Mars Atmosphere Data Assimilation workshop
at Savoie, France.
17:30 - 18:00, 29th, Aug., 2018

Venus AFES LETKF Data Assimilation System (VALEDAS)

Norihiko Sugimoto (Keio University),
Akira Yamazaki (JAMSTEC), Toru Kouyama (AIST), Hiroki Kashimura (Kobe University), Takeshi Enomoto (Kyoto University), Masahiro Takagi (Kyoto Sangyo University)

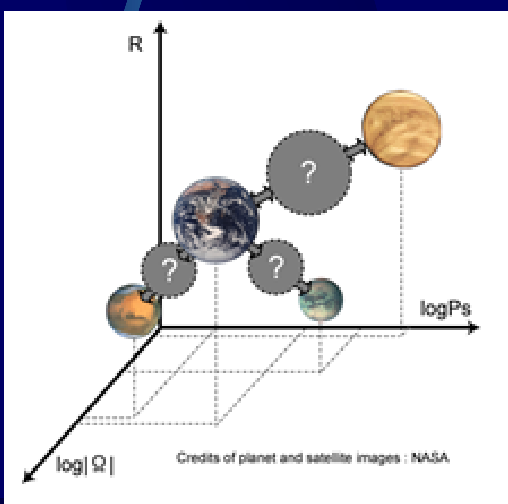
1. Introduction

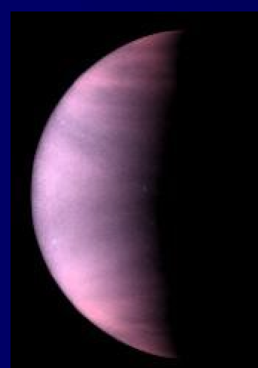
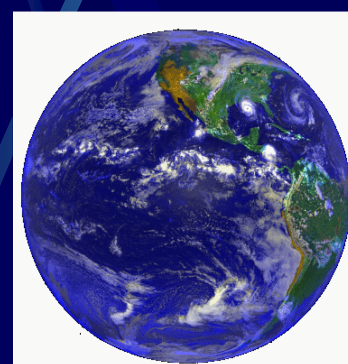
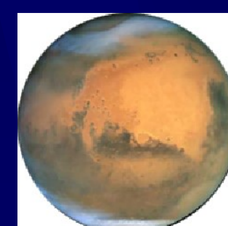
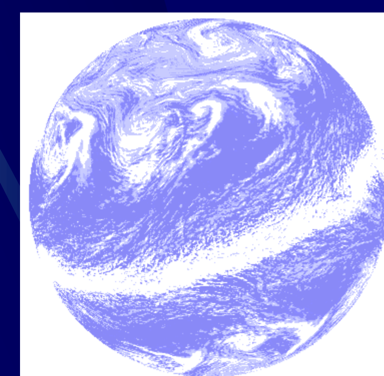
#Atmospheric GCM For the Earth Simulator

AFES# project for planetary atmosphere

(Y.-Y. Hayashi, Y. O. Takahashi, W. Ohfuchi, T. Enomoto, etc)

- To understand the varieties of global circulation in planetary atmospheres
  - ✓ Mars, Venus, Jupiter, Aqua-planet…
    - Common framework of the Atmospheric GCM (AFES)



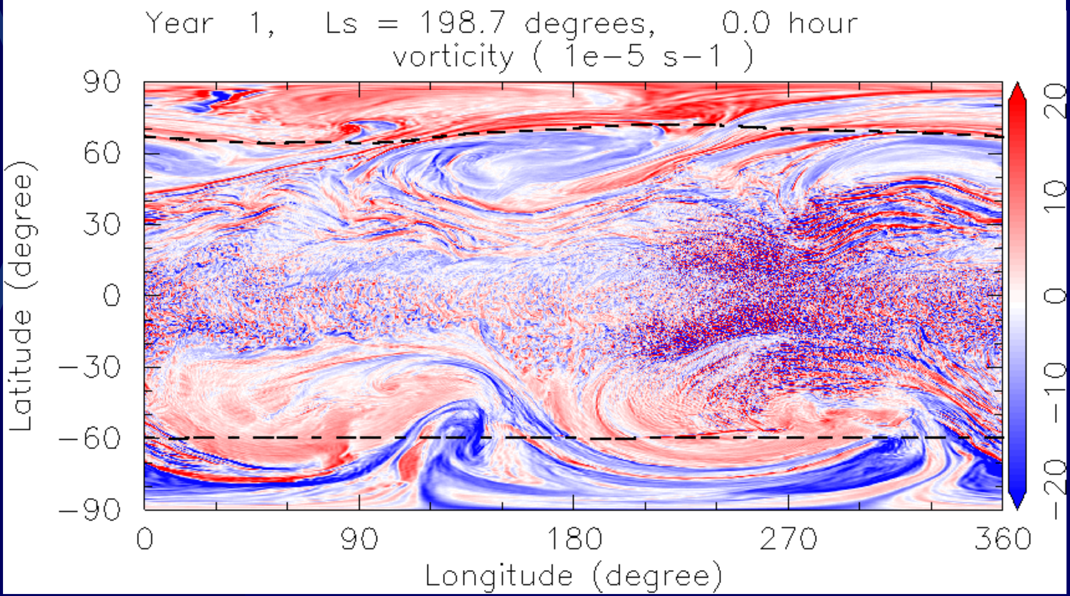
Center for Planetary Science

Computational Efficiency

- **AFES** (AGCM For the Earth Simulator)
  - ✓ Optimized for parallel vector super computer
  - ✓ T639L96 simulation for Mars (Takahashi et al.)
    grid intervals ~11 km (1920 × 960 grids with 96 layers)

Node number	64 node
Vector efficiency	99.4%
Parallel efficiency	99.8%
CPU time	1 Martian days/~4 hours

Mars T639L96 simulation (Vorticity distribution)



T; trancation wavenumbers
L; vertical layers

Venus

Solid part of Venus is similar to that of Earth but ...

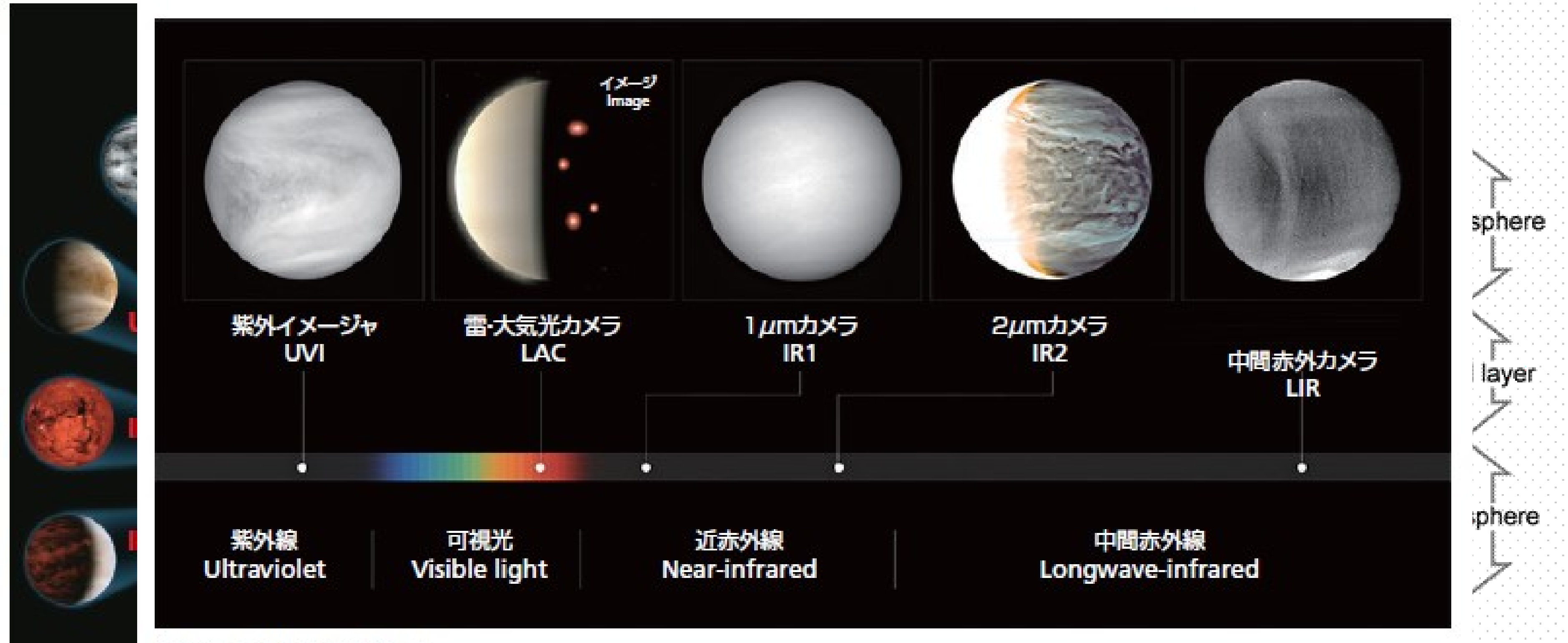
- **Rotation period：243 days, Solar day：116 days.**
  Cloud layer rotates about 4 days, "super-rotation" is not revealed.
- **Dynamical regime is different from those on the Earth and Mars.**
  Circulation below the cloud is unknown because of dense cloud.

http://www.isas.jaxa.jp

Less observations and reproducibility of Venus GCM than Mars

Akatsuki -Venus climate orbiter-

- Observations have stared from Dec. 2015.
  - ✓ Frequent meteorological observations at multiple altitudes (Nakamura et al., 2011, 2014…)



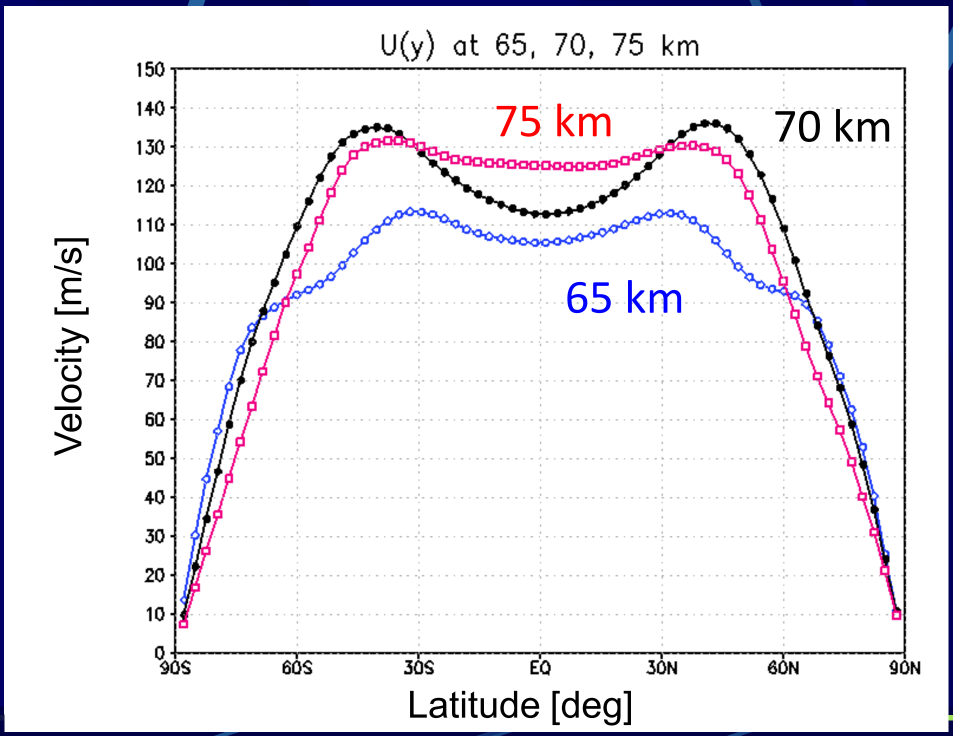
「あかつき」の観測波長
Wavelengths observed by Akatsuki

http://global.jaxa.jp/projects/sat/planet_c/

AFES-Venus

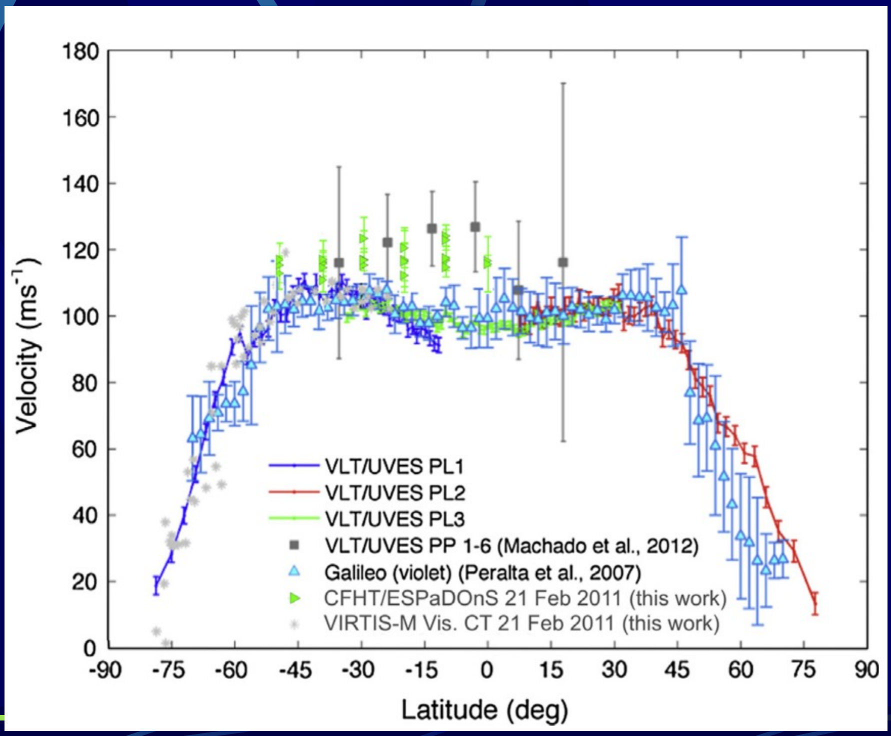
- **Atmospheric GCM (For the Earth Simulator) for Venus**
  - ✓ Dynamical GCM; high resolution, simple idealized physics.
  - ✓ Conserves angular momentum; reproduction of super-rotation.

AFES-Venus results



Sugimoto et al. (2014a, b...)

