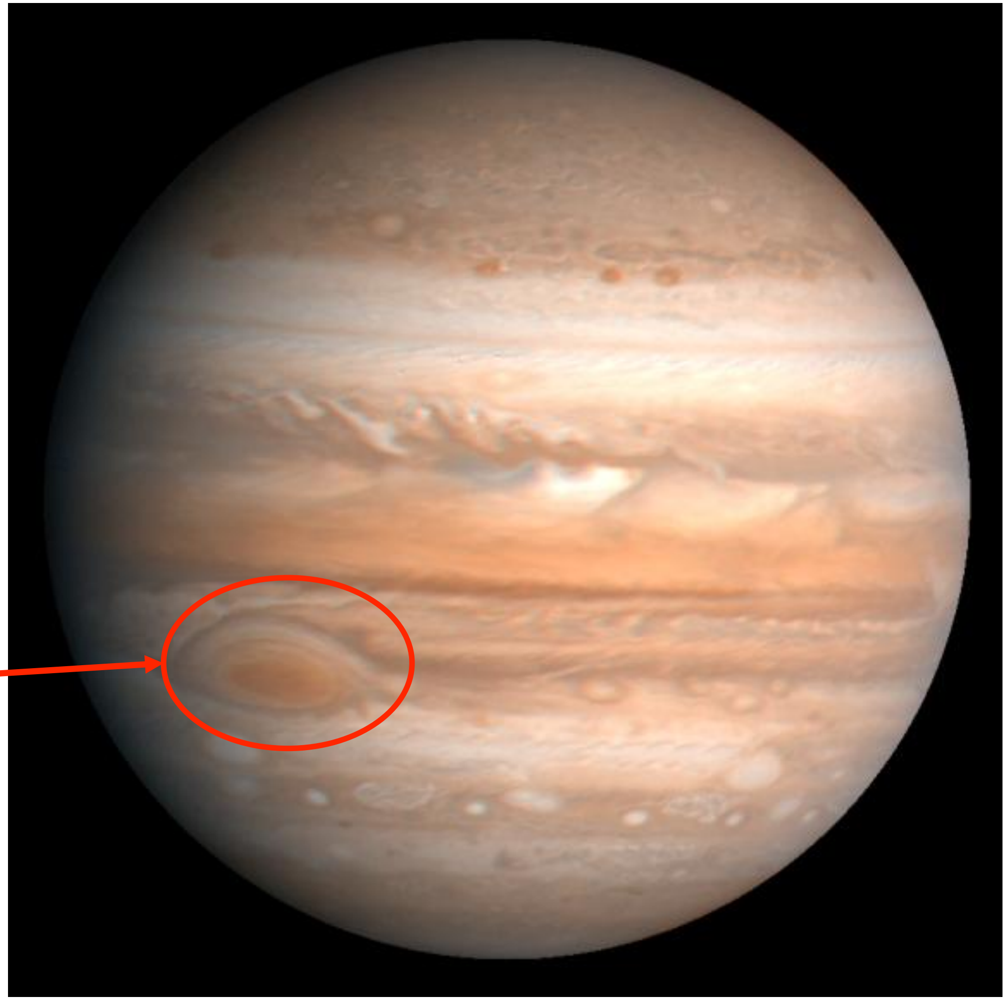
木星大気大規模渦の数値実験：
傾圧性起源の順圧不安定?

加藤 亮平（九大院理）
杉山 耕一朗（北大低温研）
中島 健介（九大院理）



GFDセミナー 2011/08/20

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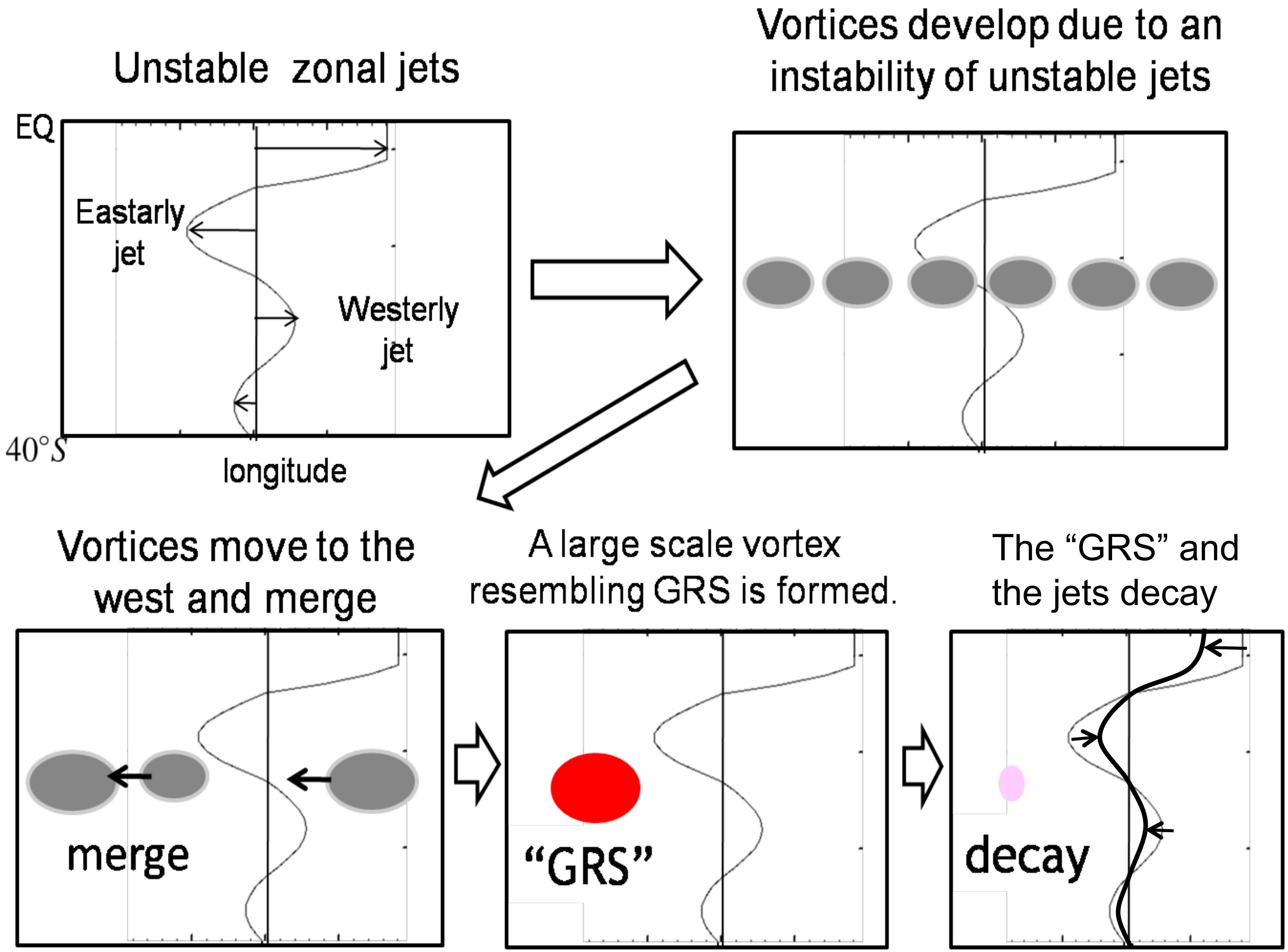
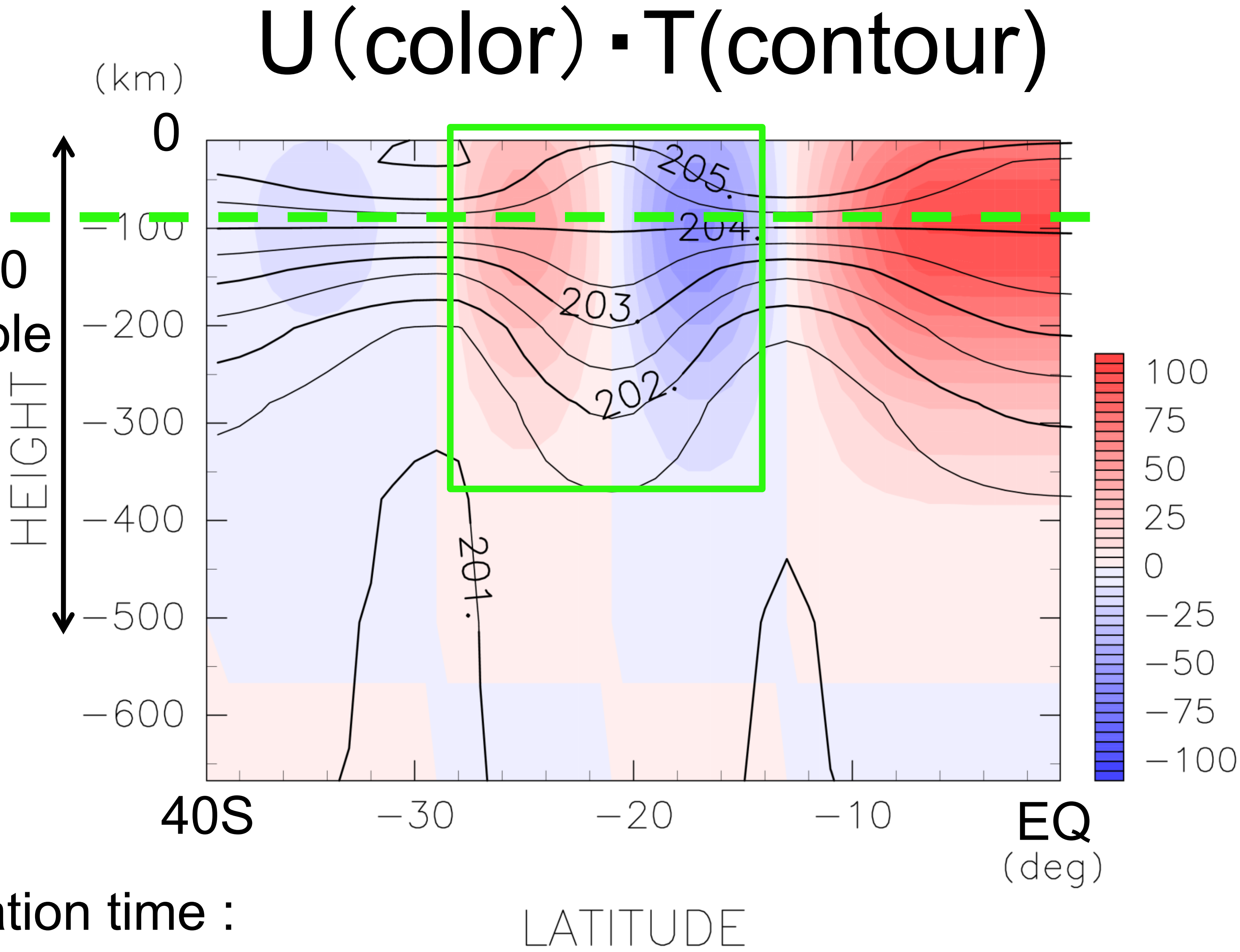
3D-calc. of the GRS by Williams(1996)



Initial condition (Only upper stable “weather layer”)

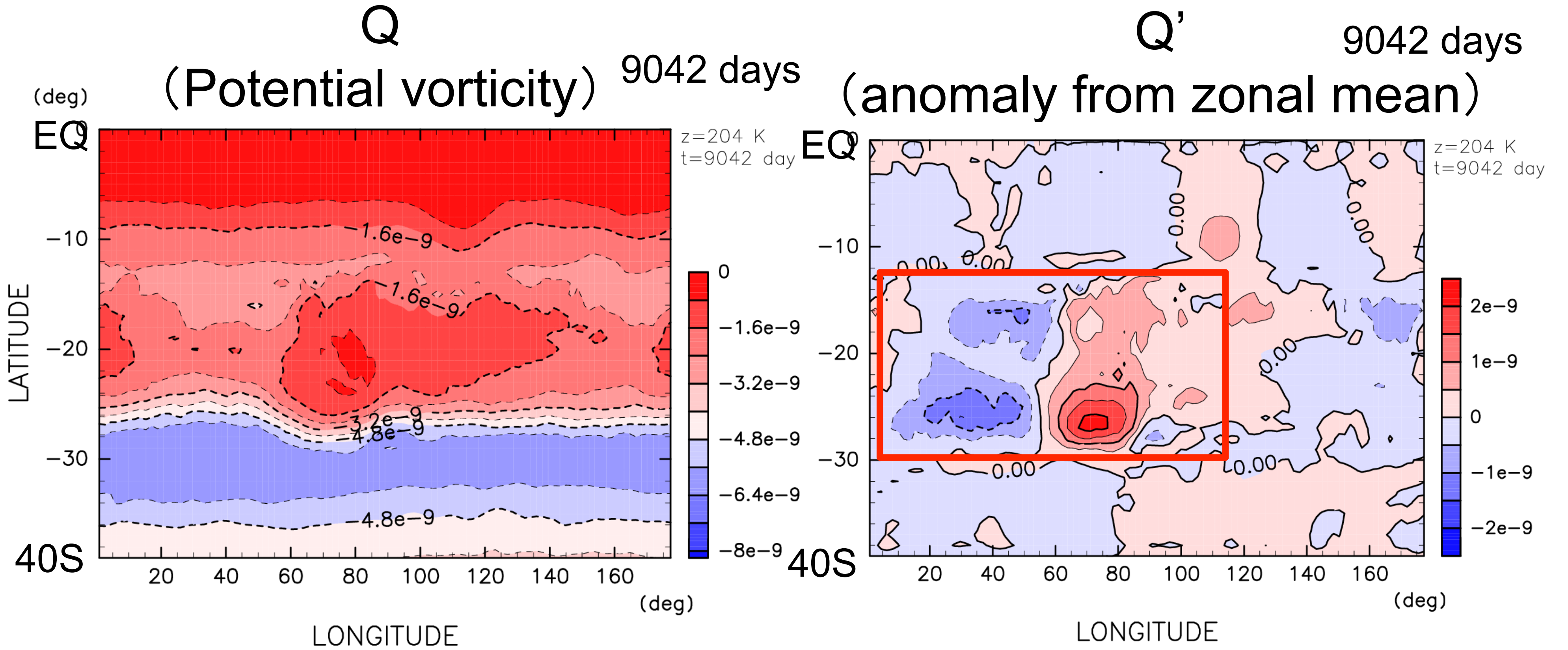


Upper 1/20 of the whole domain

Integration time : 20,000 days

Time evolution of B300

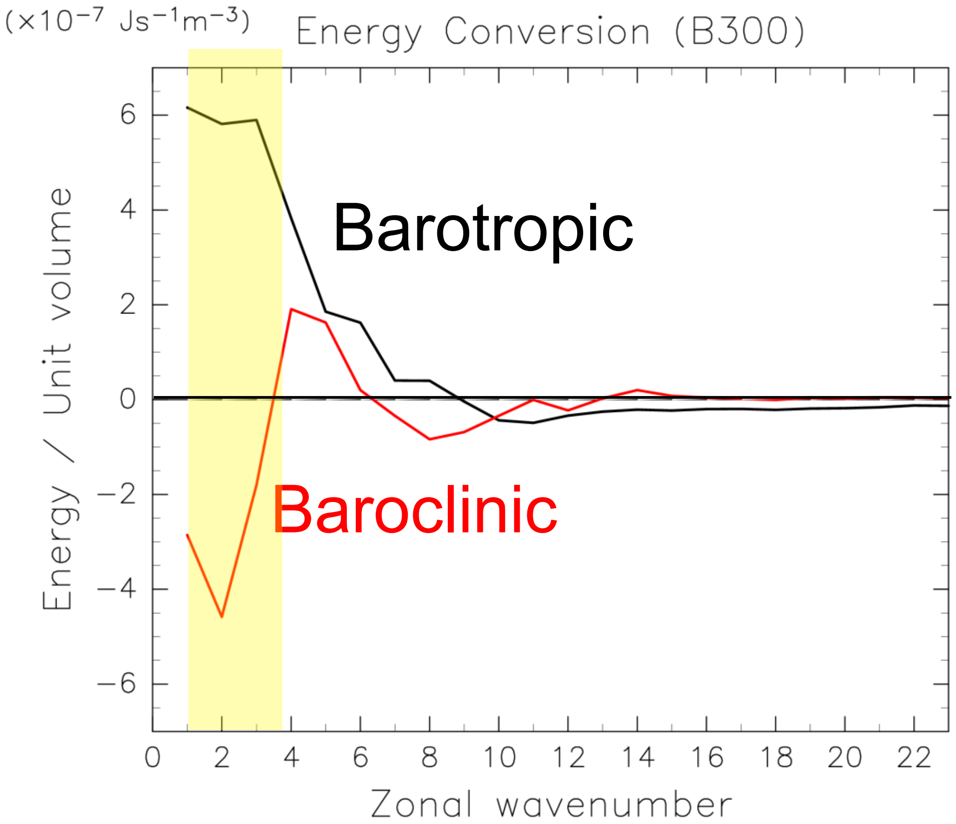
movie



- Large-scale vortices are generated intermittently at intervals of 2-3 years.
- Life time is 2-3 years.
  - Propagate westward and diminish its longitudinal scale
  - absorbed by a newly grown large-scale vortex

Energy conversion from zonal mean to wave field

(Averaged over 15.5 S ~ 27.5 S,
z= -9 km ~ -378 km,
from 8500 to 10000 days)



Large-scale vortices have positive barotropic energy conversion

TEM-based energy conversion

$$\frac{\partial E'}{\partial t} = -\frac{\partial \overline{E}}{\partial t} = \frac{1}{V}\iiint -\rho_0 \overline{u} \cdot DF dV$$

Randel and Stanford (1985)

$$\simeq \frac{1}{V}\iiint \left[\underbrace{\frac{\rho_0 \overline{u}}{a\cos^2\phi}\frac{\partial}{\partial \phi}\left(\cos^2\phi\, \overline{v'u'}\right)}_{\text{Barotripic}} - \underbrace{\rho_0 \overline{u} f \frac{\partial}{\partial z}\left(\frac{\overline{v'T'}}{\frac{\partial \overline{T}}{\partial z}}\right)}_{\text{Baroclinic}}\right] dV$$

