KEIO UNIVERSITY
PSII-63

# AFES (GCM) LETKF Data Assimilation System for Venus

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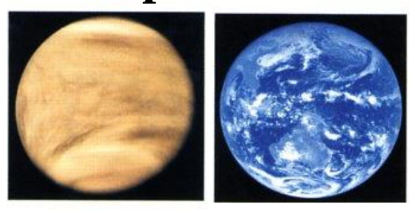
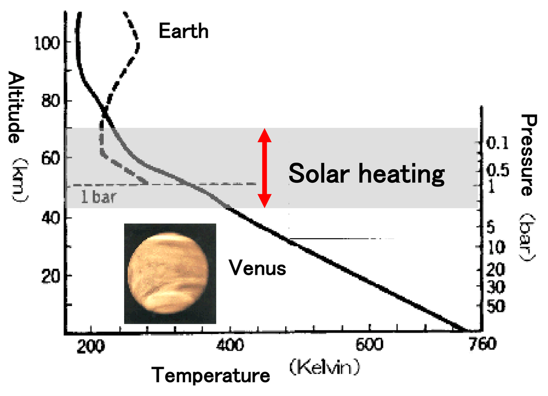
## 1. Introduction

### Venus atmosphere: Fast zonal flow (Super-rotation; SR)

Ultra-Violet image



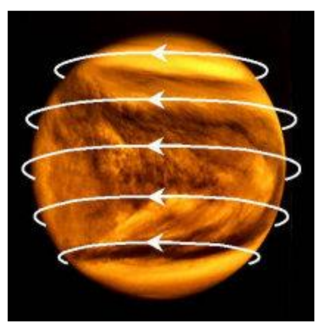
| | Venus | Earth |
|---|---|---|
| Radius | 6050 km | 6378 km |
| Revolution | 224 days | 365 days |
| Rotation | 243 days (1.8m/s) | 1 day (460m/s) |
| 1 solar day | 117 days | 1 day |
| Composition | $CO_2$ | $N_2$, $O_2$ |
| Albedo | 0.78 | 0.3 |
| Surface pres. | 92 bar | 1 bar |

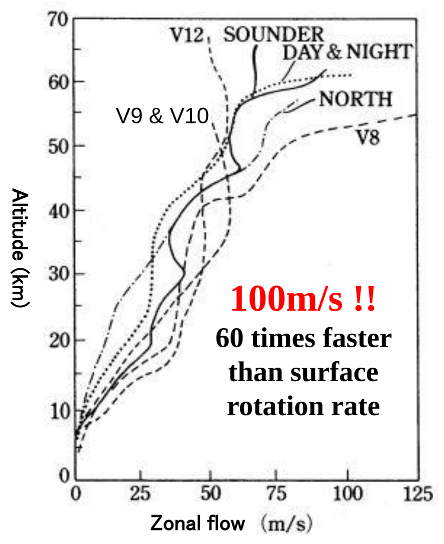



- ✓ Very slow rotation
- ✓ Dense $CO_2$ atmosphere
- ✓ Thick cloud layer (45∼70km)

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)

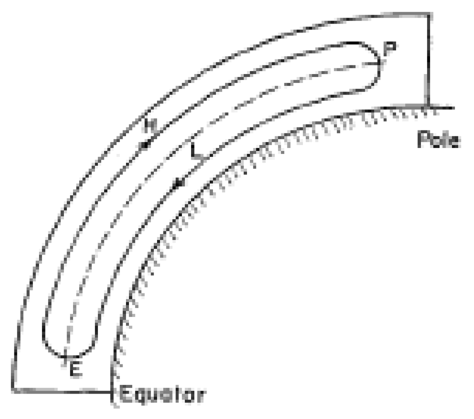





Schubert et al. (1980)

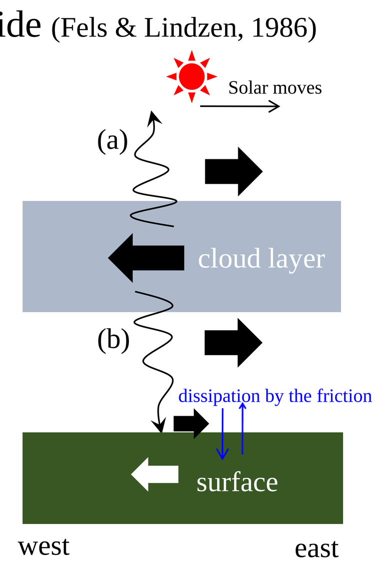
### Mechanism of the super rotation (reproduced in VGCM)