Observations: Doppler measurements



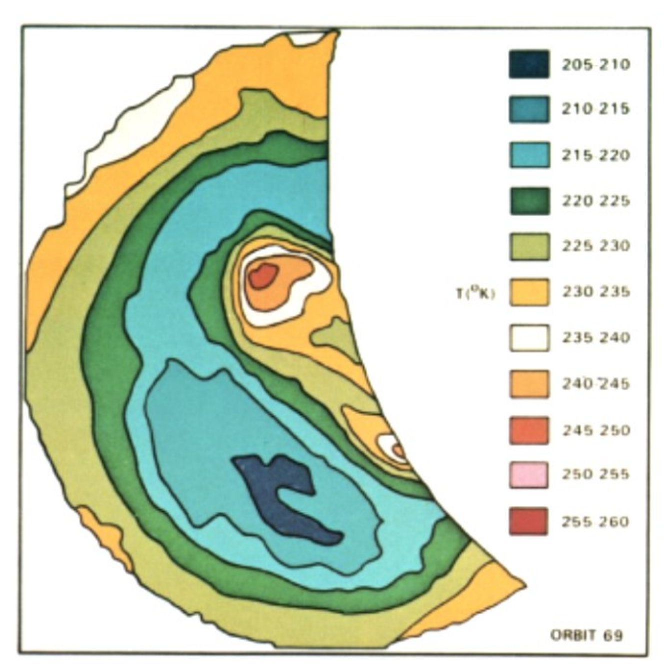
Machado et al. (2014)

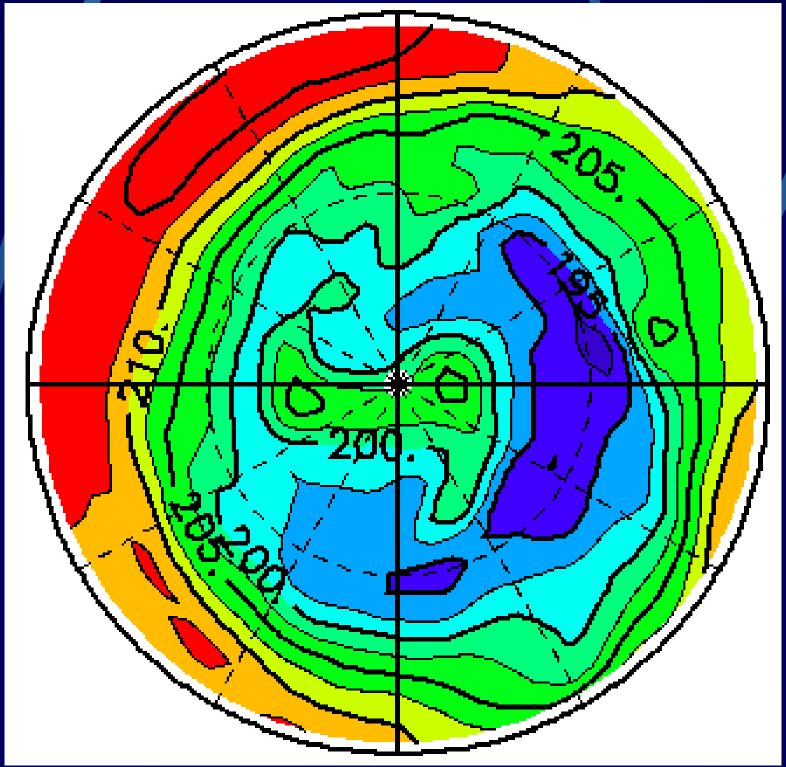
Polar vortex & Cold collar (T42L60 run)

- ✓ Warm "S-shaped" polar vortex with cold latitudinal band "cold collar"

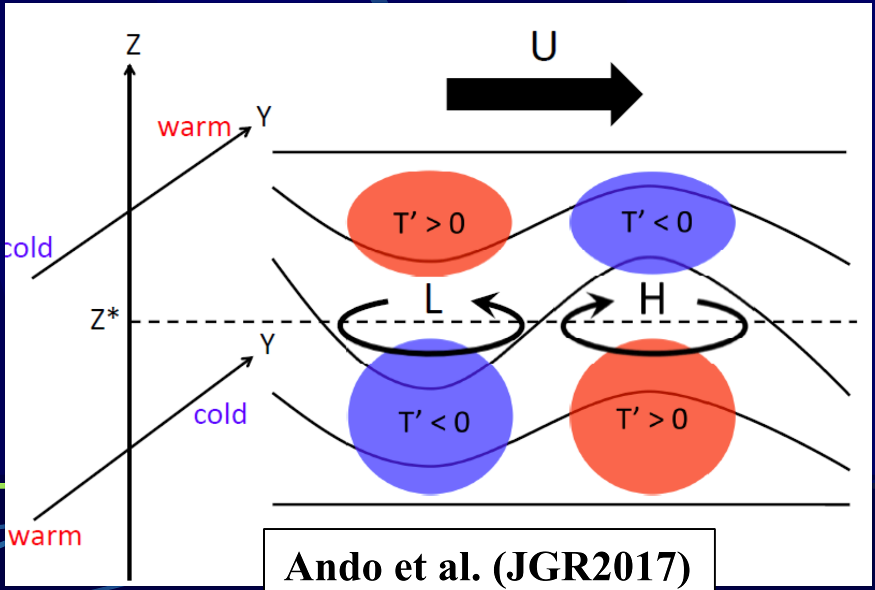
Puzzling structure is well reproduced in Venus GCM for the first time

Taylor et al.(1980)





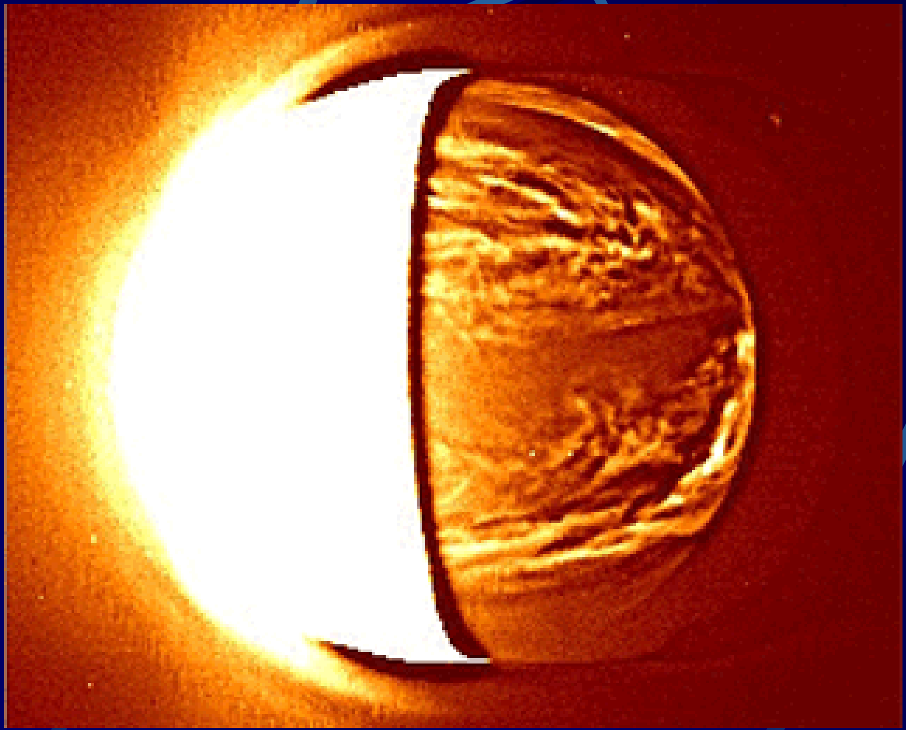
Ando et al. (Nature Communication 2016)



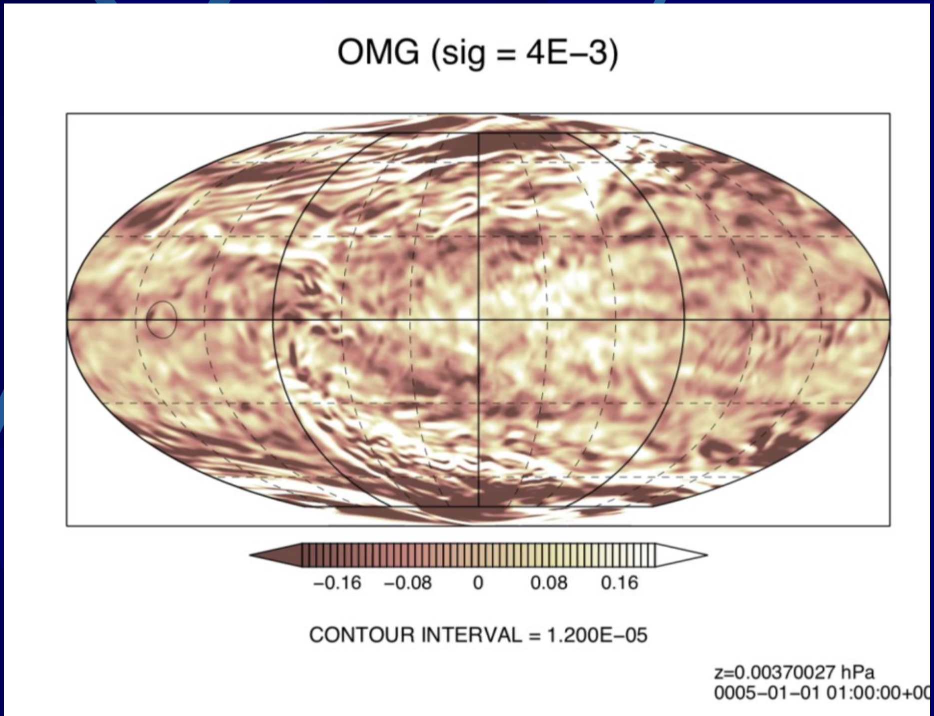
Ando et al. (JGR2017)

Akatsuki and AFES-Venus

- ✓ AFES-Venus reproduces phenomena of the Venus atmosphere.



Akatsuki IR2



AFES-Venus

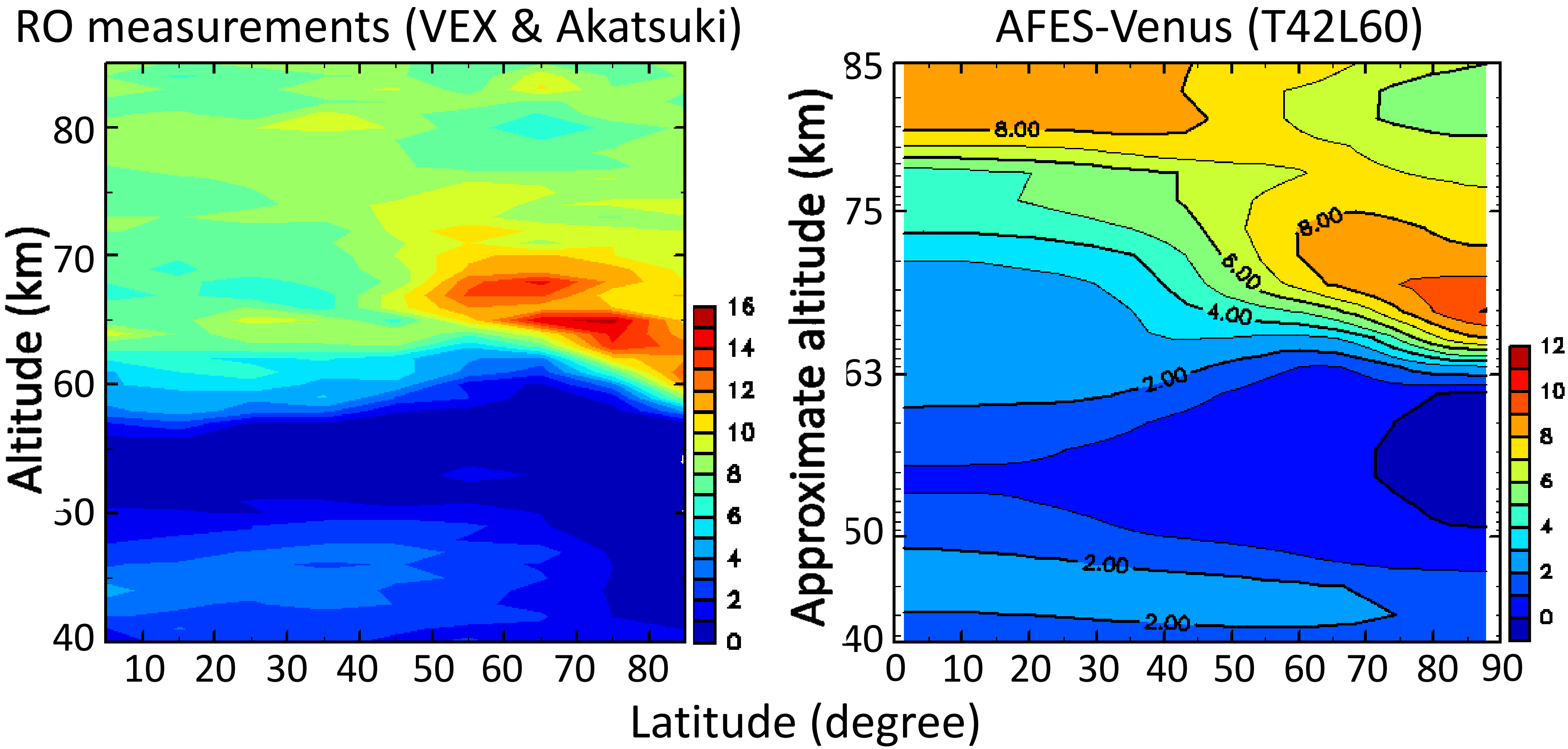
Rotation

http://www.isas.jaxa.jp/j/enterp/missions/akatsuki/compile/gallery.shtml

(Kashimura et al., Nature Com., revision submitted.)

Data assimilation of Venus has now become realistic!

Latitude-height distribution of the zonally and temporally averaged static stability



Static stability distributions obtained by RO (314 points) and AFES-Venus are also qualitatively consistent with each other.

(Ando et al., in preparation)

2. VALEDAS (VAFES-LETKF data assimilation system)

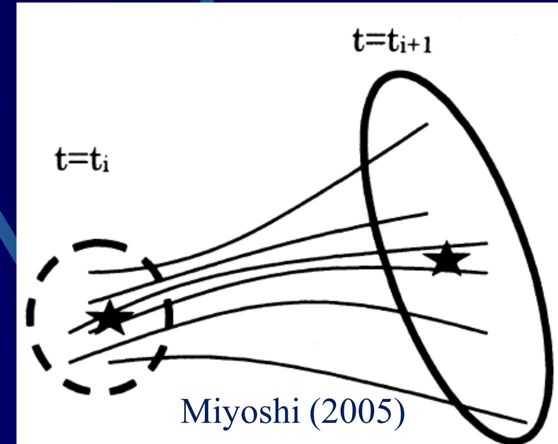
(VAFES; Venus AFES = AFES-Venus)

LETKF (Local Ensemble Transform Kalman Filter)

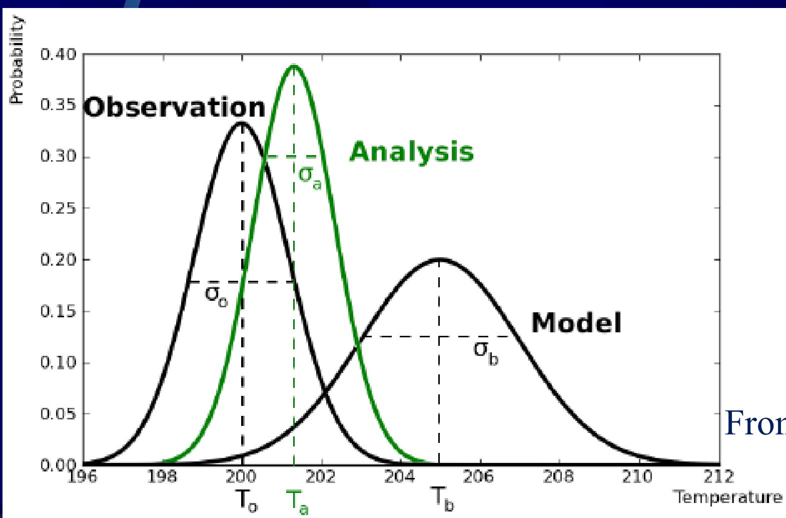
- **Already used for Earth (ALERA*) and Mars**
  (Hunt et al., 2007; Miyoshi et al., 2007…; Hoffman et al., 2010)

***AFES-LETKF experimental ensemble reanalysis**

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)



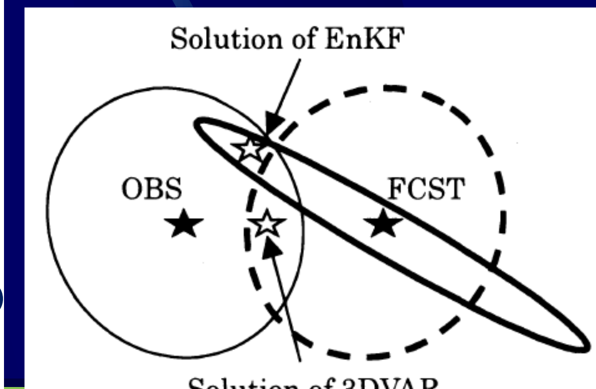
Miyoshi (2005)



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

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

From Dr. T. Navarro (personal com.)



Estimate variance by ensemble forecasts: easy to implementation

Quick summary of preliminary results

We have developed a data assimilation system for Venus (VALEDAS; VAFES-LETKF data assimilation system).

Test observations; horizontal winds at the cloud top level

①Idealized: AFES-Venus runs

②Real: Venus Monitoring Camera (VMC/VEX)

Both observations include thermal tide but **AFES-Venus forecasts forced with solar heating exclude thermal tide.**

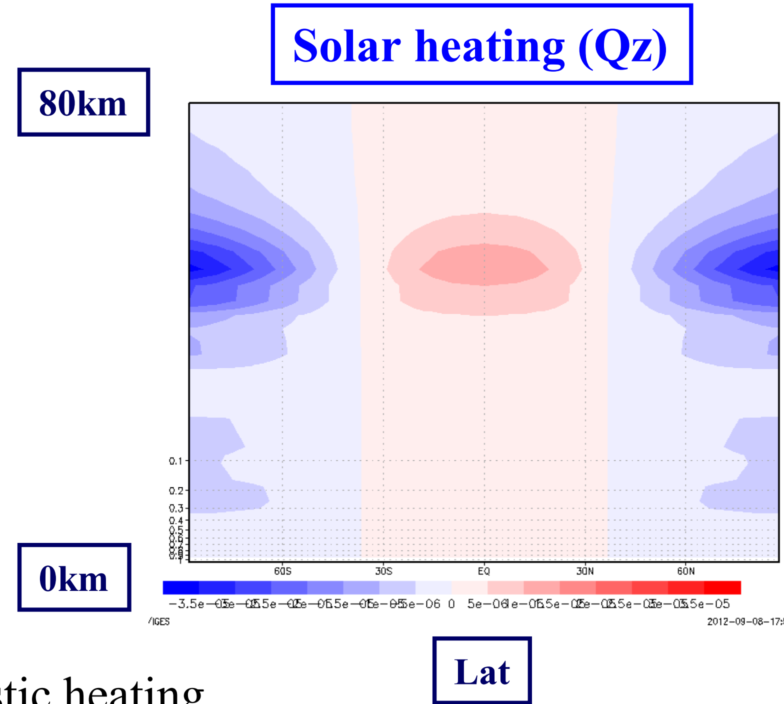
⇒ Thermal tide appears by the data assimilation.

