Numerical modeling of large-scale vortices in Jupiter's atmosphere

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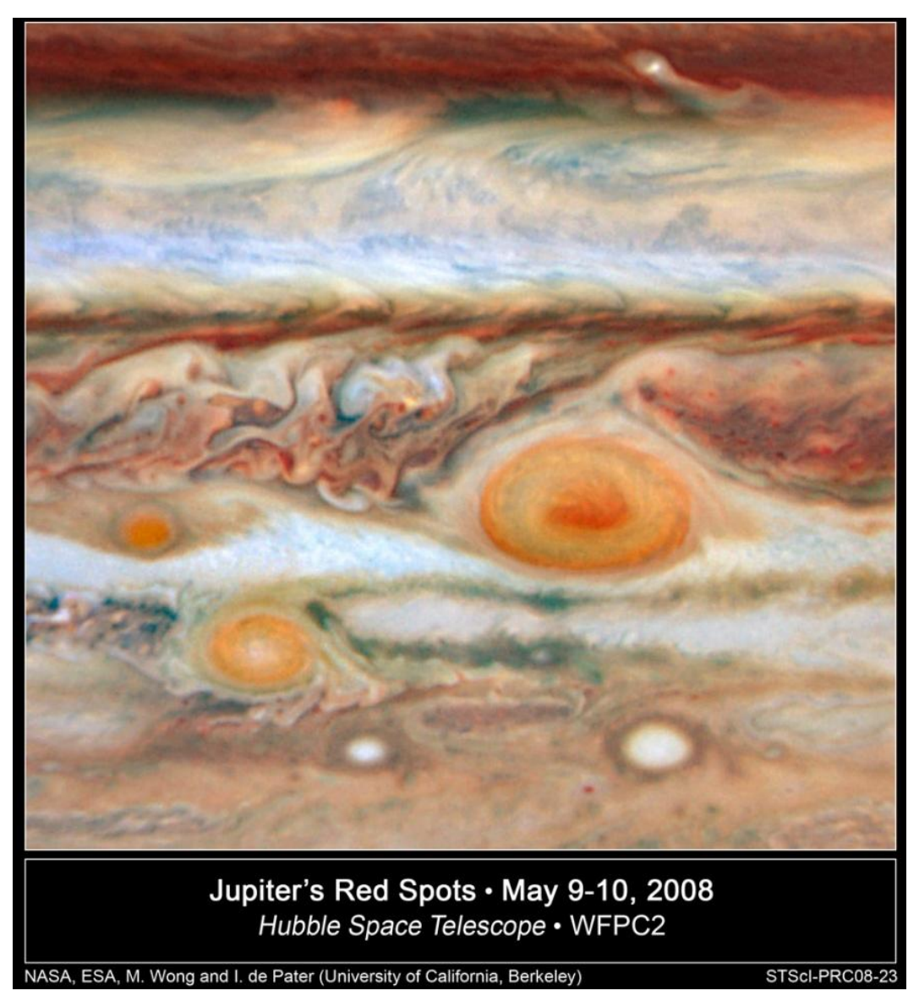
1. Introduction

Purpose

We examine possible sensitivities of the behavior of simulated large scale vortices to the **type** and the **intensity** of the forcing that maintains zonal mean fields.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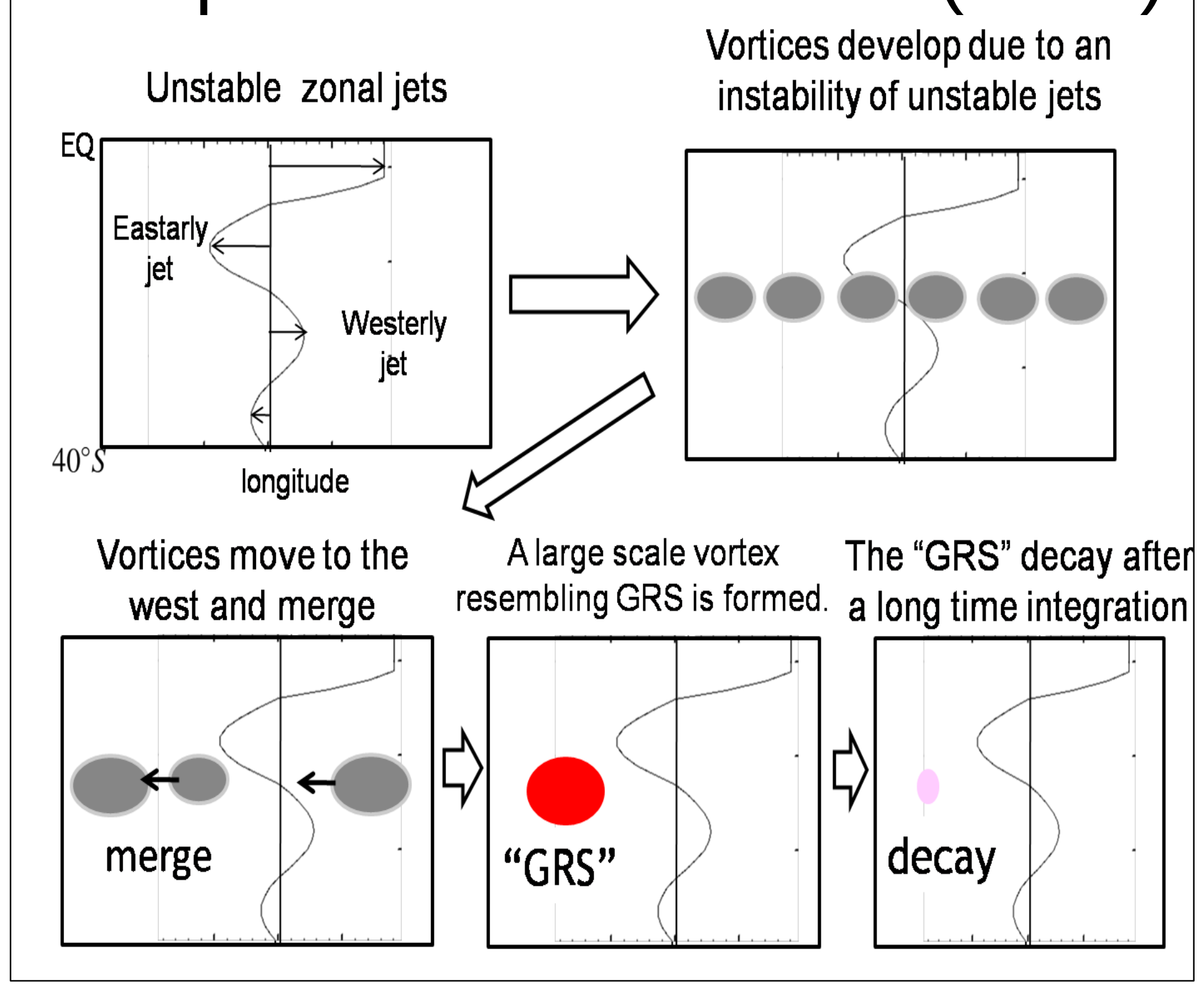
Background