1. Mean meridional circulation MMC (Gierasch 1975)

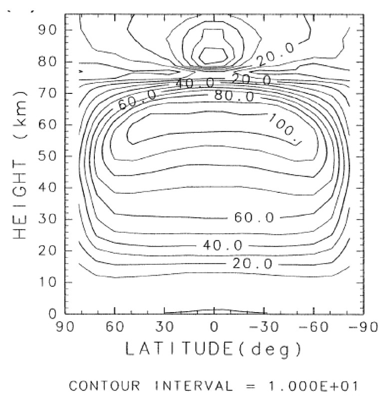



- ✓ Vertical transport by MMC
- ✓ Horizontal transport by eddies

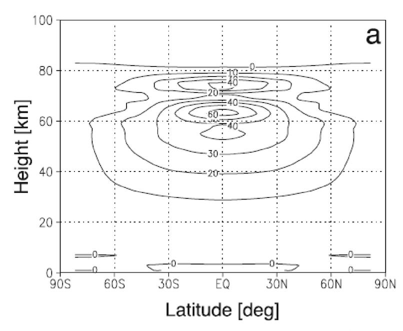
2. Thermal tide (Fels & Lindzen, 1986)




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



Yamamoto & Takahashi (2003)

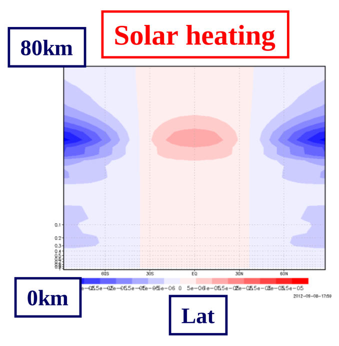


Takagi & Matsuda (2007)

## 2. AFES-Venus (Atmospheric GCM For the Earth Simulator for Venus)

### Model description

- ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
- ✓ Resolution: T42L60, T159L120 to T639L260 (Δx∼20km Δz∼0.25km)…
- ✓ Specific heat: Cp is constant (1000 $Jkg^{-1}k^{-1}$)
- ✓ Horizontal hyper-viscosity: 0.1 (T42) to 0.001 (T639) Earth days for 1/e
- ✓ Vertical eddy viscosity: 0.15 – 0.0015 $m^2s^{-1}$; 10 values
- ✓ Rayleigh friction: lowest and above 80 km (sponge layer except for zonal flow)
- ✓ No topography and planetary boundary layer + cloud physics

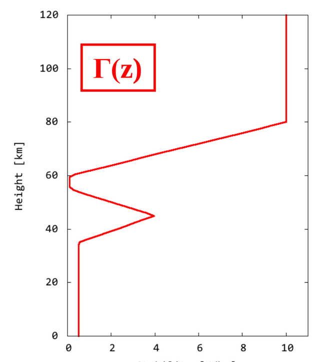



### Solar heating

- ✓ Zonal and/or diurnal component of realistic heating (Tomasko et al.,1980; Crisp, 1986)

### Infrared radiative process

- ✓ Simplified by Newtonian cooling: dT/dt = –κ (T–Tref(z)), κ: based on Crisp (1986)
- ✓ Tref(z): horizontally uniform field but realistic vertical profile of static stability



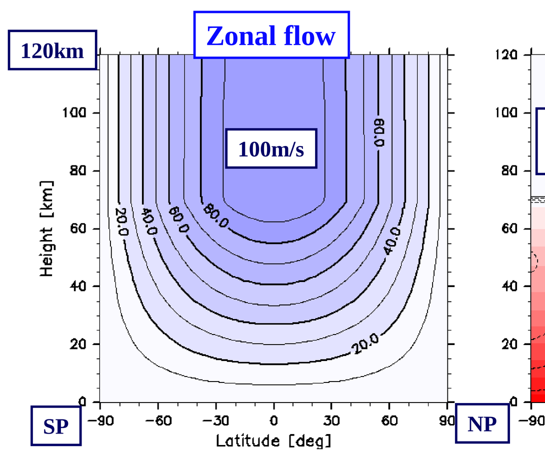

### Initial condition

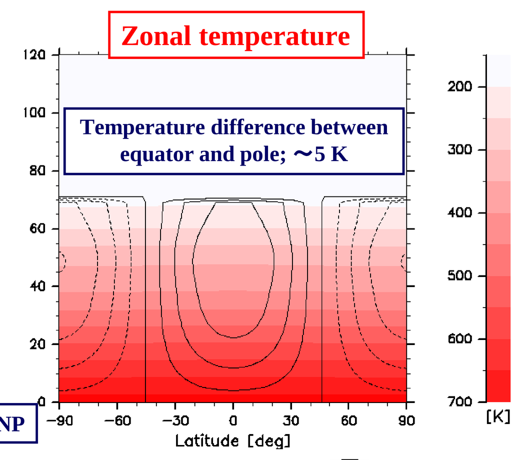
① Motionless state

- Mimic observed temperature field including cloud layer with low static stability: Γ(z) = dT/dz + g/Cp

② Idealized SR (solid body rotation)

- Zonal flow increases with height linearly from ground to 70 km. 100 m/s above 70 km (const.).
- Temperature field is in balance with zonal flow field (gradient wind balance).