The development system works well!!

Experimental setting

AFES-Venus

- Dry 3-D Primitive equation on sphere
- Resolution: T42L60 (128 × 64 × 60 grids)
- Specific heat: Cp is constant (1000 $\mathrm{Jkg^{-1}k^{-1}}$)
- Horizontal hyper-viscosity: 0.1 Earth days for 1/e
- Vertical eddy viscosity: 0.15$\mathrm{m^2s^{-1}}$
- Rayleigh friction: lowest and above 80km
- No topography and planetary boundary



✓Solar heating

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

✓Infrared radiative process

- Newtonian cooling: $dT/dt = -\kappa\,(T - T_{ref}(z))$
  κ: based on Crisp (1986)
  $T_{ref}(z)$: horizontally uniform field

AFES-Venus runs

Cases	Solar heating
Qz	Zonal mean only
Qt	Including diurnal variation

Test observations: horizontal winds at the cloud top level (70 km)

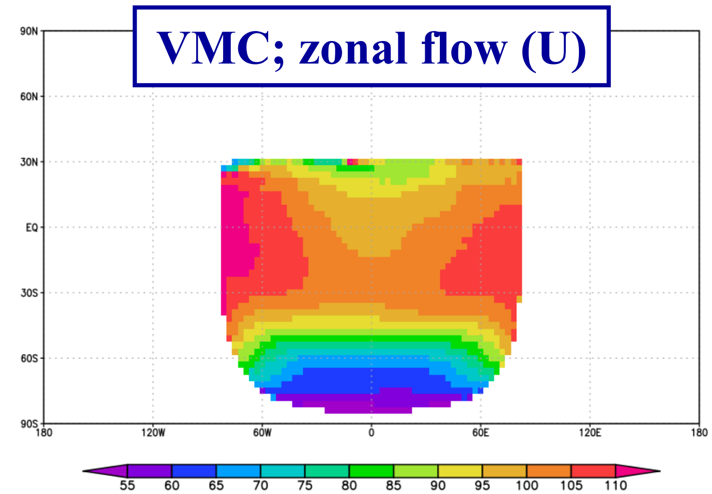
- Idealized: AFES-Venus runs: **Qt** (solar heating including diurnal variation)
- Real: VMC; Venus Monitoring Camera (73 obs. in Epoch 4: 28 Jan to 26 Apr 2008)

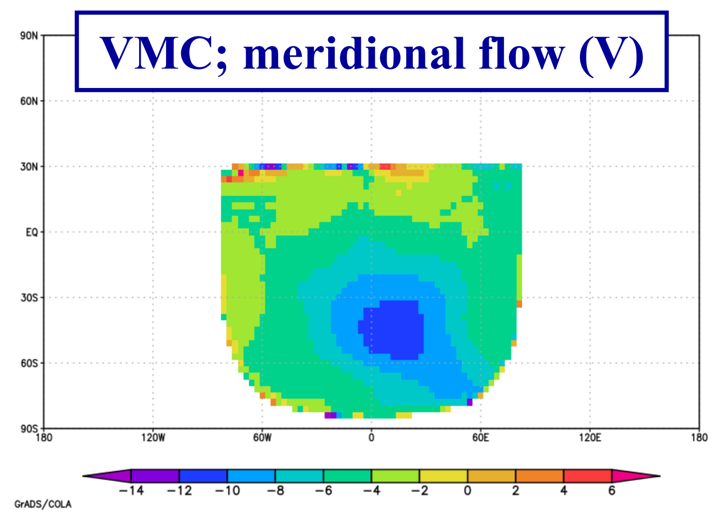
Test observations

Case	Obs	interval	AFES
H1	Qt	1h	Qz
H6	Qt	6h	Qz
H24	Qt	24h	Qz
Vmc	VMC	~24h	Qz
Frf	None	None	Qz

AFES-Venus runs

Cases	Solar heating
Qz	Zonal mean only
Qt	Including diurnal variation

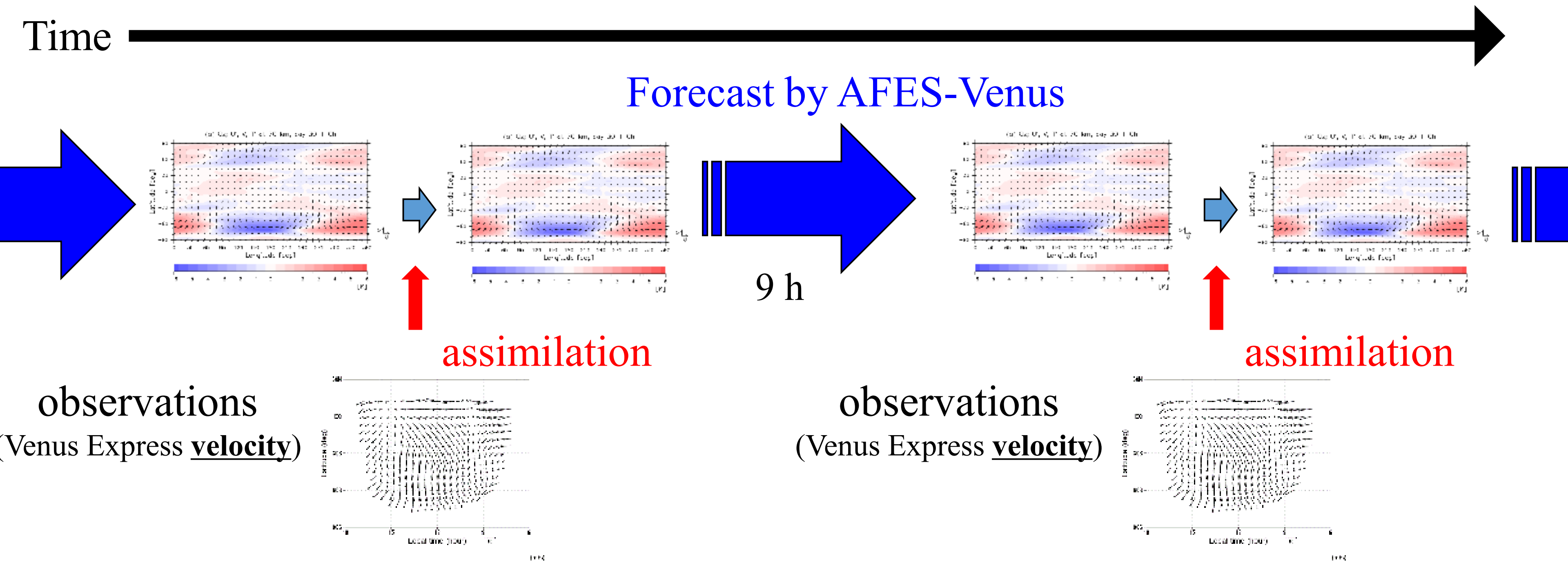




Kouyama et al. (JGR 2013)

VALEDAS (VAFES-LETKF data assimilation system)

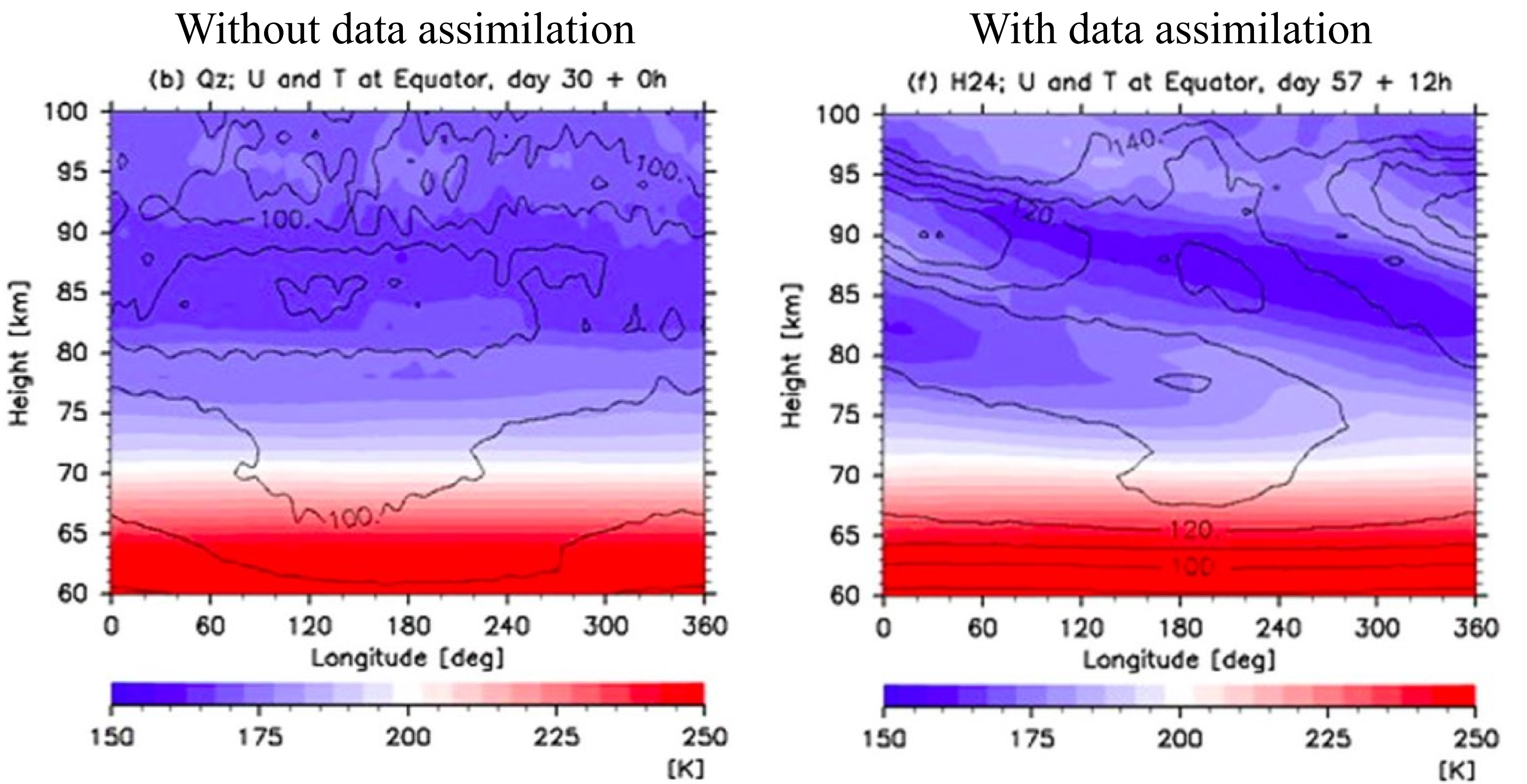
- ✓ Ensemble size: 31-member
- ✓ assimilation cycle: 6-hourly interval
- ✓ Localization: horizontally 400 km, vertically lnP~0.4
- ✓ Observational errors : 4.0 m/s
- ✓ Inflation : 10 %



- ✓ 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)

Test results

- Vertical structure (Case H24) at the equator



Sugimoto et al. (2017)

Thermal tide <u>propagates in the vertical direction</u> in Case H24 (once a day only for horizontal winds) even for the temperature field.

How much each obs. improves model forecast?

Implementation of EFSO (Ensemble Forecast Sensitivity to Observations)

Kalnay et al. (2012 Tellus), Ota et al. (2013 Tellus), Hotta et al. (2017 MWR)

$$\Delta e^2 = e_{t|0}^T \mathbf{C} e_{t|0} - e_{t|-6}^T \mathbf{C} e_{t|-6}$$

$e_{t/0}=[x^f_{t/0}]-[x^a]$

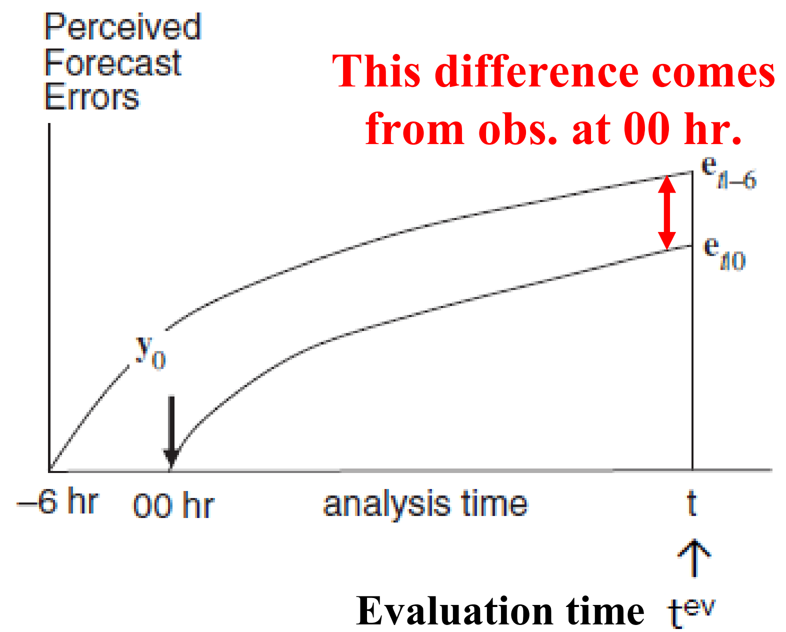
$$\Delta e^2 = \boxed{(\bar{x}_{t|0}-\bar{x}_{t|-6})^T}\mathbf{C}(e_{t|0}+e_{t|-6})$$

$$\approx \delta\bar{y}_0^{ob^T}\frac{1}{K-1}R^{-1}Y^a X_{t|0}^{fT}\mathbf{C}(e_{t|0}+e_{t|-6})$$

Obs. $y-H(x^f)$ (O-B innov) (at t=0)

$[H(x^a)]'$ **Analysis ensemble (at t=0)**

$[x^f_{t/0}]'$ **forecast ensemble (at t=t^ev)**



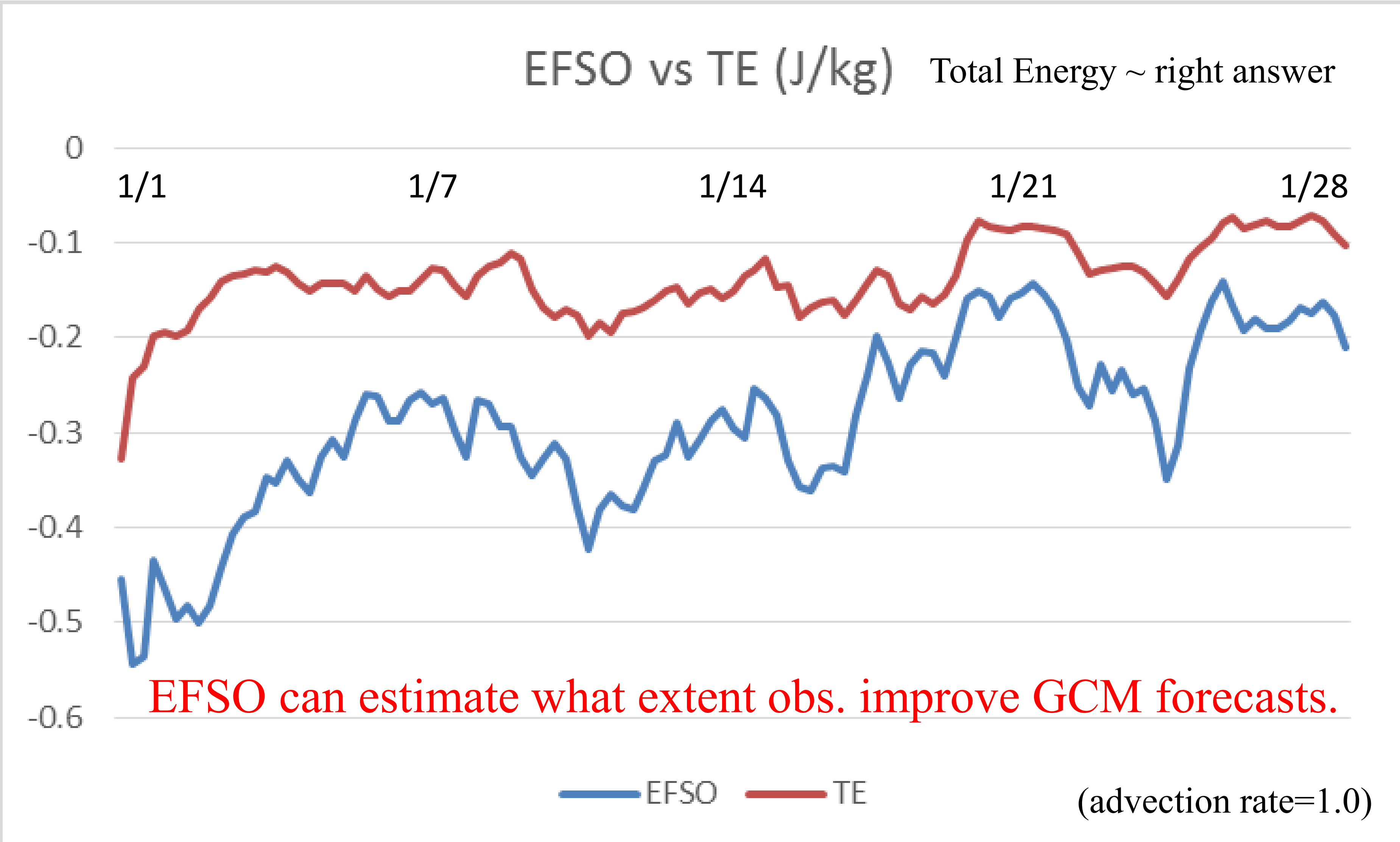
Yamazaki et al. (2018?)