Williams(1996) reproduced large scale vortex resembling the Great Red Spot within a three dimensional numerical model. However, the large scale vortex decayed after a long time integration.

Is it caused by the decay of zonal mean field?

Experiment of Williams(1996)



GP Williams. Jovian Dynamics. Part 1: Vortex Stability, Structure, and Genesis. *Journal of the Atmospheric Sciences, Vol. 53, No. 18, pp. 2685-2734, 1996.*

2. Model and Setup

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

Momentum equations

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

Advection

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

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

Momentum Forcing

Thermodynamic equation

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

Thermal Forcing

Continuity Equation(incompressible)

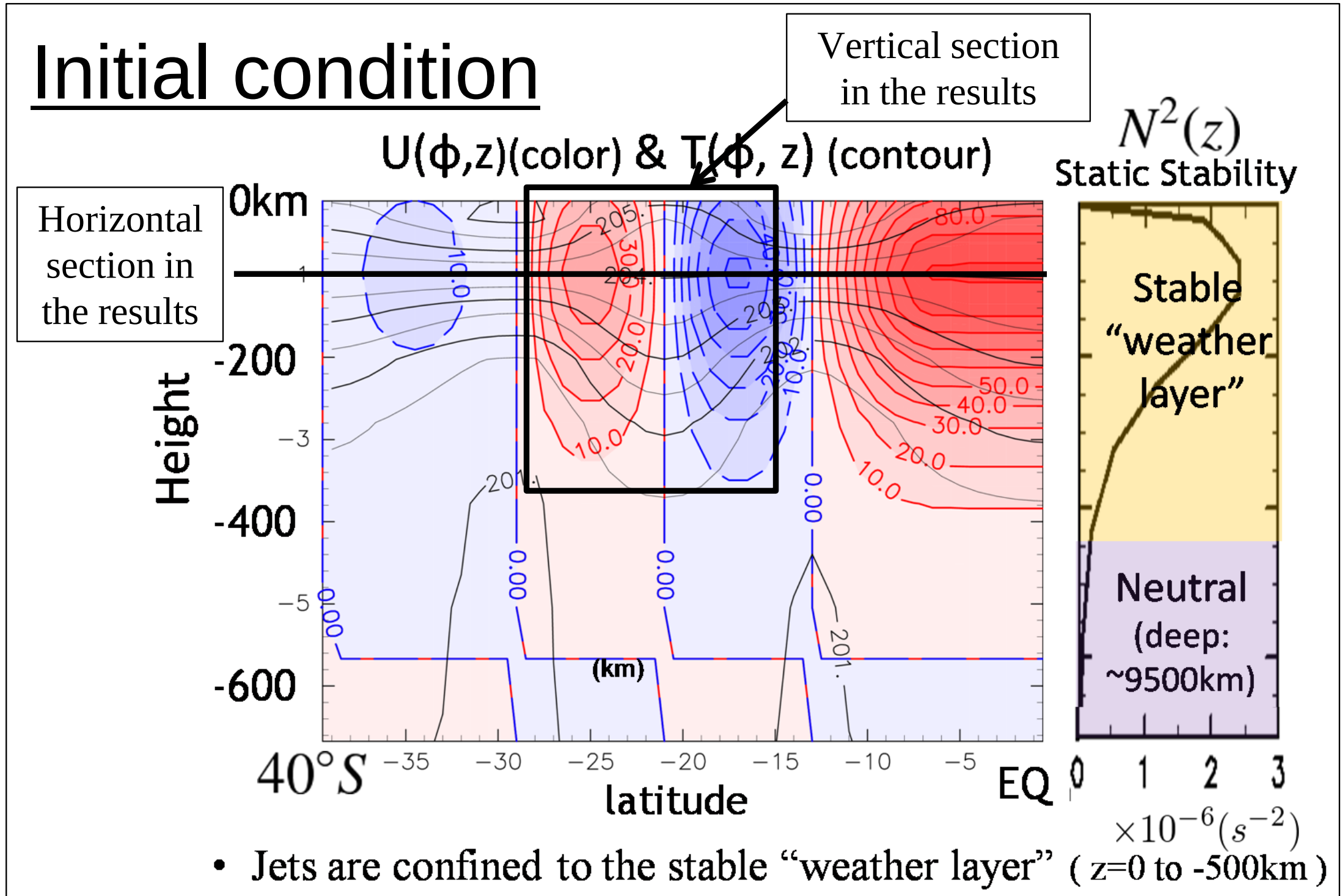
$$\frac{1}{a\cos\phi}\left[\frac{\partial u}{\partial\lambda}+\frac{\partial}{\partial\phi}(v\cos\phi)\right]+\frac{\partial w}{\partial z}=0$$

