Using Adjoint Models to Understand the Response of the Ocean Circulation to the North Atlantic Oscillation

Kettyah Chhak, Georgia School Board

Andy Moore, UC Santa Cruz

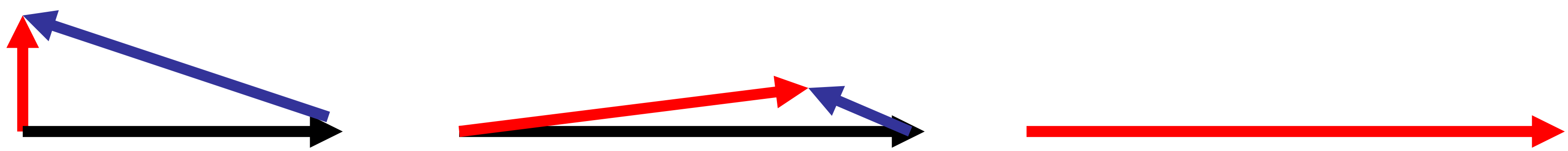
Ralph Milliff, Colorado Research Associates

Timescales

- Rapid fluctuations in ocean surface forcing are:
  - considerable in amplitude
  - “fast” compared to ocean circulation
  - can be considered as stochastic in time
  - spatially coherent (storm tracks, standing waves)
- Ocean response – perturbation development:
  - linear nonmodal
  - linear modal
  - nonlinear

Perturbation Development

Nonnormal circulation



Linear nonmodal | Linear modal | Nonlinear

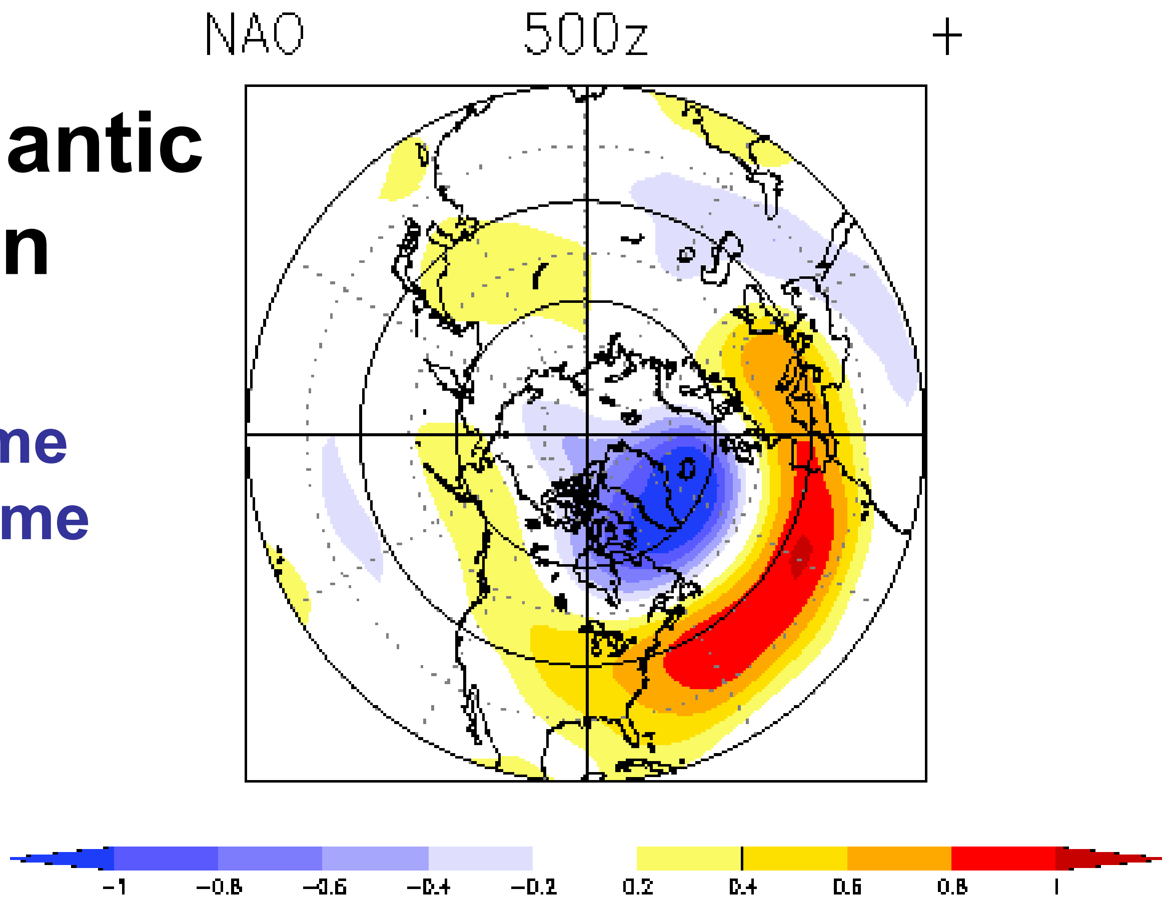
"Nonnormality enhances variance", Ioannou (JAS, 1995)
(BL, met, climate, ocean)

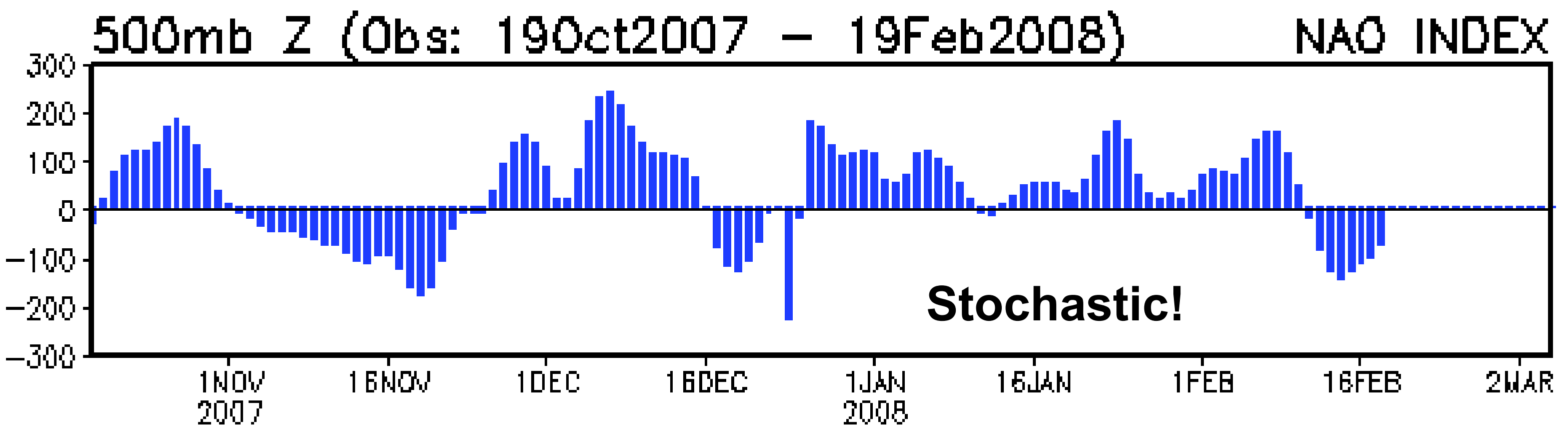
Normal circulation

Linear | Linear | Nonlinear

The North Atlantic Oscillation

-"climate" regime
-"weather" regime





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Considerable Interest!

Veronis and Stommel (1956), Phillips (1966), Veronis (1970), Rhines (1975), Magaard (1977), Willebrand (1978), Philander (1978), Leetmaa (1978), Frankignoul and Muller (1979), Willebrand et al (1980), Wearn and Baker (1980), Muller and Frankignoul (1981), Haidvogel and Rhines (1983), Lippert and Kase (1985), Treguier and Hua (1987), Alvarez et al (1987), Niiler and Koblinsky (1989), Brink (1989), Luther et al (1990), Samelson (1990), Garzoli and Dimionato (1990), Large et al (1991), Samelson and Shrayer (1991), Chave et al (1991, 1992), Lippert and Muller (1995), Fu and Smith (1996), Muller (1997), Frankignoul et al (1997), Moore (1999), Stammer and Wunsch (1999), Hazeleger and Drijfhout (1999), Cessi and Louazel (2001), Sura and Penland (2002), Moore et al (2002), Aiken et al (2002, 2003), Sirven (2005), Berloff (2005), Weijer (2005), Weijer and Gille (2005), Sirven et al (2007), Chhak et al (2006, 2007, 2008).