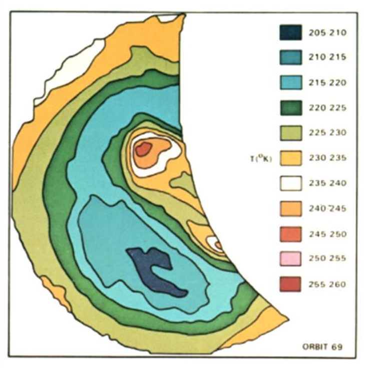

## Strategy

### Start from idealized super rotation

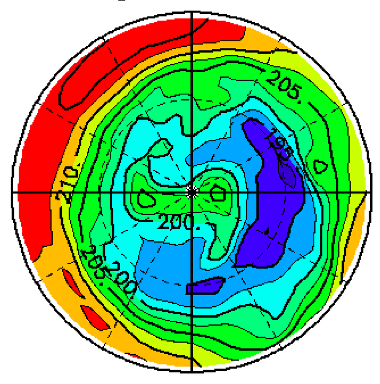
- ✓ Saving computational cost for high resolution run

### Maintain super rotation with realistic setting

- ✓ under the realistic solar heating and static stability without artificial f



Taylor et al. (1980)

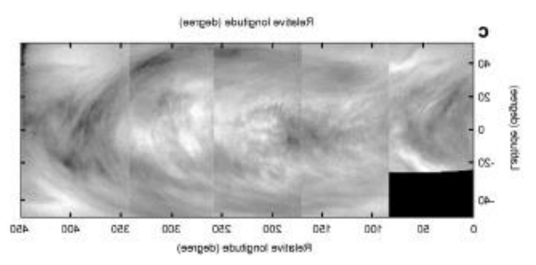


Ando et al. (Nature Com. 2016)

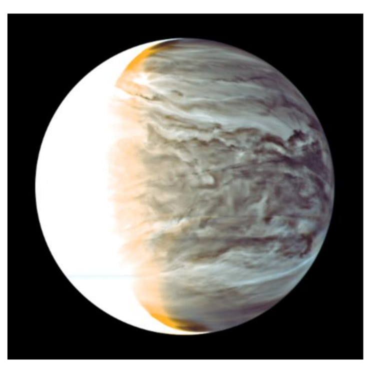
## Targets

### Focus on atmospheric motions near the cloud level

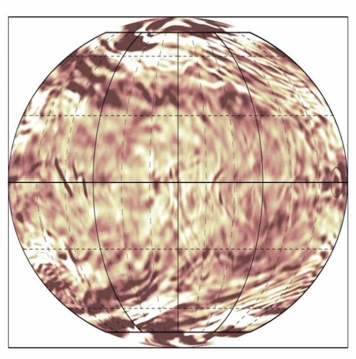
- ✓ Baroclinic instability; Not observed but predicted theoretically (Sugimoto et al., JGR2014)
- ✓ Neutral waves; Observed by cloud images but unexplained (Sugimoto et al., GRL2014)
- ✓ Thermal tide; Elucidate its role, horizontal and vertical structures (Takagi et al., JGR2018)
- ✓ Energy spectra; Traditional analysis on Earth but no Venus case (Kashimura et al., in prep.)
- ✓ Polar vortex; "Axi-asymmetric" structure observed in VIRTIS (Ando et al., JGR2017)
- ✓ Cold collar; Cold latitudinal band not reproduced in GCMs (Ando et al., Nature Com.2016)
- ✓ Planetary scale streak structure... (Kashimura et al., Nature Com. 2019)



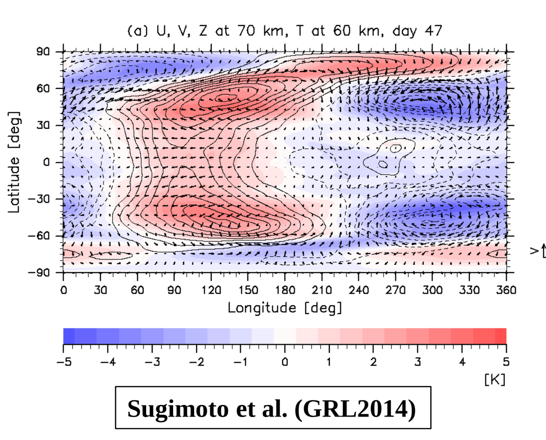
Belton et al. (1991)



Akatsuki Infrared observations



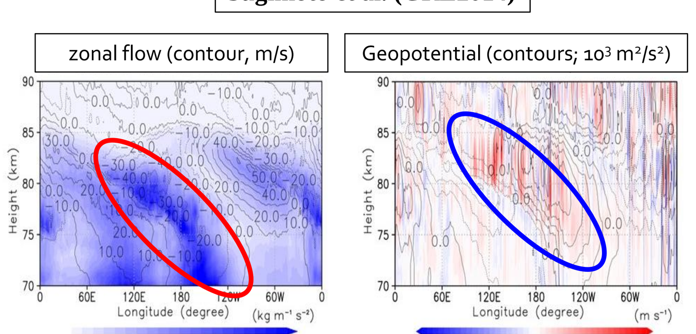
Kashimura et al. (Nature Com. 2019)