Equation of state

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

λ : longitude
ϕ : latitude
z : altitude
L : advection term
u : zonal velocity
u_i : initial zonal velocity
$\overline{u}^x$: zonal mean zonal velocity
v : meridional velocity
w : vertical velocity
T : temperature
T_i : initial temperature
$\overline{T}^x$: zonal mean temperature
p : pressure
ρ : density
τ_M : momentum forcing relaxation time
τ_T : thermal forcing relaxation time

Initial condition



- Jets are confined to the stable "weather layer" (z=0 to -500km)
- U(φ,z) and T(φ,z) are in thermal wind balance

Setup of Experiments (13 experiments)

<Four types of forcing>
1.no forcing
2. **momentum** forcing to damp the zonal mean winds to the initial structure
3. **thermal** forcing to damp the zonal mean temperature to the initial
4. **both** (momentum and thermal) forcing

<Four values of damping time>
30, 100, 300, and 1000days

Computational domain and resolution

- zonal 0° ~ 180° , NX=100, Δλ=1.8°
- meridional 0° ~ - 40° , NY=40 , ΔΦ=1.0°
- vertical H = 10000km ,NZ=20, Δz ∝exp(5z/H)
- Time step: 1/50(day),
- integral time: 6000(day)

Boundary condition

- Zonal : cyclic
- Meridional : symmetric, no-flux(EQ)
  no-slip, no-flux(South Boundary)
- Vertical : free-slip, no-flux

Parameters

(Appropriate for Jupiter's atmosphere)

$a=71400(km)$
$g=26.0(ms^{-2})$
$\omega=1.76\times10^{-4}(s^{-1})$
$T_0=200(K)$
$\alpha=0.005(K^{-1})$
$\rho_0=0.1323(kgm^{-3})$
$\nu_H=-10^{17}(m^4s^{-1})$
$\nu_V=10^{-8}(m^2s^{-1})$

Diagnosis

- EP flux

$$\mathbf{F}\equiv(0,F^{(\phi)},F^{(z)}),$$

$$F^{(\phi)}\equiv\rho_0a\cos\phi\left(\frac{\frac{\partial\overline{u}}{\partial z}\overline{v'\theta'}}{\frac{\partial\overline{\theta}}{\partial z}}-\overline{v'u'}\right),$$

$$F^{(z)}\equiv\rho_0a\cos\phi\left((f+\overline{\zeta})\frac{\overline{v'\theta'}}{\frac{\partial\overline{\theta}}{\partial z}}-\overline{w'u'}\right)$$

- Isentropic Potential Vorticity

$$Q=(f+\zeta)\frac{\partial\theta}{\partial z}$$

3. Results

The behavior of vortices are classified into 4 categories shown below.

Sensitivities of the behavior of vortices to the forcing

Damping time of **momentum** forcing (day)

Damping time of **Thermal** forcing (day)

τ_T \ τ_M	30	100	300	1000	∞
30	△				×
100		△			×
300			△		×
1000				◎	◎
∞	△	△	◎	◎	○

× : Only waves exist.
(no large scale vortices appear)

○ : Large scale vortices generate but **become weaker.**

△ : Many **large scale vortices develop but their lifetime is short .**

◎ : One or two **large scale vortices are maintained** longer than 2000days.