What did we observe and how predictable is it?

Questions

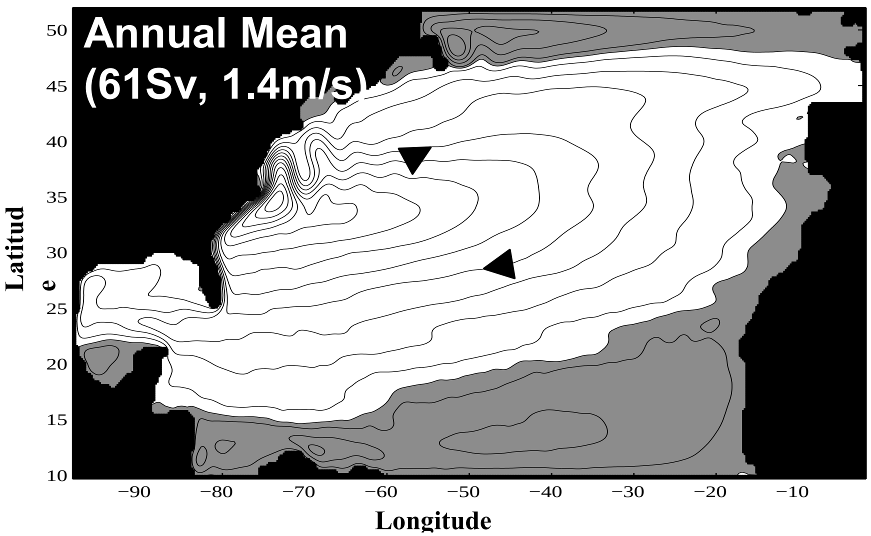
- What does the stochastically-forced ocean variability look like?
- How do the stochastically-excited perturbations evolve?
- What is the net influence of the stochastically-forced variability on the ocean circulation?
- How effective is the NAO at exciting ocean variability?

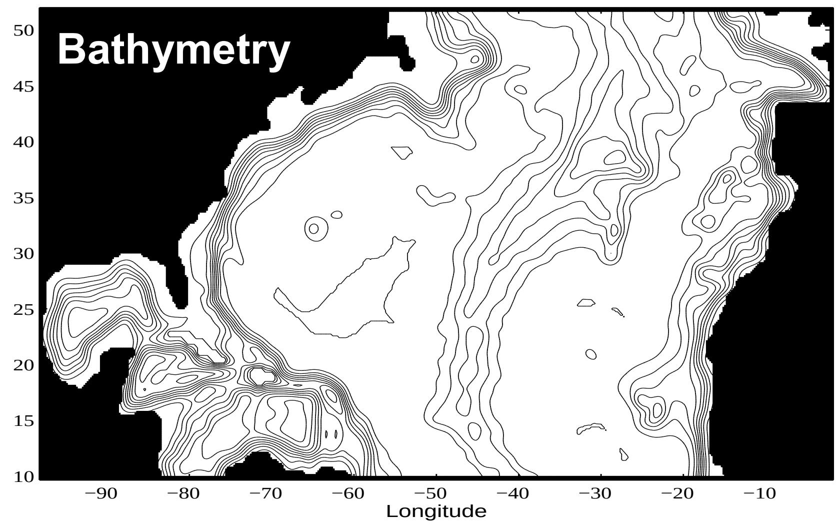
Conclusions

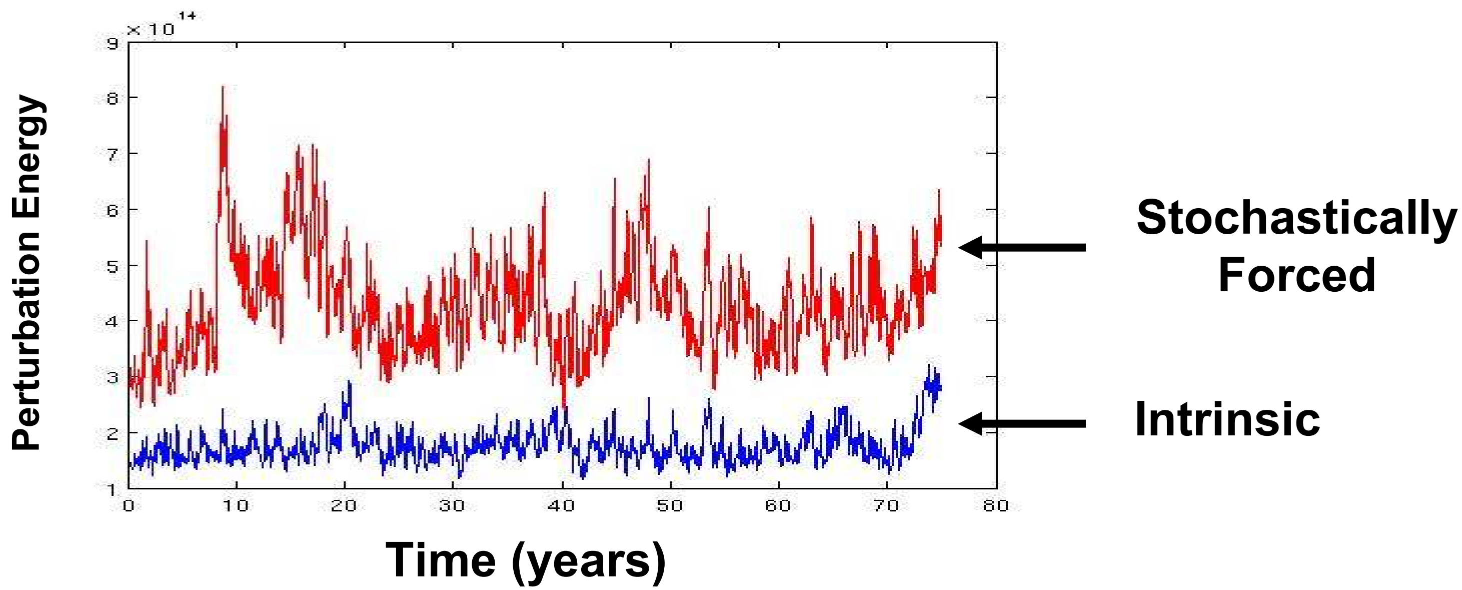
- Stochastically forced variability can be as large as intrinsic variability.
- Nonmodal interference dominates perturbation growth during first 10-14 days.
- Significant deep circulations due to rectified topographic Rossby waves.
- NAO is optimal for inducing variance on subseasonal timescales.
- Chhak et al (2009, JPO, 39, 162-184.)