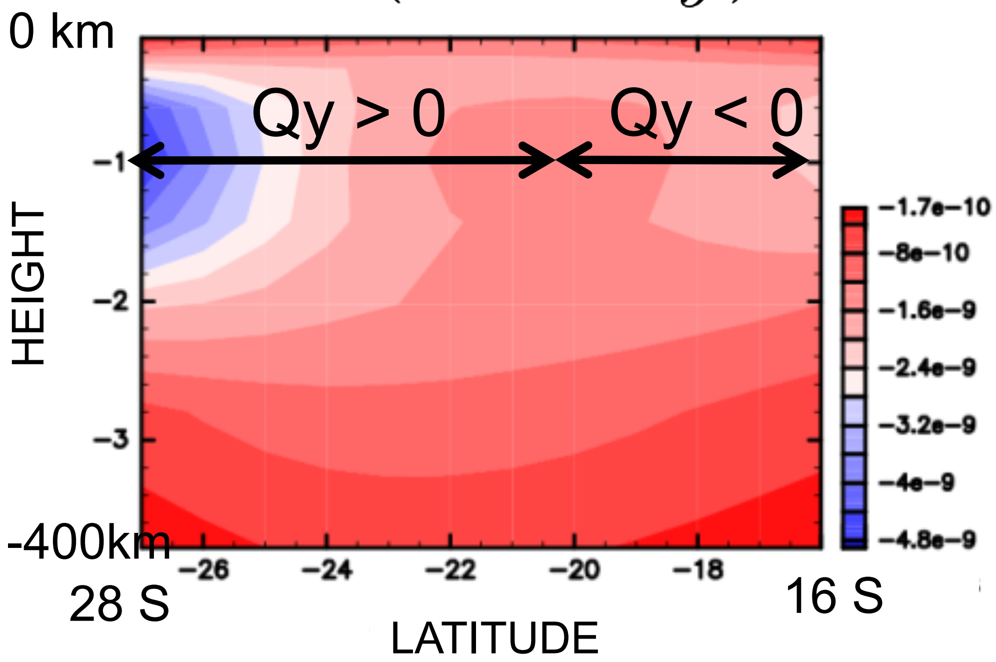
Barotripic

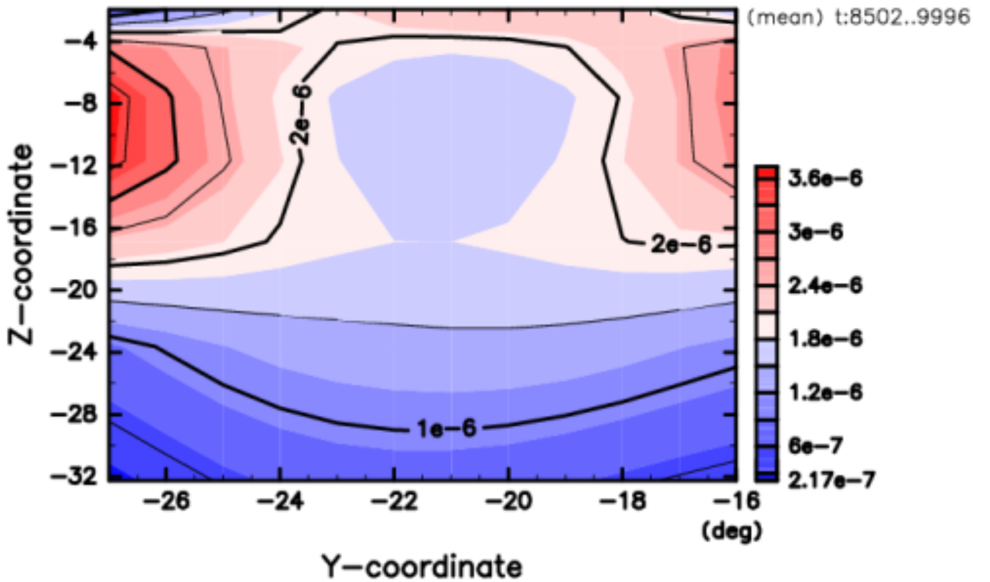
Baroclinic

Origin of Q is baroclinicity

$$\overline{N^2} = \frac{g}{T_0}\frac{\partial \overline{T}}{\partial z}$$

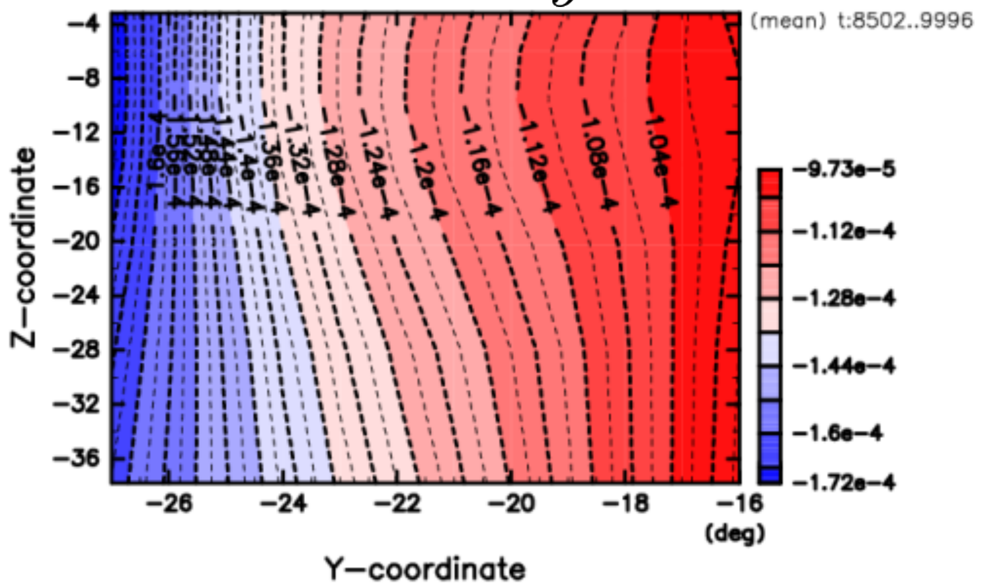
$$\overline{Q} \propto (f - U_y)\overline{N^2}$$





(Averaged form 8500 to 10000 days)

$$f - U_y$$



"baroclinic origin
barotoropic instability" ?

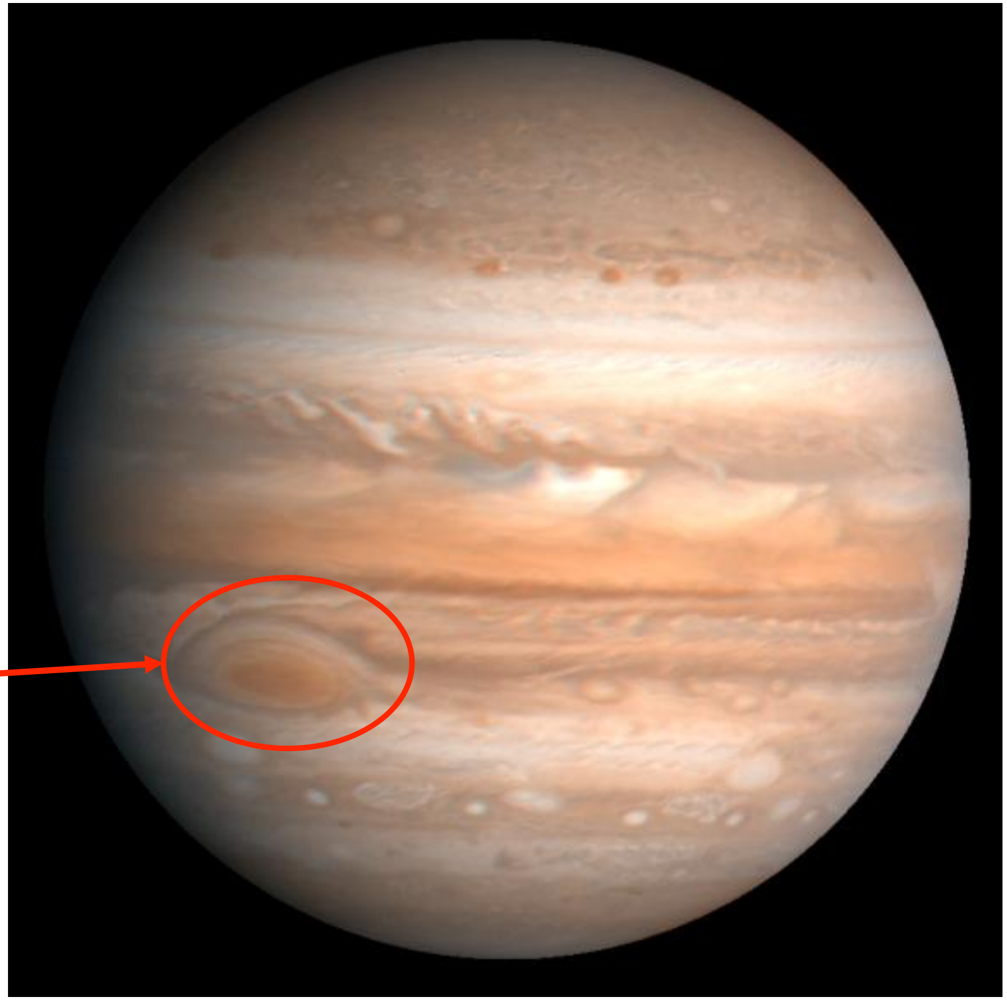
Numerical experiments of large-scale vortices in Jupiter's atmosphere:

The generation mechanism of large-scale vortices

Ryohei KATO
（Kyushu Univ. , Japan ）
Ko-ichiro SUGIYAMA
（Hokkaido Univ. , Japan ）
Kensuke NAKAJIMA
（Kyushu Univ. , Japan ）

The GRS

- genesis
- stability



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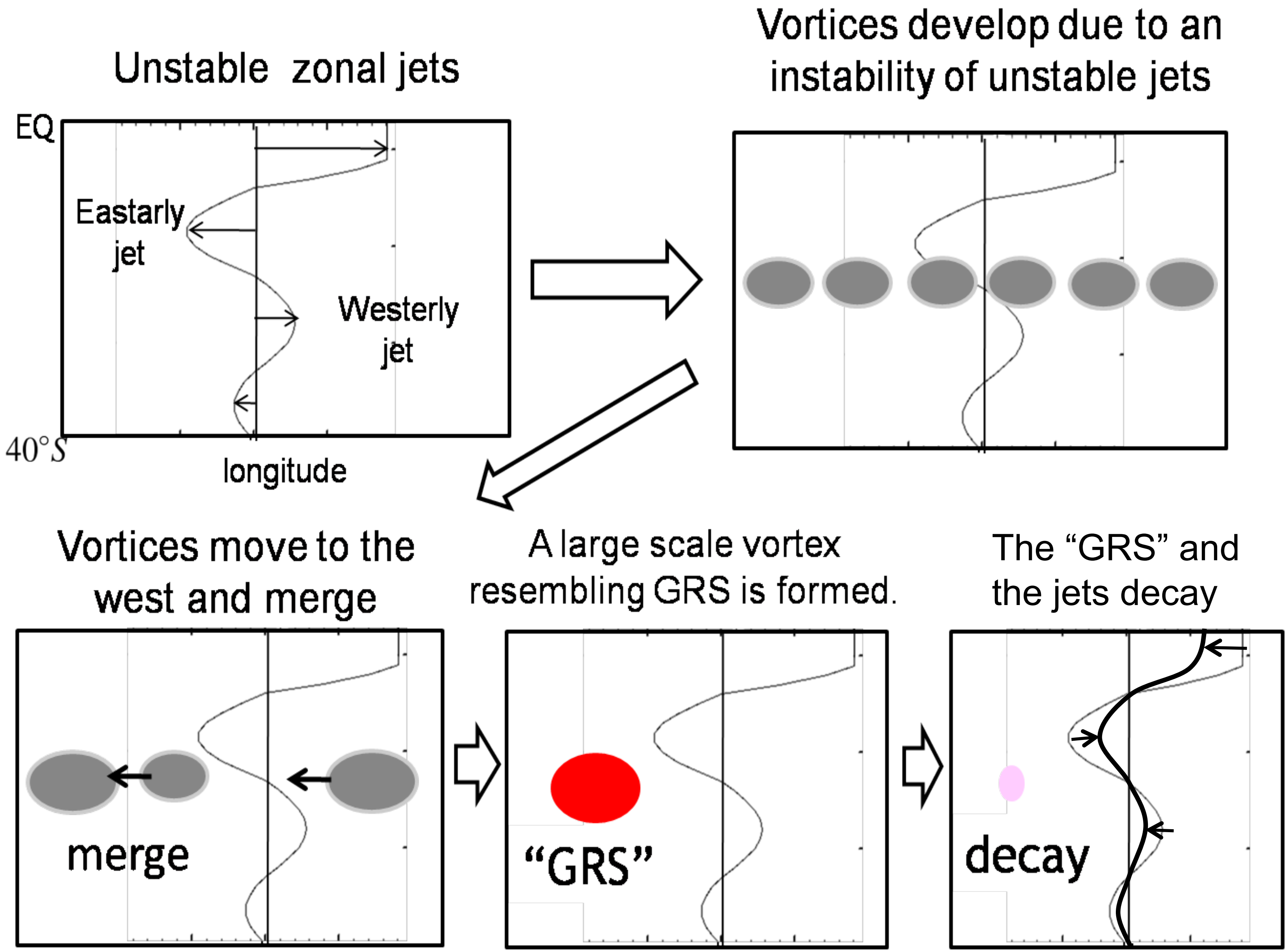
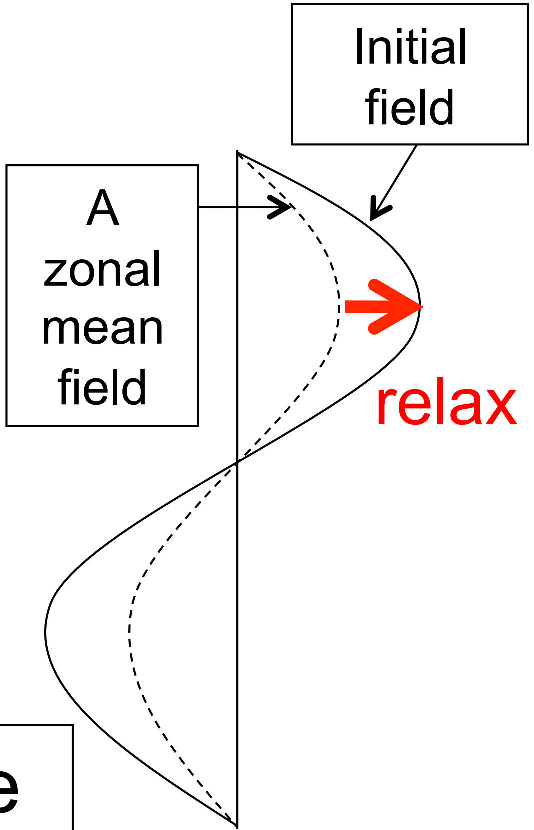


Problem of W96

- The decay of the jets in W96 is inconsistent with observations
  - The strength of the jets hasn't changed significantly for decades (Porco et al., 2003)
- If the strength of the jets is maintained, behavior of vortices are expected to change.
  - (e.g.) Large scale vortices may be long-lived.

Objective of this study

- Introduce forcings
  - that relax zonal mean field to the initial field so as to maintain the strength of the jets
- Examine the dependence of behavior of vortices on the intensity of the forcings



Results

- The behavior of vortices depend on the intensity of the forcings
- Large-scale vortices such as the GRS appear

→ Examine the generation mechanism

Model and Setup

Basic equations and parameters

(3D, spherical, Primitive equation of the Boussinesq fluid)

(finite difference method)

Momentum equations

$$\frac{\partial u}{\partial t} + L(u) - fv + \frac{uv\tan\phi}{a} = -\frac{1}{a\cos\phi\rho_0}\frac{\partial p}{\partial \lambda} + \nu_H \nabla^4 u + \nu_V \frac{\partial^2 u}{\partial z^2} - \frac{\overline{u}^x - u_i}{\tau_M}$$

Advection

$$\frac{\partial v}{\partial t} + L(v) + fu + \frac{uu\tan\phi}{a} = -\frac{1}{a\rho_0}\frac{\partial p}{\partial \phi} + \nu_H \nabla^4 v + \nu_V \frac{\partial^2 v}{\partial z^2}$$

$$\frac{\partial p}{\partial z} = -g\rho$$

Momentum Forcing

Thermal Forcing

Thermodynamic equation

$$\frac{\partial T}{\partial t} + L(T) = \nu_H \nabla^4 T + \nu_V \frac{\partial^2 T}{\partial z^2} - \frac{\overline{T}^x - T_i}{\tau_T}$$

Continuity Equation (incompressible)

$$\frac{1}{a\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \phi}(v\cos\phi)\right] + \frac{\partial w}{\partial z} = 0$$

Equation of state

$$\rho = \rho_0[1 - \alpha(T - T_0)]$$

$$a = 71400 \text{ km}$$
$$g = 26.0 \text{ m s}^{-1}$$
$$\omega = 1.76 \times 10^{-4} \text{ s}^{-1}$$
$$T_0 = \alpha^{-1} = 200 \text{ K}$$
$$\rho_0 = 0.1323 \text{ kg m}^{-3}$$
$$\nu_H = -10^{17} \text{ m}^4 \text{ s}^{-1}$$
$$\nu_V = 10^{-8} \text{ m}^2 \text{ s}^{-1}$$

λ :
ϕ :
z :
L :
u :
u_i :
$\overline{u}^x$
v :
w :
T :
T_i :
$\overline{T}^x$
p :
ρ :
τ_M
τ_T

Specification of τ_T and τ_M

Damping time of momentum forcing (day)

Damping time of Thermal forcing (day)

τ_T \ τ_M	30	100	300	1000	2000	4000	∞
30							
100							
300							
1000							
2000							
4000							
∞							