4. Summary

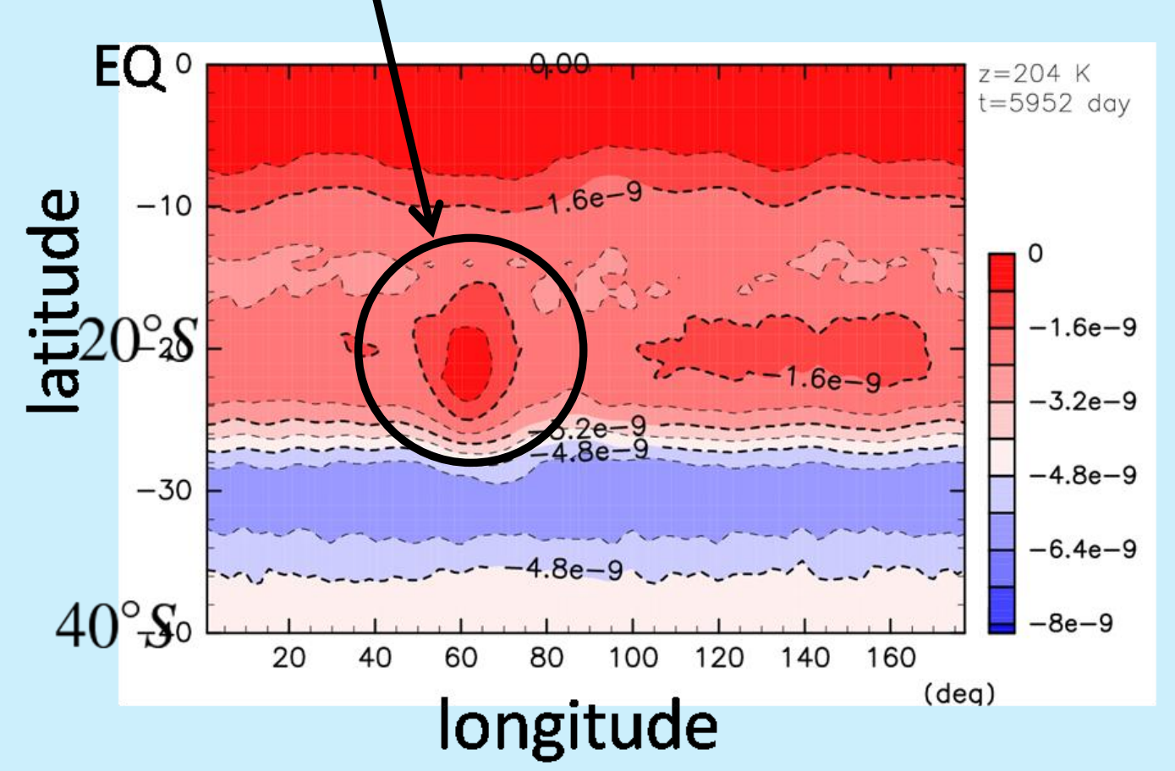
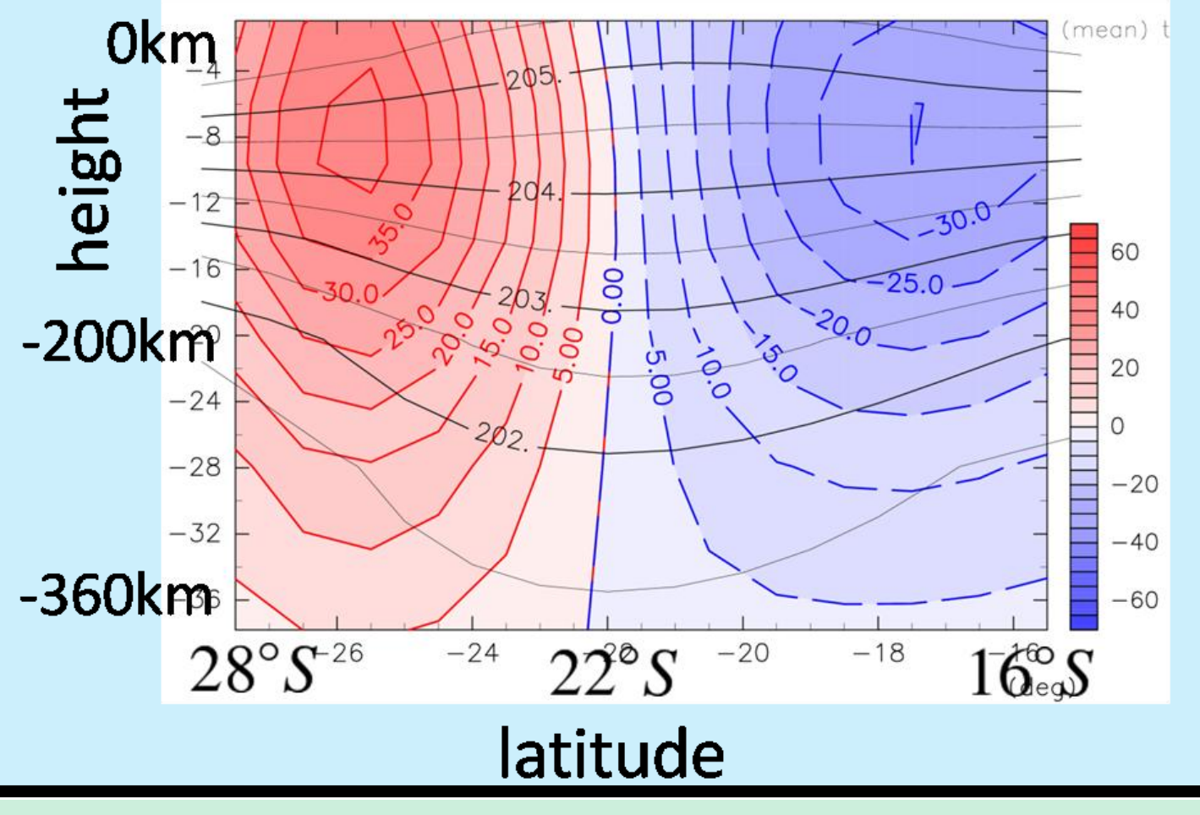
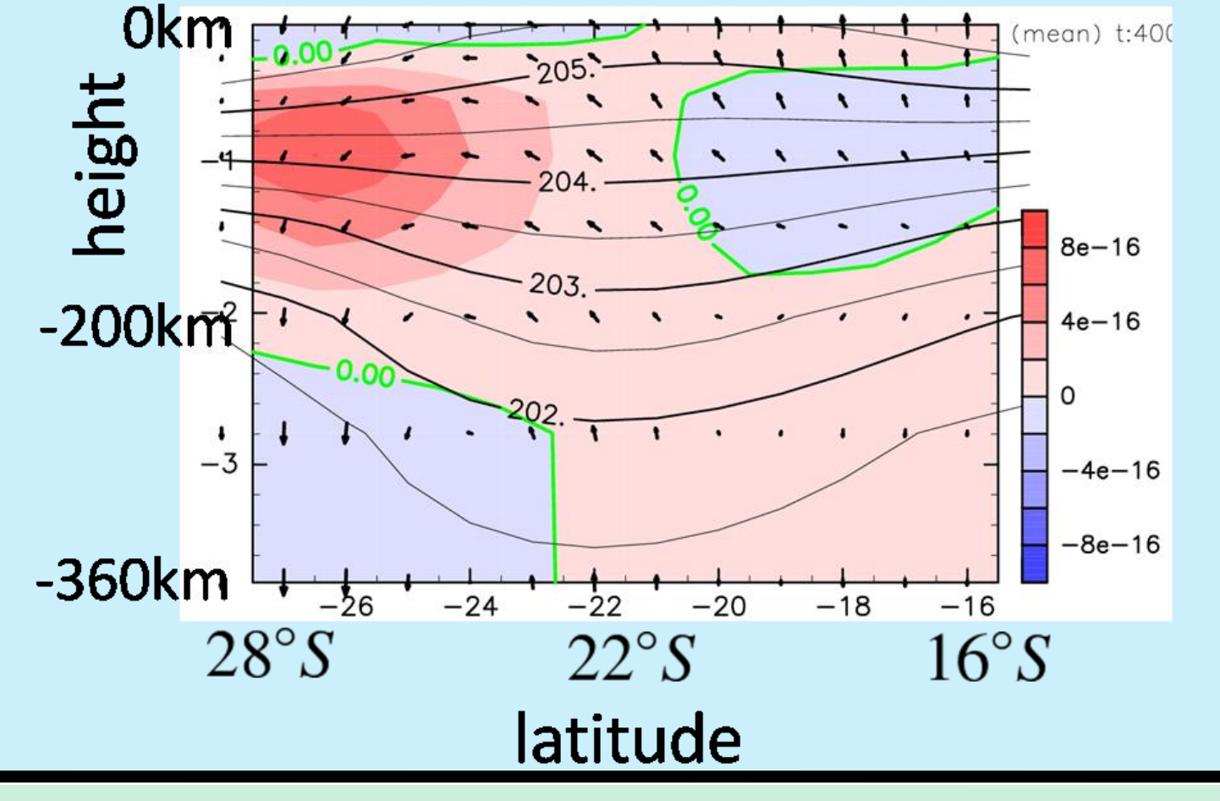
