第四章:

中纬度的经向环流系统

- Ferrel cell，baroclinic eddies and the westerly jet

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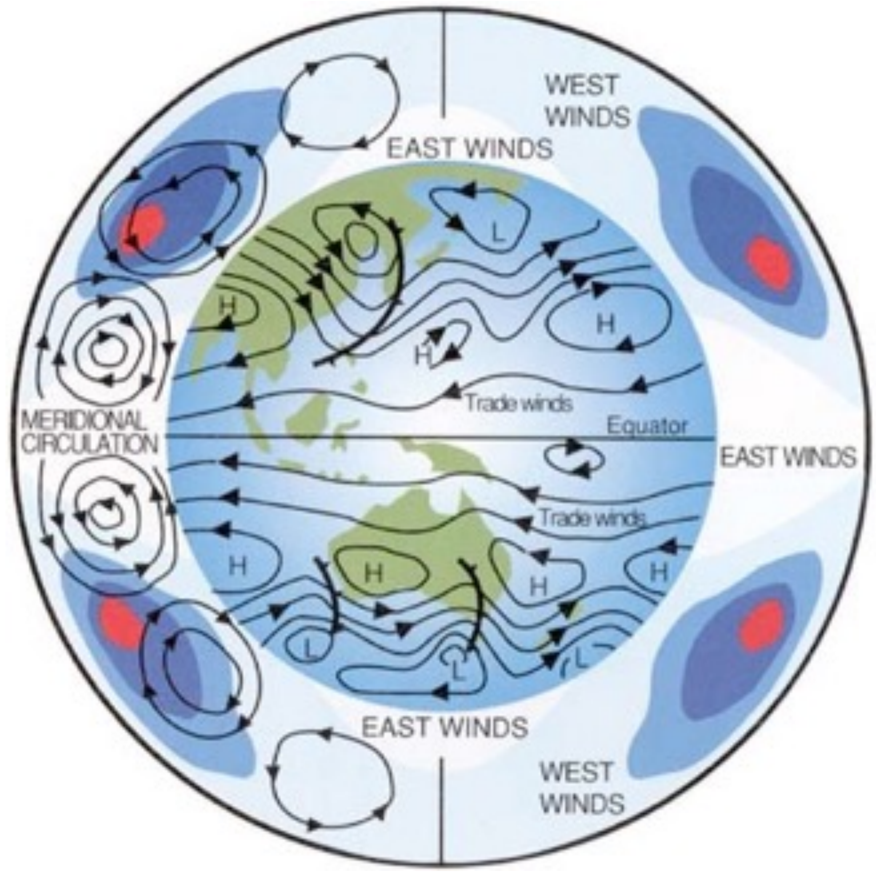
大气环流概述－内容简介

- 外部强迫：
    - 辐射强迫
    - 下界面过程
- 经向环流系统（纬向平均环流, zonally averaged circulations）：
    - Hadley 环流
    - Ferrel 环流、急流、波流相互作用
- 纬向环流系统（non-zonal circulations）：
    - Storm tracks
    - Monsoon
    - ENSO and Walker circulation



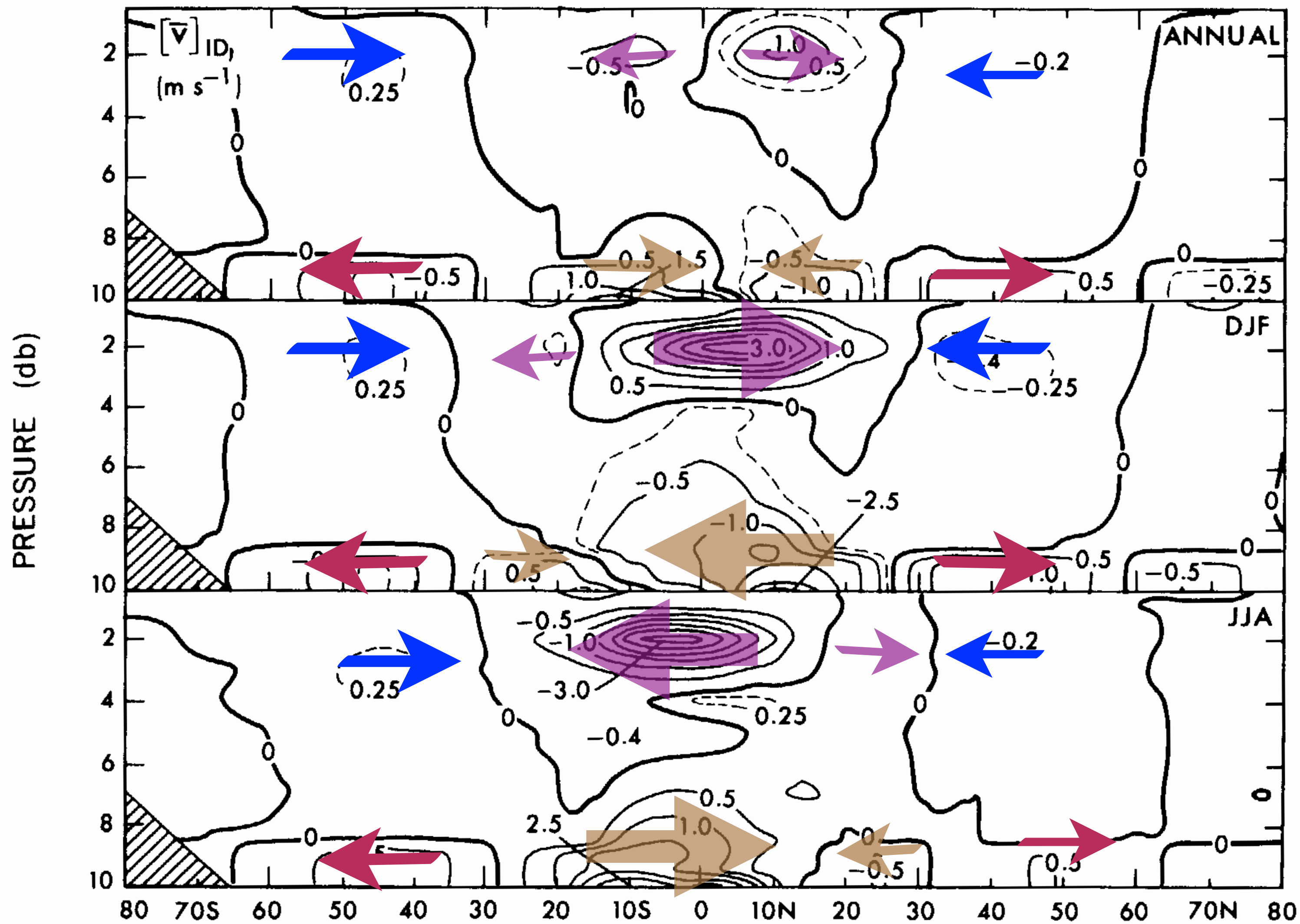
Outline

- Observations
- The Ferrel Cell
- Baroclinic eddies
  - Review: baroclinic instability and baroclinic eddy life cycle
  - Eddy-mean flow interaction
  - Transformed Eulerian Mean equation
- Eddy-driven jet
- The energy cycle