Both thermal and momentum forcings

Thermal forcing only

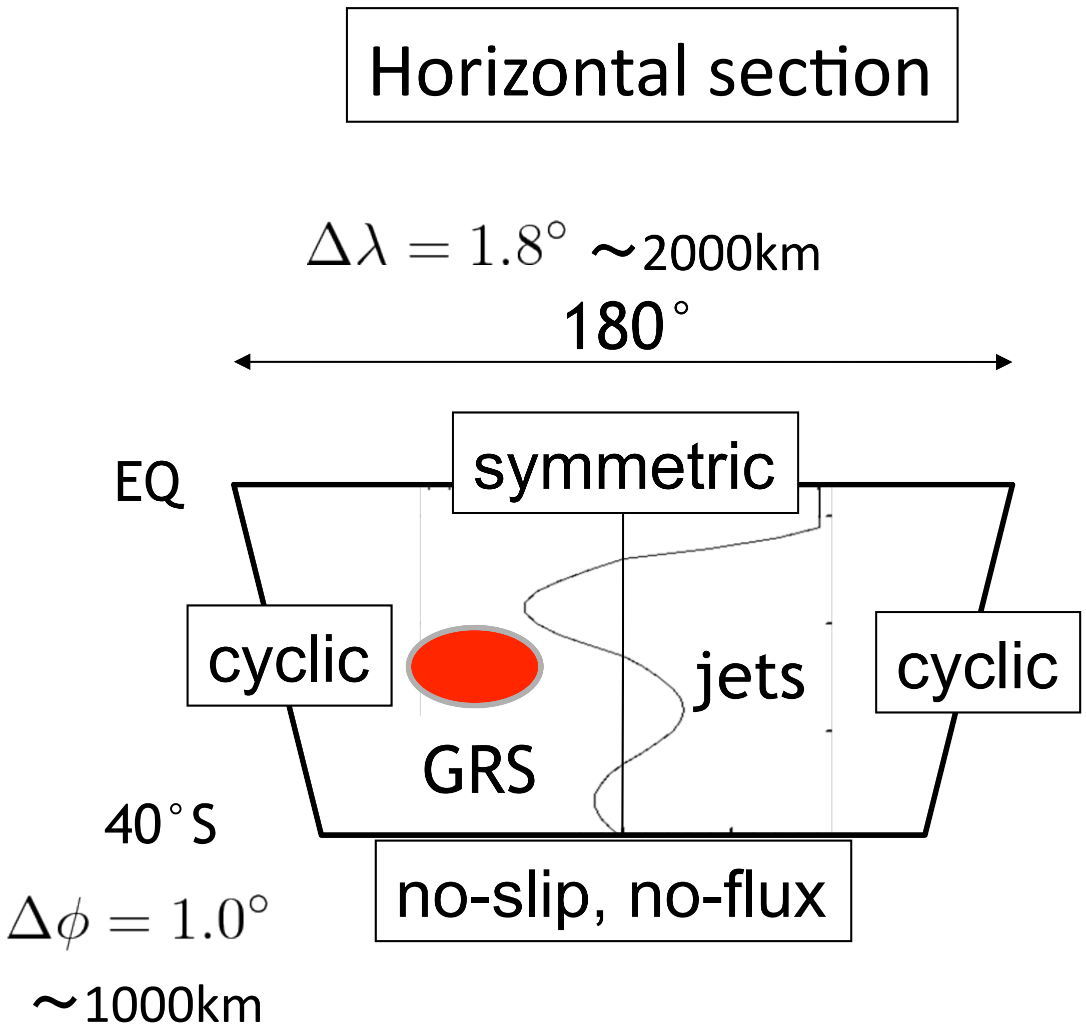
Momentum forcing only

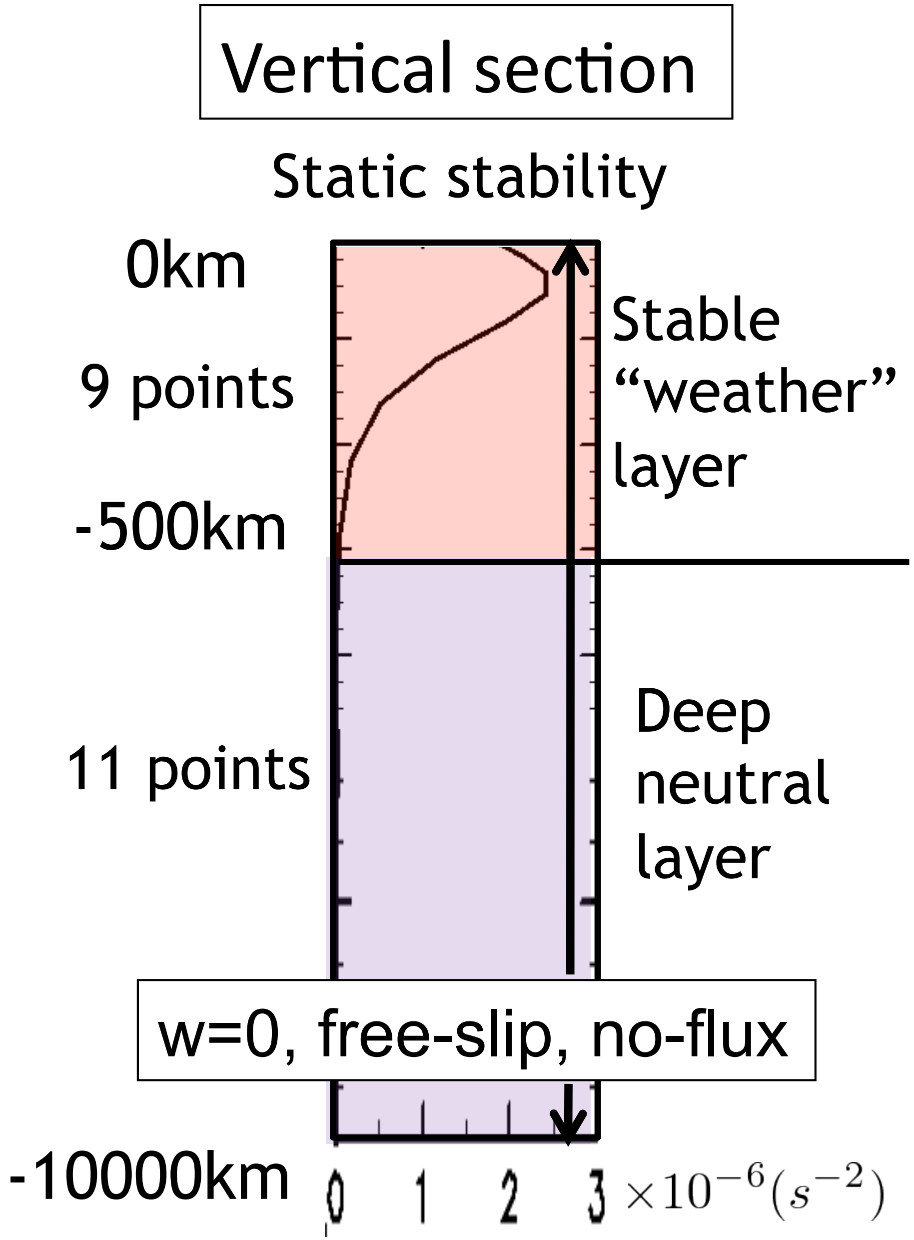
No forcing

(Only colored cases are conducted)

The same as the case A4 of Williams(1996)

Computational domain, resolution, boundary condition





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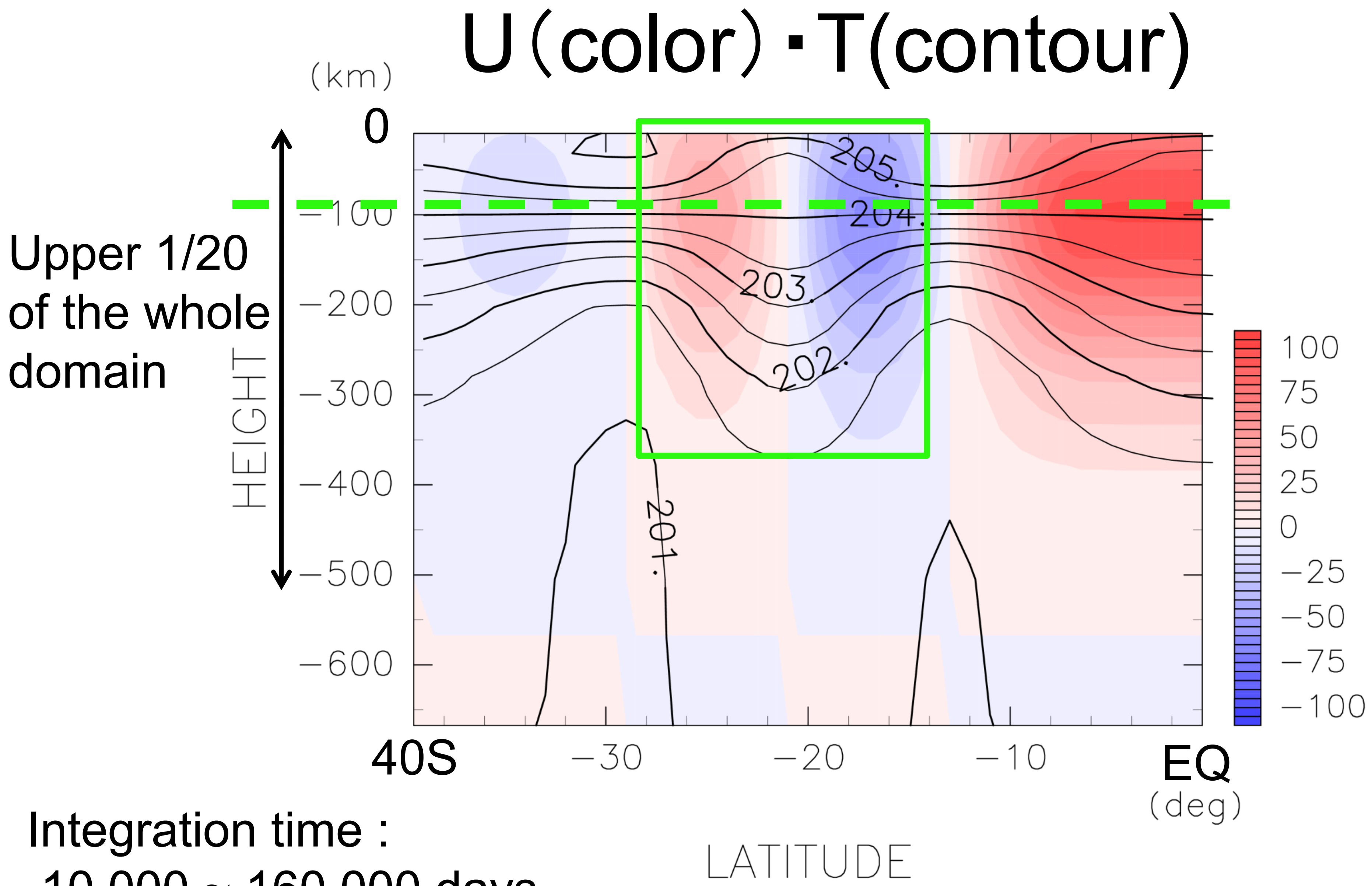


Integration time :
10,000 ~ 160,000 days

Results

Statistically steady states cases

Damping time of momentum forcing (day)

Damping time of Thermal forcing (day)

τ_T \ τ_M	30	100	300	1000	2000	4000	∞
30	B30						T30
100		B100					T100
300			B300				T300
1000				B1000			T1000
2000					B2000		T2000
4000						B4000	T4000
∞	M30	M100	M300	M1000	M2000	M4000	NF

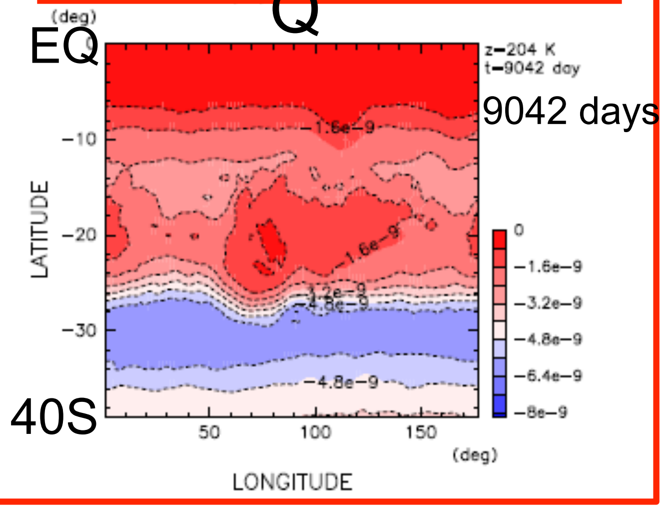
Statistically steady states cases

Damping time of momentum forcing (day)

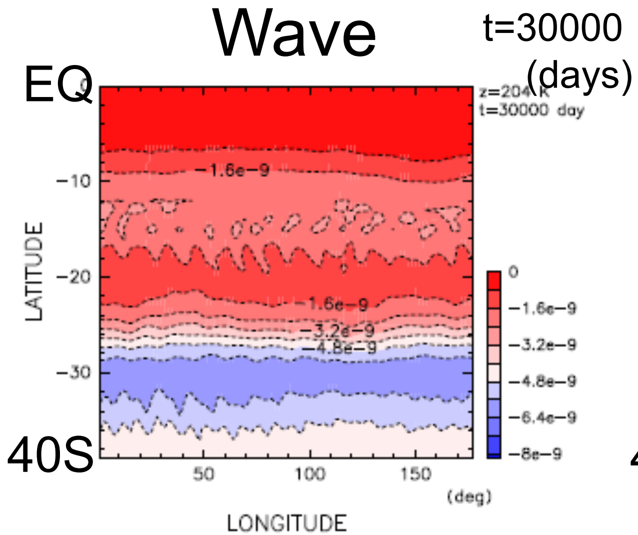
Damping time of Thermal forcing (day)

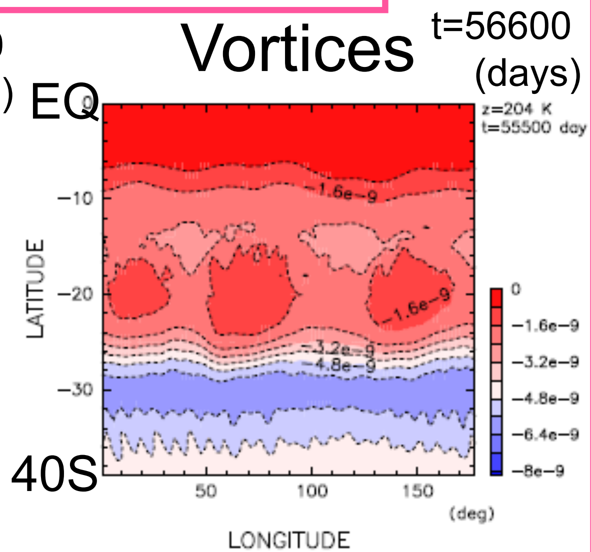
τ_T \ τ_M	30	100	300	1000	2000	4000	∞
30	B30						T30
100		B100					T100
300			B300				T300
1000				B1000			T1000
2000					B2000		T2000
4000						B4000	T4000
∞	M30	M100	M300	M1000	M2000	M4000	NF

Large-scale vortices always exist



Episodic development





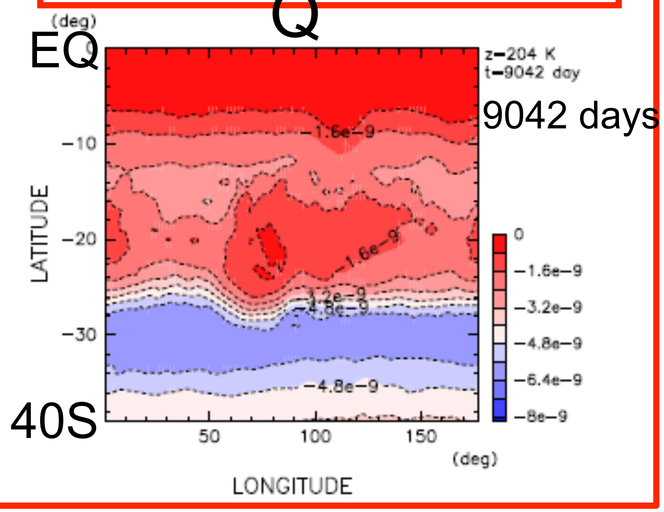
Statistically steady states cases

Damping time of momentum forcing (day)

Damping time of Thermal forcing (day)

τ_T \ τ_M	30	100	300	1000	2000	4000	∞
30	B30						T30
100		B100					T100
300			B300				T300
1000				B1000			T1000
2000					B2000		T2000
4000						B4000	T4000
∞	M30	M100	M300	M1000	M2000	M4000	NF

Large-scale vortices always exist

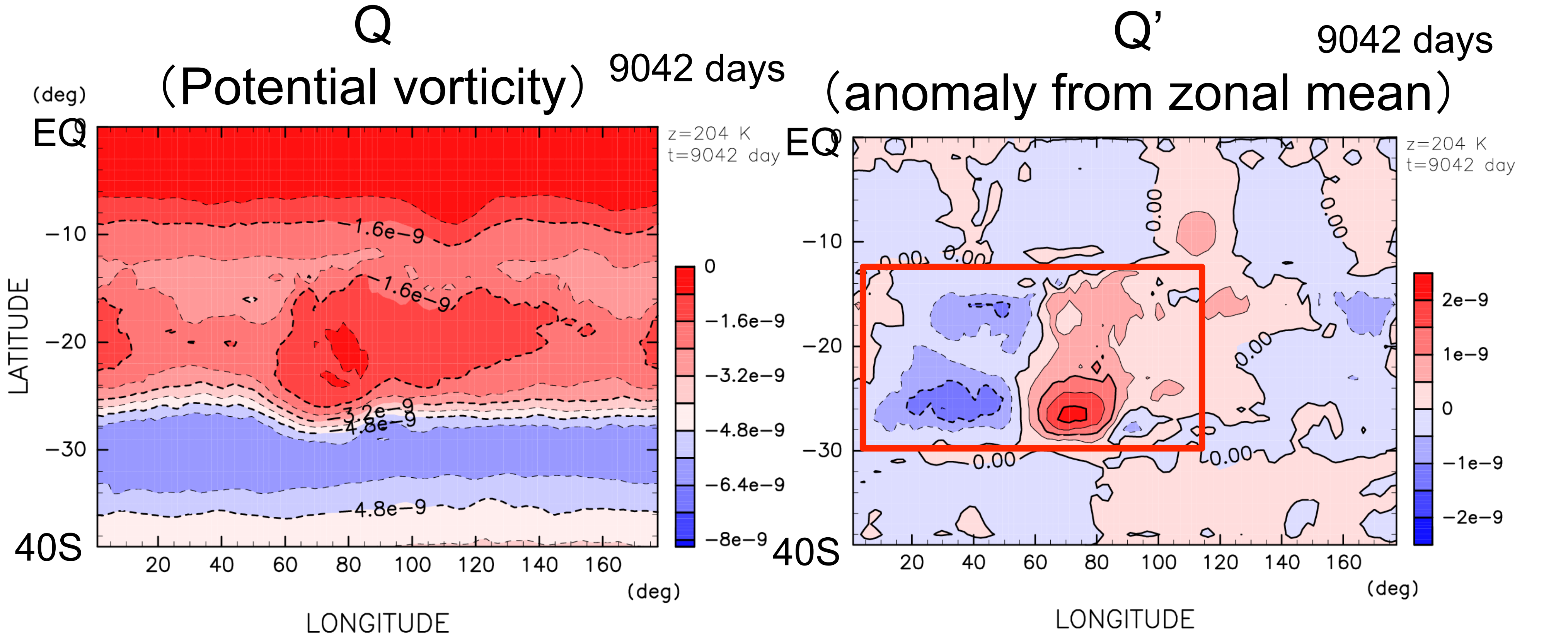


Focus on the B300 case

- The behavior of vortices are the most similar to the GRS

Time evolution of B300

movie



- Large-scale vortices are generated intermittently at intervals of 2-3 years.
- Life time is 2-3 years.
  - Propagate westward and diminish its longitudinal scale
  - absorbed by a newly grown large-scale vortex

Candidates of mechanism of the genesis of large-scale vortices

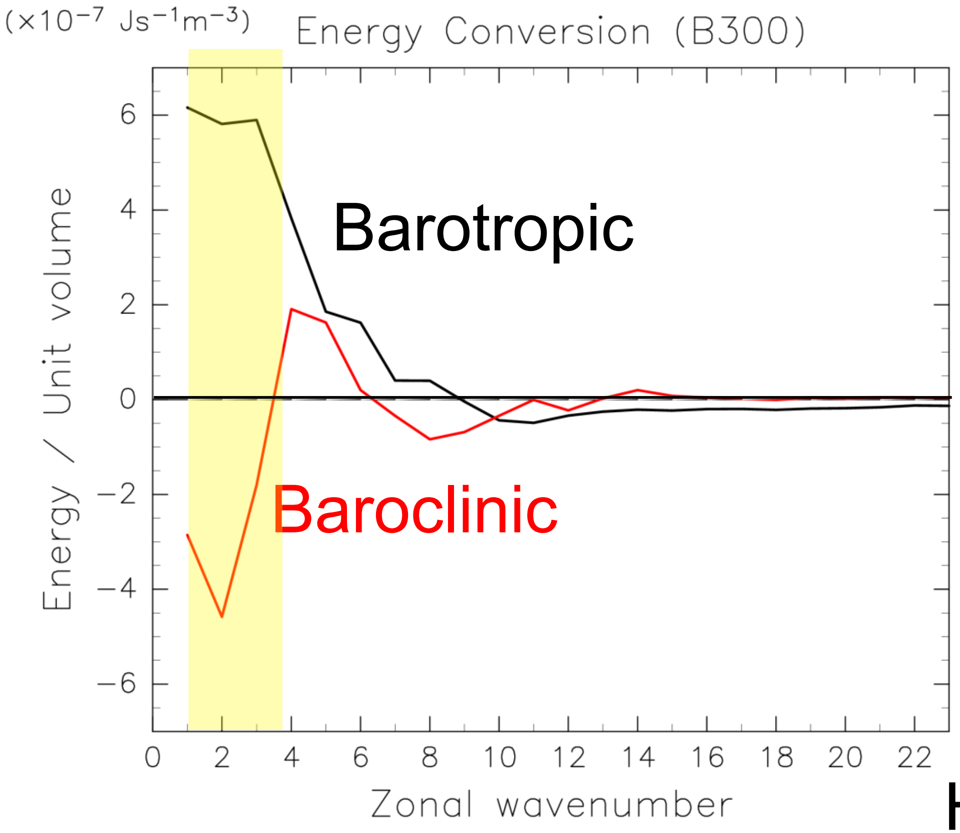
- Dynamical instability
  - Baroclinic or barotropic instability
- Merger of small scale vortices
  - Don’t discuss today
    - dynamical instability can provide large enough energy conversion for the genesis of large-scale vortices (show later).