- ✓ Forecast Sensitivity to Observations (FSO) done automatically by ensemble run.
- ✓ Estimate impacts of specific observations diagnostically (without data denial exp.).

No need for Observation System (Simulation) Exp. (OS(S)E) and adjoint model.

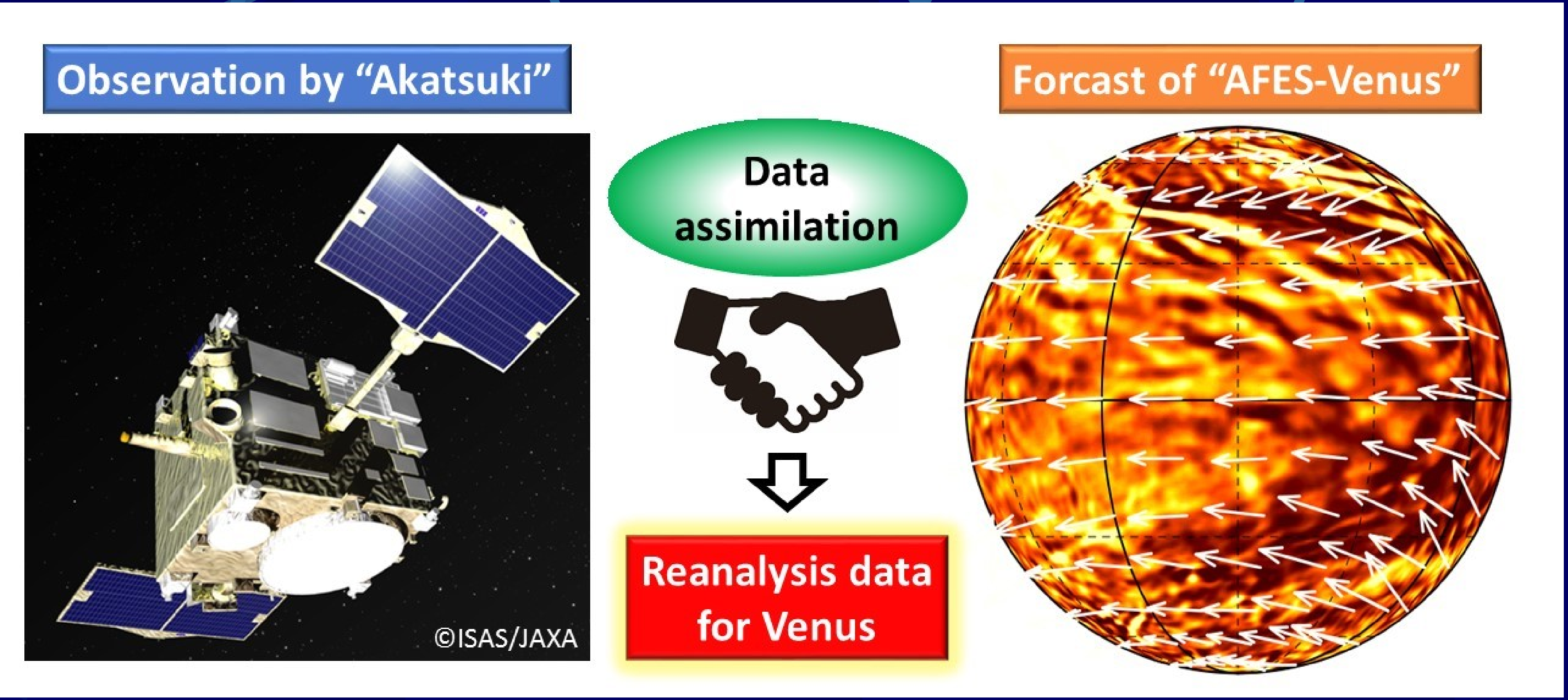
Test of EFSO (Case H1)

- ✓ Correlation 80.64%; EFSO works well *but overestimates a little*



3. Future work

- **Reanalysis data for Venus produced by VALEDAS**
  - ✓ Akatsuki data assimilation with diurnal solar variation run.



- **Data assimilation of Akatsuki continuous obs.**
  - ✓ We have planed 2-hourly continuous obs. during 20 days (Dec. 2018).

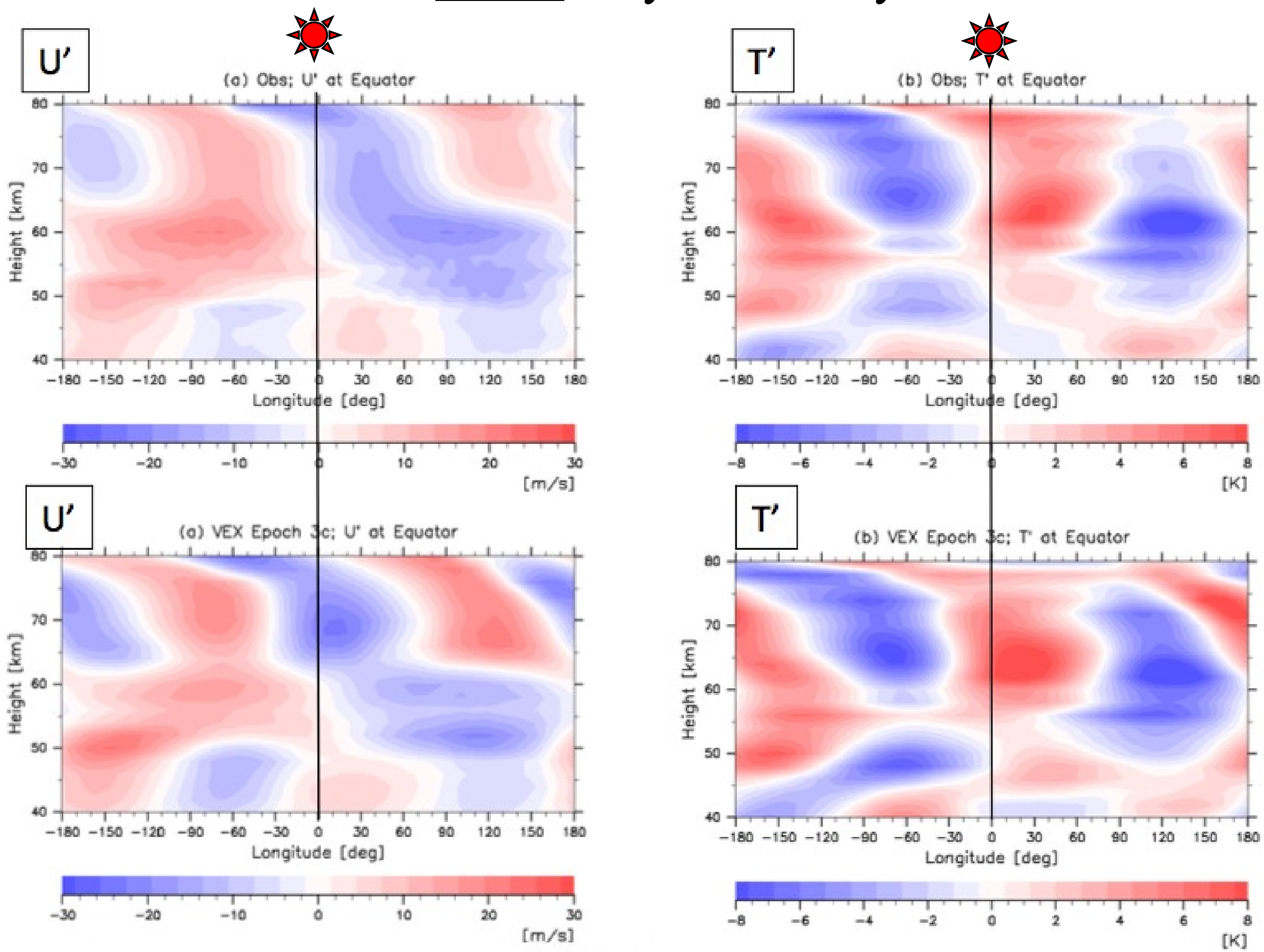
Test for Akatsuki obs. (with diurnal solar variation run)

Dayside horizontal winds of VMC/VEX at 70 km only once a day are assimilated.

Vertical structure at the equator

Without data assimilation (thermal tides in AFES)

With data assimilation (phase is improved)

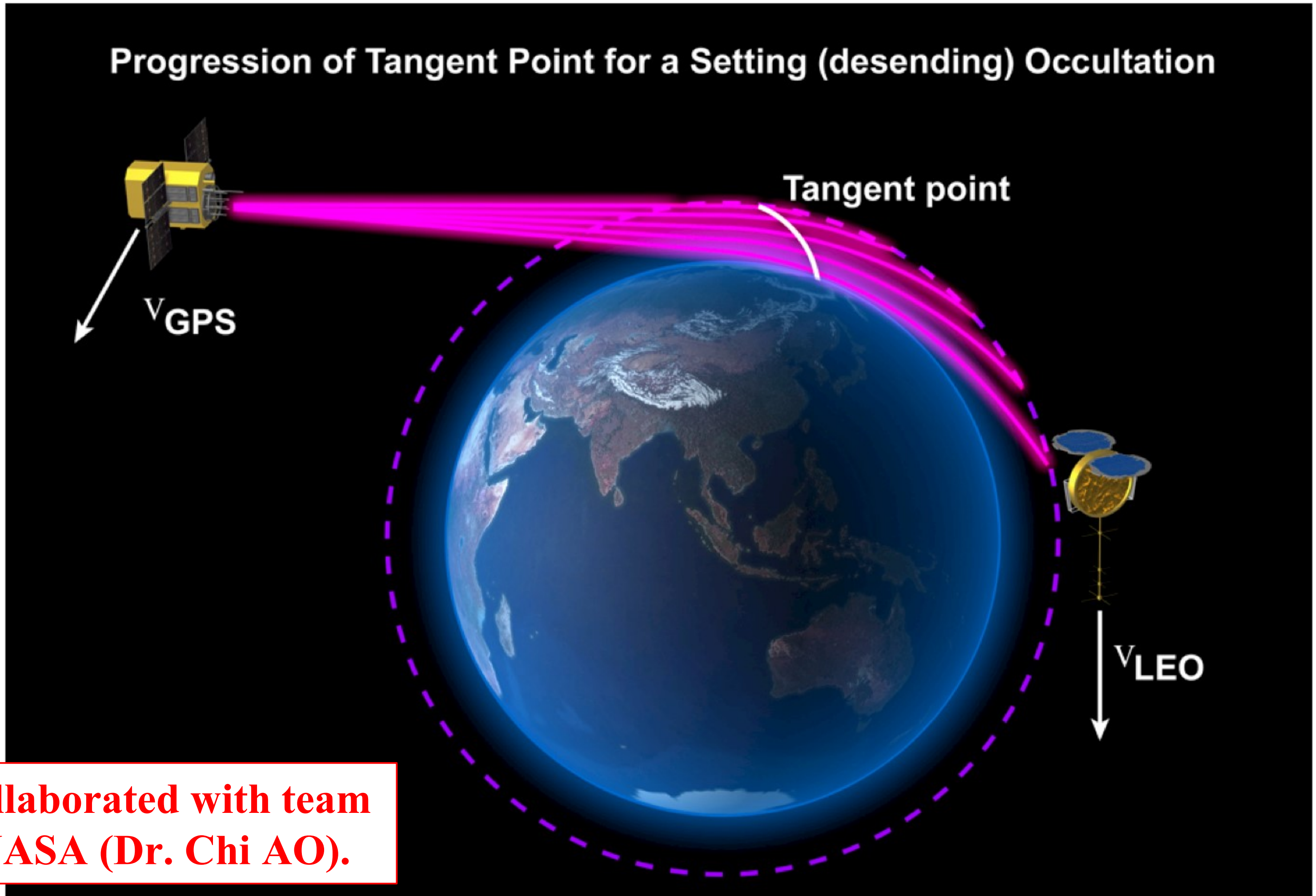


Sugimoto et al. (2018) in preparation

- ✓ With Akatsuki (Temp.) more realistic structure would be reproduced.
- ✓ But we need more frequent obs. to reproduce high frequency waves.

Radio occultation by multiple satellites for Venus

- ✓ Test data assimilation with EFSO gives useful information to propose better orbits ⇒ Contributes to future Venus missions



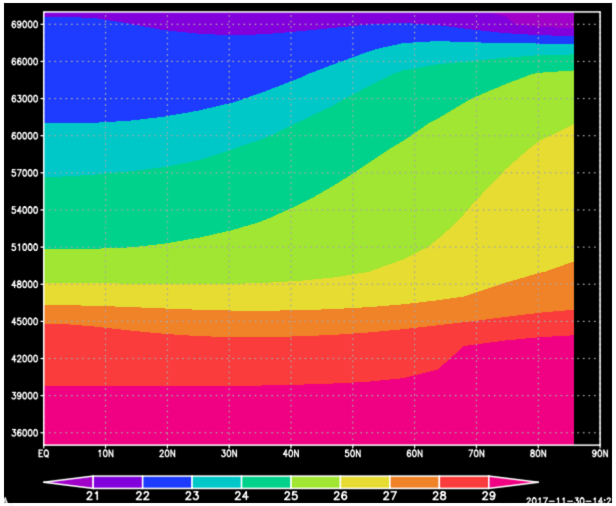
To be collaborated with team of JPL/NASA (Dr. Chi AO).

http://www.cosmic.ucar.edu/related_papers/GPS_RO_cartoon.jpg

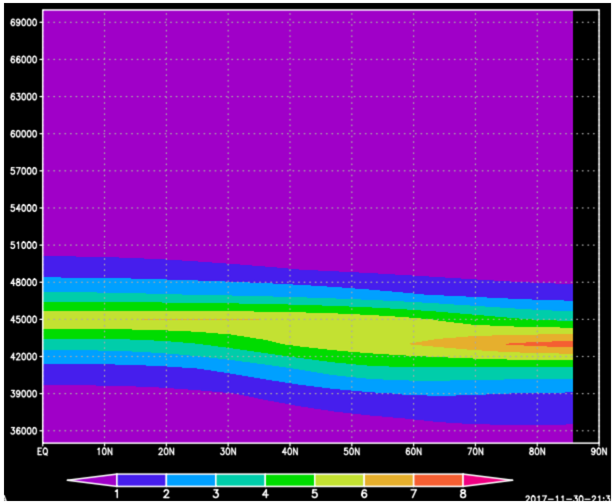
Improvement of AFES-Venus

- ✓ Implementation of cloud physics (by Dr. Ando and Takagi)
- ✓ Implementation of radiation process (by Dr. Sagawa)

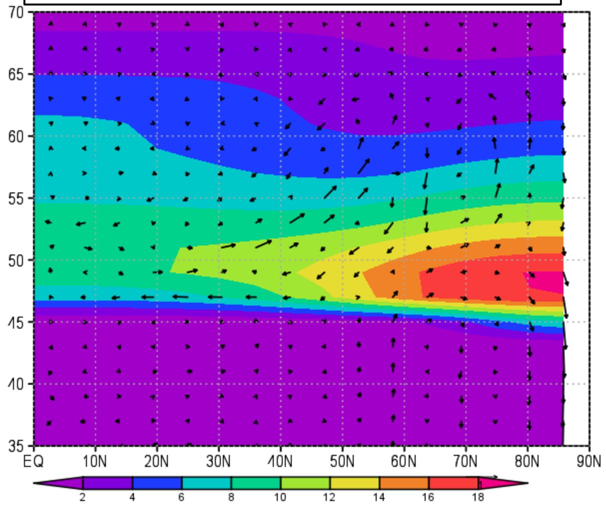
Water vapor



H_2SO_4 vapor

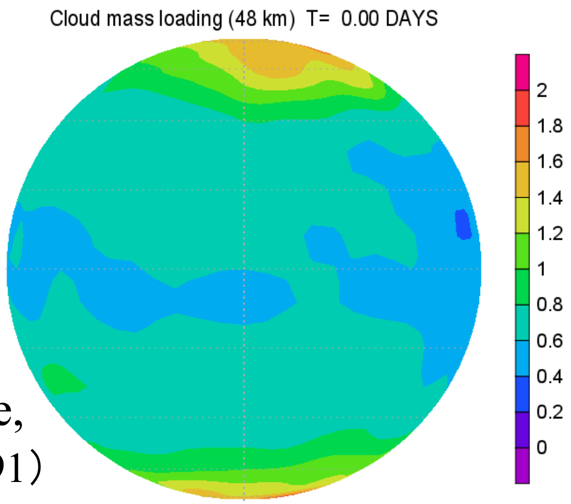


Mass loading and MMC



Data assimilation of clouds and radiance would be possible by implementation of physical processes.

