Super-rotation (SR) independent of horizontal diffusion reproduced in a Venus GCM

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EXPRESS LETTER

Super-rotation independent of horizontal diffusion reproduced in a Venus GCM

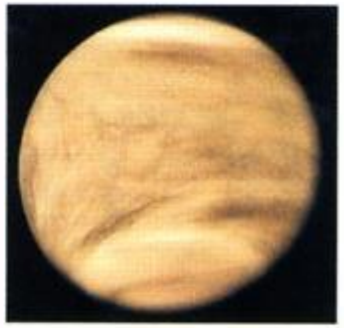
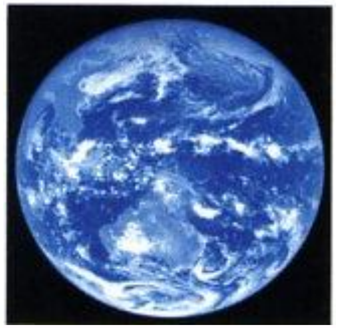
Norihiko Sugimoto[1*], Yukiko Fujisawa[1], Nobumasa Komori[1], Hiroki Kashimura[2,3], Masahiro Takagi[4] and Yoshihisa Matsuda[5]

Abstract

Horizontal diffusion and resolution are important factors to generate and maintain the super-rotation in the general circulation model (GCM) because waves which transport angular momentum are sensitive to them. Here, we investigated how the super-rotation depends on the magnitude of horizontal hyper diffusion using a Venus atmospheric GCM with medium and high resolutions. In both the runs, we found a parameter range where the structure of fully developed super-rotation is almost independent of the magnitude of horizontal diffusion. Spectral analysis shows that unrealistically strong super-rotation is developed when medium-scale disturbances are dissipated by stronger horizontal diffusion. On the other hand, artificially weak super-rotation is also realized because spurious small-scale disturbances are accumulated when the horizontal diffusion is too weak.

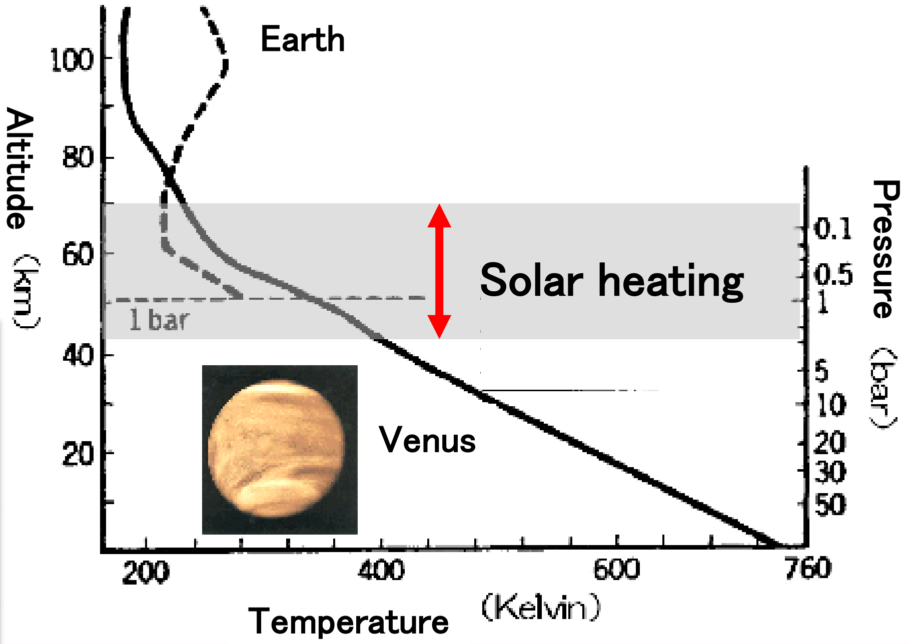
Keywords Venus atmosphere, Super-rotation, GCM, Horizontal diffusion

1. Why Venus?

UV observation

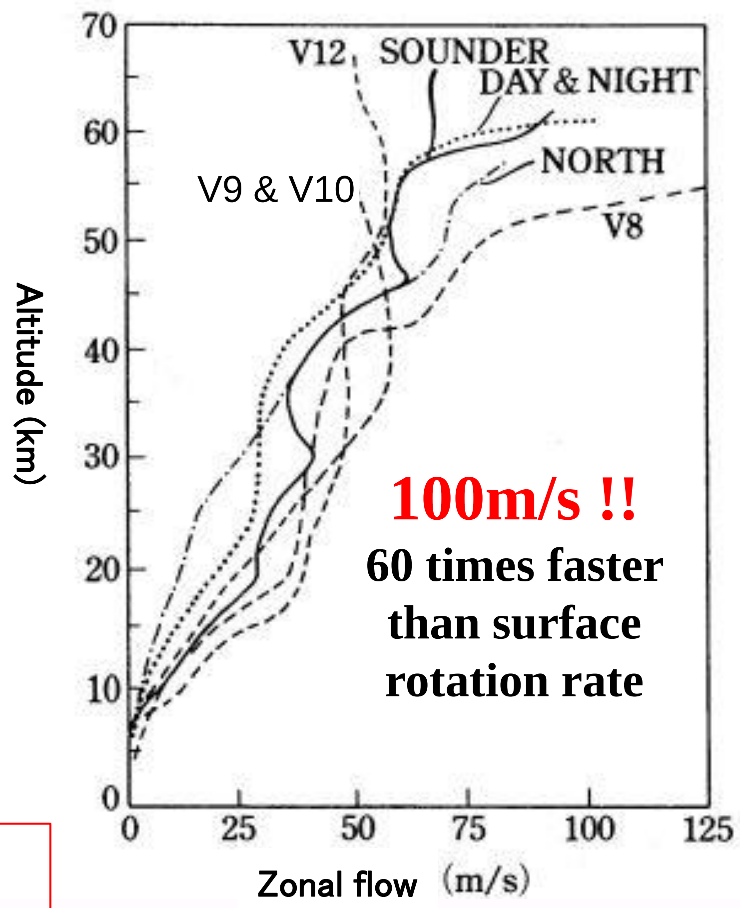
	Venus	Earth
Radius	6050 km	6378 km
Revolution	224 days	365 days
Rotation	243 days (1.8m/s)	1 day (460m/s)
1 solar day	117 days	1 day
Composition	CO_2	N_2, O_2
Albedo	0.78	0.3
Surface pres.	92 bar	1 bar



- ✓ **Very slow rotation**
- ✓ **Dense CO_2 atmosphere**
- ✓ **Thick cloud layer (45～70km)**

Mystery of the Venus's atmosphere

"Super rotation" (fast zonal flow)



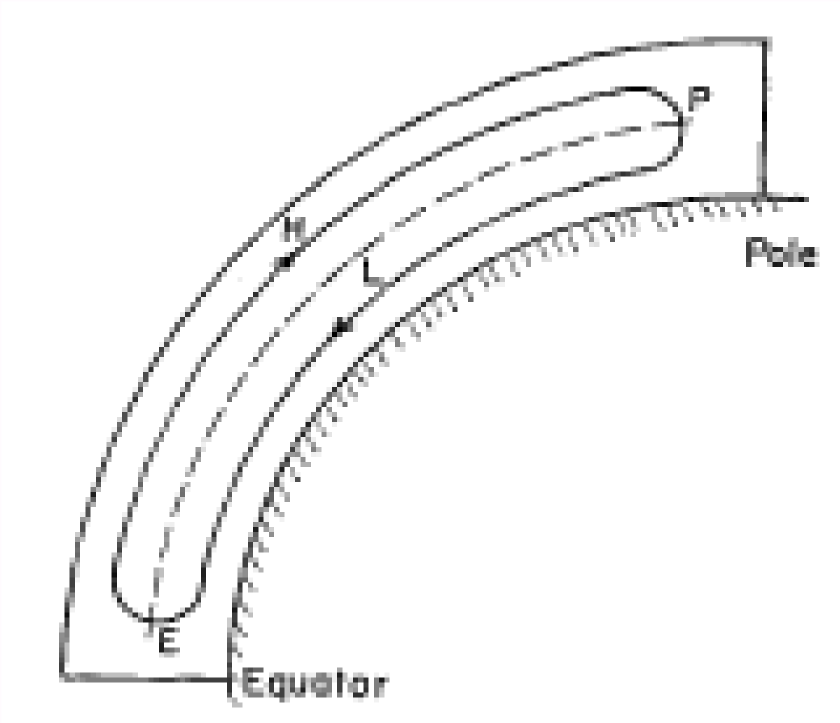
Schubert et al. (1980)

✓ The atmosphere circles the planet about 4 Earth days, much faster than the planet's sidereal day of 243 days.

Venus spins in the opposite direction from Earth (retrograde, or backward, rotation)

