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Eddy-induced growth of low-frequency flow of atmospheric circulation

KUG Jong Seong and JIN Fei-Fei

University of Hawaii at Manoa SOEST
Department of Meteorology Science of the Atmosphere
2525 Correa Road, HIG 350
HI 96822 Honolulu
U.S.A.

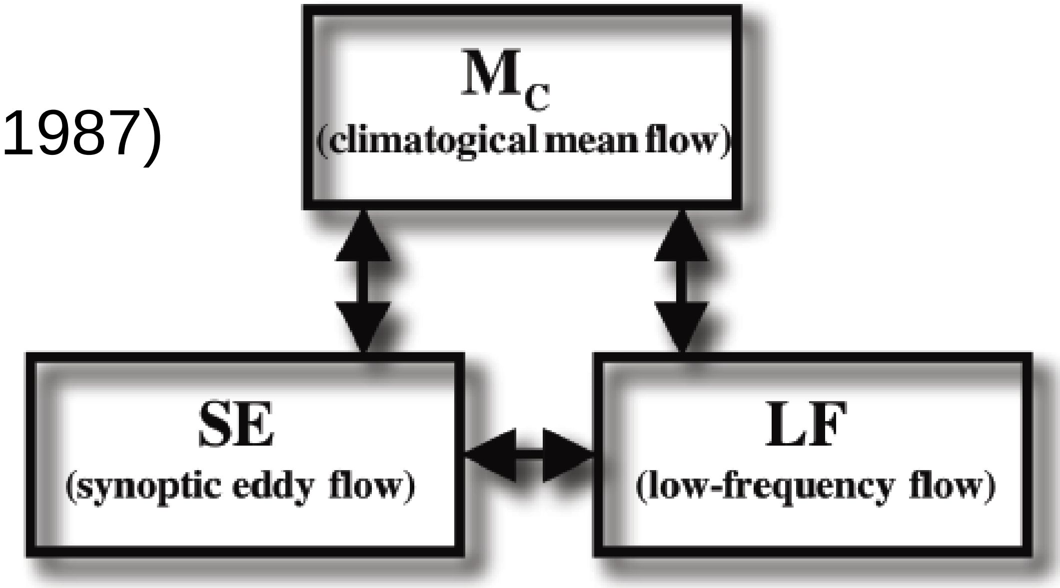
Synoptic eddy-induced instability of Climatic Flow Anomalies

F.-F. Jin[1], J.S. Kug[1], H.-L. Ren[1,3] , I.S. Kang[2], J. H. Park[2]

[1]Department of Meteorology, Univ. of Hawaii, USA,
[2]CES Research Center, SNU, Korea
[3]National Climate Center, CMA, Beijing, China

The paradigm for analyzing climatic (monthly mean) flow variability

Wallace (1987)



Three-component Interaction Paradigm

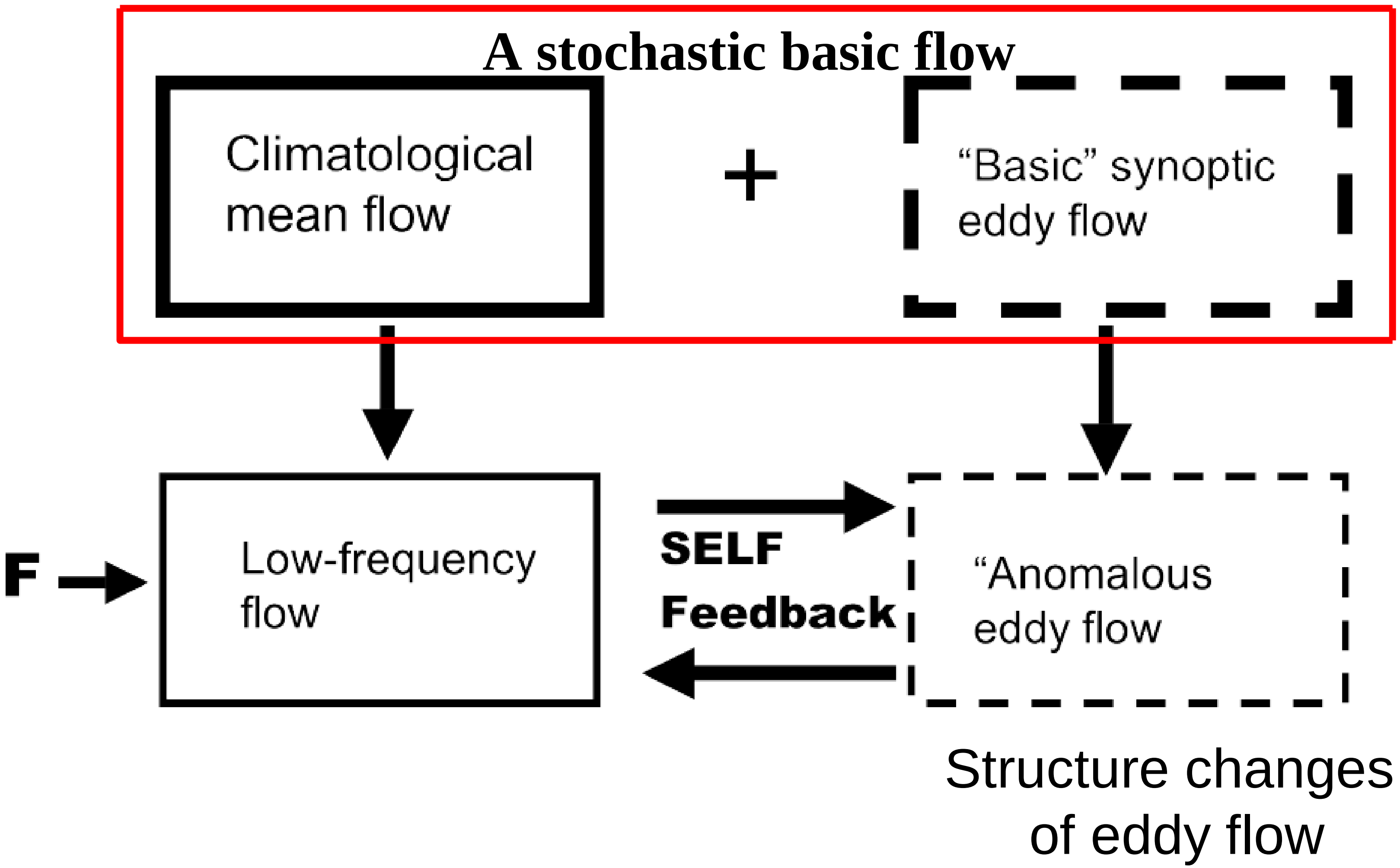
$$\psi = \bar{\psi}^c + \bar{\psi}^a + \psi'$$