<Examine>

1. Energetics
2. Linear stability

Energy conversion from zonal mean to wave field

(Averaged over 15.5 S ~ 27.5 S,
z= -9 km ~ -378 km,
from 8500 to 10000 days)



Large-scale vortices have positive barotropic energy conversion

How the energy conversion occur ?

TEM-based energy conversion

Randel and Stanford (1985)

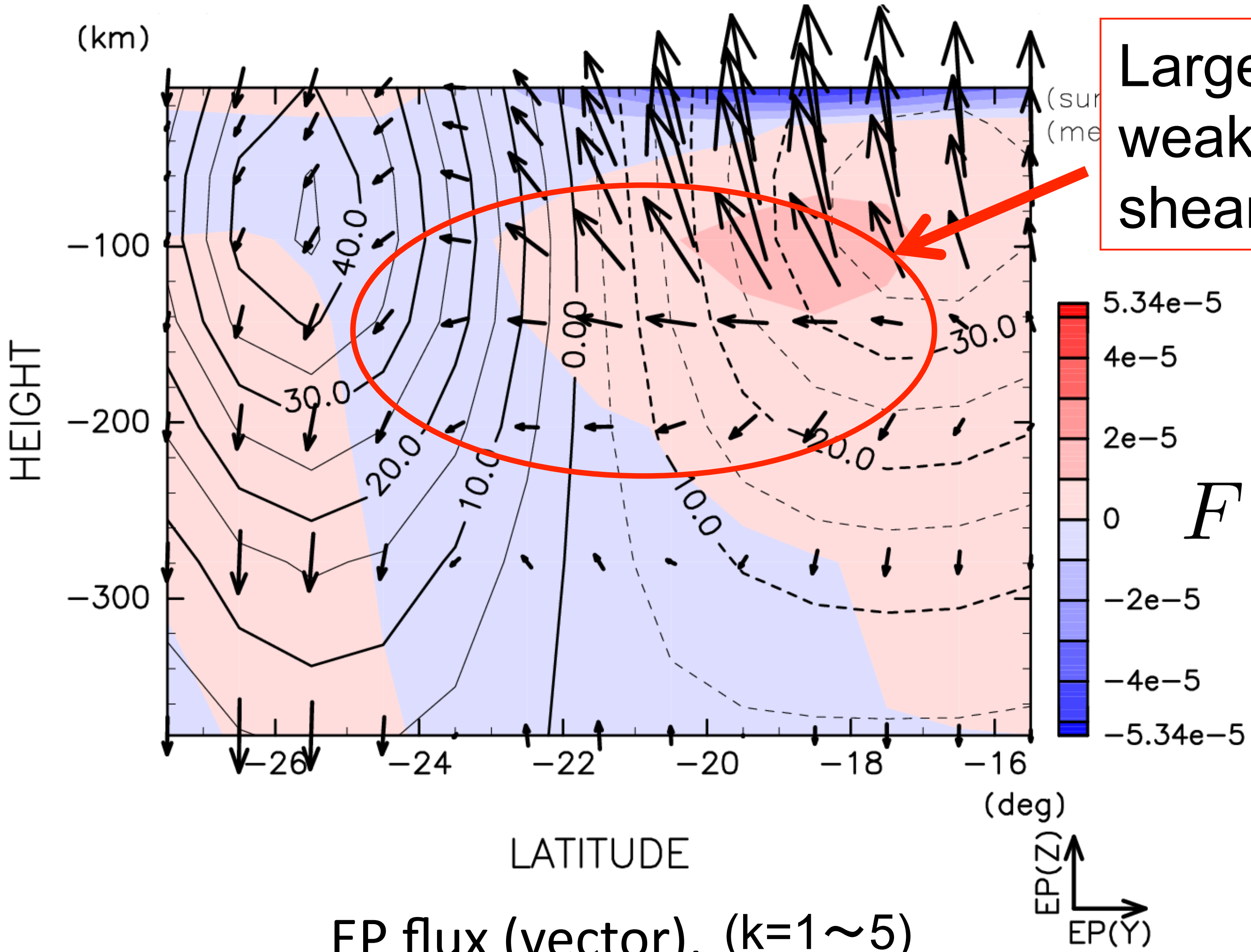
$$\frac{\partial E'}{\partial t} = -\frac{\partial \overline{E}}{\partial t} = \frac{1}{V}\iiint -\rho_0 \overline{u} \cdot DF dV$$

$$\simeq \frac{1}{V}\iiint \left[\frac{\rho_0 \overline{u}}{a\cos^2\phi}\frac{\partial}{\partial \phi}\left(\cos^2\phi \overline{v'u'}\right) - \rho_0 \overline{u} f \frac{\partial}{\partial z}\left(\frac{\overline{v'T'}}{\frac{\partial \overline{T}}{\partial z}}\right)\right] dV$$

Barotripic

Baroclinic

Dynamical properties of large-scale vortices



Large-scale vortices weaken meridional shear of the jets.

$$F^{(y)} \propto -\overline{u'v'}$$

EP flux (vector), (k=1∼5)

EP-flux divergence (color), U(contour)

(Averaged form 8500 to 10000 days)

・Energetics, dynamical property

⇩

The large-scale vortices are generated by barotoropic energy conversion

Can the behavior of the large-scale vortices be explained by a linear instability ?

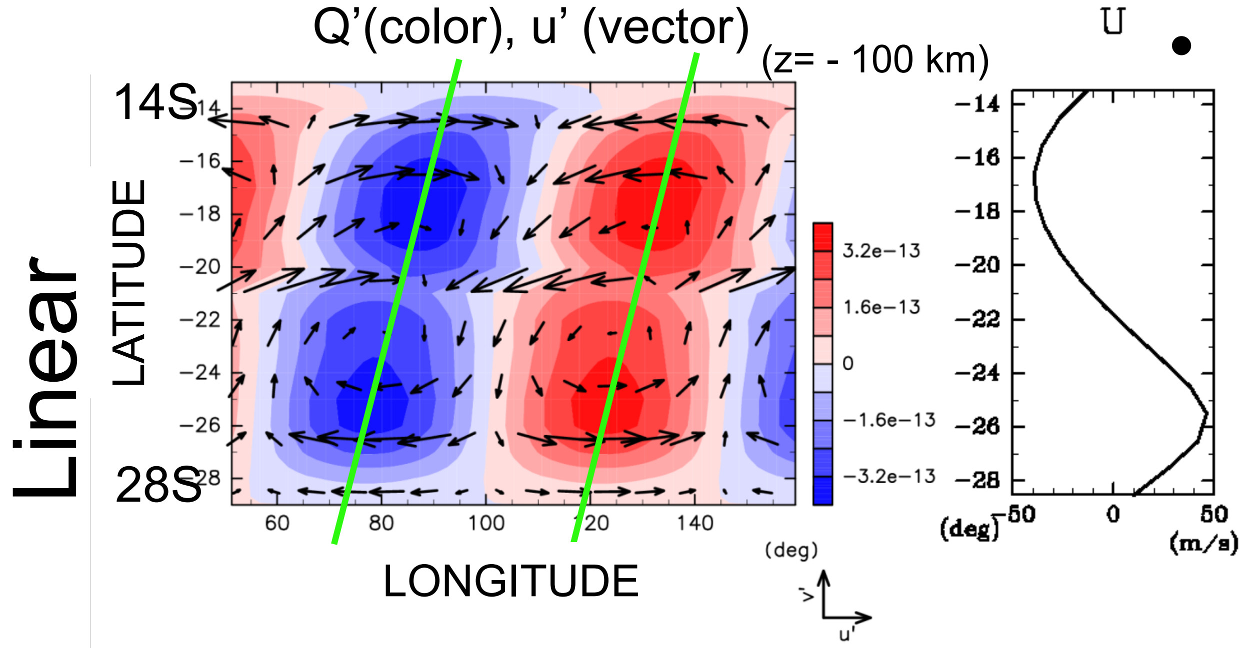
⇩

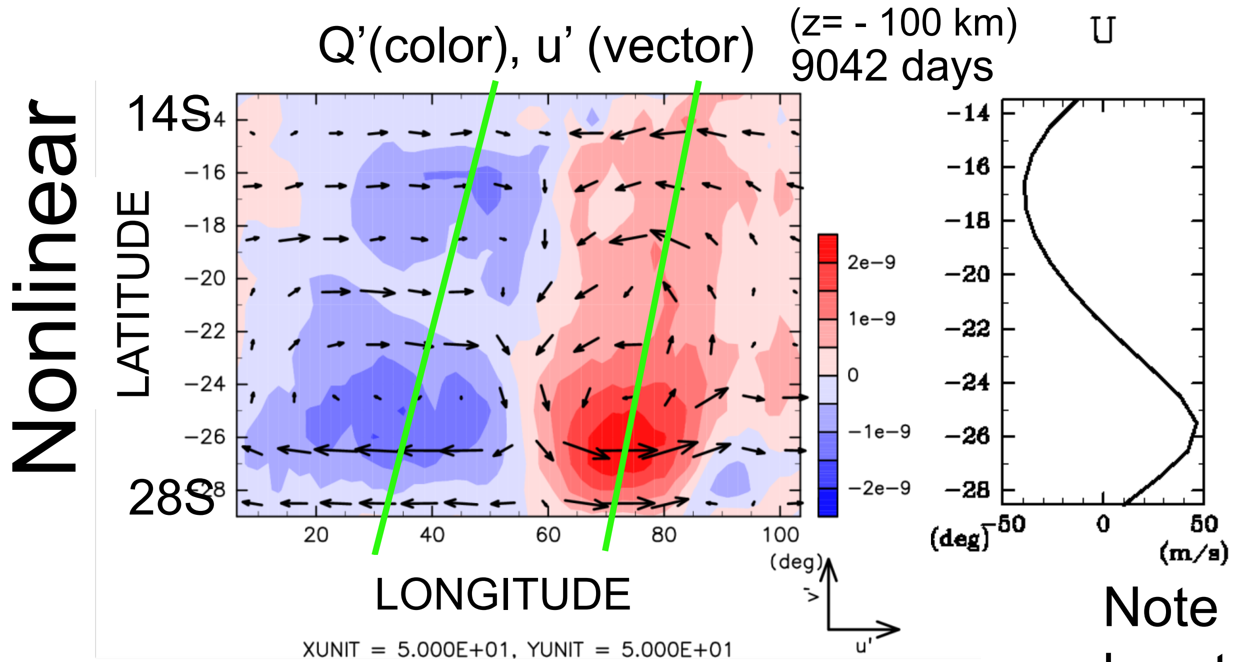
Linear stability analysis

Method for linear stability analysis

- Integrate nonlinear primitive equation model
  - Initial-value type (Wittman et al., 2002)
- The fastest growing mode is obtained for each zonal wave number.
- The basic state is zonal and time mean (8500-10000 days) field in the statistically steady state.

Horizontal structure of unstable mode





- Good correspondence
  - Zonal wave-length
  - Meridional phase tilt
  - Positive barotropic energy conversion
  - Growth rate
    - Linear : ~ 200 days
    - Nonlinear : ~ 200-400 days

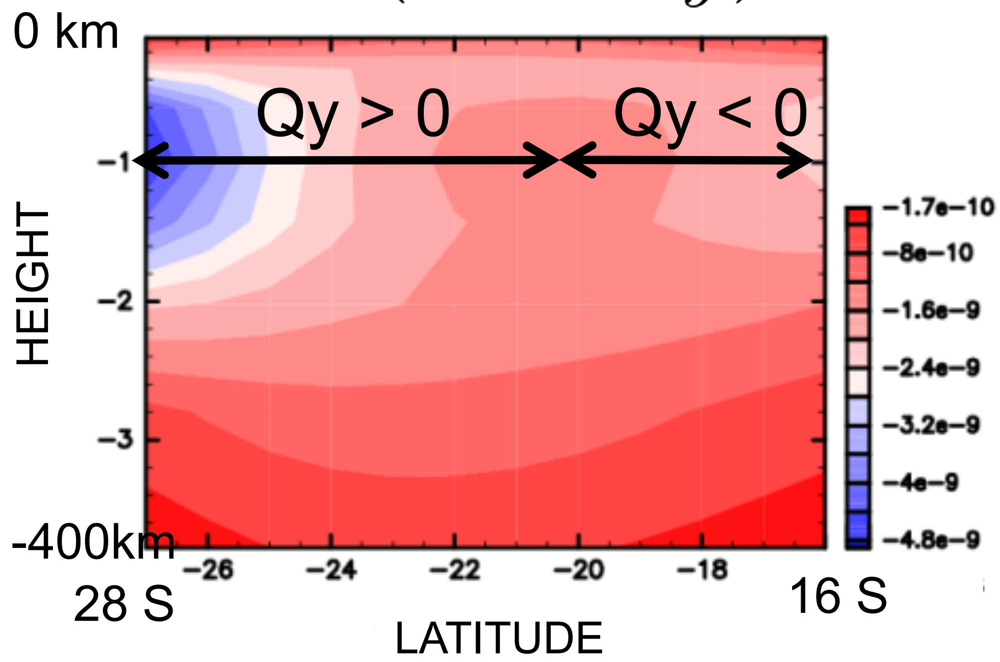
The generation mechanism of large-scale vortices is barotropic instability of the zonal jets

Note on the structure of the barotropically unstable basic state

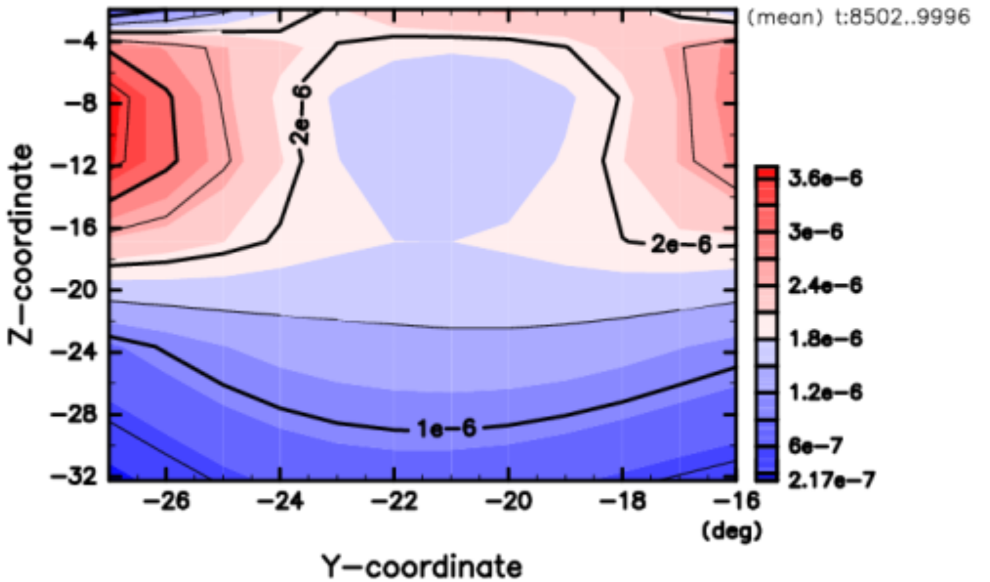
Origin of Q is baroclinicity

$$\overline{N^2} = \frac{g}{T_0}\frac{\partial \overline{T}}{\partial z}$$

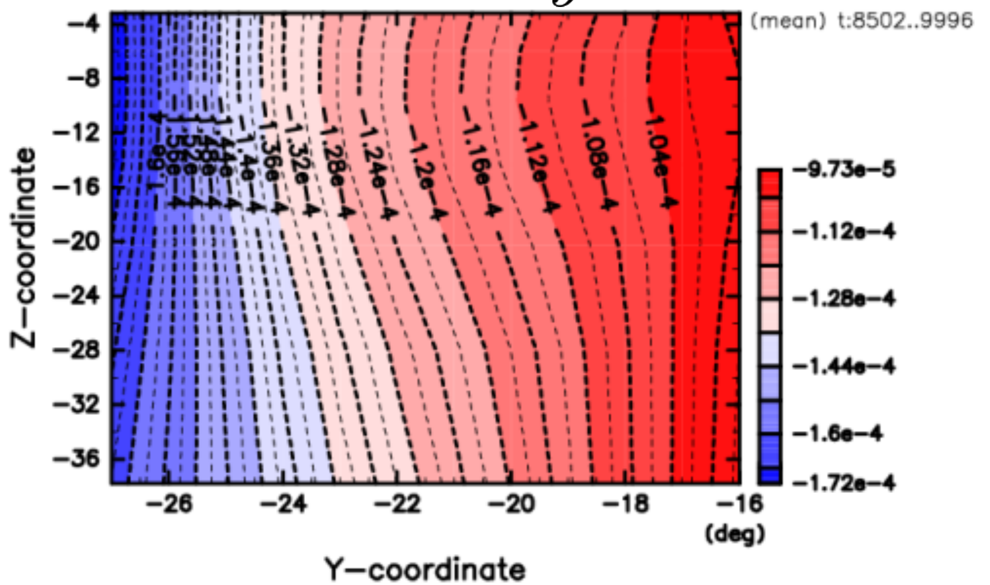
$$\overline{Q} \propto (f - U_y)\overline{N^2}$$