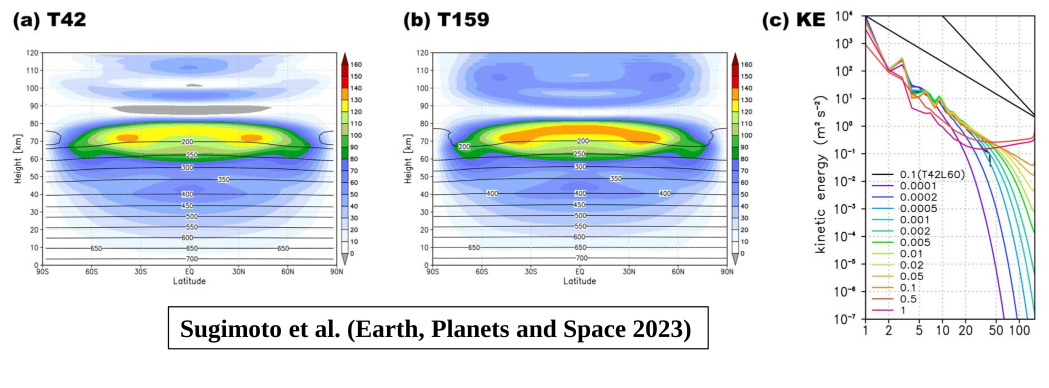



Sugimoto et al. (GRL2014)

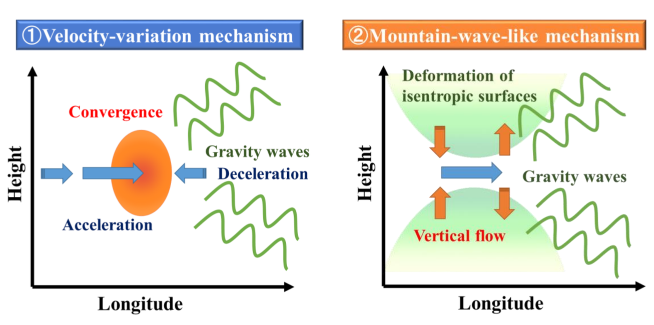
### Recent progress

- ✓ Fully developed super-rotation driven by MMC (Sugimoto et al., GRL2019a)
- ✓ Super-rotation independent of horizontal diffusion (Sugimoto et al., EPS2023)
- ✓ Static stability compared with observations (Ando et al., Sci. Rep.2020, JGR2022)
- ✓ Generation of gravity waves from thermal tides (Sugimoto et al., N.Com., 2021)
- ✓ Implementation of cloud physics and its variation (Ando et al., JGR2020, 2021)
- ✓ Improvement of static stability and thermal tides (Suzuki et al., JGR2022)
- ✓ Reproduction of 4-Day and 5-Day Waves (Takagi et al., JGR2022)



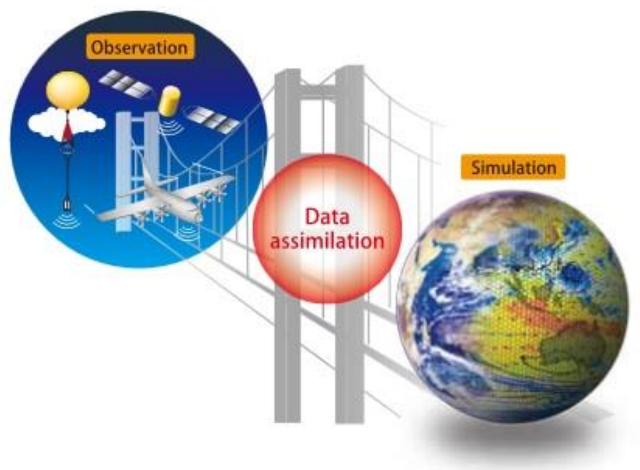

Sugimoto et al. (Earth, Planets and Space 2023)



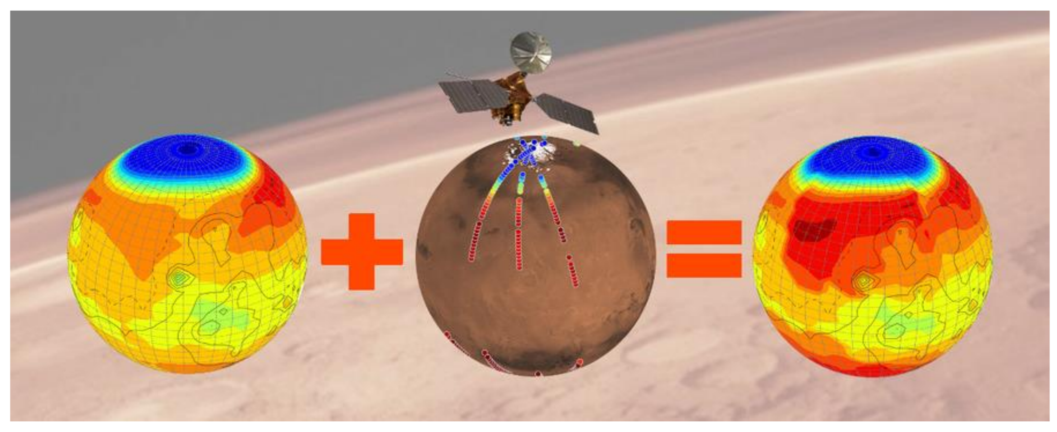

Sugimoto et al. (Nature Com. 2021)

