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Venusian atmospheric general circulation model for the Earth Simulator local ensemble transform Kalman filter data assimilation system (VALEDAS)

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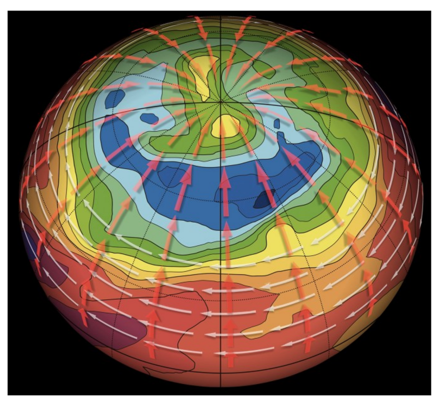
1. Introduction

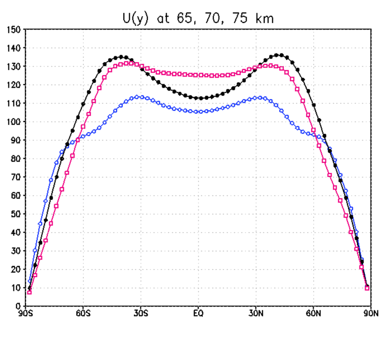
- AFES*-Venus (*Atmospheric GCM For the Earth Simulator)
  - Dynamical Venus-GCM highly optimized for parallel vector super computer
    - Start from idealized super-rotation: Saving computational cost with high resolution run
    - Maintain super-rotation with realistic setting: under the realistic solar heating and static stability

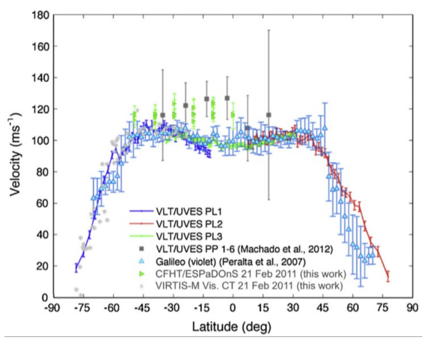
Resolutions from T42L60 to T639L260 (1920 × 960 grids with 260 layers)

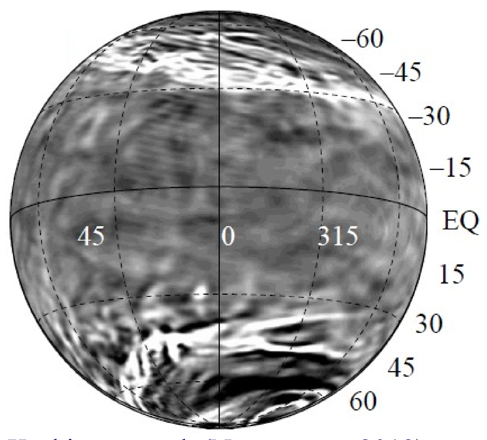
- Focus on atmospheric motions near the cloud level
  - ✓ Super rotation driven by mean meridional circulation *(Sugimoto et al., GRL 2019)*
  - ✓ Baroclinic instability & Neutral waves *(Sugimoto et al., JGR 2014; GRL 2014)*
  - ✓ Thermal tide & Short period waves *(Takagi et al., JGR 2018; Ando et al., JGR 2018)*
  - ✓ Polar vortex & Cold collar *(Ando et al., Nature Com.2016; JGR 2017)*
  - ✓ Energy spectra & Streak structures *(Kashimura et al., Nature Com.2019)*


Ando et al. (Nature com. 2016)

Final goal: To understand fundamental mechanism of super-rotation

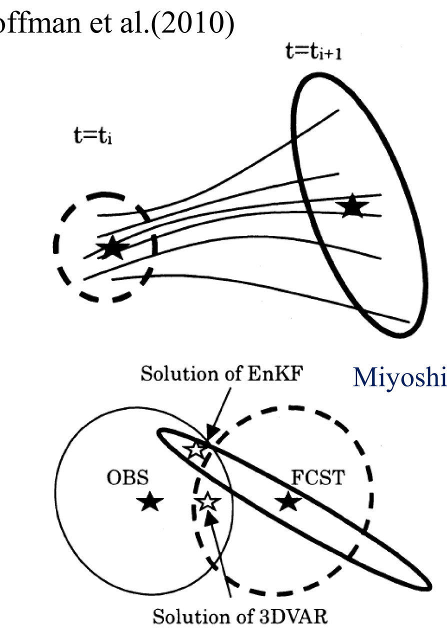

Sugimoto et al. (GRL 2014)