(Averaged form 8500 to 10000 days)



$$f - U_y$$



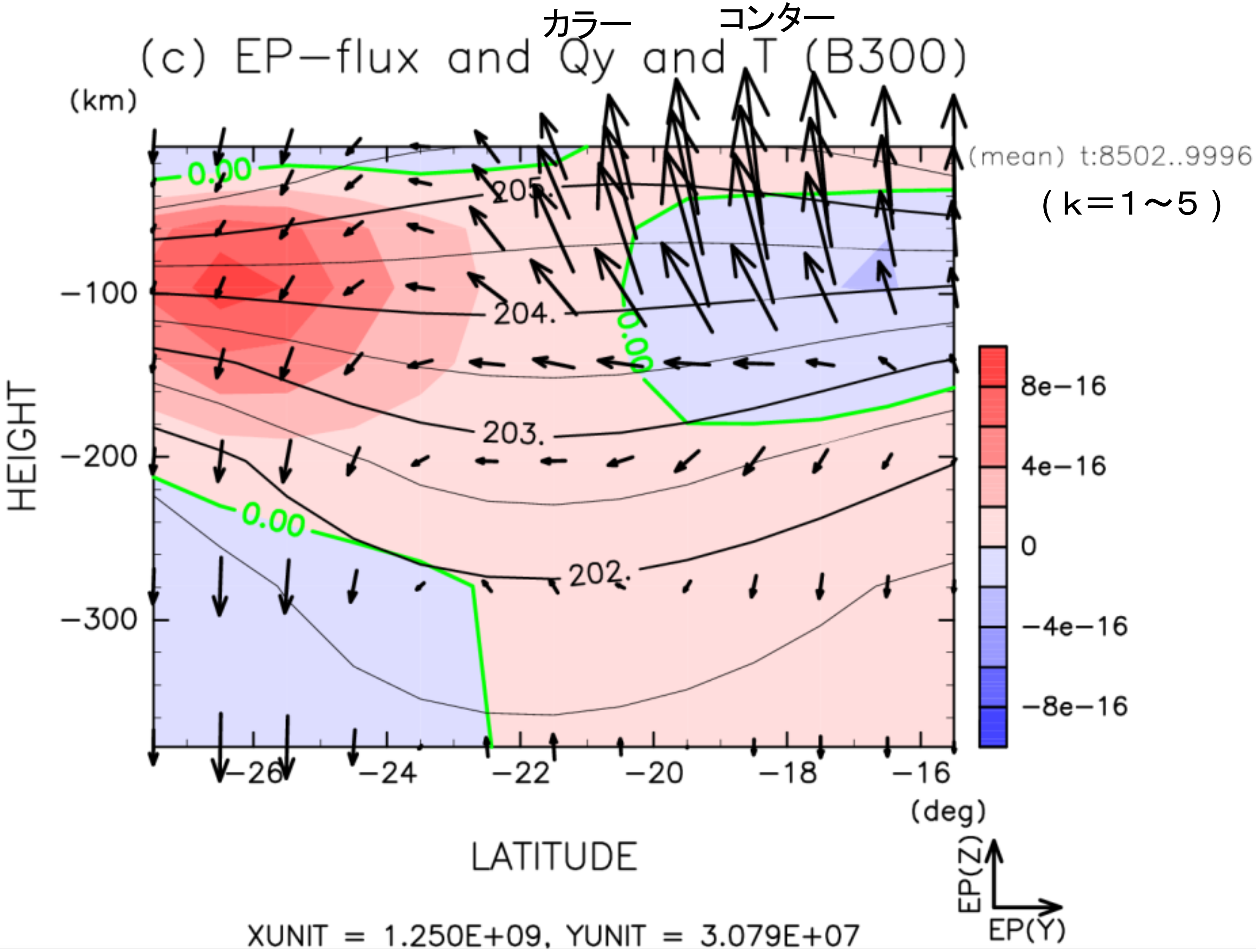
“baroclinic origin
barotoropic instability” ?

Summary

- The genesis and stability of vortices in Jupiter's atmosphere are examinedby using a 3D model.
- Forcings are introduced to maintain the strength of the jets
- Statistically steady states are realized with both momentum and thermal forcings
- Behavior of vortices can be classified into two types
  - Weak forcings : Episodic
  - Strong forcings : Large-scale vortices always exist
- The generation mechanism of the large-scale vortices is barotropic instability
  - The origin of the barotropic instability is baroclinicity

補足資料

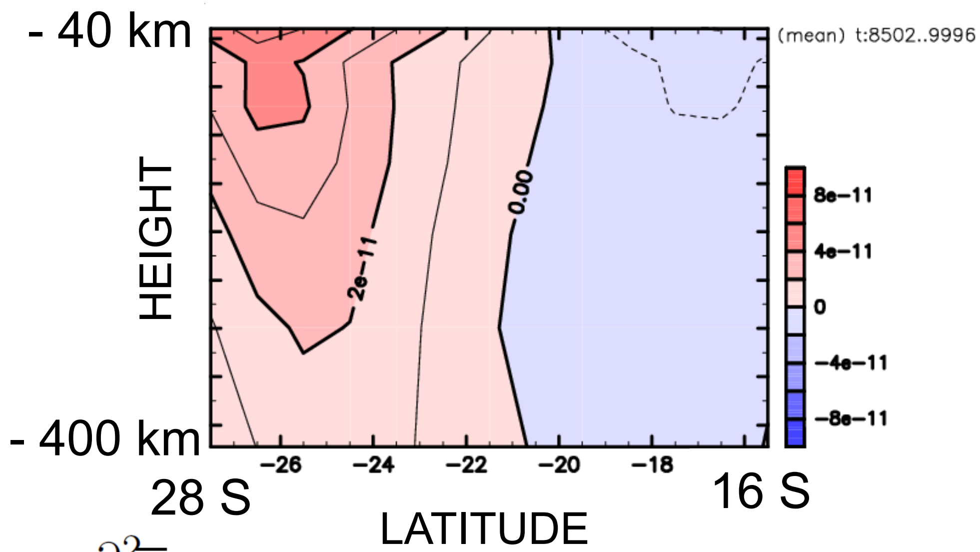
Qy は水平・鉛直どちらにも符号を変える



Origin of q_y is baroclinic

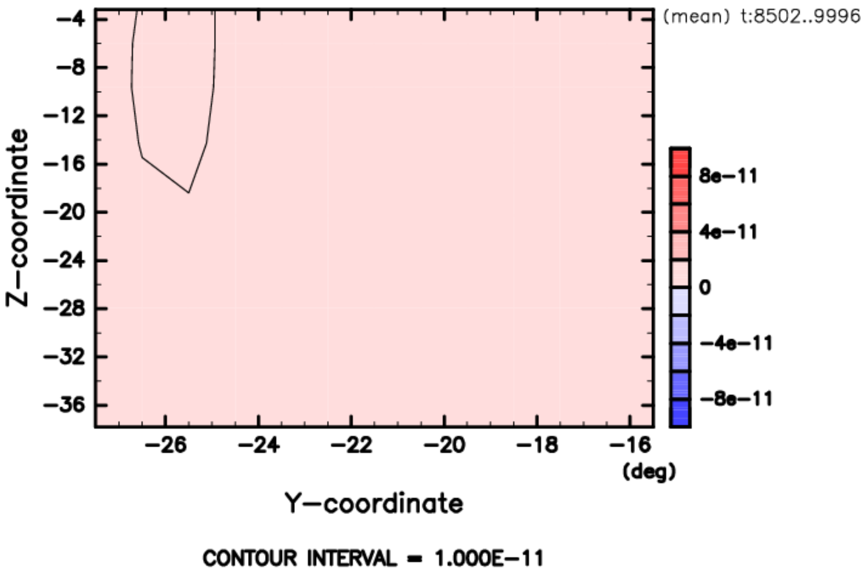
$$\overline{q}_y = \beta - \frac{\partial^2 \overline{u}}{\partial y^2} - \frac{\partial}{\partial z}\left(\epsilon \frac{\partial \overline{u}}{\partial z}\right)$$

(Averaged from 8500 to 10000 days)

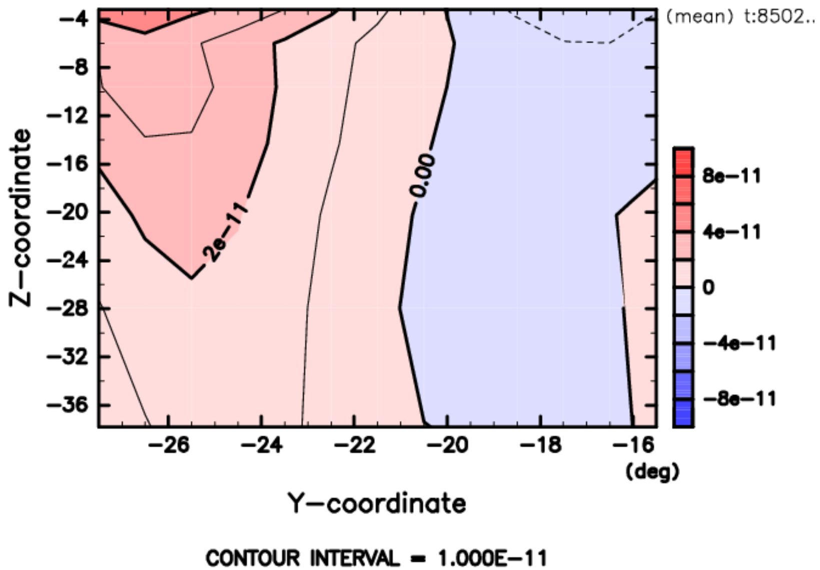


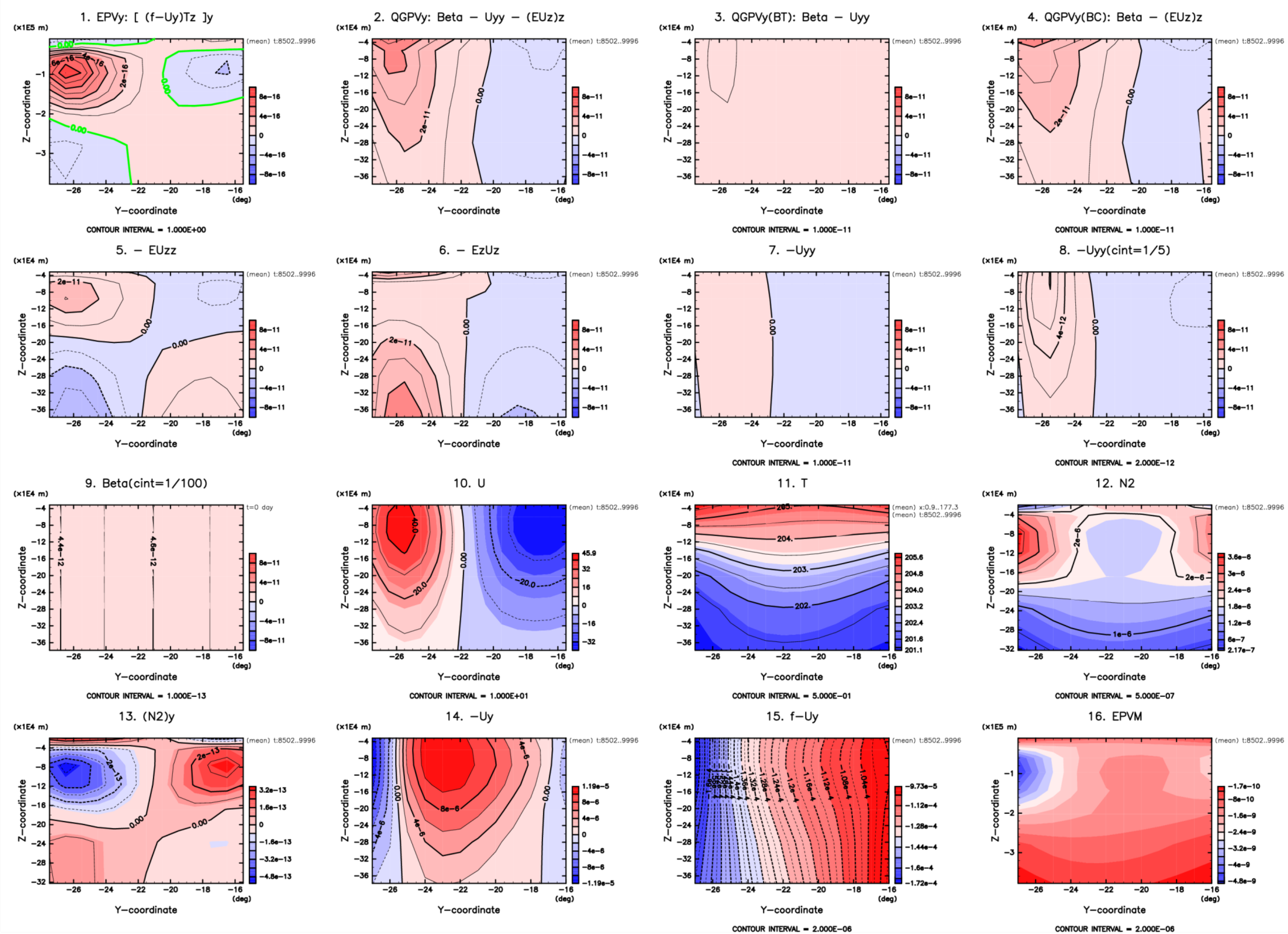
$$\epsilon \equiv \frac{f_0^2}{N^2}$$

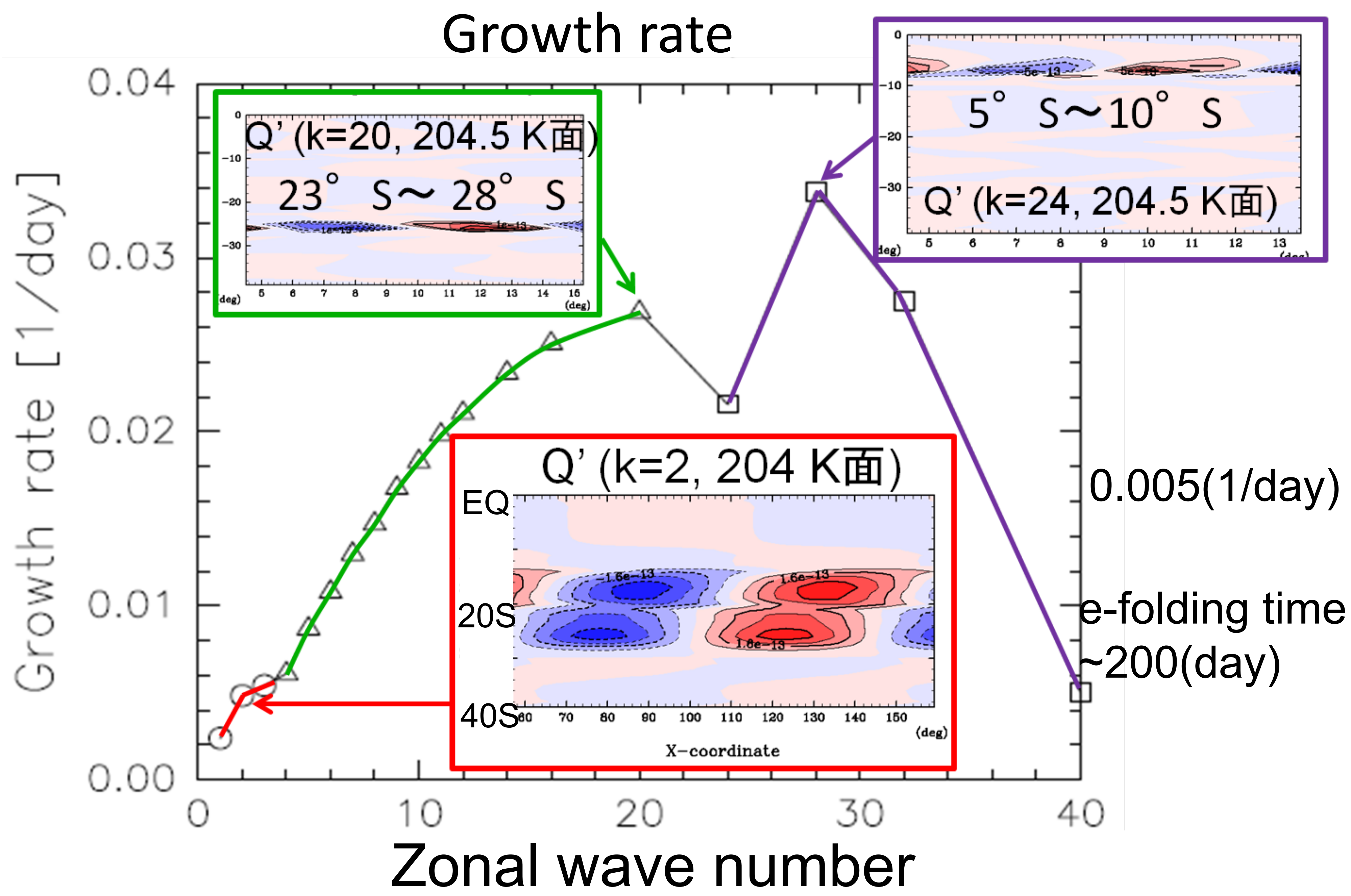
$$\beta - \frac{\partial^2 \overline{u}}{\partial y^2}$$



$$\beta - \frac{\partial}{\partial z}\left(\epsilon \frac{\partial \overline{u}}{\partial z}\right)$$



