Analyzing the Instabilities in the Venus Atmosphere Using Bred Vectors

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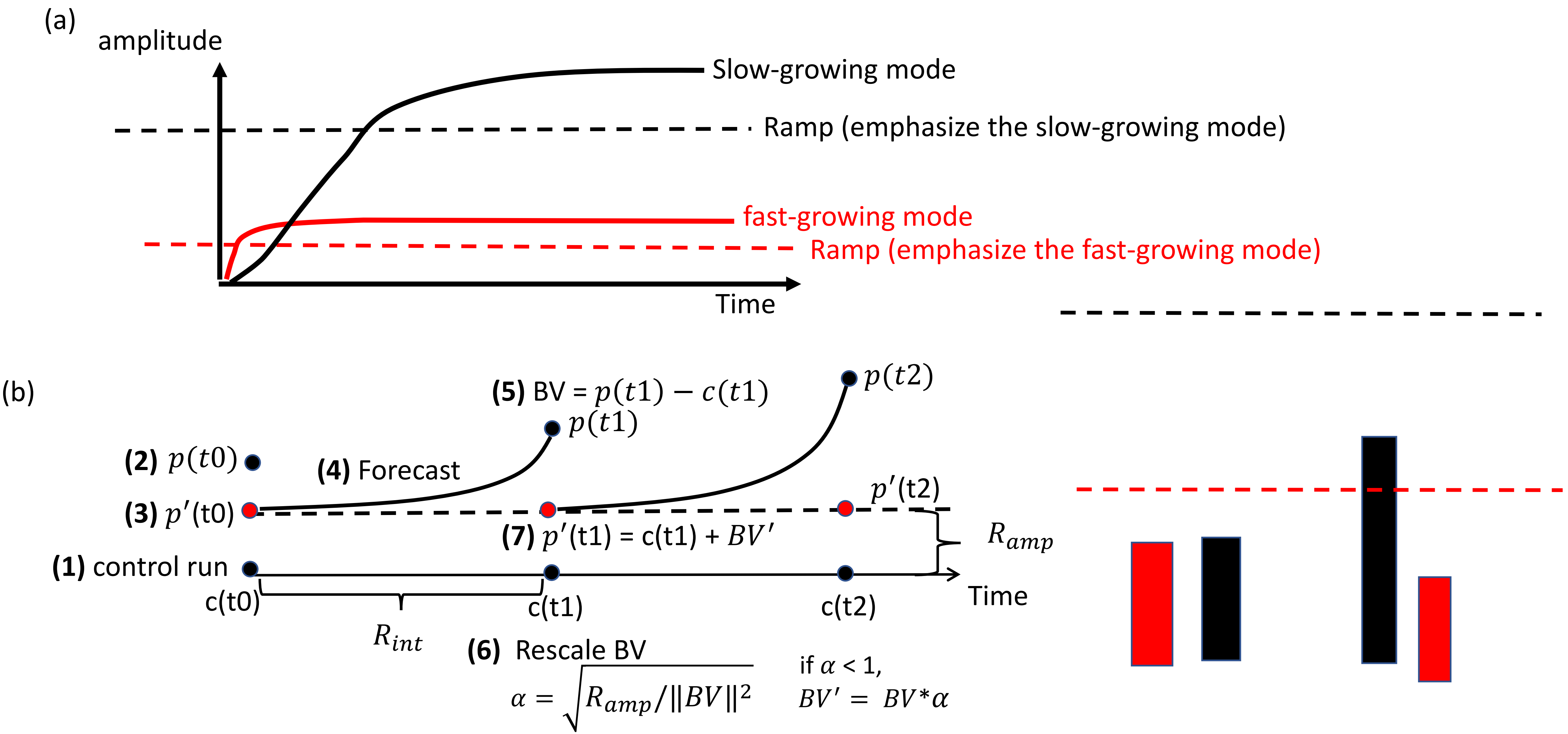
Workshop on Venus and other related atmospheres

Overview

- What is Bred vector?
- Overview of instabilities by previous studies
- Bred vector of the Venus atmosphere
- ❖ compare deviation from the zonal mean and Bred Vectors
- ❖ Bred Vector identify different growing modes
- ❖ baroclinic instability impact on thermal tide
- Predictability

Breeding cycle and Bred Vector (BV)

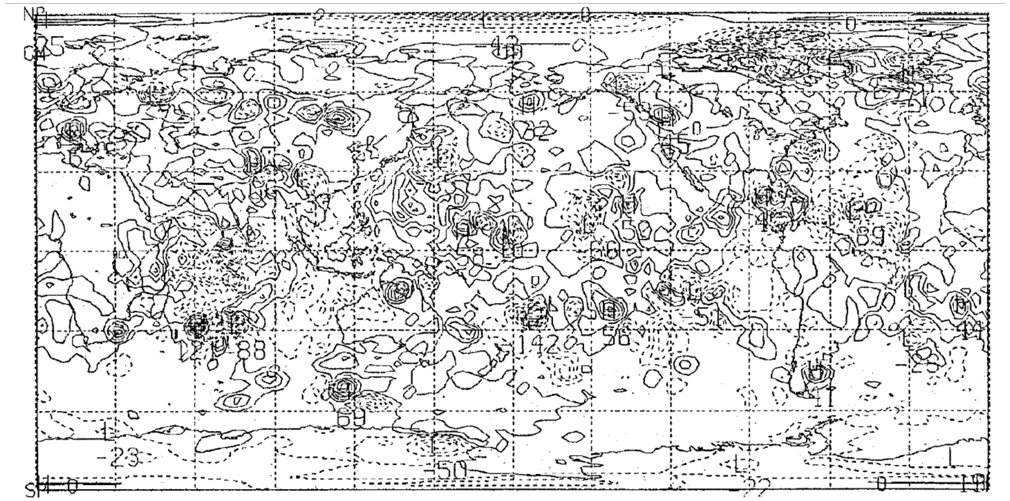


Applications of BVs

- Generating ensemble perturbations (before EnKF method is applied in Meteorology)
- Analyzing the **unstable** and growing modes of the dynamical system
- Estimating the effective local **dimension** (Patil et al. 2001) (prepare for LETKF)
- Studied **energy conversion** (Hoffman 2009; Greybush 2013)
- Applied to **Earth** (Toth and Kalnay 1993, 1997) and **Mars** atmospheres (Newman 2004; Greybush 2013)

500-hPa streamfunction perturbations

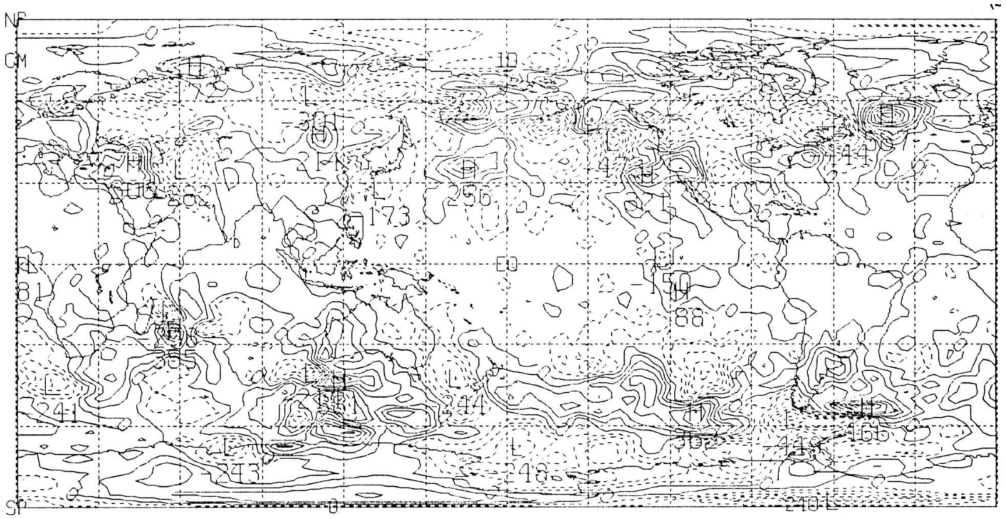
Convective modes



Toth and Kalnay 1997

Size of the perturbation: 0.015% total rms variance

Baroclinic modes



Toth and Kalnay 1993

Size of the perturbation: >1% total rms variance

Experimental setting

- AFES-Venus (VAFES)(Sugimoto et al., 2014 JGR, GRL)
  - ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
  - ✓ Resolution: T42L60 (128 × 64 × 60)
  - ✓ Horizontal hyper-viscosity: 0.1 Earth days for 1/e
  - ✓ Vertical eddy viscosity: 0.15 m^2s^{-1}
  - ✓ Rayleigh friction: lowest and above 80 km (sponge layer except for zonal flow)
  - ✓ No topography and planetary boundary layer
- Solar heating
  - ✓ Zonal (Qz) and diurnal (Qt) component of realistic heating; Based on Tomasko et al. (1980) and Crisp (1986)
- Infrared radiative process
  - ✓ Simplified by <u>Newtonian cooling</u>: $dT/dt = -\kappa\,(T - T_{ref}(z))$ κ: based on Crisp (1986) $T_{ref}(z)$: horizontally uniform field