## 3. ALEDAS-V (AFES LETKF Data Assimilation System for Venus)

### Data assimilation: First analysis for the Venus atmosphere

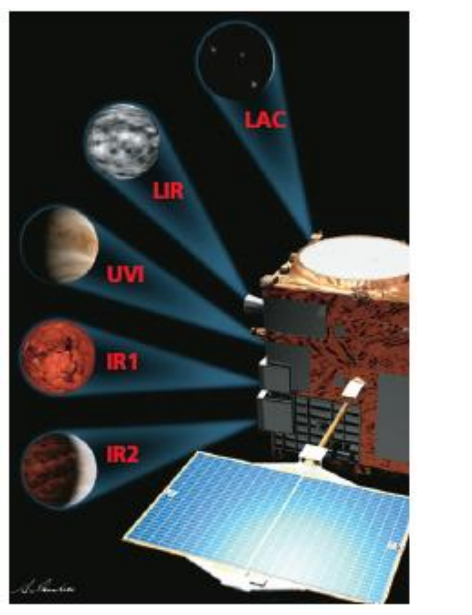


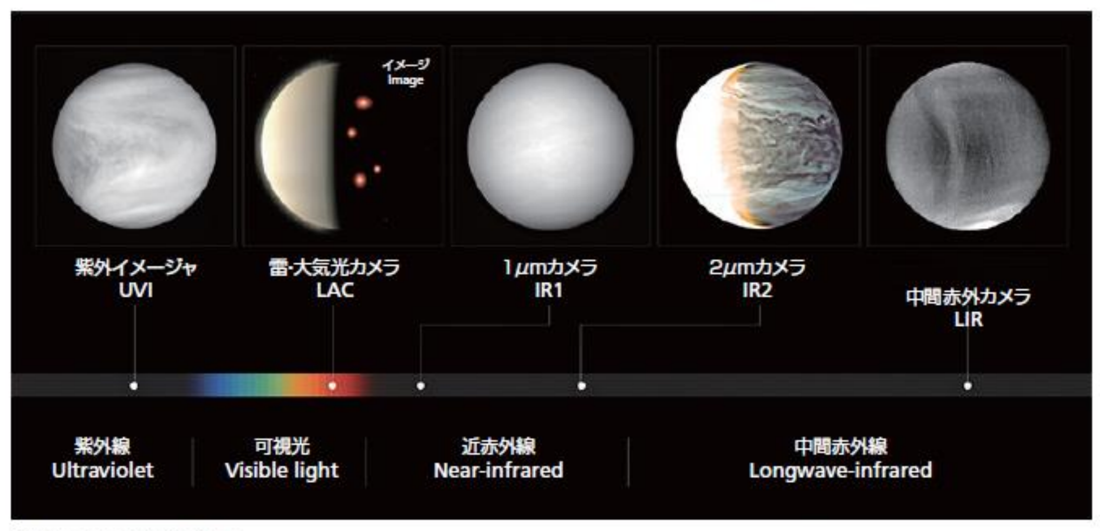

http://www.data-assimilation.riken.jp/jp/research/research.html



Mars Atmosphere Data Assimilation workshop (2018)

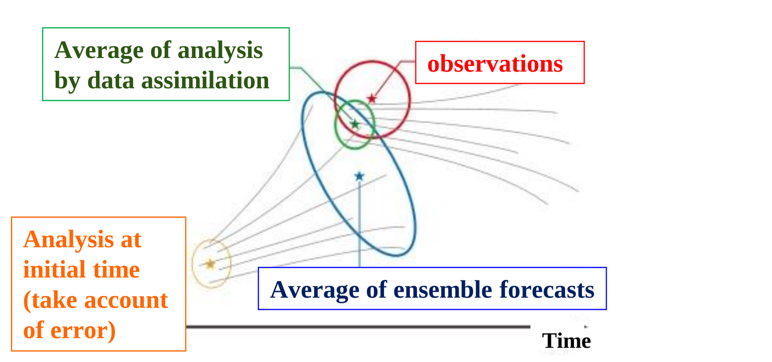
### Akatsuki (Venus climate orbiter): Frequent observations at multiple altitudes