Machado et al. (2014)

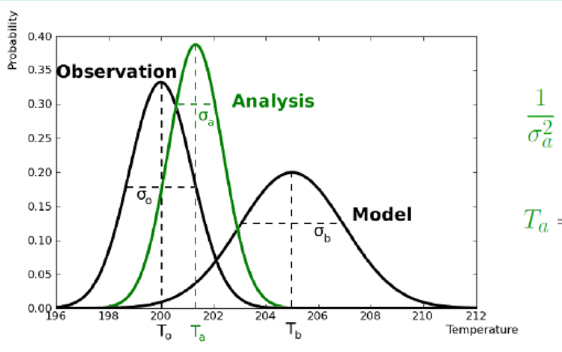

Kashimura et al. (Nature com. 2019)

- LETKF (Local Ensemble Transform Kalman Filter
  - Simple data assimilation method but computationally expensive
    - LETKF applied to Earth and Mars: Hunt et al.(2007), Miyoshi et al.(2007…), Hoffman et al.(2010)

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)



Miyoshi (2005)



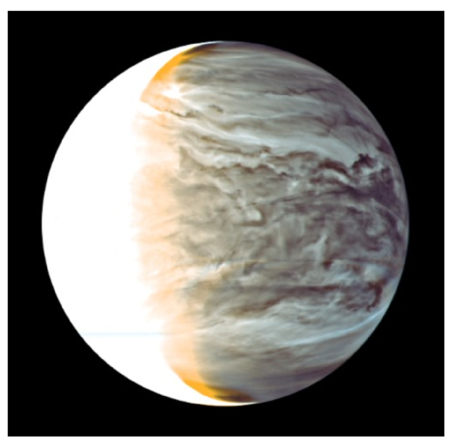
$$\frac{1}{\sigma_a^2}=\frac{1}{\sigma_b^2}+\frac{1}{\sigma_o^2}$$

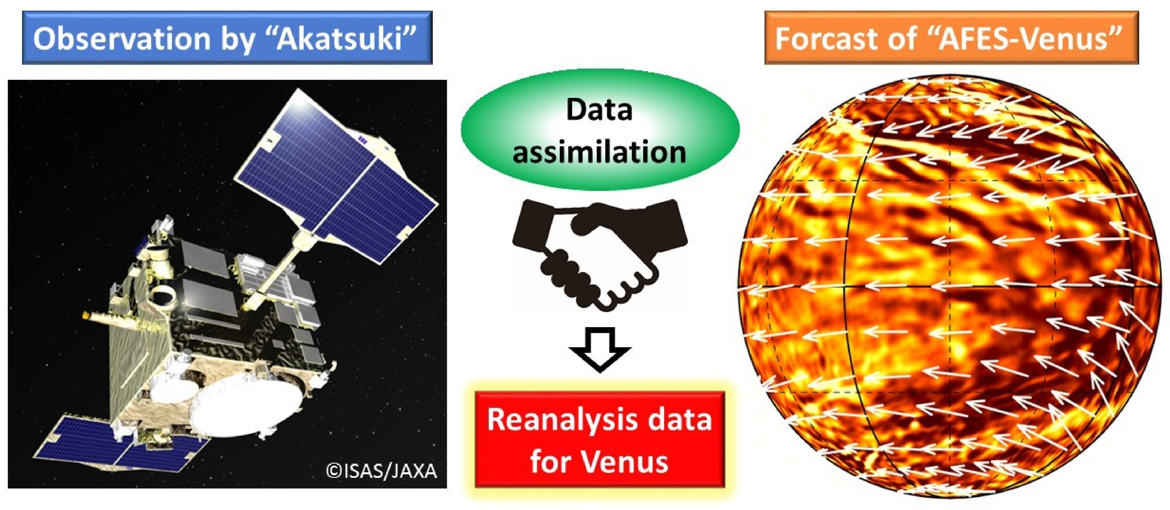
$$T_a=T_b+\frac{\sigma_b^2}{\sigma_b^2+\sigma_o^2}(T_o-T_b)$$

From Dr. T. Navarro (personal com.)