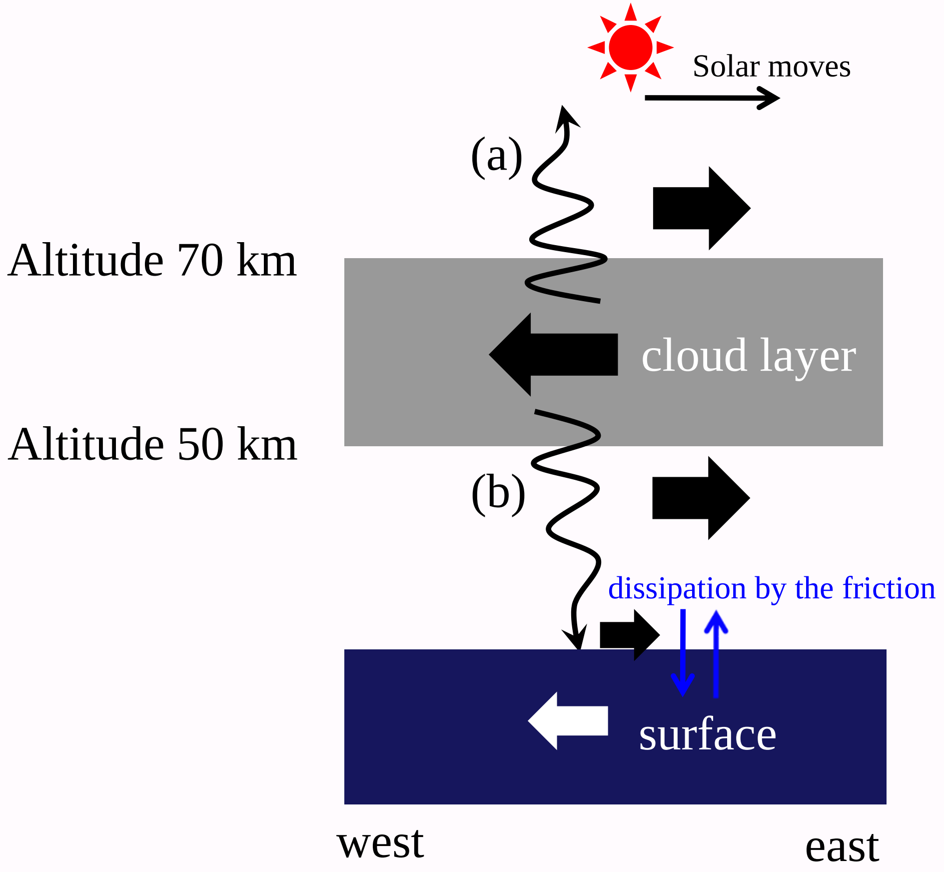
Mechanism of the super rotation

1. Mean meridional circulation
   MMC (Gierasch 1975)



- ✓ **Vertical transport by MMC**
- ✓ **Horizontal transport by eddies**

2. Thermal tide
   (Fels & Lindzen, 1986)



- ✓ **Excitation by the solar heating**
- ✓ **Dissipation by the friction**

2. Venus GCMs studies

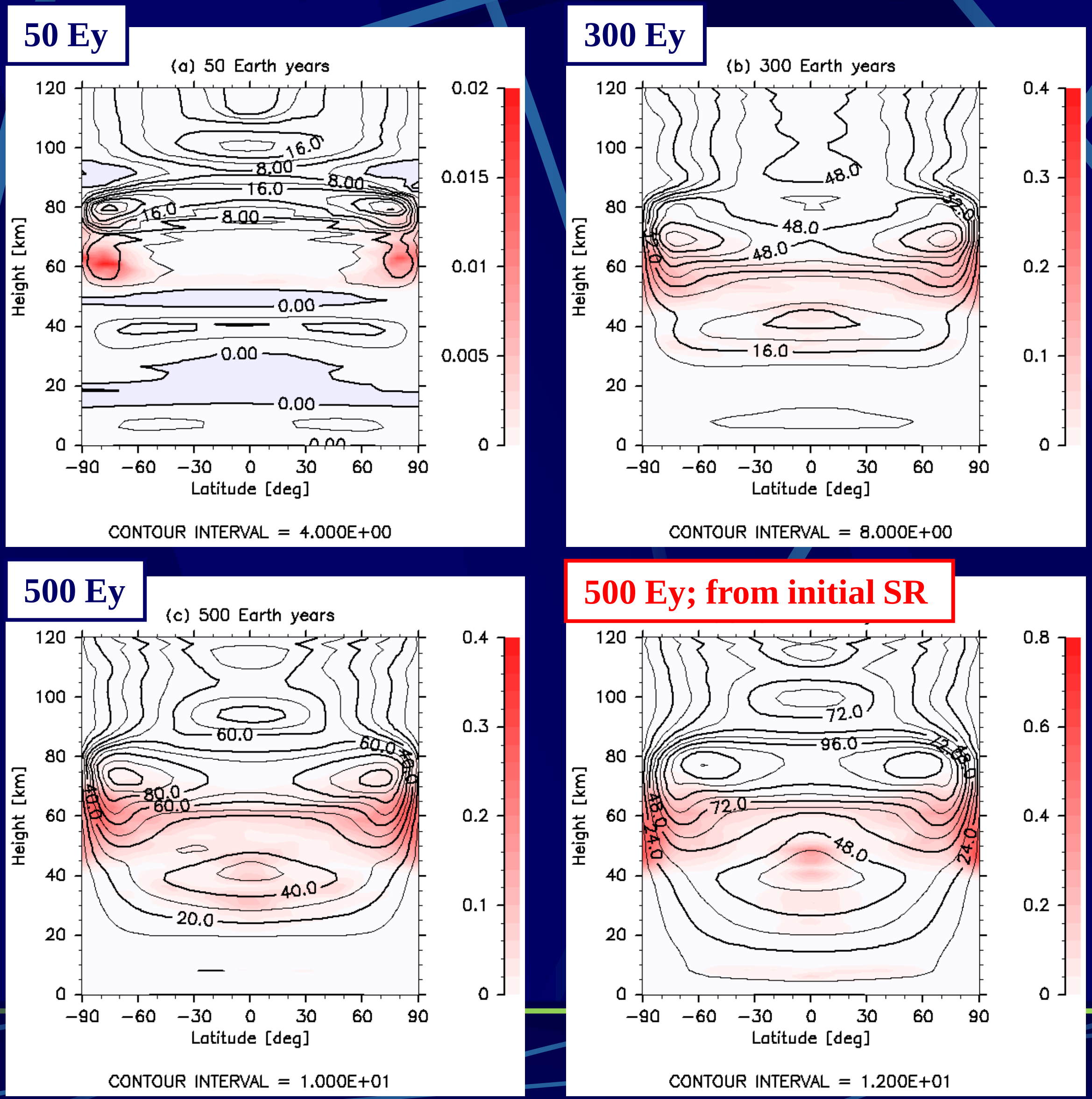
Qz(+) = Zonal solar heating (strong)
Q3D(+) = 3D solar heating (strong)
NC = Newtonian heating and cooling

Papers	Forcing	Resolution	Results
YT2003	Qz+	T10L50	Super-rotation (SR); uniform at low latitude
YT2004a	Qz+	T21L50	SR
YT2004b	Q3D+	T21L50	SR; strong thermal forcing below the cloud
YT2006	Q3D+	T21L52	SR; strong thermal forcing below 55 km
Ho2007	Qz+, Qz	~T21L56	SR; SR is not reproduced for Qz (3 cell)
TM2007	Qt	T10L60	SR; equatorial jet
Lee2005	NC	~T21L32	Weak SR; short relaxation time of NC
Lee2007	NC	~T21L32	Weak SR; short relaxation time of NC
KW2008	Qz	T21L60	Multiple equilibrium state of U50 & U0 (weak SR)
KW2009	Q3D	T21L60	Multiple equilibrium state of U50 & U0 (weak SR)
YT2009	Q3D+	T21L52	SR is not reproduced for realistic Qz
Leb2010	Q3D	~T21L50	SR (with topo.); SR is not reproduced for Qz
Leb2016	Q3D	~T42L50	SR (with rad.); equatorial jet

YT(Yamamoto & Takahashi), Ho(Hollingsworth et al.), TM(Takagi & Matsuda), Lee(Lee et al.), KW(Kido & Wakata), Leb(Lebonnois et al.)

Sugimoto+2019 GRL: Super rotation reproduced with small vertical viscosity

- ✓ After 500 Earth years (Ey): Fully developed SR is maintained for $\upsilon_V = 0.0015$ m^2/s



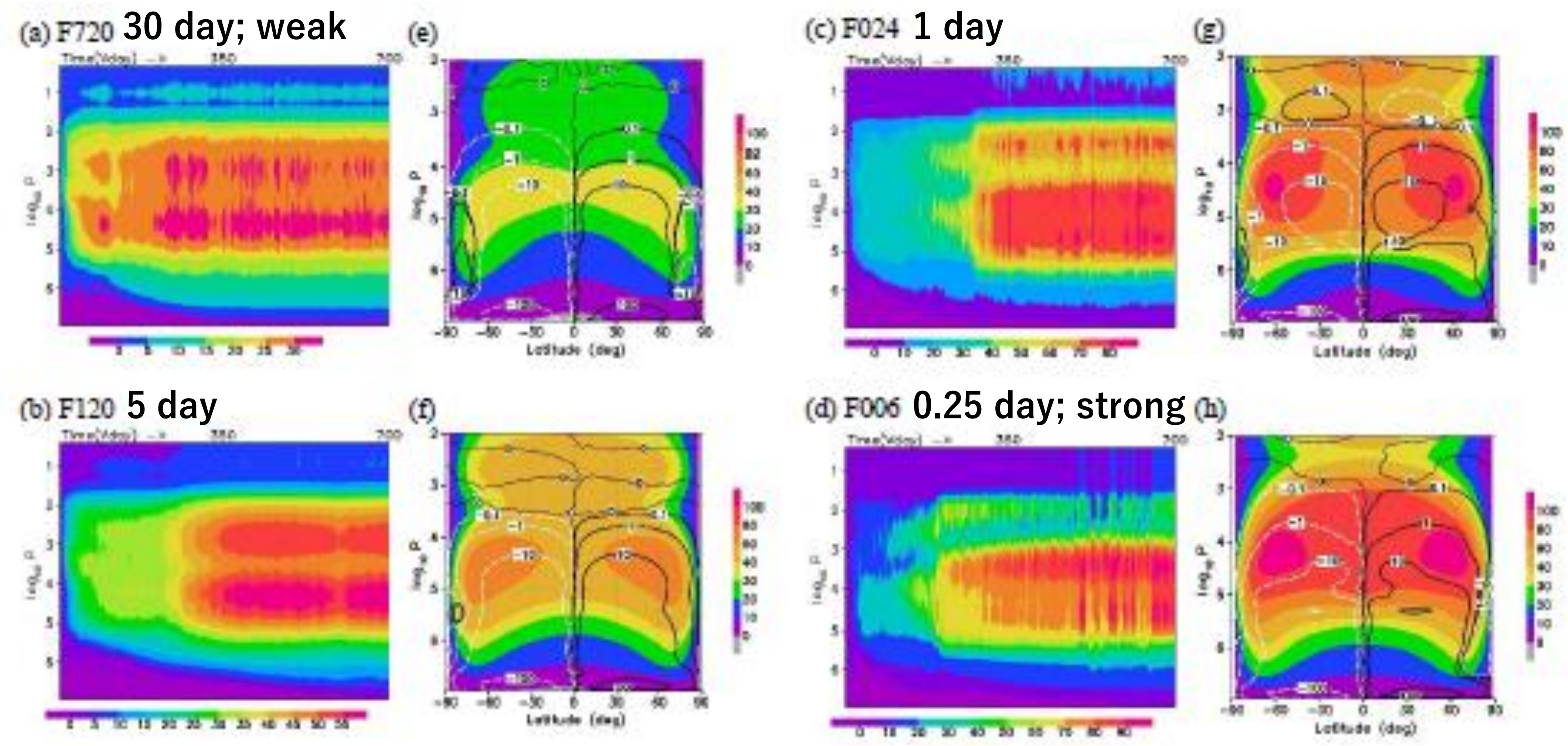
Zonal flow (contour)

Eddy Kinetic Energy (color)

Fast SR; $\upsilon_V \leq 0.02$ m^2/s
Weak SR; $\upsilon_V \geq 0.025$ m^2/s

(I) Motionless state
(II) Super rotation
converge each other
⇒ There is no multiple equilibrium state

- **Yamamoto & Takahashi (2022)**: SR in their GCM depends on the horizontal diffusion