「あかつき」の観測波長
Wavelengths observed by Akatsuki

### LETKF (Local Ensemble Transform Kalman Filter)

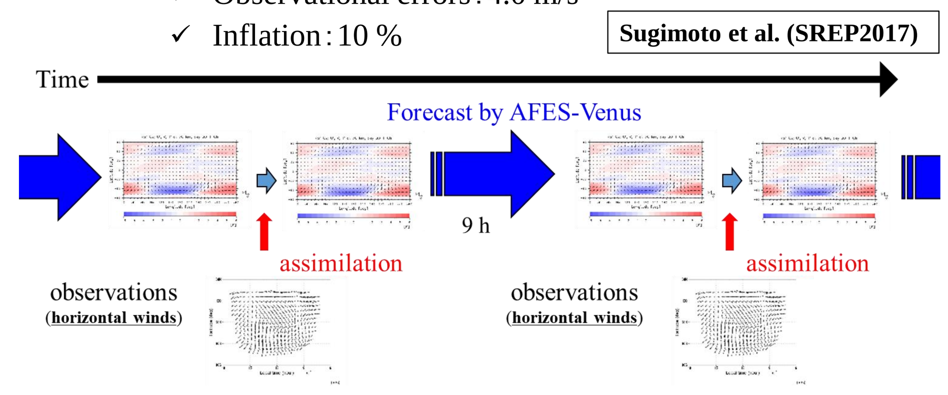



Local: considers only observations within a certain distance.
Ensemble: uses an *ensemble* of GCM forecasts.
Transform: uses a square-root filter.
Kalman Filter: uses past information to update the present state, and estimates both the state and its uncertainty (covariance)

### Settings of ALEDAS-V

- ✓ Ensemble size: 31-member
- ✓ assimilation cycle: 6-hourly interval
- ✓ Localization: horizontally 400 km, vertically lnP~0.4
- ✓ Observational errors: 4.0 m/s
- ✓ Inflation: 10 %

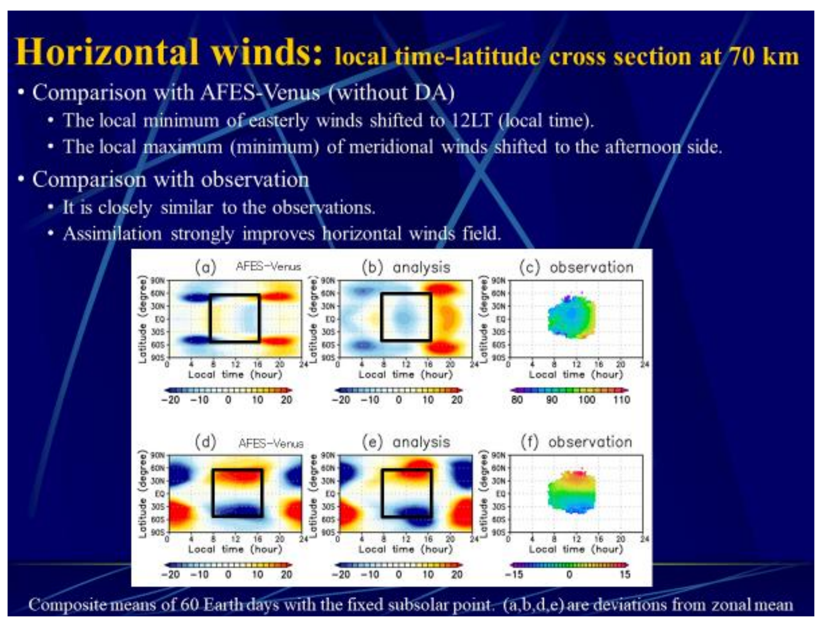
Sugimoto et al. (SREP2017)

