Understanding the Dynamics of Venus Atmosphere using Bred Vectors

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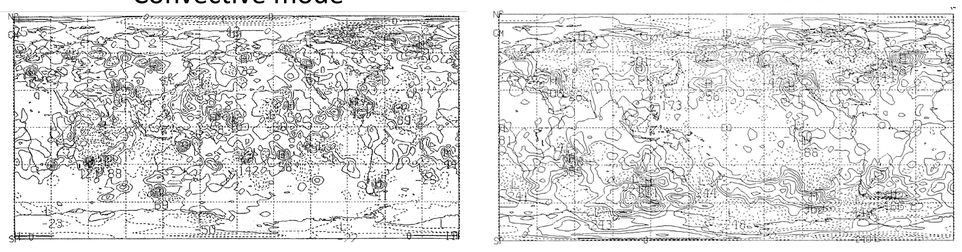
1. Introduction

- Bred Vector (BV) can find the unstable and fast-growing modes of a dynamical system
- BV can diagnose the baroclinic and barotropic energy conversions (Hoffman et al., 2009; Greybush 2013) and estimate the effective local dimension (Patil et al. 2001)
- BV has been used to study Earth (Toth and Kalnay 1993, 1997) and Mars atmospheres (Greybush 2013)

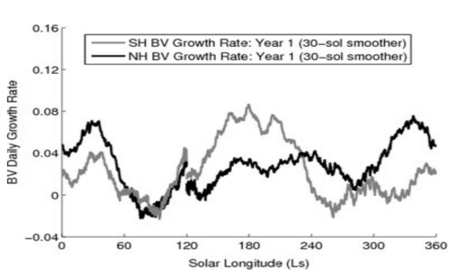
(1) Earth atmosphere (Toth and Kalnay 1993, 1997)

Convective mode | Baroclinic mode

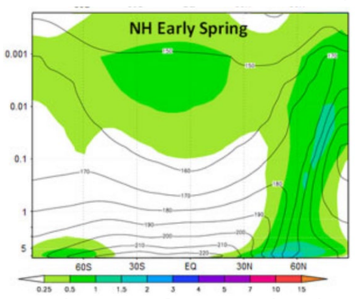


500-hPa streamfunction perturbation

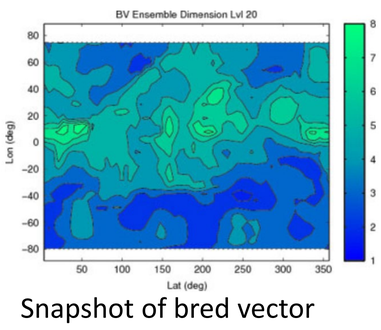
(2) Mars atmosphere (Greybush et al. 2013)



Time evolution of the growth rates (K^2/day) of BV in both hemispheres

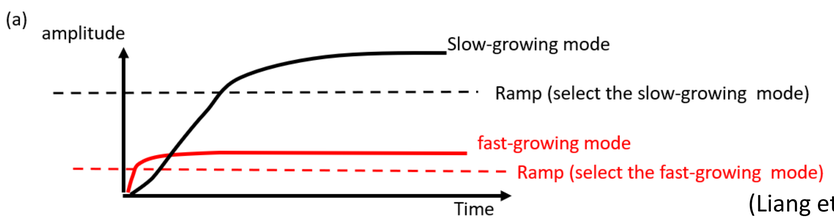


Zonal mean of BV amplitude (shaded) and temperatures (contoured) in early spring



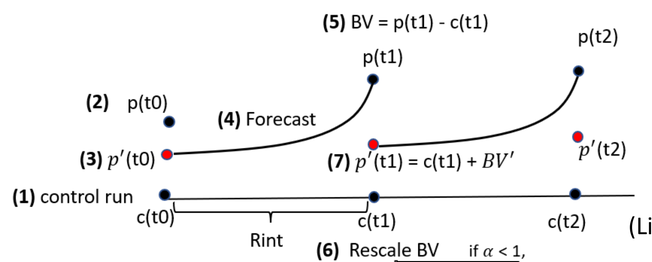
Snapshot of bred vector ensemble dimension at solar longitude 198° on model level 20 (~ 3.5 km altitude).