$\bar{\psi}^c$: Climatological mean flow

$\bar{\psi}^a$: Low-frequency (or climatic) flow anomalies

ψ' : High-frequency transient eddies

A stochastic dynamic approach to study the dynamics of SELF feedback:



Jin et al. (2006a,b); Pan et al. (2006)

A stochastic barotropic model as an example (Jin et al 2006):

$$\frac{\partial \nabla^2 \psi}{\partial t} + L\psi + J(\psi_c', \nabla^2 \psi) + J(\psi, \nabla^2 \psi_c') + r\nabla^2 \psi = Q$$

$$L(A) = J(\bar{\psi}_c, \nabla^2 A) + J(A, \nabla^2 \bar{\psi}_c + f)$$

$$\frac{\partial \nabla^2 < \psi >}{\partial t} + L\nabla^2 < \psi > + r < \psi > = Q - < J(\psi_c', \nabla^2 \psi') + J(\psi', \nabla^2 \psi_c') >$$

$$\frac{\partial \nabla^2 \psi'}{\partial t} + L\psi' + r\nabla^2 \psi' = J(\psi_c', \nabla^2 < \psi >) - J(< \psi >, \nabla^2 \psi_c')$$

$$-(J(\psi_c', \nabla^2 \psi') + J(\psi', \nabla^2 \psi_c') - < J(\psi_c', \nabla^2 \psi') + J(\psi', \nabla^2 \psi_c') >)$$

A new dynamic framework with SELF-feedback

$$\bar{\psi}^a \approx < \psi >$$

$$\nabla \cdot (\overline{V'\zeta'}^a) \approx < J(\psi_c', \nabla^2 \psi') + J(\psi', \nabla^2 \psi_c') > = L_f \bar{\psi}^a$$

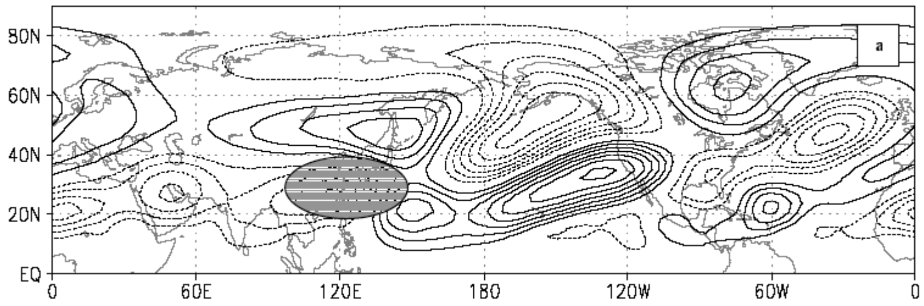
Second-order closure under a quasi-equilibrium hypothesis:

A deterministic barotropic model for climatic flow anomalies:

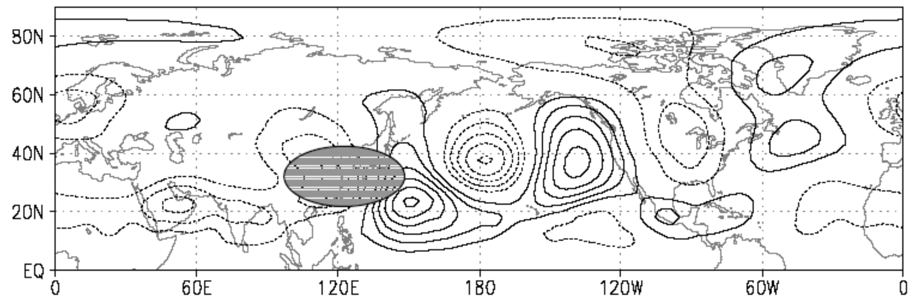
$$\frac{\partial}{\partial t} \Delta \bar{\psi}^a + L\bar{\psi}^a + L_f \bar{\psi}^a = \bar{Q}^a, \quad L_f \text{ is explicitly derived!}$$

Validation (I): Mathematical (Jin and Lin 2007)