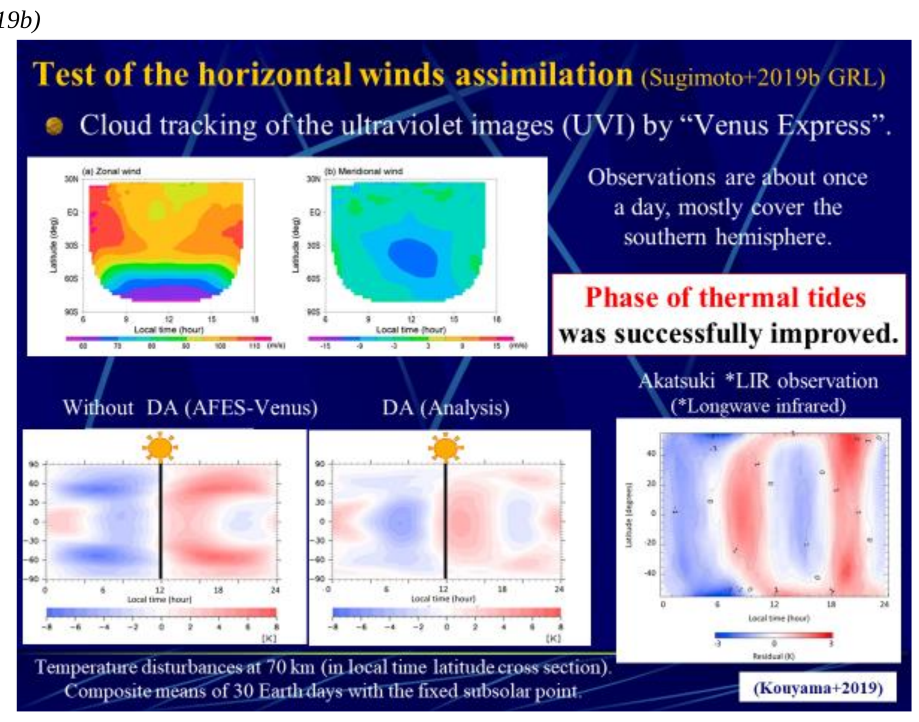


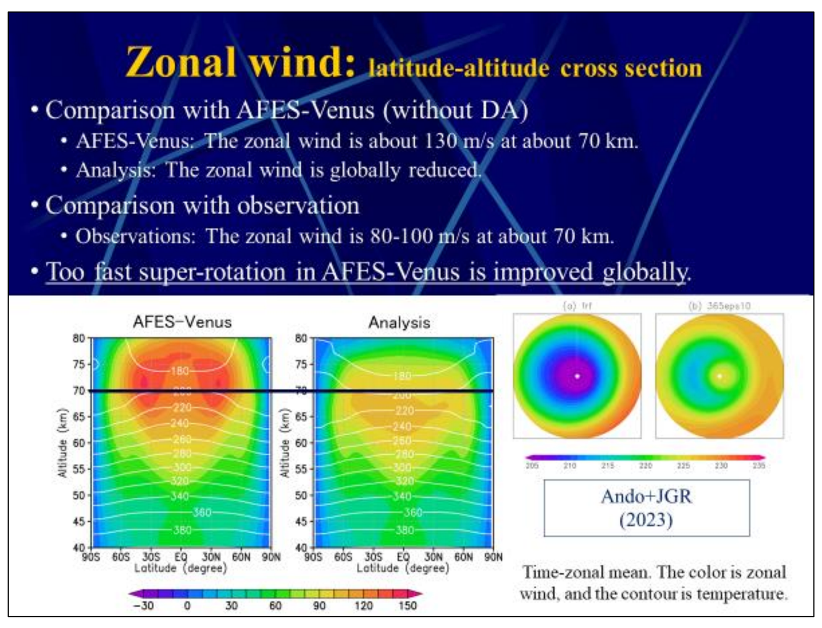

- ✓ 9-hour forecast from t=0, input observations from t=3 to 9
- ✓ Output analysis at t=6 (=4D LETKF)

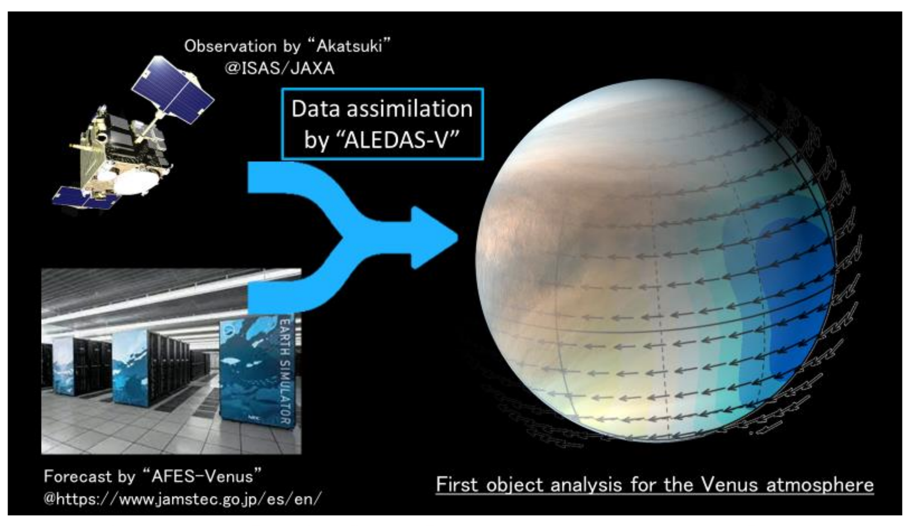
### Data assimilation for real observations

- ✓ Horizontal winds from Venus Express (Sugimoto et al., GRL2019b)
- ✓ Horizontal winds from Akatsuki (Fujisawa et al., Sci. Rep.2022)
- ✓ Cold collar in the first analysis (Ando et al., JGR2023)