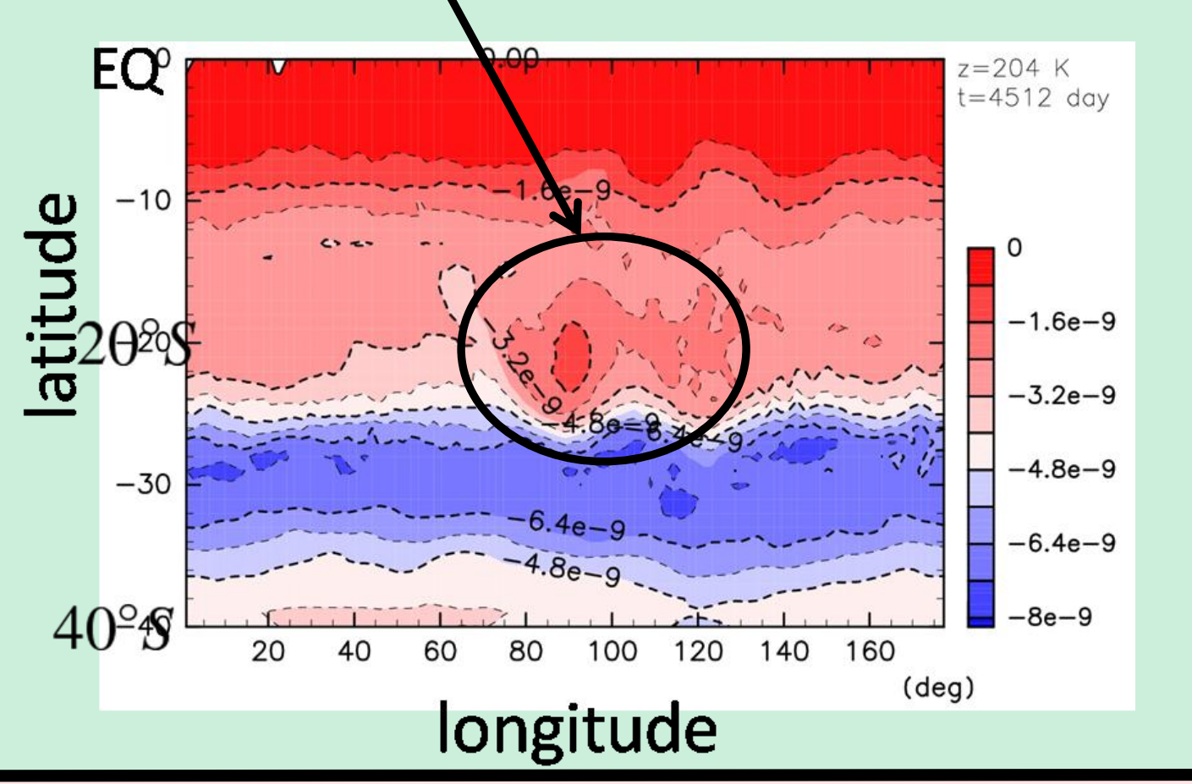
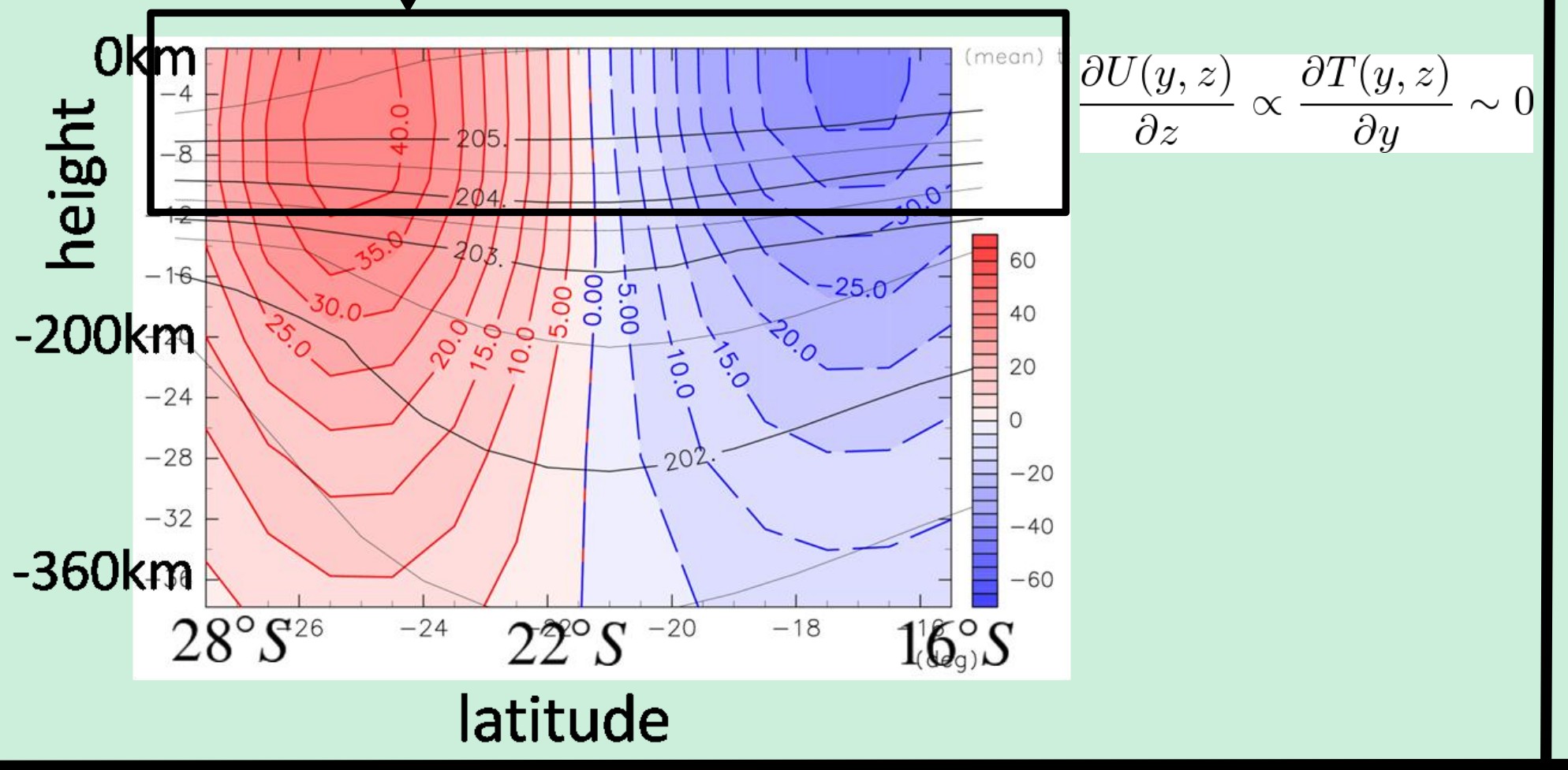