fast and slow growing modes



(Liang et al. under review)

BV breeding cycle



(Liang et al. under review)

energy norm

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

(6) Rescale BV if $\alpha < 1$,

$$\alpha = \sqrt{Ramp/\|BV\|^2} \qquad BV' = BV^*\alpha$$

This study: BV is applied to the Venus atmospheric general circulation model (AFES-Venus)

2. Experimental Setting

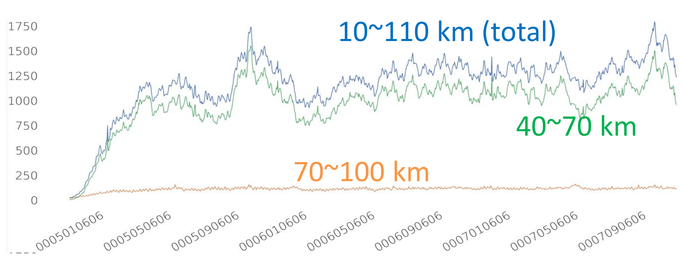
(similar to Sugimoto et al. 2014b)

- AFES-Venus (AGCM for the Earth Simulator for Venus)
  - ✓ 3-D Primitive equation on sphere (hydrostatic balance) without moist processes
  - ✓ Resolution: T42L60 (128 × 64 × 60)
  - ✓ 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 Newtonian cooling: $dT/dt = -\kappa (T - T_{ref}(z))$; κ: based on Crisp (1986) $T_{ref}(z)$: horizontally uniform field

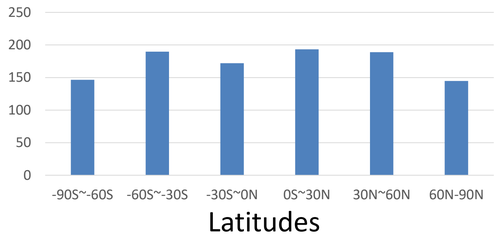
3. Results

- **Free run**

Average amplitudes at 40~70 km altitudes



(Liang et al. under review)



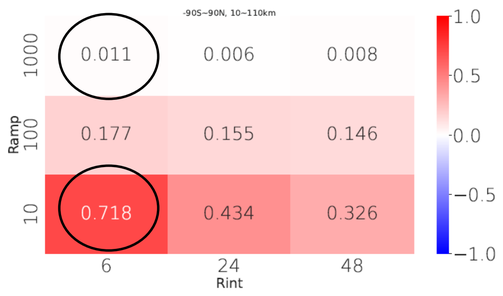
(Liang et al. under review)

perturbation at 40~70 km is the slow-growing mode

perturbation amplitudes in the low and mid-latitudes are comparable in the cloud layer, which is different from Earth.

- **Breeding cycles**

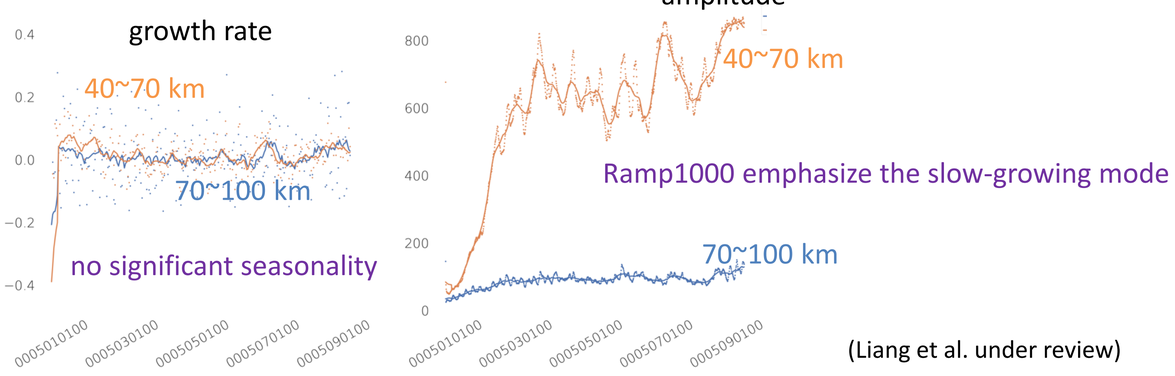
Average growth rates of BVs (1 Venus year)