Cases	Solar heating
Qz	Zonal mean component only
Qt	Including diurnal variation

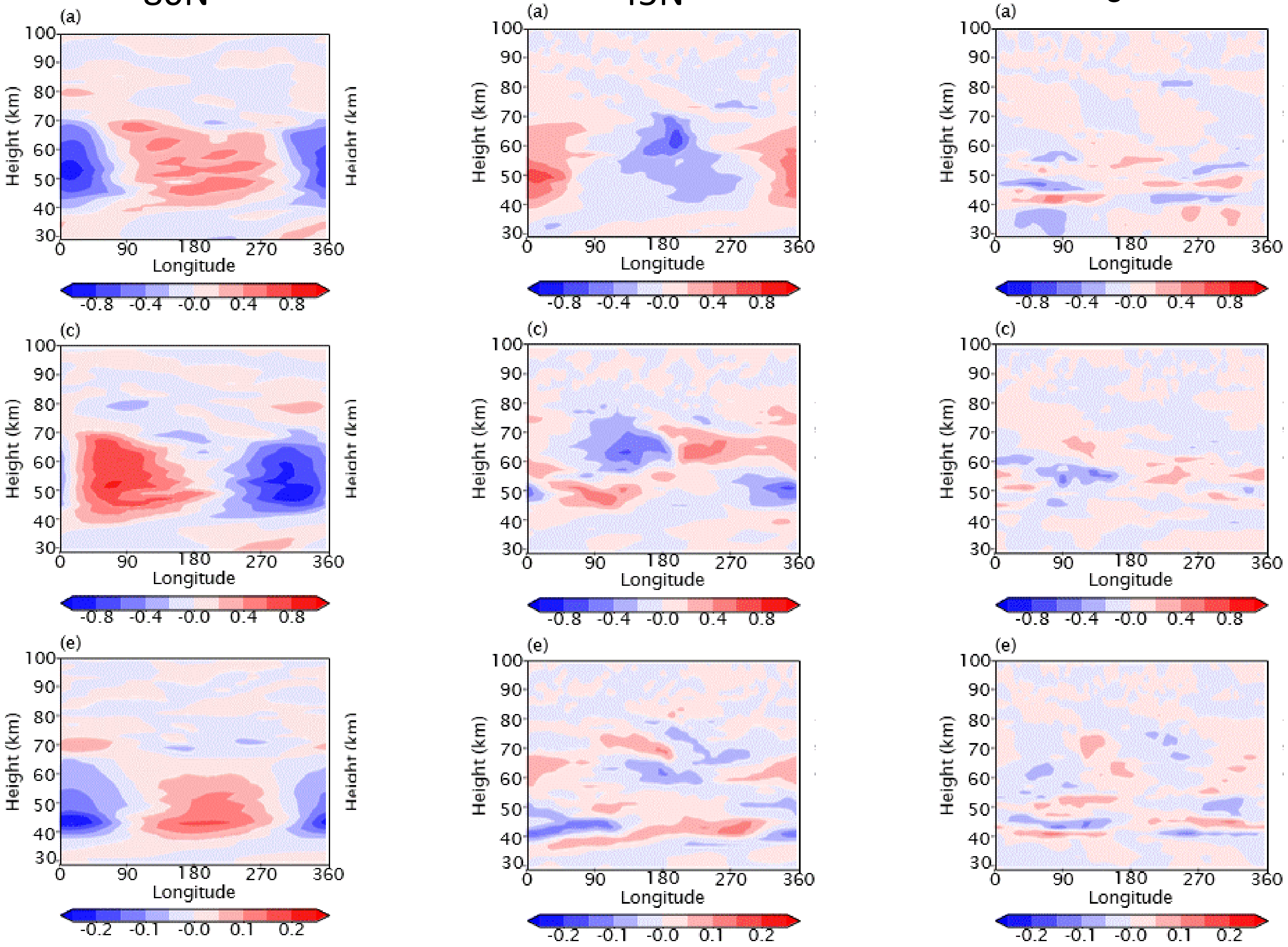
Deviation from the zonal mean

	Ando et al. 2017	Sugimoto et al. 2014	Takagi et al. 2022
	Barotropic	Baroclinic	Rossby-kelvin
	80N	45N	0

u'

v'

T'



Deviation from the zonal mean

at 0005/06/03/18 | Ando et al. 2017 | Sugimoto et al. 2014 | Takagi et al. 2022

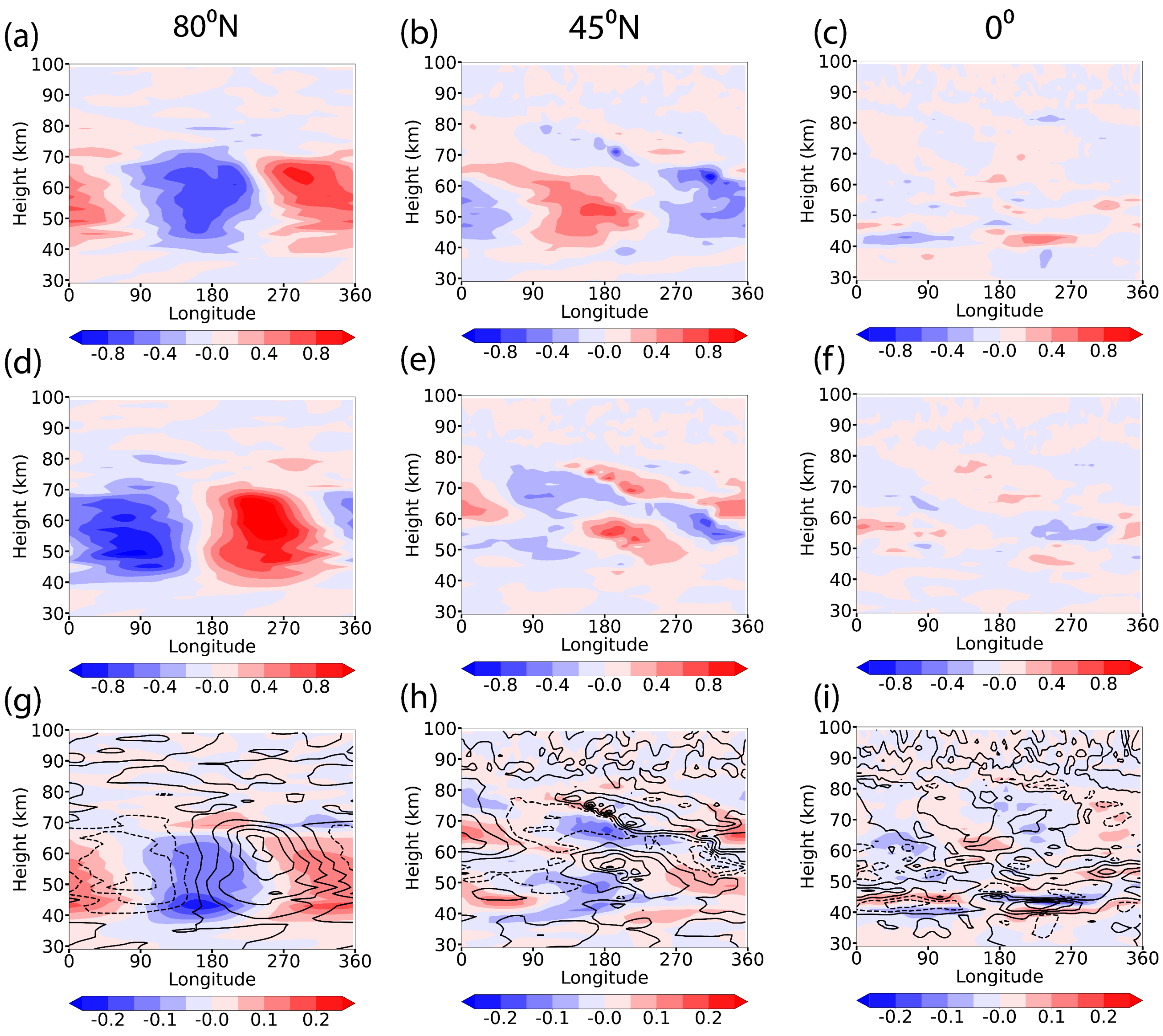
Barotropic | Baroclinic | Rossby-kelvin

$\sqrt{d\sigma u'}$

$\sqrt{d\sigma v'}$

$\sqrt{d\sigma v'}$(contour)

$\sqrt{d\sigma T'}$(shading)



$\sqrt{d\sigma u'}$(contour)

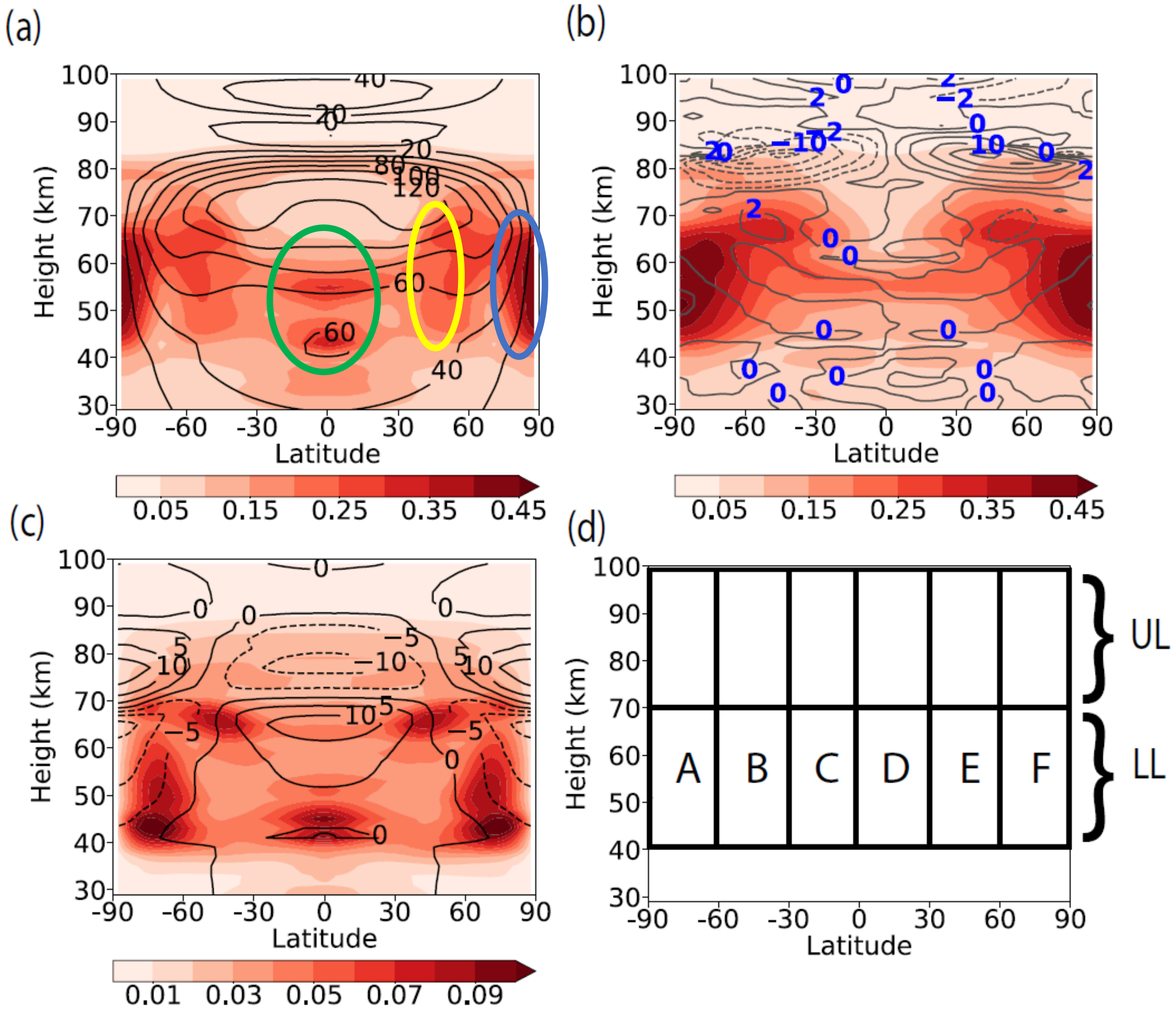
$\sqrt{d\sigma T'}$(shading)

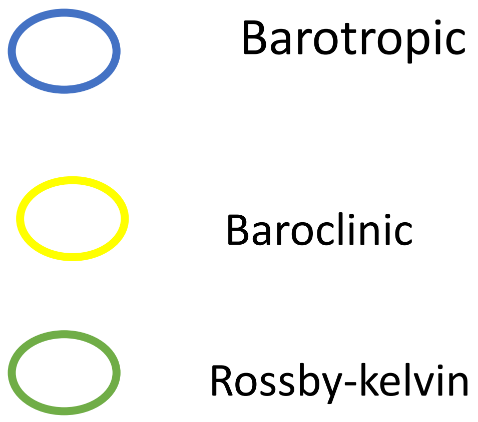
average fields and the magnitude of the deviation