The second-order hyper diffusion (Laplacian squared); the same as AFES-Venus

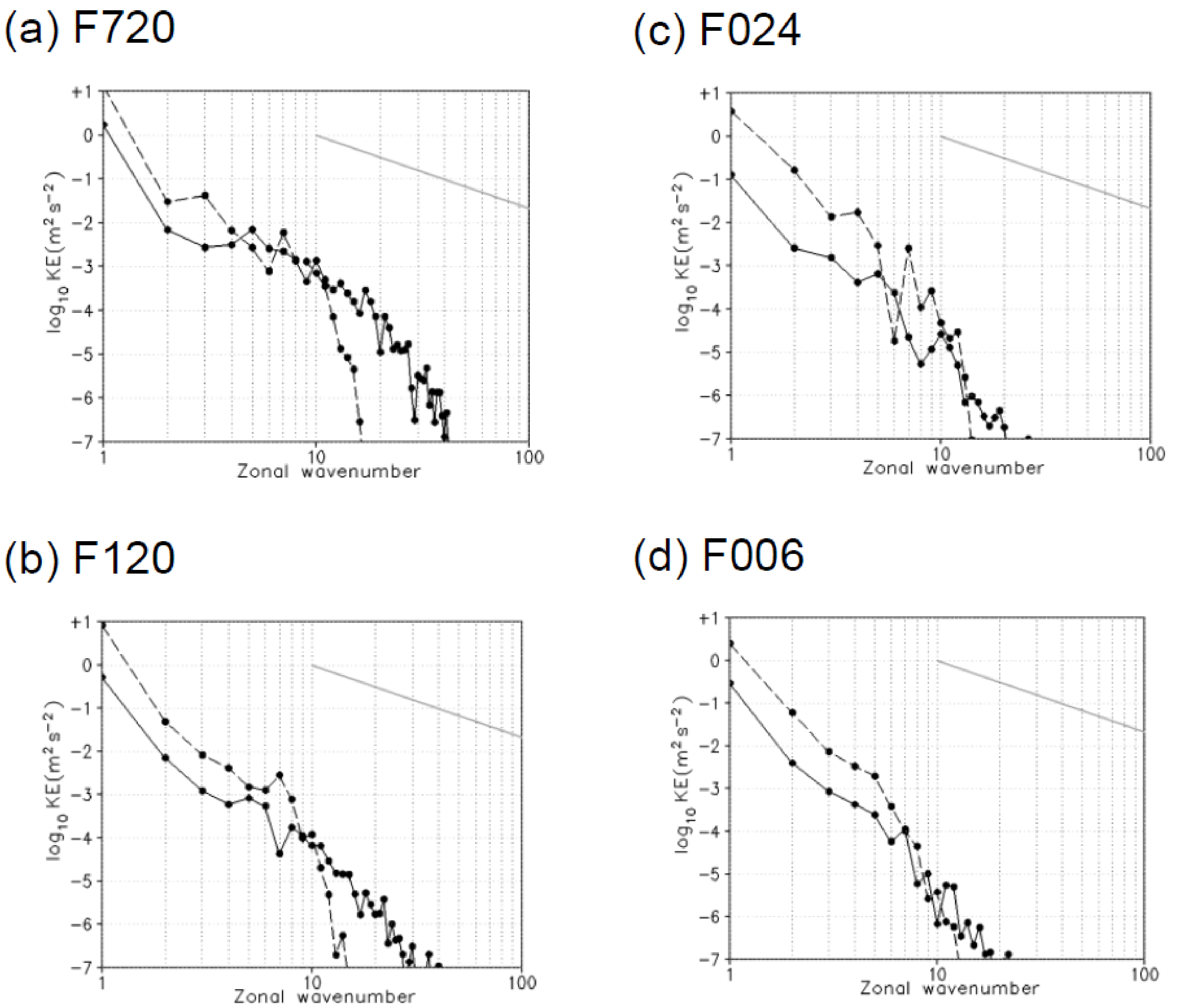
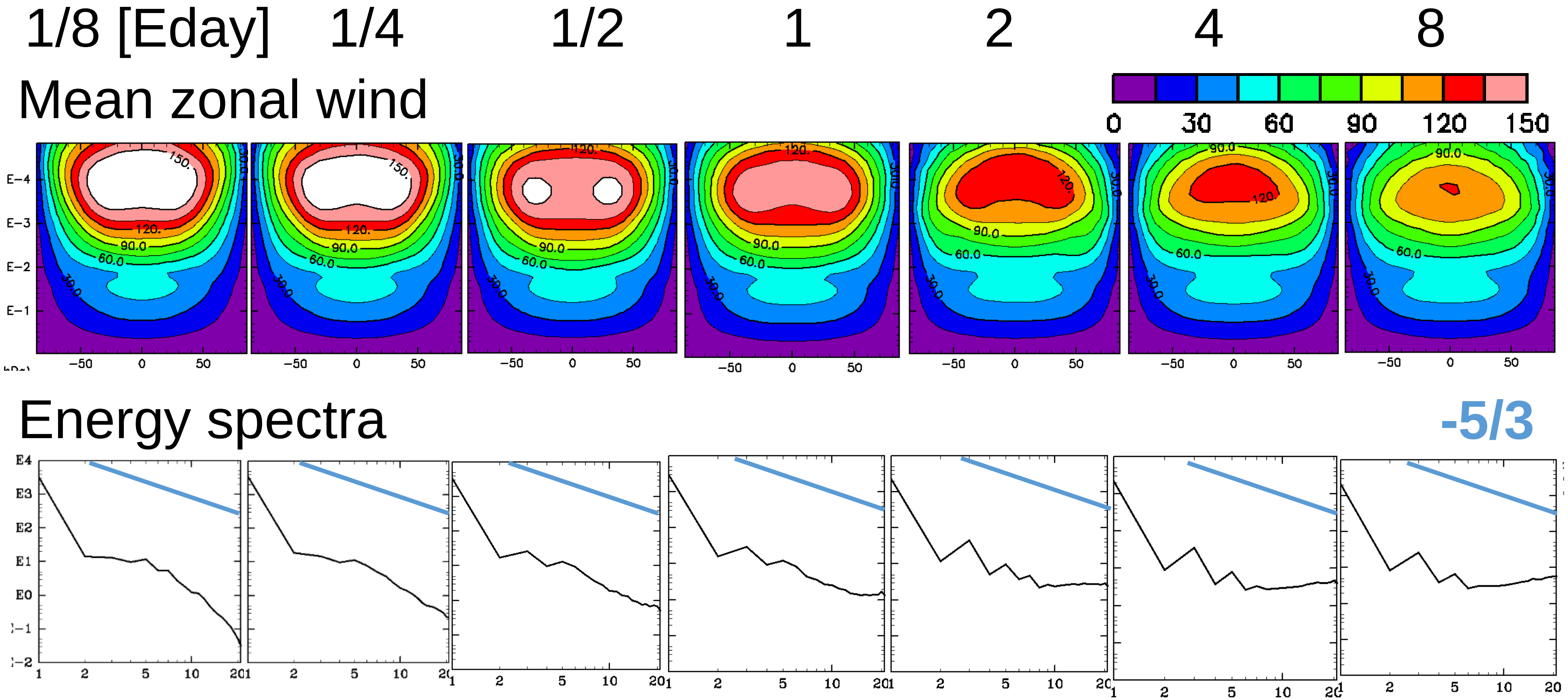


Figure S6. Spectra of kinetic energy with respect to zonal wavelength at latitudes of 1.40° (solid line) and 73.9° (dashed line) at 5.35×10^{4} Pa (~55 km) in (a) F720, (b) F120, (c) F024, and (d) F006. The gray straight lines in the right panels represent the –5/3 slope.

Dependence on the horizontal diffusion in T21 (AFES-Venus)

- Relaxation time for horizontal diffusion（∇^4）to the highest wavenumber



At least in low-resolution, SR depends on the strength of horizontal diffusion.

This study

- Sensitivity check of SR
  - with several cases of the horizontal diffusion (Hd)

- There are robust regions of SR
  - spectral analysis
  - with higher resolution

- Including thermal tides (wo. Yamamoto & Takahashi 2022, Sugimoto+2019)
  - may need for larger horizontal diffusion

Experimental setting

- **AFES-Venus** (Atmospheric GCM for the Earth Simulator for Venus)
  - Resolution: T42L60 (128 × 64 × 60) & T159L120 (480 × 240 × 120)
  - Initial state: idealized SR (*but also SR is reproduced from motionless state*)
  - Solar heating: Tomasko (1980), Qt / Qz (with/wo thermal tide)
  - Infrared radiation: Newtonian cooling based on Crisp (1986)

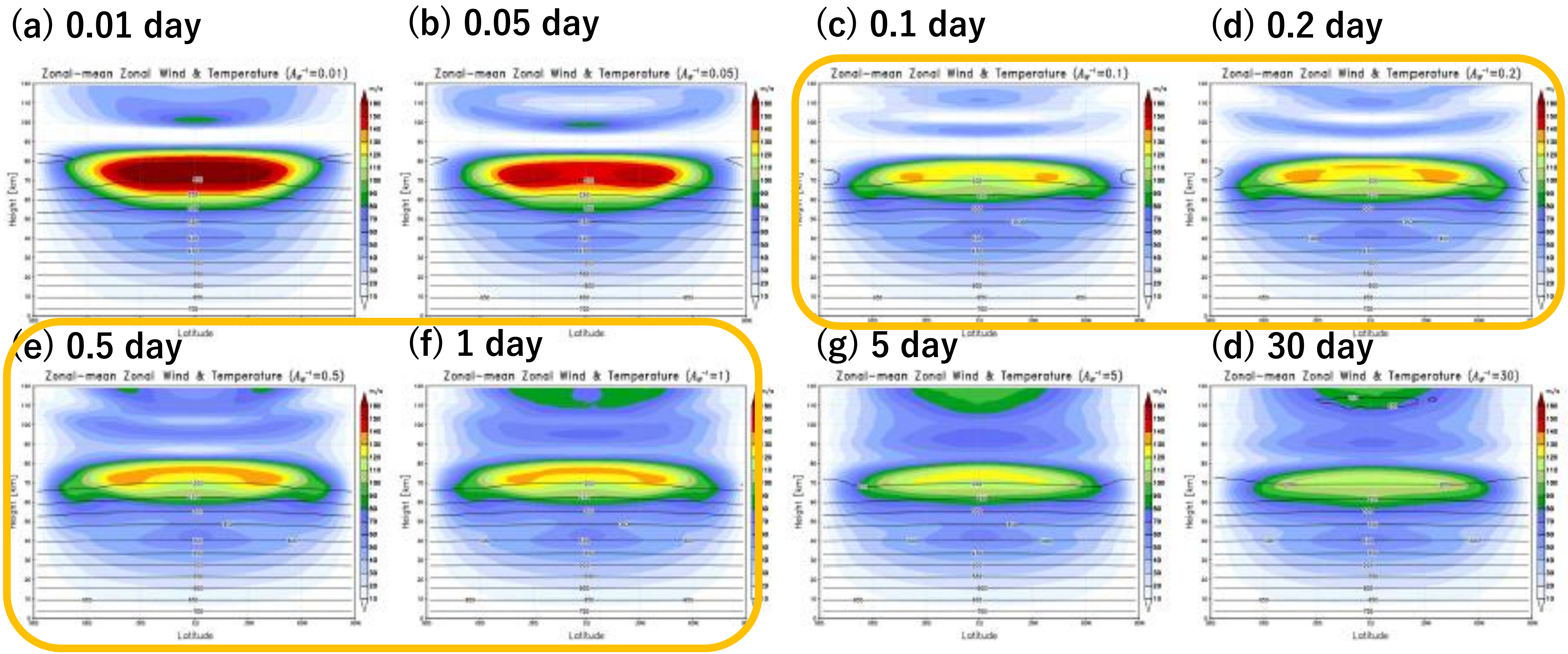
  - T42Qt: 8 cases of horizontal diffusion from 0.01 to 30 days.