The growth rate is higher when the rescaling amplitude (Ramp) is smaller or the rescaling interval (Rint) is shorter

(Liang et al. under review)

Analyze Ramp1000-Rint06

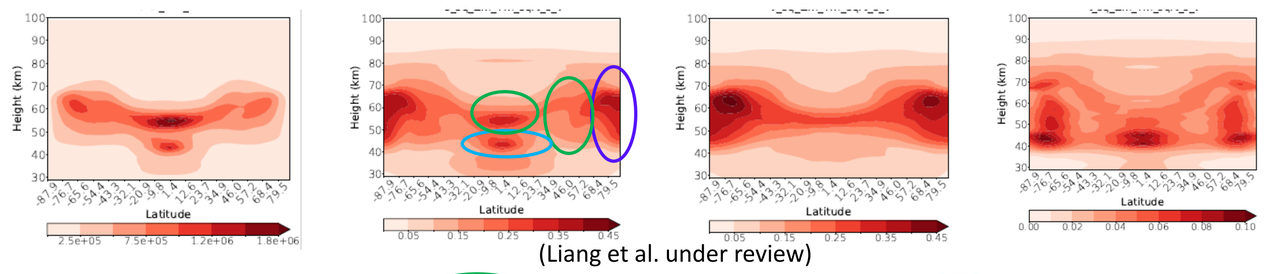


Ramp1000 emphasize the slow-growing mode

(Liang et al. under review)

- **BV amplitude**

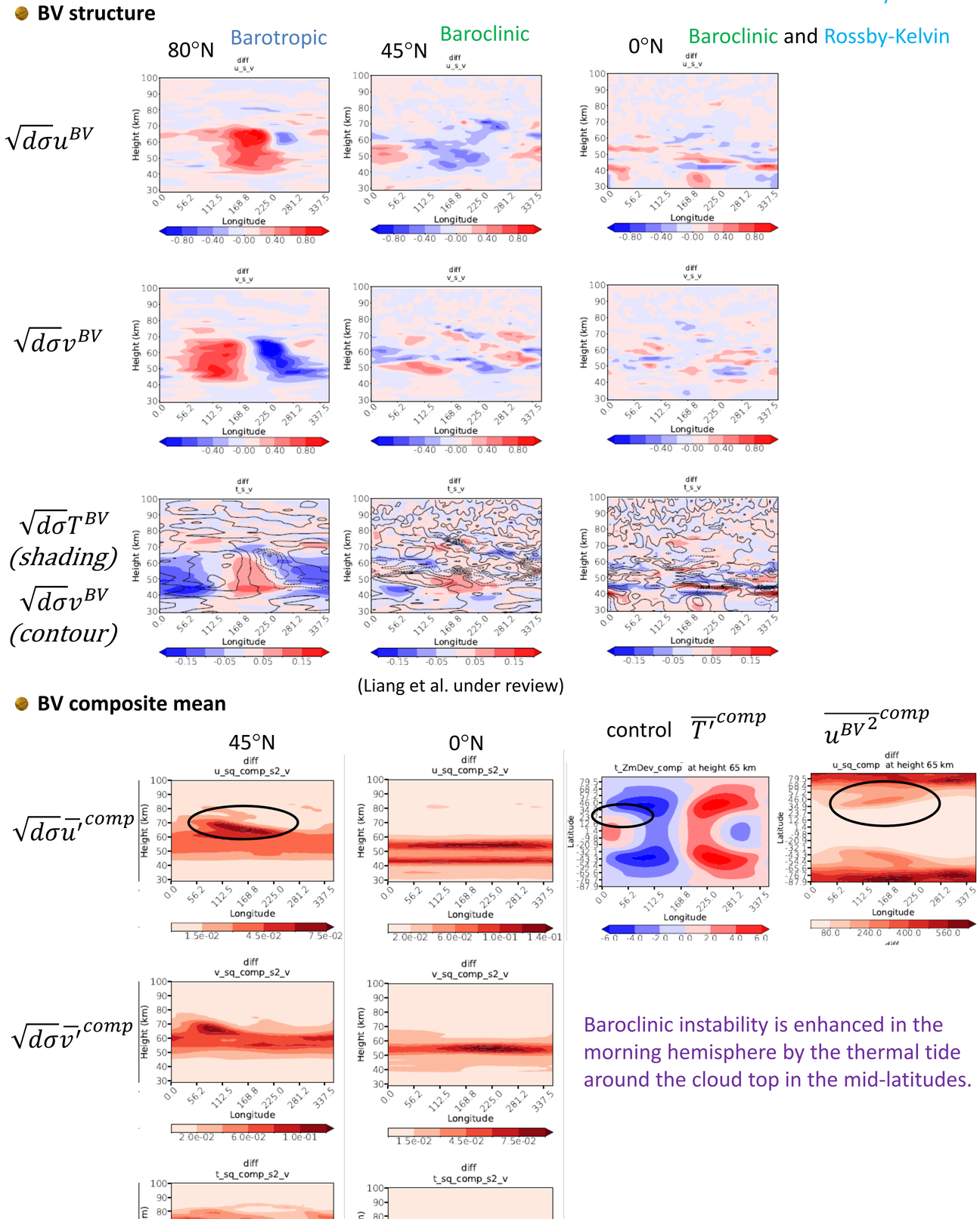
$\overline{energy}$ | $\sqrt{d\sigma}\sqrt{\overline{u^{BV\,2}}}$ | $\sqrt{d\sigma}\sqrt{\overline{v^{BV\,2}}}$ | $\sqrt{d\sigma}\sqrt{\overline{T^{BV\,2}}}$



