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Left-hand rule for synoptic eddy and low-frequency flow interaction

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A General Rule for Synoptic-Eddy Feedback onto Low-Frequency Flow

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Nov, 18/Trieste, Italy



Background

◆ Two-way Interaction between Synoptic Eddy and Low-frequency Flow (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 and Theoretical results** (Cai and Mak 1990; Robinson 1991, 2000; Branstator 1995)

➤ It is still unclear and controversial how the LF flow organizes synoptic eddies and induces positive eddy forcing.

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

- By separating the quadratic eddy-eddy interaction term into a climatological component and anomalous one.

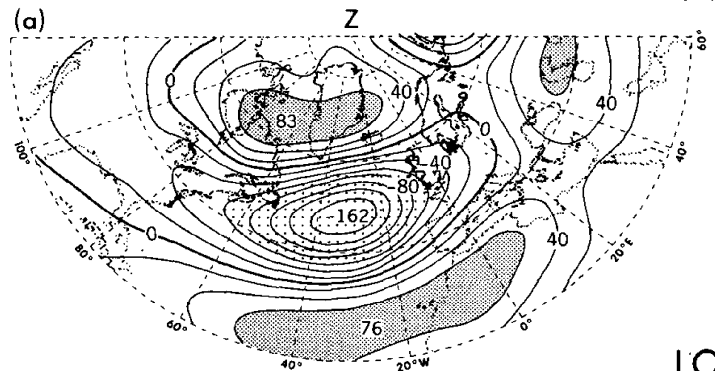
- Showed the eddy feedback can be parameterized by low-frequency flow.

$$L_f(\bar{\psi}) = -\nabla \cdot (\overline{\vec{V}'\zeta'}) \quad \text{where } L_f : \text{Linear Operator}$$



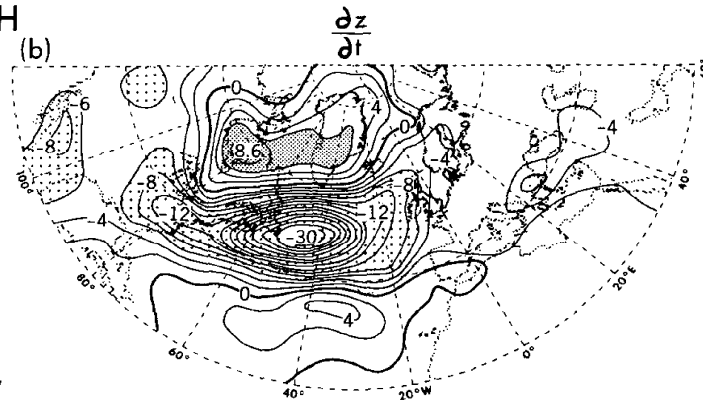
Background

Geopotential Height

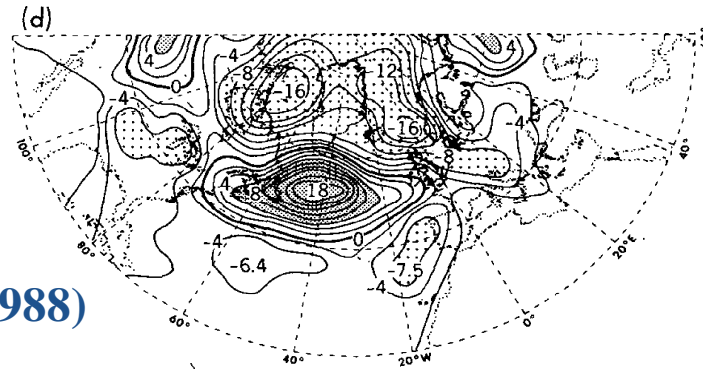
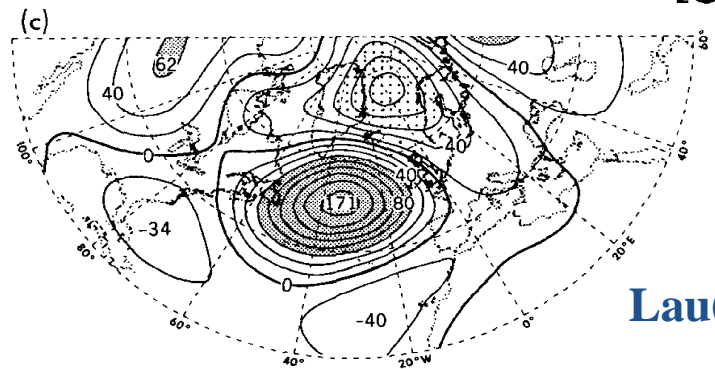


300mb
HIGH

Eddy Forcing



LOW



Lau(1988)



This Dynamical Closure serves an insightful framework for understanding the synoptic-eddy feedback process.



Objectives

- ◆ Revisit previous studies on the interaction between Synoptic Eddies and Low-frequency Flows (SELF)
- ◆ **Suggest a general rule to delineate SELF Interaction** based on theoretical frame work and observational evidences
- ◆ **Examine a collective role of synoptic eddy feedback on** Low-frequency flow



1. **Left-Hand Rule** for eddy-vorticity flux

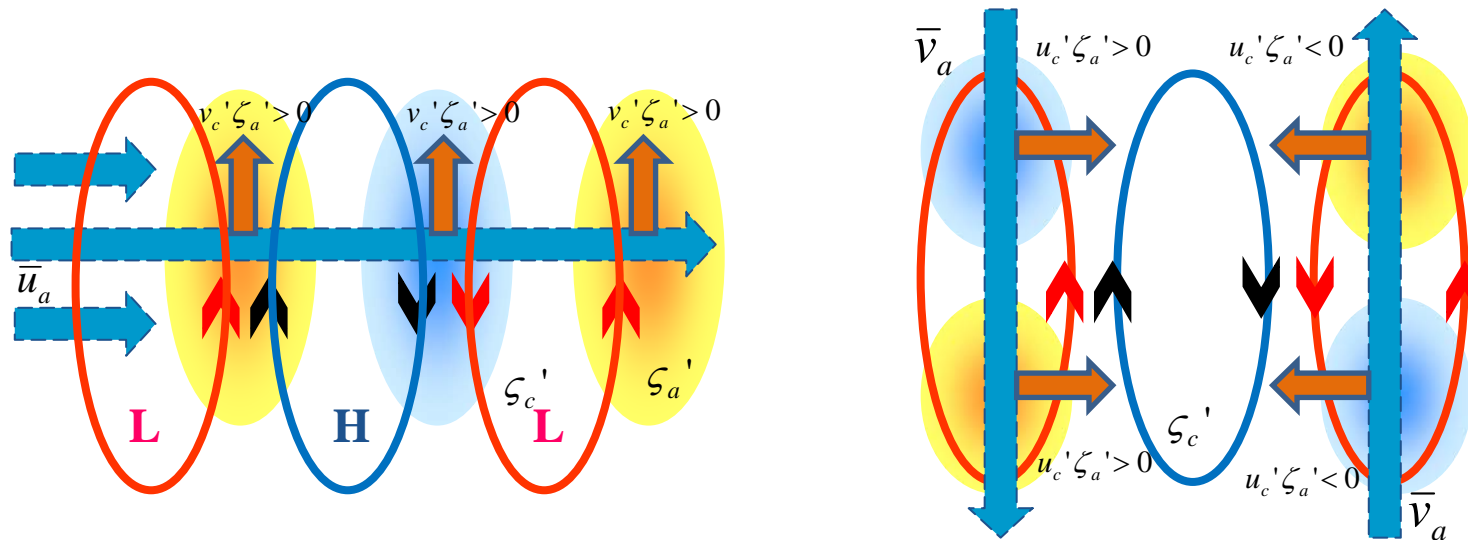
Low-frequency anomalies systematically stir and deform the transient eddies in such a way that **net anomalies in the eddy-vorticity fluxes are directed preferentially about 90 degrees towards their left-hand side**, thus this eddy positive feedback plays a role in maintaining and prolonging low-frequency flow under the stormy atmosphere.

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



Schematic Diagram I

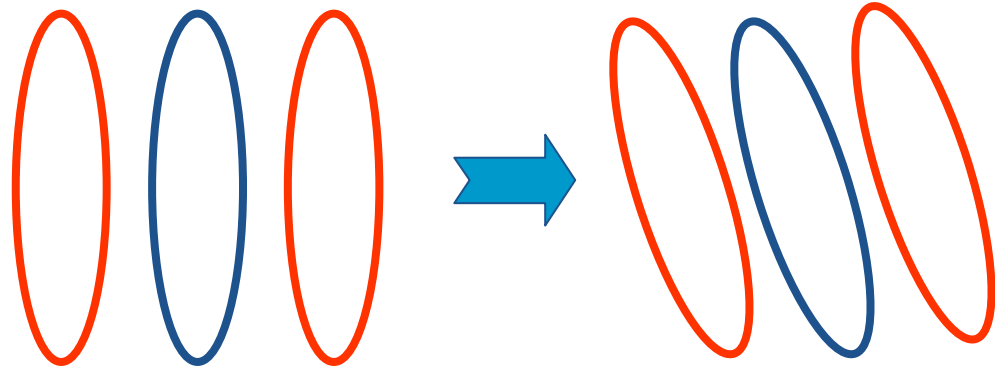
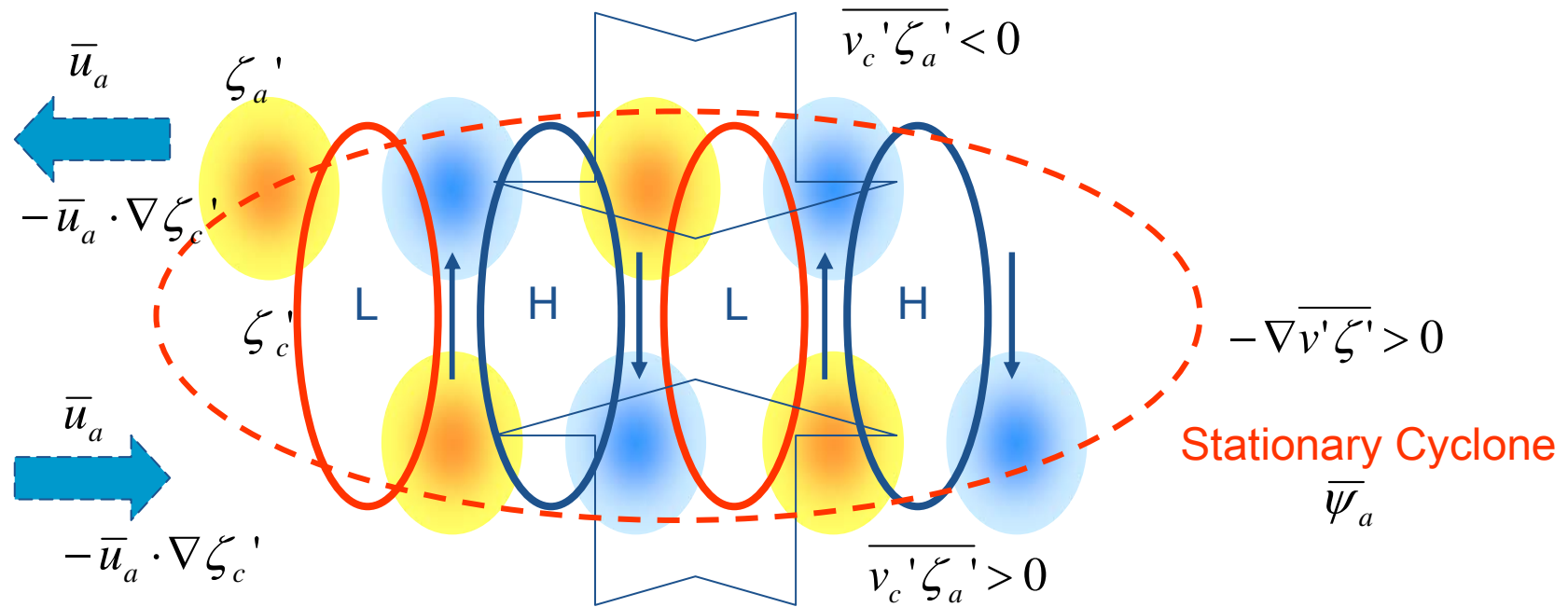
Left-Hand Rule for Interaction between Climatic Flow and Synoptic Eddies



$$\overline{v' \zeta'^a} = \overline{v_c' \zeta_a'^a} + \overline{v_a' \zeta_c'^a}$$