QG model (Milliff et al, 1996):

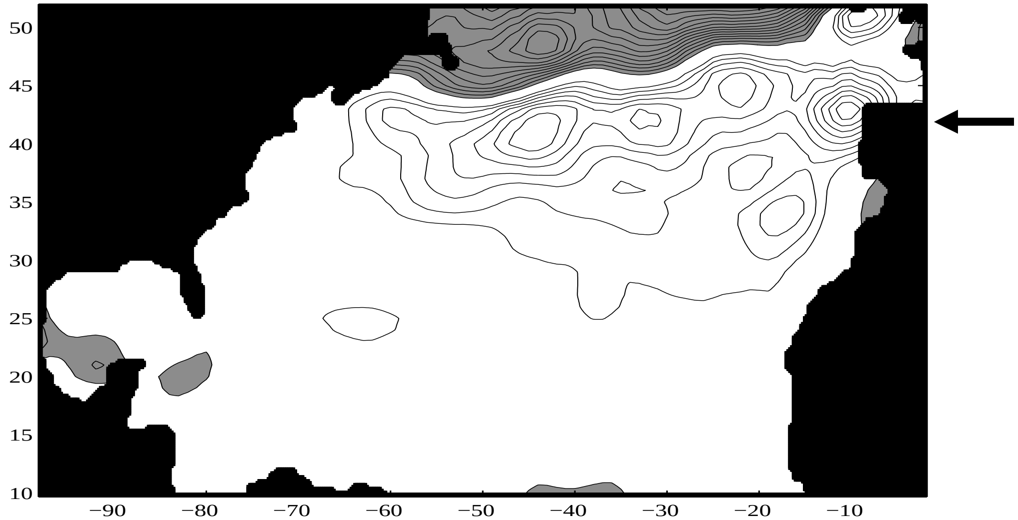
- 1/5 (zonal) X 1/6 (merid) degree resolution, 5 levels
- Wind stress derived from CCM3







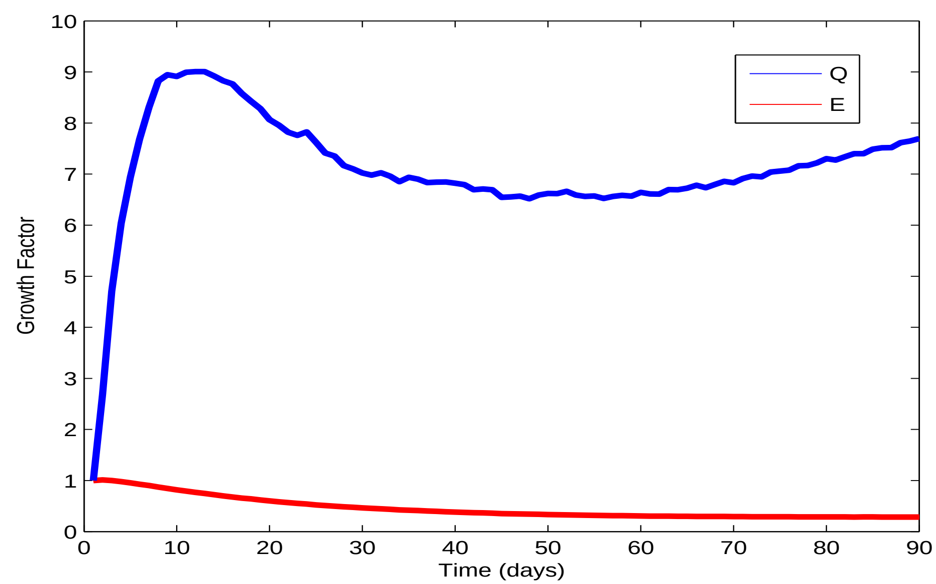
Nonmodal Linear Behaviour



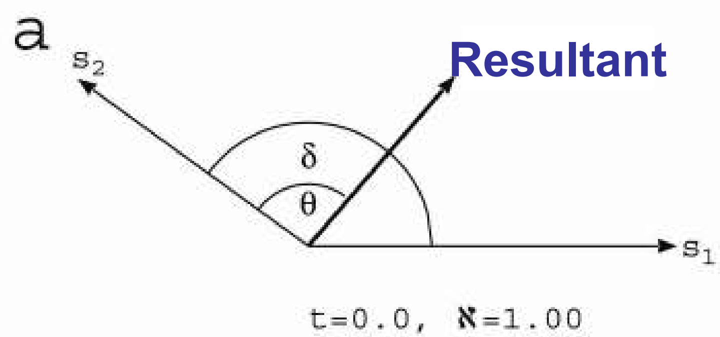
Initial structure of surface perturbation

Perturbation enstrophy undergoes nonmodal growth

Perturbation energy does not!



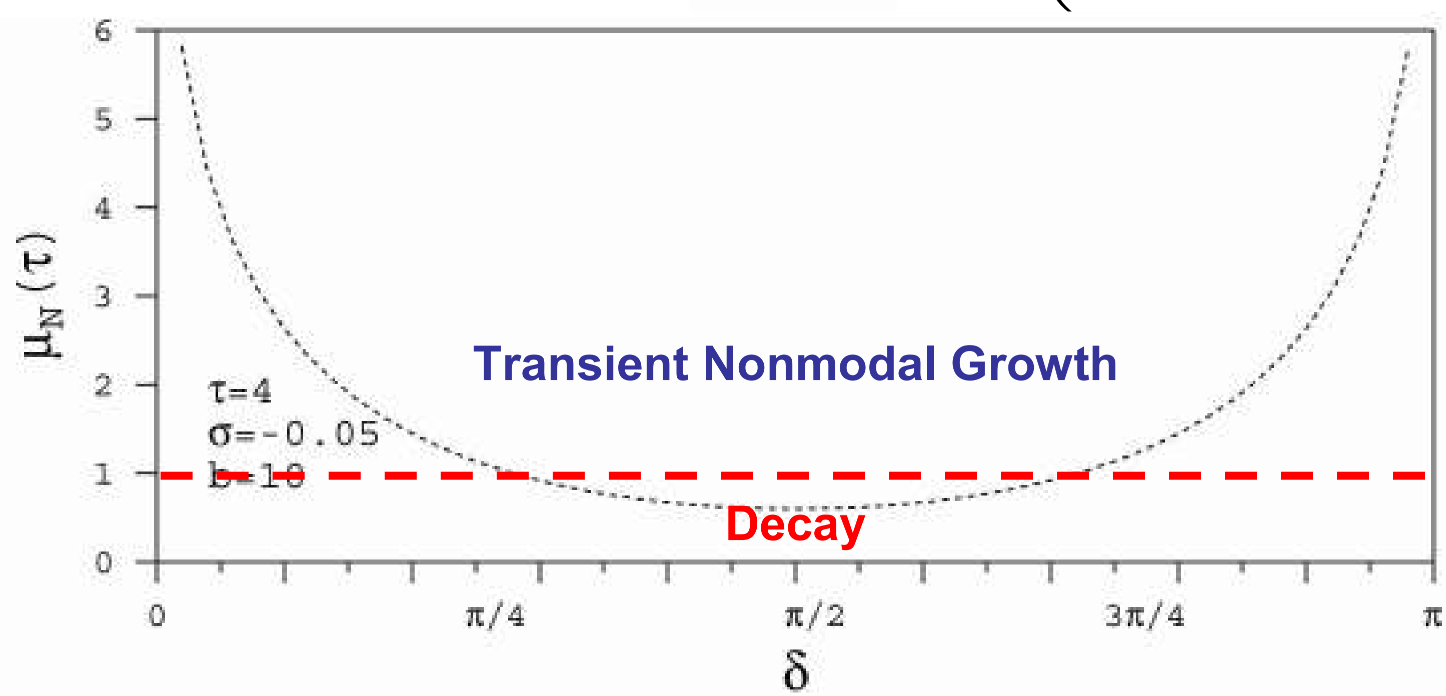
$$\delta = 4\pi/5 \quad \sigma_1 = -0.05 \quad \sigma_2 = 10\sigma_1$$



E=1

$$\mathrm{d}\mathbf{s}/\mathrm{dt} = \mathbf{A}\mathbf{s}$$

$$\mathbf{A} = \begin{pmatrix} \sigma_1 & (\sigma_2 - \sigma_1)\cot\delta \\ 0 & \sigma_2 \end{pmatrix}$$