(Liang et al. under review)

Barotropic (Ando 2017) | Baroclinic (Sugimoto 2014a) | Rossby-Kelvin (Takagi et al. 2022)

- **BV structure**



(Liang et al. under review)

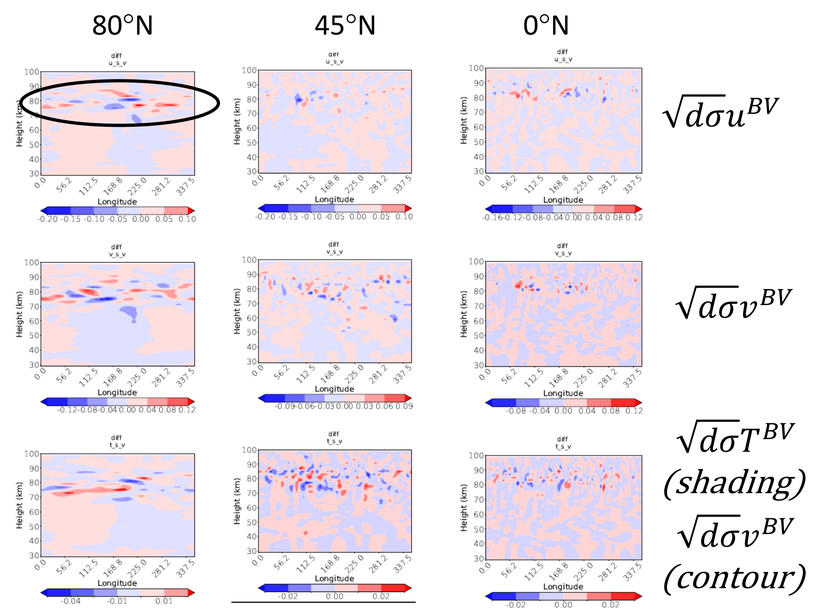
- **BV composite mean**

control $\overline{T'}^{comp}$ | $\overline{u^{BV\,2}}^{comp}$

Baroclinic instability is enhanced in the morning hemisphere by the thermal tide around the cloud top in the mid-latitudes.

(Liang et al. under review)

- BV structure (Ramp10-Rint06)



- Ramp10-Rint06 (small Ramp) emphasize the fast-growing mode above 70 km.
- may be related to the generation and breaking of gravity waves

(Liang et al. under review)

4. Summary

- In Venus Atmosphere, perturbation amplitudes in the low and mid-latitudes are comparable in the cloud layer, which is different from Earth.
- Breeding cycle experiments highlight specific perturbations associated with barotropic, baroclinic, and Rossby-Kelvin instabilities.
- Baroclinic instability is enhanced in the morning hemisphere by the thermal tide around the cloud top in the mid-latitudes.

5. Reference

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