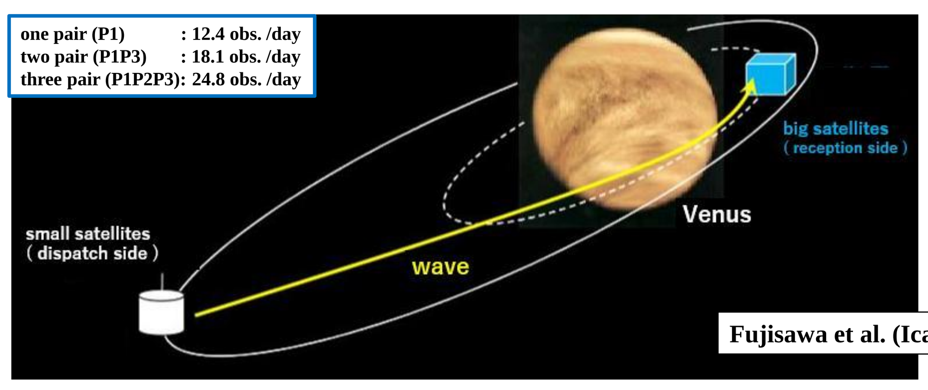



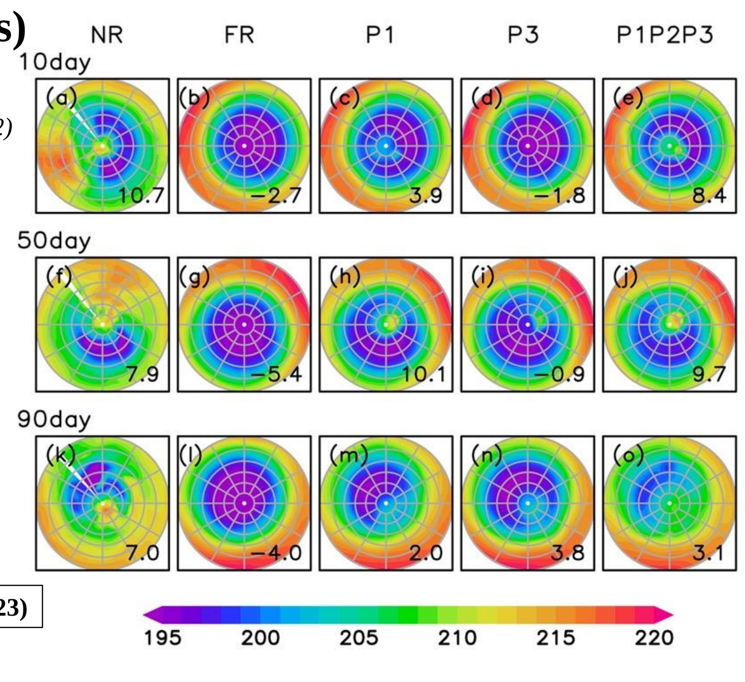

**First analysis for the Venus atmosphere (Press released in Sep., 2022)**

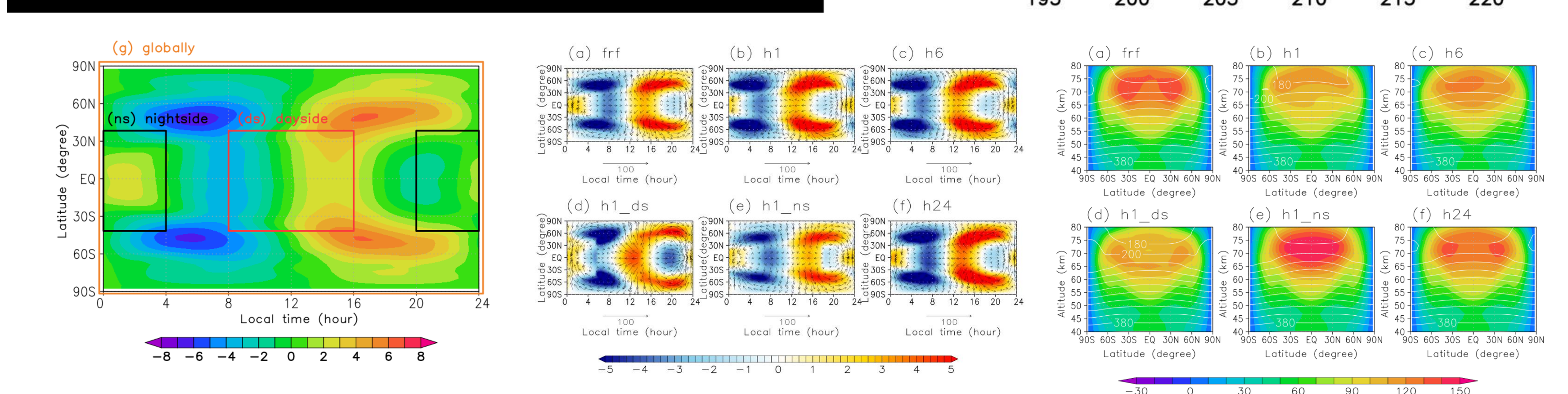
### Observing System Simulation Experiments (OSSEs)

- ✓ Cross-link Radio Occultation measurements (Fujisawa et al., Icarus, 2023)
- ✓ Ultra-Violet Images for Kelvins waves (Sugimoto et al., Atmosphere2021, 2022)
- ✓ Ultra-Violet Images for Rossby waves (Komori et al., in preparation)
- ✓ Long Infrared images for thermal tides (Sugimoto et al., GeoSci. Lett., 2022)




Fujisawa et al. (Icarus2023)



Sugimoto et al. (GeoSci. Let. 2022)

See also PSII-21 for OSSEs

## 4. Summary

**ALEDAS-V is the first data assimilation for the Venus atmosphere, and we have assimilated several real observations and conducted OSSEs for future missions.**

It would be possible to assimilate other obs. directly, such as cloud opacity and radiance, by improvement of physical processes of AVES-Venus...