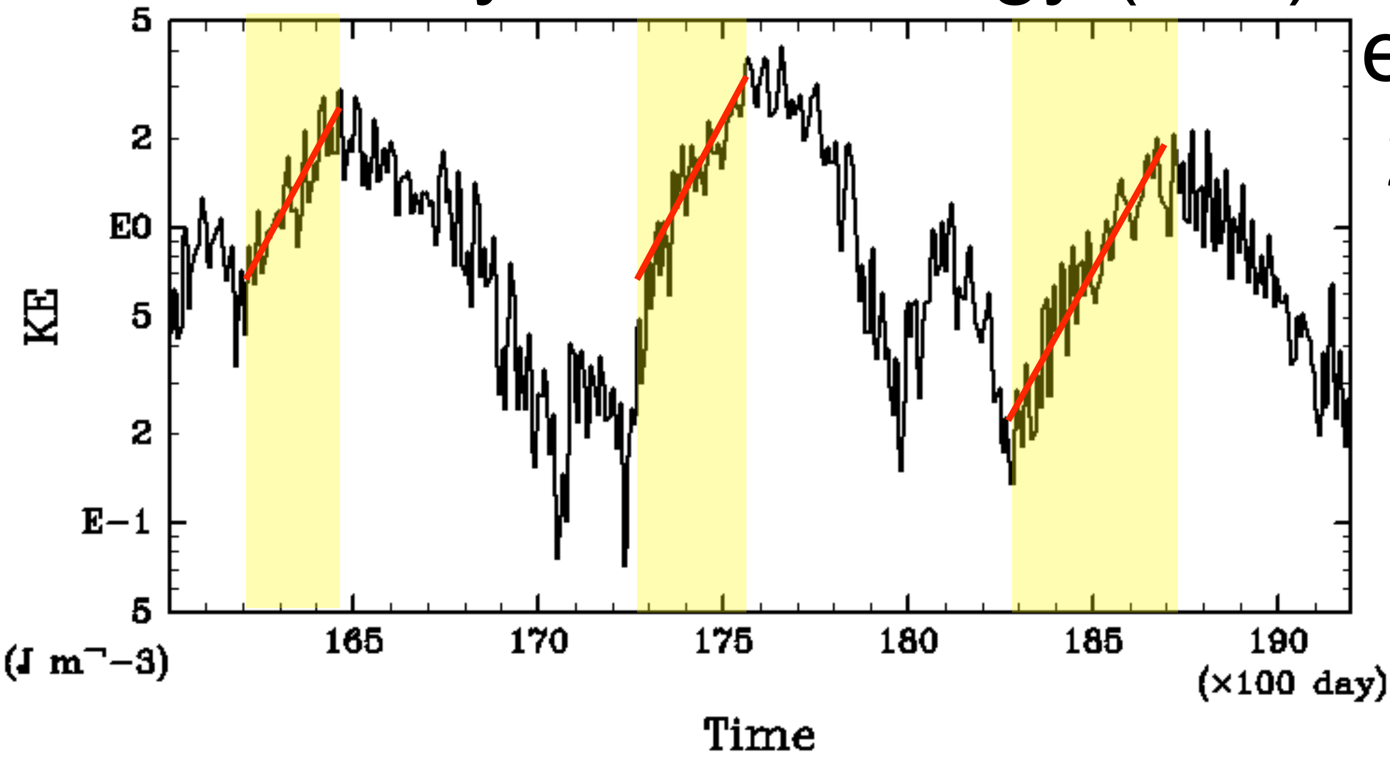

1. EPVy: [(f−Uy)Tz]y
(x1E5 m)
Z−coordinate
Y−coordinate
(deg)
(mean) t:8502..9996
CONTOUR INTERVAL = 1.000E+00
2. QGPVy: Beta − Uyy − (EUz)z
(x1E4 m)
3. QGPVy(BT): Beta − Uyy
CONTOUR INTERVAL = 1.000E−11
4. QGPVy(BC): Beta − (EUz)z
CONTOUR INTERVAL = 1.000E−11
5. − EUzz
6. − EzUz
7. −Uyy
CONTOUR INTERVAL = 1.000E−11
8. −Uyy(cint=1/5)
CONTOUR INTERVAL = 2.000E−12
9. Beta(cint=1/100)
t=0 day
CONTOUR INTERVAL = 1.000E−13
10. U
CONTOUR INTERVAL = 1.000E+01
11. T
(mean) x:0.9..177.3
CONTOUR INTERVAL = 5.000E−01
12. N2
CONTOUR INTERVAL = 5.000E−07
13. (N2)y
14. −Uy
15. f−Uy
CONTOUR INTERVAL = 2.000E−06
16. EPVM
CONTOUR INTERVAL = 2.000E−06



Growth rate
Growth rate [1/day]
0.04
0.03
0.02
0.01
0.00
0
10
20
30
40
Zonal wave number
Q' (k=20, 204.5 K面)
23° S～ 28° S
Q' (k=24, 204.5 K面)
5° S～10° S
Q' (k=2, 204 K面)
EQ
20S
40S
X−coordinate
0.005(1/day)
e-folding time
~200(day)

Growth rate of large-scale disturbance (k=2) in nonlinear calc.

Eddy kinetic energy (k=2)



e-folding time：
200～400 days

⇧

Close to the k=2 disturbance of linear stability analysis

Energy conversion property（k=2）

$$\frac{\text{Barotropic conversion}}{\text{Kinetic energy}} = \quad 0.10\,\mathrm{d}^{-1} > 0$$

$$\frac{\text{Baroclinic conversion}}{\text{Kinetic energy}} = \quad -0.01\,\mathrm{d}^{-1} > 0$$

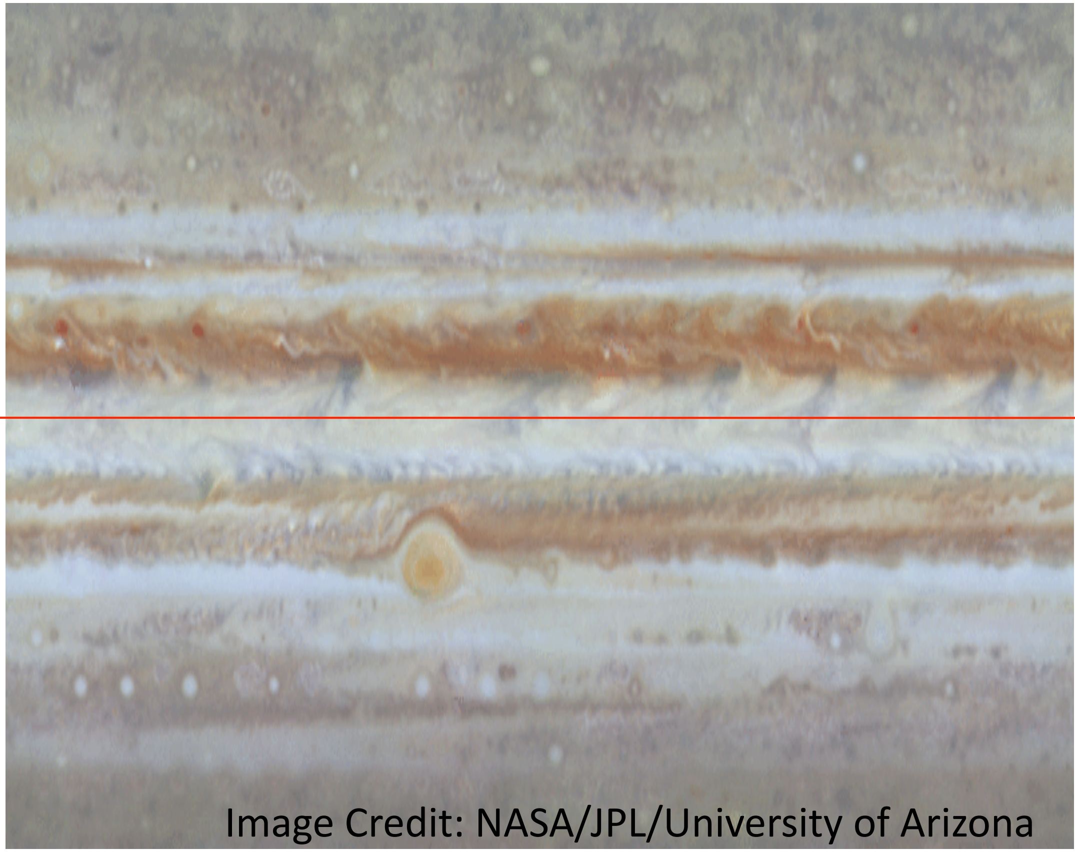
The linearly unstable mode (k=2) gain disturbance energy from the zonal mean flow thorough barotropic conversion.

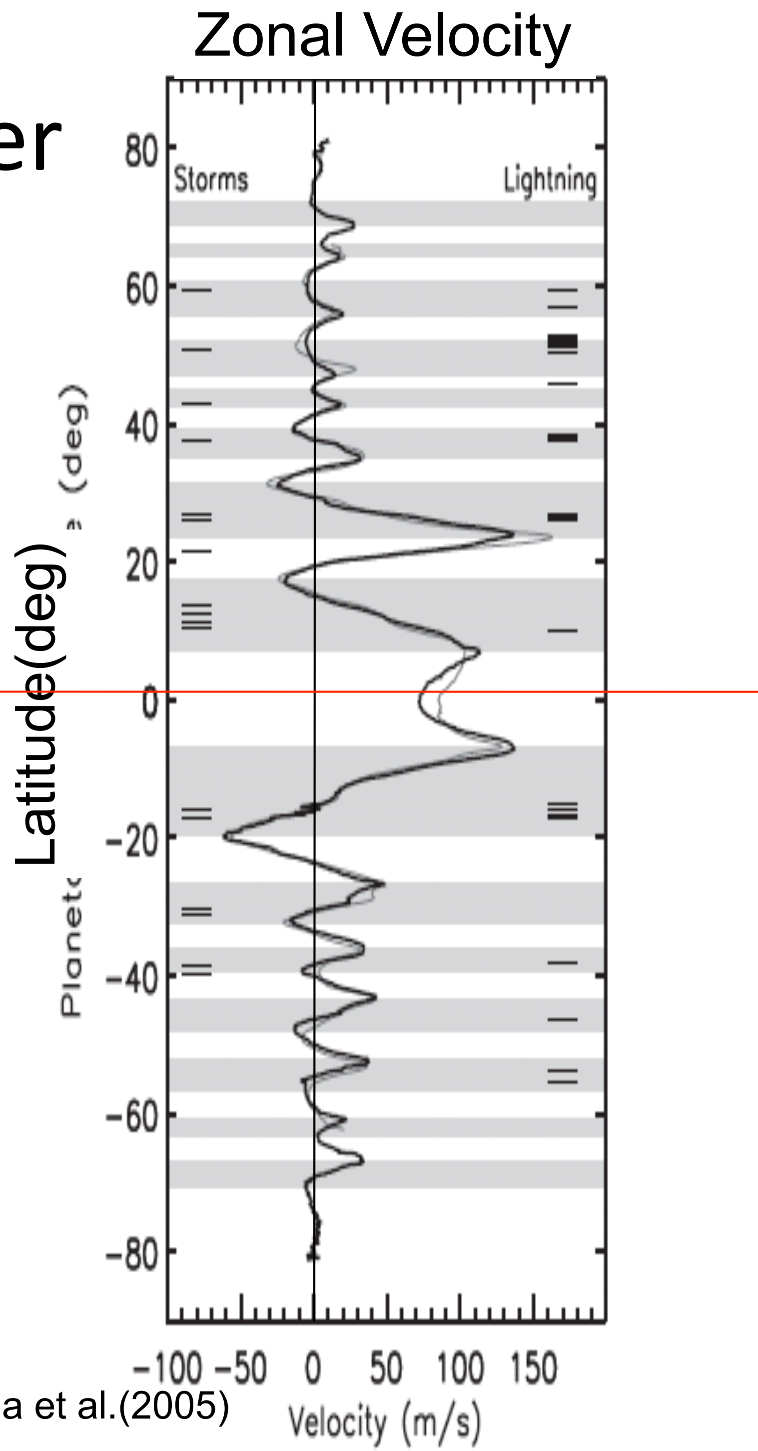
Zones, belts and vortices in Jupiter

60°N

EQ

60°S

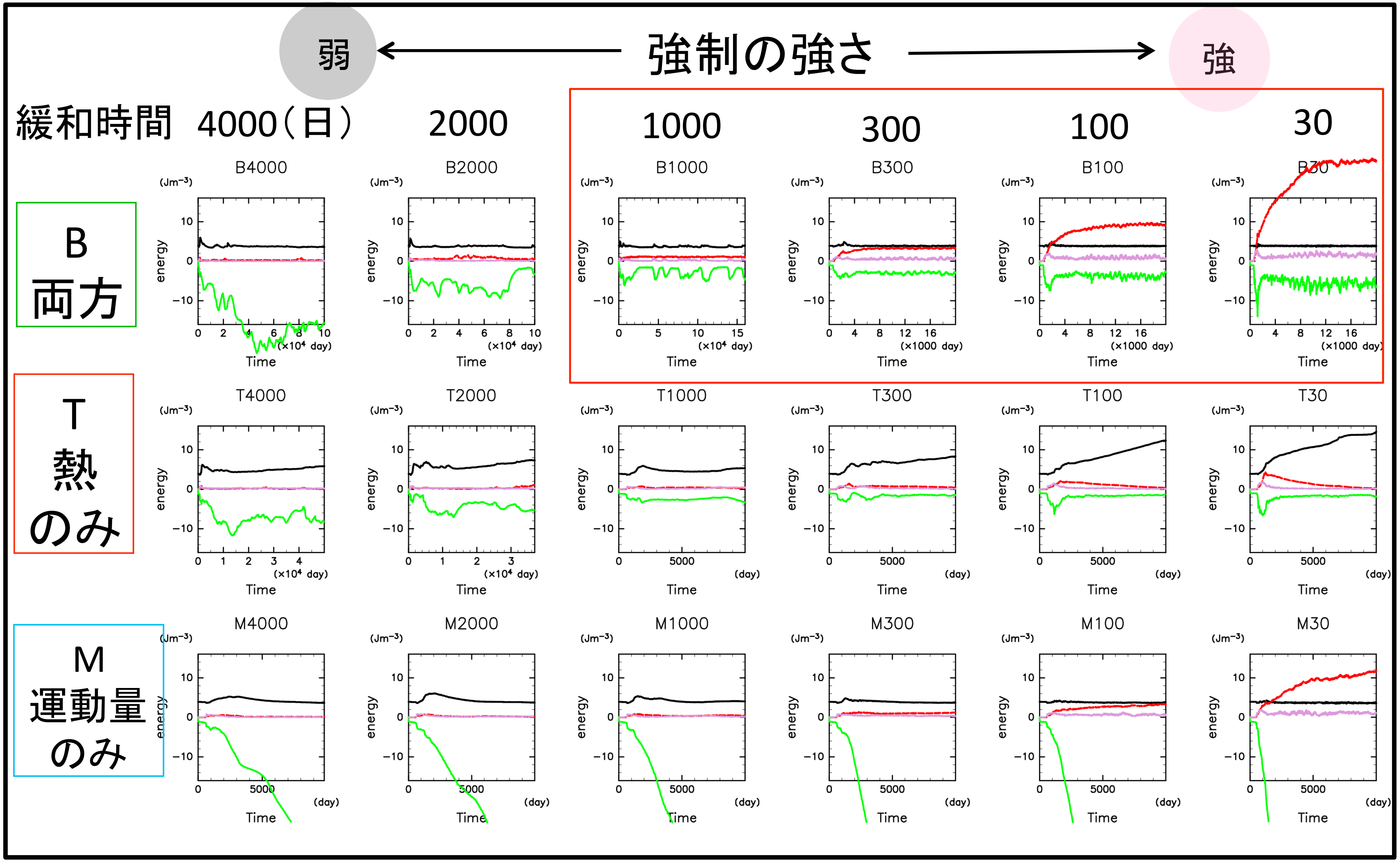




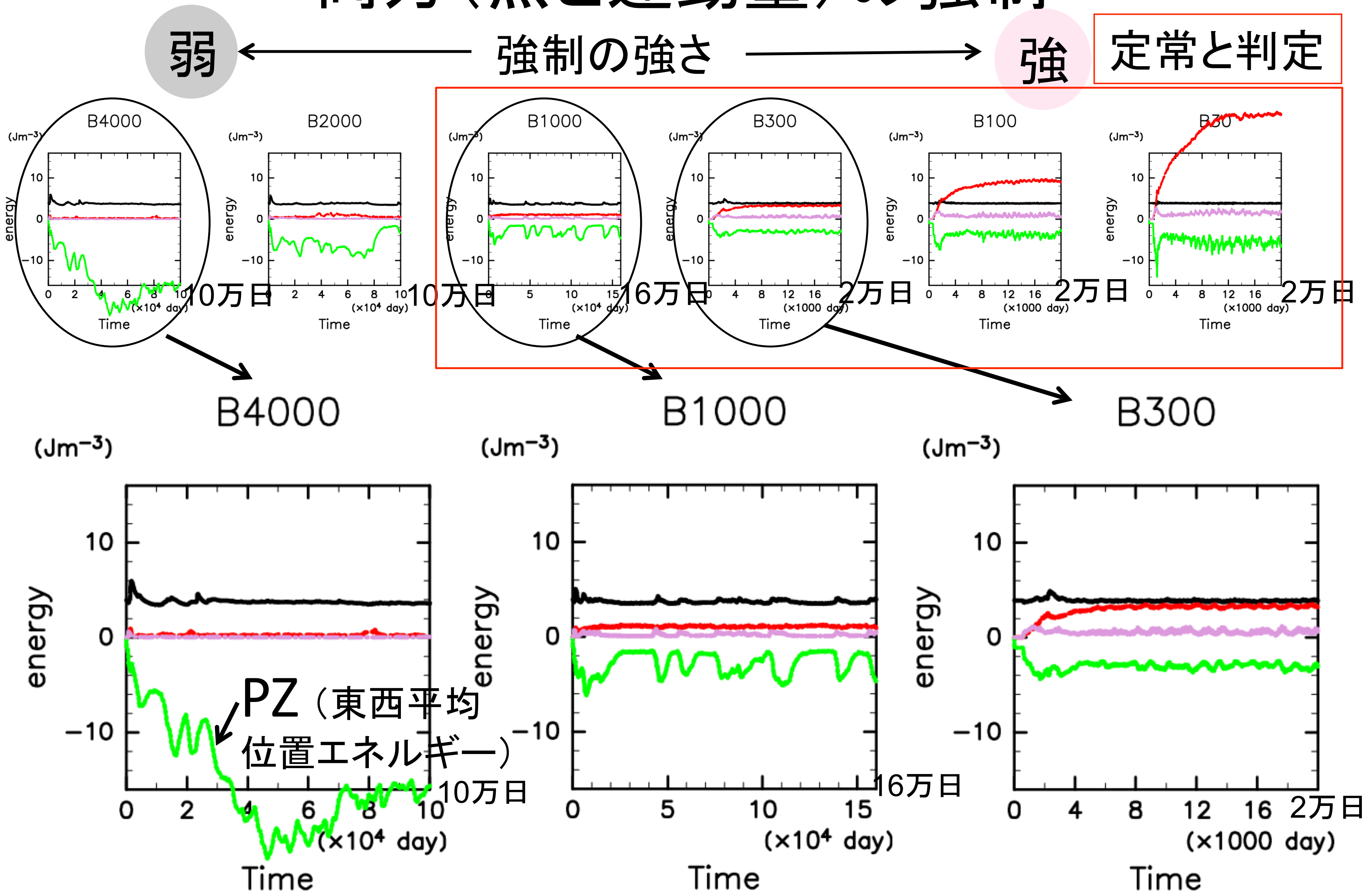
Vasavada et al.(2005)