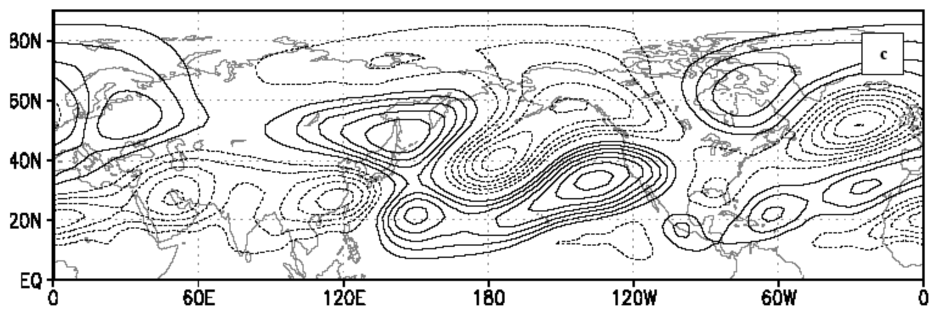
Dynamical SELF Closure



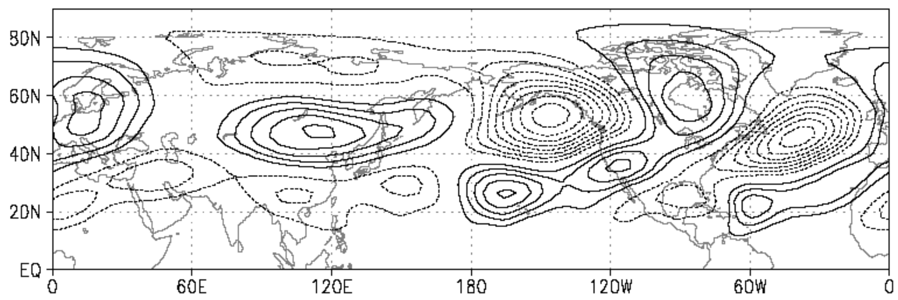
Without Eddy Effects



500 member ensemble mean



Net Eddy effect



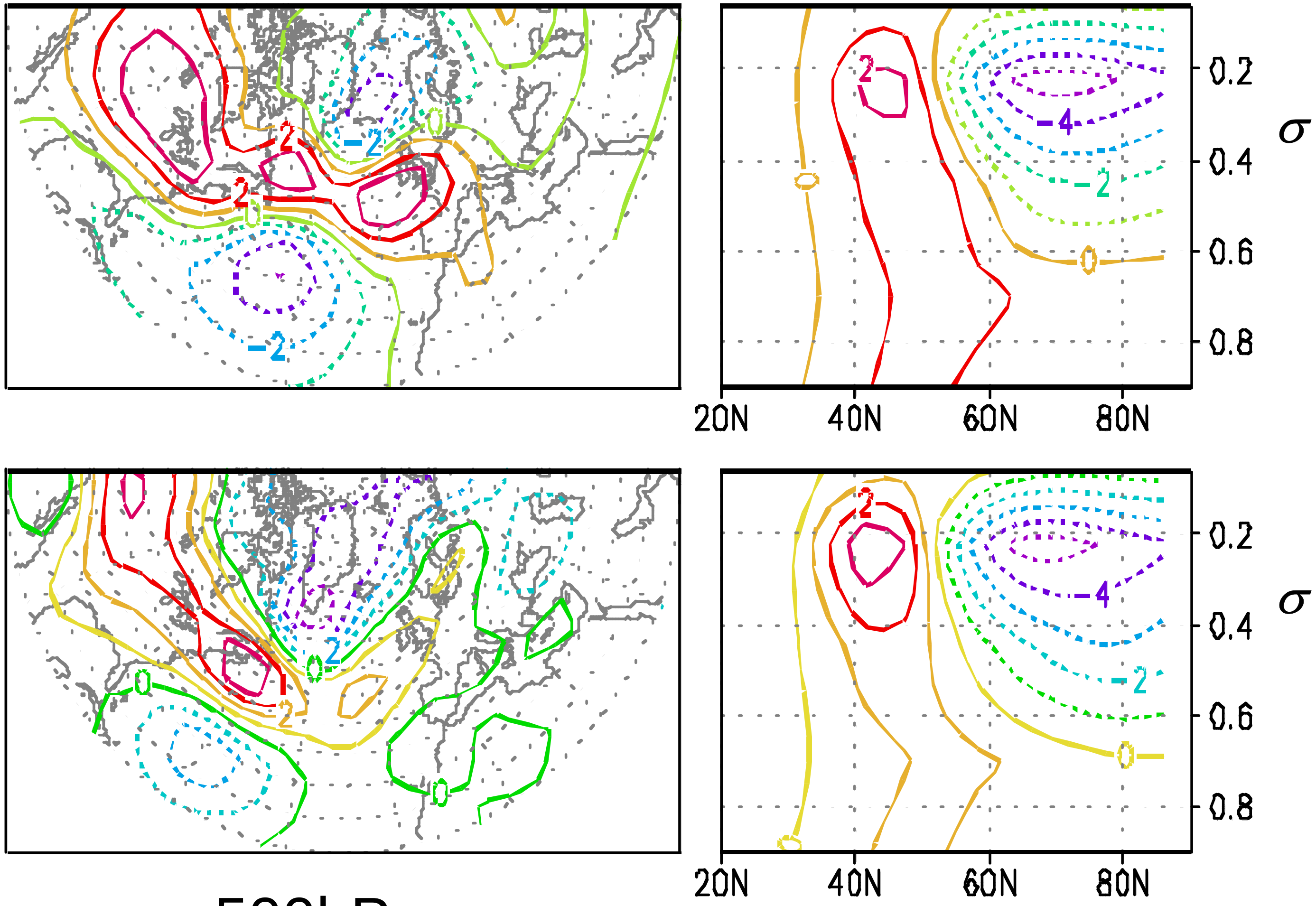
Validation (II): Reproduction of Observational Features

NAO-Related Eddy Forcing

Observed
Eddy forcing

Parameterized
Eddy forcing

by the SELF closure based on a linear 5-layer-T21 PE model



500hPa

Summary I:

A new framework with a dynamic SELF feedback closure is formulated for study climatic flow variability.

Can we use the new framework to understand dynamic SELF feedback and its role on the climatic flow variability?

A left-hand rule and Eddy-induced instability:

Synoptic eddy-induced Instability!

Climatic flow anomalies systematically stir and deform the transient synoptic eddies such that net anomalies in the eddy-vorticity fluxes are directed preferentially towards their left. As the result, **climatic flow anomalies gain significant eddy-induced growths (EIG) by drawing energy from the synoptic eddies.**

Jin et al (2008), Kug and Jin (2008)

Theoretical results (assuming single wave number structure)

$$\underbrace{L_f \bar{\psi}^a}_{\text{F: eddy feedback}} \approx \frac{1}{\tau_r} G_r (\nabla^2 + K_c^2) \underbrace{\left[E_{KE} \frac{\partial^2 \bar{\psi}^a}{\partial^2 x} + \frac{\partial}{\partial y} E_{KE} \frac{\partial \bar{\psi}^a}{\partial y}) \right]}_{\text{A: growth term}} + \ldots$$