$\sqrt{d\sigma}\sqrt{\overline{u'^2}}$

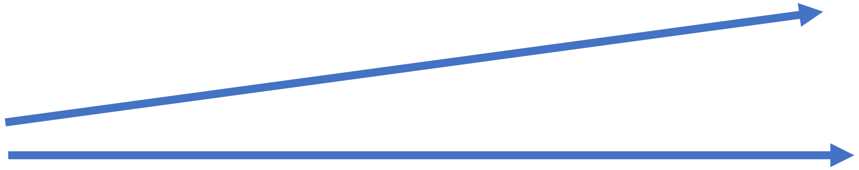
$\sqrt{d\sigma}\sqrt{\overline{v'^2}}$

$\sqrt{d\sigma}\sqrt{\overline{T'^2}}$





Identical twin experiments

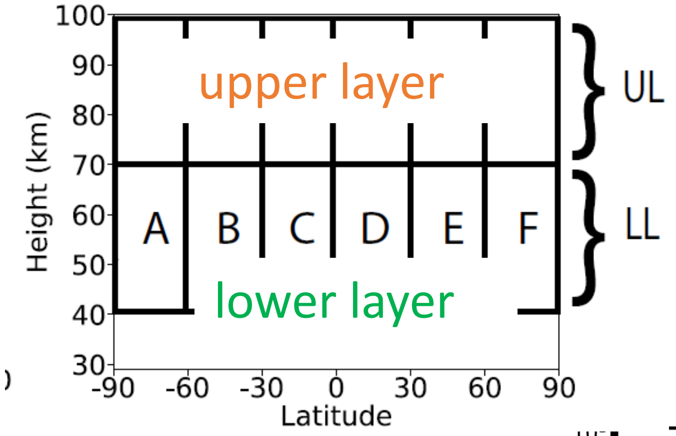


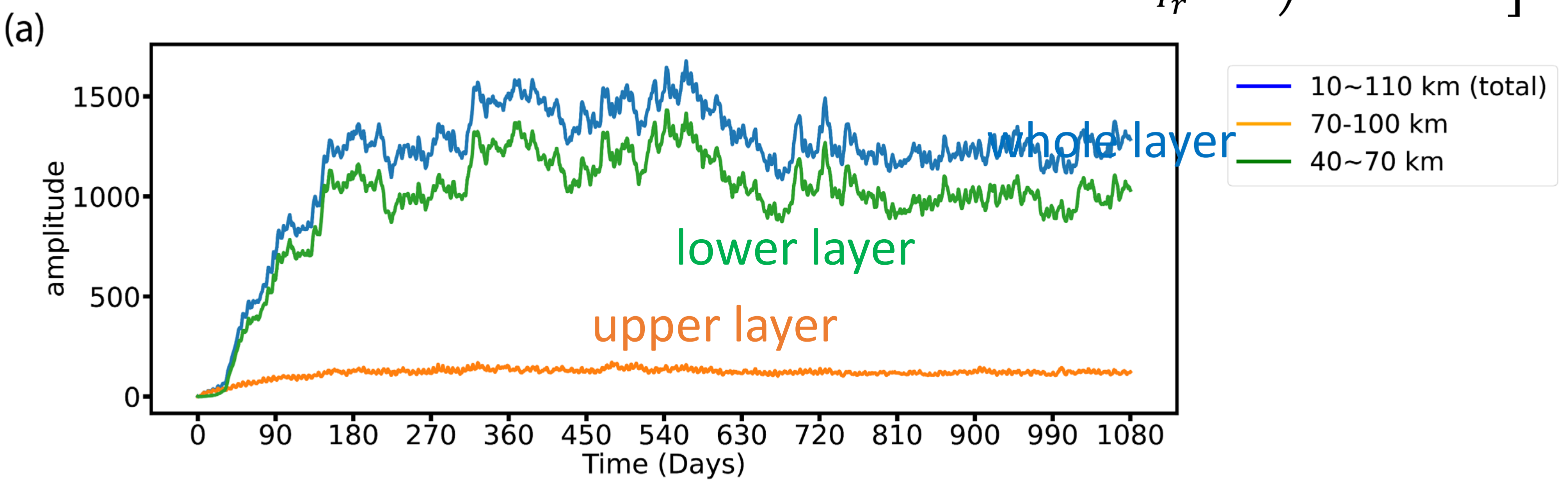
perturbed run

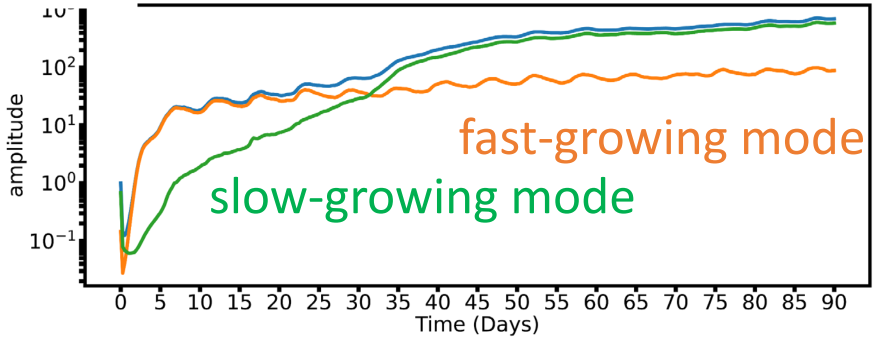
control run

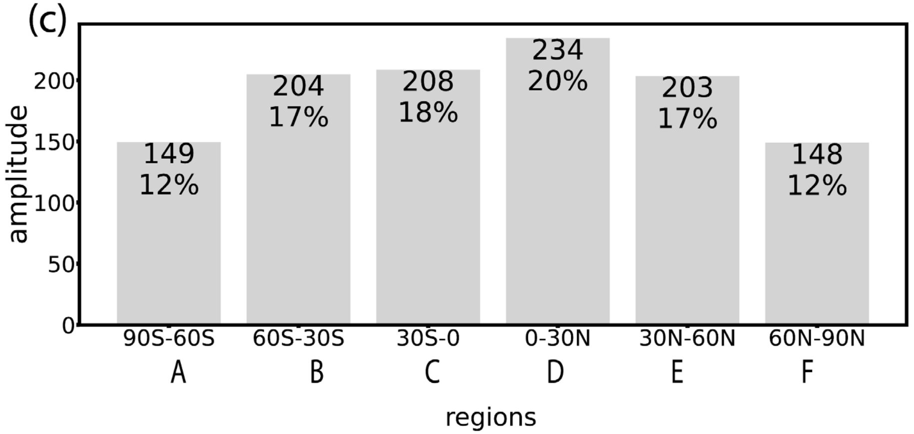
use total energy to measure the amplitude

$$E_{grid} = \frac{dLdy}{2g}\left[\left(\delta u^2 + \delta v^2 + \frac{c_p}{T_r}\delta T^2\right)p_s cos\theta d\sigma\right]/(5 * 10^{17})$$





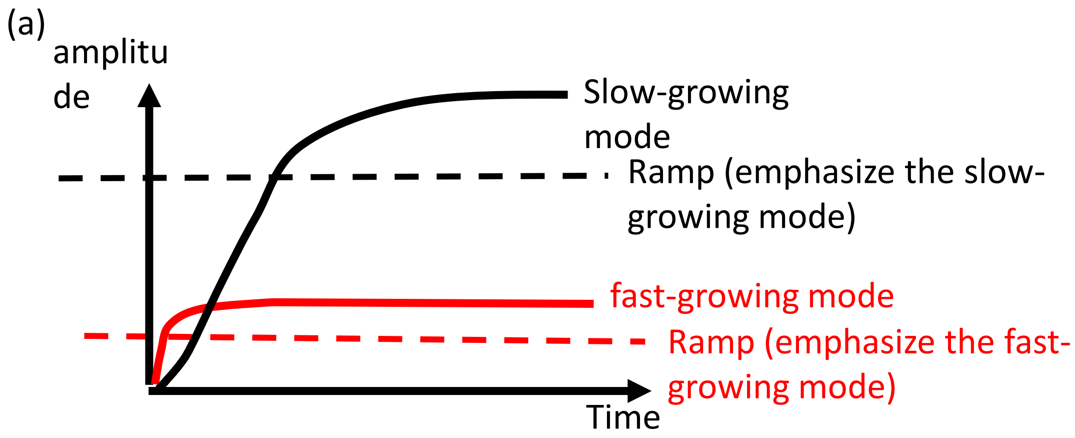


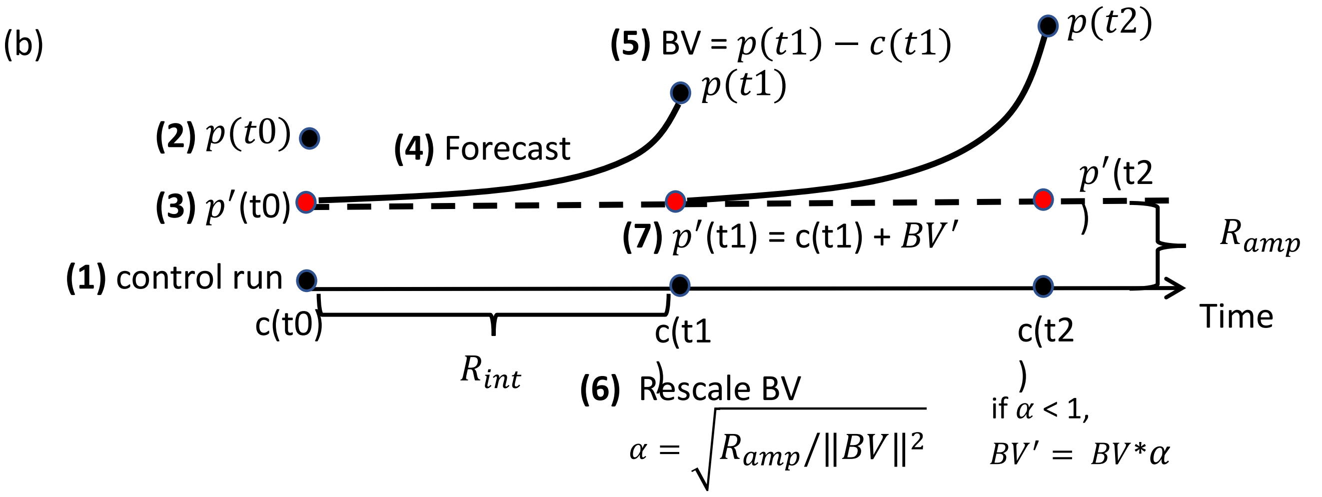


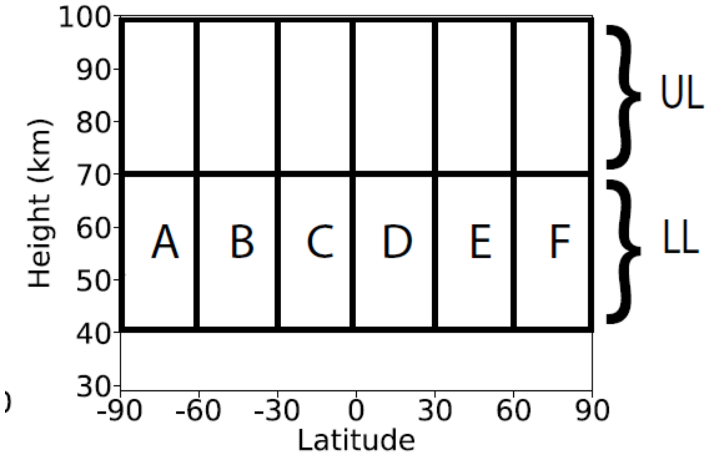
slow-growing mode grow slow at the beginning but saturate at higher amplitude