  - T159Qt: 12 cases of horizontal diffusion from 0.0001 to 1 day.

  - *T42Qz: 8 cases of horizontal diffusion from 0.01 to 30 days.*

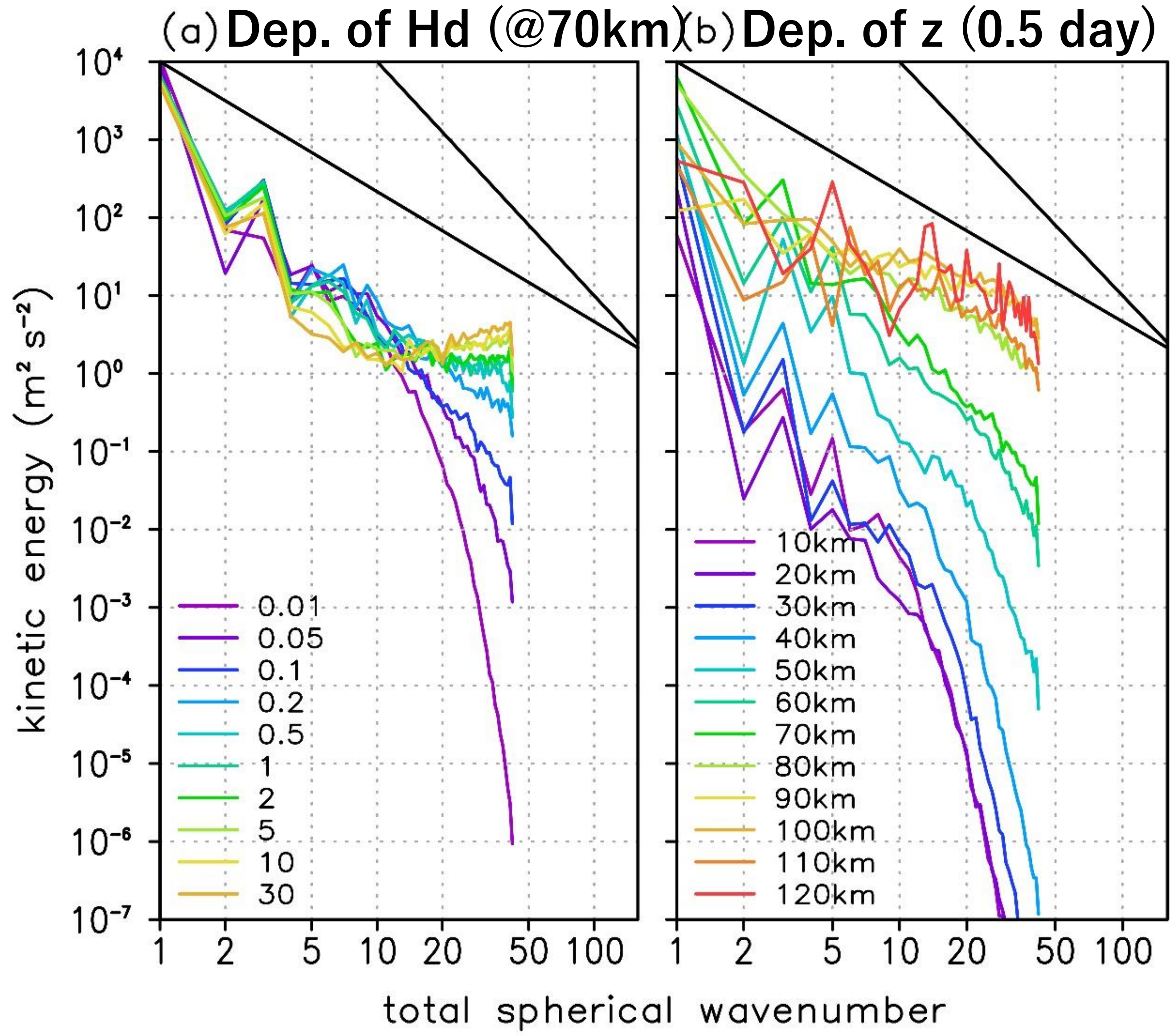
The second-order hyper diffusion (Laplacian squared) term with a diffusion coefficient; ν, $\nu\Delta^2 = \nu\nabla^4$

Results (T42Qt); Zonal mean zonal flow in latitude-height



From 0.1 to 1 day, SR is almost robust: independent of the horizontal diffusion

Results (T42Qt): Spectral analysis



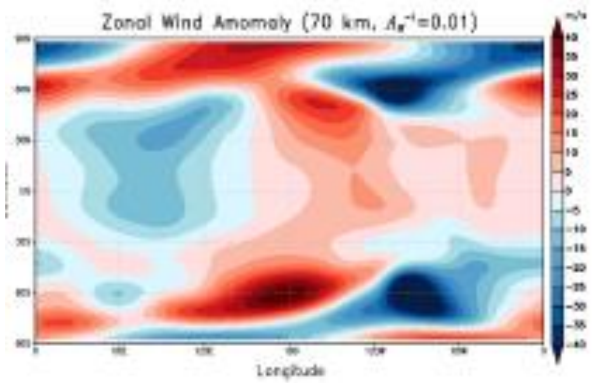
From 0.1 to 1 day, it might be OK at 70 km.

But accumulation in small-scales may appear at higher altitude for 0.5 day.

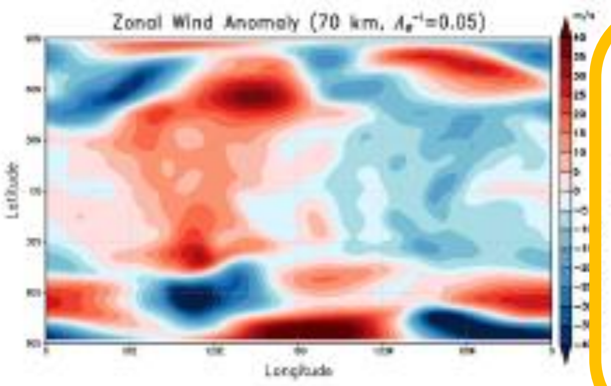
Too strong horizontal diffusion (0.01 or 0.05 day) will cause some dissipation in large-scales.