F: eddy feedback

A: growth term

$$L_f \bar{\psi}^a \approx -\lambda_{th} \bar{\psi}^a$$

$$\lambda_{th} \approx \frac{1}{\tau_r} G_r (K_c^2 - K^2) K^2 E_{KE}$$

K_c : Wave number of typical synoptic eddies

K : Wave number of Low-frequency Flow

E_{KE} : eddy kinetic energy distribution

Eddy-Induced growth rate for climatic flow anomalies

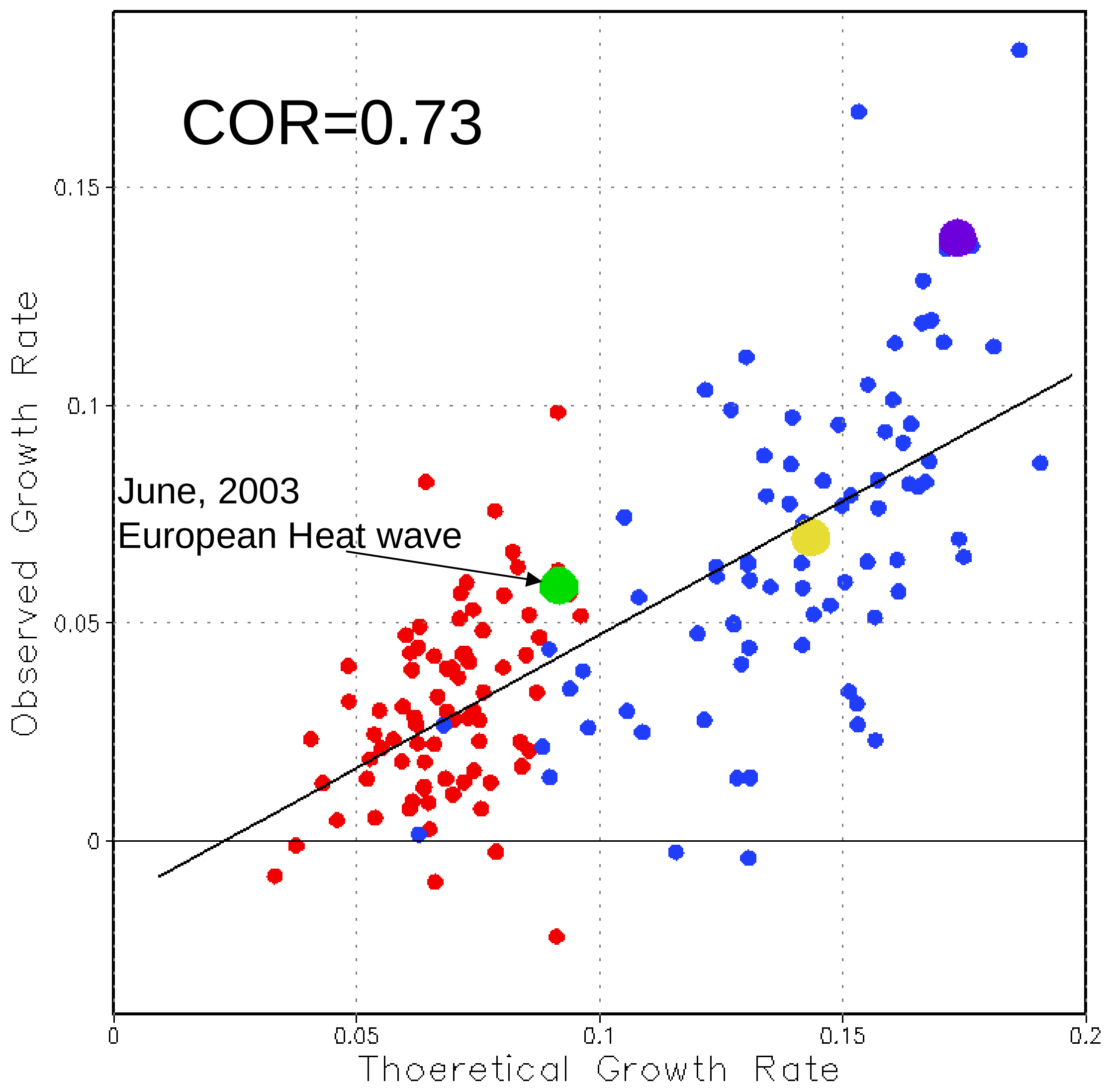
(Jin et al. 2008)

Eddy-Induced Growth rate for Monthly-mean Flow

Diagnosed growth rate from the observed data

$$\frac{\partial \overline{\psi}_a}{\partial t} \propto -\Delta^{-1}\nabla\overline{v'\zeta'} = \lambda\overline{\psi}_a$$

$$\lambda = \frac{-\iint \overline{\psi}_a \cdot \Delta^{-1}\nabla\overline{v'\zeta'}dxdy}{\iint \overline{\psi}_a{}^2 dxdy}$$