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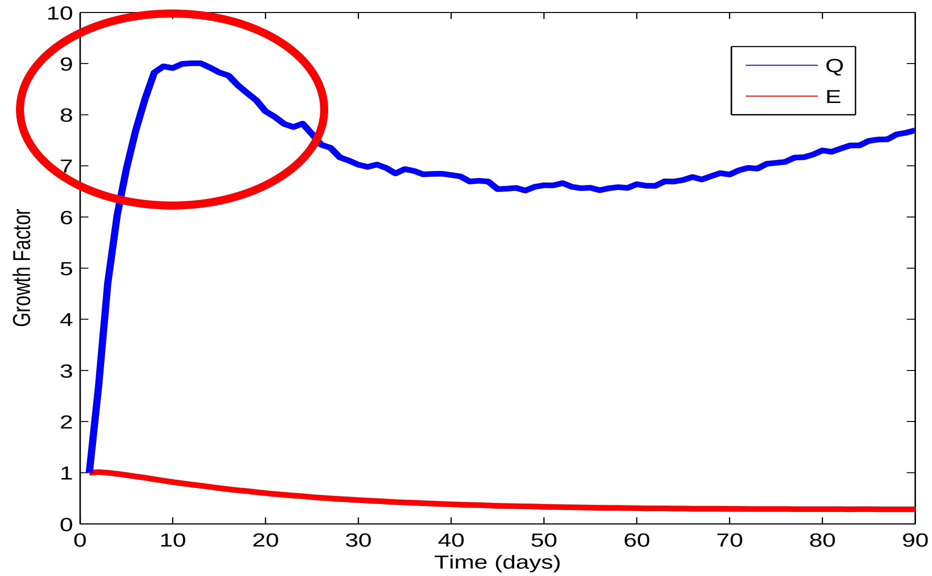
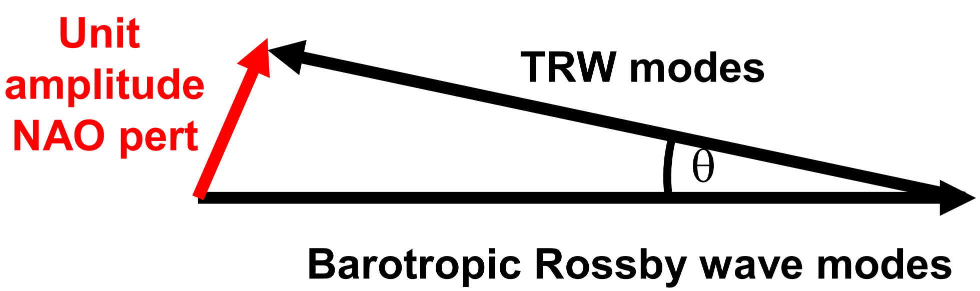
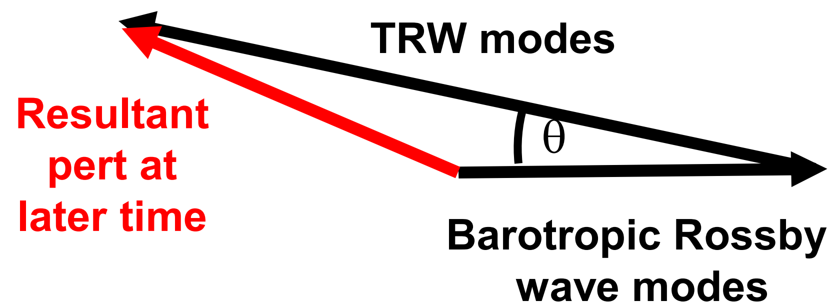


Transient growth of enstrophy
(evidence for modal interference)