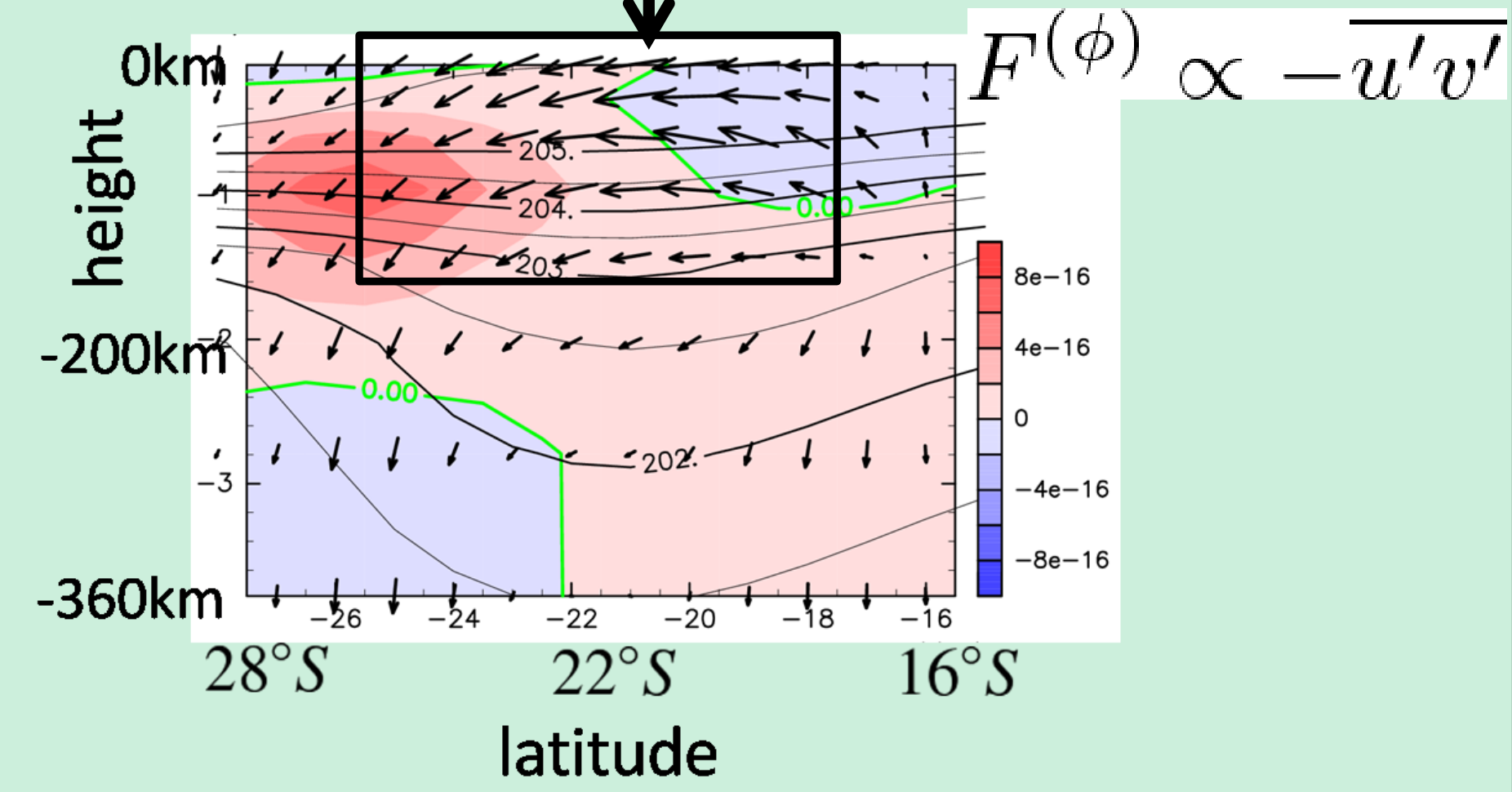
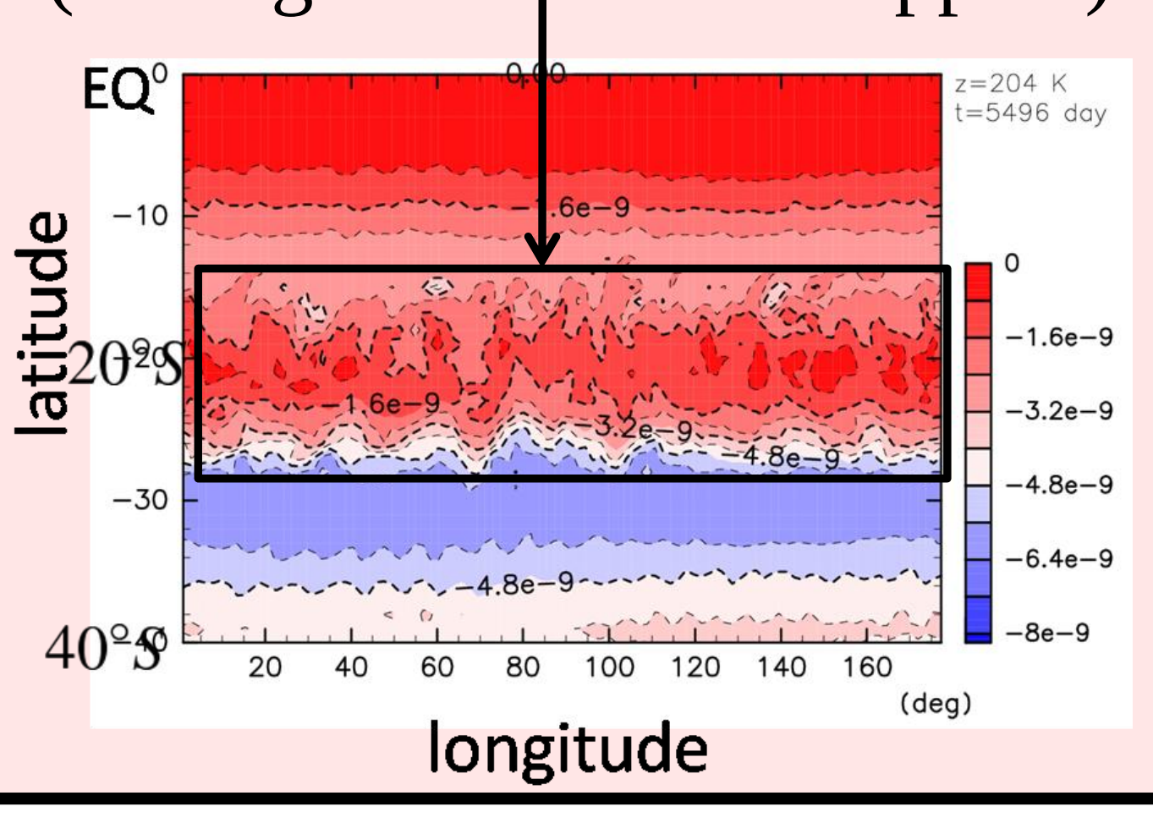
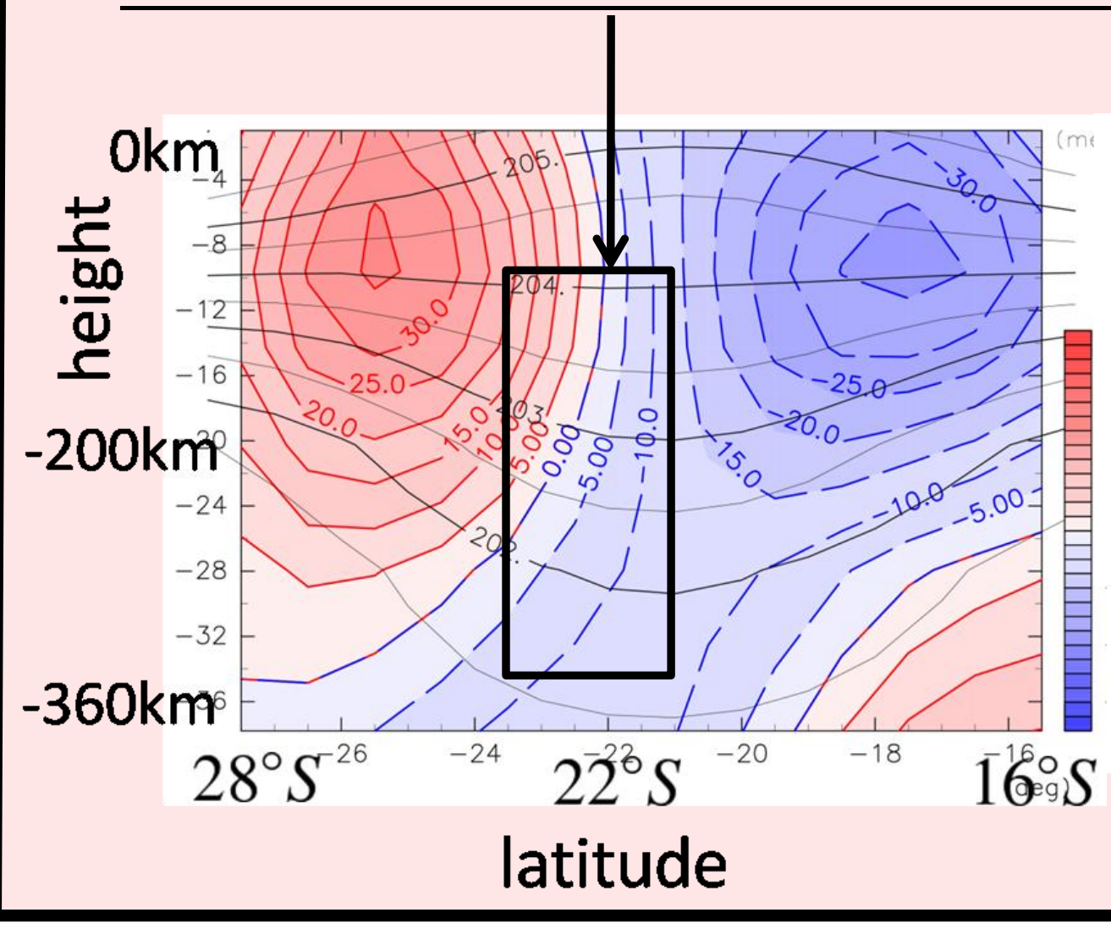