Results (T42Qt): Horizontal section (U) at 70 km

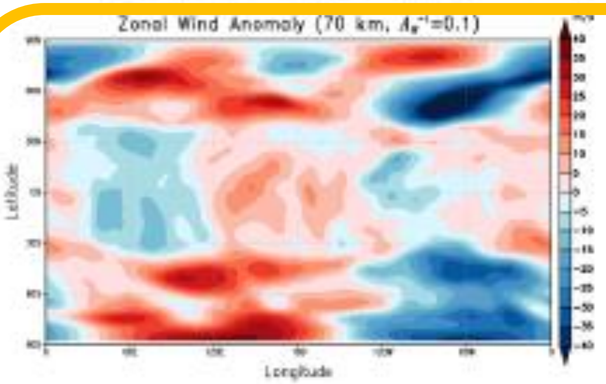
(a) 0.01 day



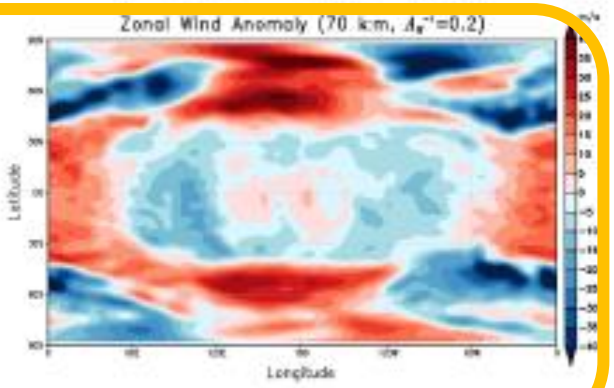
(b) 0.05 day



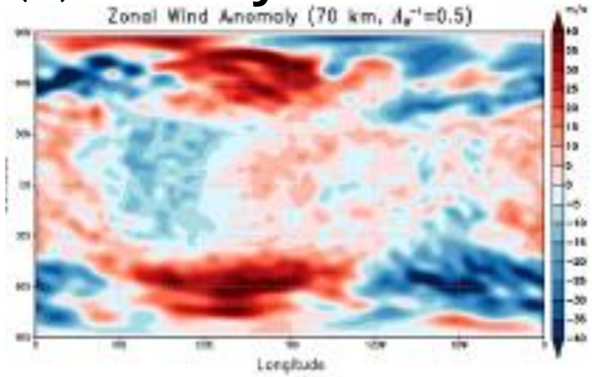
(c) 0.1 day



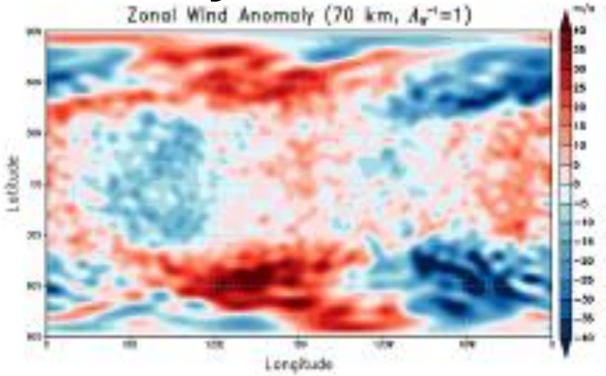
(d) 0.2 day



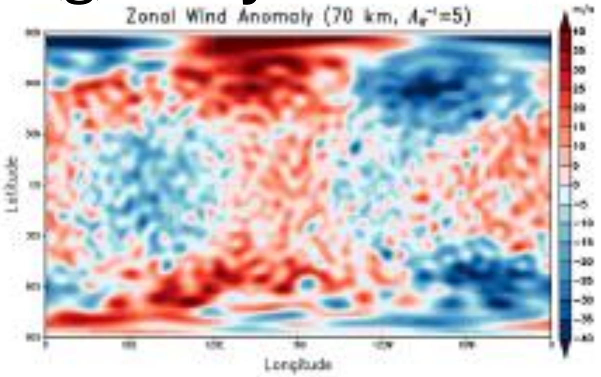
(e) 0.5 day



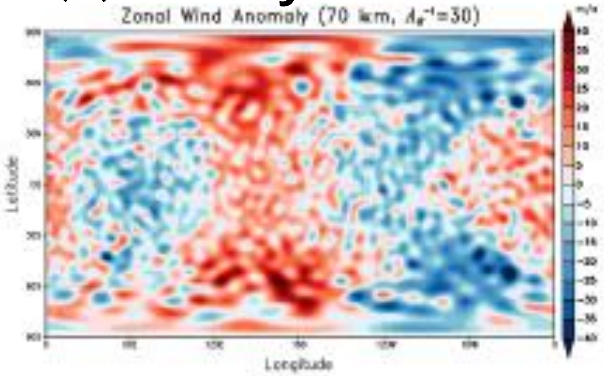
(f) 1 day



(g) 5 day

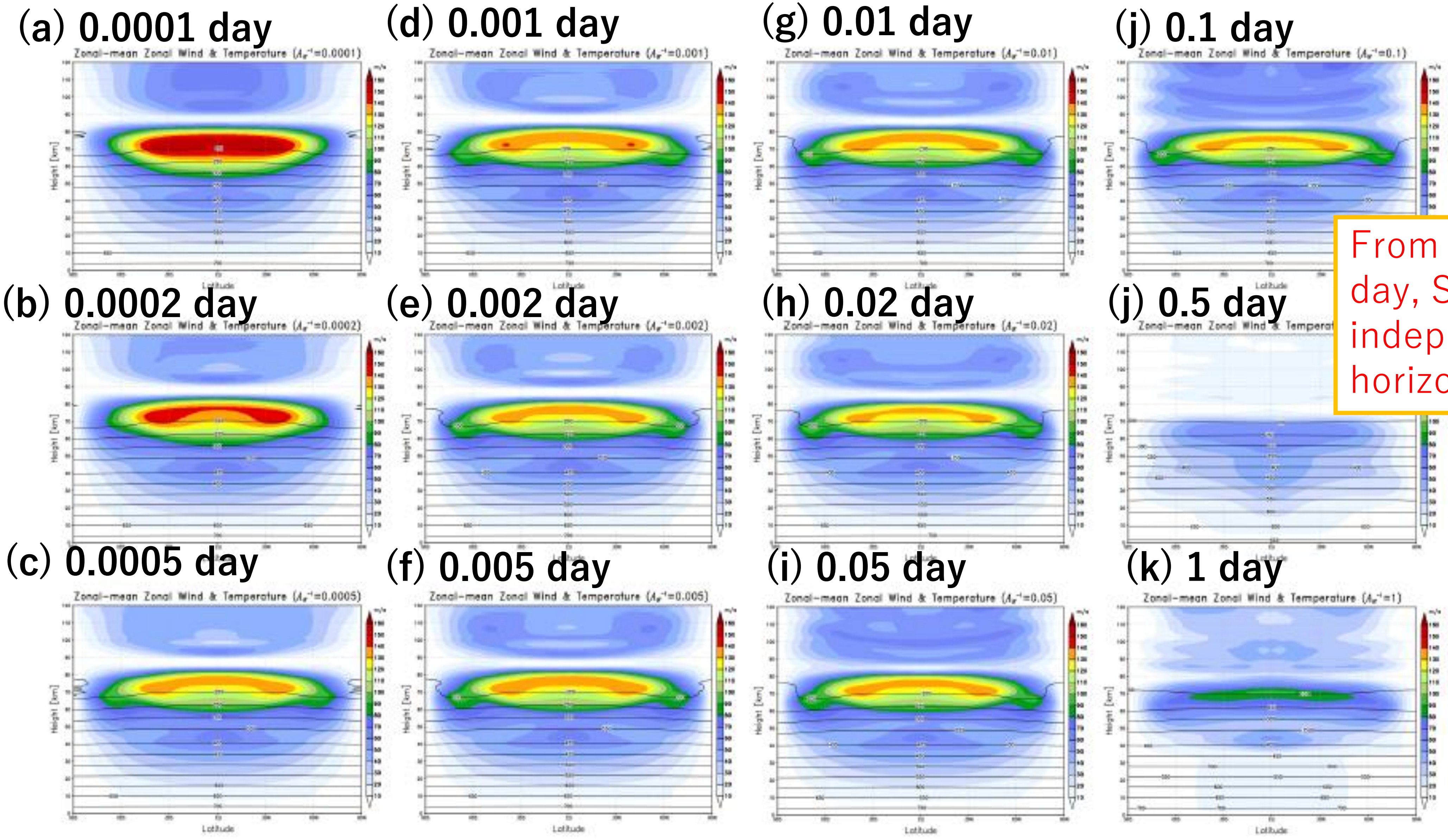


(d) 30 day



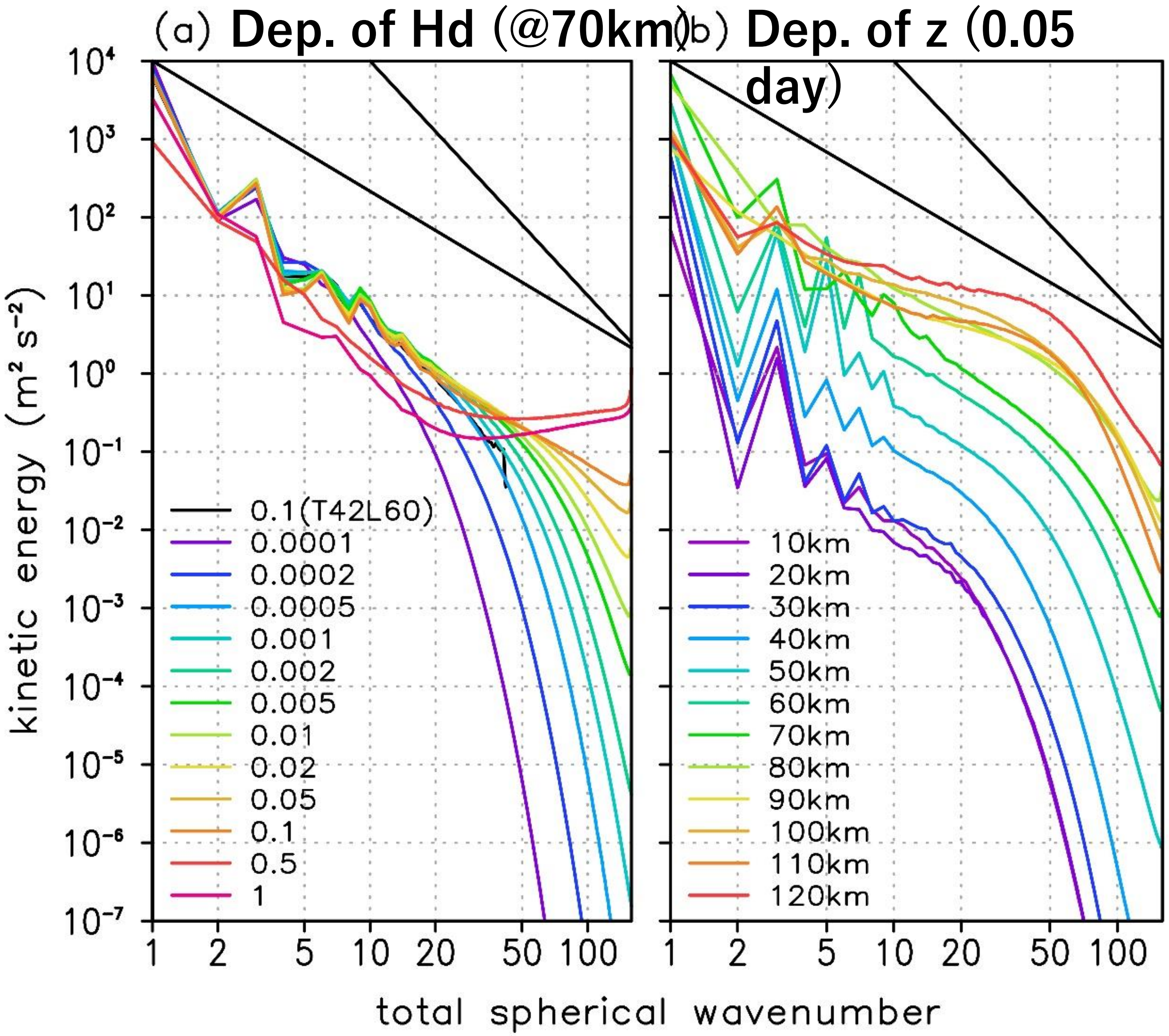
0.1 day would be the best choice

Results (T159Qt): Zonal mean zonal wind in lat-z



From 0.0005 to 0.1 day, SR is robust: independent of horizontal diffusion

Results (T159Qt): Spectral analysis



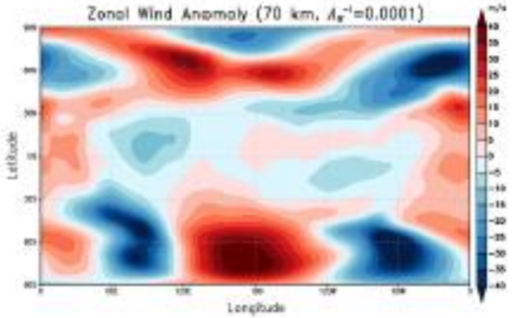
From 0.0005 to 0.1 day, it might be OK at 70 km.

Black line of T42L60 (T42Qt) is mostly overlapped to the good cases of T159Qt.

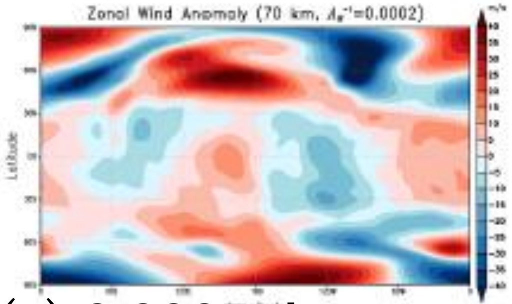
Too strong horizontal diffusion (0.0001 or 0.0002 day) will cause some dissipation in large-scales.