amplitude in the lower latitudes are comparable to those in mid-laitittudes

control BV by different rescaling amplitudes and rescaling intervals

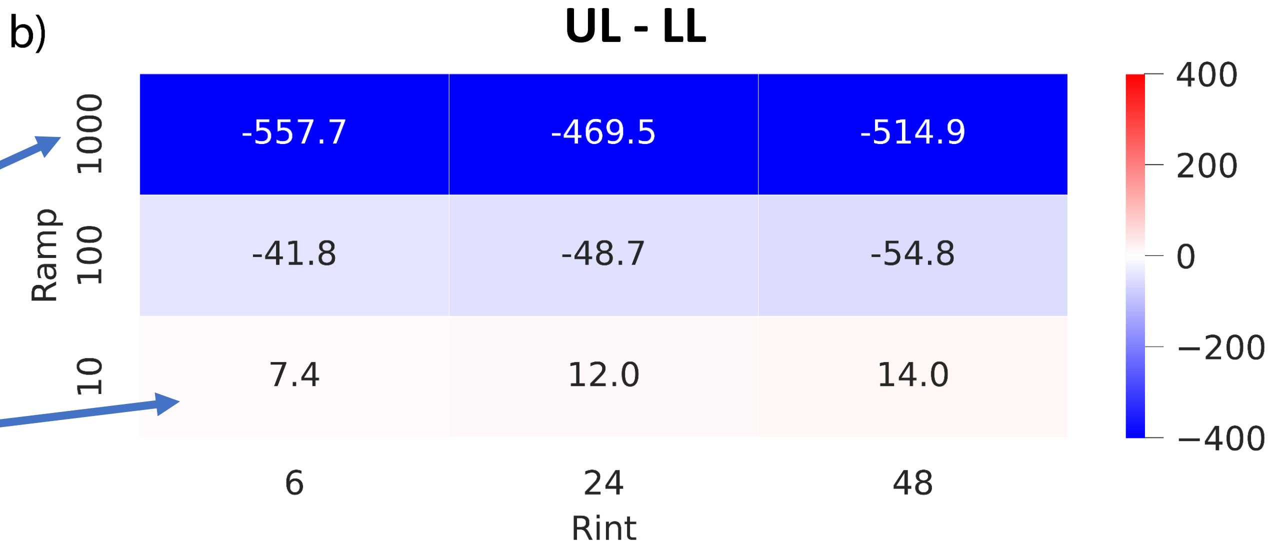






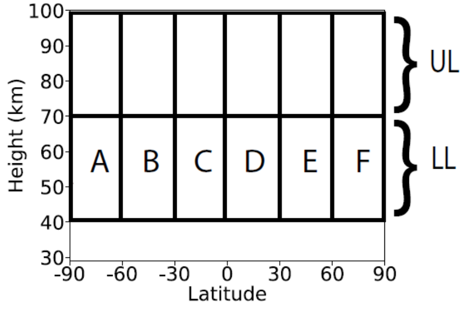
emphasize slow growing mode

emphasize fast growing mode



emphasize slow growing mode

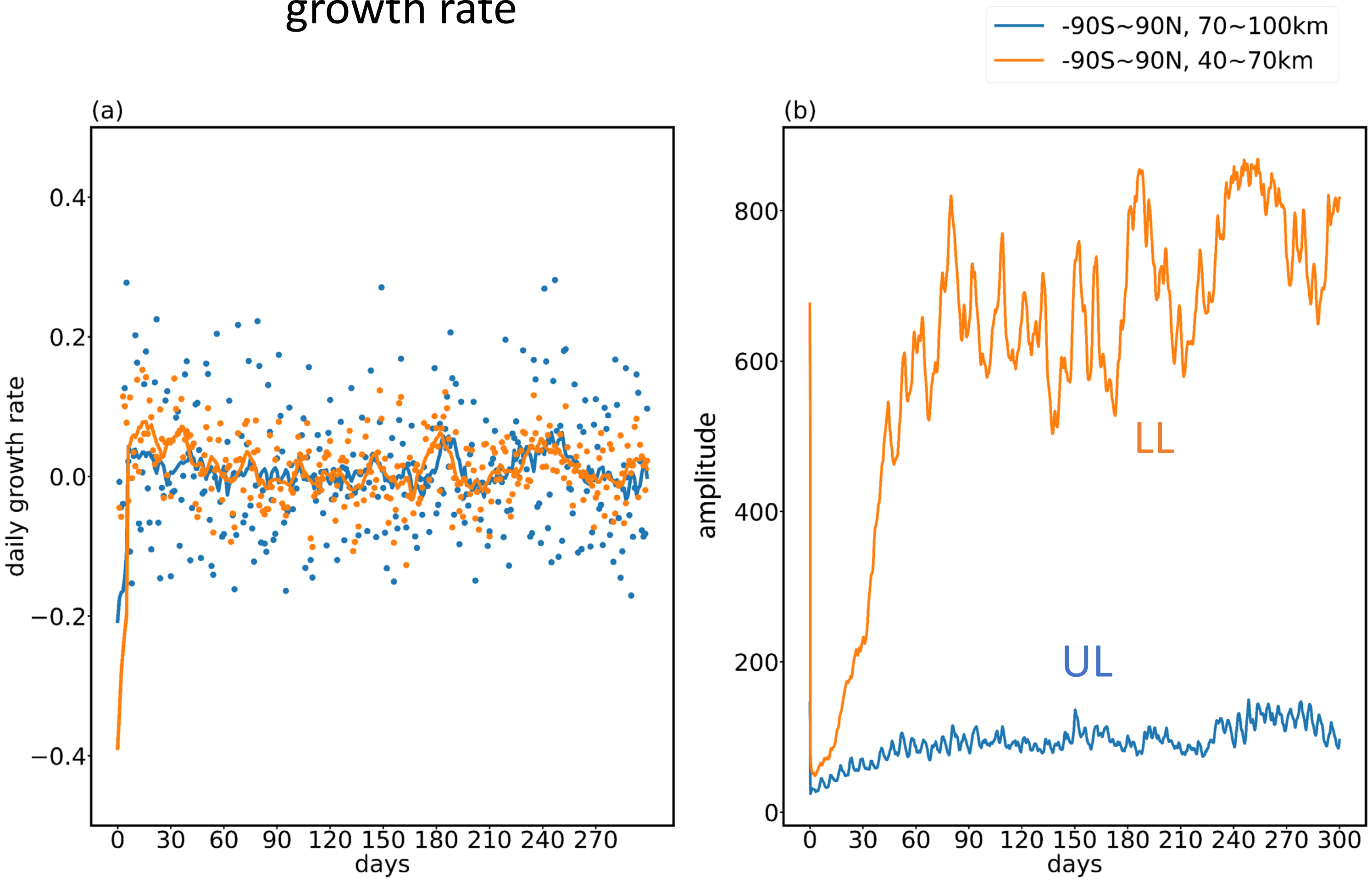
Ramp = 1000



Ramp \ Rint	6	24	48
1000	-557.7	-469.5	-514.9
100	-41.8	-48.7	-54.8
10	7.4	12.0	14.0