Schematic Diagram II



**Climatological
Eddy Structures**

**Climatological + Anomalous
Eddy Structures**

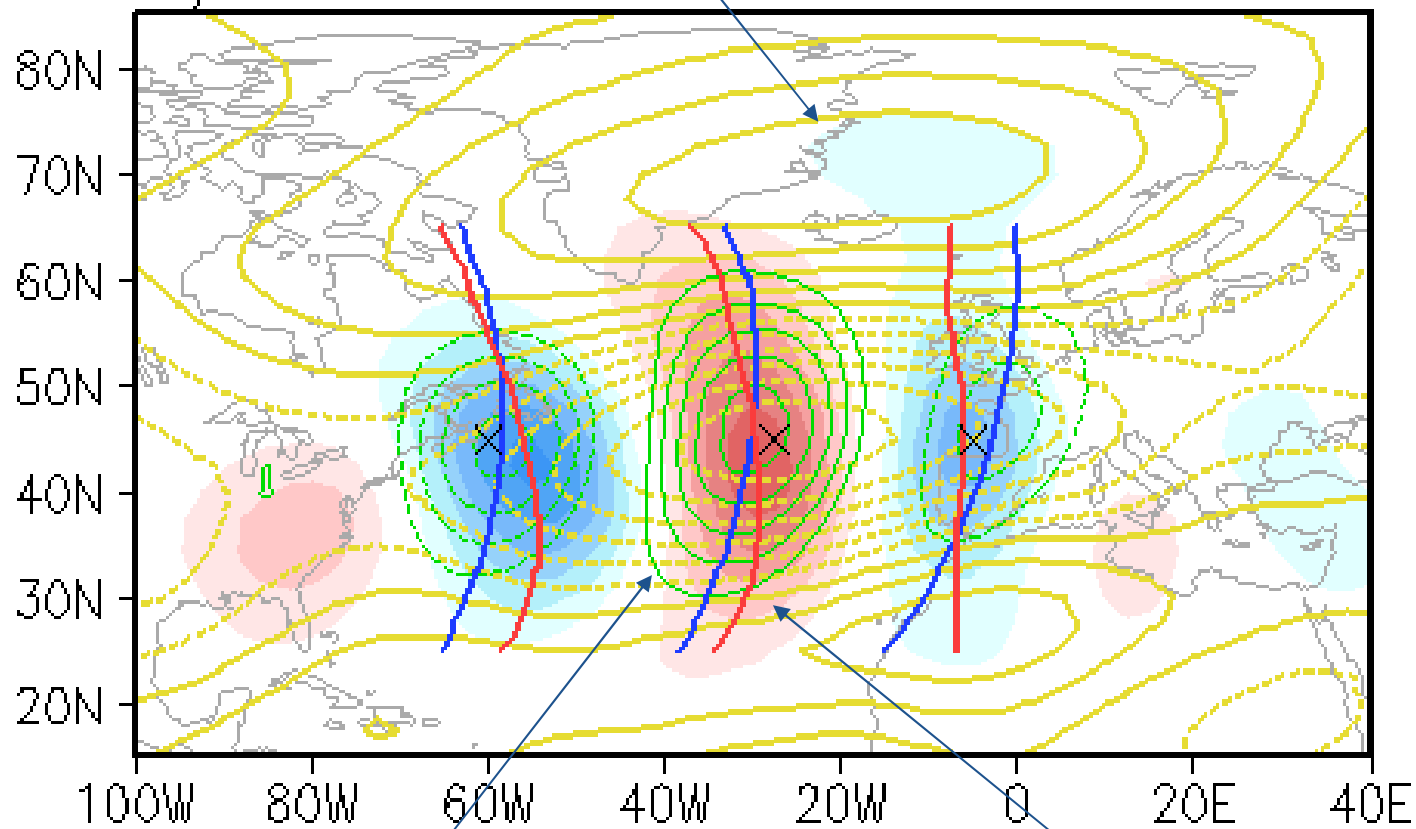


An Example for Structure Changes of Synoptic Eddies

Based on three-point covariance

NAO Composite

Yellow Contour : Monthly Mean Stream Function Anomalies



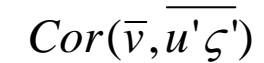
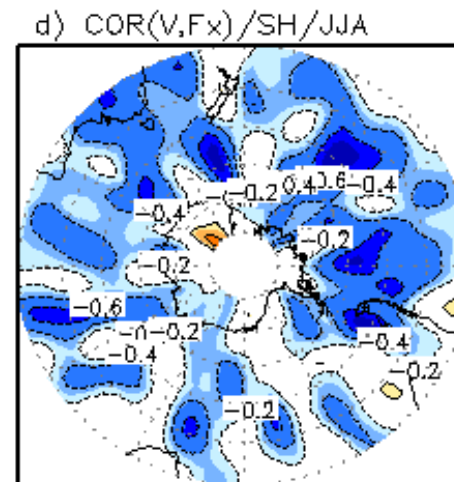
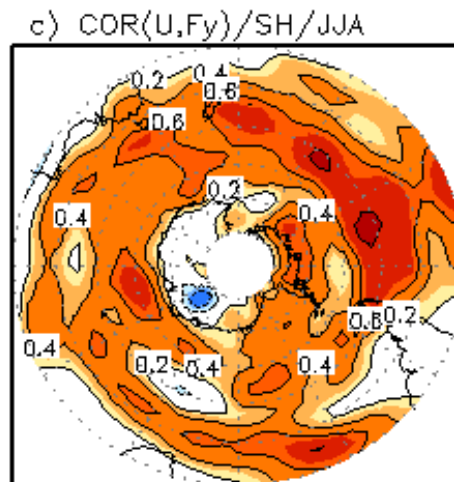
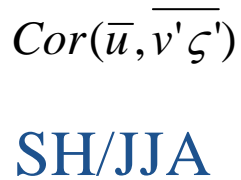
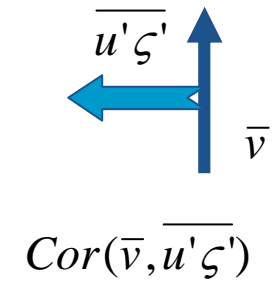
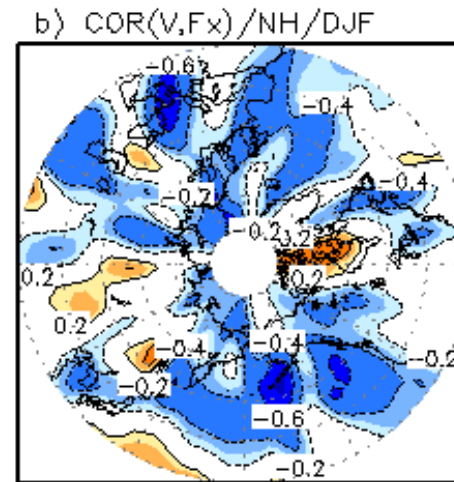
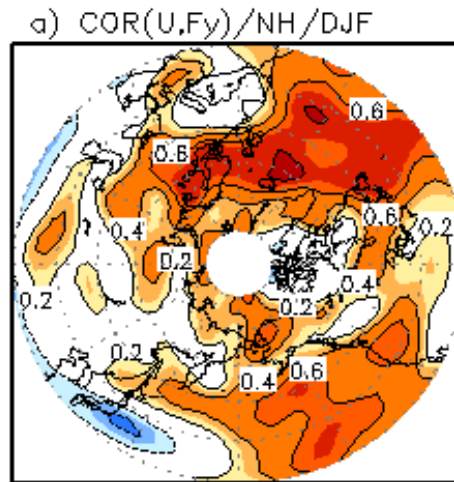
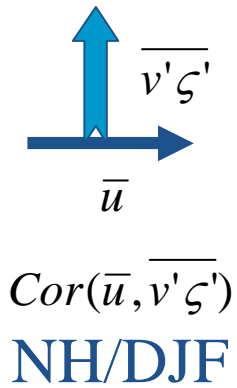
Green Contour: Synoptic Eddies while normal years

Shading: Synoptic Eddies while NAO(-) Years



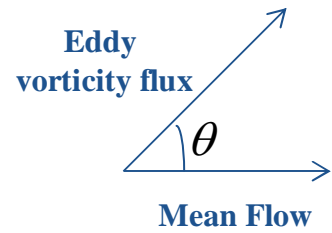
Observational Evidence I

Correlation bet. Seasonal Mean Wind & Eddy Vorticity Flux



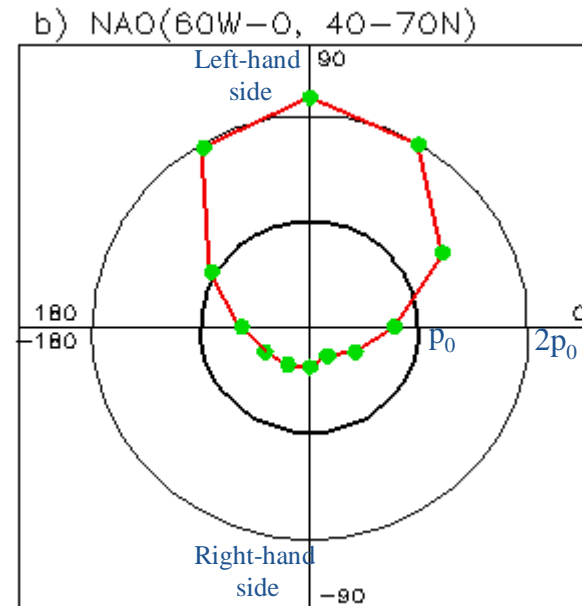
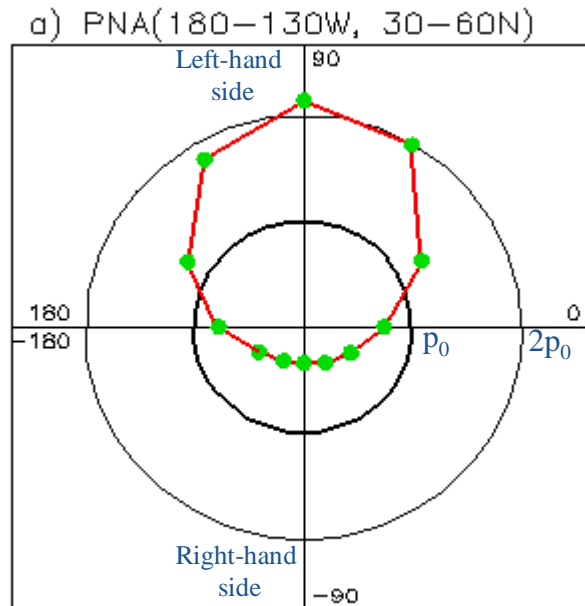


Observational Evidence II



Probability Distribution Function (PDF) of Angles

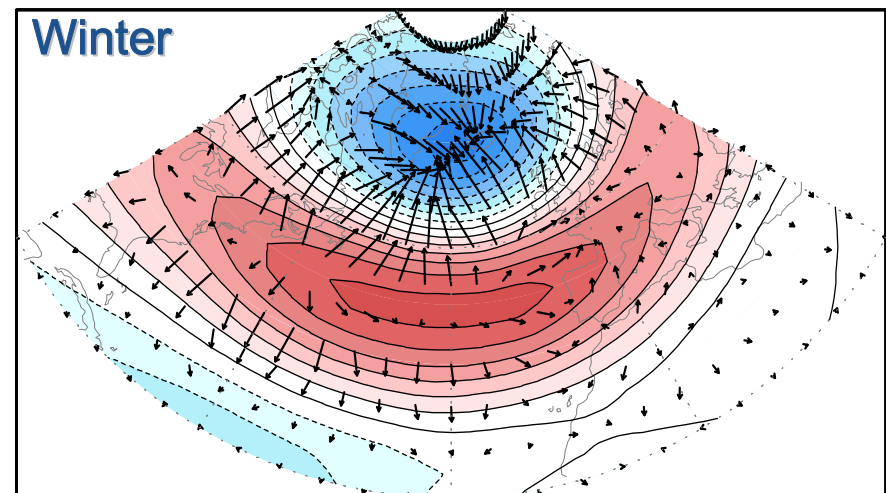
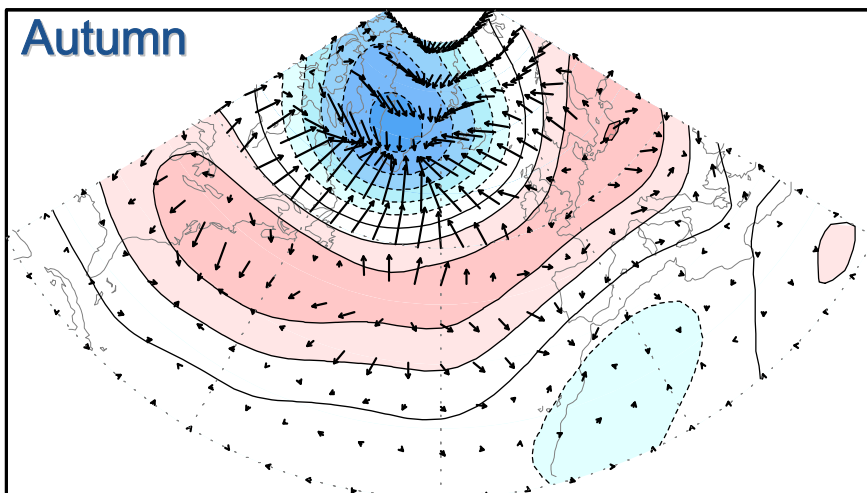
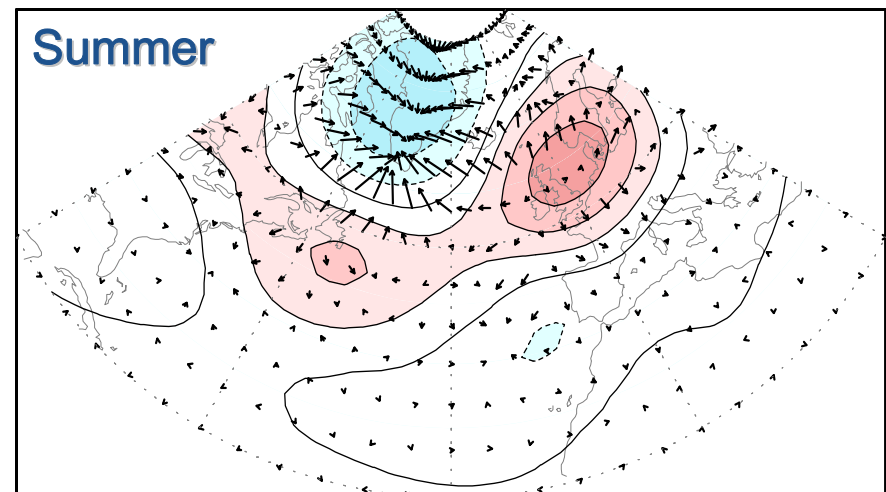
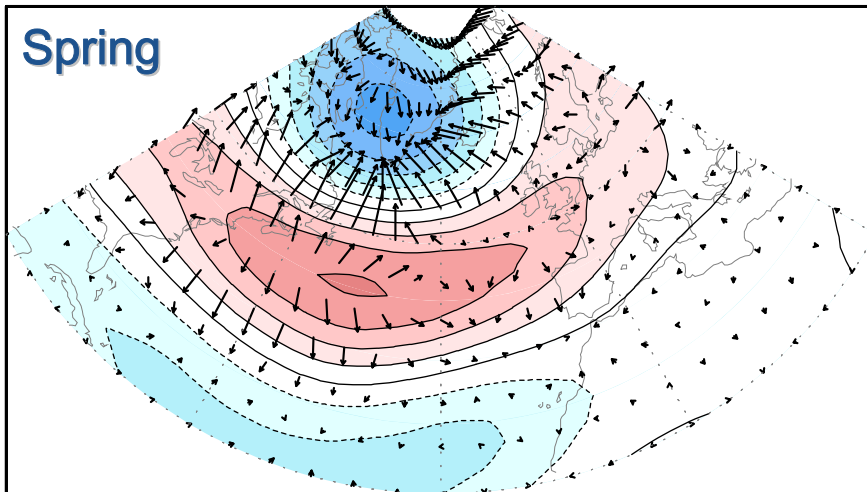
Winter (DJF)/1981-2008





NAO Mode

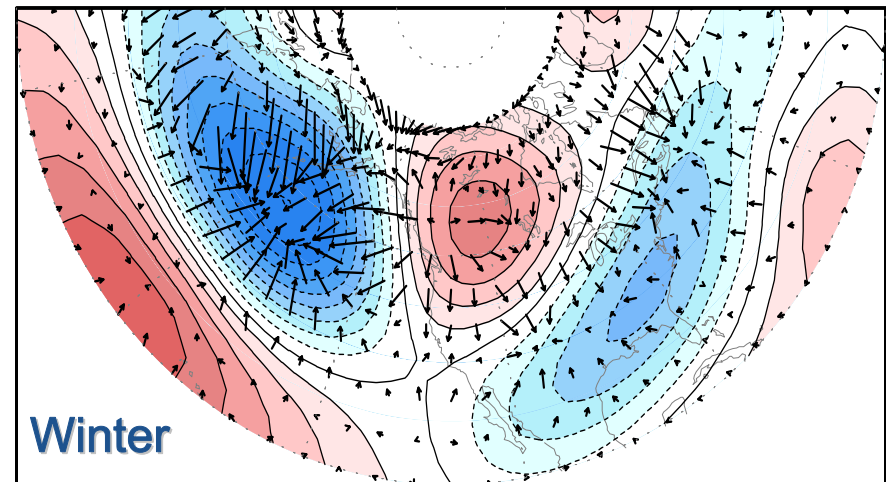
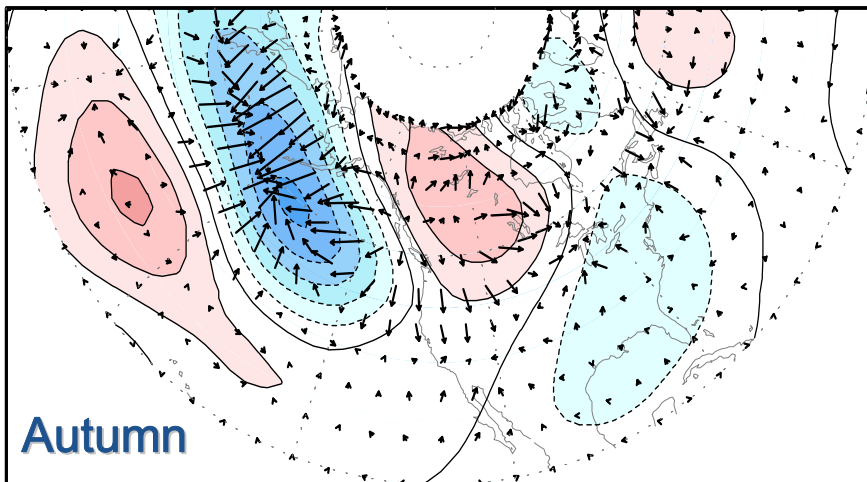
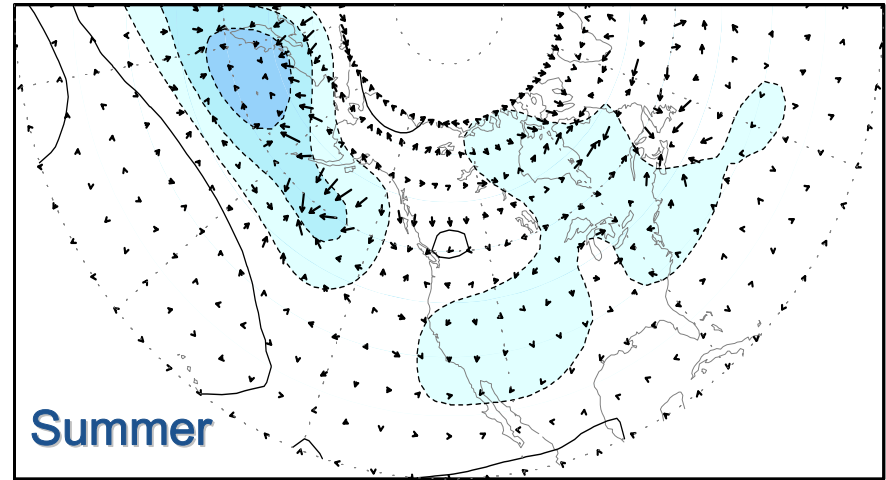
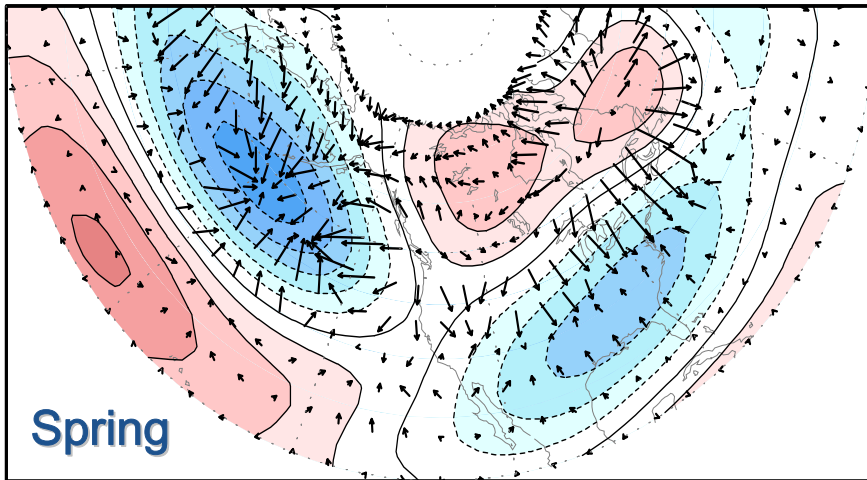
Regressed NAO pattern (shading) and Eddy-vorticity flux (vector) $(\overline{u'\zeta'}, \overline{v'\zeta'})$