Results (T159Qt): Horizontal section (U) at 70 km

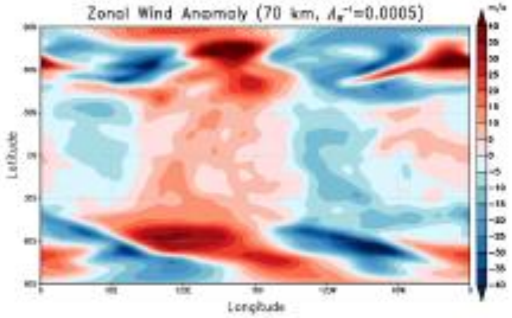
(a) 0.0001 day



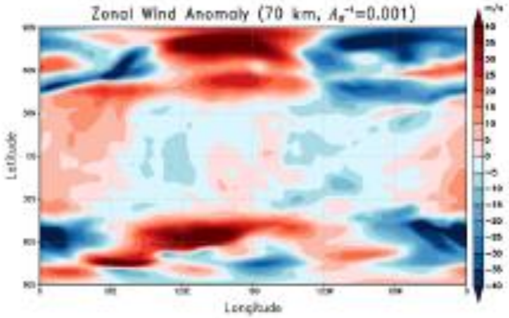
(b) 0.0002 day



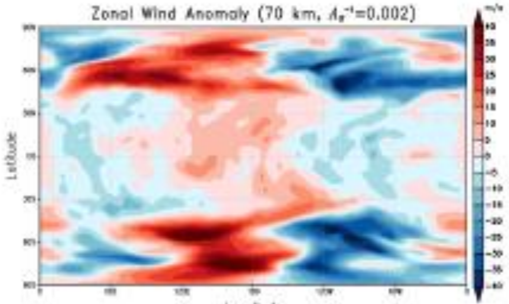
(c) 0.0005 day



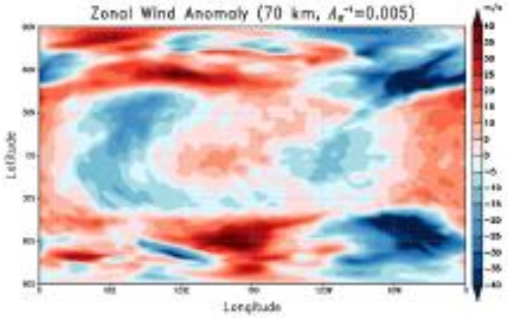
(d) 0.001 day



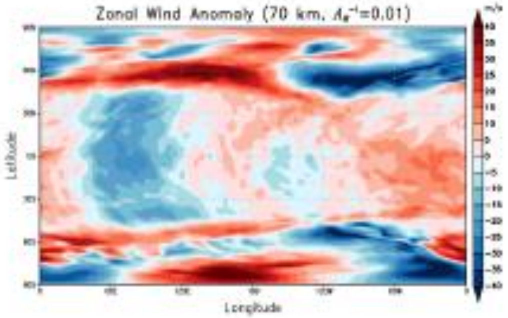
(e) 0.002 day



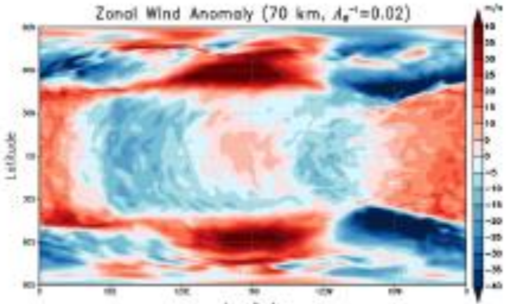
(f) 0.005 day



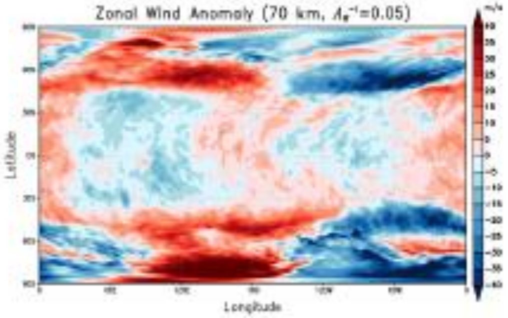
(g) 0.01 day



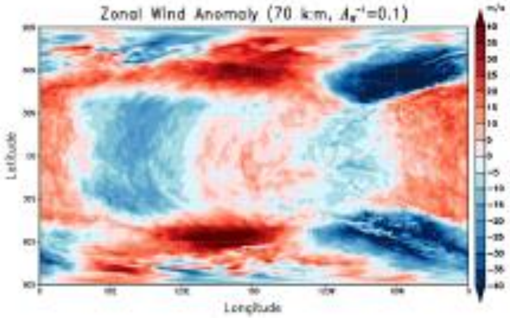
(h) 0.02 day



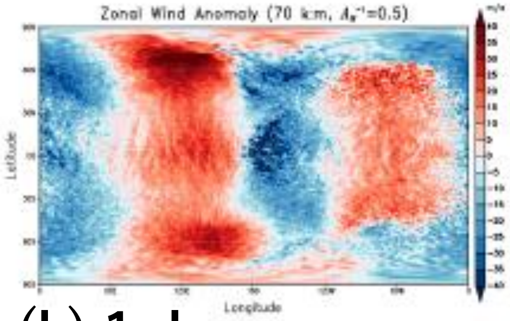
(i) 0.05 day



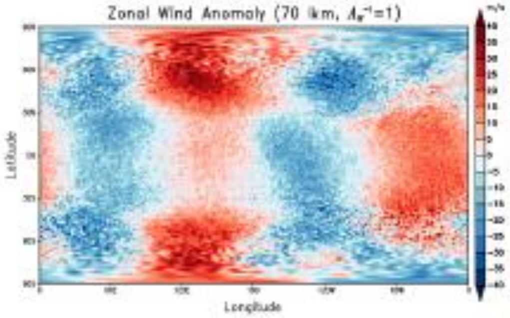
(j) 0.1 day



(j) 0.5 day



(k) 1 day



0.01 day in Kashimura (2019) would be good.

Discussion

- The expressions of the horizontal diffusion (Hd);

$$\mathcal{D}(\zeta) = K_{MH}\left[(-1)^{N_D/2}\nabla^{N_D} - \left(\frac{2}{a^2}\right)^{N_D/2}\right]\zeta$$

$$\mathcal{D}(\delta) = K_{MH}\left[(-1)^{N_D/2}\nabla^{N_D} - \left(\frac{2}{a^2}\right)^{N_D/2}\right]\delta$$

$$\mathcal{D}(T) = (-1)^{N_D/2}K_{HH}\nabla^{N_D}T$$

$$\mathcal{D}(q) = (-1)^{N_D/2}K_{EH}\nabla^{N_D}q$$

Second terms are for zonally uniform component to conserve angular momentum.

4th order Hd: Since T159 is 4 times higher resolution of T42, Hd is 4^4~256 times stronger.
Then, T42 with 1 day is comparable to T159 with 0.004 day (both cases are verified).
In contrast, T159 with 0.02 day is comparable to T42 with 5 day (T42 case is not reliable).

Summary

- We investigated how the super-rotation depends on the magnitude of horizontal hyper diffusion using a Venus GCM (AFES-Venus) with medium (T42L60) and high (T159L120) resolutions.

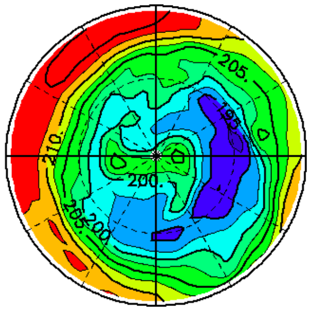
✓ In both the runs, we found **a parameter range where the structure of fully developed super-rotation is almost independent of the magnitude of horizontal diffusion.**

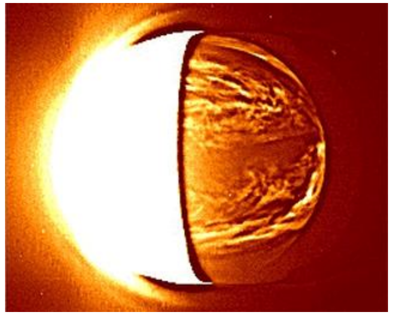
✓ Spectral analysis shows that unrealistically strong super-rotation is developed when medium-scale disturbances are dissipated by stronger horizontal diffusion.

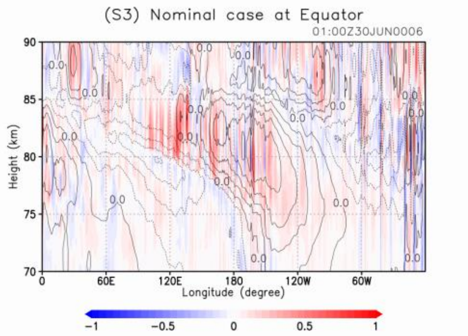
✓ On the other hand, artificially weak super-rotation is also realized because spurious small-scale disturbances are accumulated when the horizontal diffusion is too weak.

We should carefully check the magnitude of horizontal diffusion by the spectral analysis and higher resolution runs before conducting Venus GCM simulations.

Recent progress







- **AFES-Venus** (Atmospheric general circulation model For the Earth Simulator for Venus)
- ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
- ✓ Resolution: T42L60 to T639L260 (Δx〜20 km Δz〜0.25 km)…
- ✓ Rayleigh friction: lowest and above 80 km (sponge layer except for zonal flow)
- ✓ No topography and planetary boundary layer
- ✓ Simplified Solar heating based on Tomasko et al. (1980)
- ✓ Simplified Infrared radiative process by Newtonian cooling based on Crisp (1986)
- ✓ Idealized initial super rotation with realistic temperature (static stability) distribution
- **16 papers**: Baroclinic instability (Sugimoto+2014, JGR & GRL), Polar vortex with cold collar (Ando+2016, Ncom; 2017, JGR), Thermal tide (Takagi+2018, JGR; Suzuki+2022, JGR), Planetary scale streak structure (Kashimura+2019, Ncom), Super rotation (Sugimoto+2019, GRL), Static stability (Ando+2020, SciRep; 2022, JGR), Gravity wave from thermal tide (Sugimoto+2021, Ncom), 4-day and 5-day waves (Takagi+2022, JGR), Cloud physics (Ando+2020, 2021, JGR)…

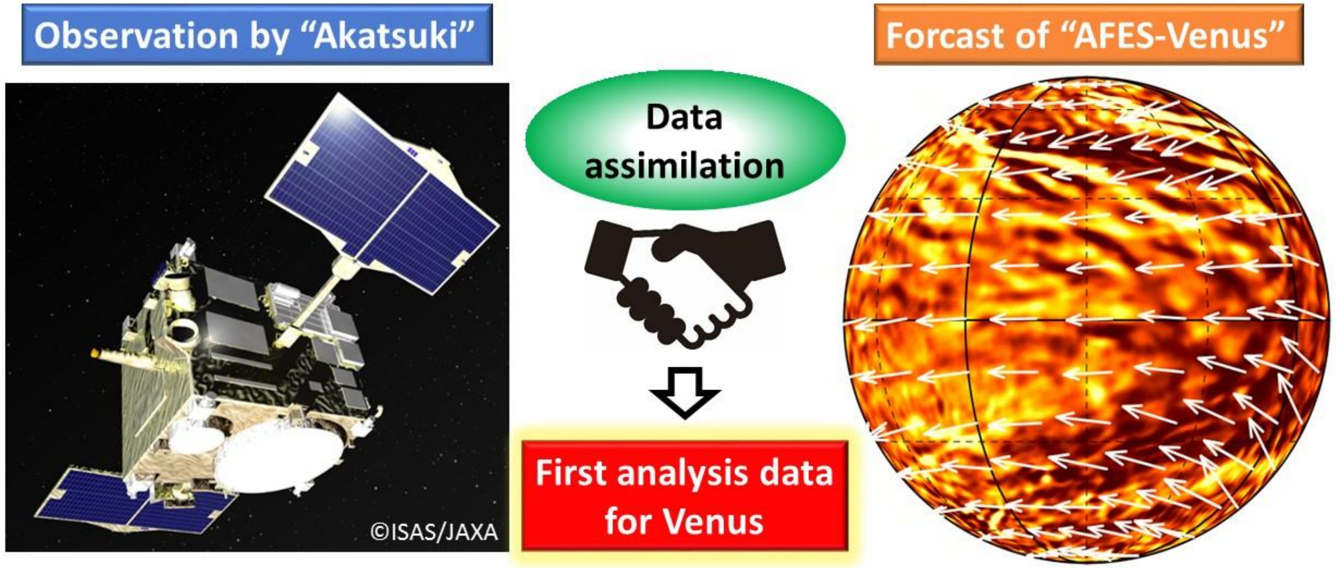
Recent progress (cont.)