amp

growth rate



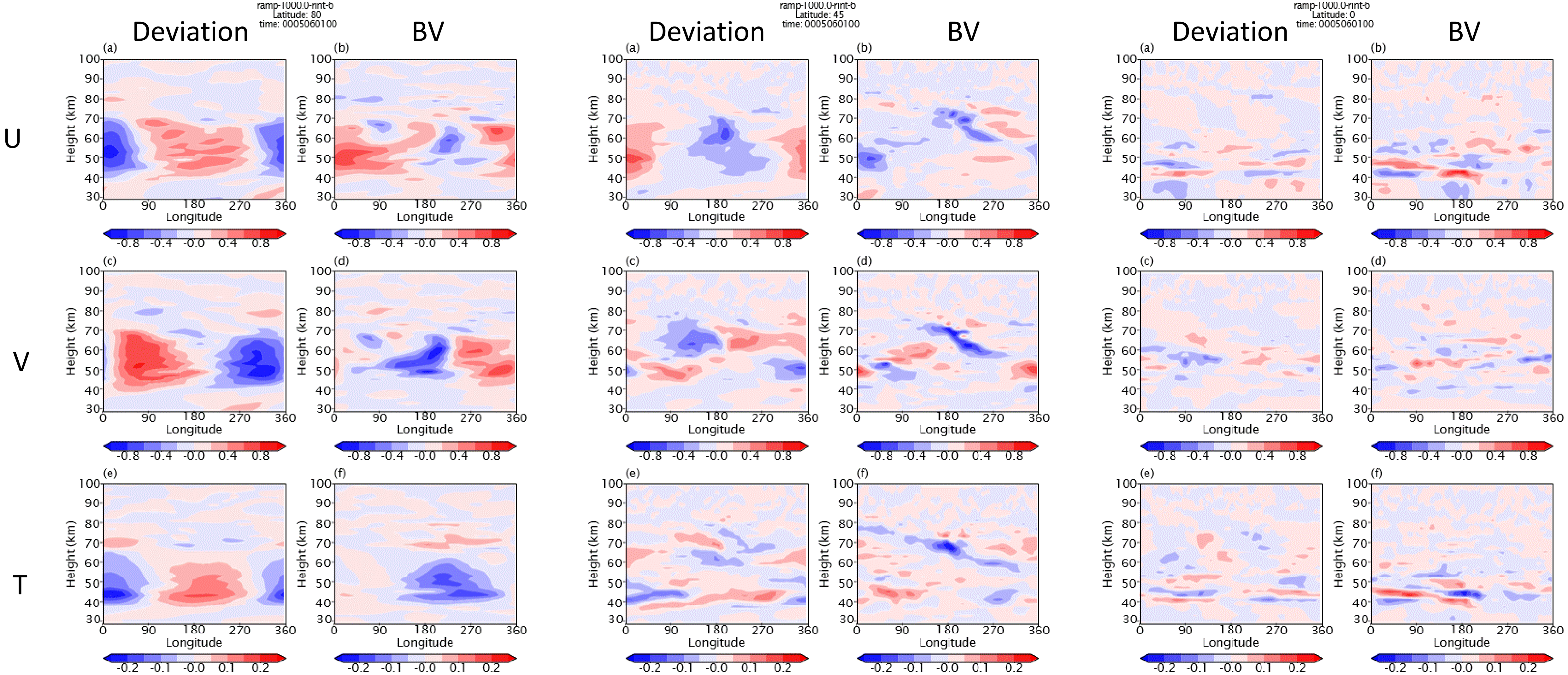
slow growing mode dominate

compare deviation and BV

80N
Barotropic

45N
Baroclinic

0
Rossby-kelvin



- the structures are similar
- the zonal phases are different

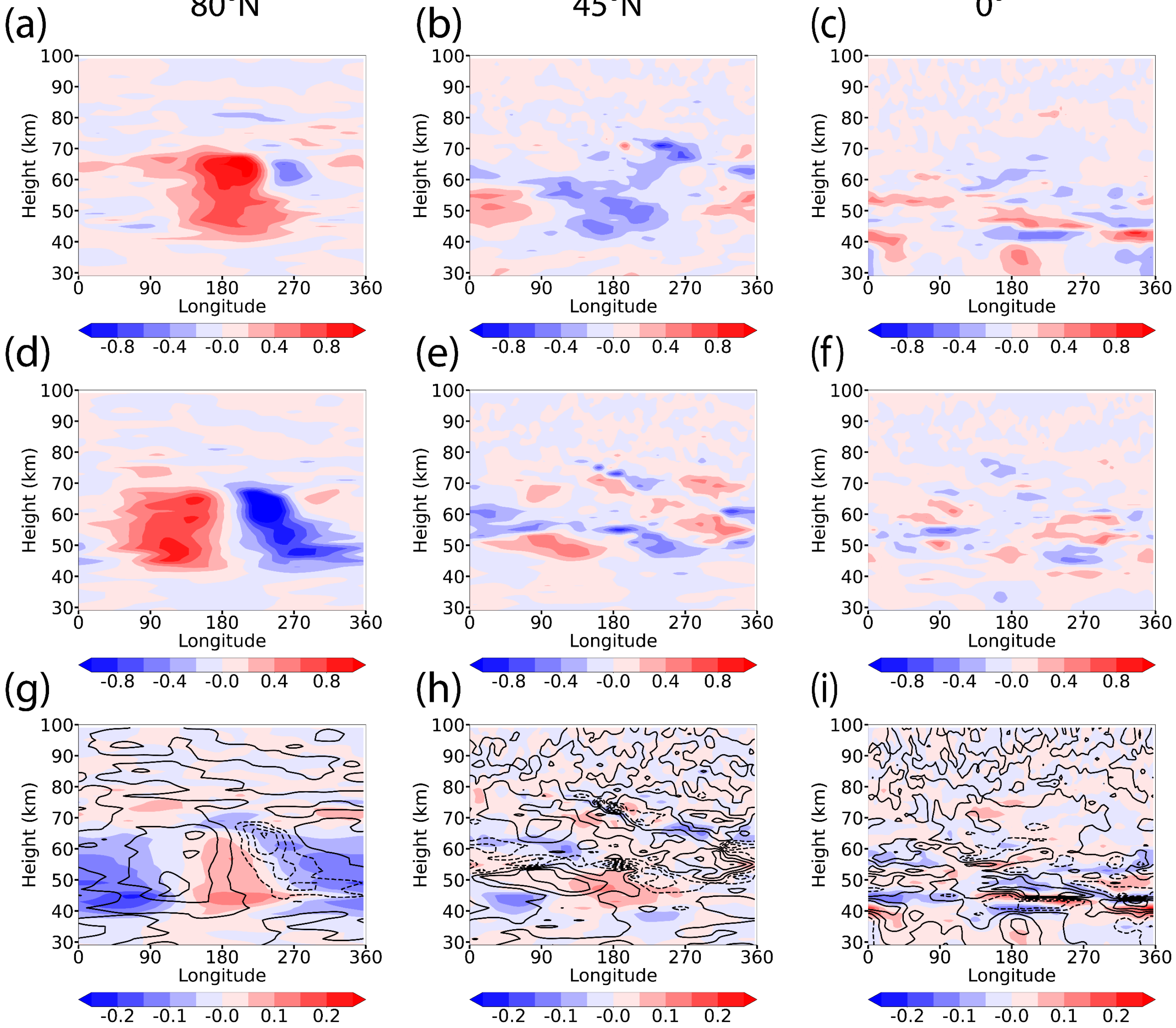
Bred Vectors at different latitudes

Barotropic 80^{0}N | Baroclinic 45^{0}N | Rossby-kelvin 0^0

$\sqrt{d\sigma}u^{BV}$

$\sqrt{d\sigma}v^{BV}$

$\sqrt{d\sigma}T^{BV}$ *(shaded)*
$\sqrt{d\sigma}v^{BV}$ (contour)



for 0N

$\sqrt{d\sigma}T^{BV}$ *(shaded)*
$\sqrt{d\sigma}u^{BV}$ (contour)

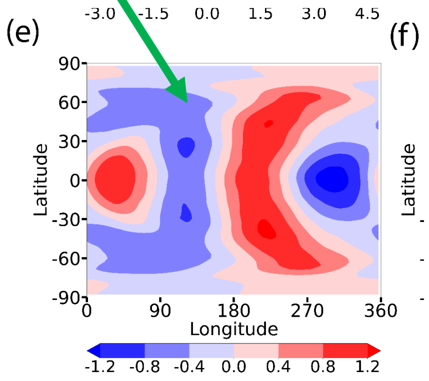
Composite mean at different latitudes

thermal tide increase baroclinic instability

temperature gradient is increased

$\overline{T'}^{comp}$

60 km



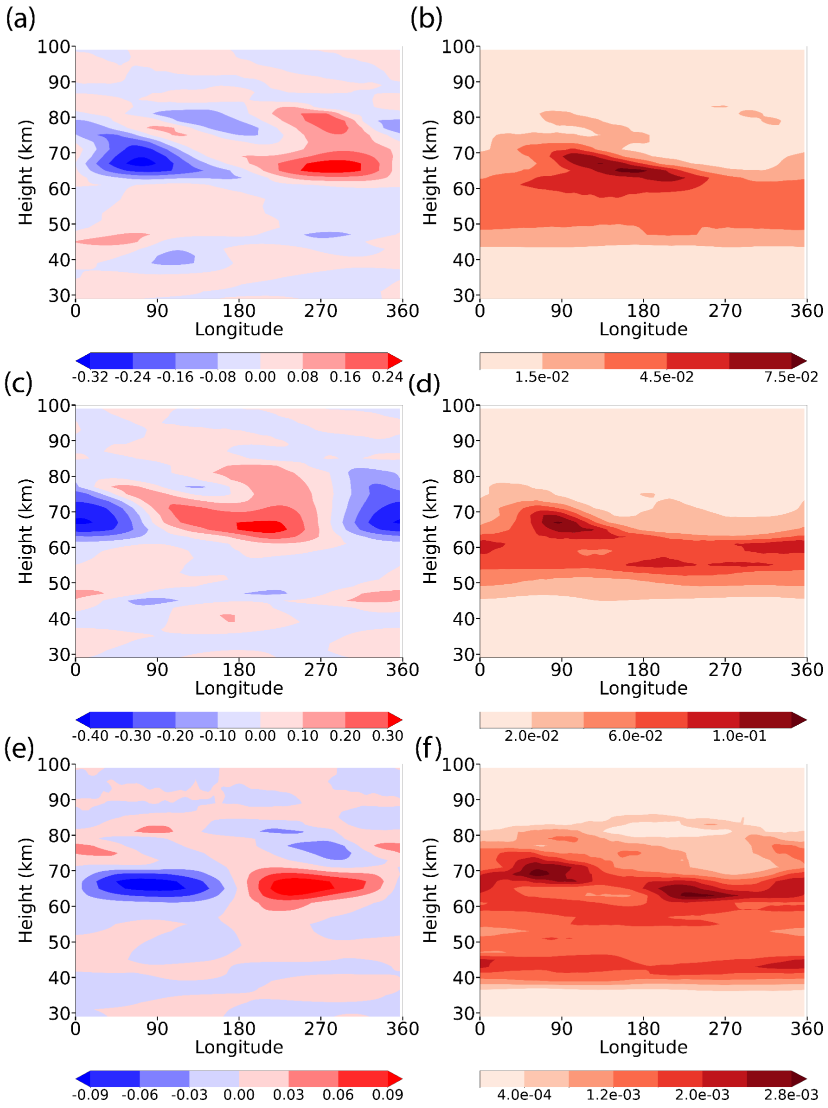
$\sqrt{d\sigma}\,\overline{u'}^{comp}$

$\sqrt{d\sigma}\,\overline{v'}^{comp}$

$\sqrt{d\sigma}\,\overline{T'}^{comp}$

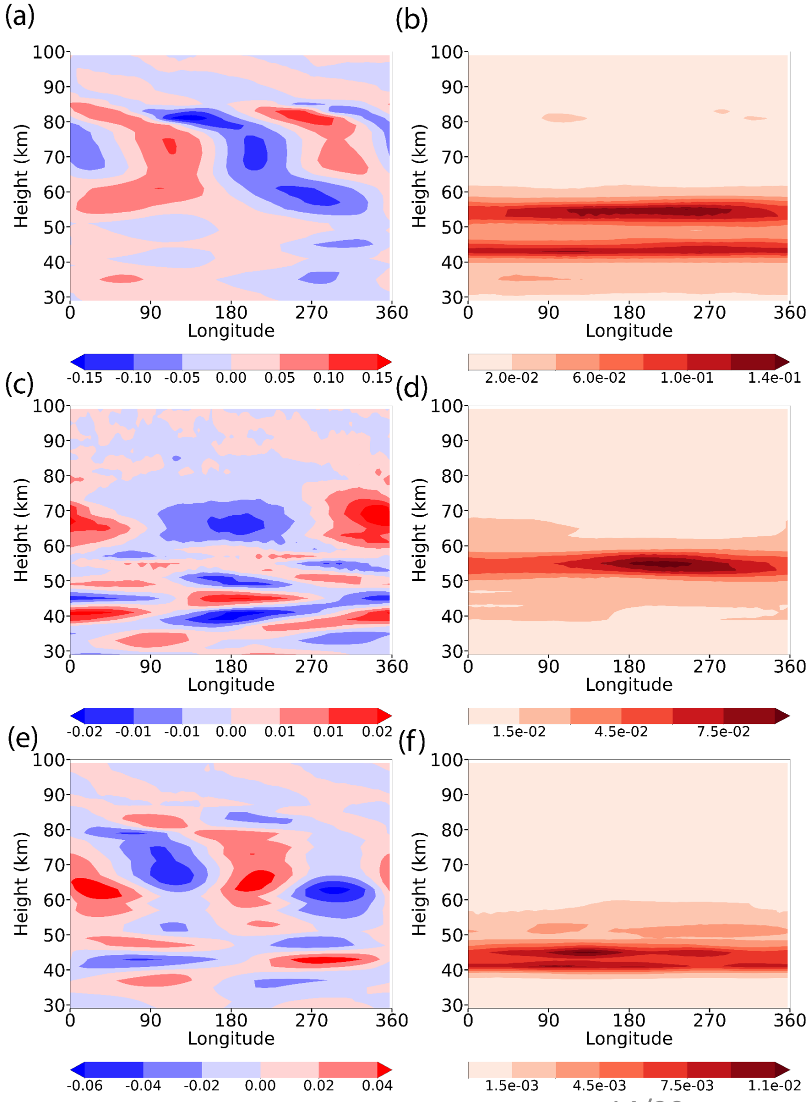
45 N

control BV



0 N

control BV



Composite mean at different height

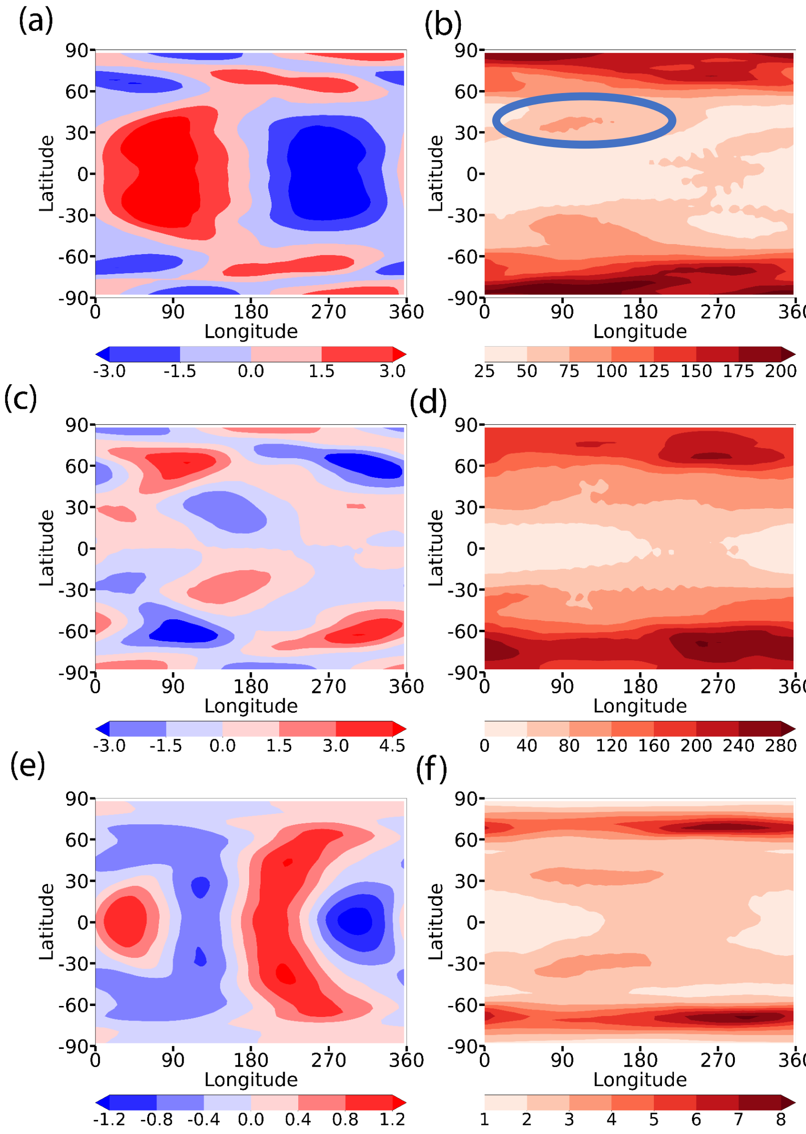
60 km thermal tide increase baroclinic instability **65 km**