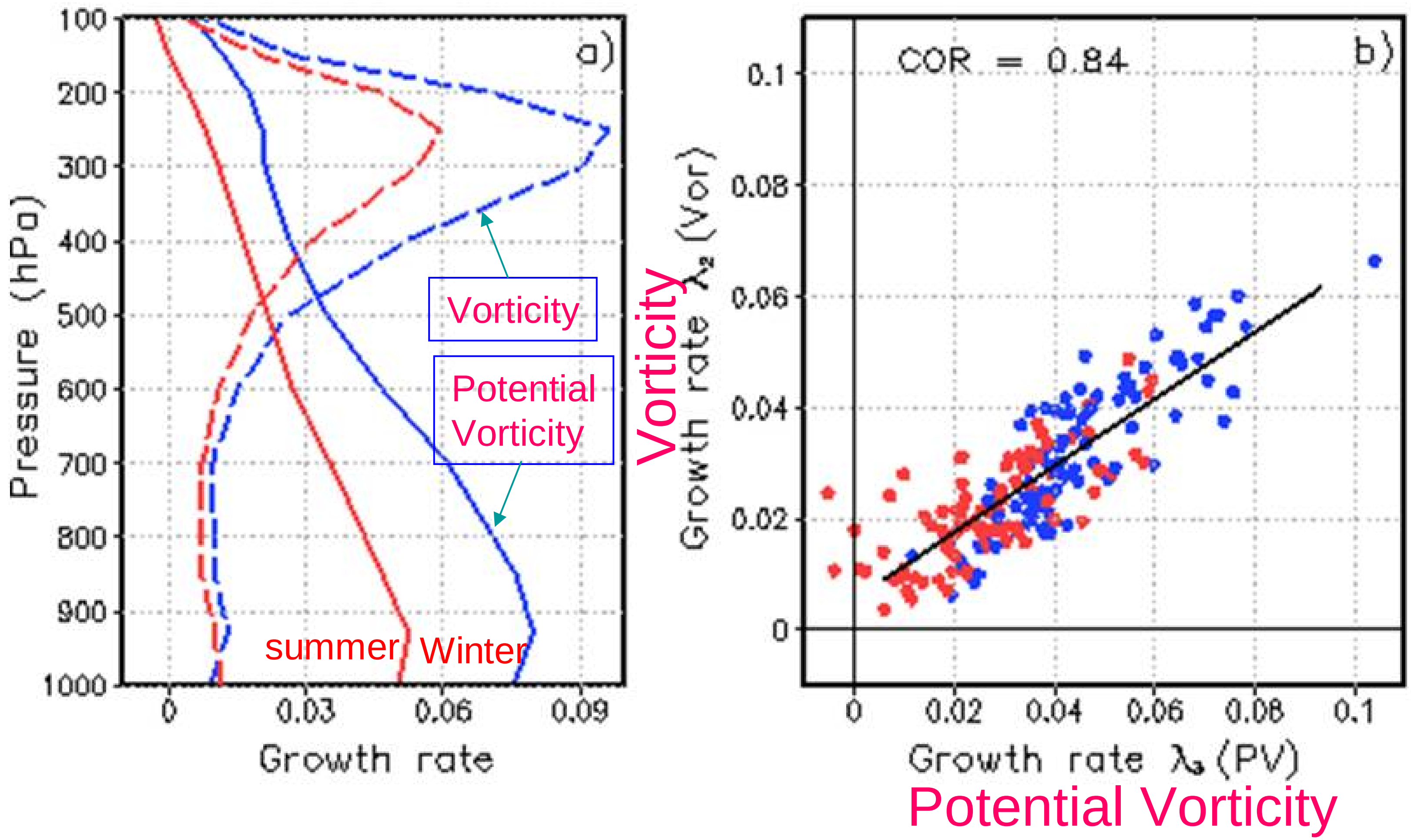


Theoretical Growth Rate

$$\lambda_{th} \propto \tau^{-1}E_{KE}(K_c^2 - K^2)K^2$$

Eddy-Induced Growth Rate

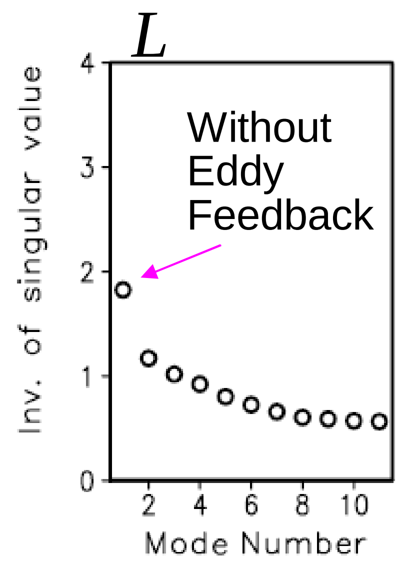
Based on Vorticity Flux and Potential Vorticity Flux

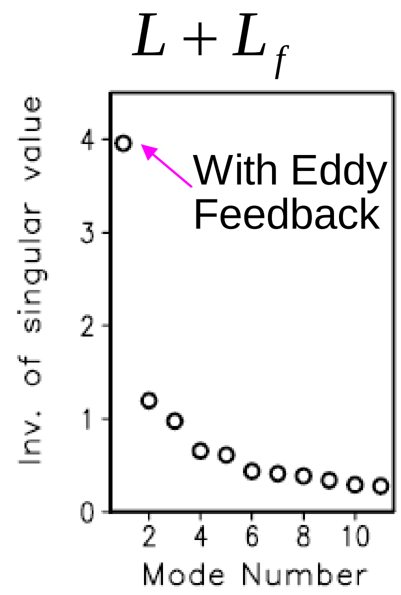


SVD modes

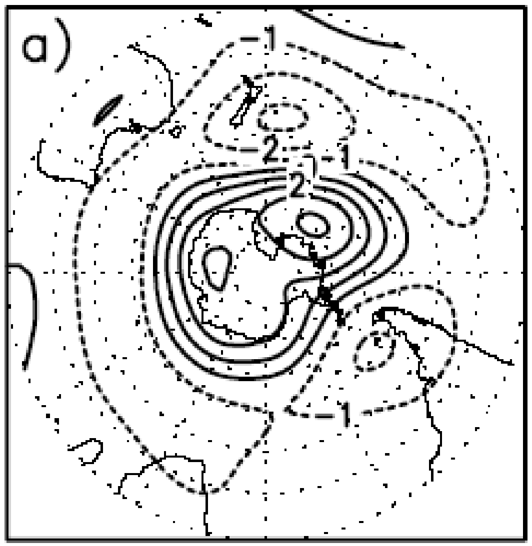
Eigen Analyses
Without and With
Synoptic Eddy Feedback

