Predominant *nonlinear* atmospheric response to meridional shift of the Gulf Stream path
GSI and the associated SSTA

**JFM Gulf Stream position**
(15°C at 200m, 55-75°W)

*Joyce et al. 2000*

*Linearly regressed SSTA* ~0.3°C

~+0.3°C

*Kwon and Joyce 2013*
Identifying atmospheric response to GS-induced SSTA: Hemispheric WRF

40-km, 6-month (NDJFMA)

Lateral boundary @ ~20N: NCEP climatology

NOAA-OI SST daily climatology

Exps | SST | N
--- | --- | ---
CTL | daily climatology | 40

Processes not present:
- Tropical influence
- Interannual SST variability
- Thermodynamic O-A coupling

NDJFMA $Z_{250}$/SLP EOF1

NCEP 40-yrs (1971-2010) Var=32%

Realistic level of internal variability in the model

CTL 40-ensemble members Var=31%
SST perturbation experiments

cf: GS smoothing for presence/absence (e.g., O'Reilly et al. 2015)

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<th>Exps</th>
<th>SST</th>
<th>N</th>
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<tr>
<td>CTL</td>
<td>daily climatology</td>
<td>40</td>
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<tr>
<td>d1σ+</td>
<td>1σ</td>
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<td>d1σ-</td>
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<td>d3σ-</td>
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<td>d1/3σ+</td>
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<tr>
<td>d1/3σ-</td>
<td>1/3σ</td>
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</tbody>
</table>

total response = d1σ+ - CTL - d1σ- - CTL

symmetric (linear) = \( \frac{1}{2} \times (d1σ+ - d1σ-) \)

asymmetric (nonlinear) = \( \frac{1}{2} \times [(d1σ+ - CTL) + (d1σ- - CTL)] \)
Strongly nonlinear equilibrium response independent of GS-SSTA

- Barotropic ridge over the Greenland and the subpolar NA
- Barotropic troughs in the subtropics and the Europe
- Overall, the response is projected on to the -ve NAO pattern, the leading mode of internal variability

\[ d_1 \sigma^+ - CTL \]
\[ d_1 \sigma^- - CTL \]
\[ d_3 \sigma^+ - CTL \]
\[ d_3 \sigma^- - CTL \]

\[ Z_{250}/SLP \]

NDJFMA

\[ \text{Linear} \]

\[ d_1 \sigma^+ \]

\[ d_1 \sigma^- \]

\[ \text{Predominant asymmetric (nonlinear) response independent of the amplitude and sign of SSTA} \]

\[ \text{Linearly regressed poleward eddy heat flux (MERRA)} \]

Kwon and Joyce 2013
Some nonlinearity in circulation anomalies in NCEP
— Composite NCEP (1971-2010) JFM $Z_{250}/SLP$ when JFM GSI leads by 1-yr

GSI$>+0.25\sigma$ N=16
GSI$>+0.50\sigma$ N=15
GSI$>+1.0\sigma$ N=9
GSI$>+1.25\sigma$ N=4

Distinctive asymmetric circulation anomalies when composited with higher GSI amplitude
Differences between the composite averages hint the ridge/trough anomalies

GSI$<-0.25\sigma$ N=20
GSI$<-1.0\sigma$ N=8
GSI$<-1.25\sigma$ N=5
GSI$<-0.50\sigma$ N=19

ENSO influence is removed, but a very similar result is found if using the full fields, suggesting that adding tropical influence does not change the nonlinearity pattern

$10\%$ level
Two main questions:

#1. Why +ve blocking ridge?
Barotropic feedback by transient eddies (HF) +
Wave activity flux due to a stationary Rossby wave train (LF)
(e.g., Nakamura et al. 1997)

#2. Why is the response nonlinear?
The blocking ridge maintained in part by anomalous vorticity flux convergence by transient eddies

\[ \left( \frac{\partial Z_{250}}{\partial t} \right)_{HFT} = \frac{f_0}{g} \nabla^{-2} \left[ -\nabla \cdot (\mathbf{v}' \zeta' + \bar{v} \bar{\zeta}' + \mathbf{v}' \bar{\zeta}) \right] \]

Nakamura et al. 1997

primes: 8 day high-passed (HF); over-bars: 8-day low-passed (LF)

NDJFMA  
\[ \text{d1σ+ - CTL} \]  
\[ (\partial Z_{250}/\partial t)_{HF} \text{ response} \]  
\[ Z_{250} \text{ response} \]  
\[ \text{d1σ- - CTL} \]
Contribution by the transient eddy feedback to $Z_{250}$ high:
Lead/lag composites about the onset of a block

Blocking index at 40°W, 60°N
(Low-passed $Z_{250}$ time-series)

(\frac{\partial Z_{250}}{\partial t})_{HF\Delta t}: shading
Low-passed $Z_{250}$: contours

Nakamura and Wallace 1990

Day-5 (Initial) $\rightarrow$ Onset $\rightarrow$ Day+5

Transient eddy feedback contributes to the total height response by $\sim$50%
The blocking ridge formation due to low-frequency dynamics

\[ \text{d1} \sigma+ - \text{CTL} \]
\[ \text{TOTAL} - \text{HF} \approx (\frac{\partial Z_{250}}{\partial t})_{\text{LF}} \Delta t \]

Apparent quasi-stationary wave signatures

Wave activity density flux convergence within the amplifying blocking ridge (Nakamura et al. 1997)

Wave activity flux calculation from http://www.atmos.rcast.u-tokyo.ac.jp/nishii/programs/index.html
Summary and Discussion

Predominant nonlinear response to various GS shift scenarios
— resembles the -ve NAO pattern, the leading mode of internal variability

- The blocking response is formed and maintained both by
  - HF: barotropic feedback by transient eddies (forced response)
  - LF: wave activity density flux associated with an incoming Rossby wave train (internal dynamics)

- Both HF and LF feedback processes are nonlinear.
  - The cause of the nonlinearity is under investigation.

- Observational analysis also suggests some asymmetry in the NA circulation

Thanks!

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