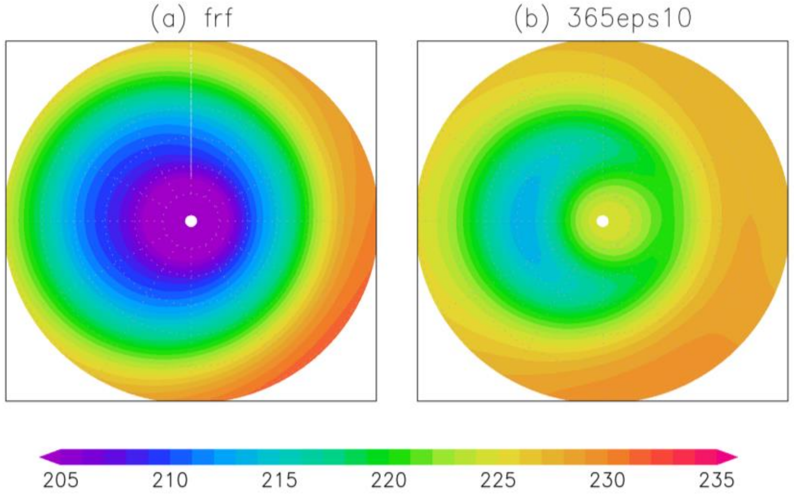
*Local Ensemble Transform Kalman Filter
#Observing System Simulation Experiment

- **ALEDAS-V** (AFES LETKF* Data Assimilation System for Venus)

✓ First data assimilation system for the Venus atmosphere

- **9 papers**: First check (Sugimoto+2017, SciRep), Vex UVI wind (Sugimoto+2019, GRL), OSSE# for cross-link radio occultation (Sugimoto+2020, JSCE, Fujisawa+2023, Icarus), OSSE for Kelvin wave (Sugimoto+2021, 2022, Atmos.), First analysis of Akatsuki UVI wind (Fujisawa+2022, SciRep), OSSE for Akatsuki LIR temperature (Sugimoto+2022, GeoSciLett), Cold collar (Ando+2023, JGR)…





Horizontal diffusion is expressed by the second-order hyper diffusion (Laplacian squared) term with a diffusion coefficient ν, $\nu\Delta^2 = \nu\nabla^4$. If we consider 1 dimensional case for simplicity, it is expressed by $\nu\left(\frac{\partial^4}{\partial x^4}\right)$. Let λ as the wavelength for the maximum wavenumber, the damping time for the maximum wavenumber component, τ, is calculated by $\frac{1}{\tau} \sim \nu\frac{1}{\lambda^4}$. Then, the diffusion coefficient can be written by $\nu \sim \frac{\lambda^4}{\tau}$. Therefore, for the same value of τ, the diffusion coefficient is proportional to λ^4. Then, in case the horizontal resolution is doubled (i.e., the wavelength for the maximum wavenumber component is halved), the horizontal diffusion coefficient is 2^4 times smaller than the original case. Similarly, because T159 is 4 times higher horizontal resolution of T42, horizontal diffusion is $4^4 \sim 256$ times smaller than the original case.

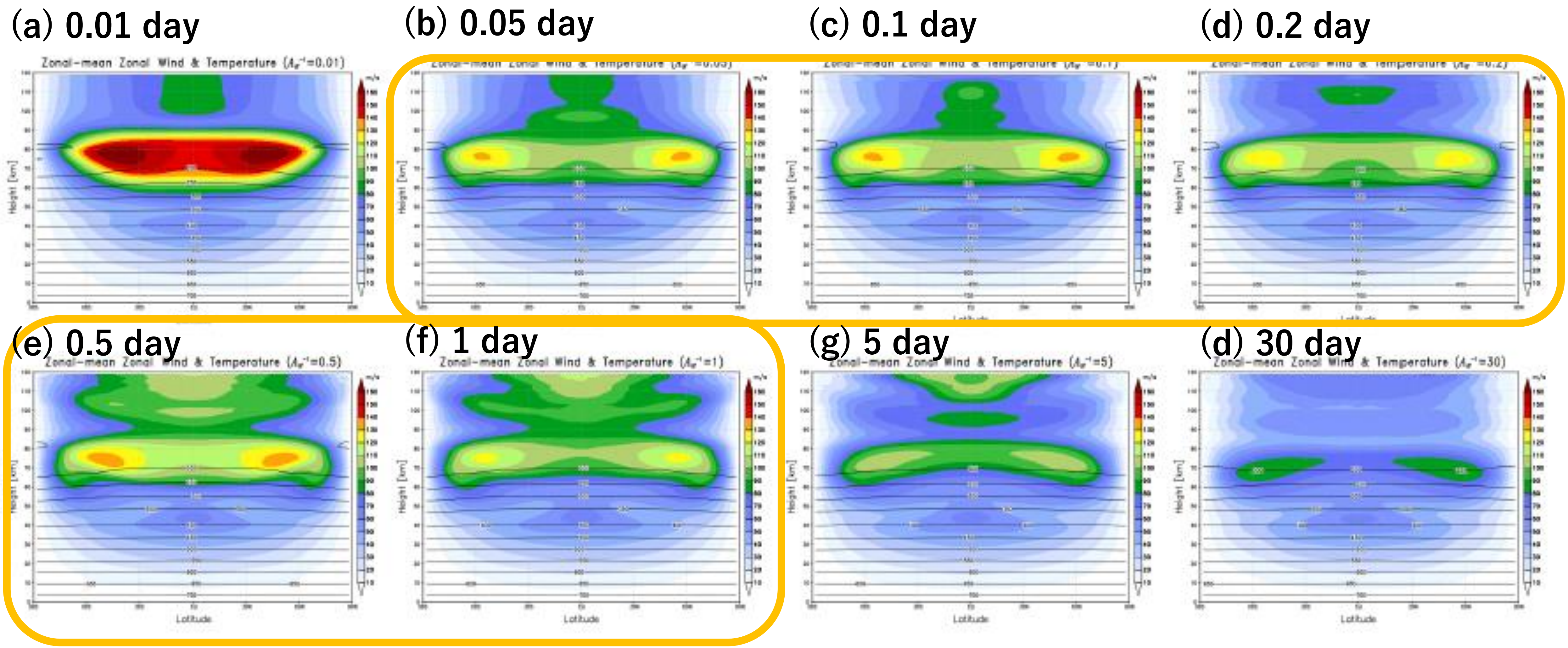
S4 Calculation of diffusion coefficient

Generally, the solution of $\frac{\partial X}{\partial t} = -DX$ is $X = e^{-Dt}$. Then, if $D > 0$, X exponentially decays by a factor of $1/e$ with a time interval of $1/D$. If we define K as a diffusion coefficient, the horizontal diffusion term in the spectral space is expressed by $\frac{\partial X_n^m}{\partial t} = -K\Delta^2 X_n^m = -K\left(-\frac{n(n+1)}{a^2}\right)^2 X_n^m$, where $a = 6052$ [km] is the radius of the Venus and m, n are zonal and total wavenumbers, respectively. Here, we determine the value of K by setting the damping time of 0.1 Earth days ($1/D = 0.1$ [Earth days] $= 2.4$ [h]) so that X decays by a factor of $1/e$ at the maximum wavenumber $N = 42$. Since $D = K\left(-\frac{N(N+1)}{a^2}\right)^2$, K can be estimated by

$$K = \frac{D}{\left(-\frac{N(N+1)}{a^2}\right)^2} = \frac{\frac{1}{(2.4 \times 60 \times 60)}}{\left(-\frac{42(43)}{(6052 \times 10^3)^2}\right)^2} \sim 4.8 \times 10^{16}\ [\mathrm{m}^4/\mathrm{s}]$$

＊T 42 L 60の4年積分；最後の1年(360データ)分を平均した東西平均風(Qt)