Observations

-Zonal mean fields

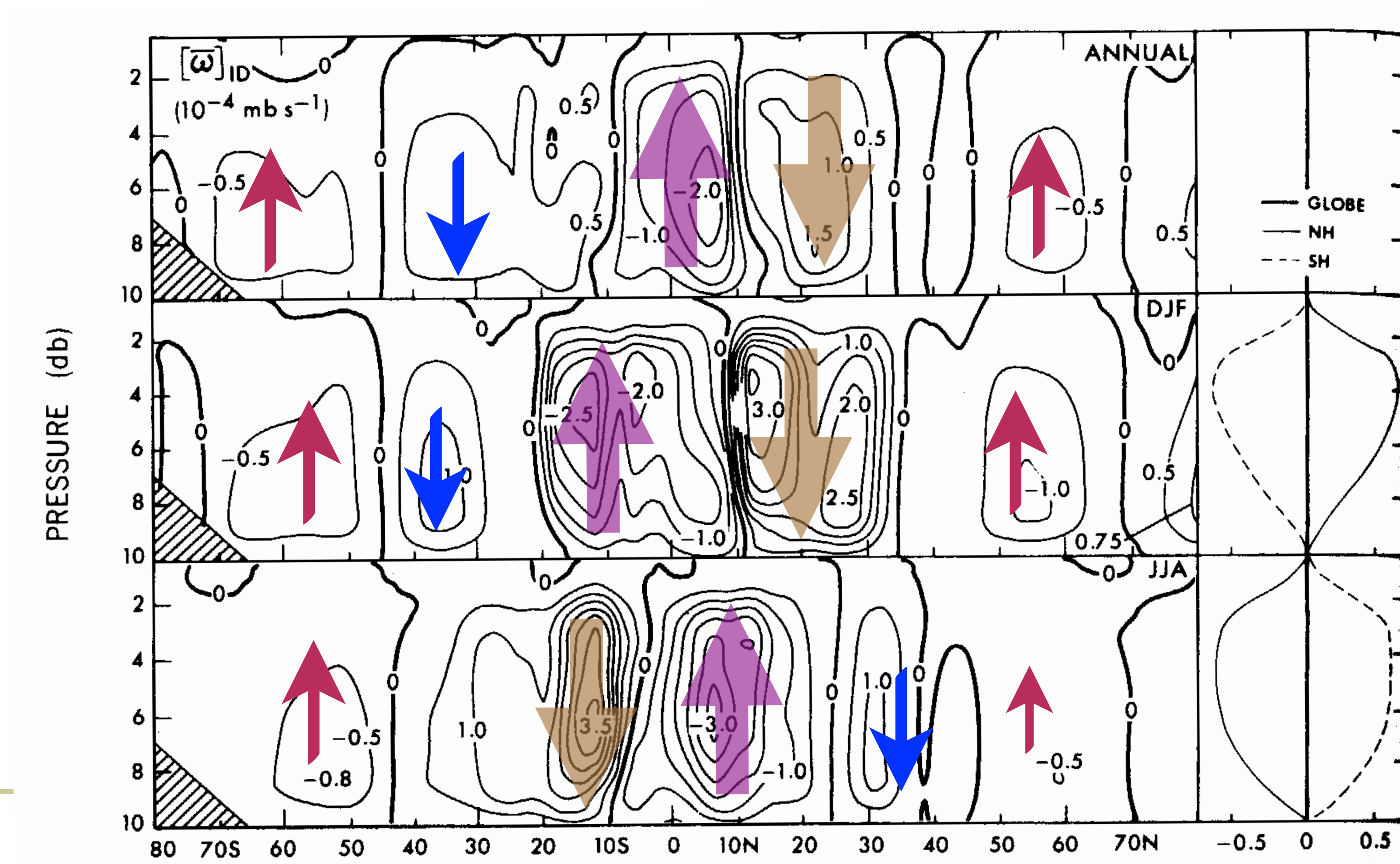
- Meridional wind (v, 经向风)



Observations

-Zonal mean fields

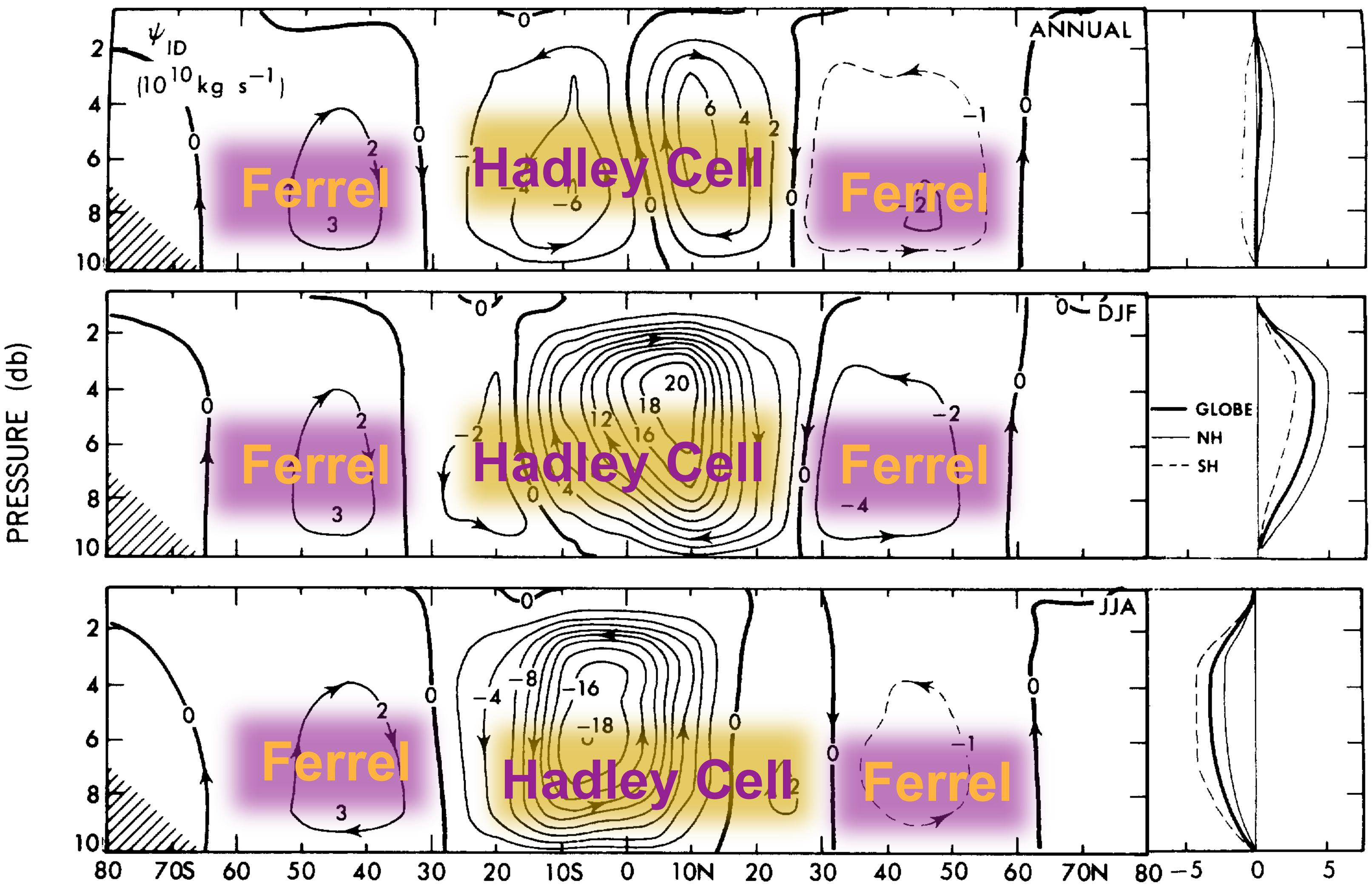
- Vertical velocity (垂直速度)