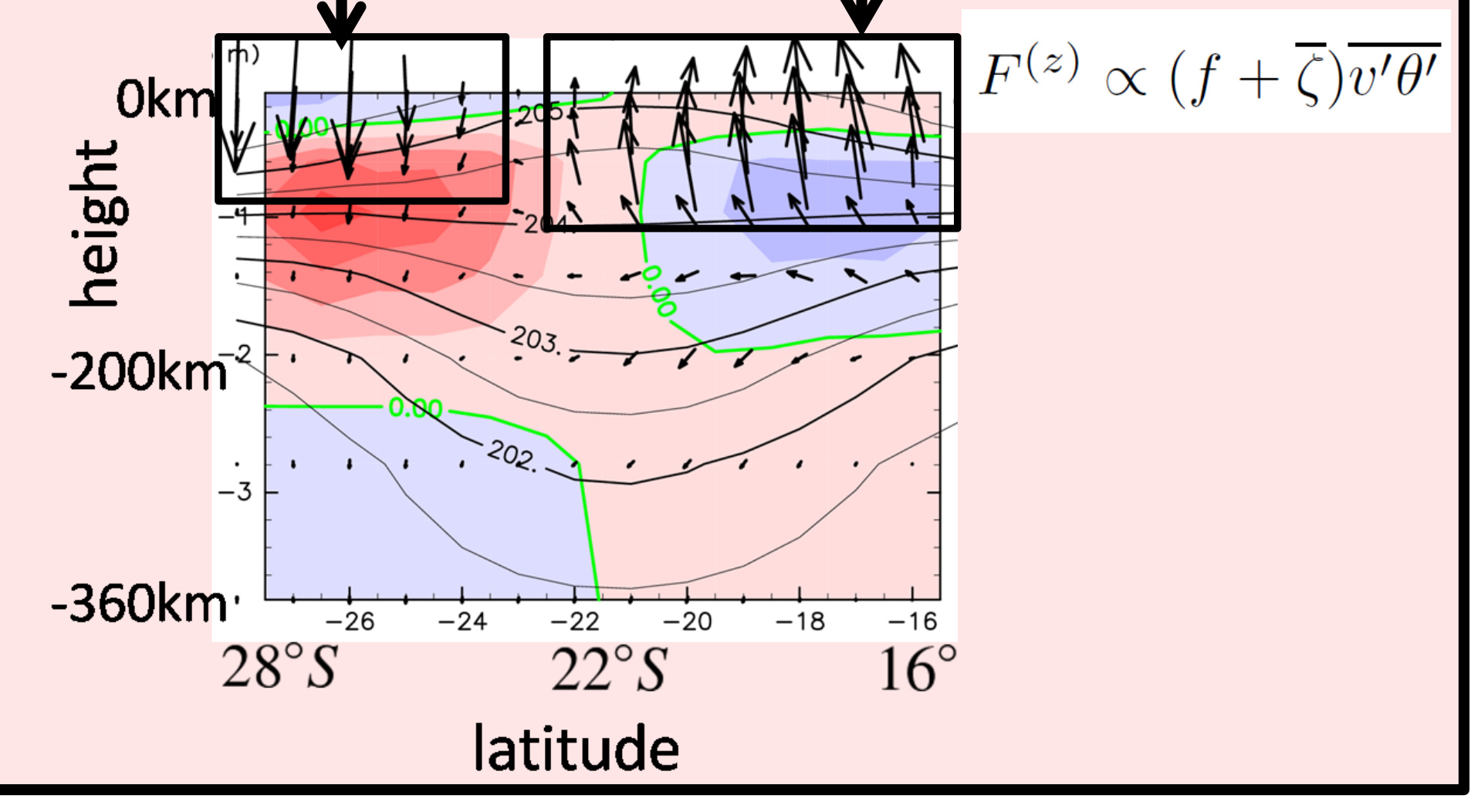
The behavior of simulated vortices depend on the type and the damping time of forcing.