Galileo obs.：many clouds are at pole, few at mid-latitude. Carlson et al. (1991)



Summary

Venus AFES LETKF Data Assimilation System* is introduced.

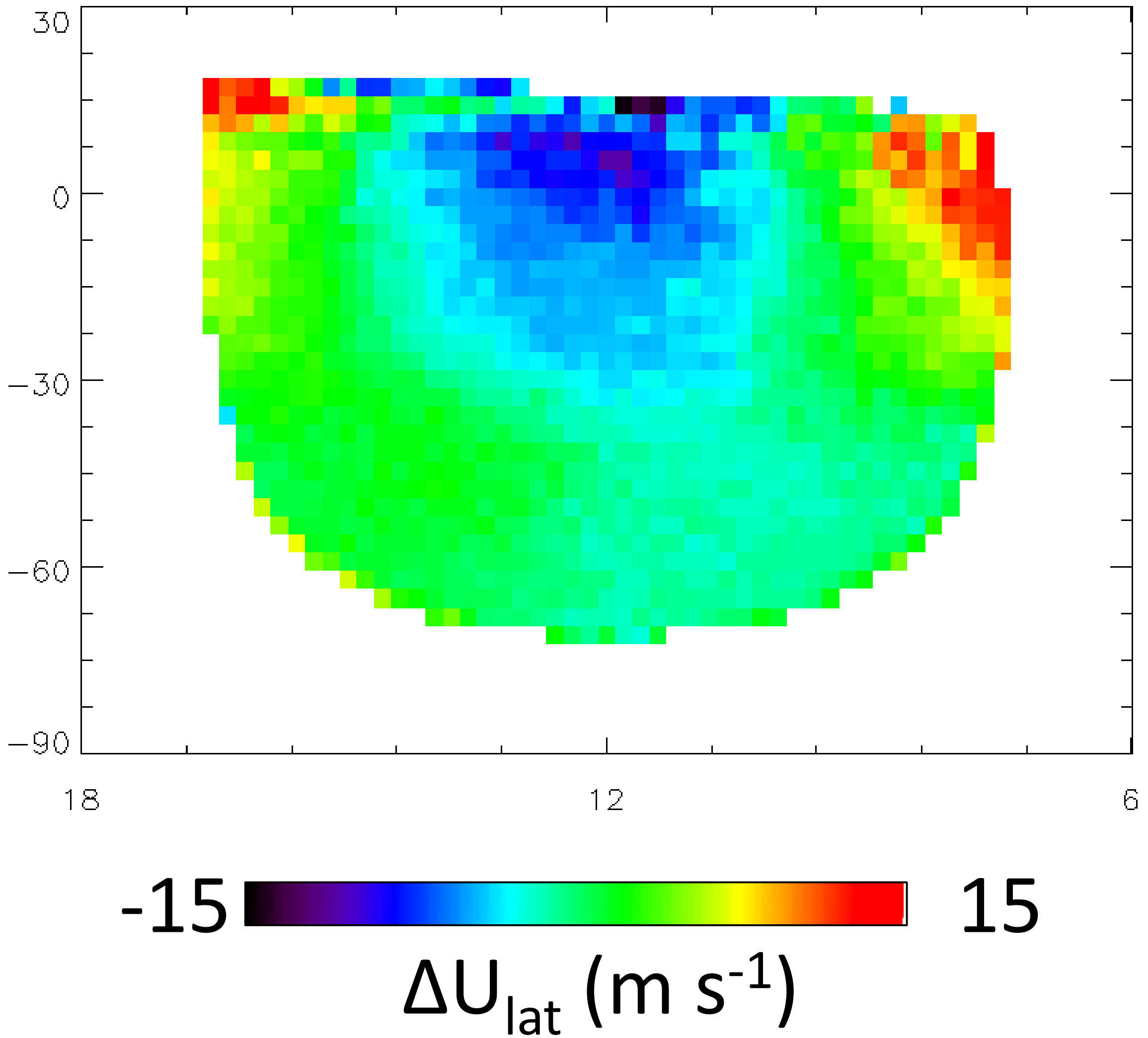
- ✓ ***The mechanism of the super rotation has not been revealed so far.***
  - *There is no GCM that reproduces realistic super rotation from a motionless state with realistic setting by the long time integration.*
- ✓ **AFES-Venus enables to maintain realistic super-rotation and reproduce atmospheric motions near the cloud level.**
  - *Several interesting results have been obtained and analyzed so far.*
  - *It is necessary to compare our results with obs. and other GCMs, consider more realistic model settings, and improve GCM physical processes.*
- ✓ **VALEDAS* is the first data assimilation system for the Venus atmosphere.**
  - Produce reanalysis datasets by the data assimilation of Akatsuki obs.
  - Estimate impacts of past real and future observations by EFSO.
  - It would be possible to assimilate other obs., such as cloud opacity and radiance, by improvement of physical processes of AVES-Venus...

References

- ✓ M. Takagi, N. Sugimoto, H. Ando, and Y. Matsuda, **Three dimensional structures of thermal tides simulated by a Venus GCM**, *Journal of Geophysical Research: Planets,* Vol. 123, (2018), 18pp.
- ✓ N. Sugimoto, A. Yamazaki, T. Kouyama, H. Kashimura, T. Enomoto, and M. Takagi, **Development of an ensemble Kalman filter data assimilation system for the Venusian atmosphere,** *Scientific Reports*, Vol. 7, (2017), 9321, 9pp.
- ✓ H. Ando, T. Imamura, N. Sugimoto, M. Takagi, S. Tellmann, M. Pätzold, B. Häusler, H. Kashimura, and Y. Matsuda, **Vertical structure of the axi-asymmetric temperature disturbance in the Venusian polar atmosphere: Comparison between radio occultation measurements and GCM results,** *Journal of Geophysical Research: Planets,* Vol. 122, (2017), 17pp.
- ✓ S. Lebonnois, N. Sugimoto, and G. Gilli, **Wave analysis in the atmosphere of Venus below 100-km altitude, simulated by LMD Venus GCM,** *Icarus*, Vol. 278, (2016), p38-51.
- ✓ H. Ando, N. Sugimoto, M. Takagi, H. Kashimura, T. Imamura, and Y. Matsuda, **The puzzling Venusian polar atmospheric structure reproduced by a general circulation model,** *Nature Communications*, Vol. 7, (2016), 10398, 8pp.
- ✓ N. Sugimoto, M. Takagi, and Y. Matsuda, **Waves in a Venus general circulation model**, *Geophysical Research Letters*, Vol. 41, (2014), p7461–7467.
- ✓ N. Sugimoto, M. Takagi, and Y. Matsuda, **Baroclinic modes in the Venus atmosphere simulated by GCM**, *Journal of Geophysical Research: Planets,* Vol. 119, (2014), p1950-1968.
- ✓ T. Imamura, T. Higuchi, Y. Maejima, M. Takagi, N. Sugimoto, K. Ikeda, and H. Ando, **Inverse insolation dependence of Venus' cloud-level convection,** *Icarus*, Vol.228, (2014), p181-188.
- ✓ A. Yoshizawa, H. Kobayashi, N. Sugimoto, N. Yokoi, and Y. Shimomura,**A Reynolds-averaged turbulence modeling approach to the maintenance of the Venus superrotation**, *Geophysical and Astrophysical Fluid Dynamics*, Vol.107, No.6, (2013), p614-639.
- ✓ N. Sugimoto, M. Takagi, Y. Matsuda, Y. O. Takahashi, M. Ishiwatari, and Y.-Y. Hayashi, **Baroclinic modes in the atmosphere on Venus simulated by AFES**, *Theoretical and Applied Mechanics Japan*, Vol.61, (2013), p11-21.

Thermal tide (VMC/VEX)

Kouyama et al. (in prep.)

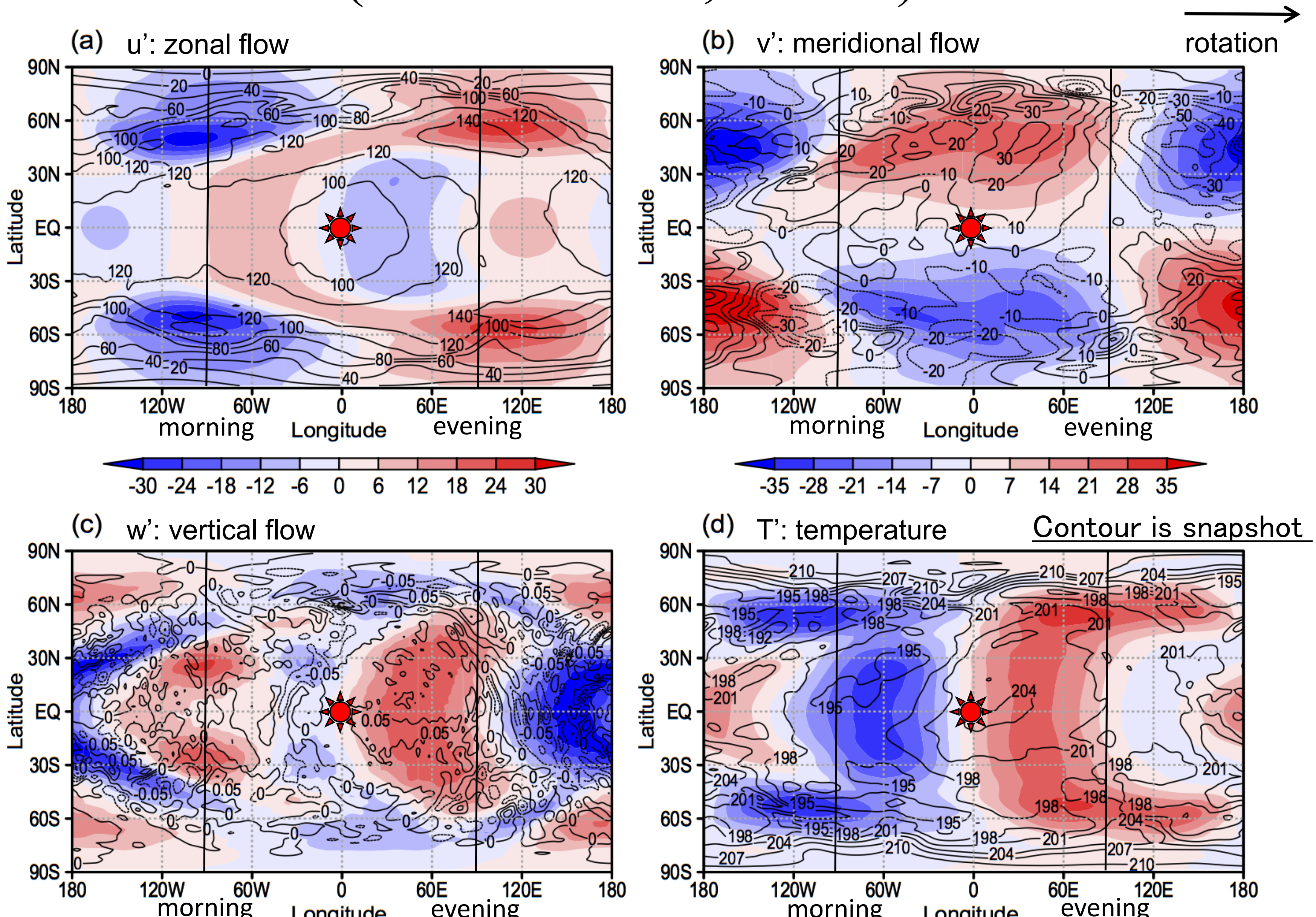


Clear local minimum around noon.

Morning and evening regions show faster.

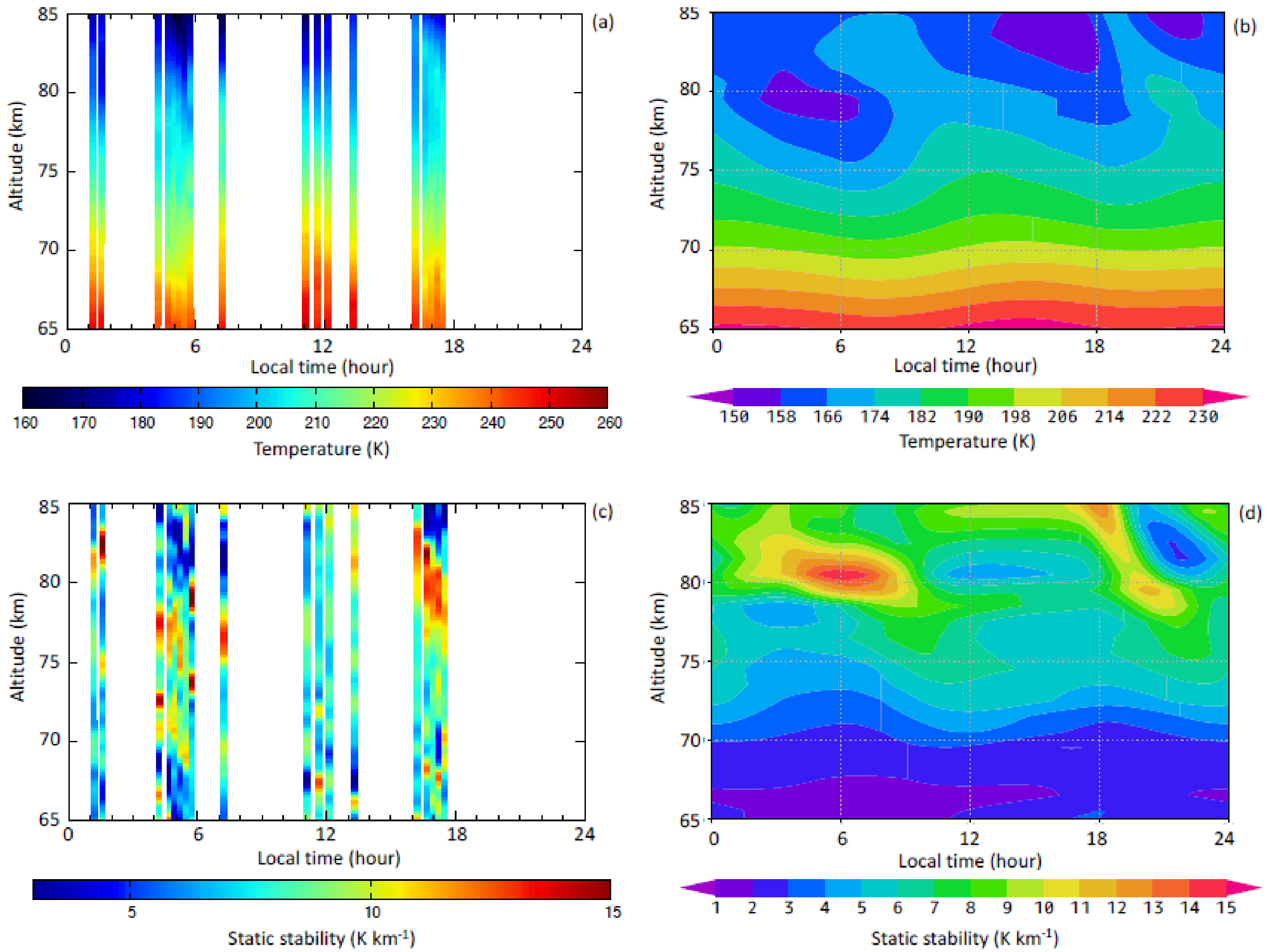
Thermal tide (AFES-Venus; 70 km)

Takagi et al. (JGR2018)



AFES-Venus; U' and T' change their signs at noon.