Observations

-Zonal mean fields

- Stream function (流函数)



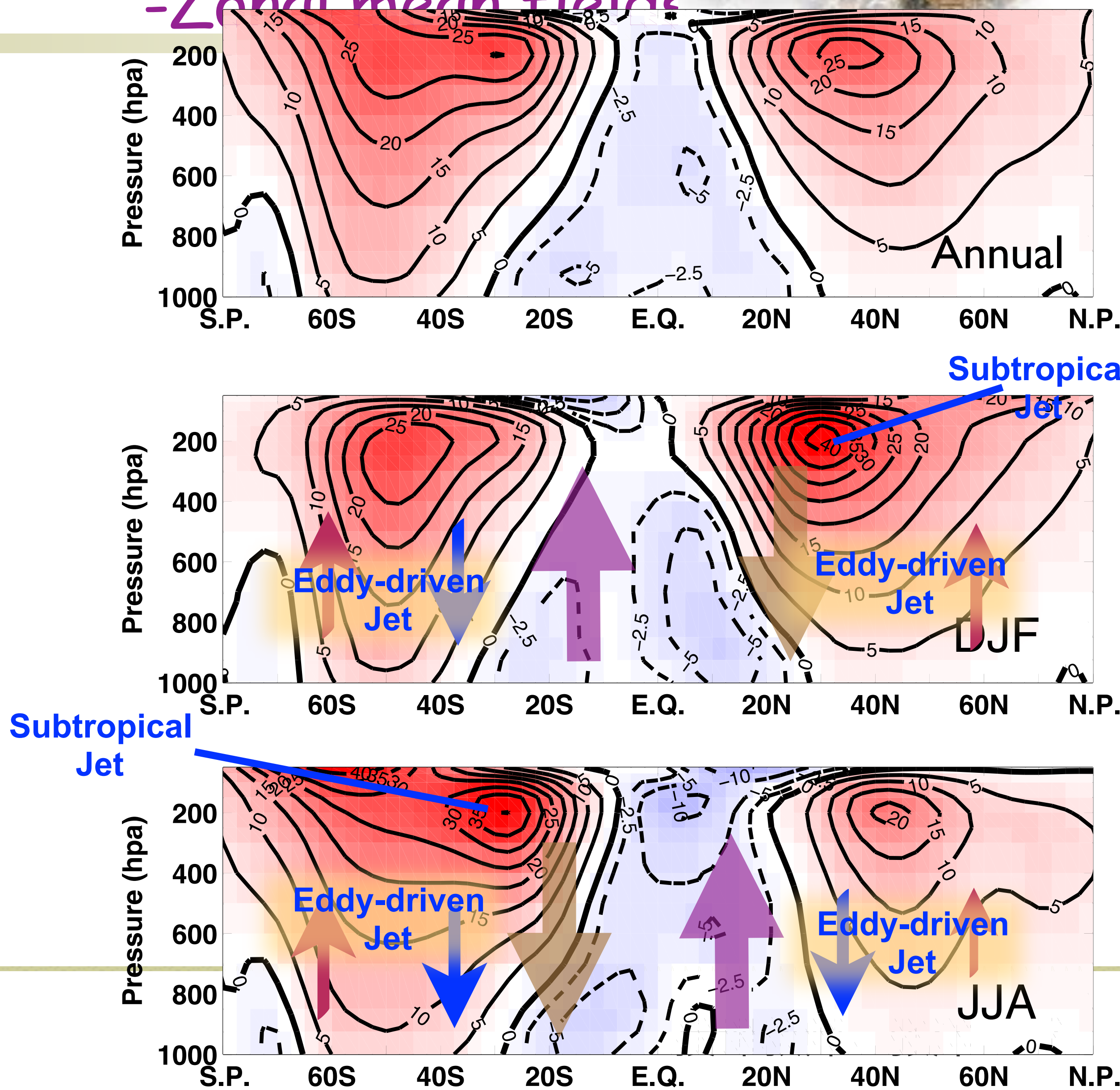
Observations

-Zonal mean fields

- Zonal winds (U, 纬向风)

Midlatitude Jet
or
Polar-front Jet
or
Eddy-driven Jet

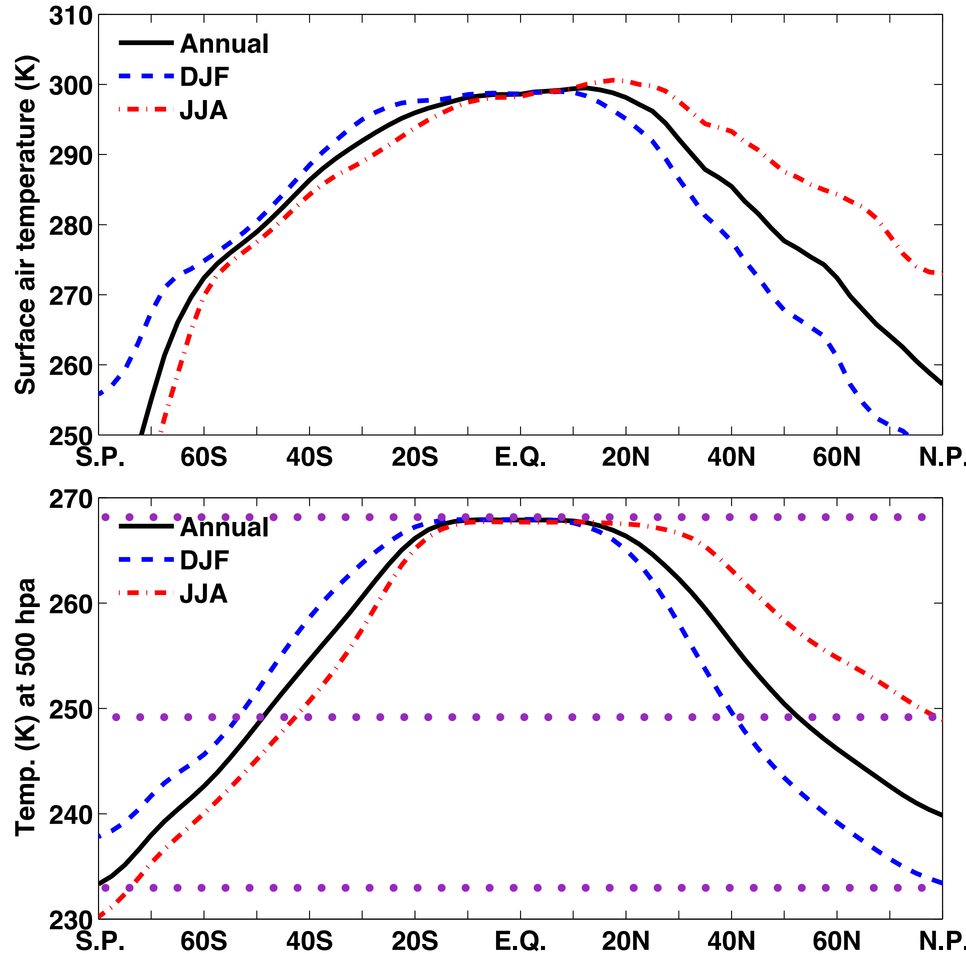
Surface westerly is always centered and strongest at 50 degree south and north, which is always considered as the **center of the eddy-driven jet**. It is also the **centric** latitude of Ferrel cell.