PNA Mode

Regressed PNA pattern (shading) and Eddy-vorticity flux (vector) $(\overline{u'\zeta'}, \overline{v'\zeta'})$





2. **Left Hand Rule** for Temperature and Moisture flux

The **eddy-temperature and moisture fluxes** are also preferentially about 90 degrees **toward the left-hand side of the low-frequency flow** in the northern hemisphere. The temperature fluxes and their vertical structure play a role in constructing **equivalent barotropic structure** of the low frequency flow. The moisture fluxes play a role in enhancing low-frequency flow by providing **eddy-induced moisture feedback**. In addition, **the eddy-potential vorticity fluxes** are also directed to the left-hand side of low-frequency flow in both hemispheres.



Correlation between Seasonal Mean Wind and Eddy Flux

NH/Winter

$$Cor(\bar{u}, \overline{v'T'})$$

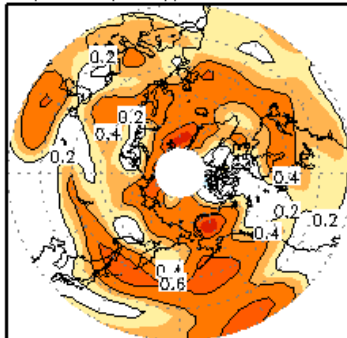
$$Cor(\bar{v}, \overline{u'T'})$$

$$Cor(\bar{u}, \overline{v'q'})$$

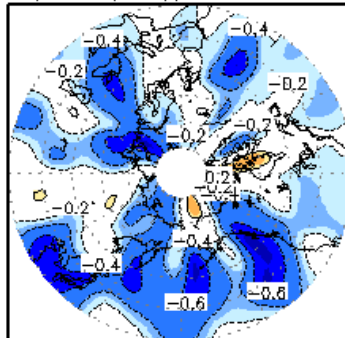
$$Cor(\bar{v}, \overline{u'q'})$$

300hPa

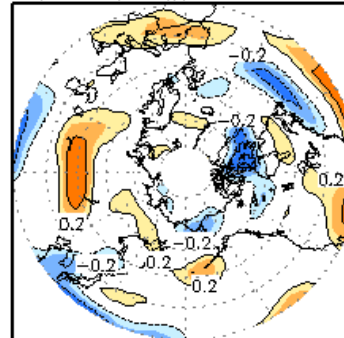
a) COR(U,vT)/NH



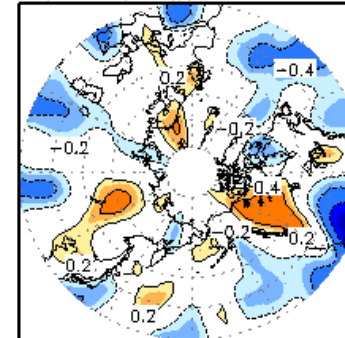
b) COR(V,uT)/NH



a) COR(U,vq)/NH

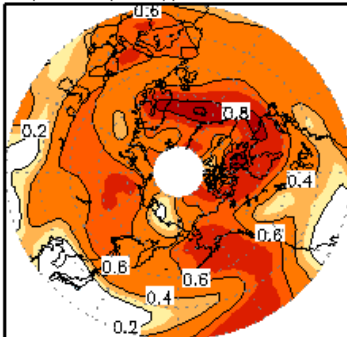


b) COR(V,uq)/NH

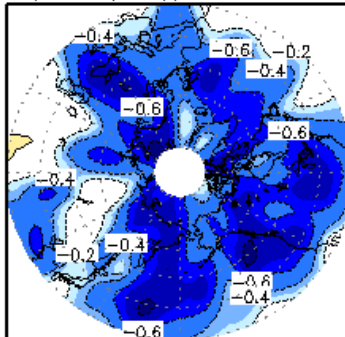


700hPa

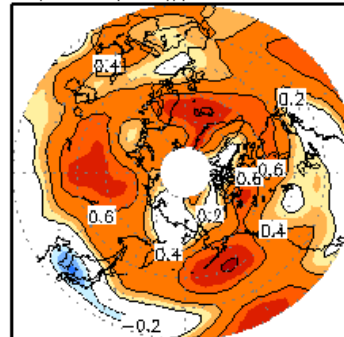
a) COR(U,vT)/NH



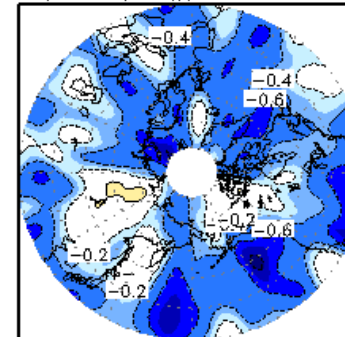
b) COR(V,uT)/NH



a) COR(U,vq)/NH

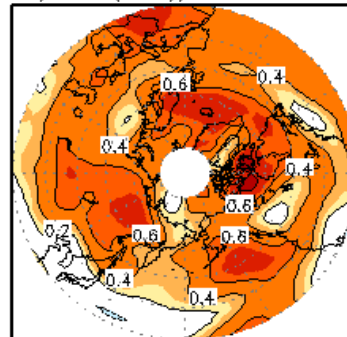


b) COR(V,uq)/NH

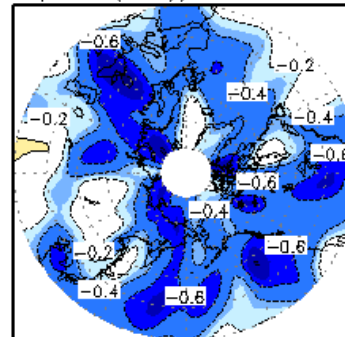


850hPa

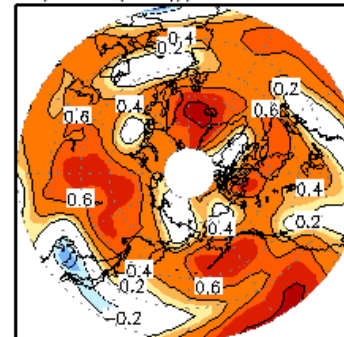
a) COR(U,vT)/NH



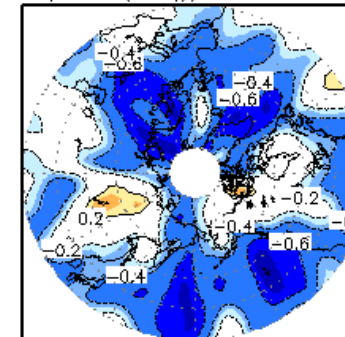
b) COR(V,uT)/NH



a) COR(U,vq)/NH



b) COR(V,uq)/NH



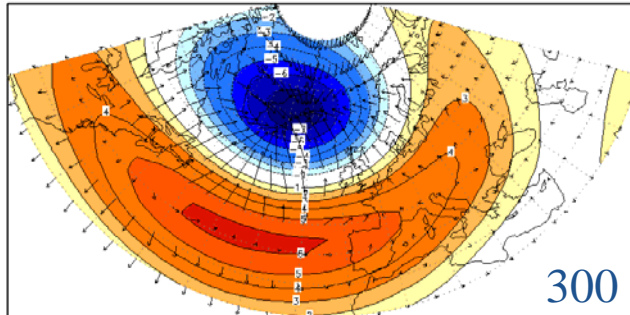


NAO/3-dimensional eddy forcing

Vector: Eddy flux

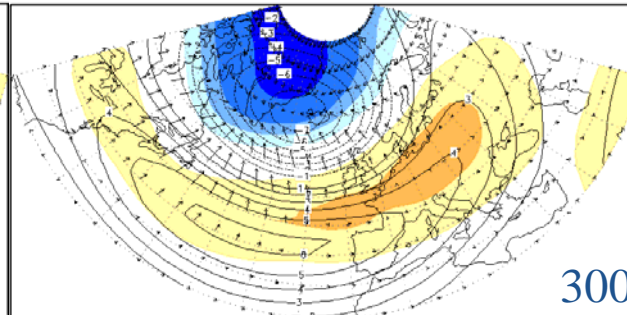
Stream Function

Strm, vorflux at 300hPa



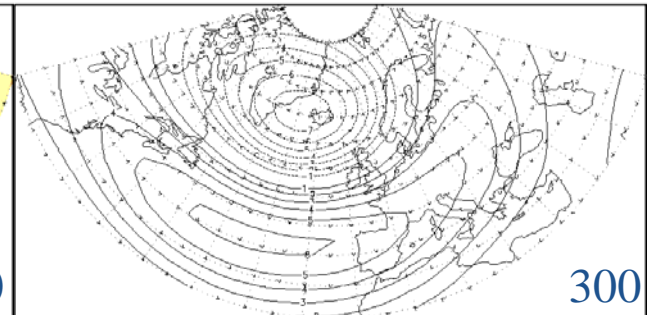
Temperature

Strm, Temp, Tflux at 300hPa

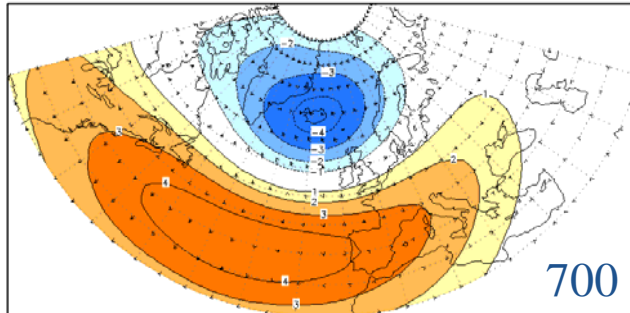


Moisture

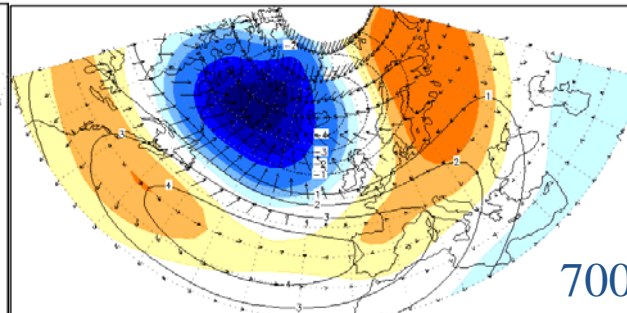
Strm, q, qlflux at 300hPa