Results (T42qz)　zonal mean zonal flow in lat-z

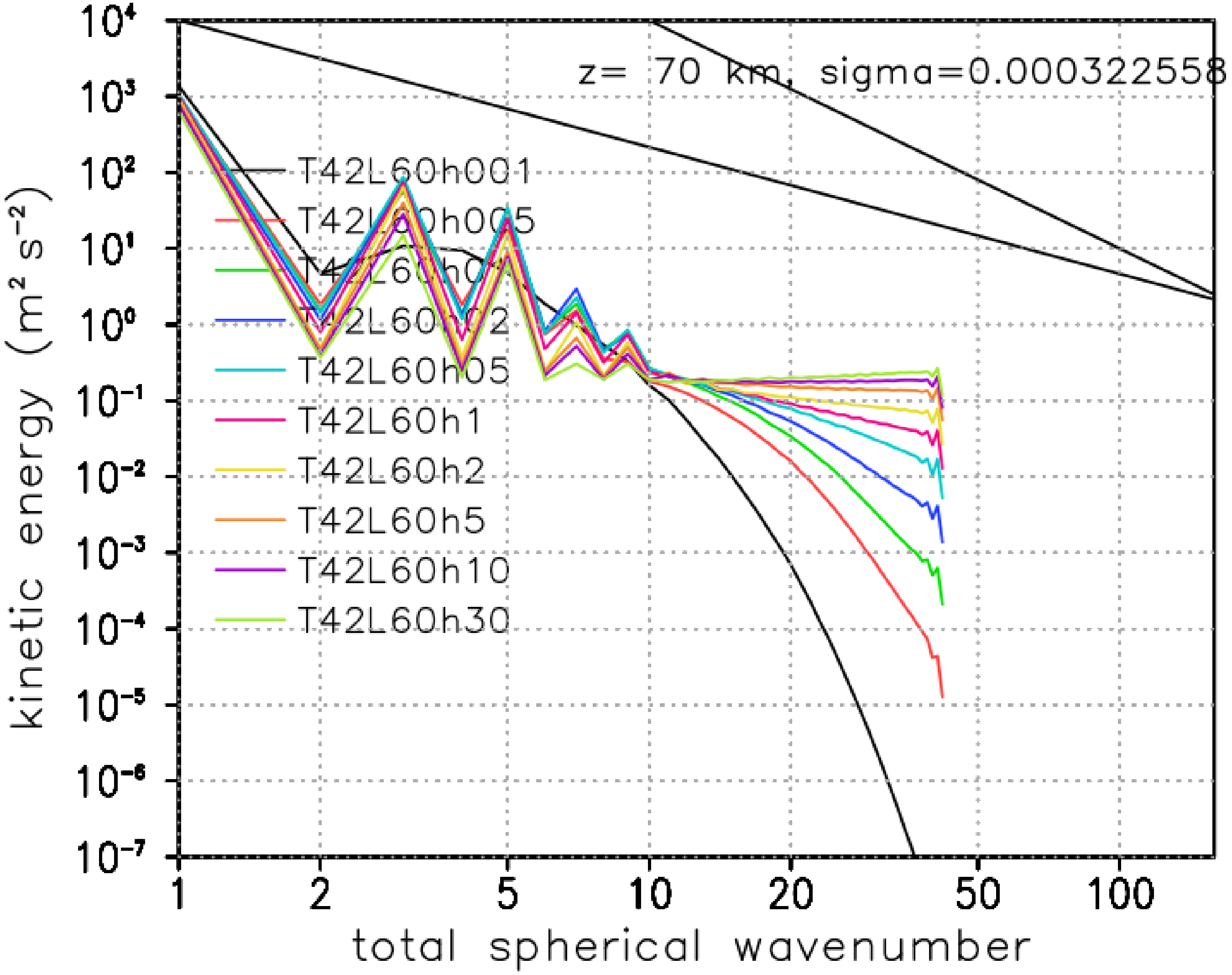


From 0.05 to 1 day SR is robust: independent of horizontal diffusion

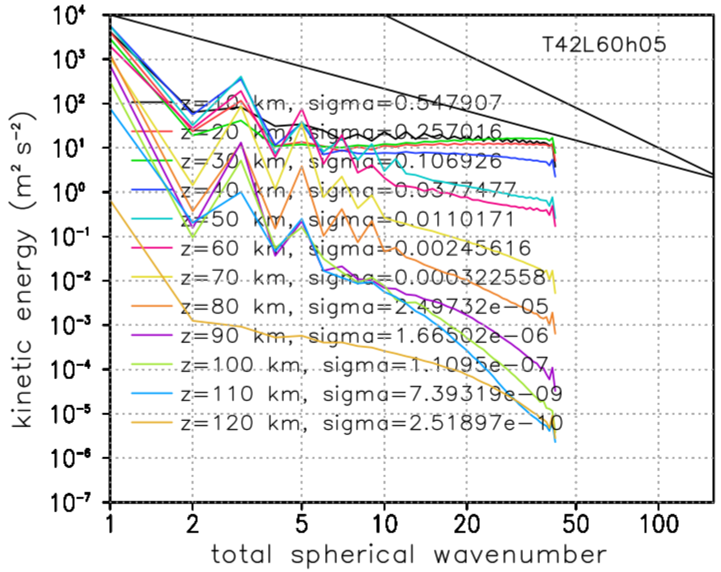
*最後の一年平均

Results (T42qz) spectral analysis

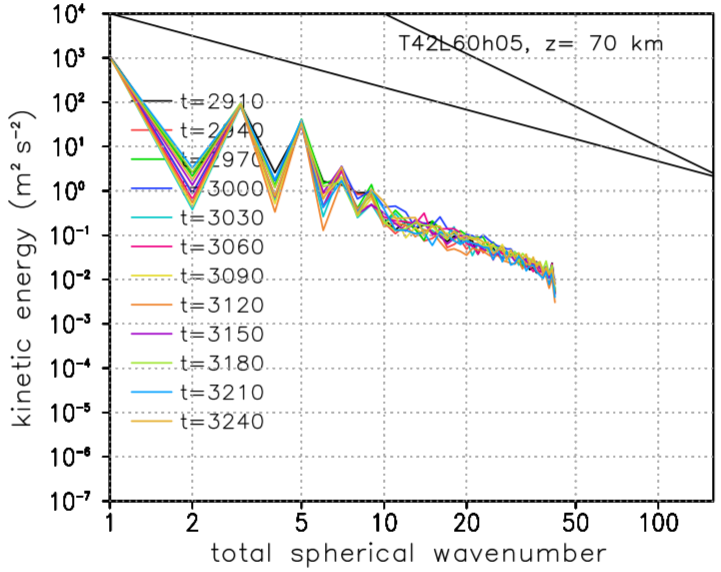
(a) Dep. of hd (@70km)



(b) Dep. of z (0.5 day)



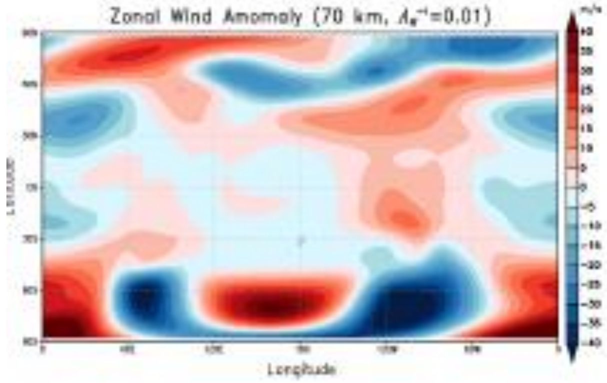
(c) Dep. of t (0.5 day)



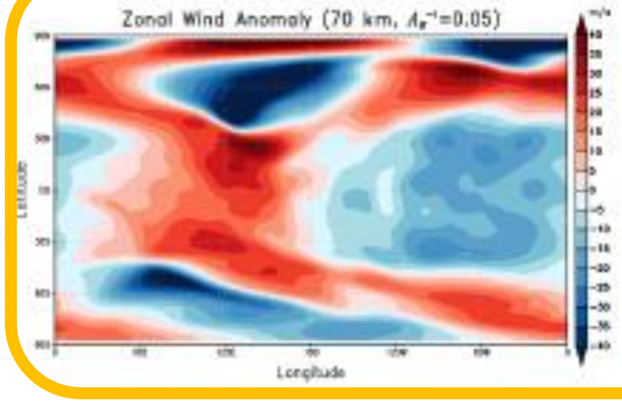
*最終日のスナップショット：高波数の溜まりを確認

Results (T42qz)　horizontal section at 70 km

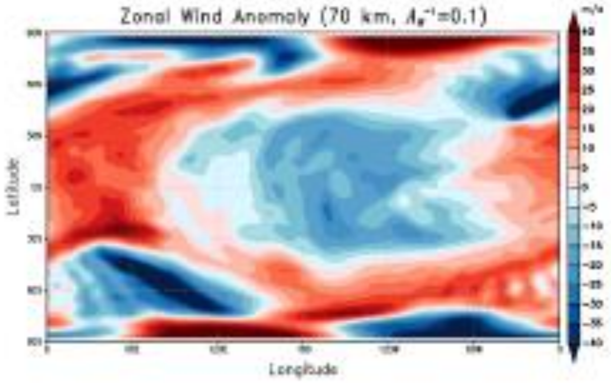
(a) 0.01 day



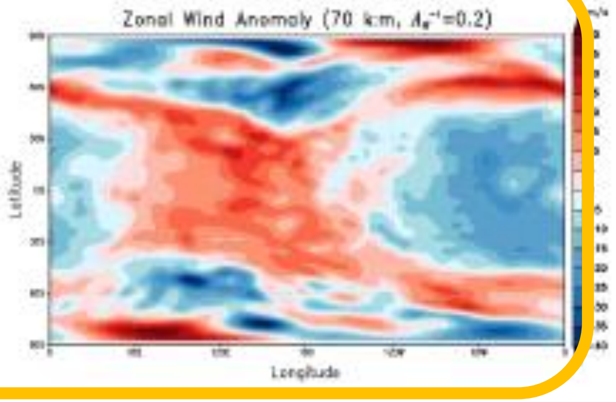
(b) 0.05 day



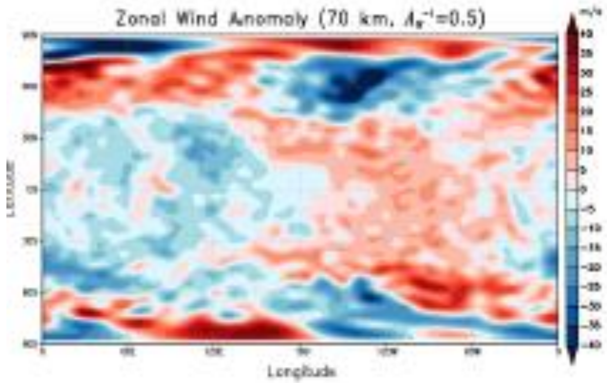
(c) 0.1 day



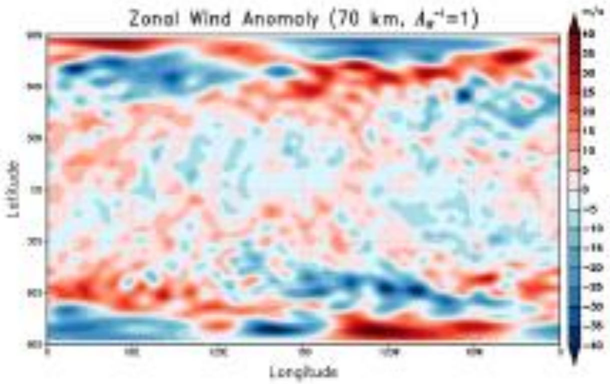
(d) 0.2 day



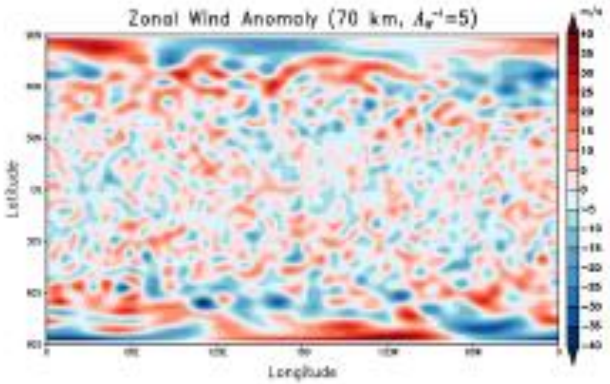
(e) 0.5 day



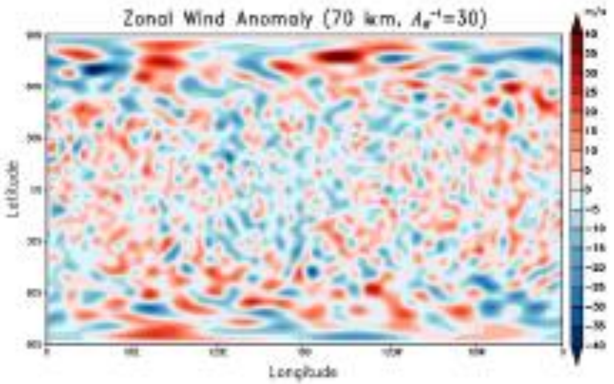
(f) 1 day



(g) 5 day



(d) 30 day



0.1 would be the best choice