Observations
-Zonal mean fields

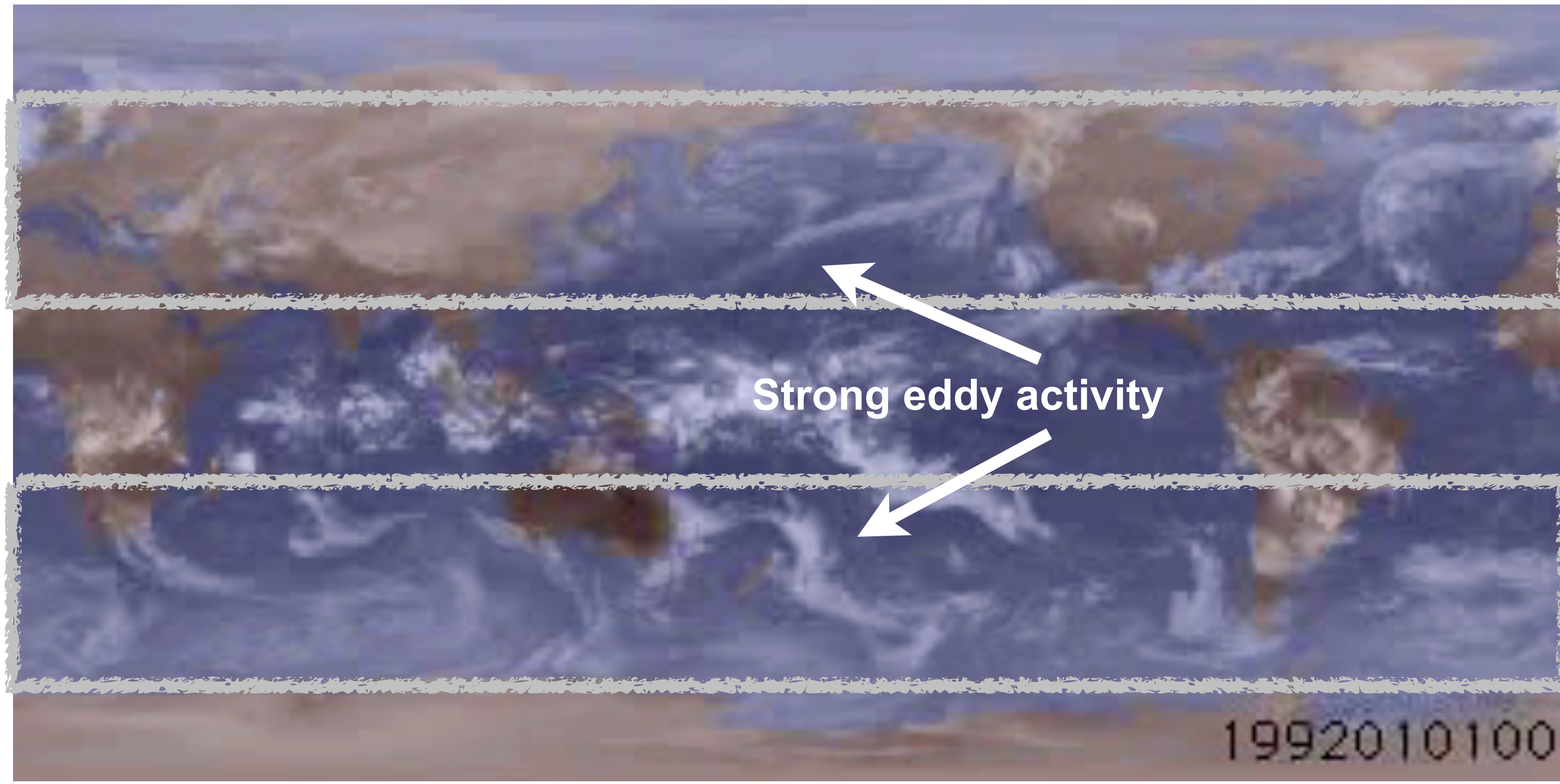
- Temperature (温度场)

Strong temperature gradient at midlatitudes, with obvious seasonal variation in the Northern Hemisphere compared to that in the Southern Hemisphere.



Observations

- Eddy fields



The British Atmospheric Data Centre (BADC)
www.badc.nerc.ac.uk/data/claus (infra-red)

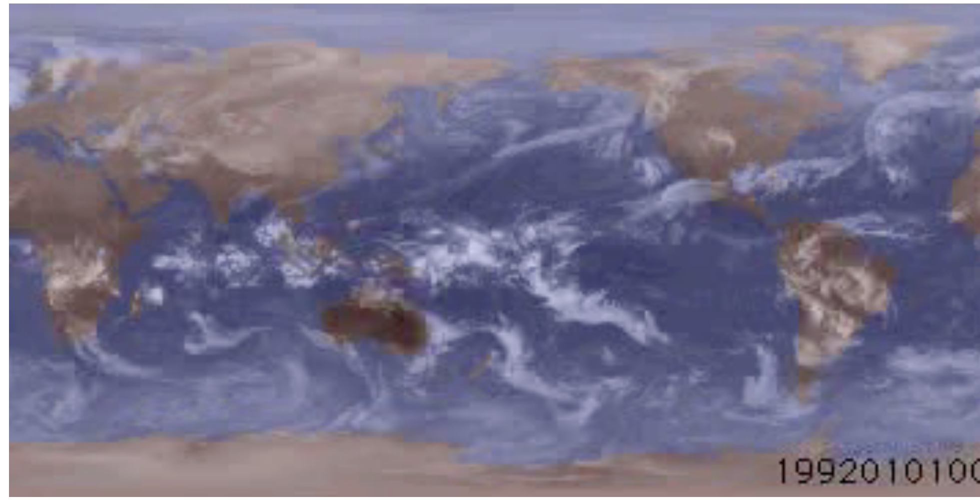
Observations

- Eddy fields

Strong **baroclinic eddy** activity

$L_R \sim O(1000km)$

Synoptic time scale (2-8 days)



$$
\begin{aligned}
[\overline{AB}] &= [\overline{(\bar{A}+A')(\bar{B}+B')}] = [\bar{A}\bar{B}] + [\overline{A'B'}] \\
&= [([\bar{A}]+\bar{A}^*)([\bar{B}]+\bar{B}^*)] + [\overline{A'B'}] \\
&= [\bar{A}][\bar{B}] + [\bar{A}^*\bar{B}^*] + [\overline{A'B'}]
\end{aligned}
$$

$$A = [\bar{A}] + \bar{A}^* + A^{'}$$

Observations

- Eddy fields

- Kinetic energy:

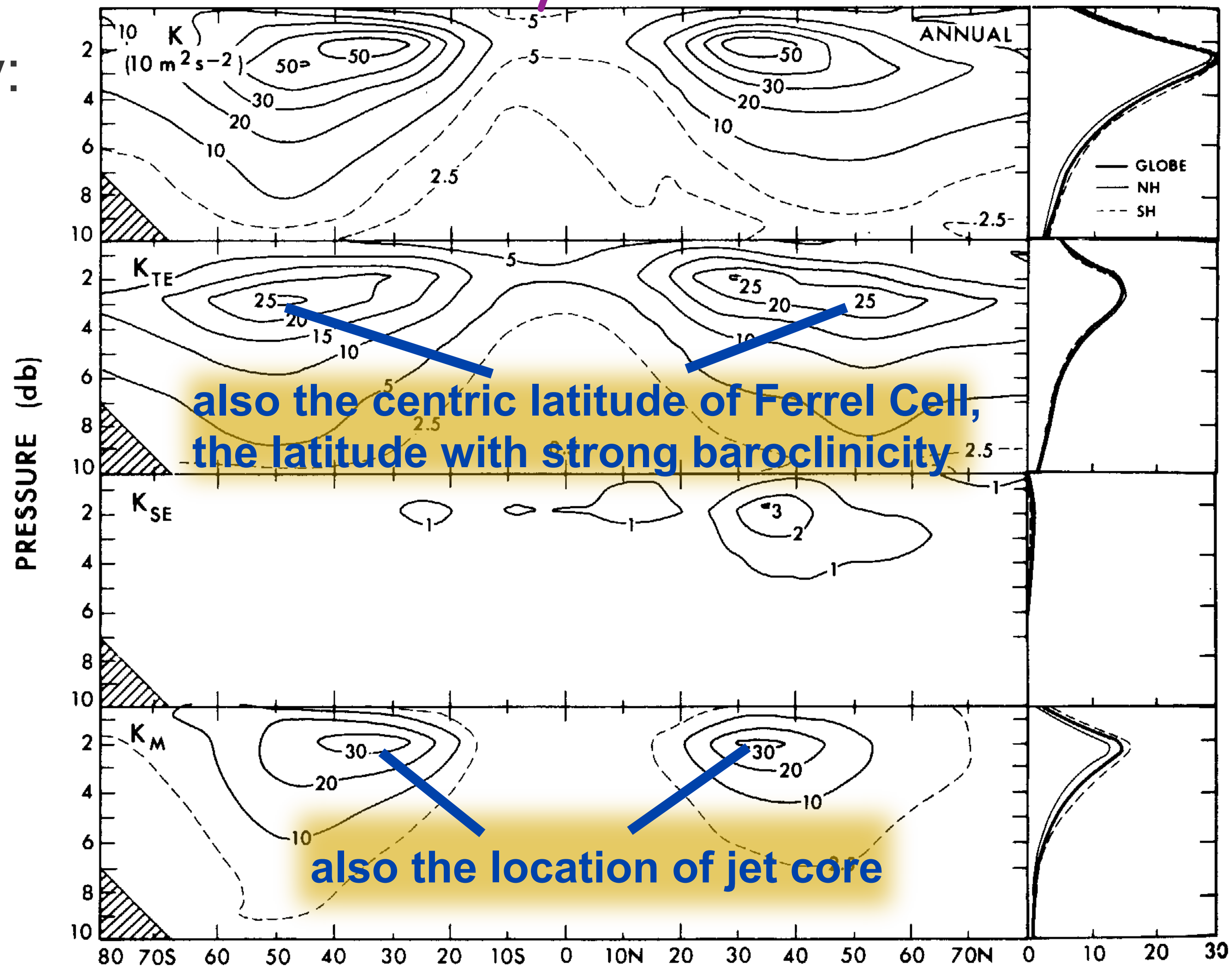
$$A = [\bar{A}] + \bar{A}^* + A^{'}$$

$$K = K_M + K_{SE} + K_{TE}$$

$$K_M = \frac{1}{2}([\bar{u}]^2 + [\bar{v}]^2)$$

$$K_{\mathrm{SE}} = \frac{1}{2}[\bar{u}^{*2} + \bar{v}^{*2}]$$

$$K_{\mathrm{TE}} = \frac{1}{2}[\overline{u'^2} + \overline{v'^2}]$$



Observat

- Kinetic energy:

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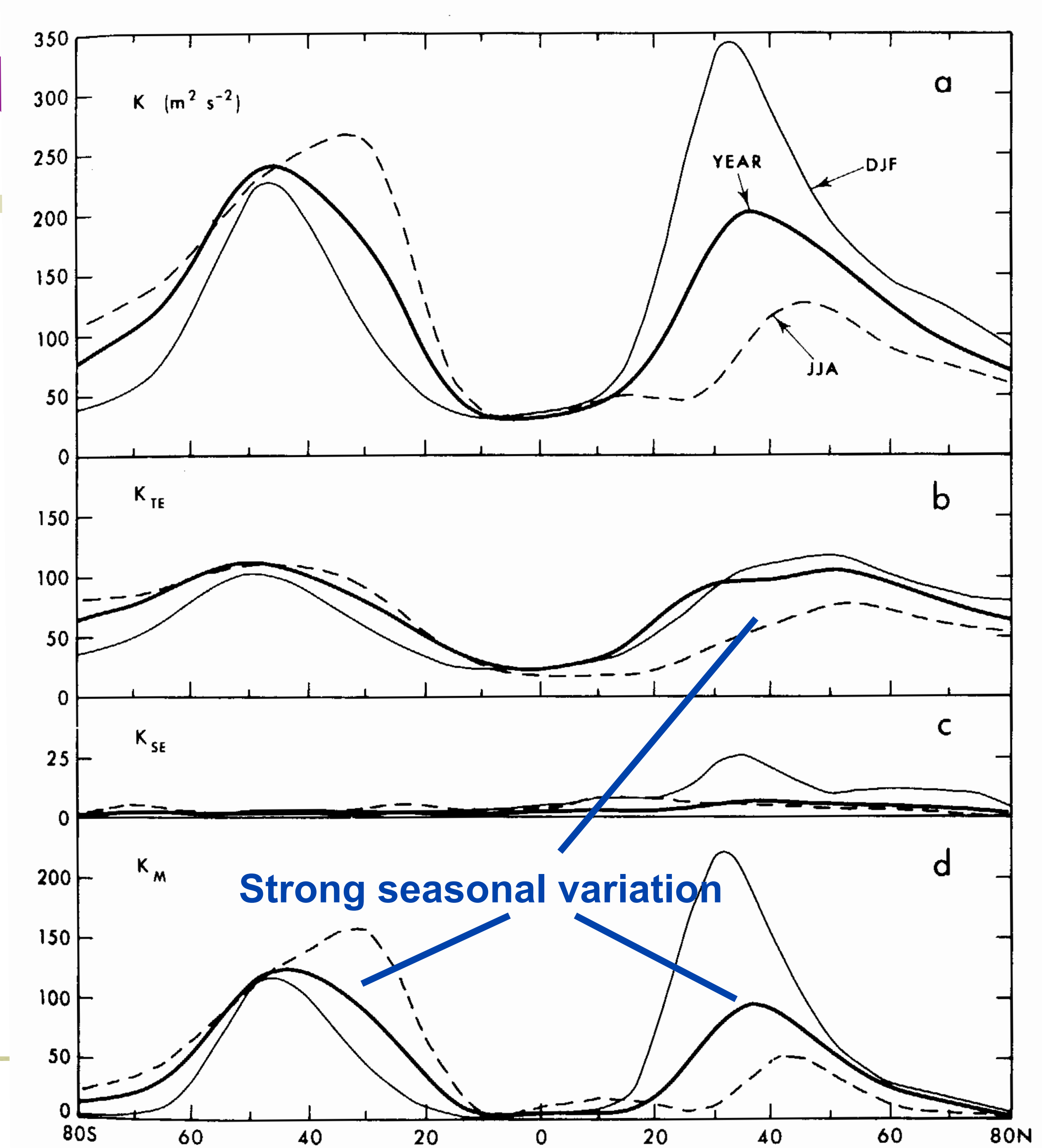
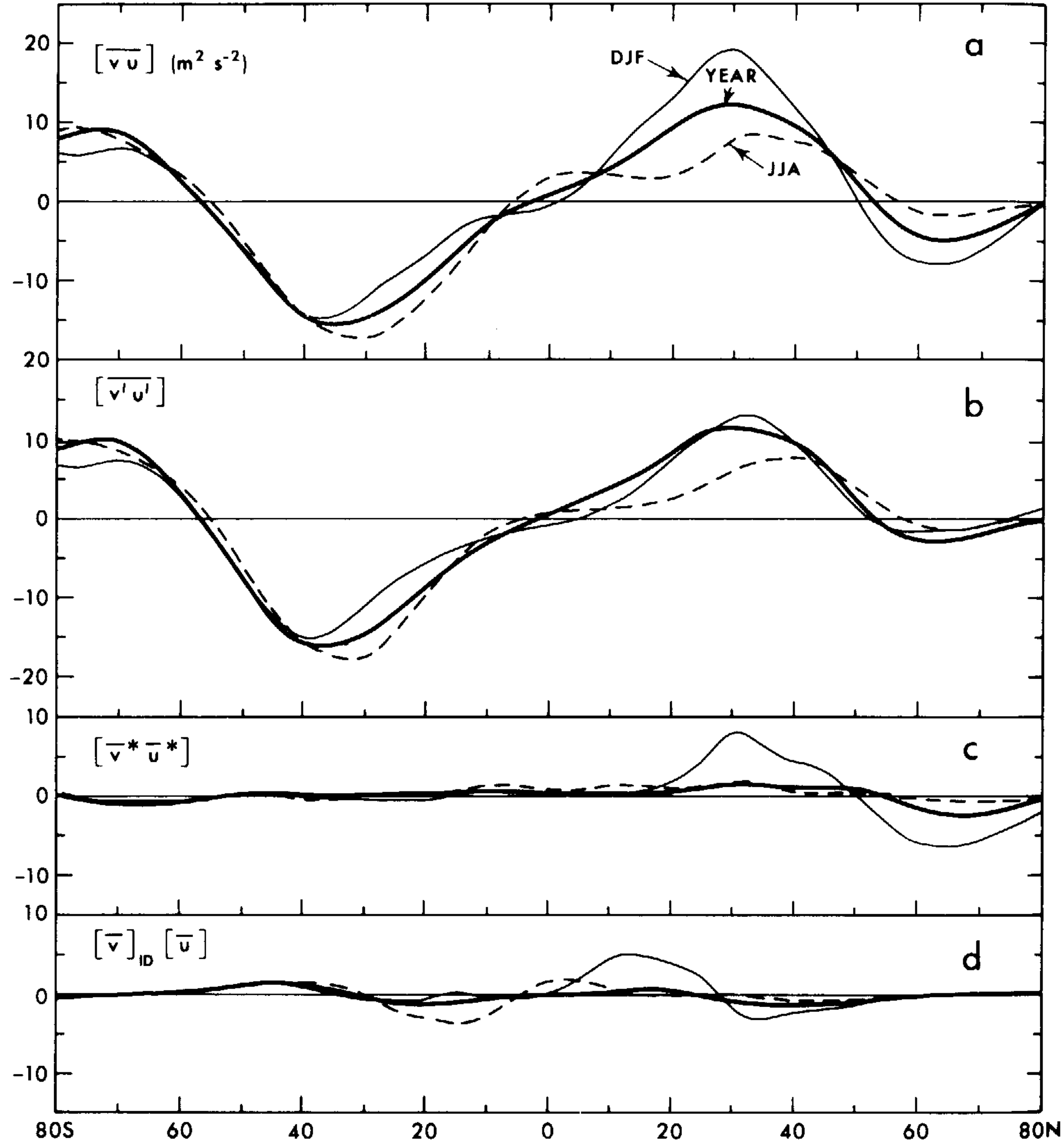


Observations

- Momentum flux:

The total momentum flux is strongest around 30-40 degree north and south, which is mainly due to the contribution of transient eddies.

In N.H., the contributions from the zonal mean flow and the stationary eddies are comparable, but centered in the tropic and subtropic, respectively.



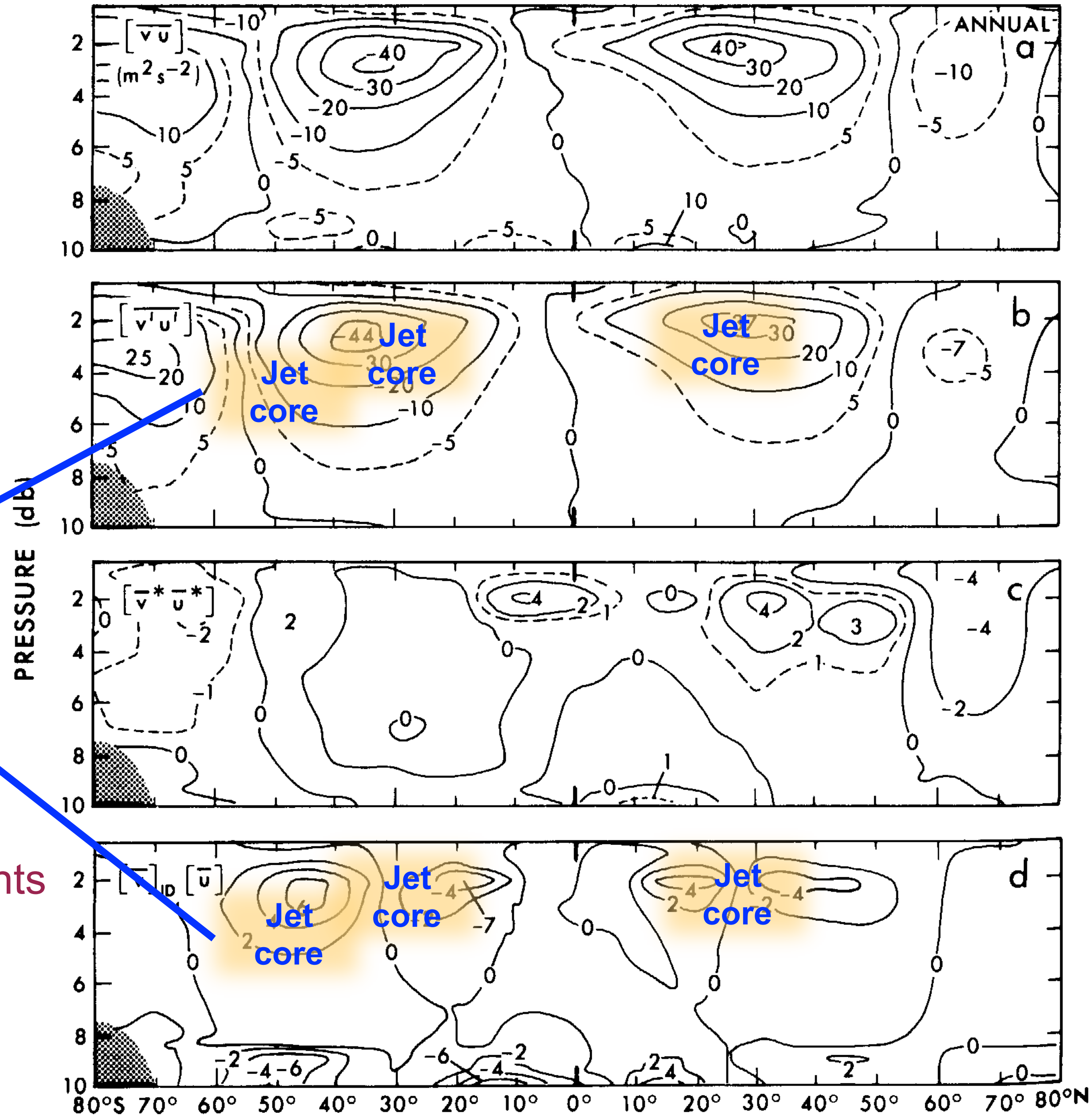
Observations

- Momentum flux:

The eddy components are centered at upper level, near tropopause.

