig. 9: Spectral analysis of the SST time series, in GBR, of Monte Carlo MSSA (MC-MSSA) spectrum computed with a window width of $M = 150$ months; the variance of each mode in the data is in black square, while lower and upper ticks on the error bars indicate the 5th and 95th percentiles of a red noise process constructed from a surrogate data ensemble of 100 series, each with the same variance and lag-one autocorrelation as the original record. The surrogate time series (Allen and Smith, 1996) were produced by projecting the first 10 principal components of the MSSA analysis onto the basis vectors of a red noise process, with $M = 150$ years.

Fig. 1: Mean SST in the North Atlantic between $15\text{N}$-$65\text{N}$ and $85\text{W}$-$0\text{W}$. The heavily lines are the land boundaries.

Fig. 2: Mean SSH in the North Atlantic between $15\text{N}$-$65\text{N}$ and $85\text{W}$-$0\text{W}$.

MSSA Power spectrum

10.5-yr compt at (47W, 44N)

- extension/contraction of the current
- 5.7 and 3.2-yr modes exhibit similar structure

(M = 150 months, detrended)
Atmospheric model

A quasi-geostrophic (QG) atmospheric model in a periodic β-channel, first barotropic (Fekik et al., 2004; FGS’04), then baroclinic (FGS’07). Marine atmospheric boundary layer (ABL), analytical solution. \( \Delta x = \Delta y = 50 \text{km} \)

**QG Potential Vorticity eqn:**

\[
\frac{\partial q}{\partial t} + \beta \frac{\partial \psi}{\partial x} + J(\psi, q) = r_H \nabla^4 \psi,
\]

\[
q \equiv \nabla^2 \psi + \frac{\partial}{\partial z} \left( \frac{1}{S} \frac{\partial \psi}{\partial z} \right)
\]

**Lower boundary condition:**

\[
\frac{H}{H_a} \frac{d}{dt} \left[ \frac{\partial}{\partial z} \left( \frac{1}{S} \frac{\partial \psi}{\partial z} \right) \right] = \frac{H}{H_a} w_a(x, y, z = 0, t) = \gamma \nabla^2 \psi - \alpha \nabla^2 T,
\]

**Atmospheric boundary layer model:**

constant-depth, well-mixed moist boundary layer in equilibrium with the underlying SST field

\[
\frac{1}{\rho_0} \frac{\partial p}{\partial y} = \frac{1}{\rho_0} \frac{\partial}{\partial y} p(H_E) - \frac{g}{\theta_0} (H_E - z) \frac{\partial \theta}{\partial y}.
\]

\[
k_0 \frac{\partial^2 u}{\partial z^2} - f u - \frac{1}{\rho_0} \frac{\partial p}{\partial y} = 0.
\]
Response to an idealized SST front

Fig. 1. Prescribed SST pattern for an oceanic front of length 600 km with strength $T^* = 6.1^\circ C$ and frontal-width parameter $d = 50$ km; see Eq. (15). Contour interval (CI) is 2°C, starting at $\pm 6^\circ C$; positive contours are solid; negative and zero contours dashed. Axes in nondimensional units of $\Delta x$ counts, where $\Delta x = \Delta y = 50$ km/L, $L$ being the length scale; see Eq. (1).

Fig. 3. Mean streamfunction field for $T^* = 6.1^\circ C$ (CI = 2): (a) barotropic and (b) baroclinic.

Total circulation: stronger and longer jet in the upper layer than in the lower
Interpretation of atmospheric response

\[ \frac{H}{H_a} \frac{d}{dt} \left[ \frac{\partial}{\partial z} \left( \frac{1}{S} \frac{\partial \psi}{\partial z} \right) \right] = \frac{H}{H_a} w_a(x, y, z = 0, t) \]

\[ = \gamma \nabla^2 \psi - \alpha \nabla^2 T, \]

SST-front driven pumping drives thermally direct circulation
“PV injection”
Response to SODA: Streamfunction snapshots

**Barotropic**

![Fig. 12: Evolution of the atmospheric barotropic component induced by SODA SST. Snapshots shown at unequally spaced time; each plot ci=8, the max and min values are given in the legend of each plot.](image)

**Baroclinic**

![Fig. 13: Evolution of the atmospheric baroclinic component induced by SODA SST. Snapshots shown at unequally spaced time; each plot ci=6, the max and min values are given in the legend of each plot.](image)

**Surface**

(BT-2*BC)
SST front and \( w(H_E) \)

- **Time = 1980.8**
  - Thermal: \( \min = -4.0 \), \( \max = 2.75 \)
  - Mechan.: \( \min = -0.6 \), \( \max = 0.47 \)

- **Time = 1992.3**
  - Thermal: \( \min = -3.7 \), \( \max = 4.35 \)
  - Mechan.: \( \min = -0.8 \), \( \max = 0.67 \)
Spectrum of atmospheric response

Fig. 1: Spectral analysis of the atmospheric barotropic-baroclinic modes time series of MC-MSSA spectrum computed with a window width of $M = 150$ months, the other details are as in Fig. 9.

$95\%$ conf interval

barotropic and baroclinic streamfunctions stacked together

$(M = 150\ mon)$
Structure of 8.2-yr mode at the surface
Bi-spectra of observed and simulated NAO index

MSSA Power spectrum

Reconstructed components

--- simulated index
-- obs NAO

Fig. 2: Spectral analysis of the NAO index and SI of MC-MSSA spectrum computed with a window width of $M = 200$ months, the other details are as in Fig. 9.

Fig. 20: The RC of the significant oscillatory modes of the NAO index (dashed line) and SI (solid line), ordered by decreasing variance, along with the associated periods and variances. The dotted line in (a) is the SST (divided by 45.6) reconstructed 8.5-year oscillatory mode at the point (74W, 37N) also shown in Fig. 6.
Atmospheric response when driven by spatially-smoothed SODA SST

**Surface streamfunction snapshots**

- **time=1980.8**
  - Min: -1.6, Max: 73.45
  - [Graph Image]

- **time=1992.3**
  - Min: -11.3, Max: 57.46
  - [Graph Image]

**MSSA Spectra**

- Overall energy is much weaker
Postscript: spectrum of Nile River flow

Feliks et al. (2010, sub judice)
Summary

• spectral analyses of the SODA reanalysis SST field in two regions along the Gulf Stream front, 1958-2007
  ‣ prominent and statistically significant interannual oscillations

• mechanistic model of atmospheric response to SST fronts
  ‣ marine ABL + QG free atmosphere
  ‣ transverse thermally direct circulation spins up QG jet over front
  ‣ anticyclonic vorticity to the south and cyclonic to the north of the jet axis gives rise to Ekman damping and spin down

• atmospheric model response to SODA monthly history
  ‣ two extreme states of the atmospheric simulations
    • eastward extension of the westerly jet associated with the front
    • quiescent state of very weak flow
  ‣ similar interannual periodicities to those found in SST
additional slides
Phase composites of Grand Banks SST: 10.5-yr mode

- extension/contraction of the current
- 5.7 and 3.2-yr modes exhibit similar structure
The JJG model’s equilibria

Nonlinear (advection) effects break the (near) symmetry: (perturbed) pitchfork bifurcation?

Subpolar gyre dominates

Subtropical gyre dominates

Jiang, Jin and Ghil, JPO, 1995
Observed and simulated NAO indices

Fig. 1: (a) NAO index (dashed line), SI (solid line), (b) trend and (c) dtrend.

- Simulated index
- Obs NAO