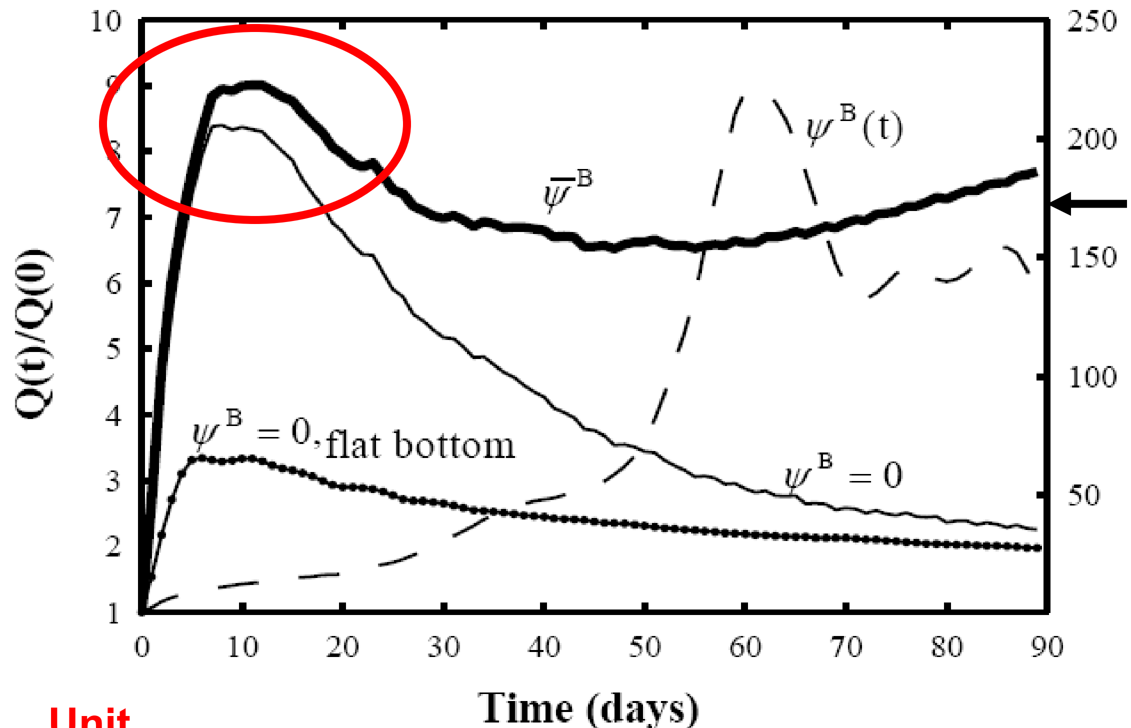


t=0



t=10

Nonmodal Linear Behaviour



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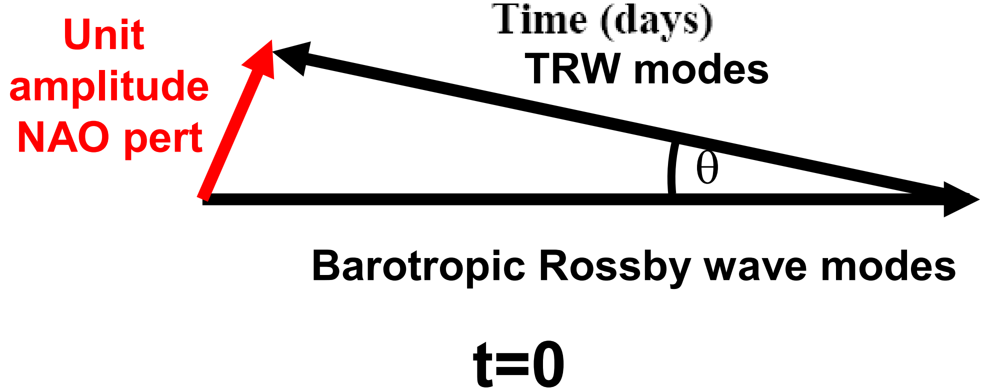
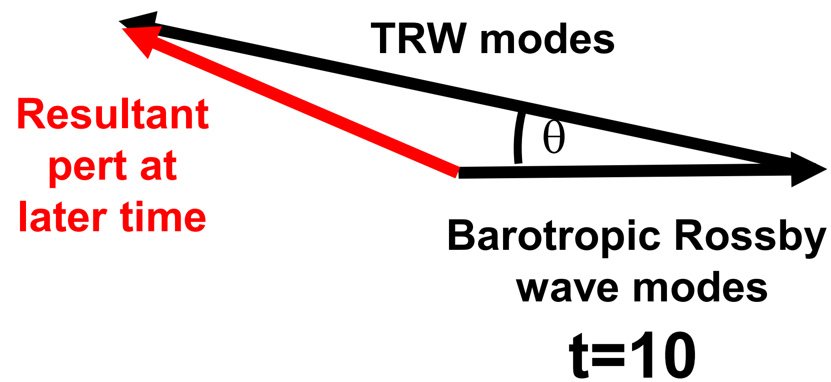
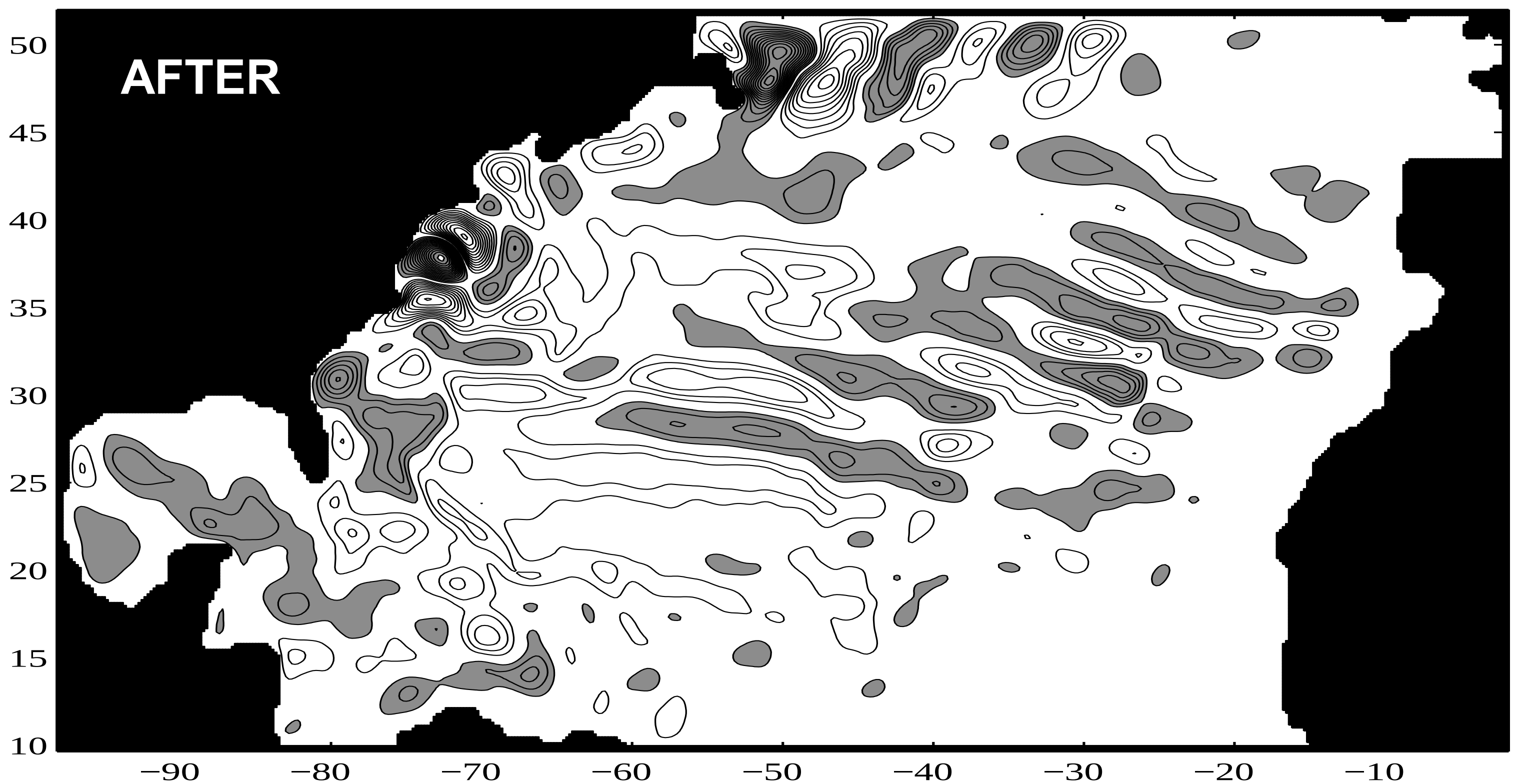


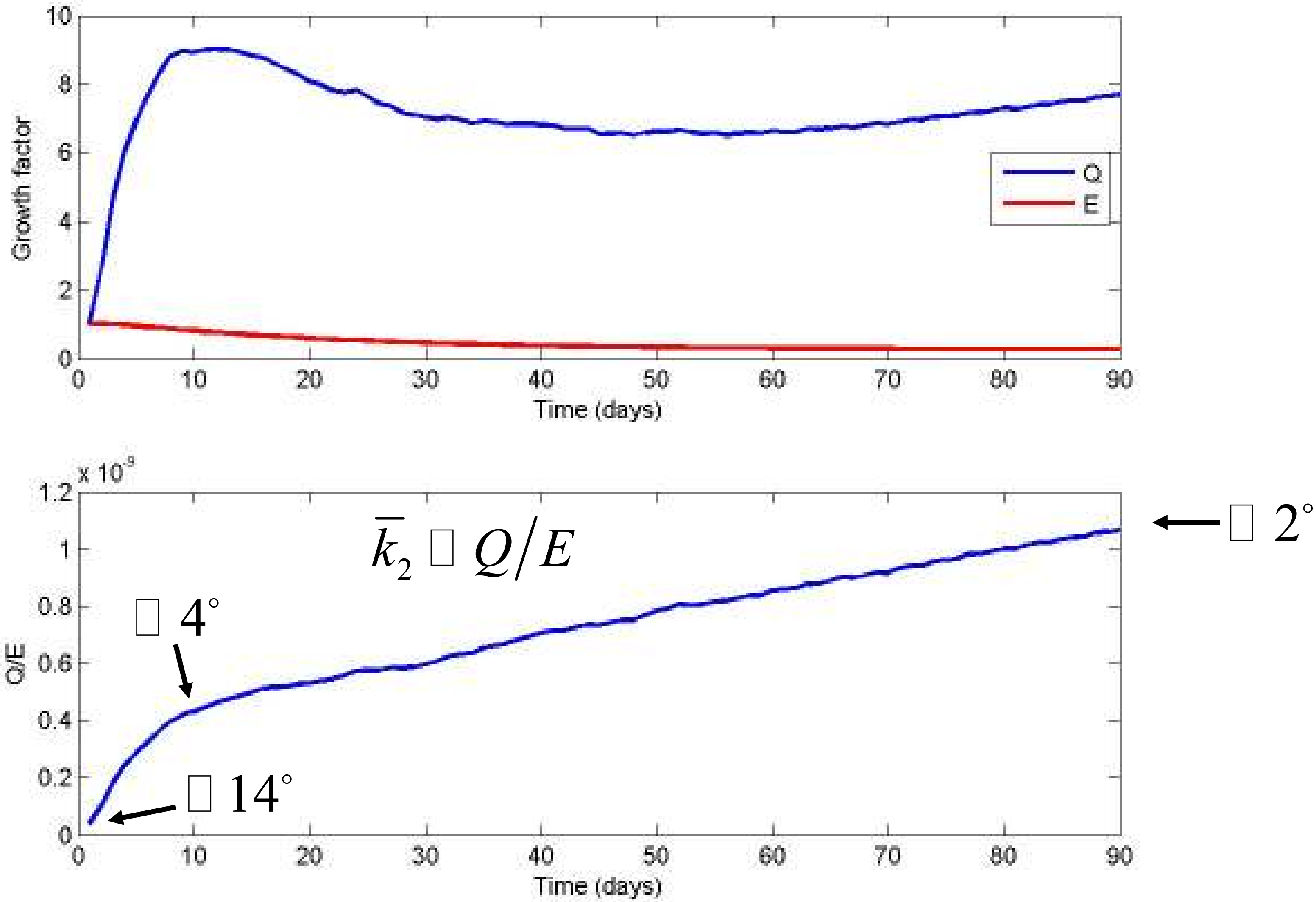



AFTER
50
45
40
35
30
25
20
15
10
−90
−80
−70
−60
−50
−40
−30
−20
−10

$$\overline{k}_2 \; \square \; \frac{\text{Pert. Enstrophy}}{\text{Pert. Energy}}$$