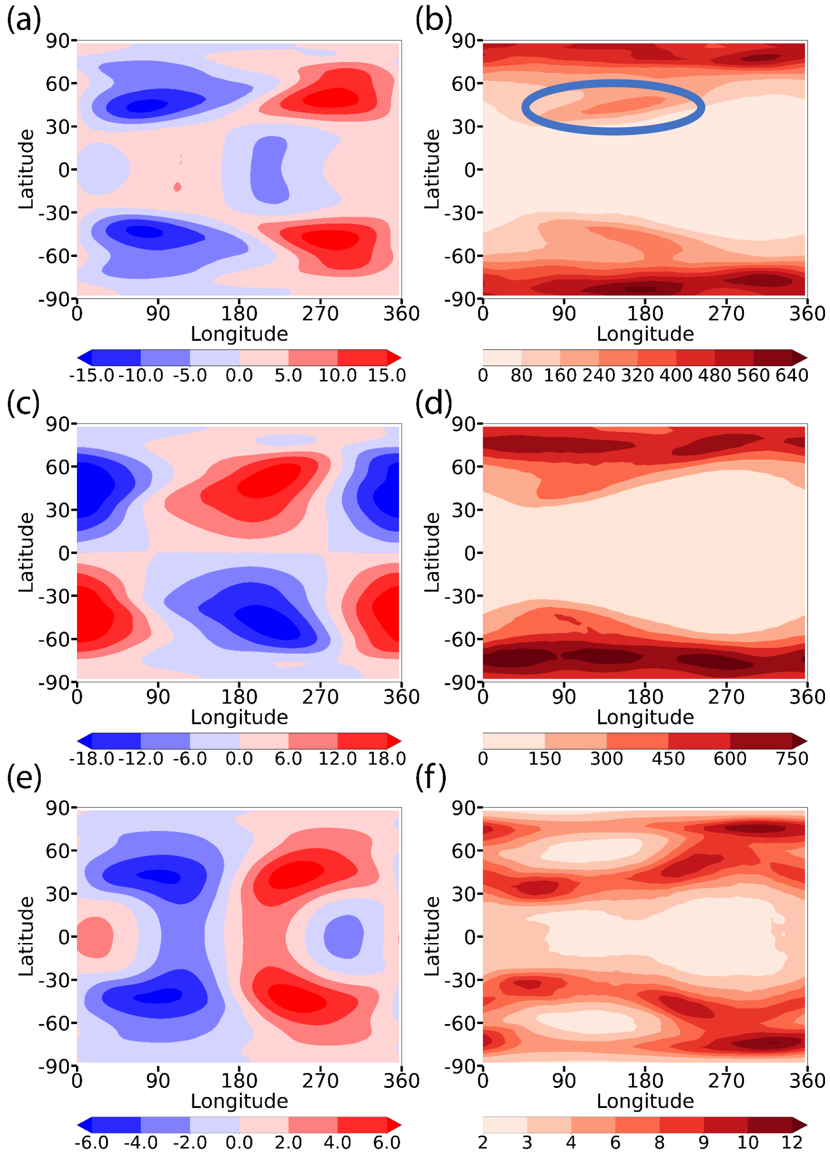
control BV control BV

$\overline{u'}^{comp}$ $\overline{u^{BV^2}}^{comp}$

$\overline{v'}^{comp}$ $\overline{v^{BV^2}}^{comp}$

$\overline{T'}^{comp}$ $\overline{T^{BV^2}}^{comp}$

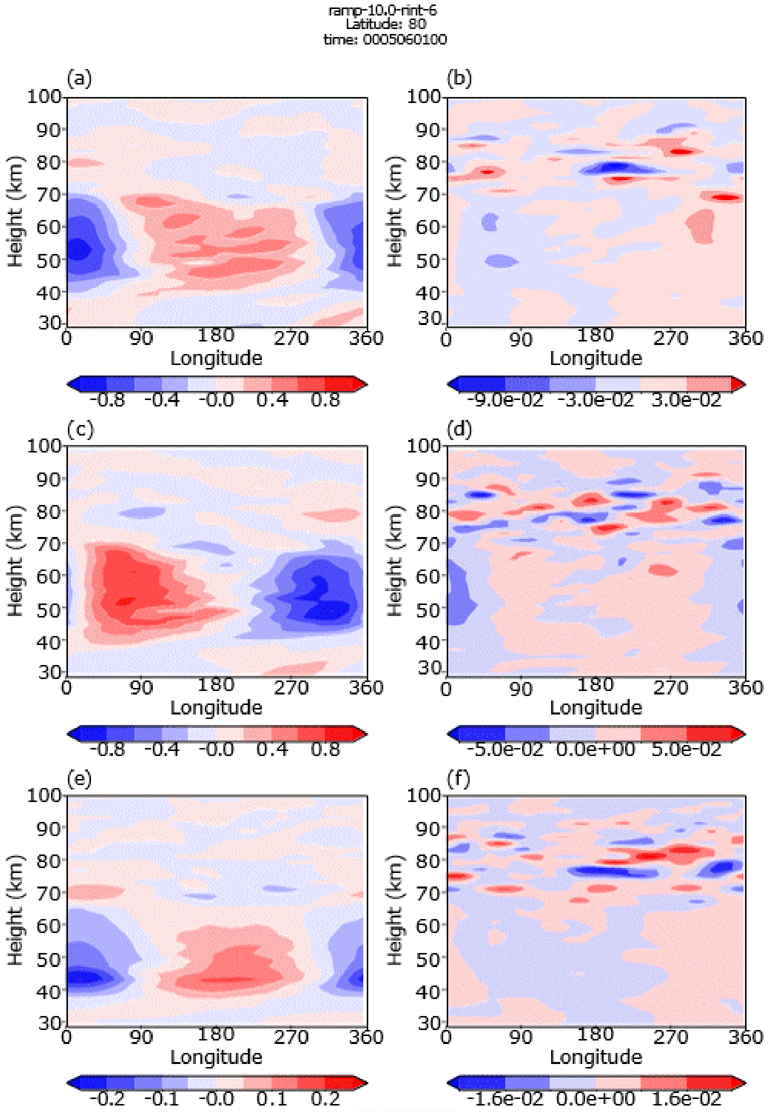




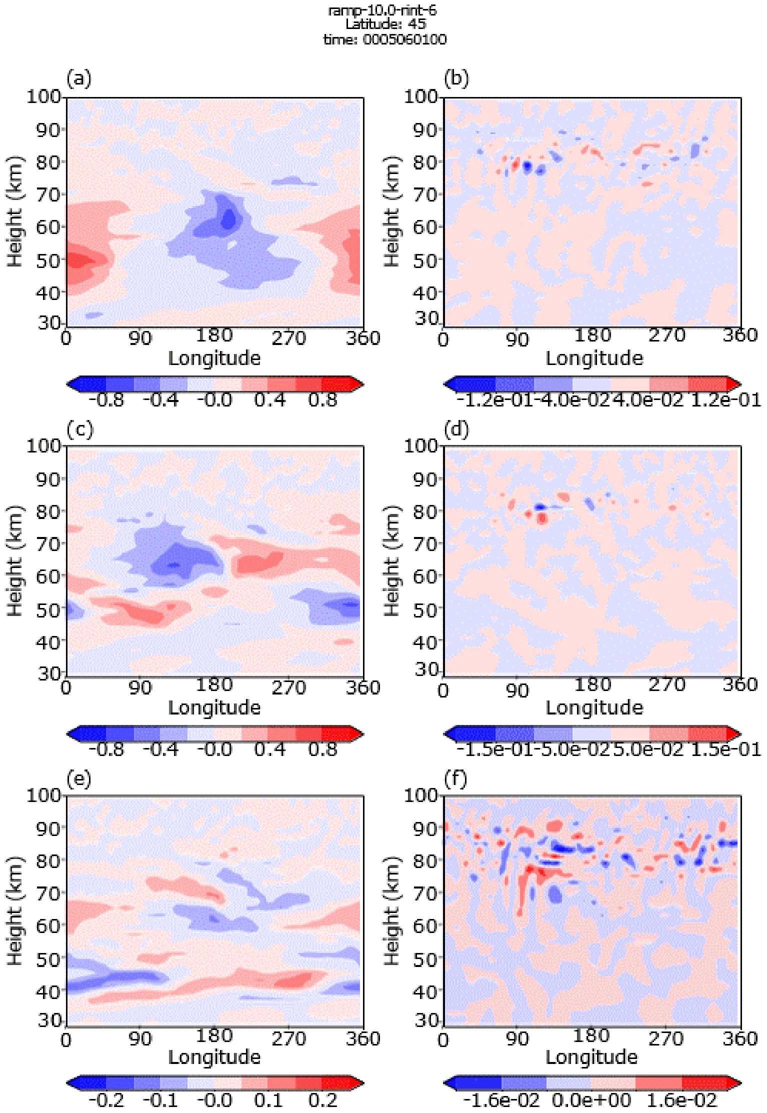
emphasize fast growing mode

Ramp10-Rint06

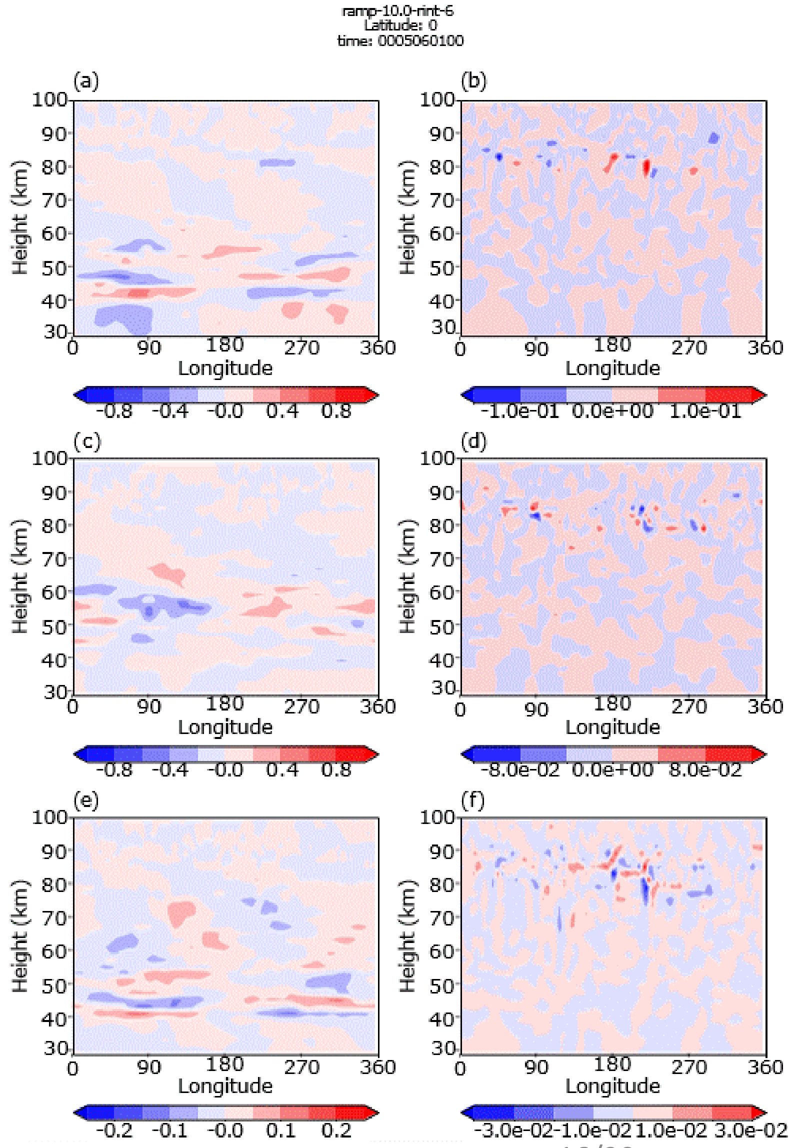
80N



45N



0



gravity waves generation and breaking

80 km

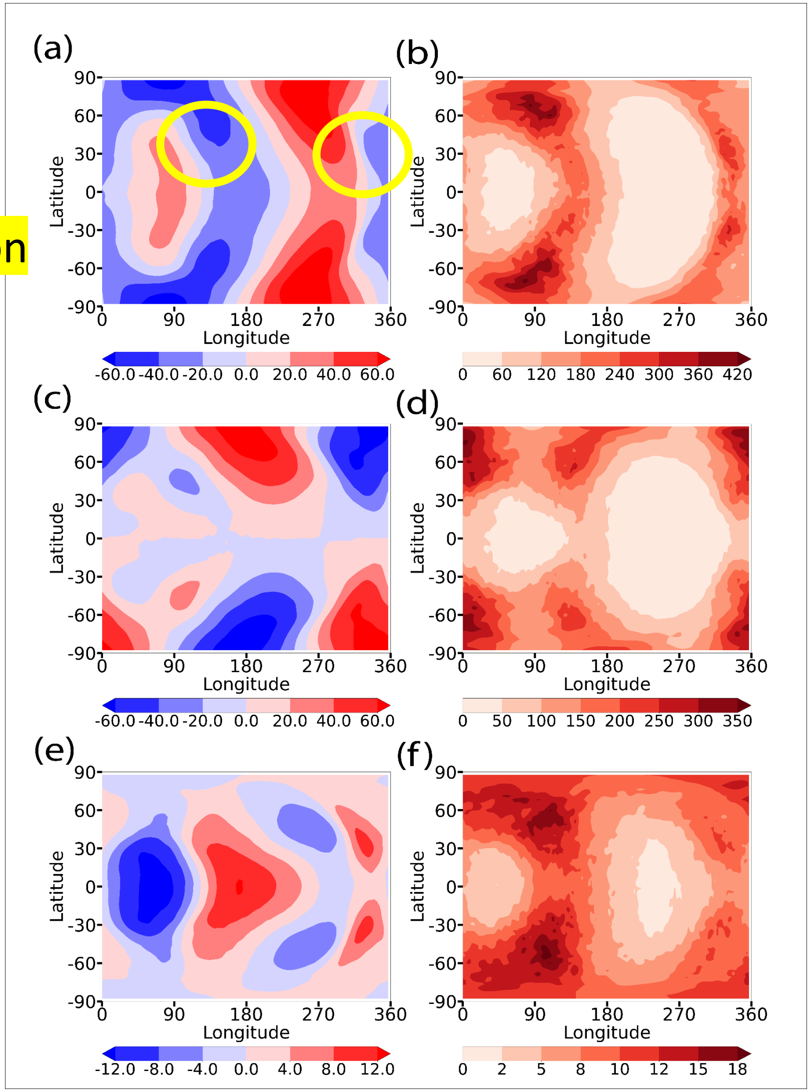
control BV