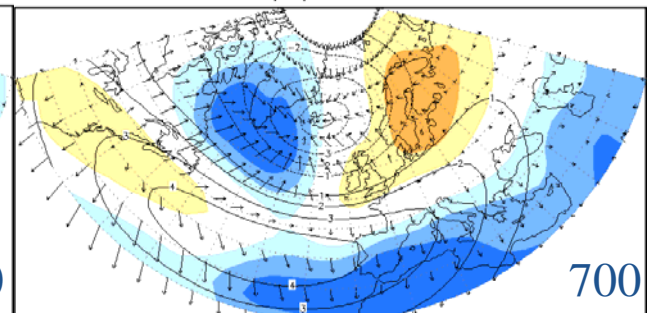
Strm, vorflux at 700hPa



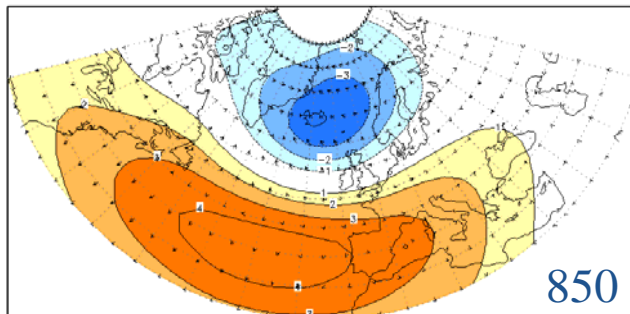
Strm, Temp, Tflux at 700hPa



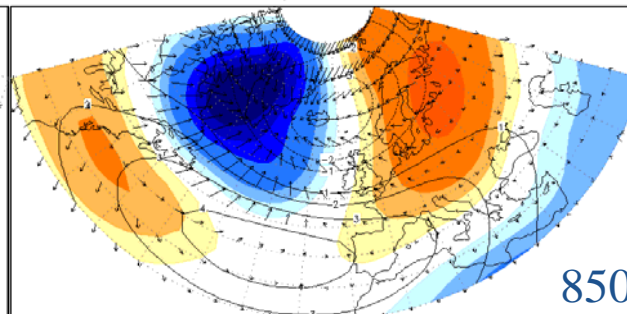
Strm, q, qlflux at 700hPa



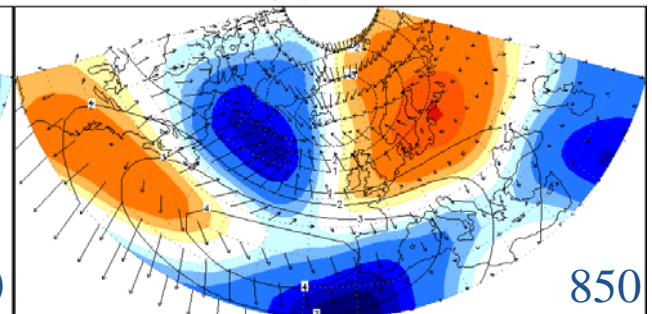
Strm, vorflux at 850hPa



Strm, Temp, Tflux at 850hPa



Strm, q, qlflux at 850hPa



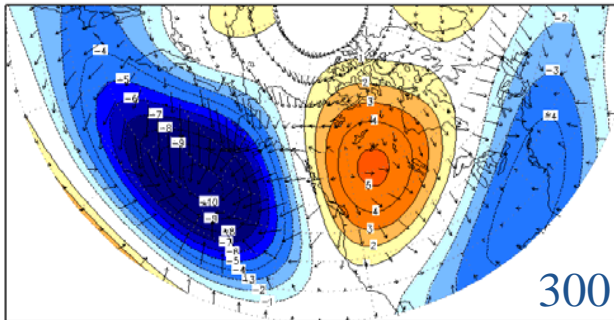


PNA/3-dimensional eddy forcing

Vector: Eddy flux Moisture

Stream Function

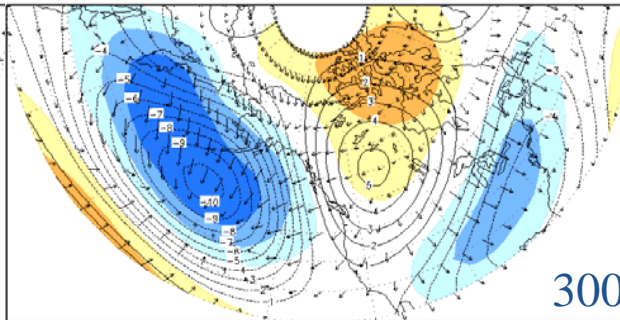
Strm, vorflux at 300hPa



300

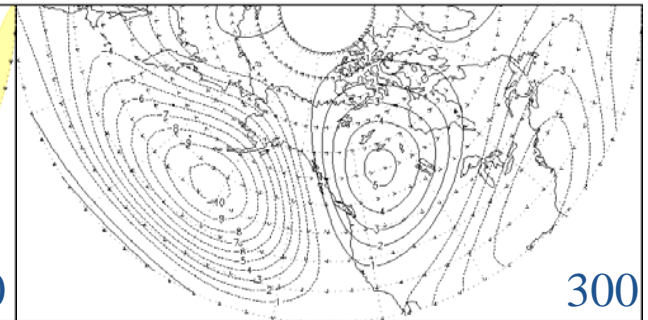
Temperature

Strm, Temp, Tflux at 300hPa



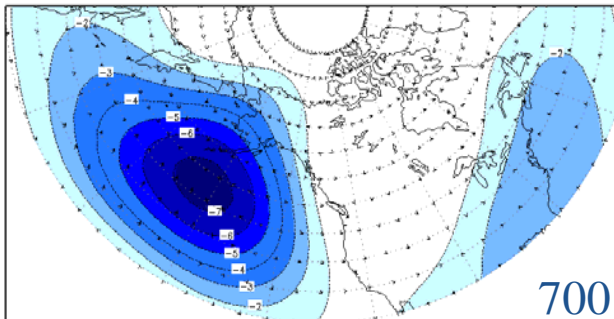
300

Strm, q, qflux at 300hPa



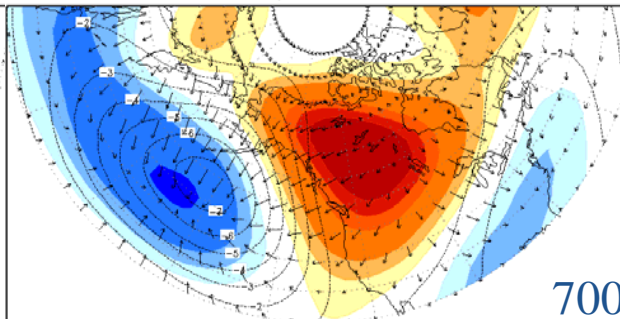
300

Strm, vorflux at 700hPa



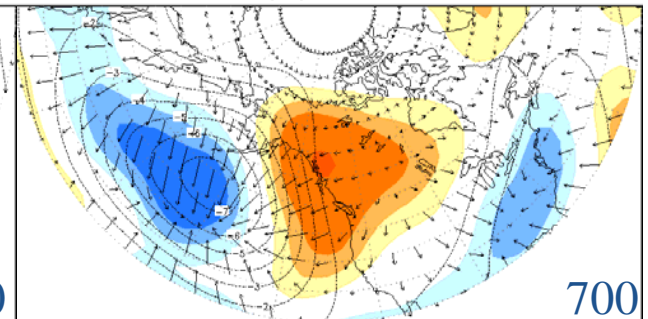
700

Strm, Temp, Tflux at 700hPa



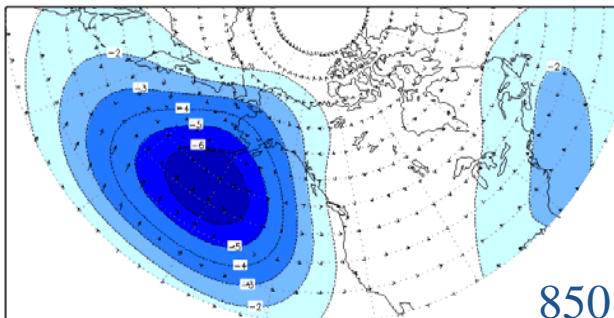
700

Strm, q, qflux at 700hPa



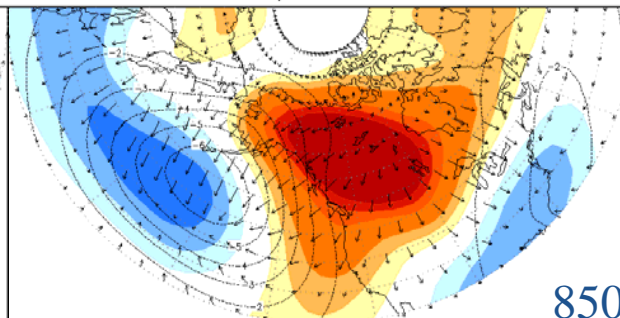
700

Strm, vorflux at 850hPa



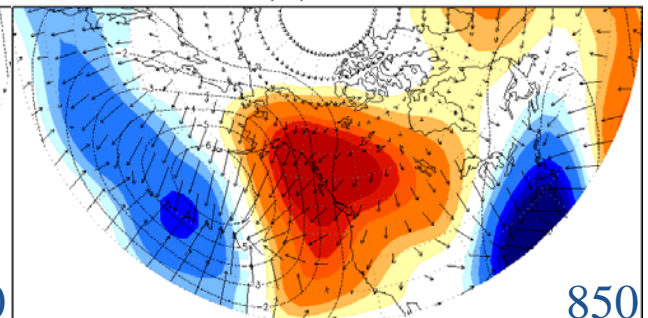
850

Strm, Temp, Tflux at 850hPa



850

Strm, q, qflux at 850hPa



850



Eddy Feedback with 3-Dimensional Structure

◆ Quasi-geostrophic Potential Vorticity

$$q \equiv \frac{1}{f_0} \nabla^2 \Phi + f + \frac{\partial}{\partial p} \left(\frac{f_0}{\sigma} \frac{\partial \Phi}{\partial p} \right)$$

◆ Eddy Potential Vorticity Flux

$$\nabla \cdot \overline{\vec{V}' q'} \approx \nabla \cdot \overline{\vec{V}' \zeta'} + \frac{\partial}{\partial p} \left(-\frac{f}{\sigma} \nabla \cdot \overline{\vec{V}' T'} \right)$$

◆ Eddy-Induced Circulation

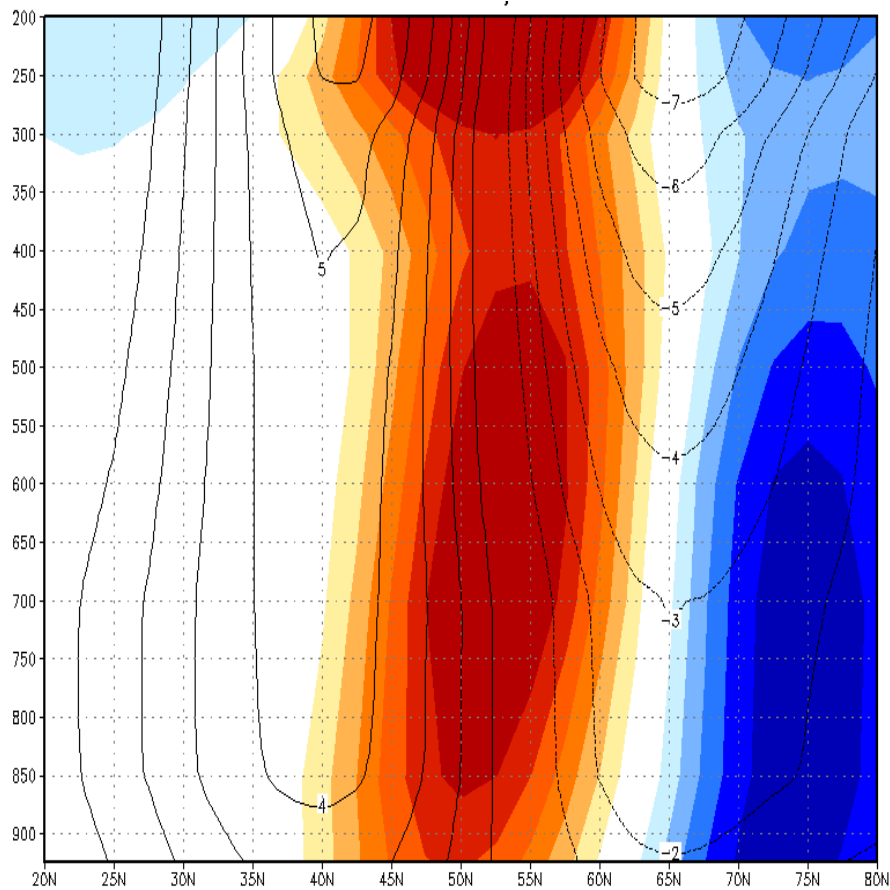
$$\left[\nabla^2 + \frac{\partial}{\partial p} \left(\frac{f^2}{\sigma} \frac{\partial}{\partial p} \right) \right] \frac{\partial \overline{\Phi}_a}{\partial t} \approx -f \nabla \cdot \overline{\vec{V}' \zeta'} - \frac{\partial}{\partial p} \left(-\frac{f^2}{\sigma} \nabla \cdot \overline{\vec{V}' T'} \right)$$



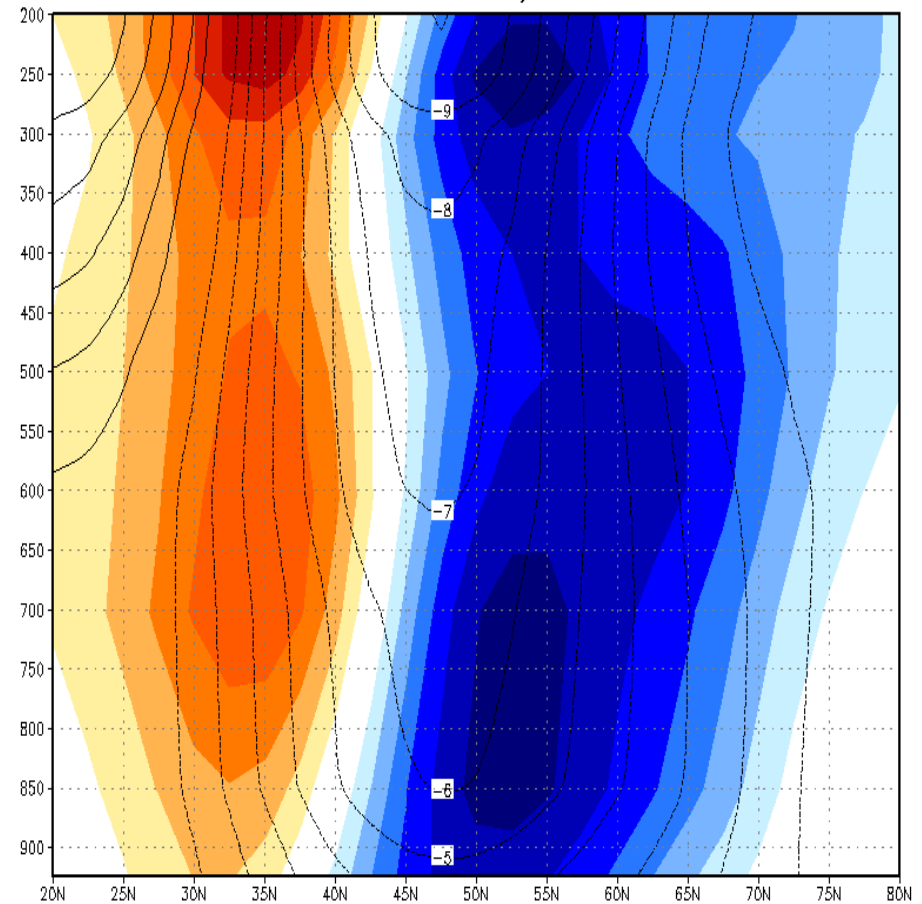
Vertical Structure of Eddy Temperature Flux

Contour: **Streamfunction**, Shading: **Meridional Temperature Flux** ($\overline{v'T'}$)