AFES-LETKF data assimilation system provides Re-Analysis (ALERA) data for the Earth

- Akatsuki Venus Climate Orbiter
  - Frequent observations with multiple altitude: Nakamura et al. (2011, 2014…)
    - Datasets will be available for the data assimilation


From ISAS/JAXA (Satoh et al., 2016)



This study: AFES-LETKF data assimilation system for the Venusian atmosphere

2. Experimental setting

- AFES-Venus (VAFES)
  - ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
  - ✓ Resolution: T42L60 (128 × 64 × 60)
  - ✓ Specific heat: Cp is constant (1000 $Jkg^{-1}k^{-1}$)
  - ✓ 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

AFES-Venus runs

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

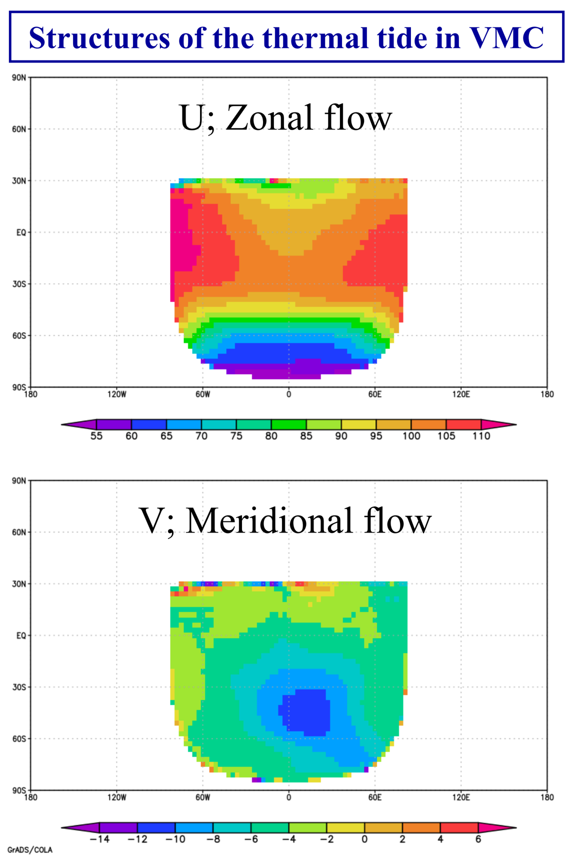
- Solar heating
  - ✓ Zonal (Qz) and diurnal (Qt) component of realistic heating
  - ✓ Based on Tomasko et al. (1980) and Crisp (1986)

Test observations

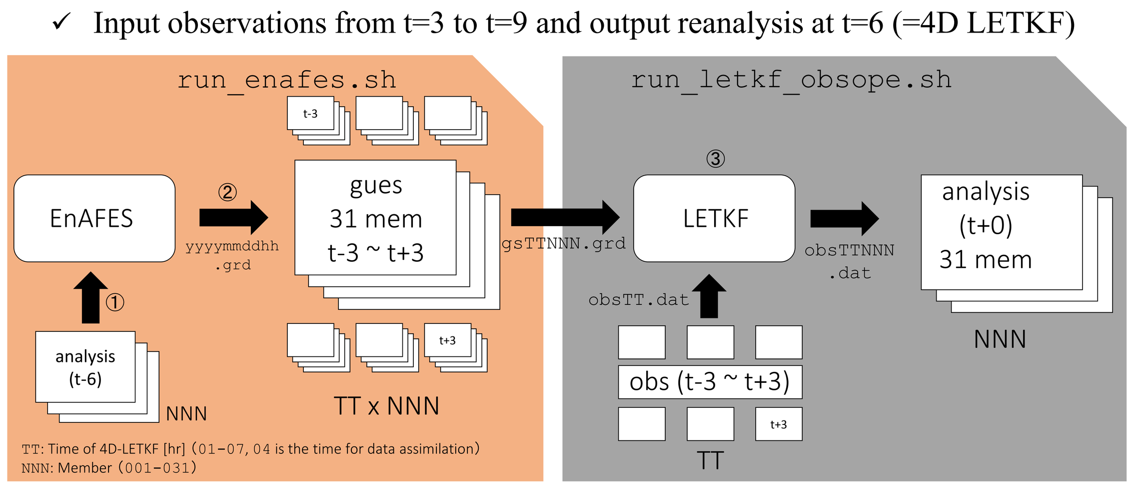
Case	Obs	interval	AFES
H1	Qt	1h	Qz
Vqz	VMC	~24h	Qz
Vqt	VMC	~24h	Qt