The relation with jets

The zonal-mean components are centered near tropopause and surface.



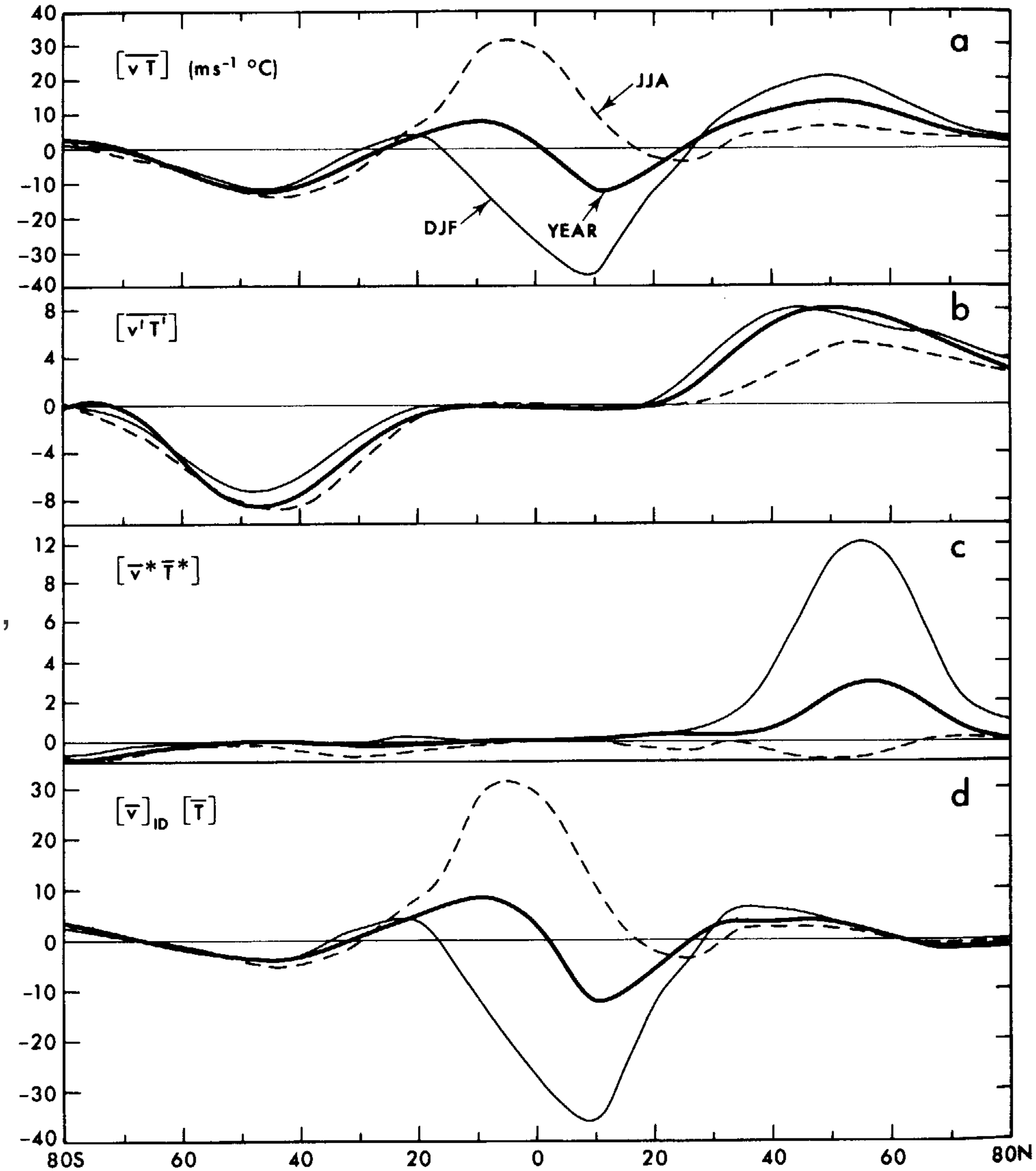
Observatio

- Heat flux:

Transient components: strongest at 40-50 degree, with obvious seasonal variation in N.H..

Stationary components: strongest at mid-latitude in N.H., whose directions are reversed from winter to summer.

Zonal mean flow: centered in the tropics, whose directions are reversed from winter to summer.