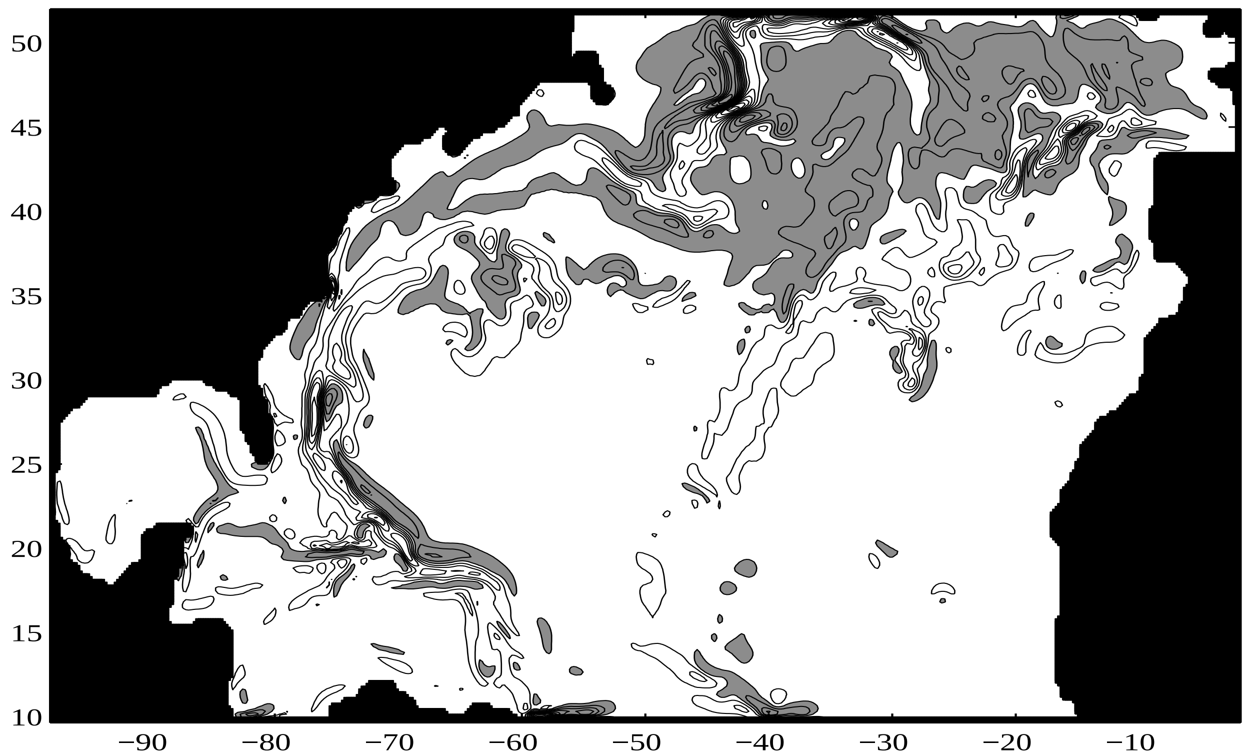
(Mean squared wavenumber or radius of gyration)

Time Evolution of δE, δQ, and $\bar{k}_2$



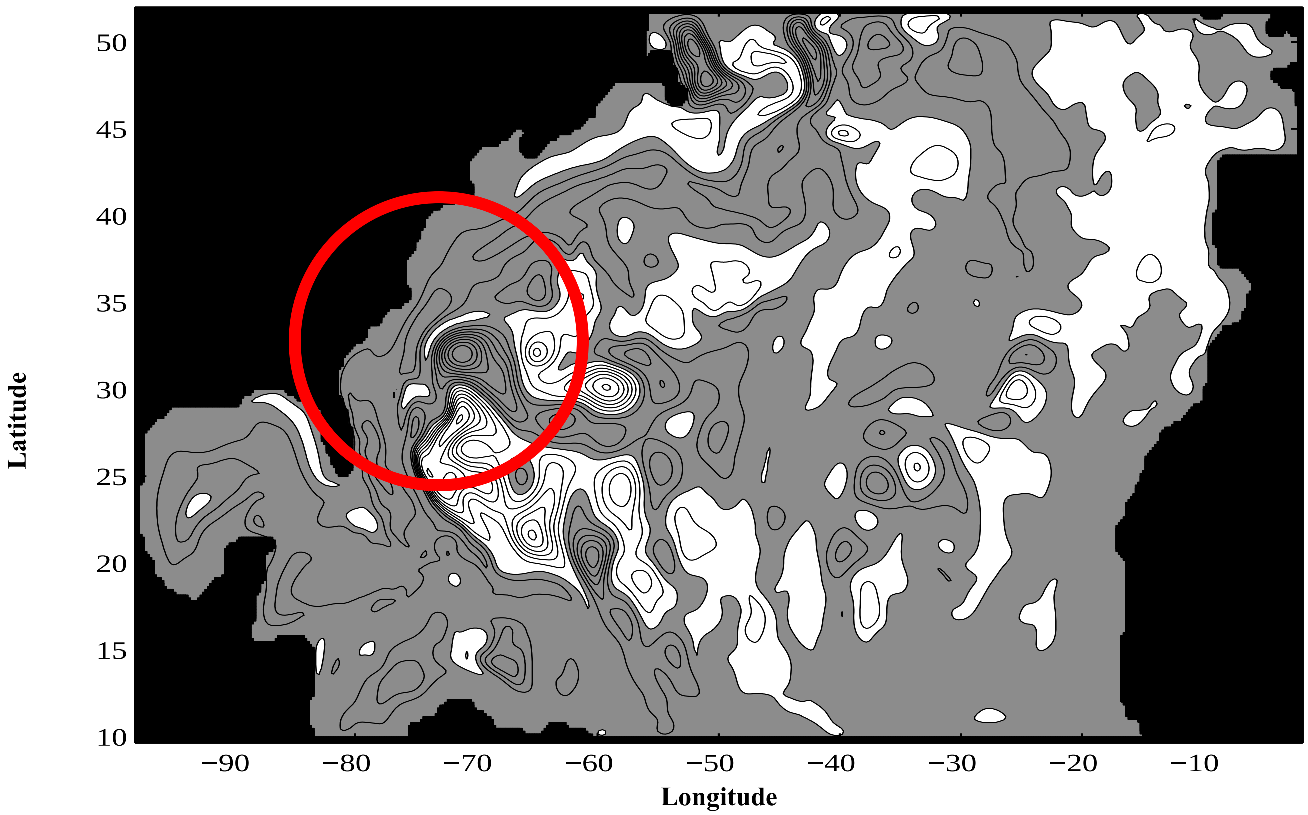
Linear Behaviour via Ensemble Methods

100 member, 30 day ensembles forced by different wintertime realizations of the NAO



Deep ocean structure of 1st EOF of Enstrophy (~87%)