$\overline{u'}^{comp}$

Jet exit region

$\overline{v'}^{comp}$

$\overline{T'}^{comp}$

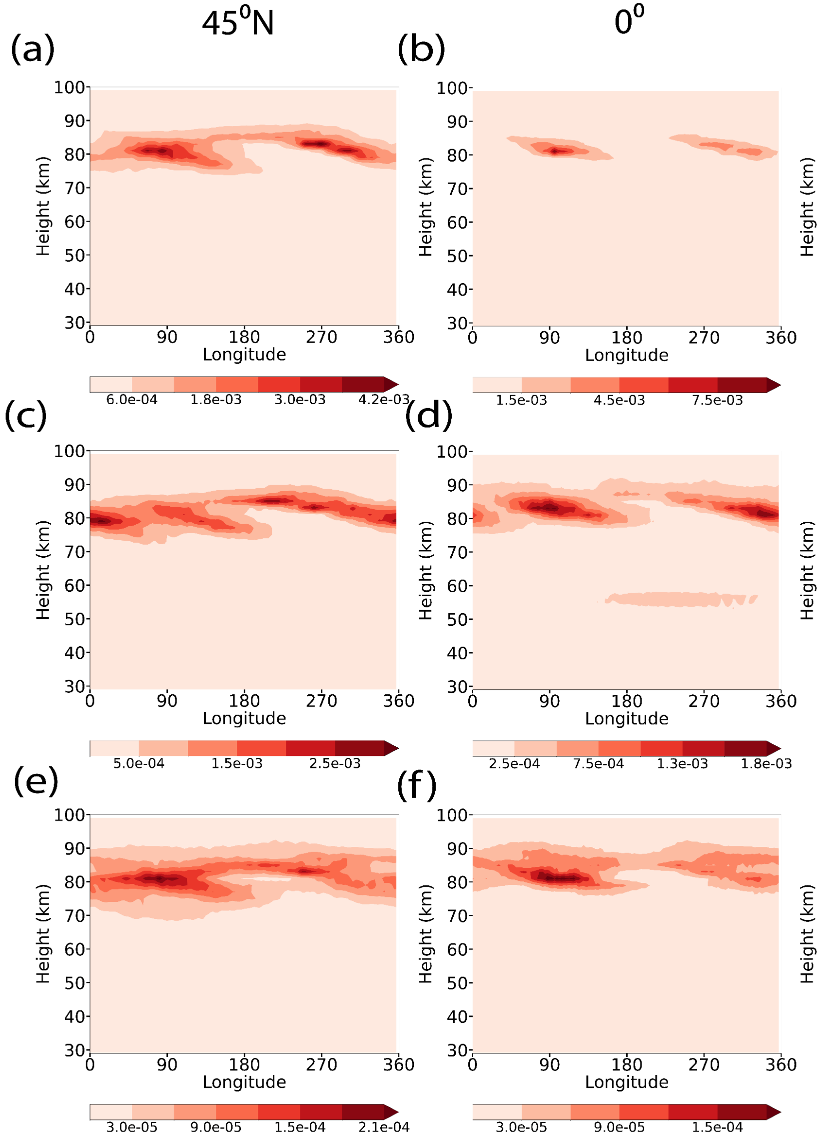


$\overline{u^{BV\,2}}^{comp}$

$\overline{u^{BV\,2}}^{comp}$

$\overline{u^{BV\,2}}^{comp}$

BV



$\overline{d\sigma u^{BV\,2}}^{comp}$

$\overline{d\sigma u^{BV\,2}}^{comp}$

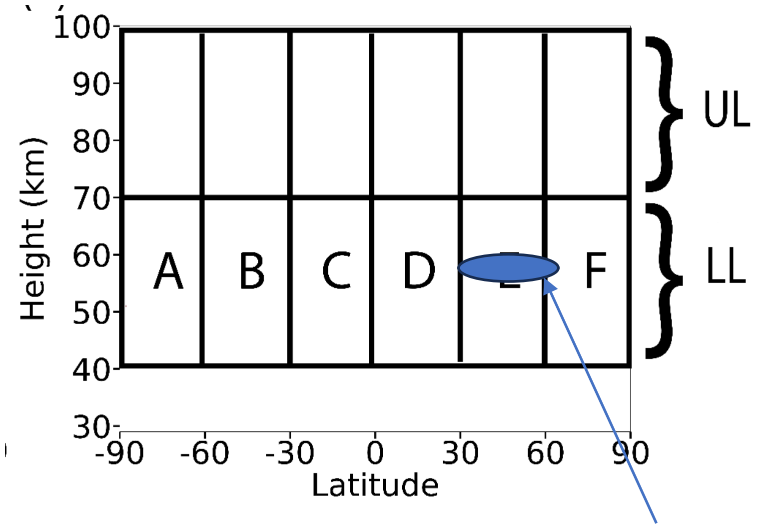
$\overline{d\sigma u^{BV\,2}}^{comp}$

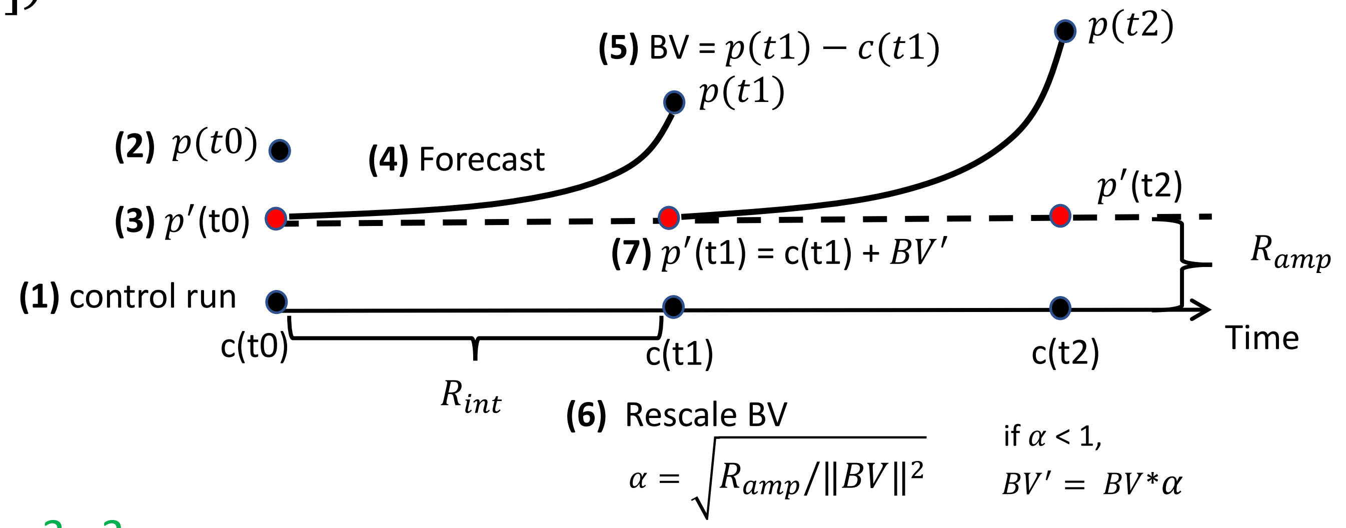
gravity waves generated by the thermal tide through the spontaneous mechanism (Sugimoto 2021)