- 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
- Test observations; horizontal flows at the cloud top level
  - ✓ Idealized: AFES-Venus runs; Qt (including diurnal variation)
  - ✓ Real: VMC; Venus Monitoring Camera (73 obs. in Epoch 4: 28 Jan to 26 Apr 2008)
- AFES-Venus runs; Qz and Qt
  - ✓ T42L60: 31-member ensemble, 6-hourly assimilation cycle interval
  - ✓ Localization: horizontally 400 km, vertically lnP~0.4
  - ✓ Observational errors: 4.0 m/s
  - ✓ Inflation: 10 %
- Flow chart of the VAFES-LETKF data assimilation system
  - ✓ 9-hour forecast from t=0 and use from t=3 to t=9 for the assimilation
  - ✓ Input observations from t=3 to t=9 and output reanalysis at t=6 (=4D LETKF)

Structures of the thermal tide in VMC

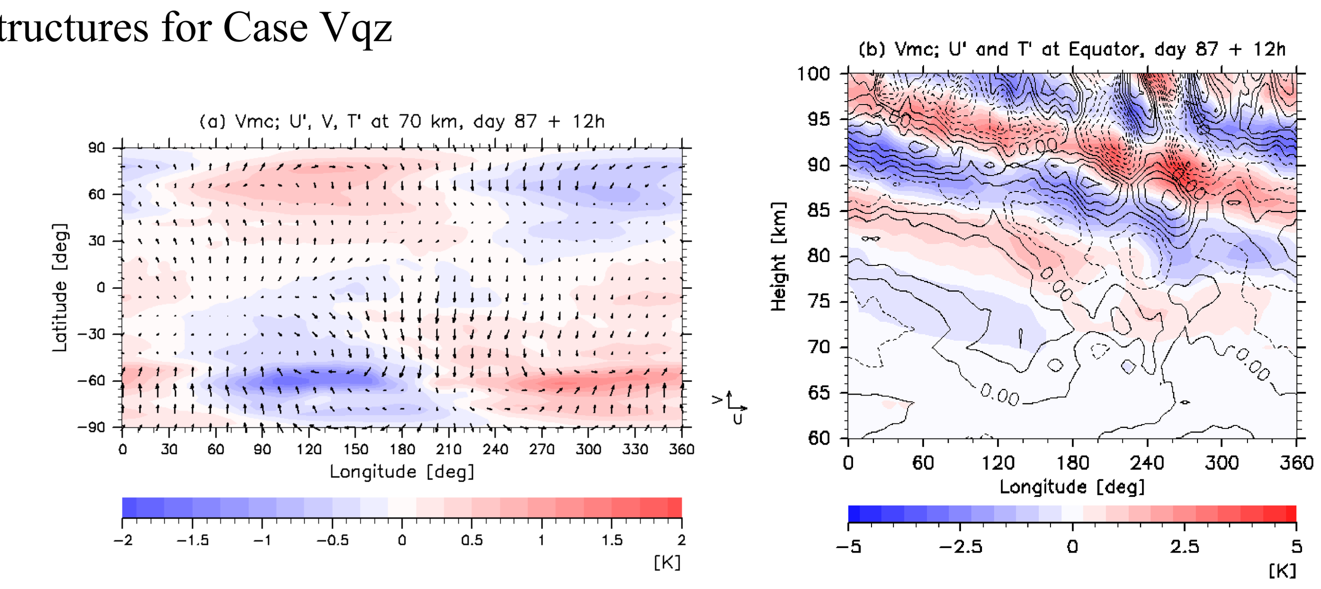


Kouyama et al. (JGR 2013)