- Cassini Flyby
  - 360°in longitude
  - from Oct 31 to Nov 9, 2000 (24 Jupiter's day)

エネルギーによる統計的定常状態の判定

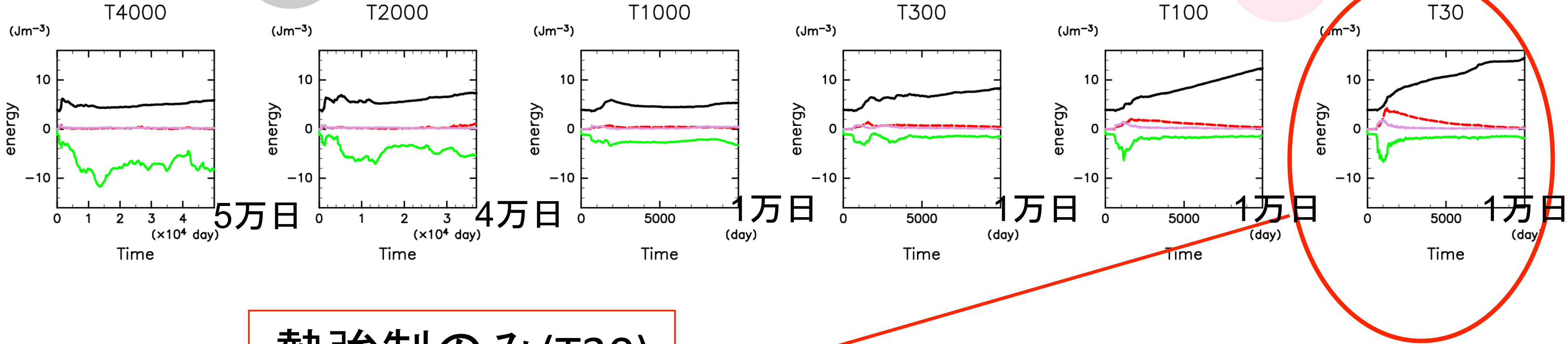


両方(熱と運動量)の強制

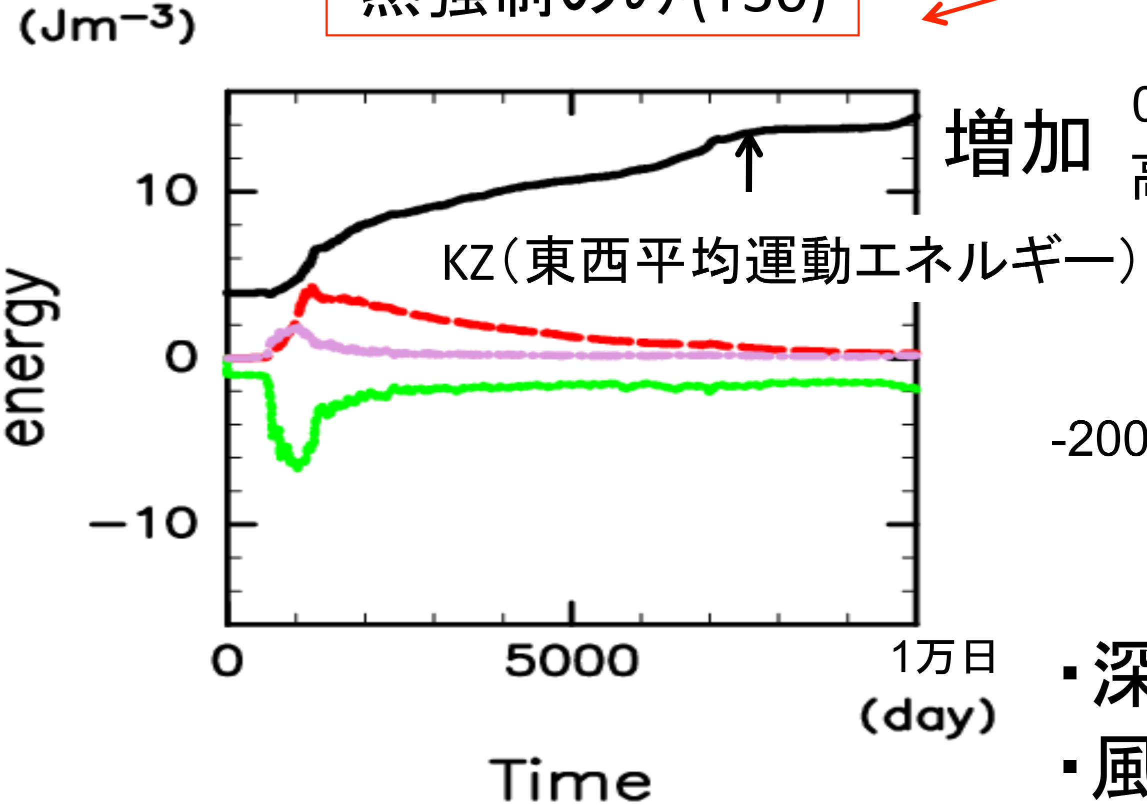

弱
強制の強さ
強
定常と判定
B4000
B2000
B1000
B300
B100
B30
(Jm⁻³)
energy
Time
(×10⁴ day)
(×1000 day)
10万日
10万日
16万日
2万日
2万日
2万日
B4000
B1000
B300
PZ（東西平均
位置エネルギー）
10万日
16万日
2万日

熱強制のみ

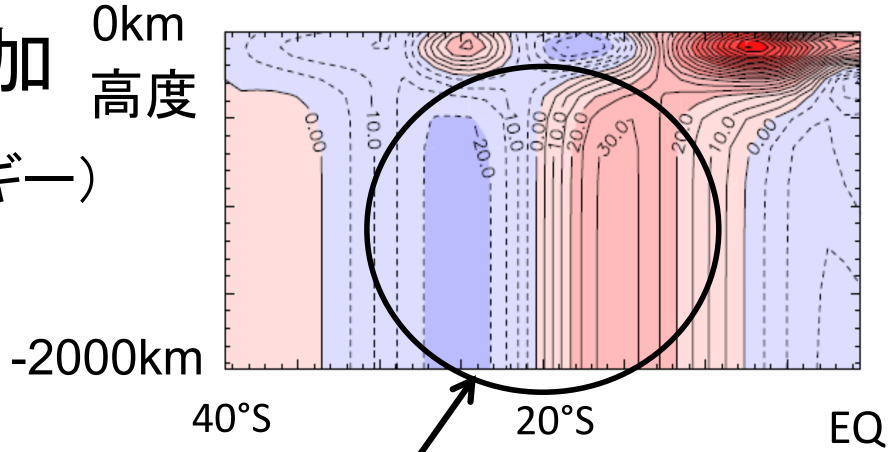
弱 ← 強制の強さ → 強



熱強制のみ(T30)



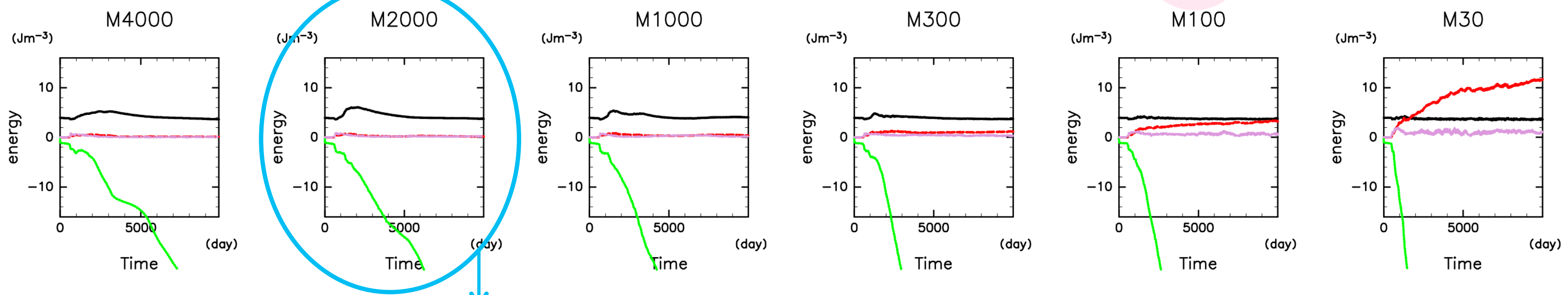
U（20000日）

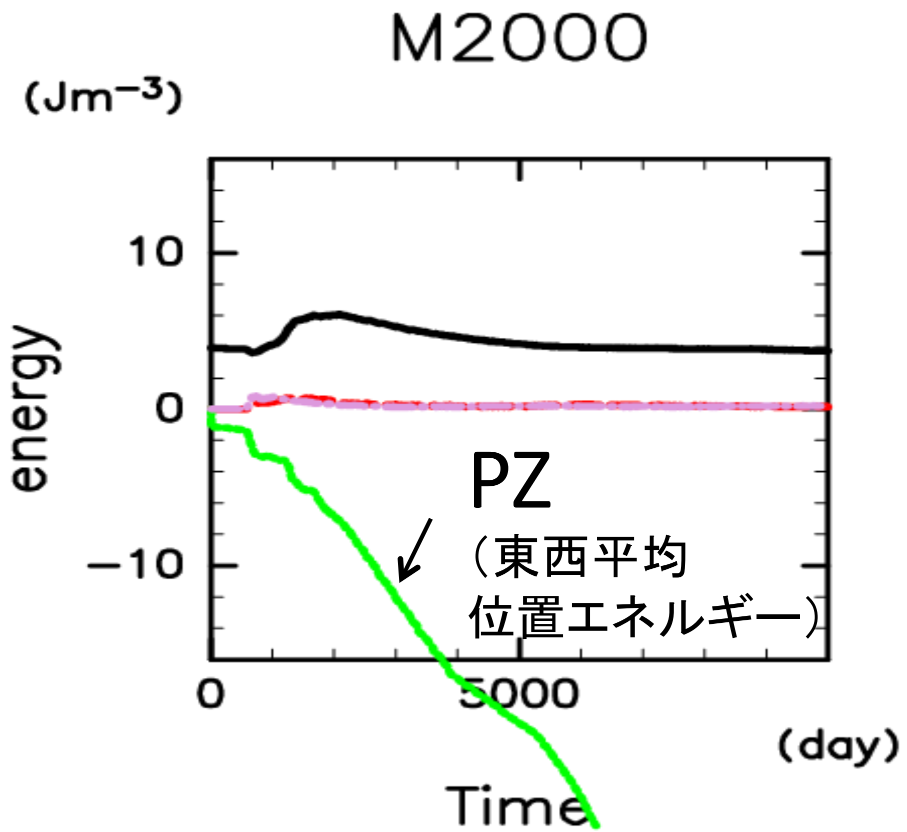


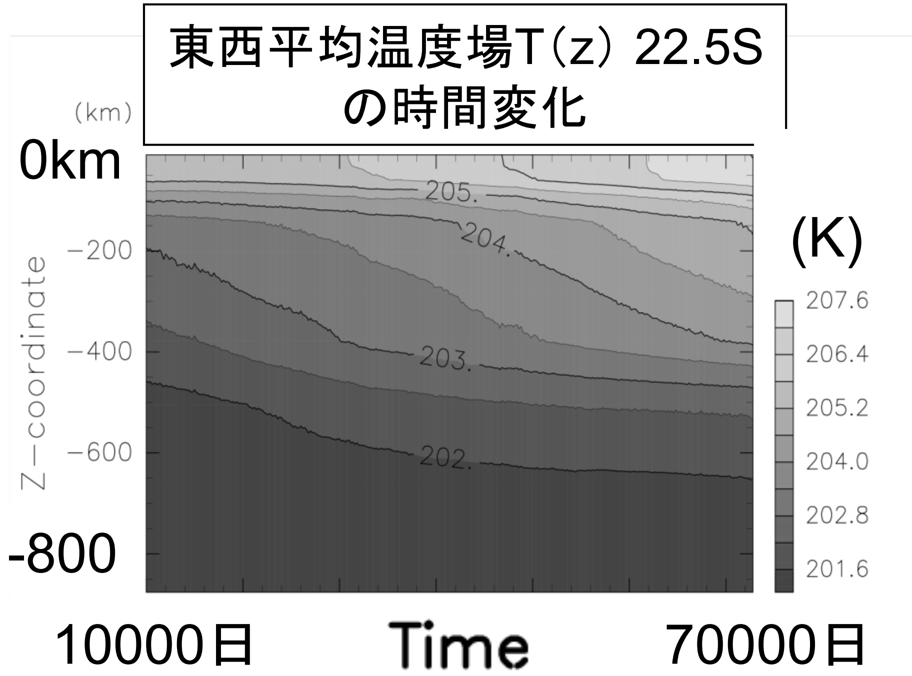
- 深部に及ぶジェットが形成
- 風速が増加し続けた

運動量強制のみ

弱 ← 強制の強さ → 強







上部で温度が増加

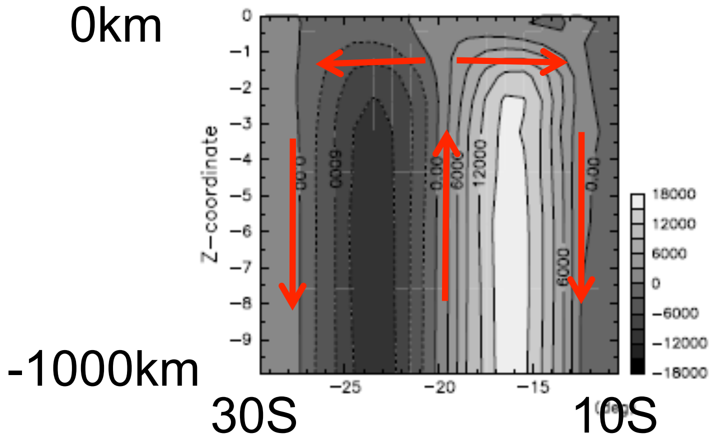
疑問

- 熱強制のみの場合の深部のジェットの加速はどのようにして引き起こされたか？
- 運動量強制の場合になぜ上部の温度が増加し続けたか？

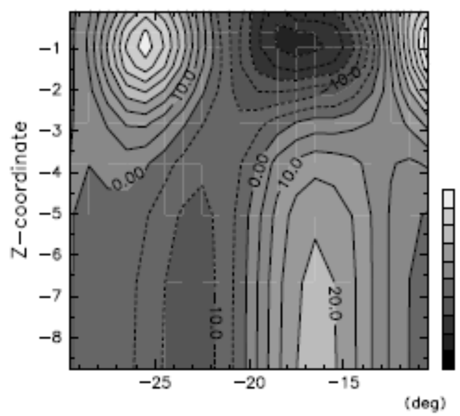
運動量収支（上部） 600-2100日平均

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\overline{v}}{a}\frac{\partial \overline{u}}{\partial \phi} - \overline{w}\frac{\partial \overline{u}}{\partial z} + \underbrace{f\overline{v}}_{(d)} + \frac{\tan\phi}{a}\overline{u}\,\overline{v} \underbrace{- \frac{1}{a\cos^2\phi}\frac{\partial}{\partial\phi}(\overline{v'u'}\cos^2\phi)}_{(e)} - \frac{\partial}{\partial z}(\overline{w'u'}) \underbrace{+\overline{Visc}}_{(f)}$$

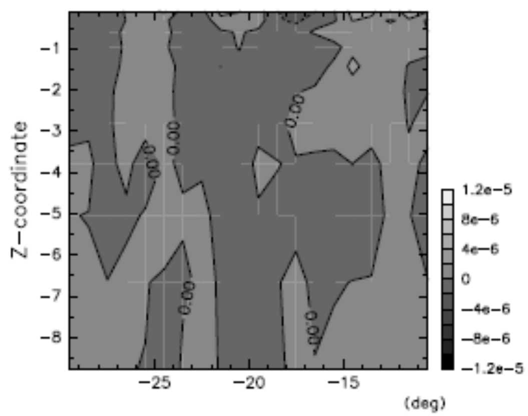
子午面流線関数



U(2100日)

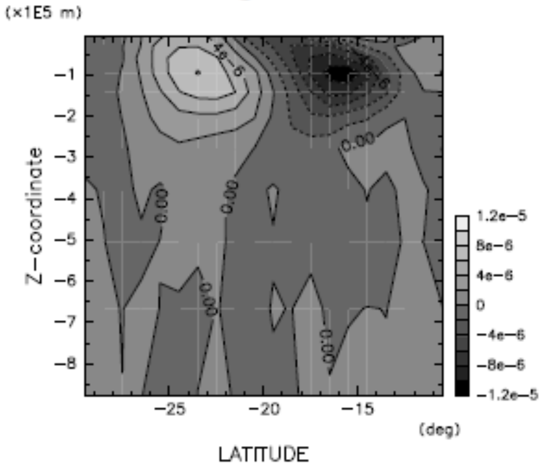


右辺の和

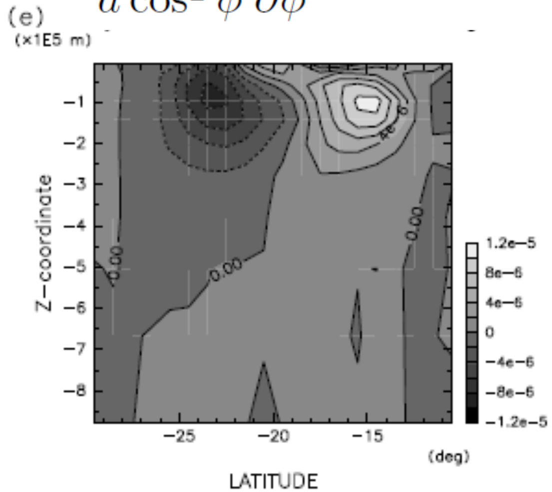


$\mathrm{m\,s^{-2}}$

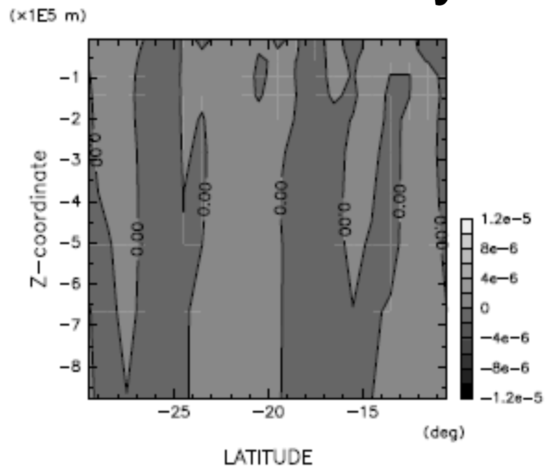
(d) $f\overline{v}$



(e) $-\frac{1}{a\cos^2\phi}\frac{\partial}{\partial\phi}(\overline{v'u'}\cos^2\phi)$