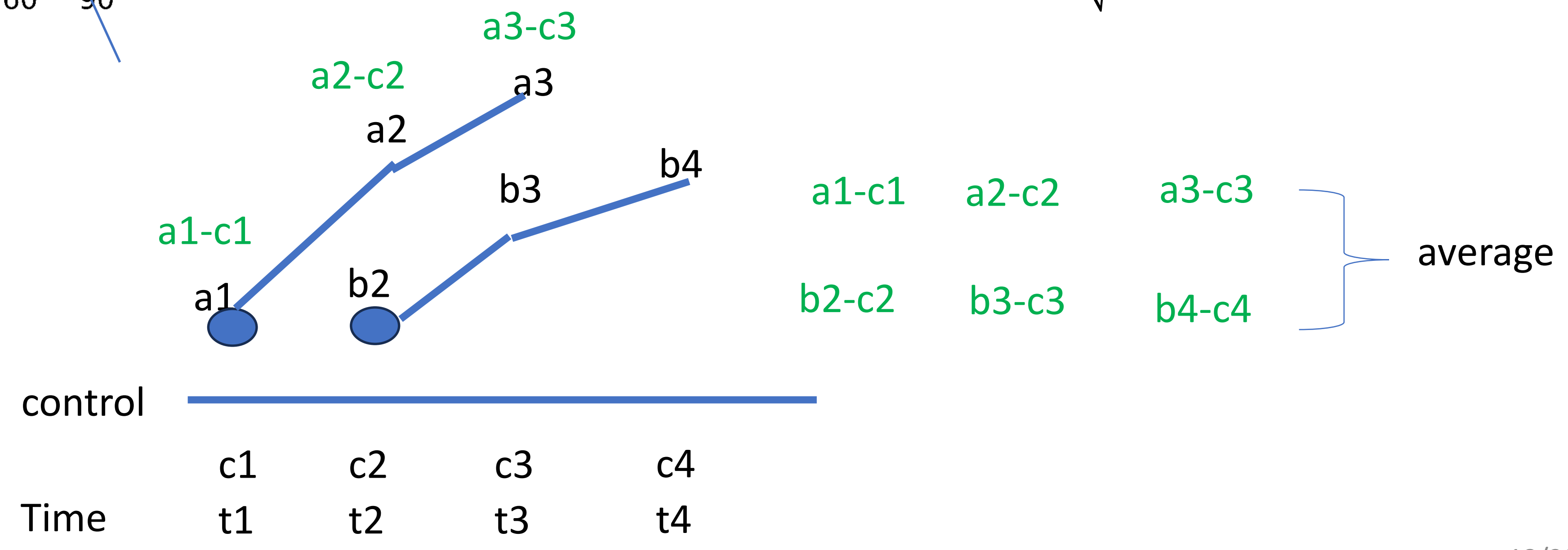
Predictability

kinetic energy
54 km
30-60N

$$E_{grid} = \frac{1}{2}[(\delta u^2 + \delta v^2)])$$



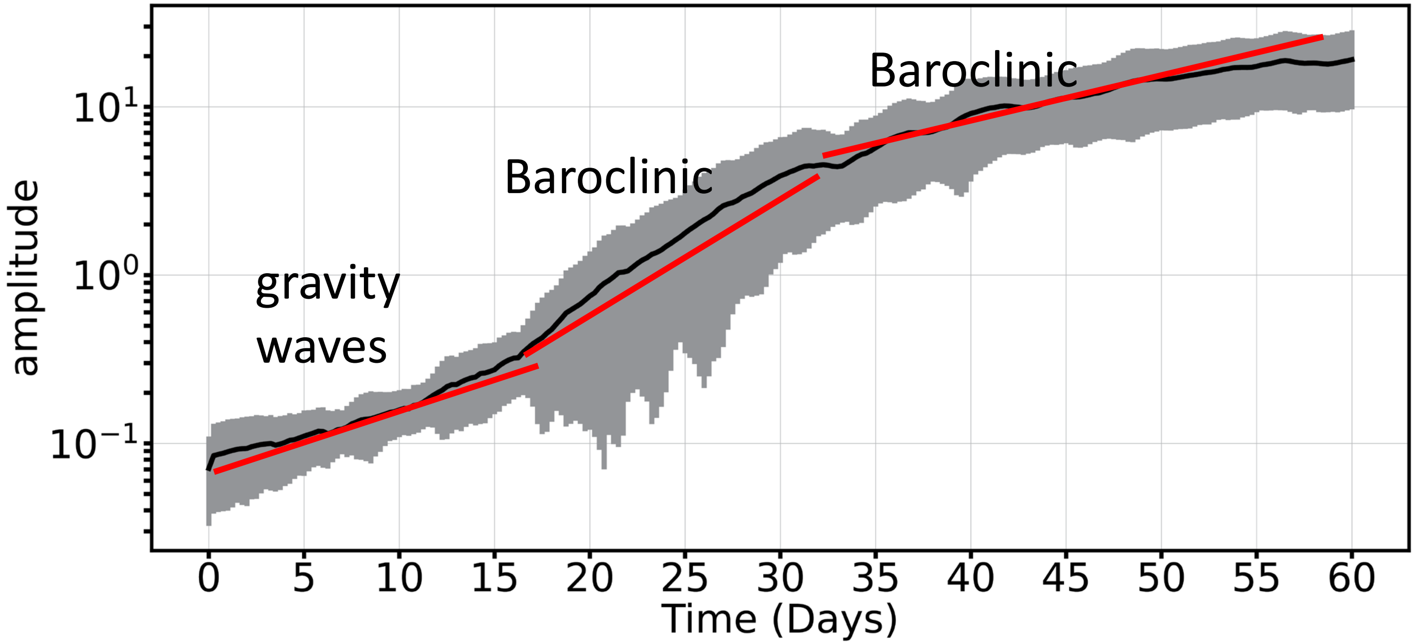




Predictability

54 km,
30-60N

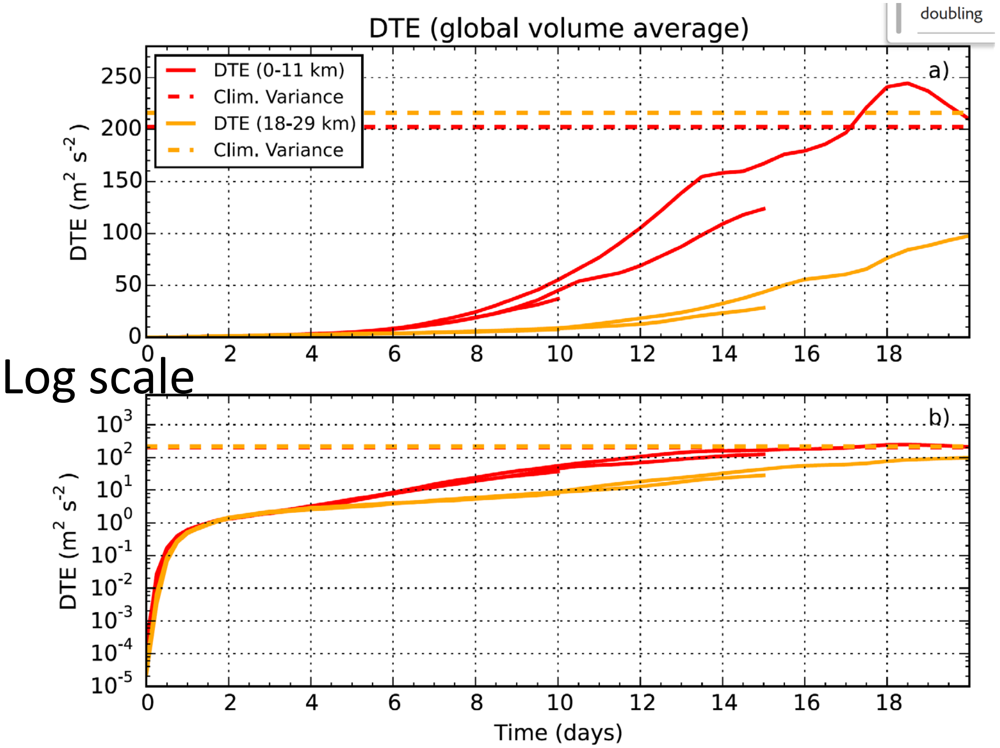
Predictability: > 1 month



days	daily growth rate	error doubling time (days)	e folding time (days)
0-to-17	0.11	6.6	9.5
17-to-32	0.15	4.6	**6.6**
32-to-60	0.05	13.8	19.9

Earth atmosphere

Predictability: 2-3 weeks



Judy
2018

Summary

- Identical twin experiments show that perturbations at 40-70 (cloud layer) and 70-100 km (above cloud layer) altitudes are **slow-growing** and **fast-growing** modes, respectively.
- Breeding cycle experiments generate perturbations associated with **barotropic, baroclinic, Rossby-Kelvin** instabilities in the lower layer, and the **generation and breaking of the gravity waves** in the upper layer.
- BVs show that **thermal tide** enhances the baroclinic instability
- The intrinsic **predictability** related to the baroclinic instability is >1 month, longer than that for the Earth's atmosphere of ~2 weeks.

Future works

- study **predictability** in different regions, different model resolution, different models
- use **Bred vector energy equation** to identify the origin of the instability
- use data assimilation to **estimate the model parameters**: solar heating parameters, etc.

Liang, J., N. Sugimoto, and T. Miyoshi, 2024: Analyzing the Instabilities in the Venus Atmosphere Using Bred Vectors. *Journal of Geophysical Research: Planets*, in press

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Definition of the norm of BV

$$E = \left\{\sum\sum\sum\left[\left(\delta u^2 + \delta v^2 + \frac{c_p}{T_r}\delta T^2\right)p_s d\sigma cos\theta\right]\right\}/10^8,$$

- where $\delta u\ (m\ s^{-1}), \delta v\ (m\ s^{-1}), and\ \ \delta T(K)$ are the zonal wind, meridional wind, and temperature in the perturbations, respectively.
- dL (m) is the longitudinal distance of a model grid at the equator.
- dy (m) is the latitudinal distance of a model grid.
- g is the gravitational force constant.
- c_p is the specific heat at constant pressure with a value of 1000 J $kg^{-1}\ K^{-1}$.
- T_r is the reference temperature with a value of 737.15 K.
- p_s is the surface pressure (Pa) in the control run.
- $d\sigma$ is the difference between two sigma levels.
- θ is the Latitude.
- $\Sigma\Sigma\Sigma$ is the horizontal and vertical summation.
- The first two terms are the kinetic energy of the perturbation while the third term is related to the potential energy of the perturbation.