- Weak forcing : Large scale vortices are maintained.
- Strong forcing : Large scale vortices are not maintained.

・These difference might be caused by **the differences of instability activities or types** due to the differences of zonal mean fields.

・Latest results suggest that **vertical shear** is also important. For details, please ask me.

Three cases representing long lived vortices(◎), short lived vortices(△), and wavy(×) are shown below.

	Potential Vorticity : Q (θ=204K)	T(φ, z) (contour) , U(φ, z) (color) Averaged from 4000 to 5500day	EP flux (vector) , T(φ, z) (contour) , $\frac{\partial Q(y,z)}{\partial y}$ (color) Averaged from 4000 to 5500day
TM1000 Weak forcing $\tau_M=\tau_T=1000(day)$ Momentum and Thermal forcing with long damping time	A Large scale vortex is maintained. 	Initial structure of zonal mean field is better maintained than the strong forcing cases shown below. 	The activity of **baroclinic** or/and **barotropic** instability is weaker than strong forcing cases. 
M30 Strong Momentum forcing $\tau_M=30(day)$ $\tau_T=\infty(day)$ Only Momentum forcing with short damping time	Many large scale vortices continuously develop but their life time is short. 	Baroclinicity above -100km is almost vanished.  $\frac{\partial U(y,z)}{\partial z}\propto\frac{\partial T(y,z)}{\partial y}\sim0$	The activity of **barotropic** instability is strong  $F^{(\phi)}\propto-\overline{u'v'}$
T30 Strong Thermal forcing $\tau_M=\infty(day)$ $\tau_T=30(day)$ Only Thermal forcing with short damping time	Only waves exist. (no large scale vortices appear) 	Vertical shear at around 22° S are generated.  The vertical shear (ΔU>5m/s) can tear large scale vortices within 30 days. $T\sim\frac{L}{U}\sim\frac{15000km}{5ms^{-1}}\sim30(day)$ L: longitudinal scale of large scale vortices	The activity of **baroclinic** instability is strong.  $F^{(z)}\propto(f+\overline{\zeta})\overline{v'\theta'}$