At 330E/ NAO



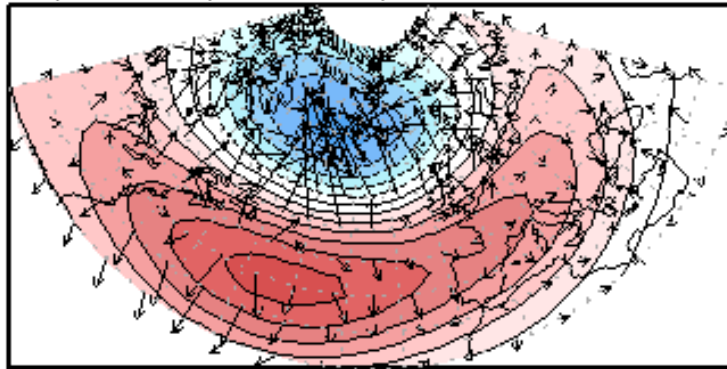
At 210E/ PNA



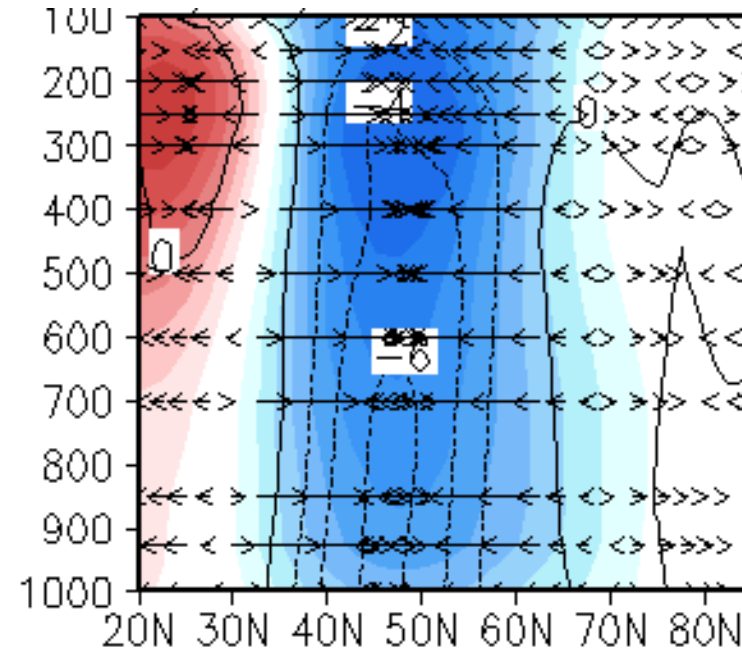
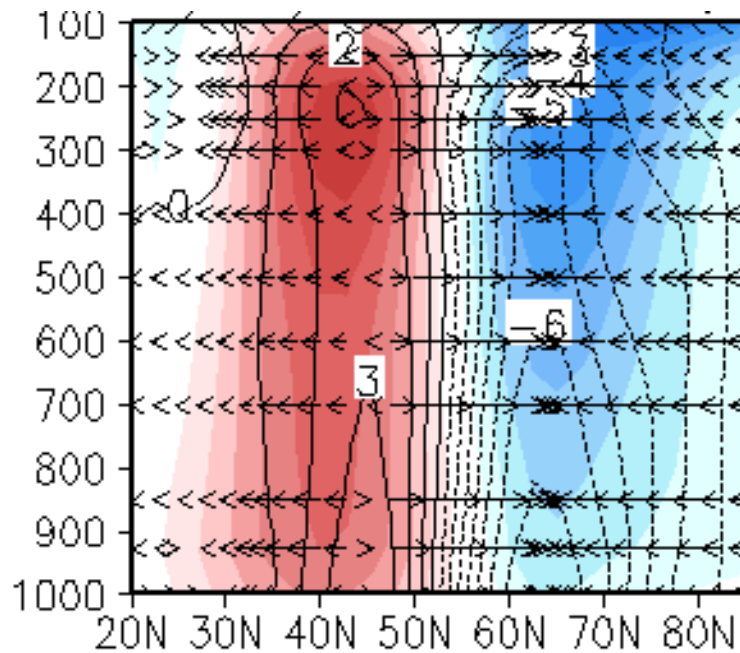
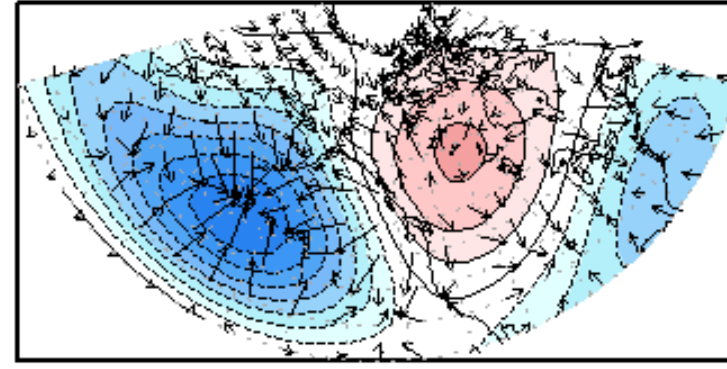


Left-Hand Rule For Eddy-Potential Vorticity Flux

NAO/500hPa



PNA/500hPa



Shading: Stream Function, Contour: Potential Vorticity, Vector: Eddy-PV Fluxes

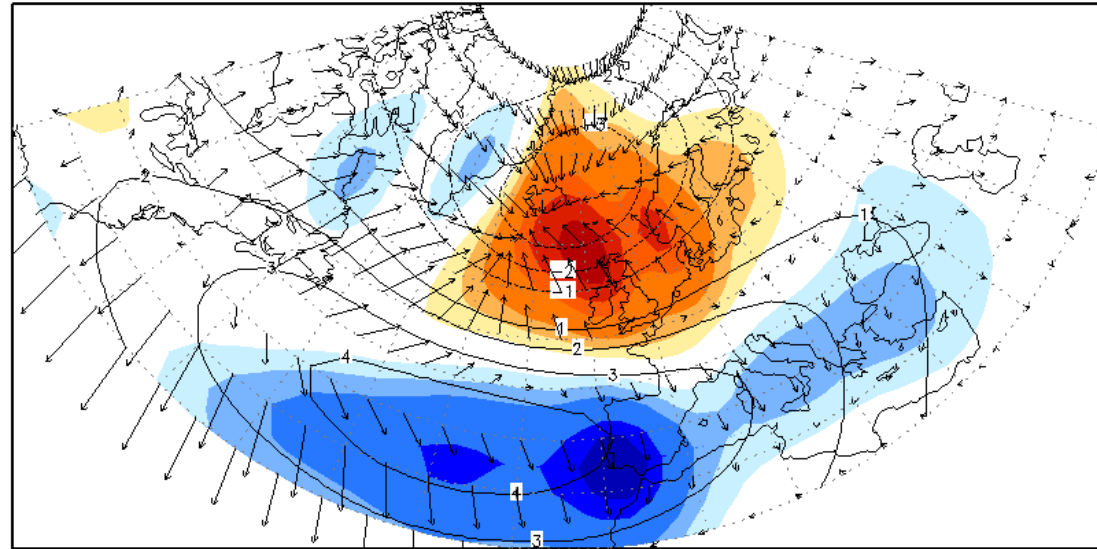


Eddy Moisture flux and Precipitation I

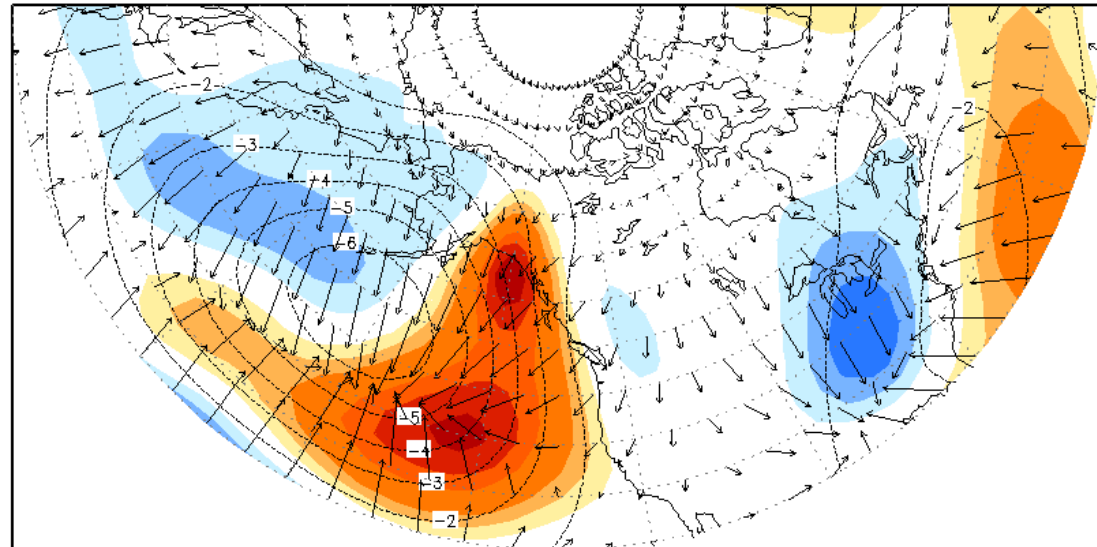
NAO

Streamfunction (contour)
Precipitation (Shading)
Eddy moisture flux (vector)

Strm, PRCP, qflux at 850hPa



Strm, PRCP, qflux at 850hPa



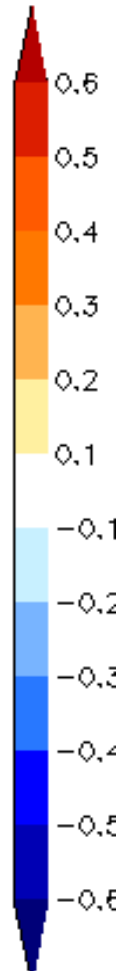
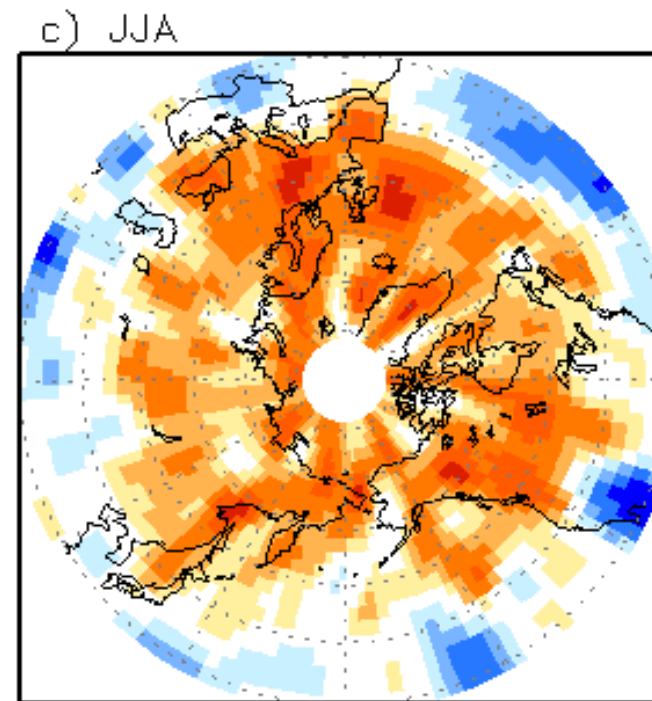
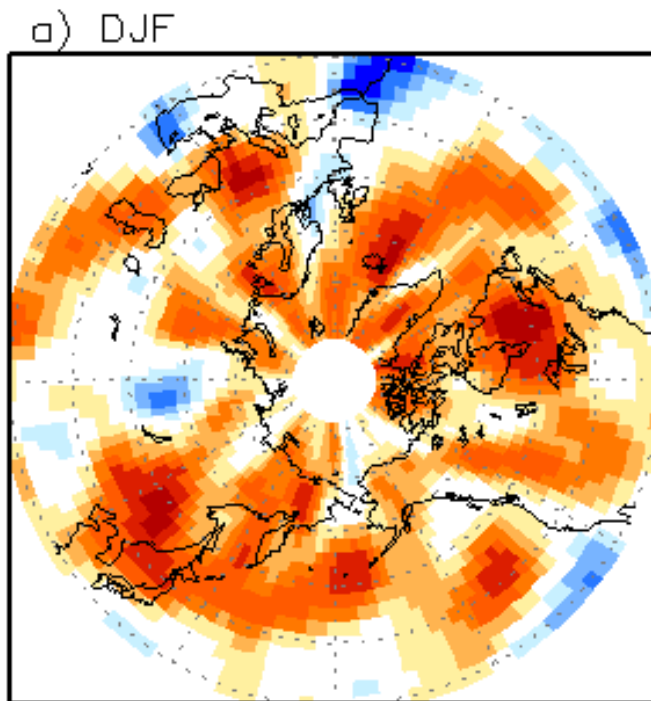
PNA



Eddy Moisture flux and Precipitation II

Correlation

Eddy-induced moist. Convergence and Precipitation

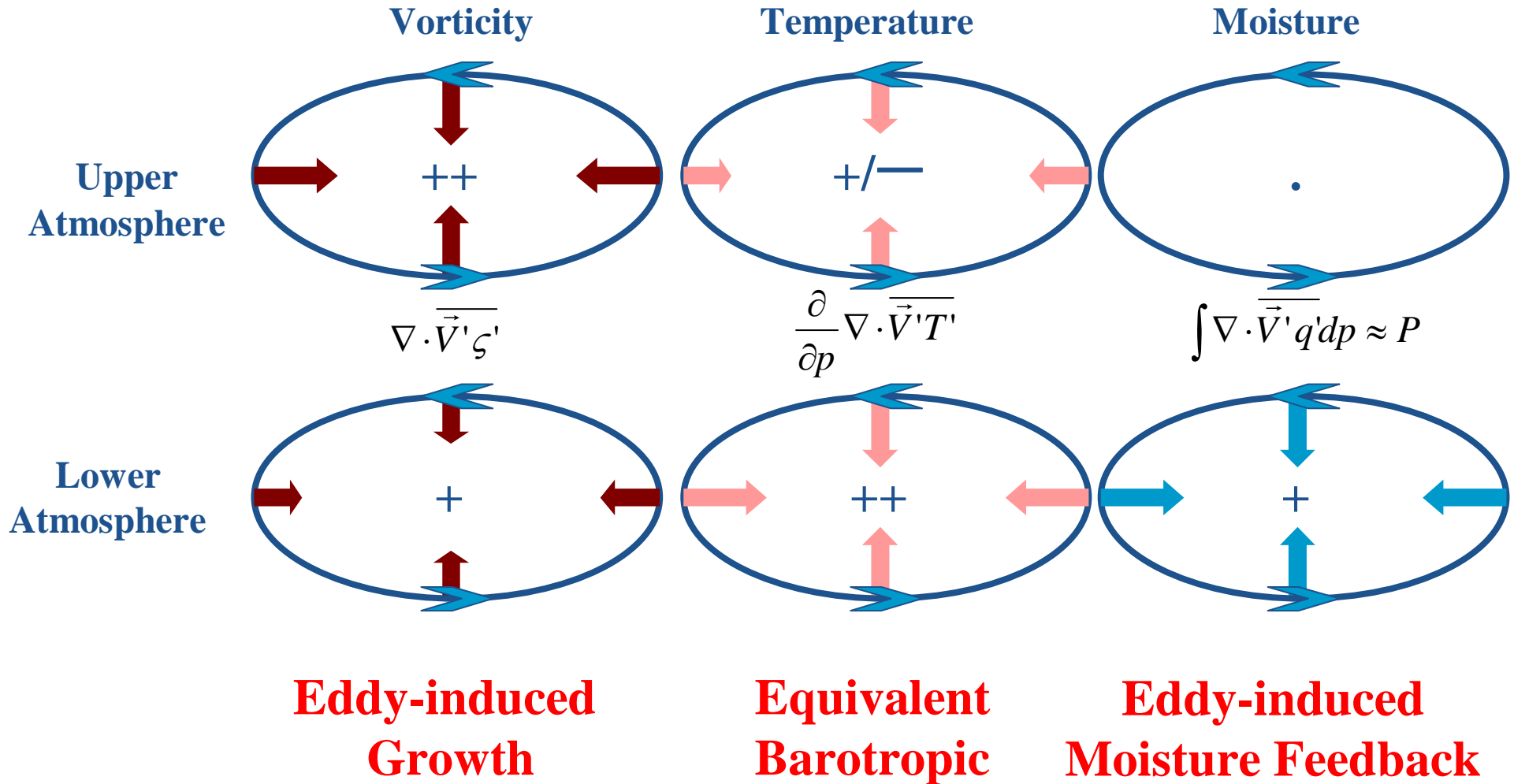


Based on Monthly Mean Data



Collective Roles of Synoptic-Eddy forcing

$$\left[\nabla^2 + \frac{\partial}{\partial p} \left(\frac{f^2}{\sigma} \frac{\partial}{\partial p} \right) \right] \frac{\partial \bar{\Phi}_a}{\partial t} \approx -f \nabla \cdot \overline{\vec{V}' \zeta'} - \frac{\partial}{\partial p} \left(-\frac{f^2}{\sigma} \nabla \cdot \overline{\vec{V}' T'} \right)$$