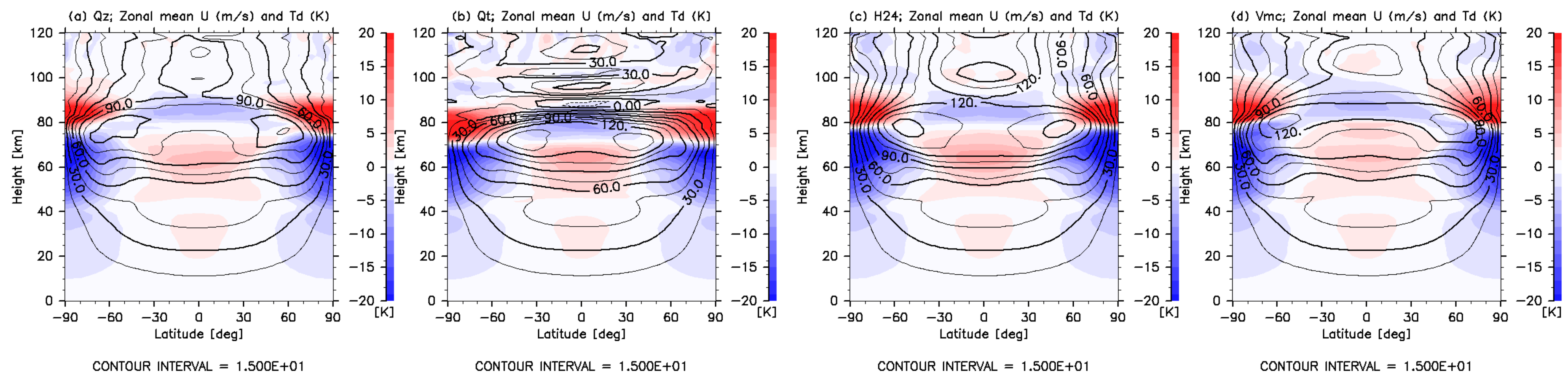
3. Results

- Structures for Case Vqz



Thermal tides appear but amplitudes of them are very weak

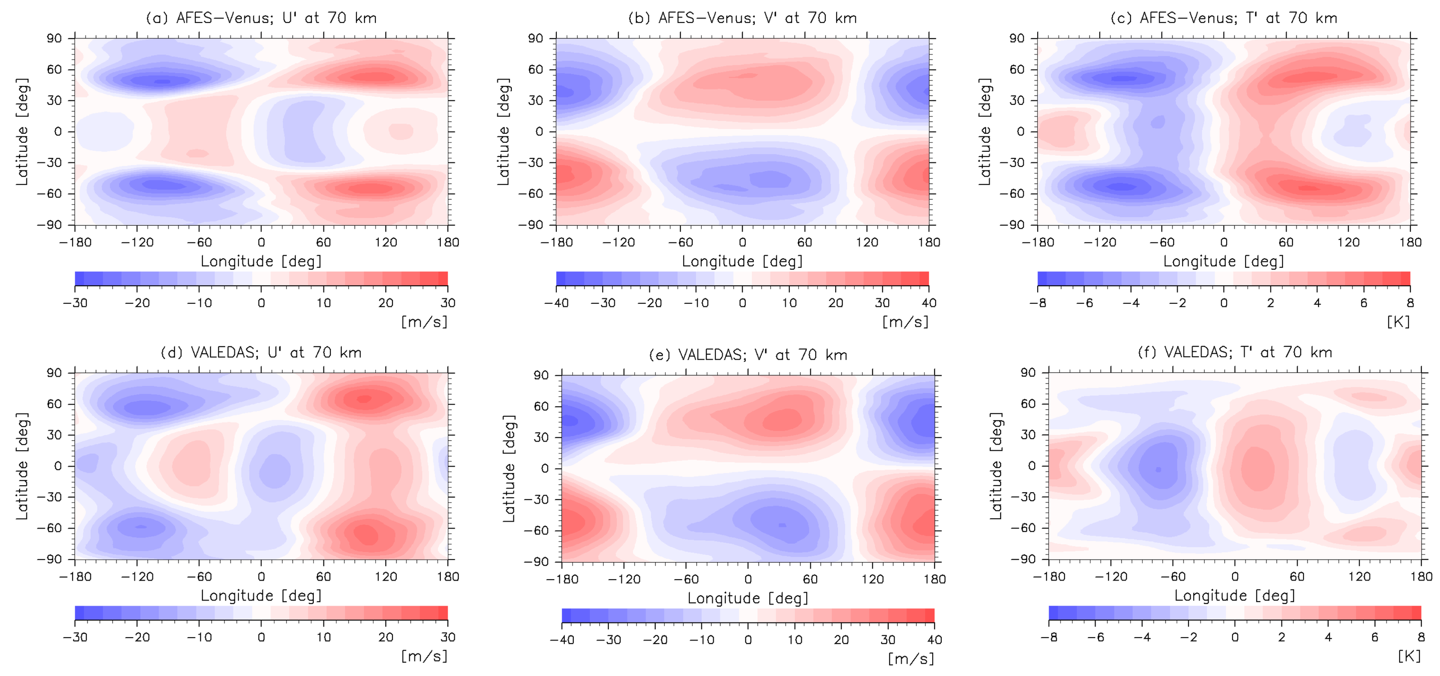
- Latitude-height cross sections for Cases Qz, Qt, H1, Vqz — ***Sugimoto et al., Sci. Rep. 2017***