Thermal tide (Akatsuki RO & AFES-Venus)



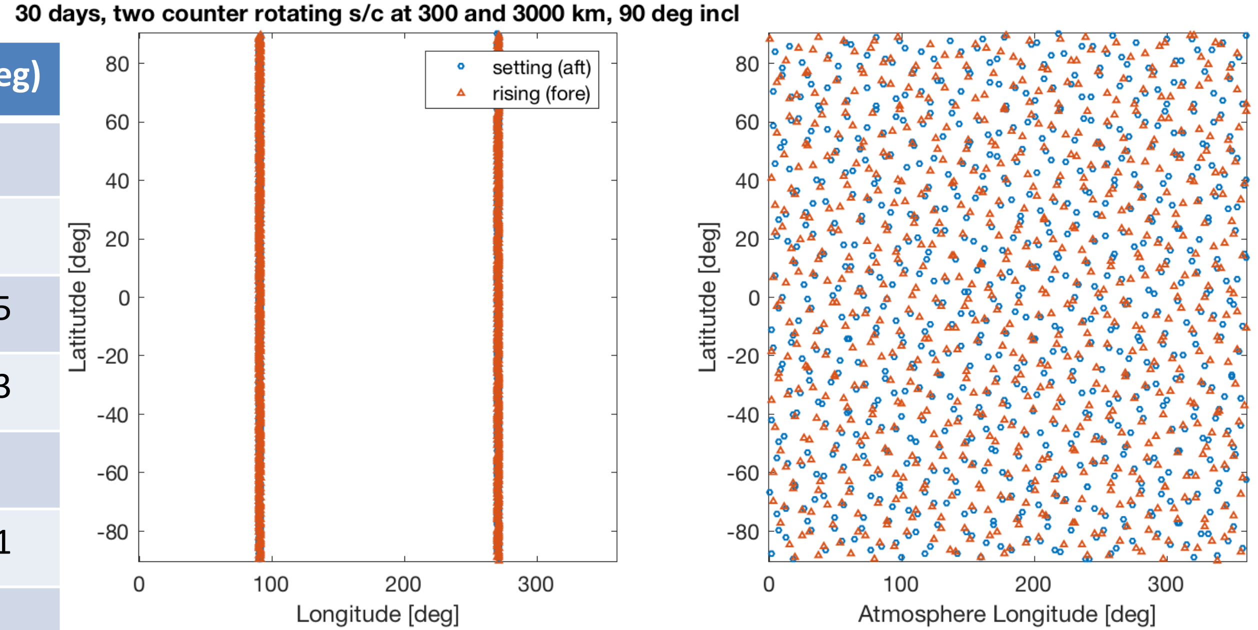
34 observations

Ando et al. (JGR2018)

Test orbit by two satellites (provided from Dr. Chi AO)

- ✓ Almost uniform horizontal coverage
- ✓ Time intervals are 2h or 4h alternately

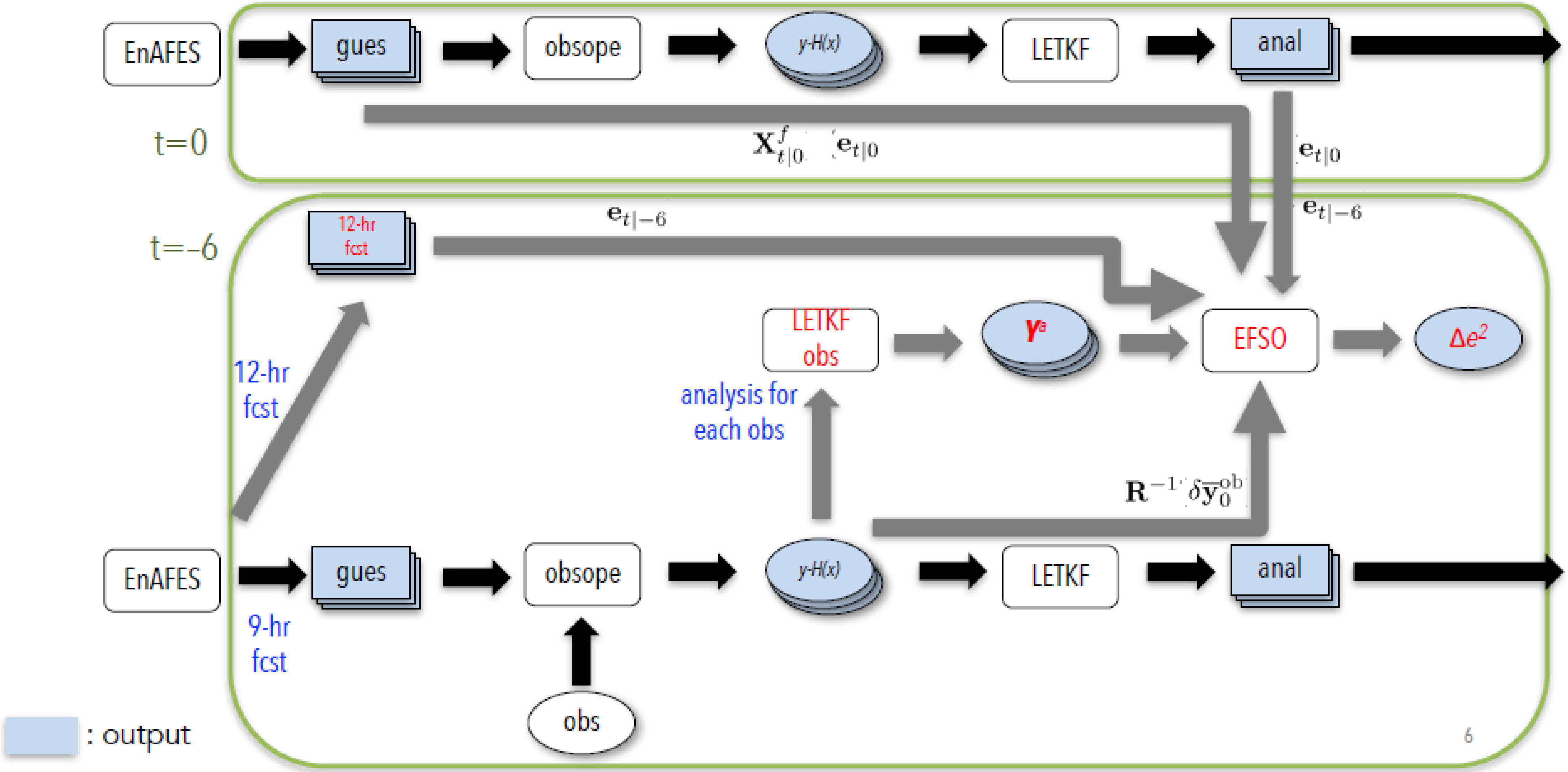
time(sec)	longitude(deg)	latitude(deg)
2139.	-89.222646	50.036357
3367.	90.798408	81.335689
5654.	-89.162380	-83.235865
6882.	-89.141326	-34.605783
9169.	90.897886	36.508091
10398.	90.918957	-12.101241
...	...	...



We can estimate how much observations improve GCM forecasts

Forecast-analysis cycle w/ EFSO

$$\Delta e^2 = (\delta \bar{\mathbf{y}}_0^{\mathrm{ob}})^{\mathrm{T}} \frac{1}{K-1} \mathbf{R}^{-1} \mathbf{Y}^a (\mathbf{X}_{t|0}^f)^{\mathrm{T}} \mathbf{C}(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6})$$

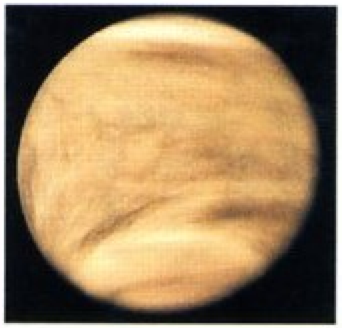


Yamazaki et al. (2018?)

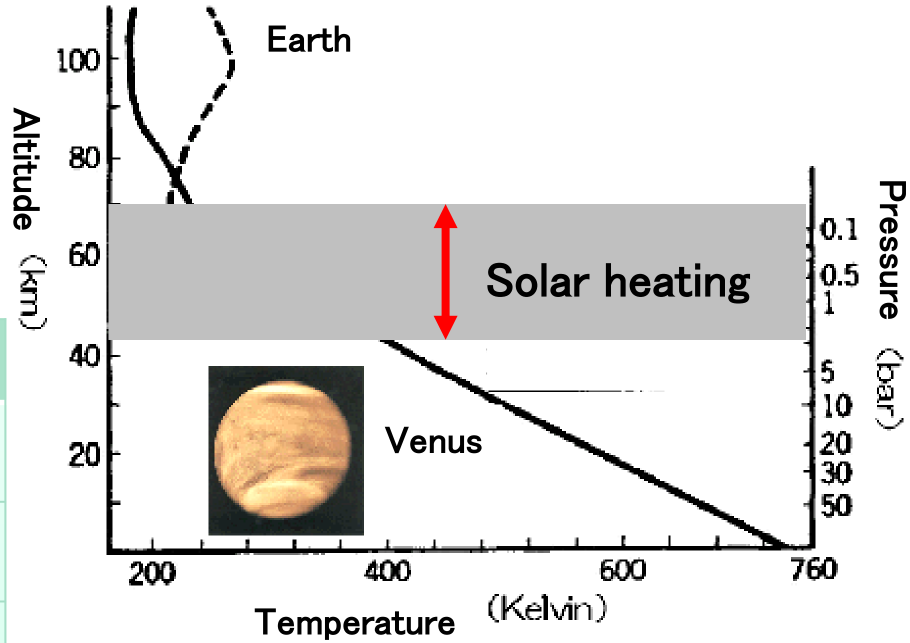
Two types of ensemble runs are performed to estimate impacts of observations.

1. Why Venus?

UV observation



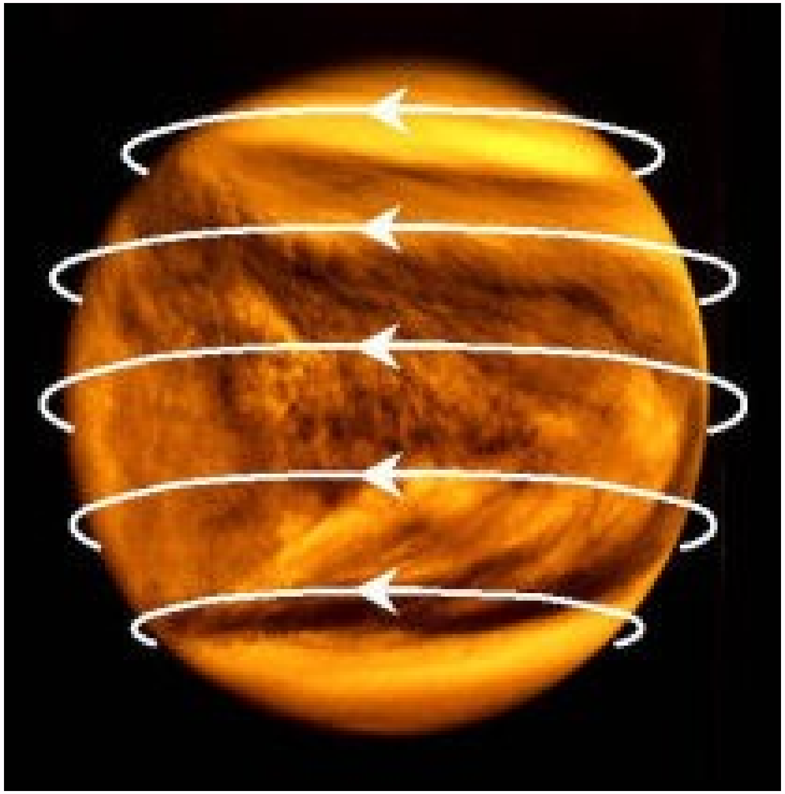
	Venus	Earth
Radius	6050 km	6378 km
Revolution	224 days	365 days
Rotation	243 days (1.8m/s)	1 day (460m/s)
1 solar day	117 days	1 day
Composition	CO_2	N_2, O_2
Albedo	0.78	0.3
Surface pres.	92 bar	1 bar

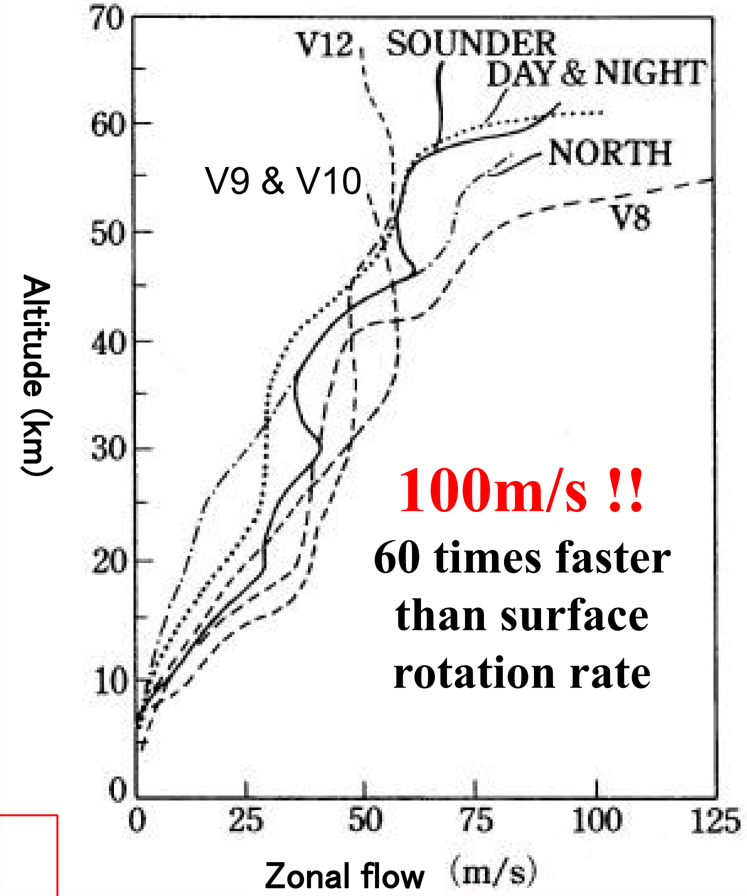


- ✓ **Very slow rotation**
- ✓ **Dense CO_2 atmosphere**
- ✓ **Thick cloud layer (45～70km)**

Mystery of Venus's atmosphere

"Super rotation" (fast zonal flow)





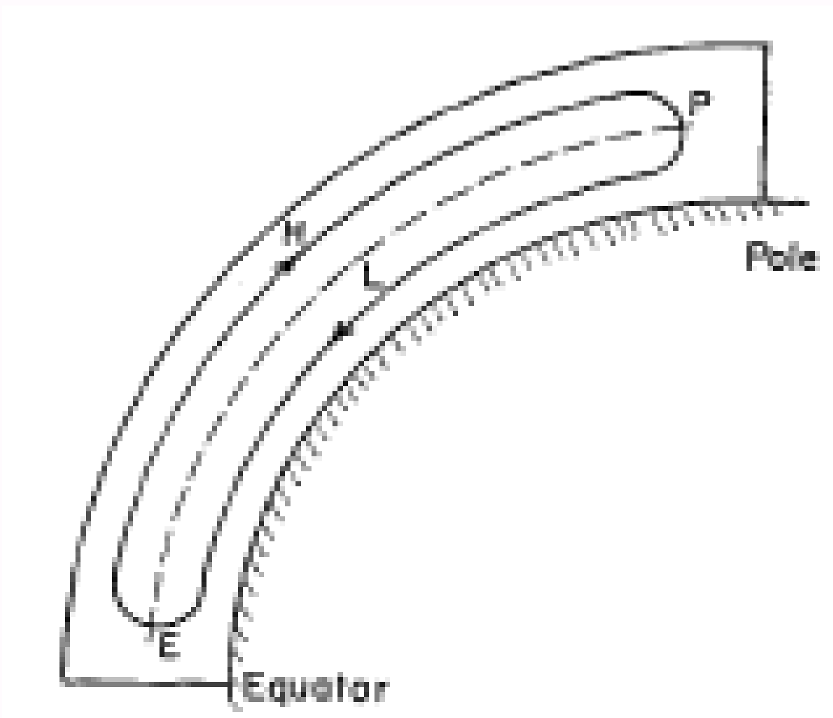
Schubert et al. (1980)