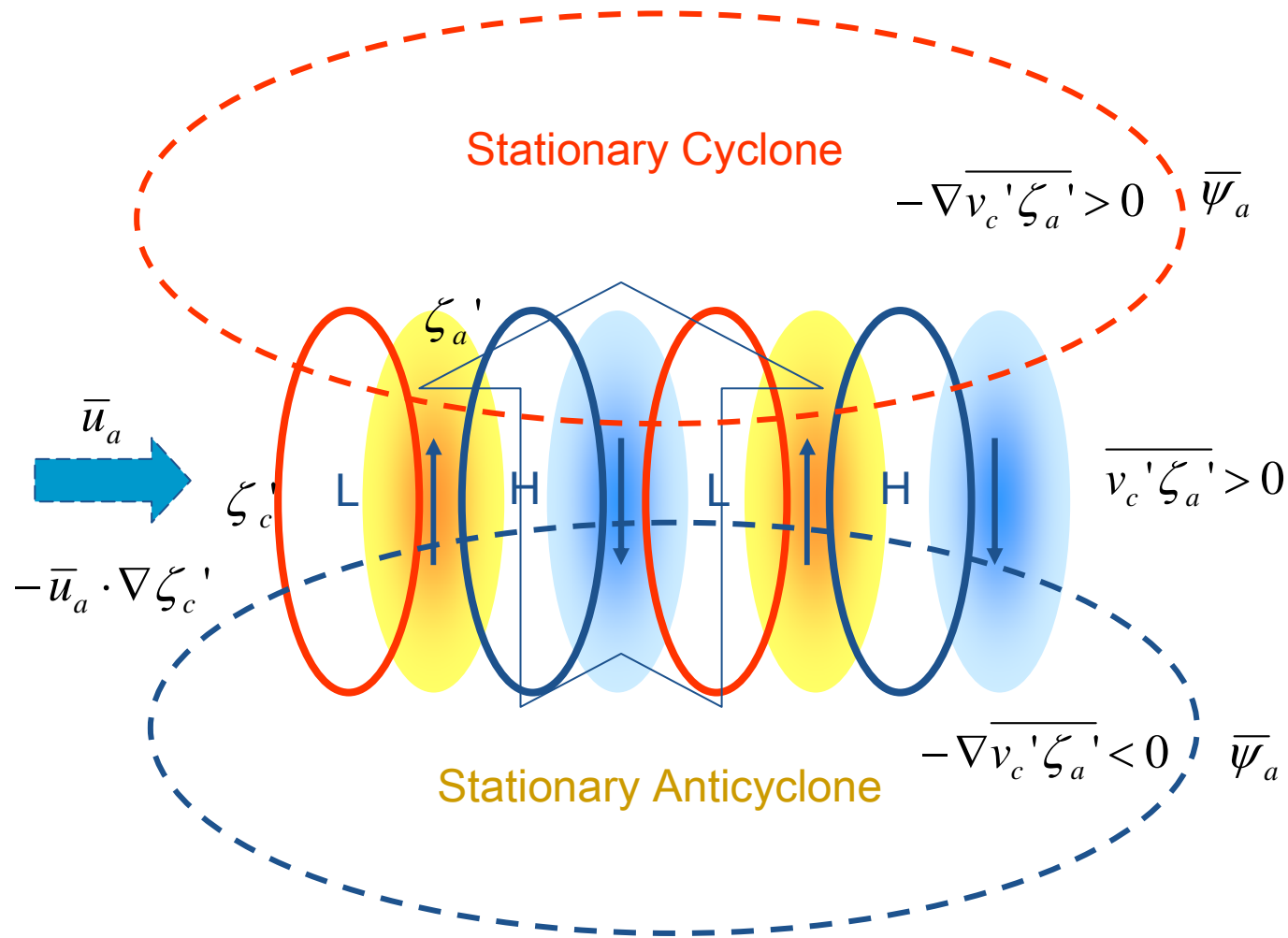


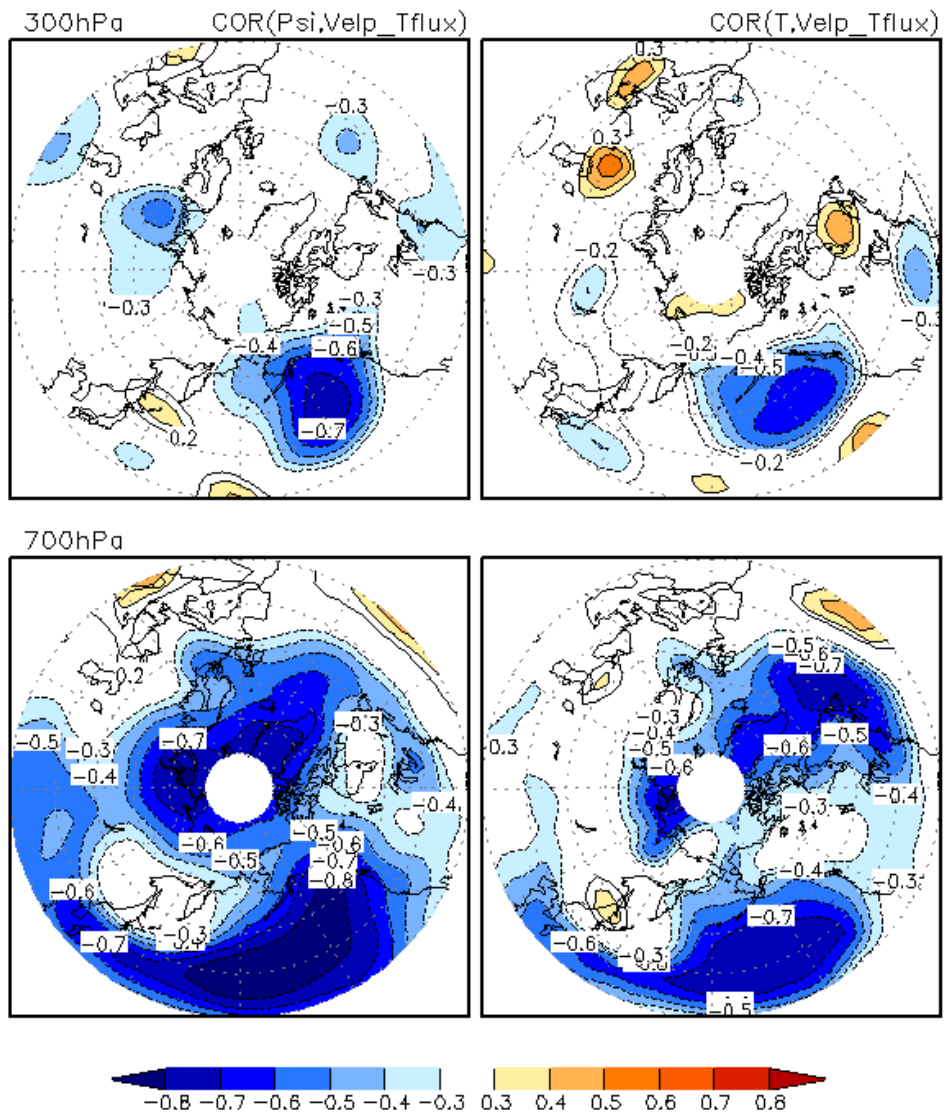
Summary

- ◆ We found a general rule on the synoptic eddy and low-frequency flow interaction.
- ◆ The Left-hand rule indicates that **all eddy-induced vorticity, temperature, moisture and potential vorticity fluxes tend to be directed to the left-hand side of the low-frequency flow.**
- ◆ The Low-frequency flow has **self-organization processes by harvesting synoptic eddies** based on the left-hand rule.
 - **Eddy-induced Growth Rate**
 - **Scale Selection**
 - **Equivalent Barotropic Structure**
 - **Eddy-induced Moisture Feedback**
- ◆ The Left-hand rule, synoptic eddy-low frequency interaction, works not only monthly mean flow but also **decadal time scale and climate change projection.**



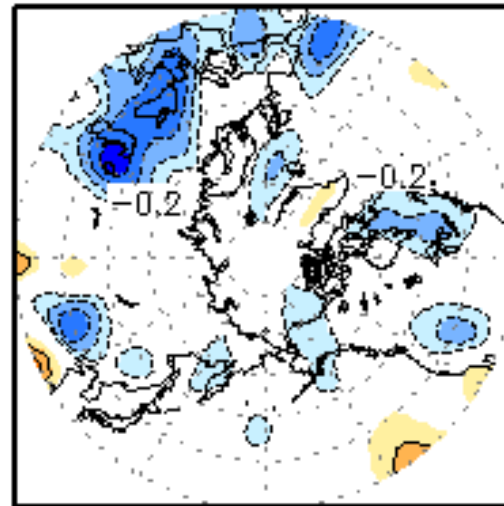
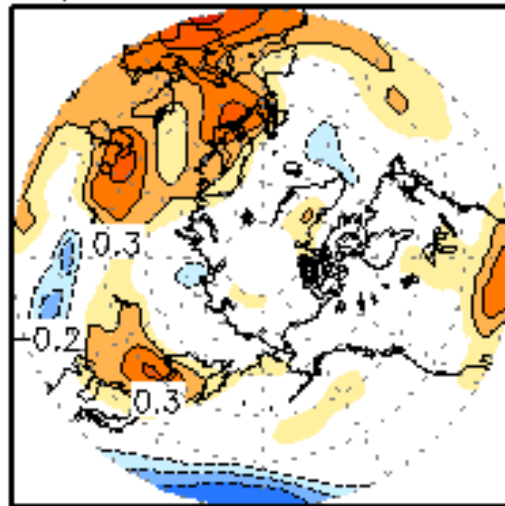
Schematic Diagram II



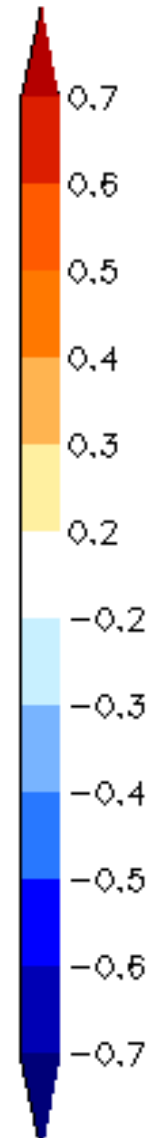
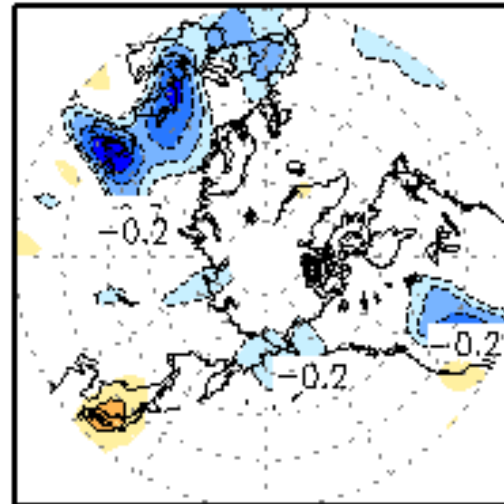
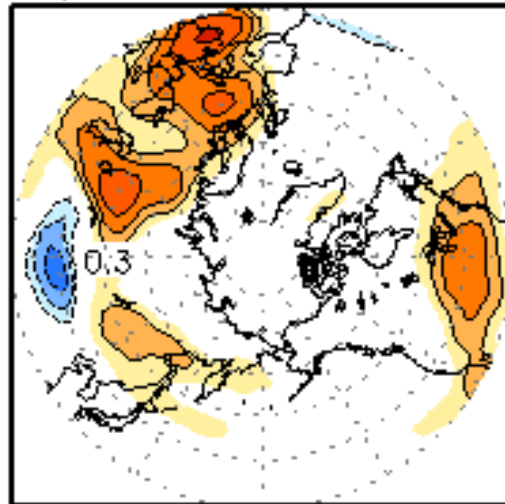




b) MAM



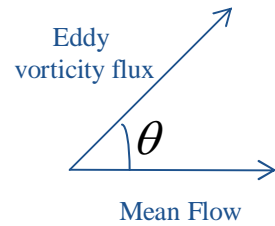
c) JJA





Observational Evidence II

Probability for the Left-Hand Rule

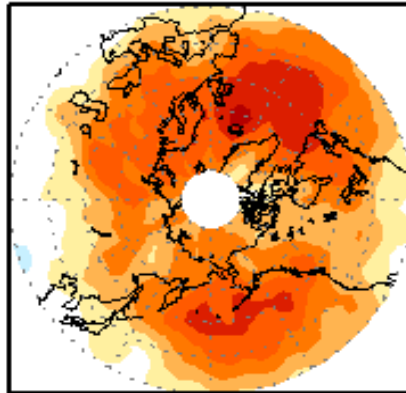


$0 < \theta < 180$: Left - hand Side

$-180 < \theta < 0$: Right - hand Side

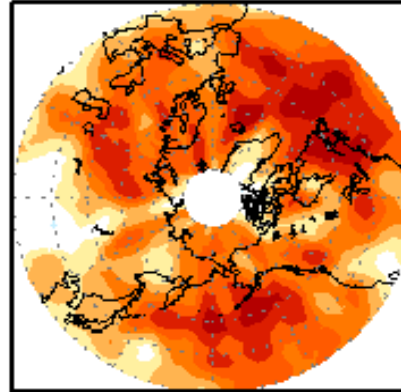
Probability for Left-hand Rule

a) All Seasons

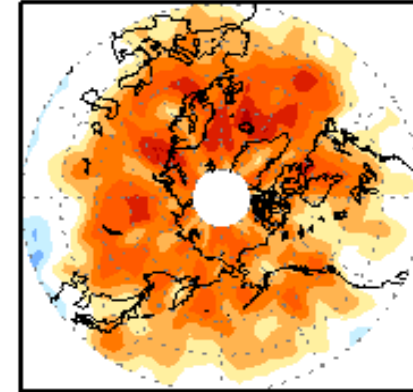


Mean=50%, C.I.= 5%

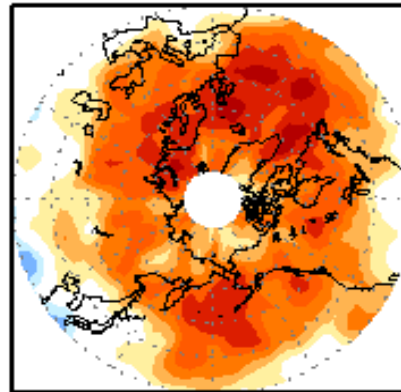
b) MAM



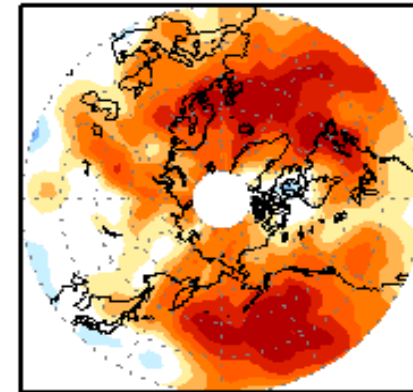
c) JJA



d) SON



e) DJF



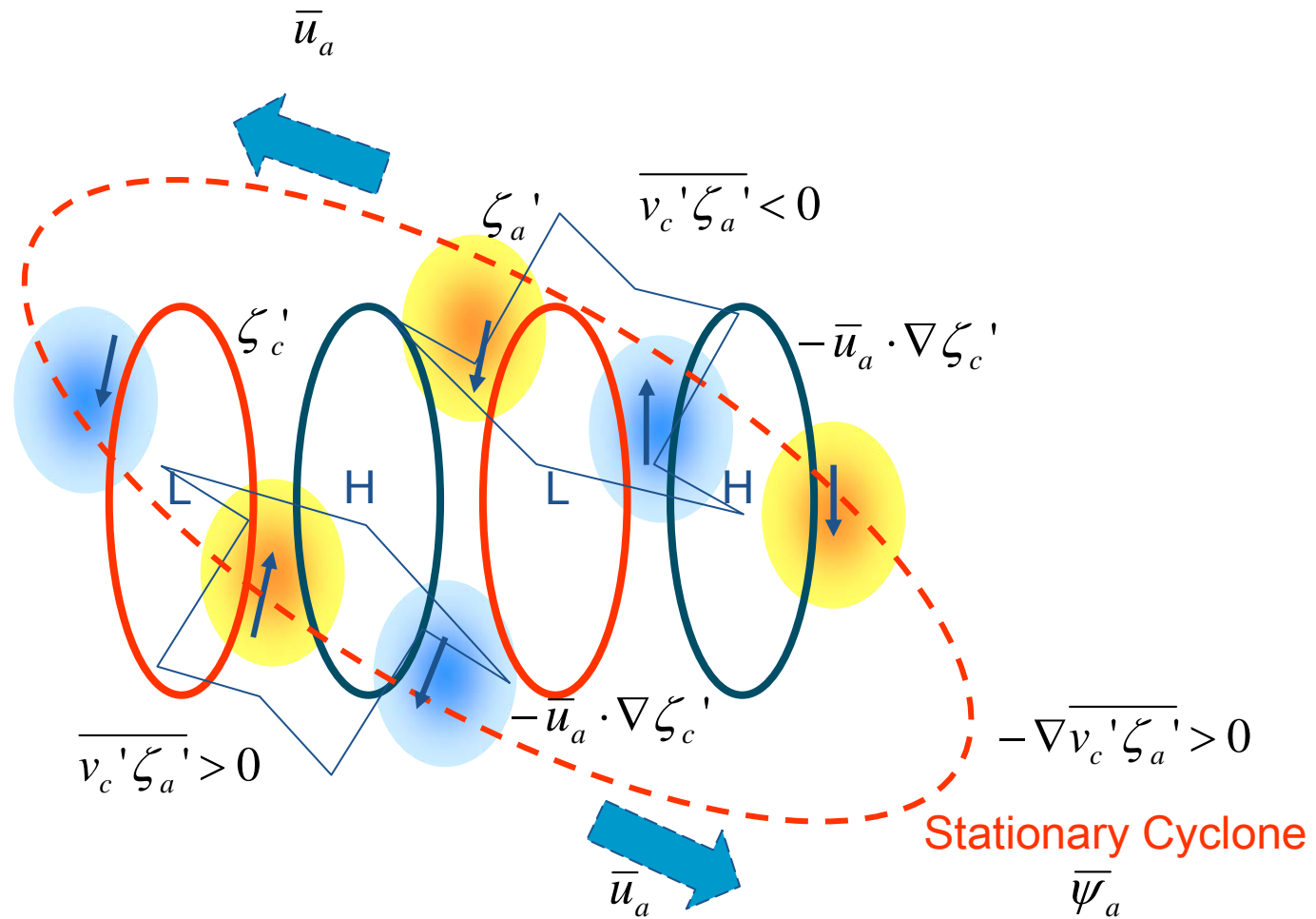


Key Questions

- How can **the low-frequency climate mode persist** under stormy atmospheric circulation in middle latitude?
- How does **low-frequency flow harvest chaotic synoptic eddies** to obtain the positive eddy feedback?
- What is **3-dimensional structure of the eddy forcing** and its role on the low-frequency flow?
- How does **low-frequency flow** in middle latitude have **equivalent barotropic structure**?
- How can we understand the change of general circulation in global warming scenario?
- How will we utilize our knowledge and findings to climate prediction?