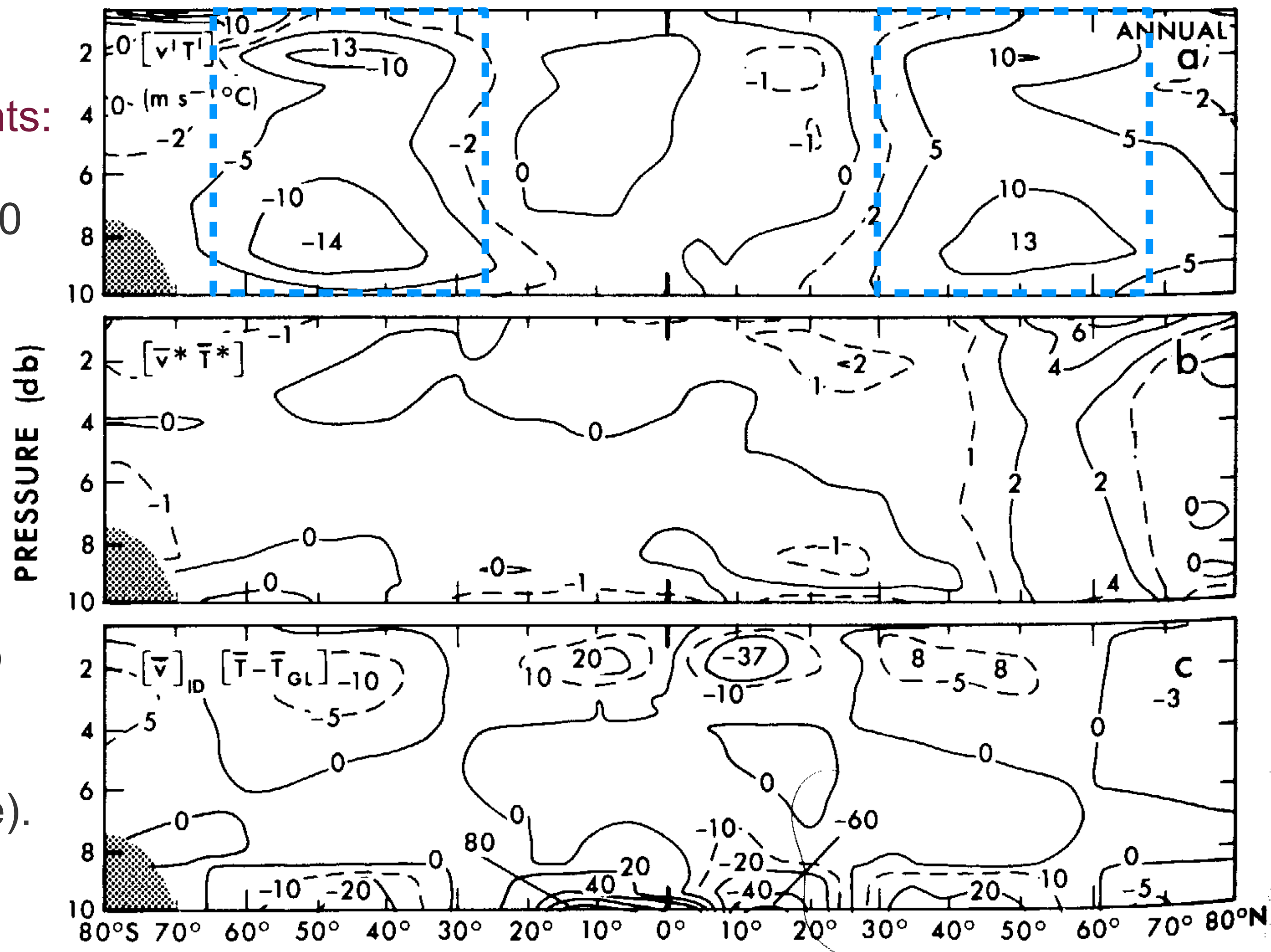


Observations

- Eddy fields

- Heat flux:

Transient components: two peaks in vertical direction (around 800 and 200 hPa).



Zonal-mean flow: two peaks in vertical direction (around 200 hPa and near surface).

Observations

- Summary:
  - Zonal-mean flow:
    - Ferrel Cell: an indirect cell centered at 40-60 degree, with strong seasonal variation in N.H.
    - Westerly jet: surface westerlies centered at 40-60 degree
  - Eddies: transient eddies are dominant with stationary eddies only obvious in N.H.
    - Kinetic energy
    - Momentum flux
    - Heat flux

The Ferrel Cell
eddy-zonal flow interaction (I)

- Start from the equations:
  - Momentum equation: $$\left(\frac{du}{dt}\right)_p - fv = -\left(\frac{\partial \Phi}{\partial x}\right)_p + F_x$$
  - Continuity equation: $$\nabla_p \cdot \boldsymbol{v} + \frac{\partial \omega}{\partial p} = 0$$
  - Thermodynamic equation: $$\left(\frac{d \ln \theta}{dt}\right)_p = \frac{Q}{c_p T}$$

$$\left(\frac{d}{dt}\right)_p = \left(\frac{\partial}{\partial t}\right)_p + u\left(\frac{\partial}{\partial x}\right)_p + v\left(\frac{\partial}{\partial y}\right)_p + \omega\frac{\partial}{\partial p}$$

Decompose into zonal mean and eddy components:

$$A = [A] + A^*$$

The Ferrel Cell

eddy-zonal flow interaction (I)

- Start from the equations:
  - Momentum equation:

$$\frac{\partial [u]}{\partial t}+\frac{\partial ([u][v])}{\partial y}+\frac{\partial ([u][\omega])}{\partial p}=-\frac{\partial ([u^* v^*])}{\partial y}-\frac{\partial ([u^* \omega^*])}{\partial p}+f[v]+[F_x]$$

  - Continuity equation:

$$\frac{\partial [v]}{\partial y}+\frac{\partial [\omega]}{\partial p}=0$$

  - Thermodynamic equation:

$$\frac{\partial [\theta]}{\partial t}+\frac{\partial ([v][\theta])}{\partial y}+\frac{\partial ([\omega][\theta])}{\partial p}=-\frac{\partial ([\theta^* v^*])}{\partial y}-\frac{\partial ([\theta^* \omega^*])}{\partial p}+\left(\frac{p_o}{p}\right)^{R/c_p}\frac{[Q]}{c_p}$$

$$\left(\frac{d}{dt}\right)_p=\left(\frac{\partial}{\partial t}\right)_p+u\left(\frac{\partial}{\partial x}\right)_p+v\left(\frac{\partial}{\partial y}\right)_p+\omega\frac{\partial}{\partial p}$$

Under the quasi-geostrophic approximation $(R_o \ll 1)$, above equations can be simplified.

The Ferrel Cell

eddy-zonal flow interaction (I)

- Start from the equations:

$$\frac{\partial[u]}{\partial t}+\frac{\partial([u][v])}{\partial y}+\frac{\partial([u][\omega])}{\partial p}=-\frac{\partial([u^*v^*])}{\partial y}-\frac{\partial([u^*\omega^*])}{\partial p}+f[v]+[F_x]$$

$$\frac{\partial[\theta]}{\partial t}+\frac{\partial([v][\theta])}{\partial y}+\frac{\partial([\omega][\theta])}{\partial p}=-\frac{\partial([\theta^*v^*])}{\partial y}-\frac{\partial([\theta^*\omega^*])}{\partial p}+\left(\frac{p_o}{p}\right)^{R/c_p}\frac{[Q]}{c_p}$$

$$\frac{\partial[v]}{\partial y}+\frac{\partial[\omega]}{\partial p}=0$$

- Simplification:
  - For midlatitude large scale flow, the eddy components of the meridional heat and momentum transports are dominant. (recall the observations)

$$\frac{\partial}{\partial y}[u^*v^*]\gg\frac{\partial}{\partial y}([u][v])\qquad\frac{\partial}{\partial y}[\theta^*v^*]\gg\frac{\partial}{\partial y}([\theta][v])$$

  - From the QG approximation, $\frac{\partial\omega^*}{\partial p}\sim R_o\frac{\partial v^*}{\partial y}$ → $\frac{\partial}{\partial y}[u^*v^*]\gg\frac{\partial}{\partial p}[u^*\omega^*]$
  - Horizontal variation of the stratification is small: $\frac{\partial}{\partial p}([\theta][\omega])\approx[\omega]\frac{\partial\theta_s}{\partial p}$

The Ferrel Cell

eddy-zonal flow interaction (I)

- The simplified equations:
  - Momentum equation:

$$\frac{\partial [u]}{\partial t} = -\frac{\partial([u^* v^*])}{\partial y} + f[v] + [F_x]$$

  - Continuity equation:

$$\frac{\partial [v]}{\partial y} + \frac{\partial [\omega]}{\partial p} = 0$$

  - Thermodynamic equation:

$$\frac{\partial [\theta]}{\partial t} + [\omega]\frac{\partial \theta_s}{\partial p} = -\frac{\partial([\theta^* v^*])}{\partial y} + \left(\frac{p_o}{p}\right)^{R/c_p} \frac{[Q]}{c_p}$$

$$\left(\frac{d}{dt}\right)_p = \left(\frac{\partial}{\partial t}\right)_p + u\left(\frac{\partial}{\partial x}\right)_p + v\left(\frac{\partial}{\partial y}\right)_p + \omega\frac{\partial}{\partial p}$$

Under the quasi-geostrophic approximation $(R_o \ll 1)$