Ū: zonal mean zonal flow (contour), Td: temperature deviations from the horizontally averaged temperature (colour)

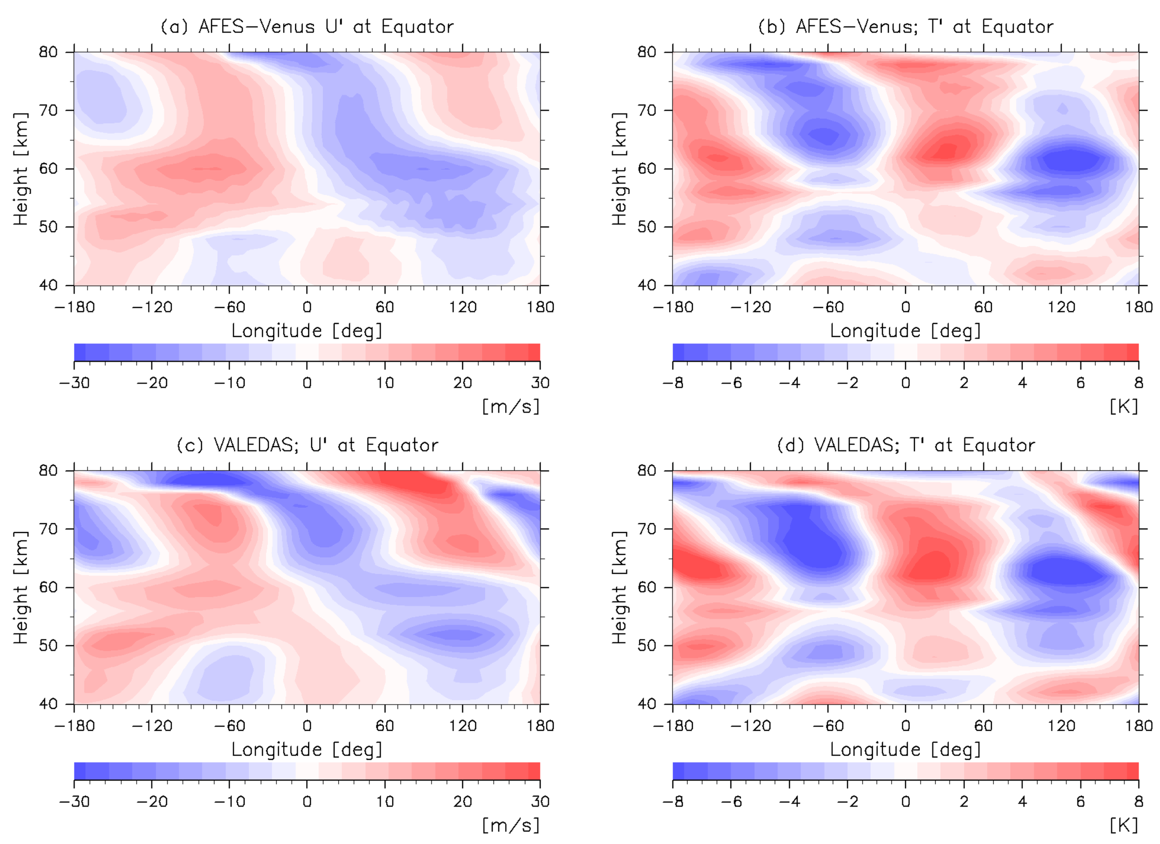
General circulation can not be changed by the data assimilation with sparse observations.