✓ 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)

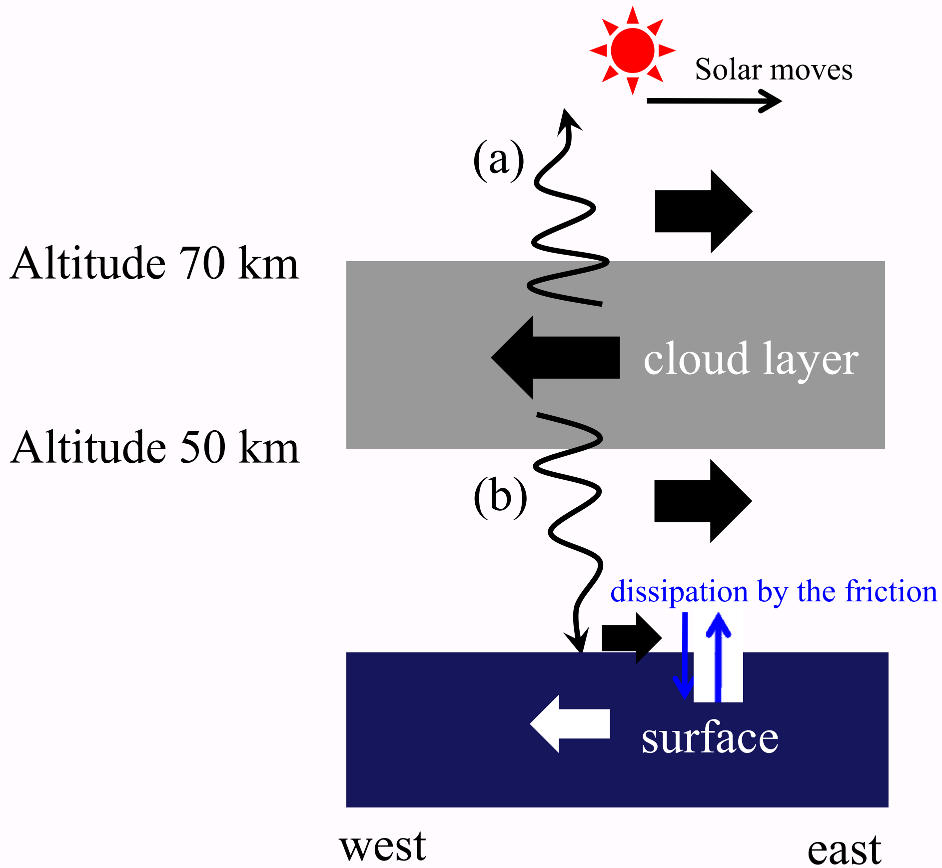
Mechanism of the super rotation

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**

Venus GCM studies

- **Super rotation might be driven by both mechanism**
  - ✓ Mean meridional circulation (*Yamamoto & Takahashi(YT), 2003…*)
  - ✓ Thermal tides (*Takagi & Matsuda, 2007…*)

Basically, starting from motionless state, long time integration, low resolution, not realistic solar heating and static stability

References	Horizontal resolution		Vertical grid
Yamamoto & Takahashi (2003)	T10 (~ 11° × 11°)	32×16 grids	50 levels
Lee et al. (2005)	5° × 5°	72×36 grids	32 levels
Kido & Wakata (2008)	T21 (~ 5.6° × 5.6°)	64×32 grids	60 levels
Takagi & Matsuda (2007)	≦T21 (~ 5.6° × 5.6°)	64×32 grids	60 levels
Lebonnois et al. (2010)	7.5° × 5.6°	48×32 grids	50 levels
Parish et al. (2011)	1.2° × 0.9°	300×200 grids	50 levels

GCMs: large computational cost for high resolution run
Obs.: difficulty to observe MMC and inside cloud layer

Hollingsworth et al. (GRL2007)

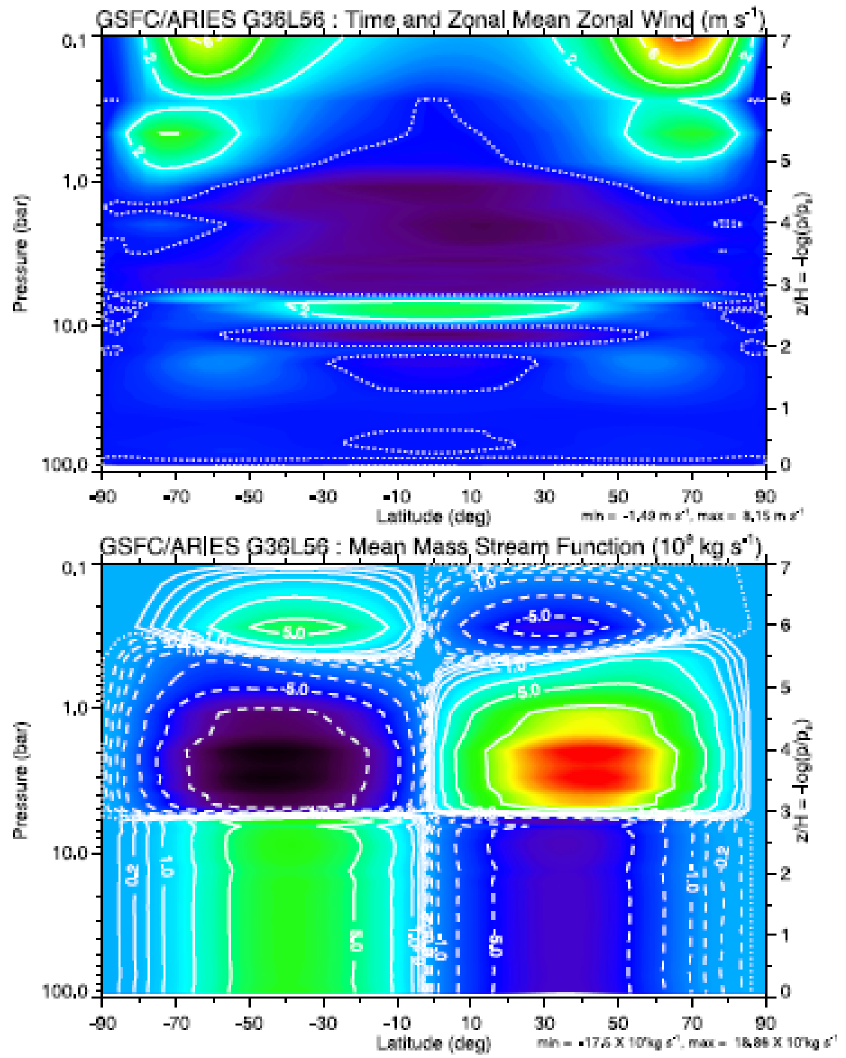


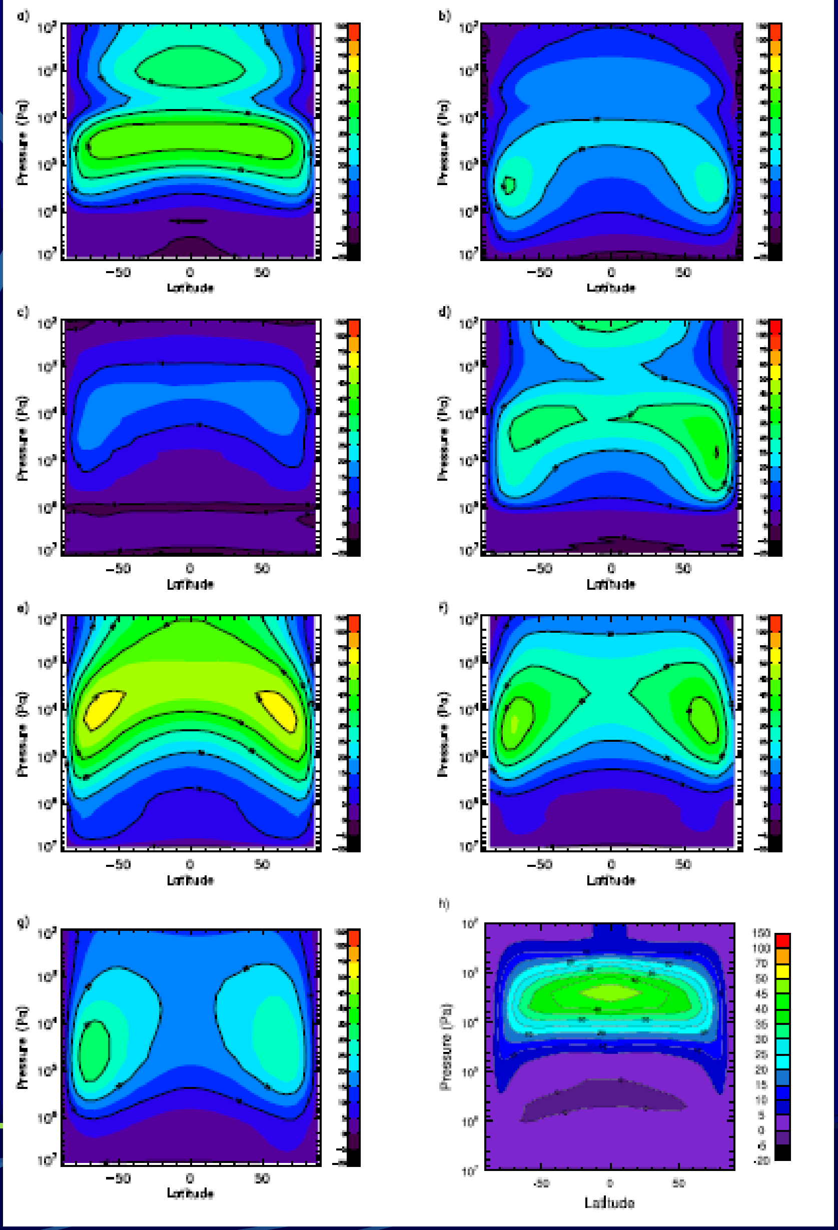
Figure 4. As in Figure 2 but for a simulation that uses a more realistic diabatic heating in the lower atmosphere (i.e., below 35 km).

With realistic diabatic heating, weak super rotation results.

Mean Meridional Circulation (i.e., Hadley circulation) consists of numerous cells.

Further Venus GCM studies

Lebonnois et al. (2013)



Intercomparison project

- ✓ Super rotations are quite different among the models

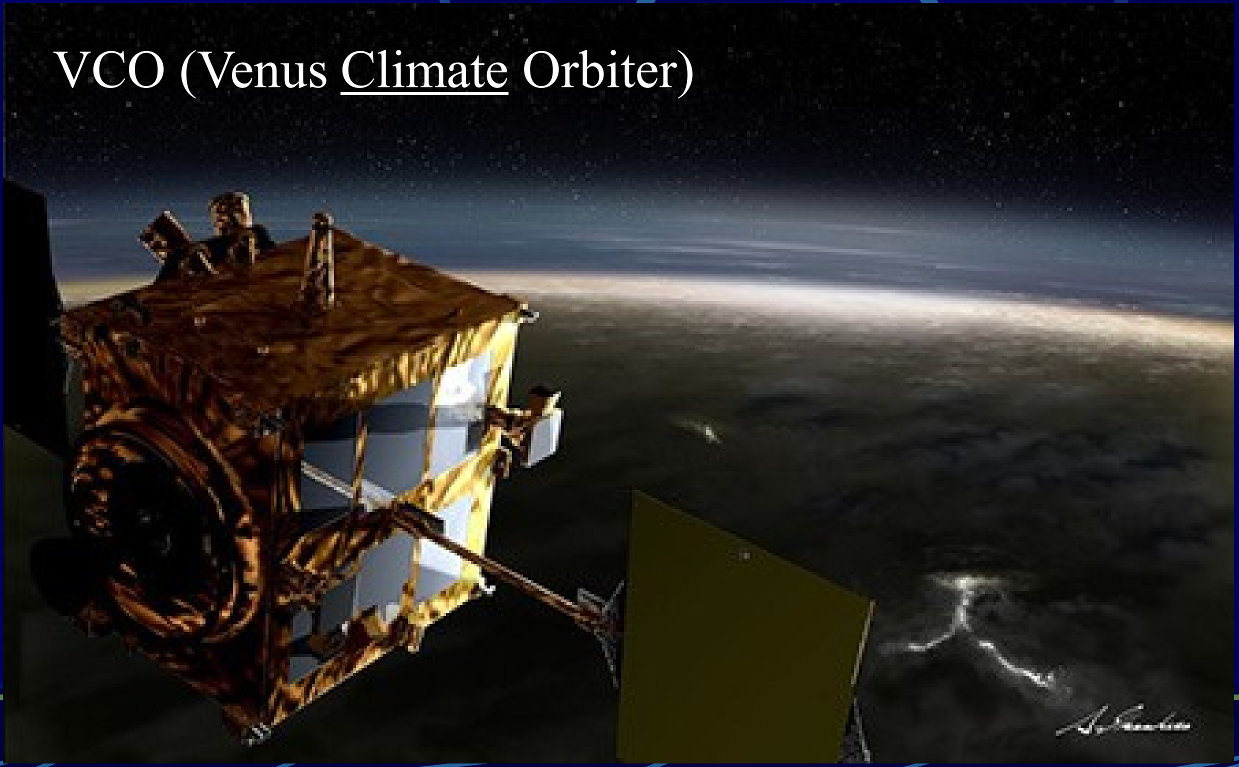
Multiple equilibrium?
Waves or Missing processes?

More realistic GCM

- ✓ Radiation *(Ikeda2011, Lebonnois2015)*
- ✓ Gravity wave parameterization
- ✓ Microphysics *(YT2006)*
- ✓ Topography *(Lebonnois et al., 2010)*
- ✓ Middle atmosphere *(YT2011, Gilli2015)*
- ✓ Non-hydrostatic *(Mingalev et al., 2012)*

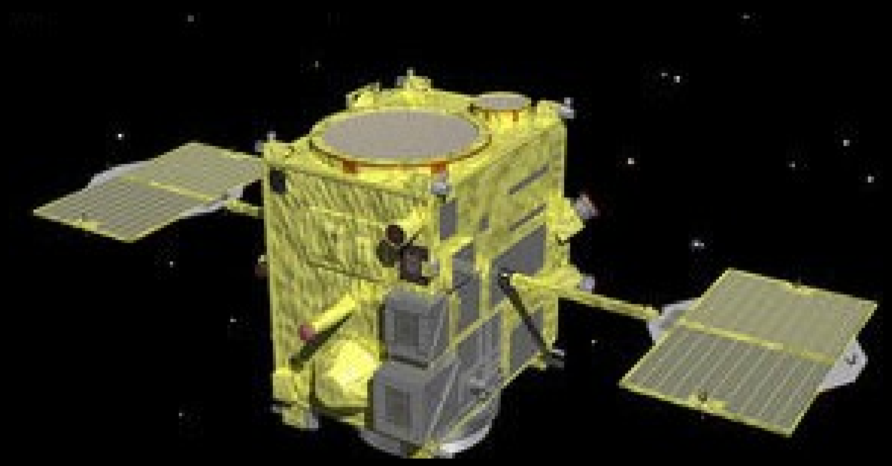
Akatsuki

20th, May, 2010. Launched aboard an H-IIA rocket.
6th, Dec, 2010. Failed to enter orbit around Venus.
Trouble for main engines.
7th, Dec, 2015. Enter an alternative elliptical Venusian orbit
by firing its attitude control thrusters.



To understand Venus climate

Satellite observation



Venus Climate Orbiter（Akatsuki from 2016）

Observe temperature, wind, cloud and constituents distribution, and lightning...