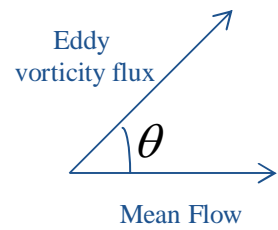


Schematic Diagram IV



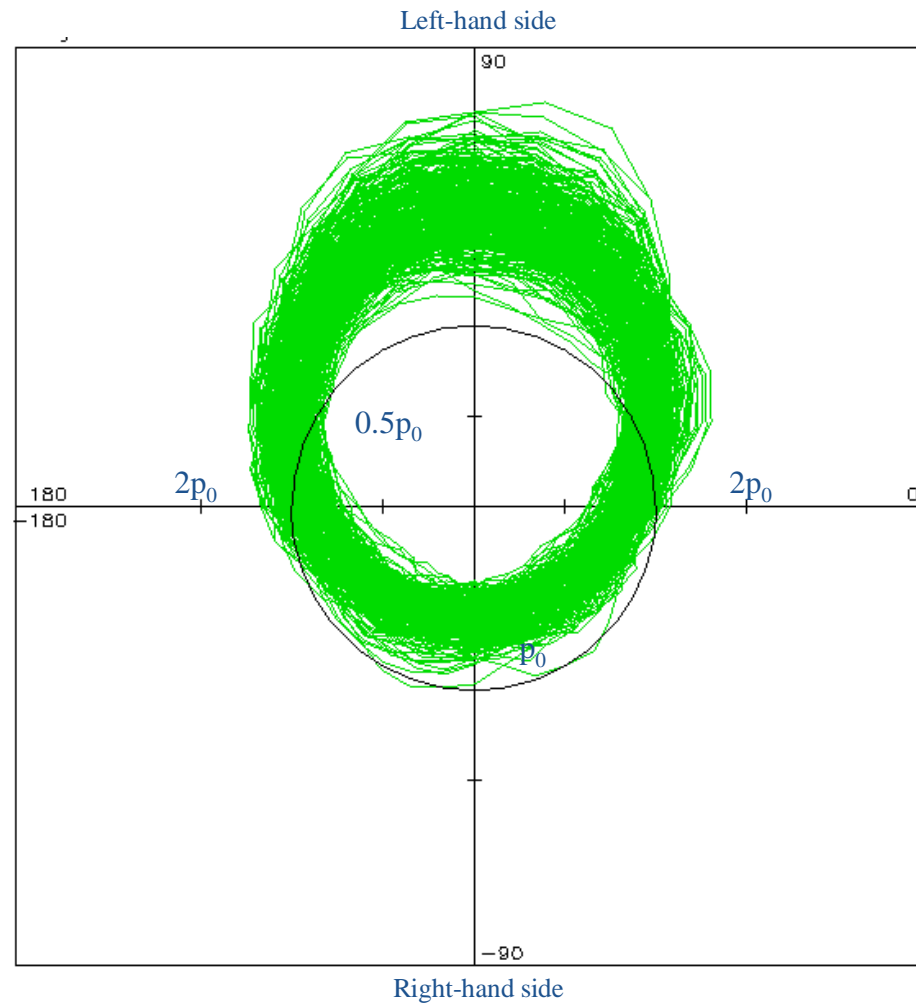


Observational Evidence IV



Probability Distribution Function (PDF) of Angles

1981-2008

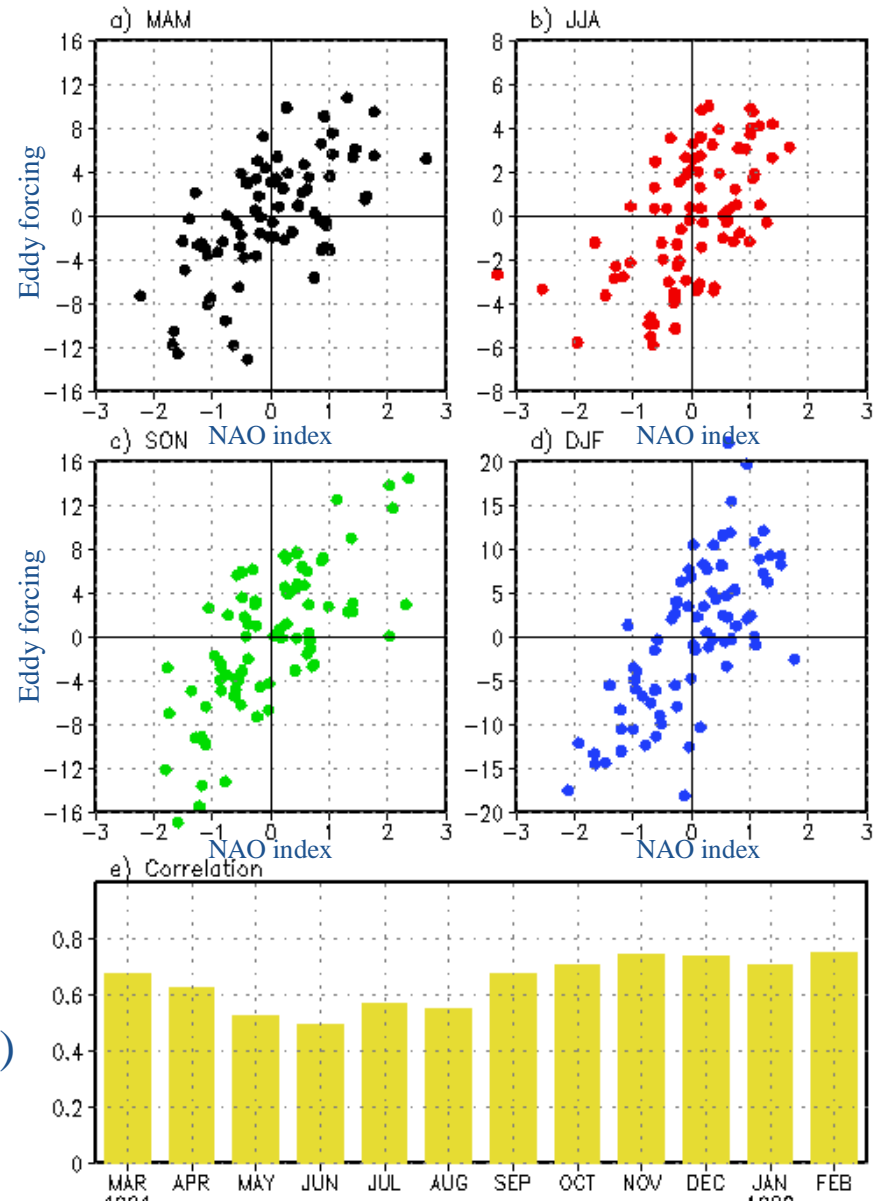


Each Month



Eddy Forcing associated with NAO Mode

$$-\overline{\nabla v' \zeta'^a}$$



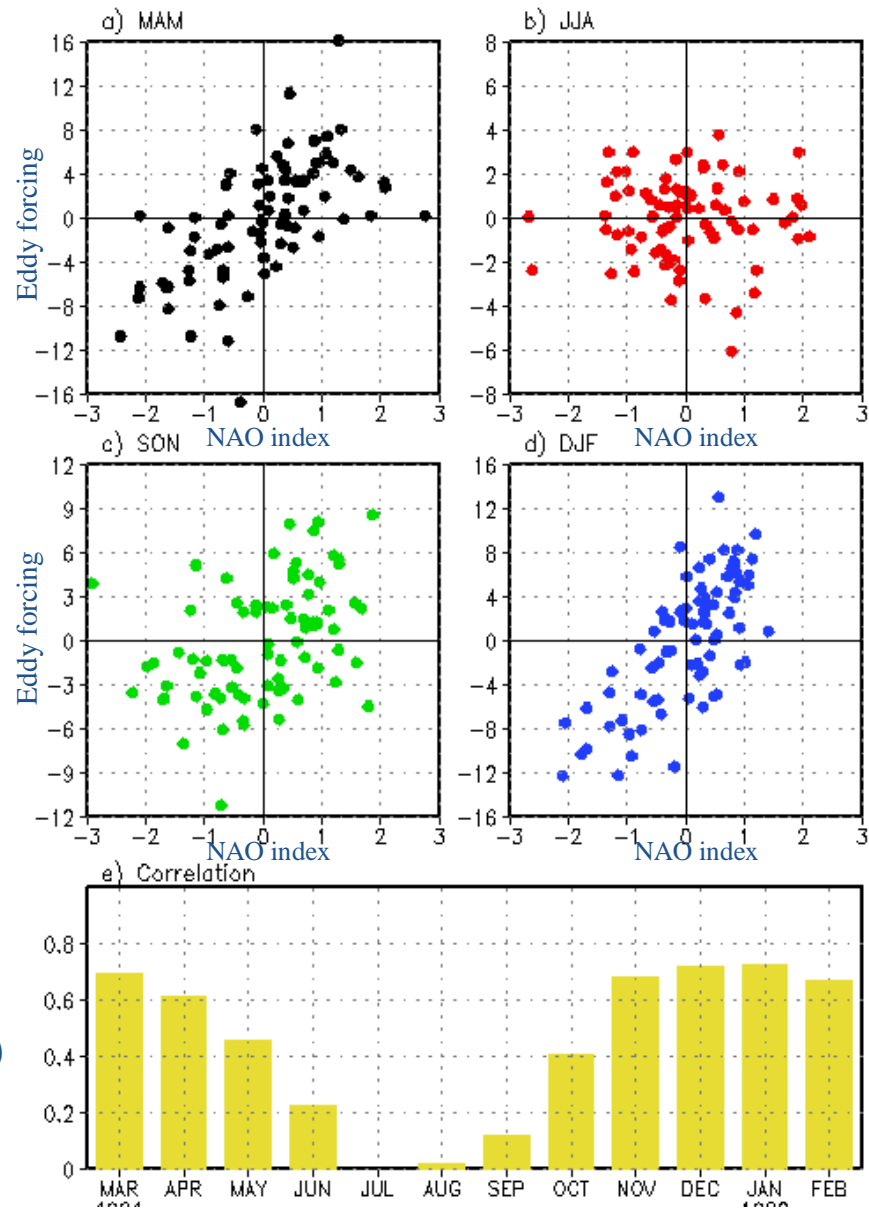
COR
(NAO index, Eddy forcing)



Eddy Forcing associated with PNA Mode

$$-\nabla v' \zeta'^a$$

COR
(PNA index, Eddy forcing)

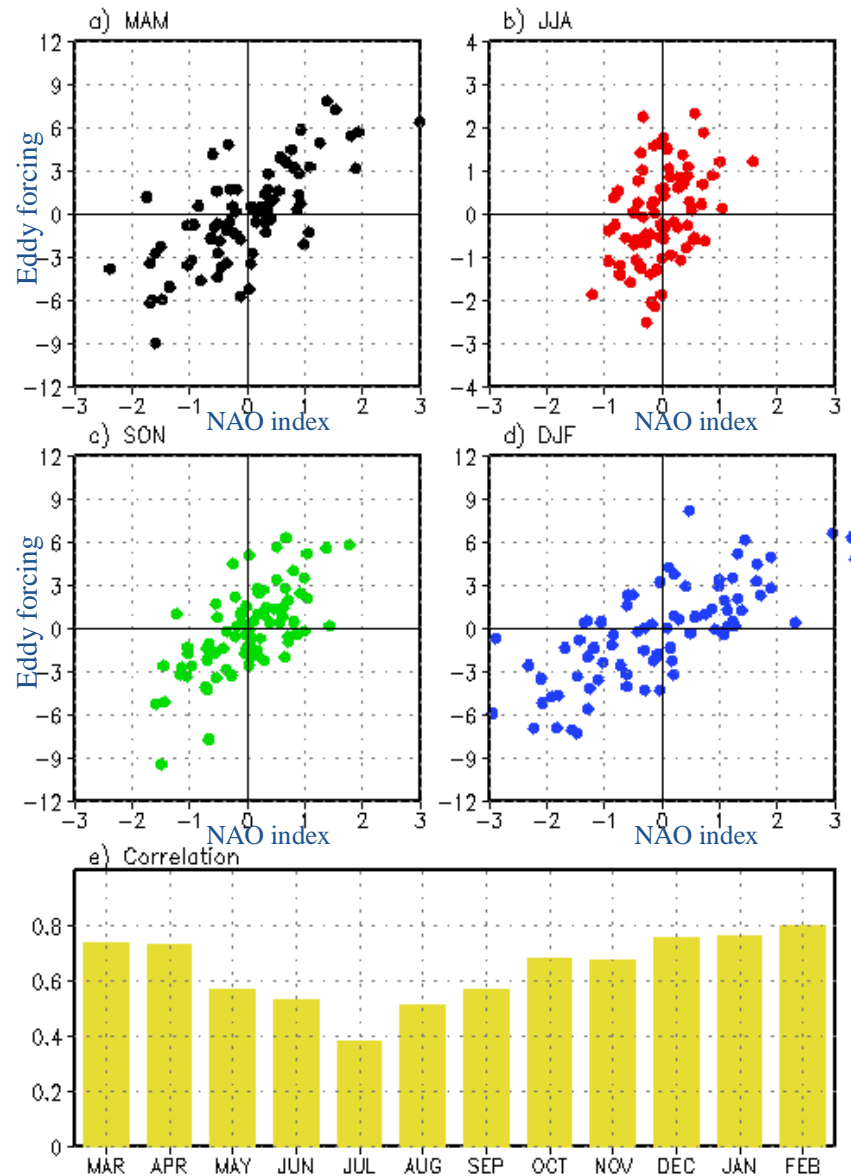




Eddy Forcing associated with AO Mode

$$-\overline{\nabla v' \zeta'^a}$$

COR
(AO index, Eddy forcing)