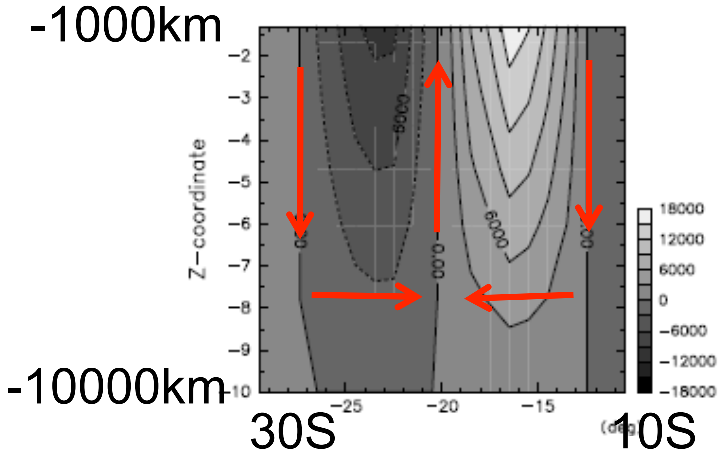
(f) Viscosity



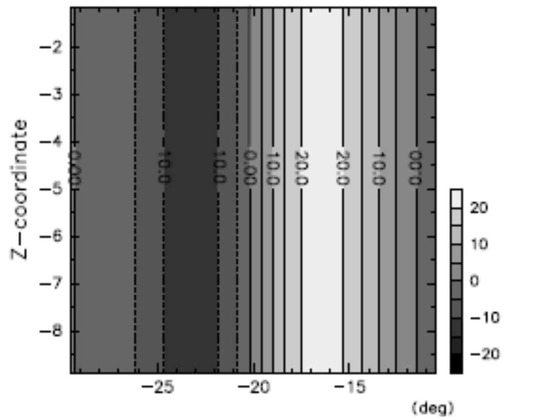
運動量収支（深部） 600-2100日平均

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\overline{v}}{a}\frac{\partial \overline{u}}{\partial \phi} - \overline{w}\frac{\partial \overline{u}}{\partial z} + \underbrace{f\overline{v}}_{(d)} + \frac{\tan\phi}{a}\overline{u}\,\overline{v} \underbrace{- \frac{1}{a\cos^2\phi}\frac{\partial}{\partial \phi}(\overline{v'u'}\cos^2\phi)}_{(e)} - \frac{\partial}{\partial z}(\overline{w'u'}) \underbrace{+\overline{Visc}}_{(f)}$$

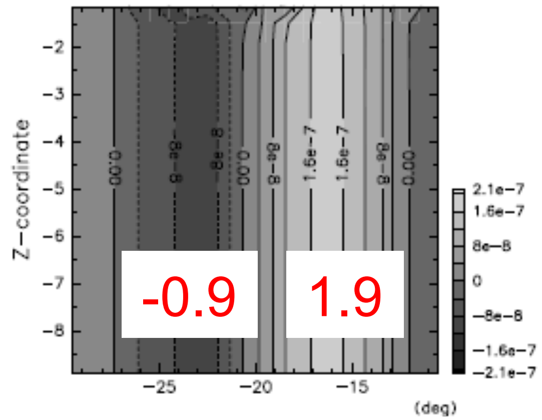
子午面流線関数



U(2100日)



右辺の和

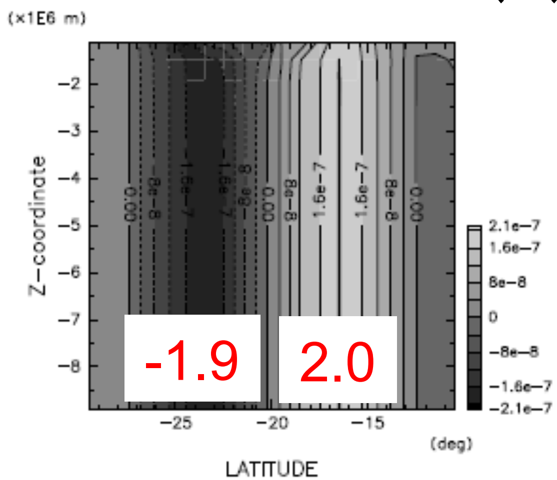


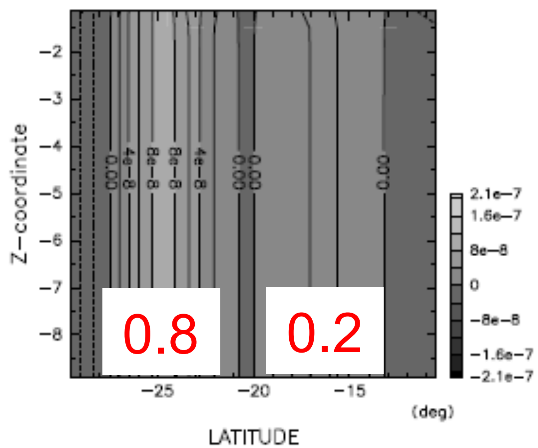
値は×10^-7

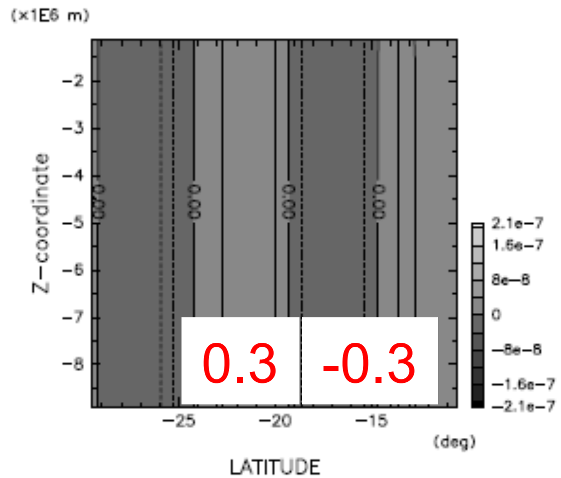
(d) $f\overline{v}$

(e) $-\frac{1}{a\cos^2\phi}\frac{\partial}{\partial \phi}(\overline{v'u'}\cos^2\phi)$

(f) Viscosity $\mathrm{m\,s^{-2}}$







温度風の関係

$$\frac{\partial u}{\partial z} = -\frac{g}{fT_0}\frac{\partial T}{\partial y}$$

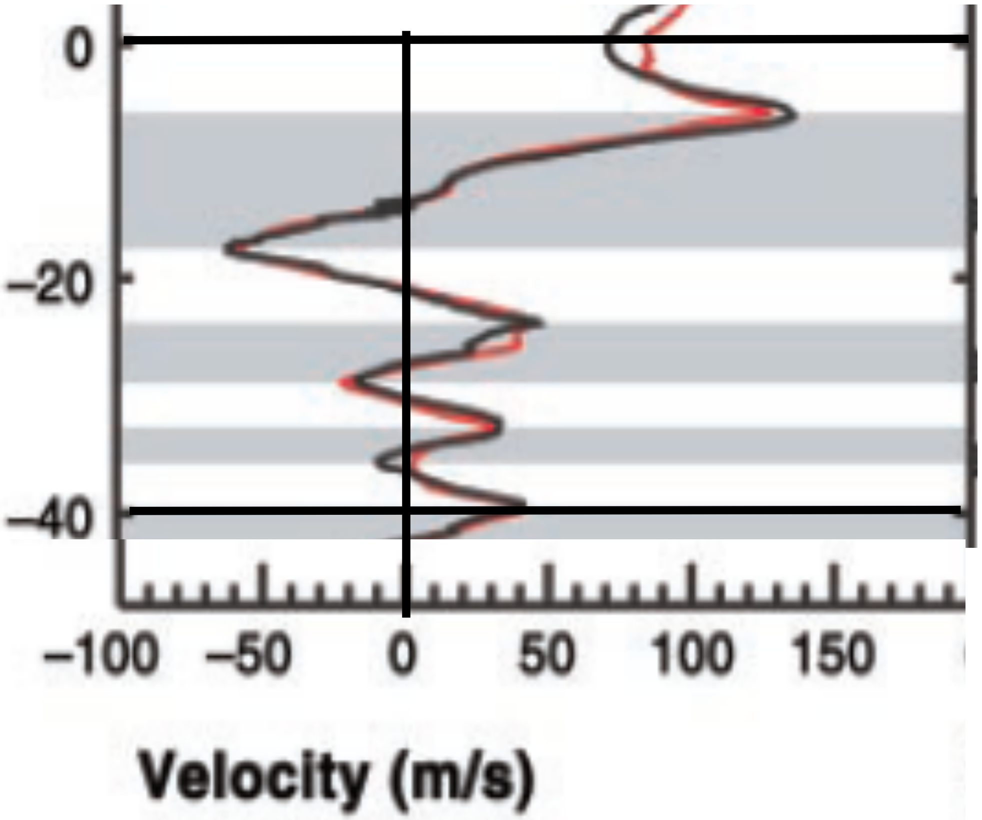
$$u(y,z) = -\frac{g}{fT_0}\int \frac{\partial T}{\partial y}dz + u_b(y)$$

- 温度風の関係はジェットの順圧成分には制限を与えない
  →熱強制のみだとジェットは加速しうる
- 深部に摩擦を加えるとジェットの加速は起こらず定常状態が得られた

運動量強制のみの場合に T(z) が変化し続ける理由

$$T(y,z) = -\frac{fT_0}{g}\int \frac{\partial u}{\partial z}dy + T_a(z)$$

- 温度風の関係は温度の鉛直構造を制限しない
- ある高度の温度を固定しておけば, 定常状態が実現することが予想される.
  - 運動量強制のみの場合でも定常状態の実現は十分ありうる.
    - ∵現実の大気では放射収支によって大気上端の温度が固定されている



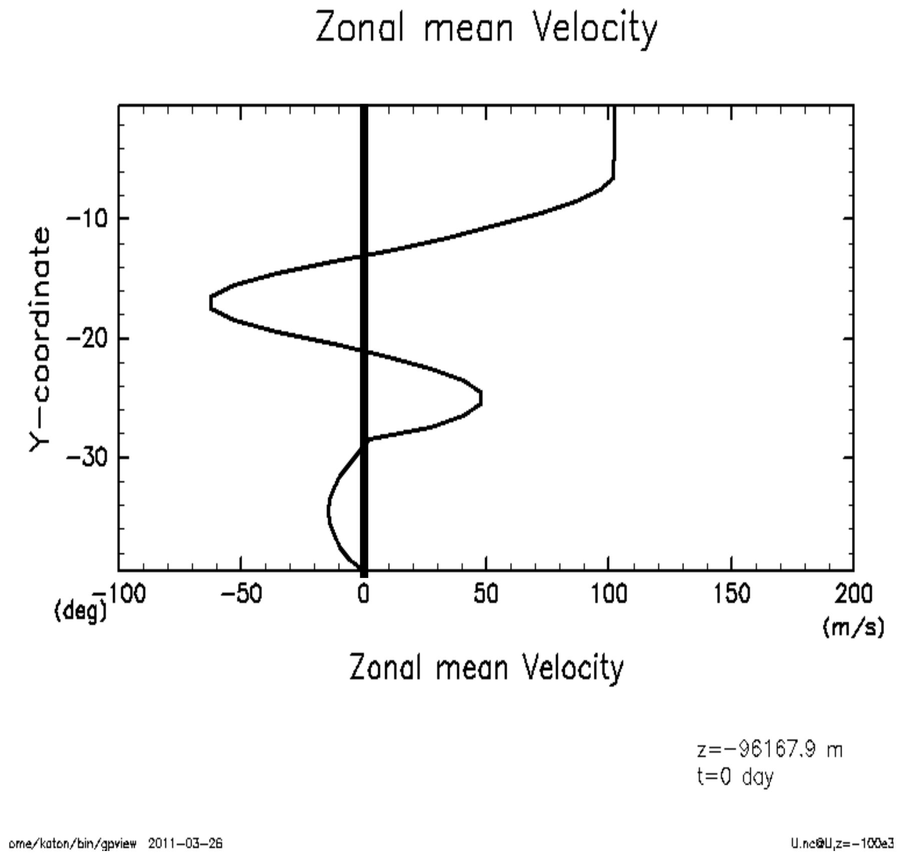


Fig. 1.
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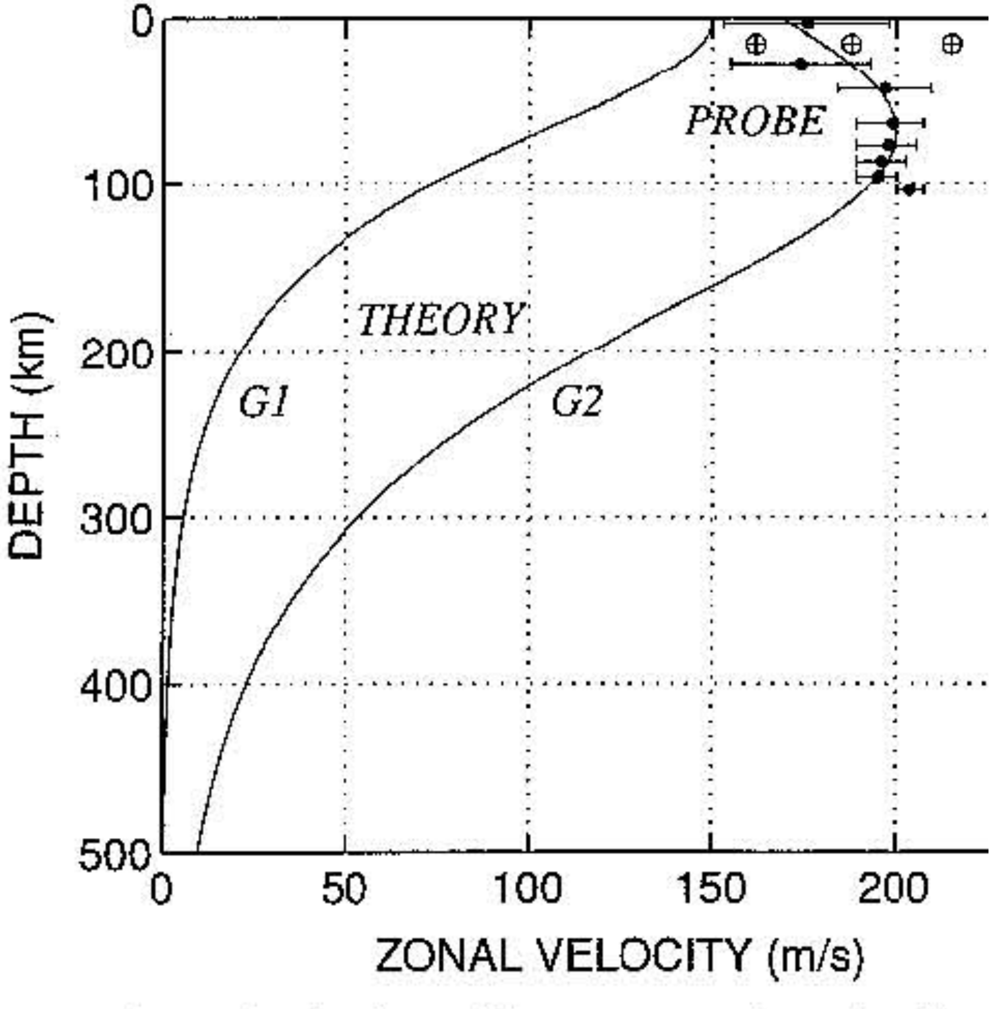

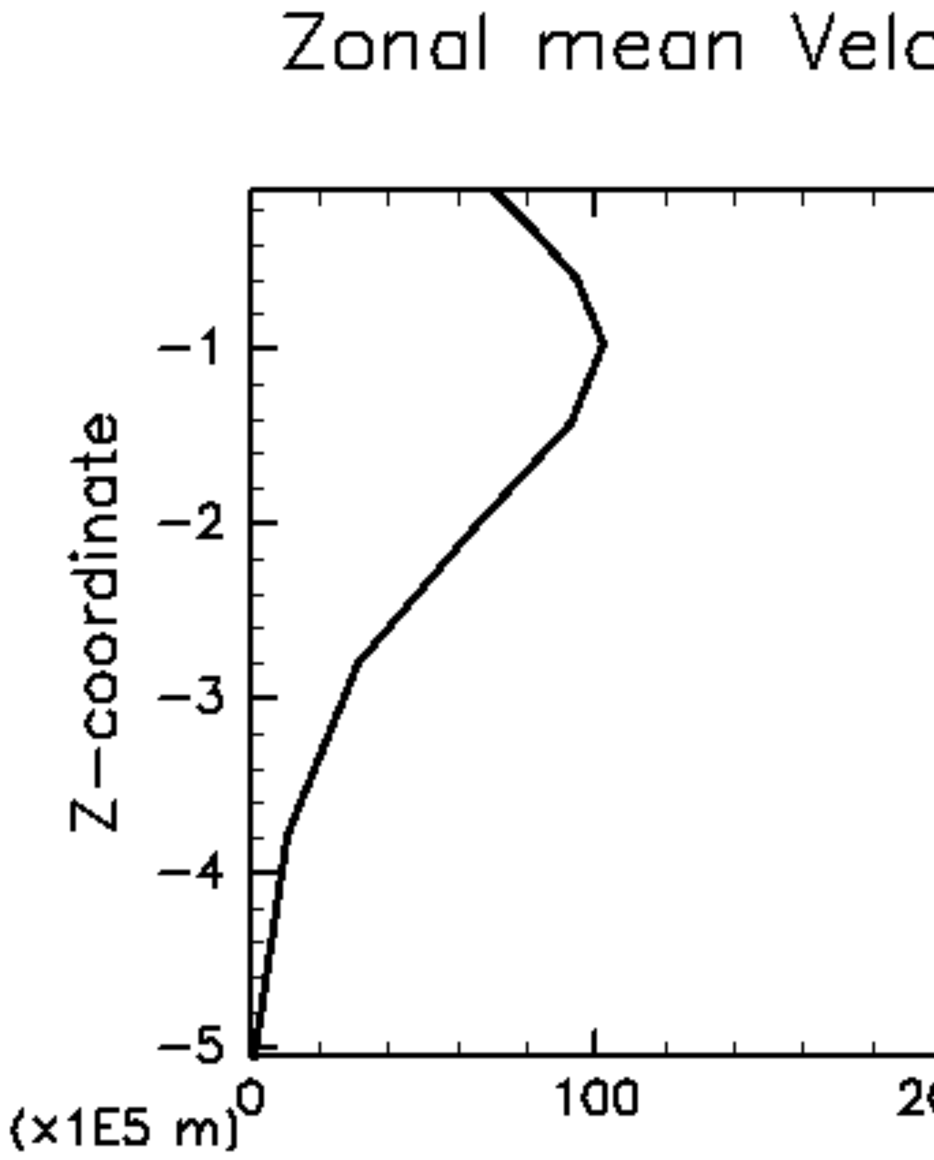

Figure 1. Zonal wind profiles comparing the flo