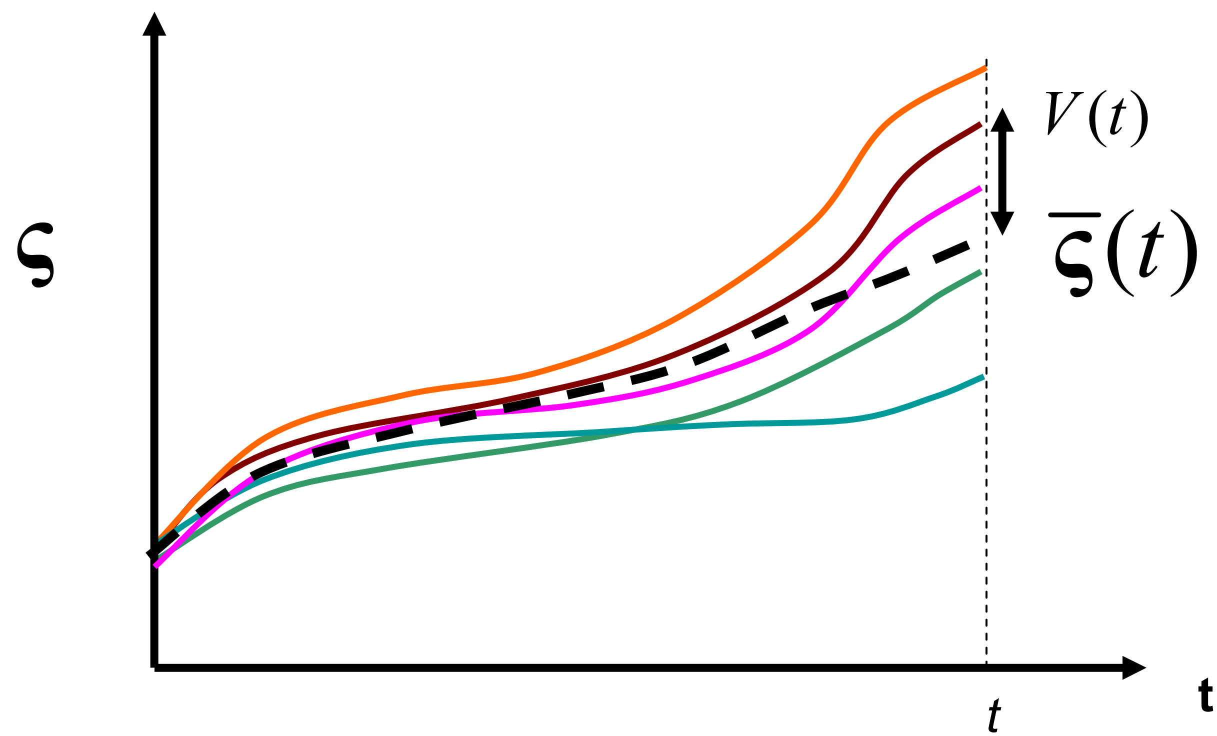
Nonlinear Behaviour



Rectified deep wintertime circulation due to Topographic Rossby Waves ~ 2Sv

(Also noted by McWilliams, 1974; Willebrand et al, 1980)

Ensemble Variance

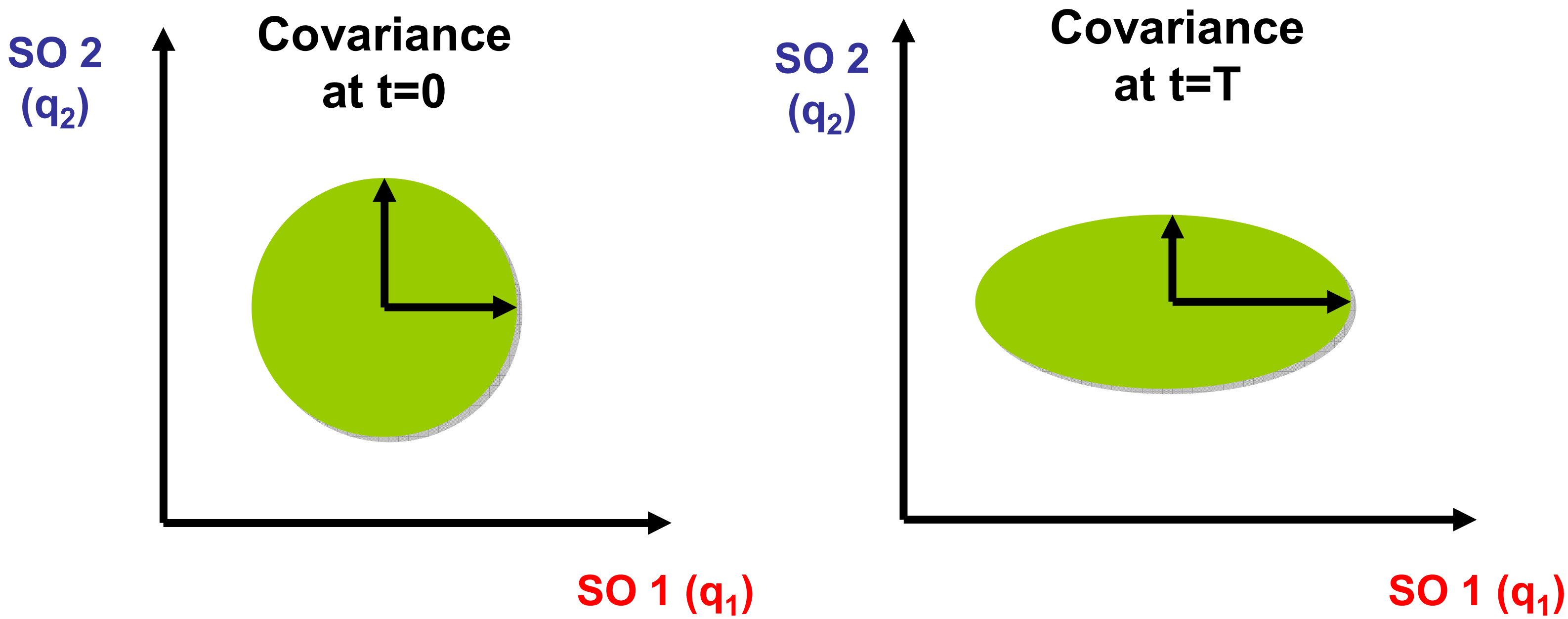


Stochastic Optimals

Ensemble variance:

$$V(t) = \left\langle \varsigma'^{\mathbf{T}} \mathbf{B} \varsigma' \right\rangle = \sigma^2 \sum_{i=1}^{N} \lambda_i \left(\mathbf{e}^{\mathbf{T}} \mathbf{q}_i \right)^2$$

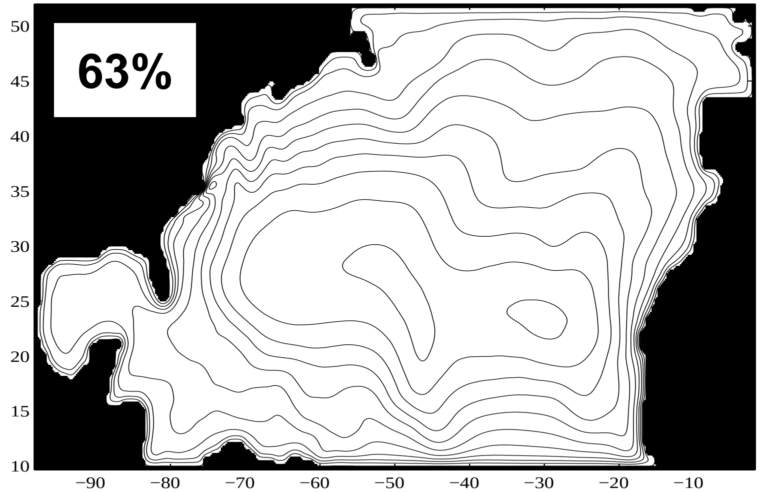
Observability and Stochastic Optimals (SOs)