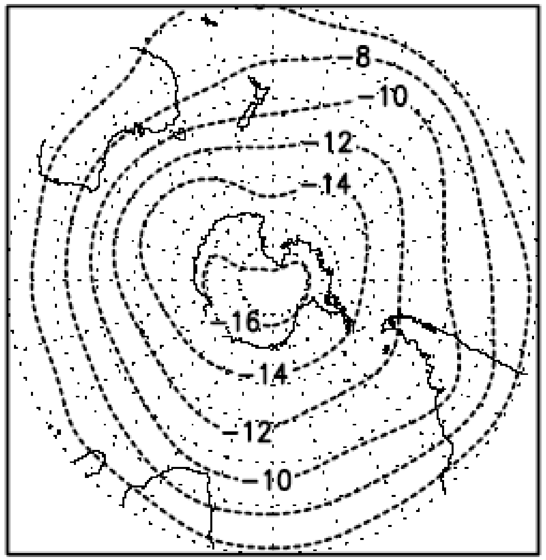
Southern Hemisphere

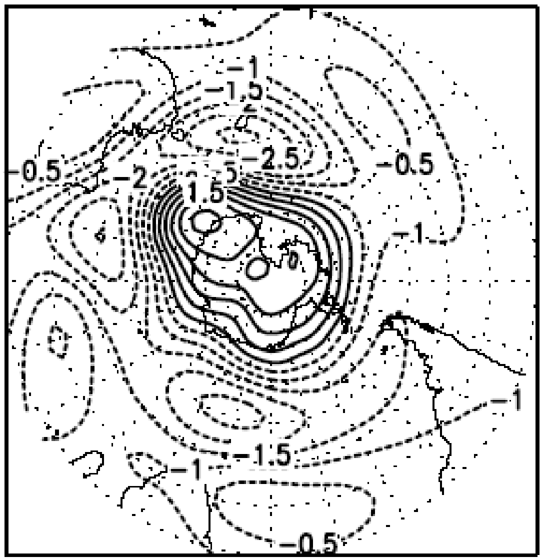




Observed AAO

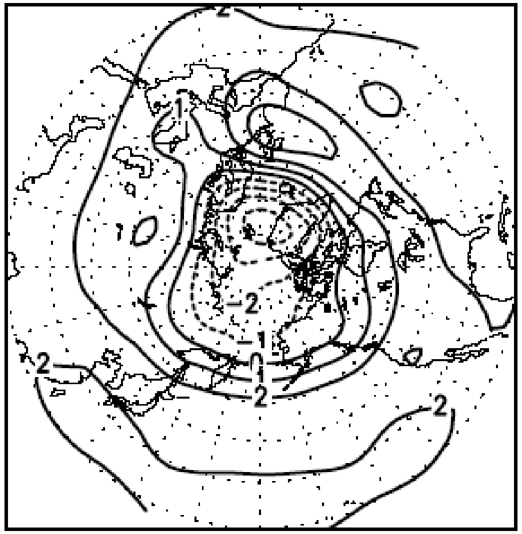




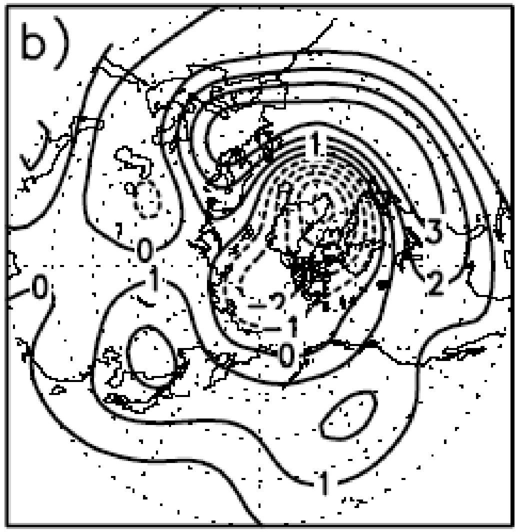


Jin et al 2006b

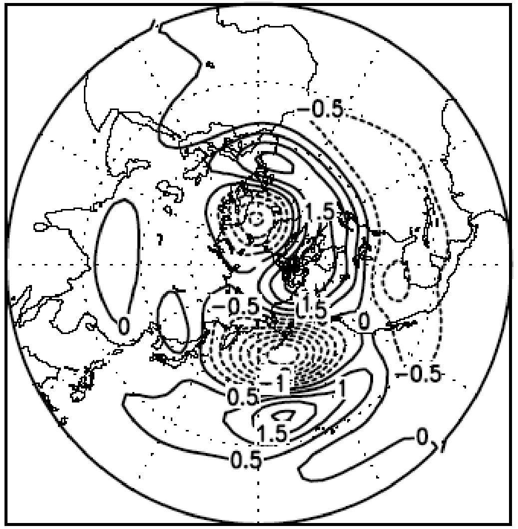
#1 SDV mode



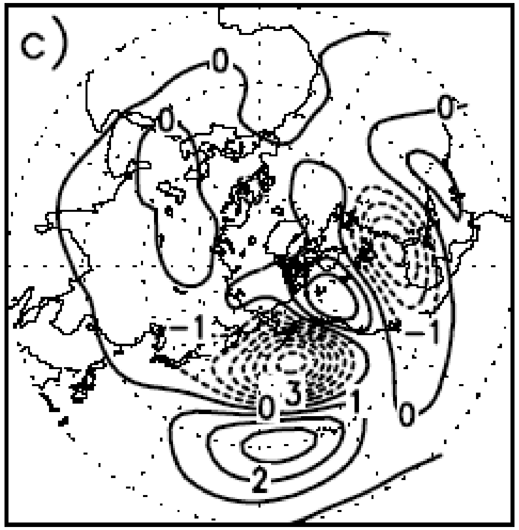
Observed AO



#3 SVD mode



Observed PNA



Northern Hemisphere

Summary:

SELF feedback gives rise to synoptic eddy-induced instability which can be elucidate by the left-hand rule : anomalous eddy fluxes is directed to left of the climatic flow anomalies to reinforce the latter.

Synoptic eddy-induced Instability is responsible for the making of climate modes (NAO, AO, AAO, PNA etc).

Eddy-Induced Growth rates (EIG) are proportional to climatologic distribution of storm track strength (synoptic eddy kinetic energy), inversely proportional to eddy decay timescale.