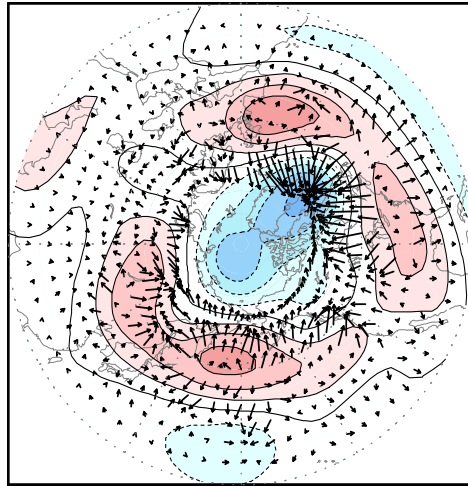


AO Mode

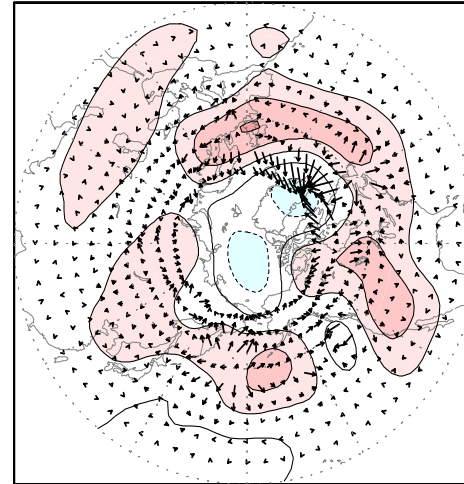
Regressed AO pattern (shading) and Eddy-vorticity flux (vector)

$$(\overline{u'\zeta'}, \overline{v'\zeta'})$$

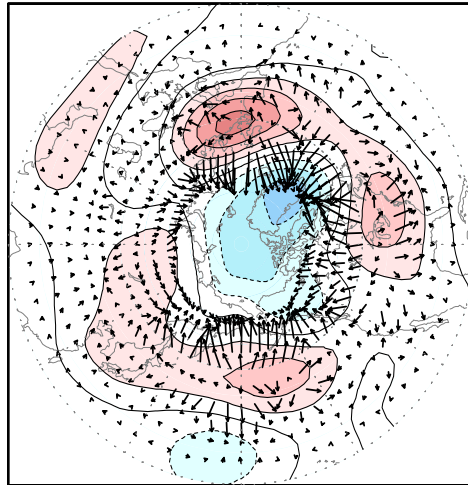
Spring



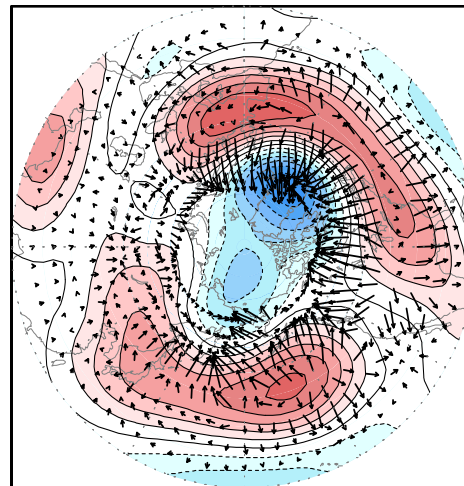
Summer



Autumn



Winter

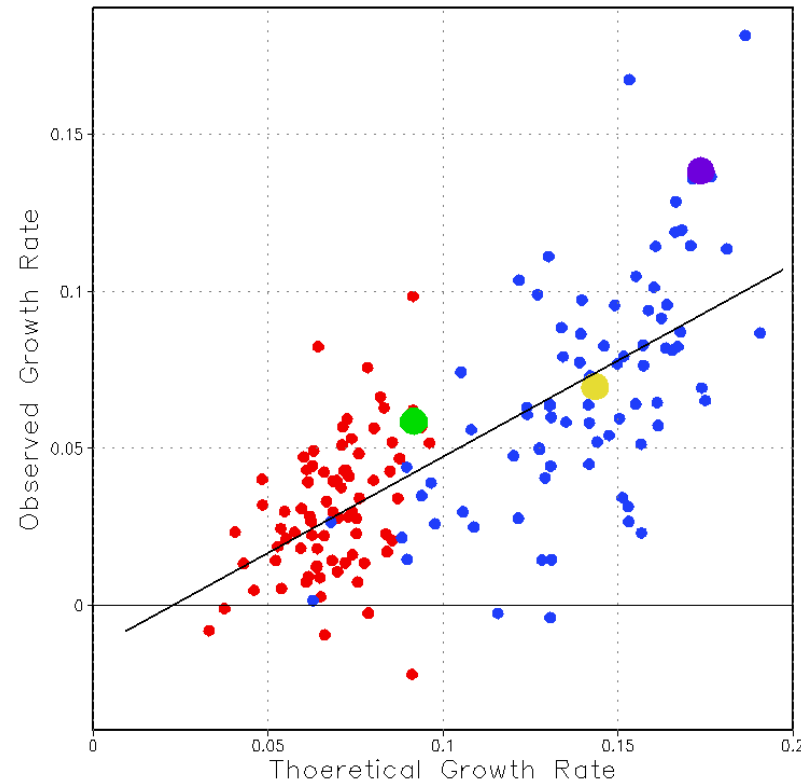




Eddy-Induced Growth rate for Monthly-mean Flow

Observed Growth Rate

$$\frac{\partial \bar{\psi}_a}{\partial t} \propto -\Delta^{-1} \nabla \overline{v' \zeta'} = \lambda \bar{\psi}_a$$
$$\lambda = \frac{-\iint \bar{\psi}_a \cdot \Delta^{-1} \nabla \overline{v' \zeta'} dx dy}{\iint \bar{\psi}_a^2 dx dy}$$



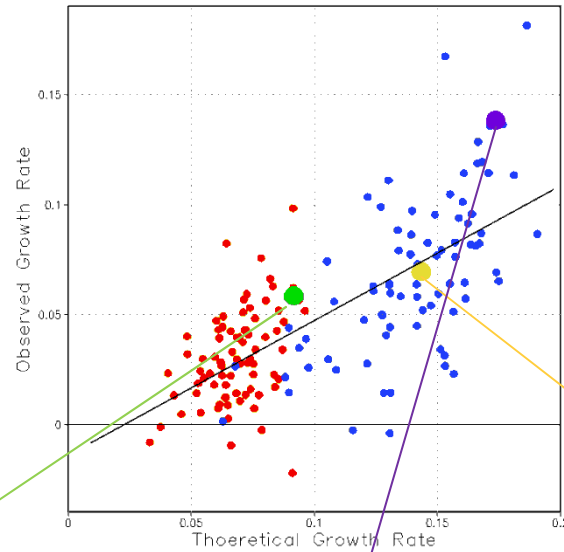
Theoretical Growth Rate

$$\lambda \propto \tau^{-1} E(K_c^2 - K^2) K^2$$

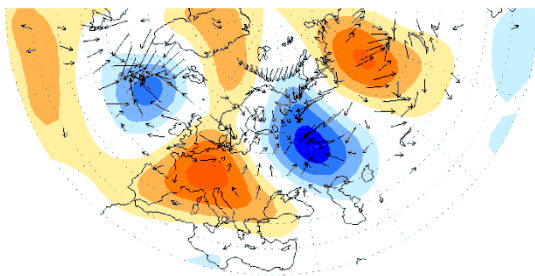
K_c: Wave number of Climatological Eddy
K: Wave number of Low-Frequency Flow



Blocking and Extreme Climate Events and Eddy Feedback

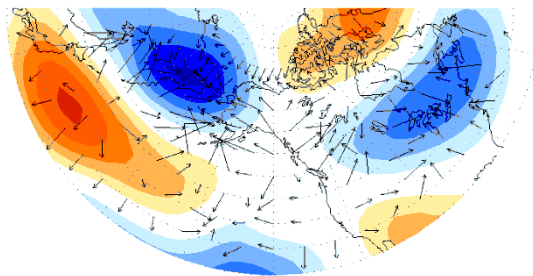


Europe (60W–120E,30–90N) at JUN2003



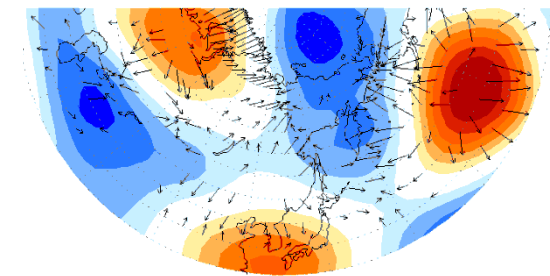
Europe Heat wave (Jun2003)

Hawaii (130E–50W,30–90N) at FEB2006



Hawaii Flood (Feb2006)

CHINA (40E–140W,30–90N) at JAN2008



China Heavy Snowfall (Jan2008)



Theoretical View and its Validation

Theoretical Estimate

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

$$\underbrace{\nabla^{-2}(\nabla \cdot \bar{V}' \zeta'^a)}_{\text{F: Streamfunction Tendency}} \approx \frac{1}{\tau_r} G_r (\nabla^{-2} + K_c^2) \underbrace{\left[E_x^2 \frac{\partial^2 \bar{\psi}^a}{\partial^2 x} + \frac{\partial}{\partial y} \left(E_y^2 \frac{\partial \bar{\psi}^a}{\partial x} \right) \right]}_{\text{A: Weighted Vorticity}} - G_i (\nabla^{-2} + K_c^2) \underbrace{E_x^2 \frac{\partial \bar{\psi}^a}{\partial x}}_{\text{B: Meridional wind}}$$

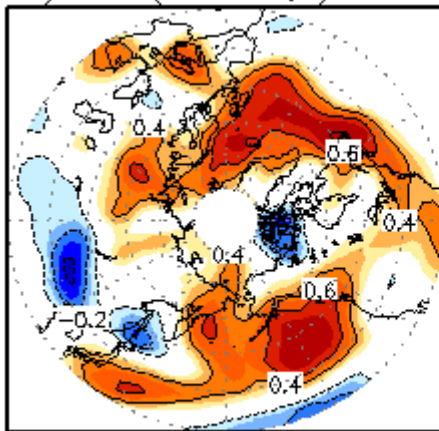
F: Streamfunction Tendency

A: Weighted Vorticity

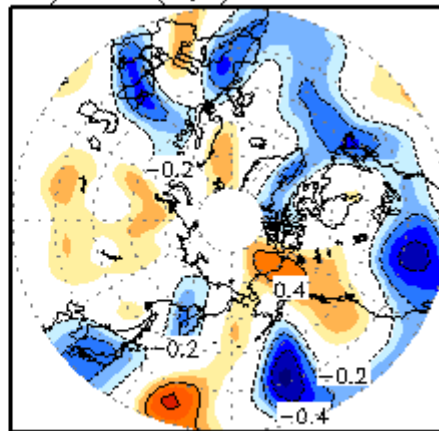
B: Meridional wind

Observational Validation

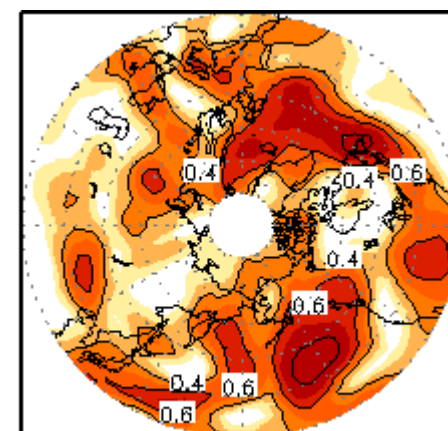
COR (A,F)



COR (B,F)



COR (A+B,F)



(Jin et al. 2008b)



Correlation between Seasonal Mean Wind and Eddy Flux

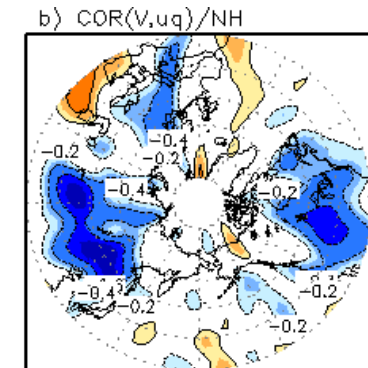
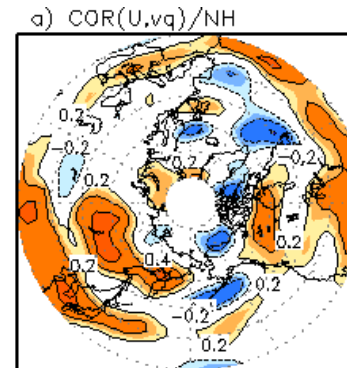
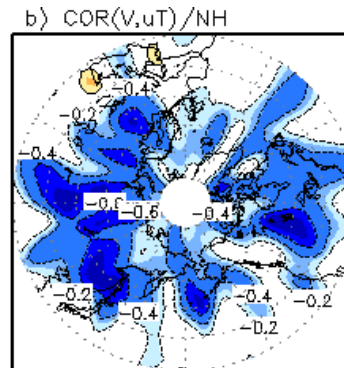
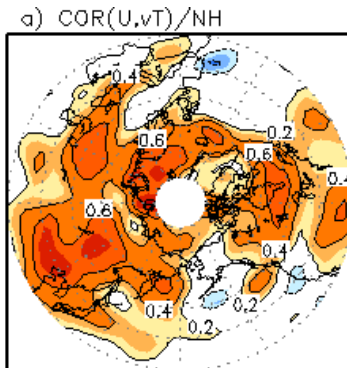
NH/Summer $Cor(u, \overline{v'T'})$

$Cor(v, \overline{u'T'})$

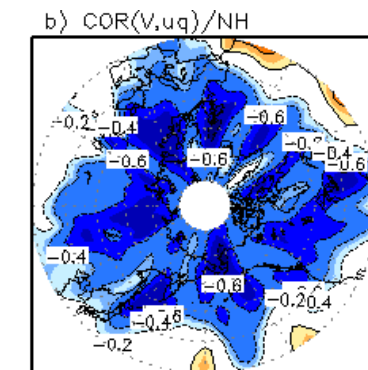
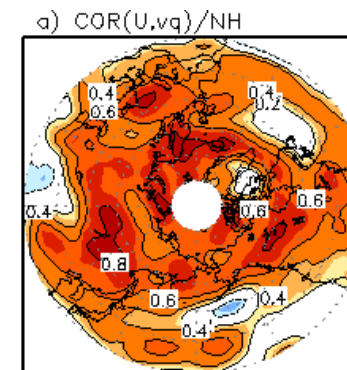
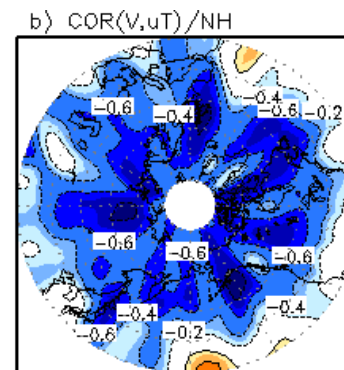
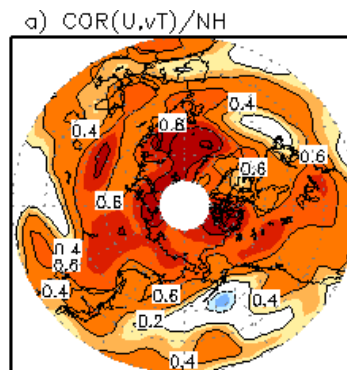
$Cor(u, \overline{v'q'})$

$Cor(v, \overline{u'q'})$

300hPa



700hPa



850hPa