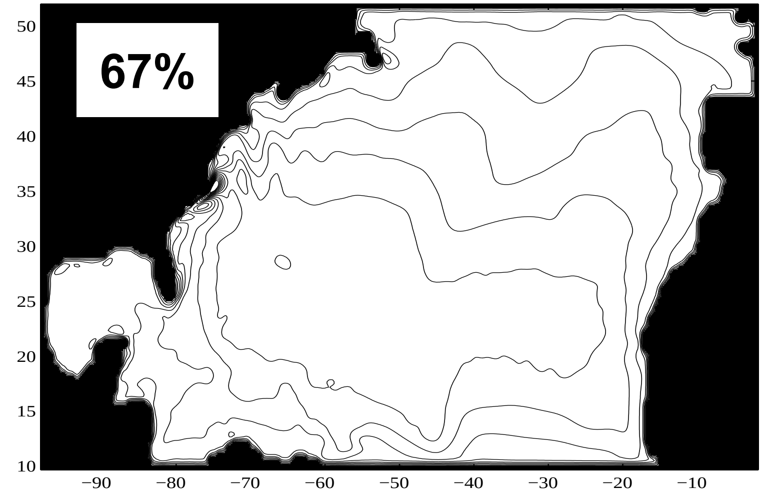
Entire forcing space Dimension ~ 10^5

For T~10-90 days, 1st Stochastic Optimal accounts for ~65% of variance

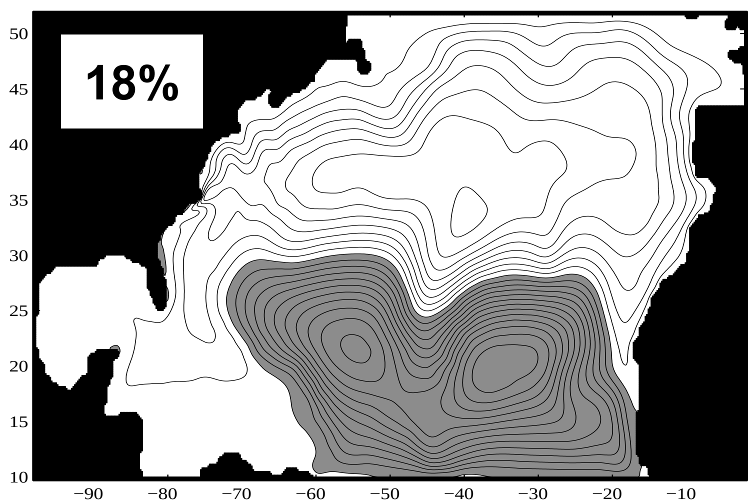
Stochastic Optimals



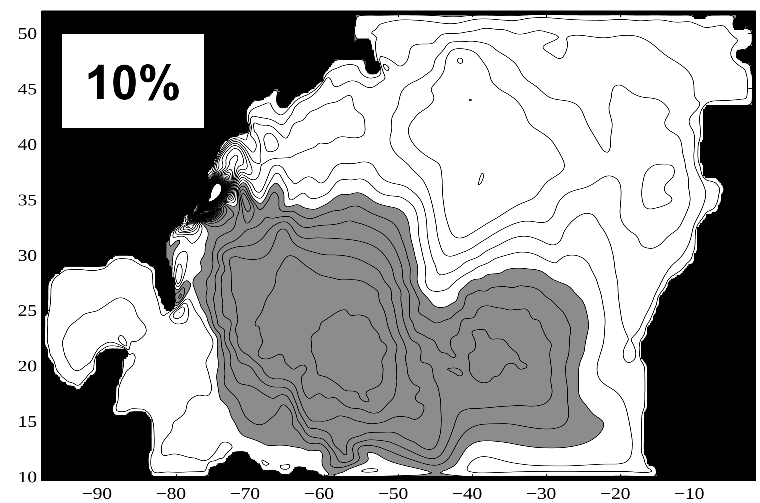
Energy SO #1



Enstrophy SO #1



Energy SO #2



Enstrophy SO #2

Ekman
Pumping Velocity

Conclusions

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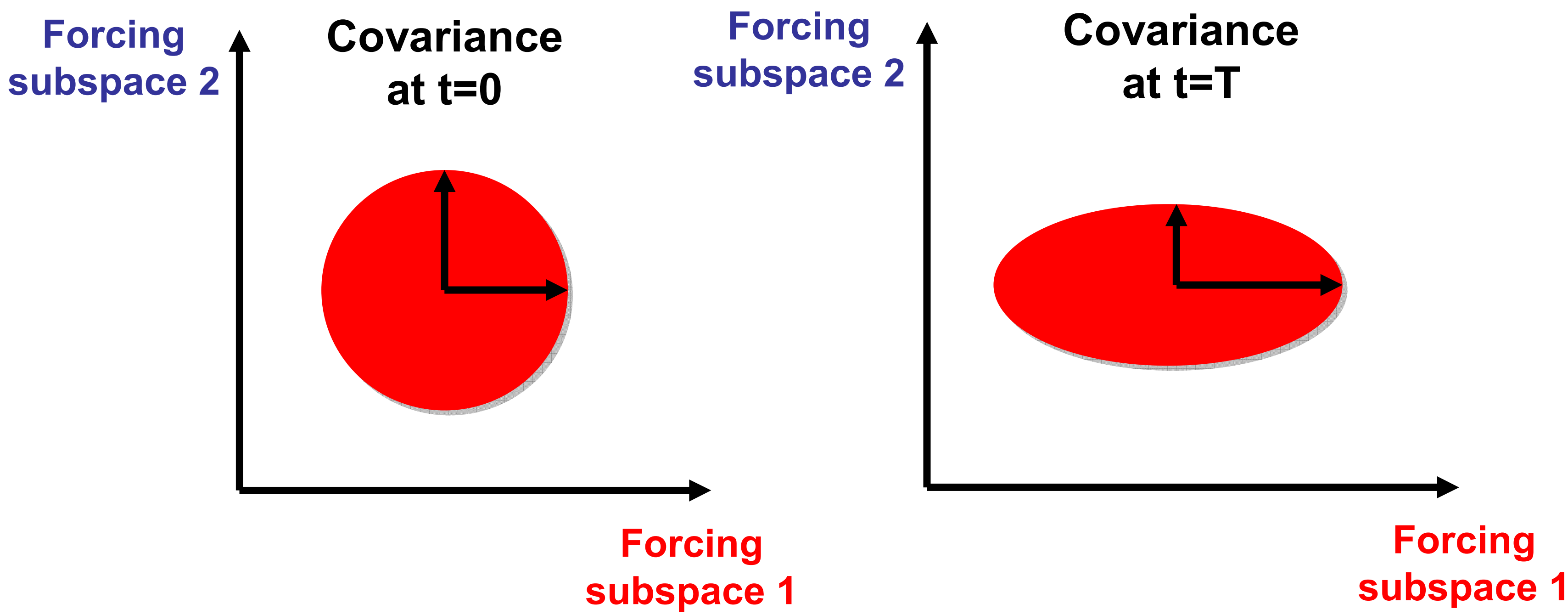
Comments

- Results applicable to stochastic forcing of ocean by other teleconnection patterns.
- Implications for interpretion of observations.
- Implications for ocean predictability.

Observability and Stochastic Optimals (SOs)



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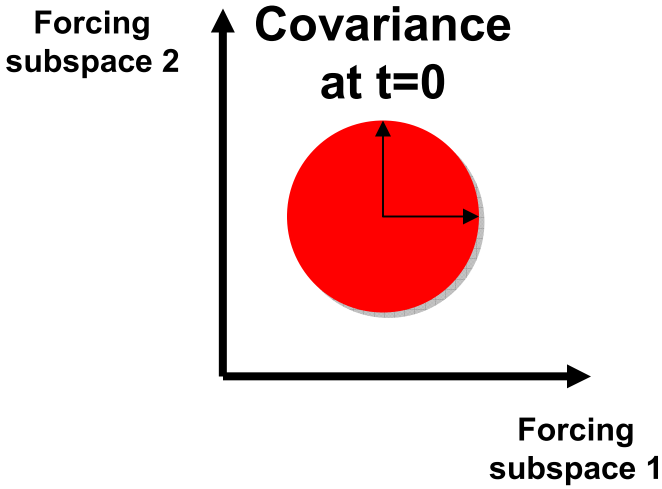

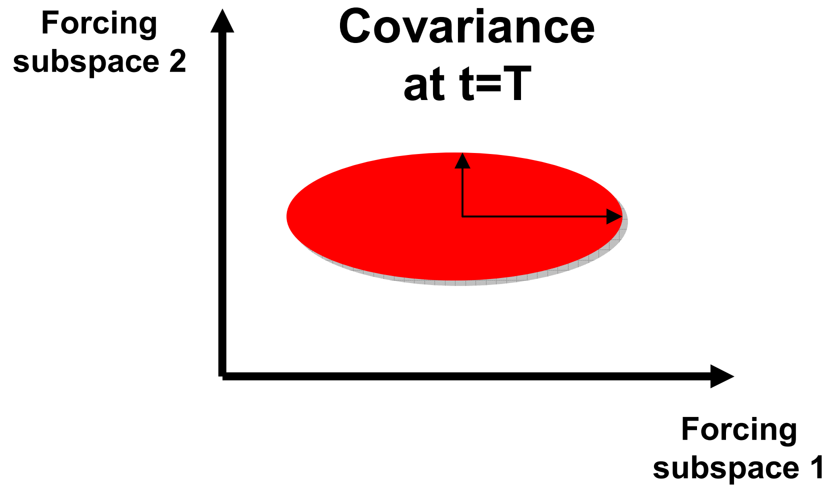

Entire forcing space Dimension ~ 10^5

T (days)	NAO variance explained by 1st SO	
	Q	E
10	~67%	~63%
20	~67%	~62%
30	~67%	~62%
60	~65%	~45%
90	~65%	~15%