- Horizontal structures for Cases Qt, Vqt



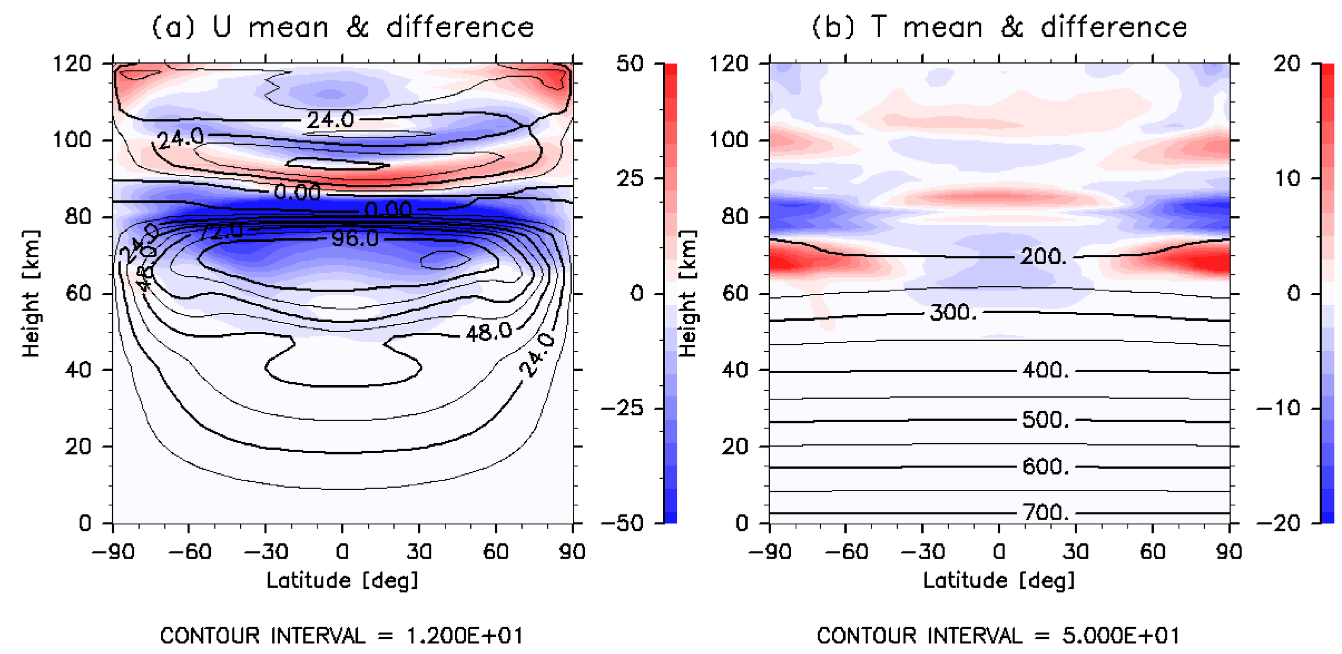
Phases of thermal tides are improved not only horizontal winds but temperature.

- Vertical structures for Cases Qt, Vqt



Vertical structures of thermal tides are also improved.

- Latitude-height cross sections for Case Vqt — ***Sugimoto et al. GRL, 2019***



(a) Zonal mean zonal flow (contour), (b) Zonal mean temperature (contour), and differences from case Qt (colour)

General circulation can be significantly improved by the data assimilation with thermal tides.

4. Summary

- AFES-LETKF data assimilation system for the Venusian atmosphere has been developed.
- VMC/VEX horizontal winds improve phases of thermal tides and general circulation.
- Akatsuki frequent observations will improve AFES-Venus forecast significantly.

References:

Sugimoto, N., A. Yamazaki, T. Kouyama, H. Kashimura, T. Enomoto and M. Takagi, (2017), "Development of an ensemble Kalman filter data assimilation system for the Venusian atmosphere", Scientific Reports, 7, 9321, 9pp, doi:10.1038/s41598-017-09461-1.

Sugimoto, N., T. Kouyama and M. Takagi, (2019), "Impact of data assimilation on thermal tides in the case of Venus Express wind observation", Geophys. Res. Lett., 46, doi:10.1029/2019GL082700.

See P29 also "The study on the reproducibility of cold collar assuming radio occultation measurement by small satellites"