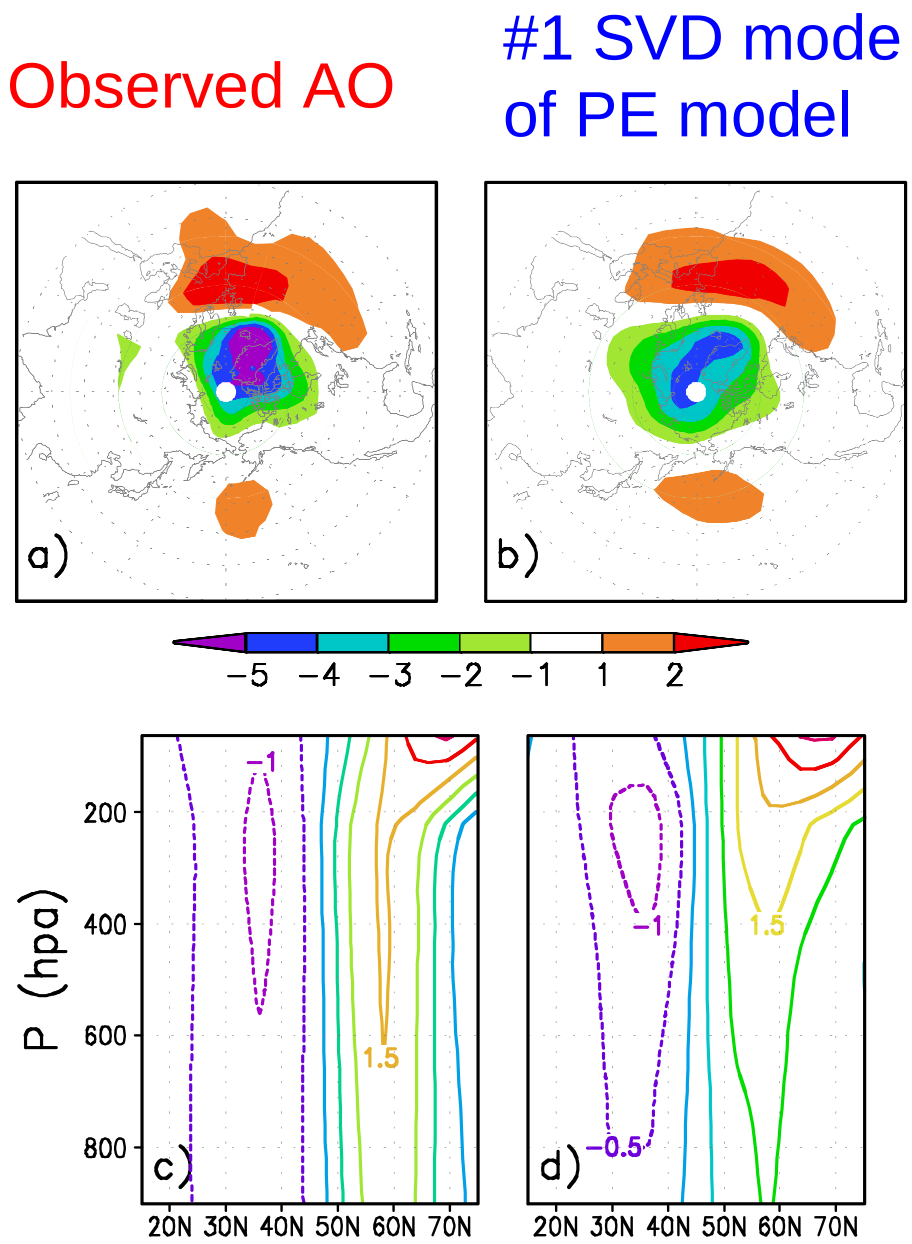
EIG is highly scale dependent and favors climate patterns of dipole and triple middle structures.

New dynamic framework shall be a useful tool for understanding climate anomalies related to middle-latitude ocean-atmosphere interactions and global warming etc.

Surface Pressure

Zonal mean

zonal winds



Constructing a stochastic basic flow

$$\psi_c = \langle \psi_c \rangle + \psi_c' \qquad \textbf{with:}$$

a) prescribed climatological mean flow

$$\langle \psi_c \rangle \approx \bar{\psi}^c(x, y)$$

b) a Gaussian eddy flow:

$$\psi_c' = \sum_{n=1}^{N_c} \sigma_n \xi_n(t) E_n(x, y) e^{i\omega_n t} + cc$$

$\xi_n(t)$: **independent Gaussian processes,**

$E_n(x, y)$: **propagating principle eddy patterns.**

Both $\bar{\psi}^c(x, y)$ and ($E_n(x, y), \sigma_n, \omega_n, \tau_n$) can be obtained from observation!

◆ Two-way Interaction between Synoptic Eddy and Low Frequency (SELF)

-Observational analyses

(Lau 1988; Lau and Nath 1992; Nakamura and Wallace 1990; Cai and Van den Dool 1991; Hoerling and Ting 1994; Lorenz and Hartmann 2001, 2003)

- **Model results** (Cai and Mak 1990; Robinson 1991, 2000; Branstator 1995)

◆ Dynamical Closure for the SELF Feedback (Jin et al. 2006a,b)

- Anomalous time-mean eddy-fluxes are a function of low-frequency flow anomalies:

$$-\nabla \cdot (\overline{\vec{V}'\zeta'}^{a}) = L_f \bar{\psi}^a \quad \text{where } L_f \textit{ is a} \text{ linear operator}$$

Theoretical Estimate

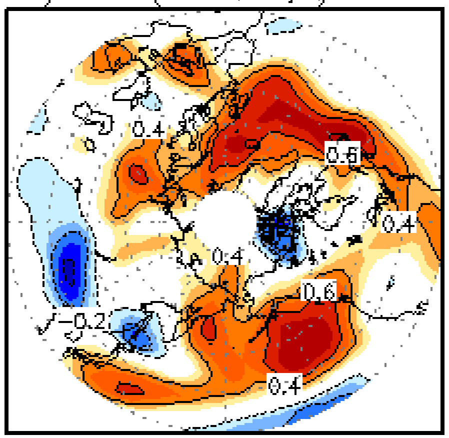
- Assume only one dominant wave number in synoptic eddy and low-frequency

$$\underbrace{\nabla^{-2}(\nabla\cdot\overline{\vec{V}'\varsigma'}^{a})}_{\text{F}} \approx \frac{1}{\tau_r}G_r\underbrace{(\nabla^{-2}+K_c^2)\left[E_x^2\frac{\partial^2\overline{\psi}^{a}}{\partial^2 x}+\frac{\partial}{\partial y}\left(E_y^2\frac{\partial\overline{\psi}^{a}}{\partial x}\right)\right]}_{\text{A}} - G_i(\nabla^{-2}+K_c^2)E_x^2\underbrace{\frac{\partial\overline{\psi}^{a}}{\partial x}}_{\text{B}}$$

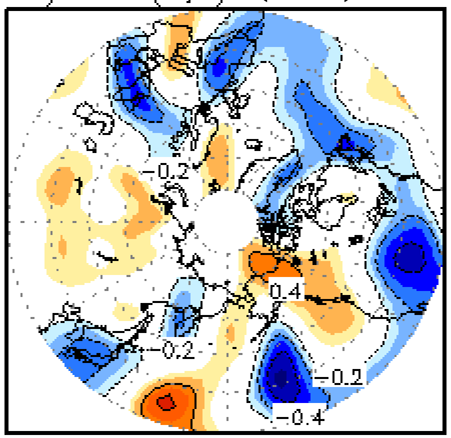
F: Streamfunction Tendency **A: Weighted Vorticity** **B: Meridional wind**

Observational Validation

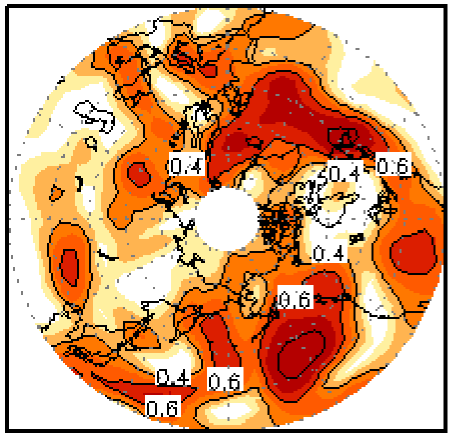
COR (A,F)



COR (B,F)



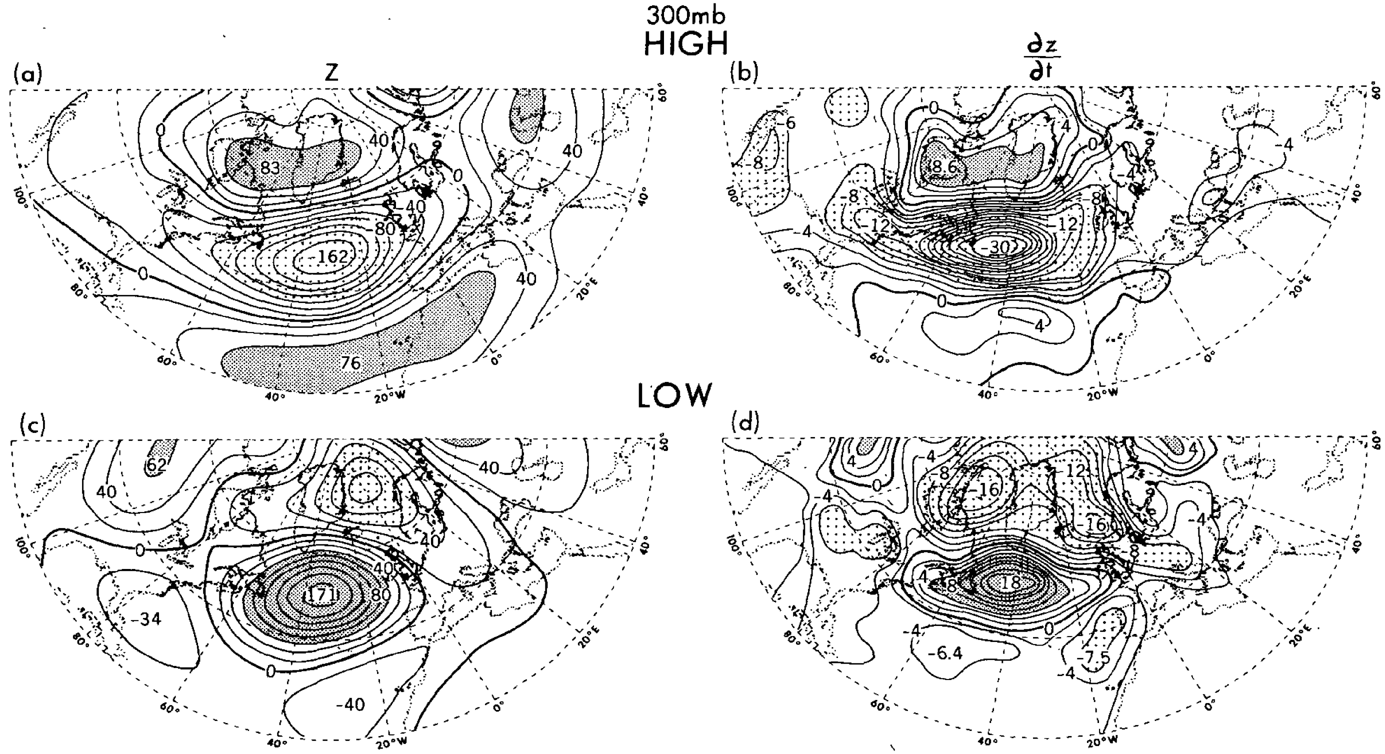
COR (A+B,F)



(Jin et al. 2008b)

Lau, 1988

$$\overline{\psi}^{a} = \overline{\psi} - \overline{\psi}^{c}, \qquad -\Delta^{-1}\left(\nabla\cdot\left(\overline{\vec{V}'\zeta'}^{a}\right)\right),$$



Definition: $\overline{\vec{V}'\zeta'}^{a} = \overline{\vec{V}'\zeta'} - \overline{\vec{V}'\zeta'}^{c}$

Implication: SELF-feedback

Main sources for climatic flow anomalies $\bar{\psi}^a$:

(I) External forcing

(ii) Basic flow instability

(III) Eddy forcing --> SELF feedback-->

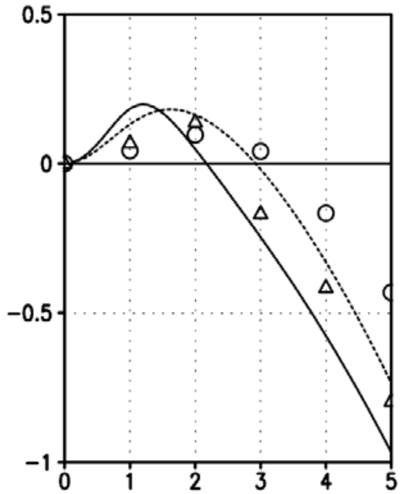
Synoptic eddy-induced Instability

Consider an idealized basic state

$$\psi_c = -y\bar{u}^c + \xi(t)\sin l_c y e^{ik_c(x-ct)} + cc$$

The factor from SELF feedback that controls the growth rate of annular modes:

$$\alpha \propto \sigma^2(k_c^2 + l_c^2 - l^2)l^2$$



Dipole and tri-pole modes (in zonal wind anomalies) $l = 1, or\ 2$ have largest **synoptic eddy-induced Instability** .