Numerical simulation

Super computing system (Earth simulator)
（https://www.jamstec.go.jp/j/kids/press_release/20101117/）

Elucidate generation and maintenance mechanisms for observed phenomena

High resolution AFES-Venus run on the Earth Simulator

Our 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 forcing

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)*

Now we perform T42L60 ~ T319L240, **T639L260** run

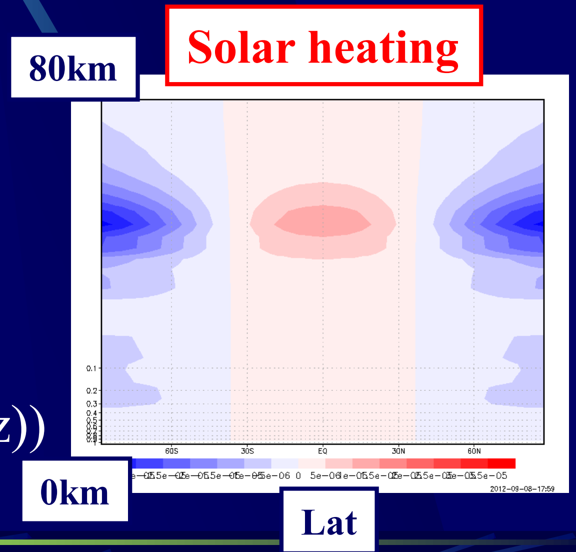
2. AFES-Venus <u>see Sugimoto et al. (JGR2014a)</u>

Model description

- ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
- ✓ Resolution: T42L60, T63 to T639L120 ($\Delta x \sim 20$km $\Delta z \sim 1$km), T319L240…
- ✓ Specific heat: Cp is constant (1000 $Jkg^{-1}k^{-1}$)
- ✓ Horizontal hyper-viscosity: 0.1(T42) to 0.003(T639) Earth days for 1/e
- ✓ Vertical eddy viscosity: $0.15 m^2 s^{-1}$
- ✓ Rayleigh friction: lowest and above 80km(sponge layer except for zonal flow)
- ✓ No topography and planetary boundary layer

Solar heating

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



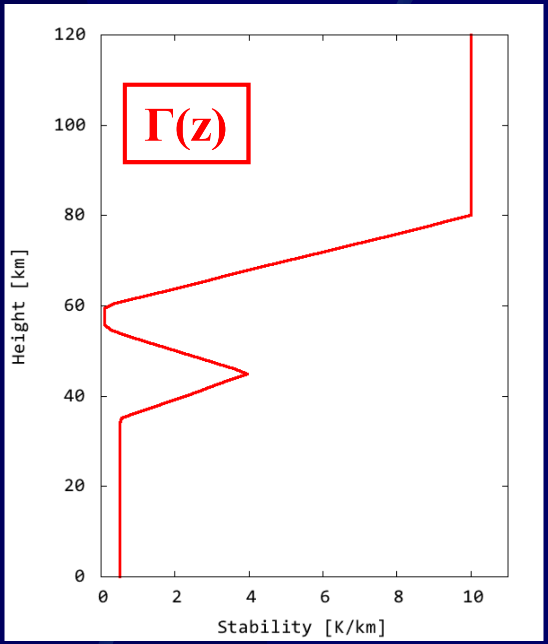
Infrared radiative process

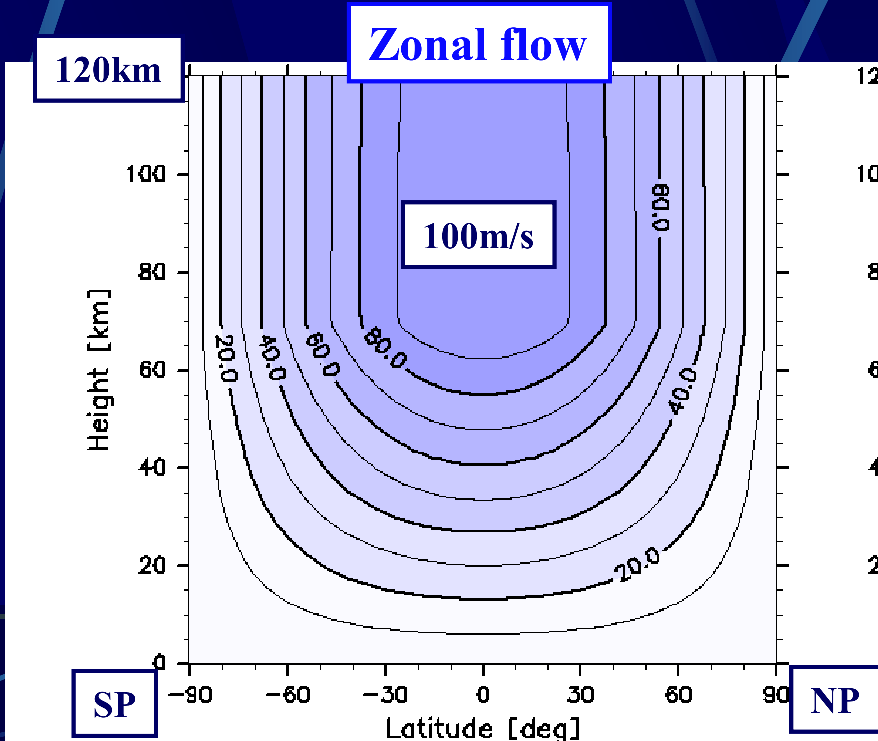
- ✓ Simplified by <u>Newtonian cooling</u>: $dT/dt = -\kappa\,(T - T_{ref}(z))$

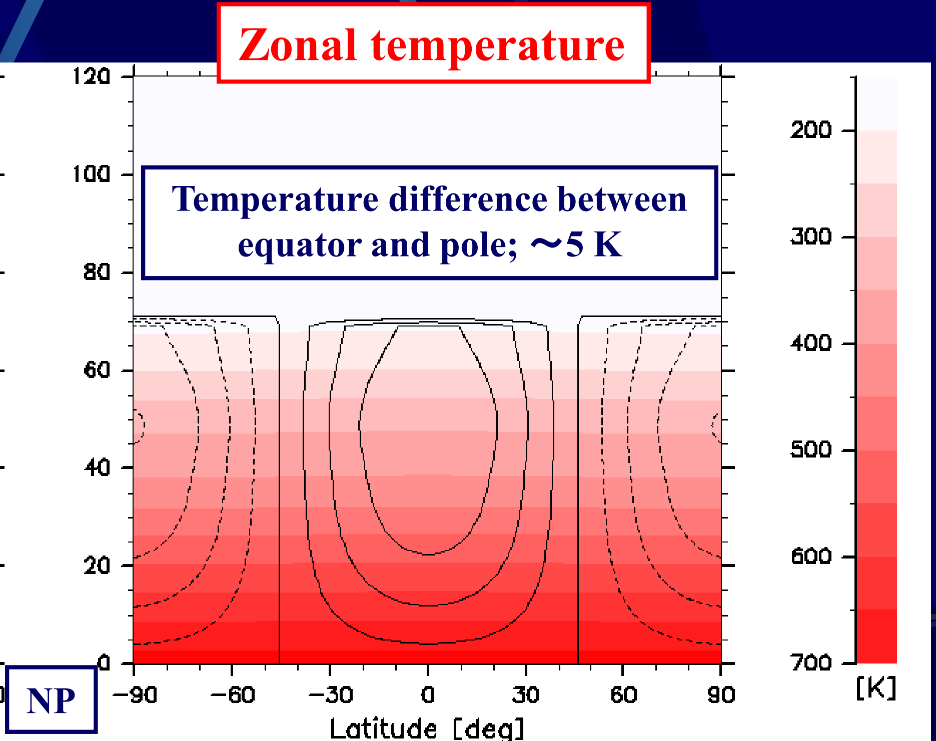
  κ: based on Crisp (1986)

  $T_{ref}(z)$: horizontally uniform field

- Initial condition: Super-rotation
  - ✓ Zonal flow increases with height linearly from ground to 70 km. 100 m/s above 70 km (const.).
  - ✓ Meridional distribution: solid-body rotation.
  - ✓ Temperature field is in balance with zonal flow field (gradient wind balance).
- Static stability: Γ(z) = dT/dz + g/Cp
  - ✓ Mimic observed realistic static stability.

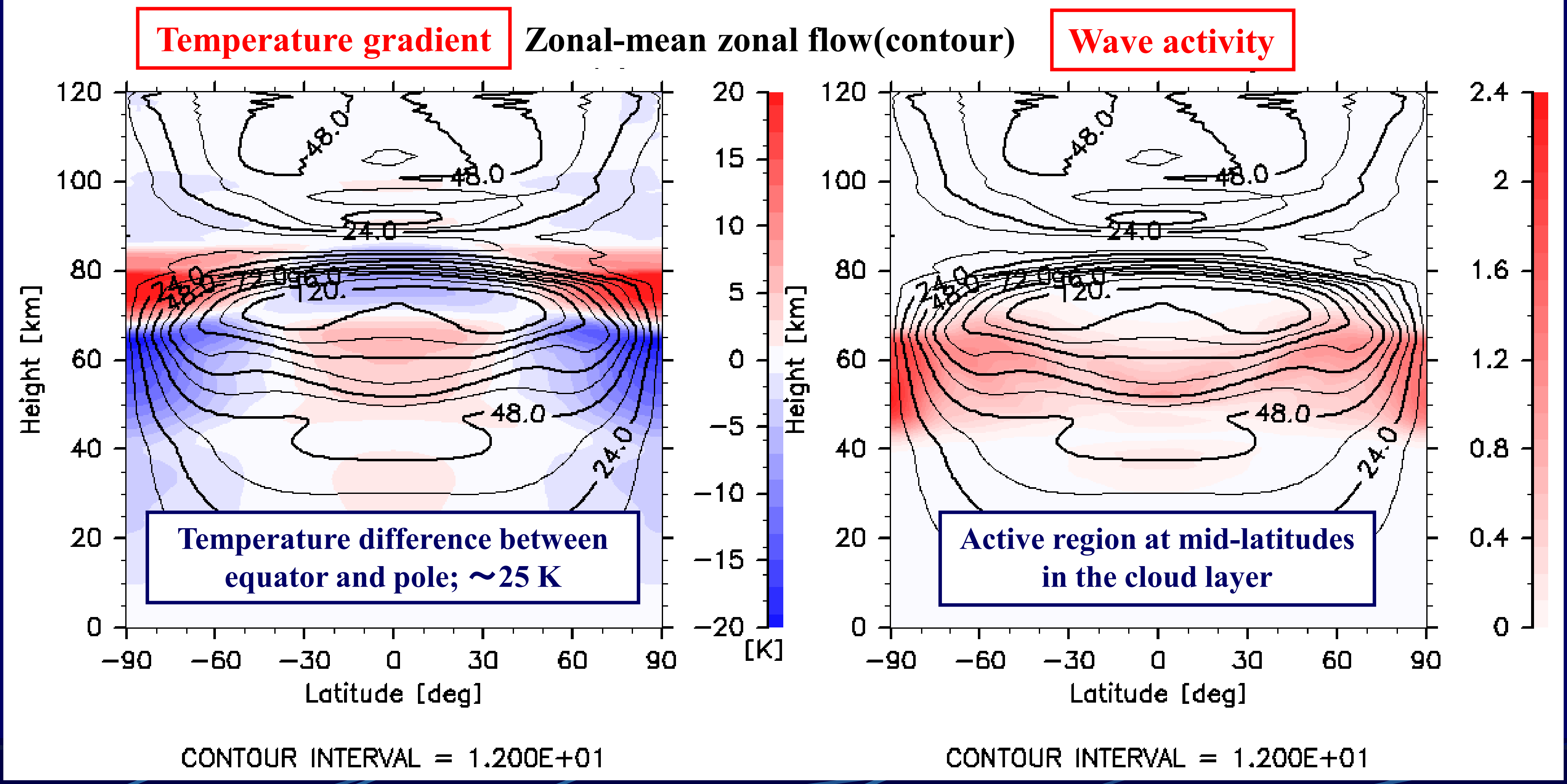






Summary results

- **Realistic super-rotation is reproduced** (more than 10 Earth years).
  - ✓ Acceleration in equatorial region by thermal tides (120m/s).
  - ✓ Temperature difference between equator and pole; more than 25 K.

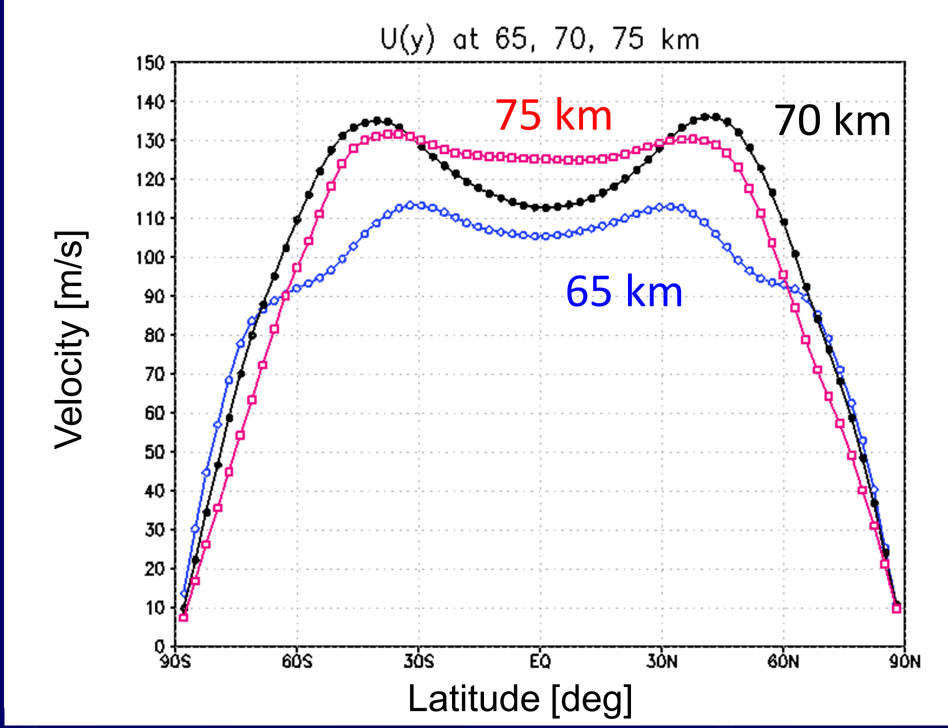


(T63L120 run) **See Sugimoto et al. (GRL2014)**

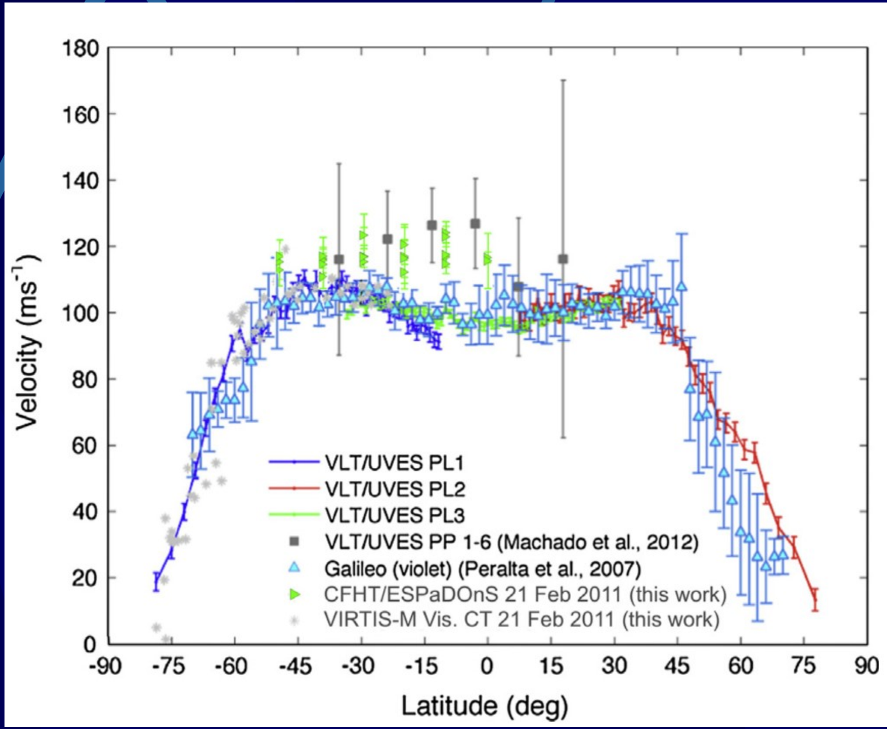
Super-rotation near the cloud

- ✓ Constant velocity at equatorial region with weakly mid-latitude jets.
- ✓ Close agreement with observations. (for the first time in GCM)

AFES results



Observations: Doppler measurements



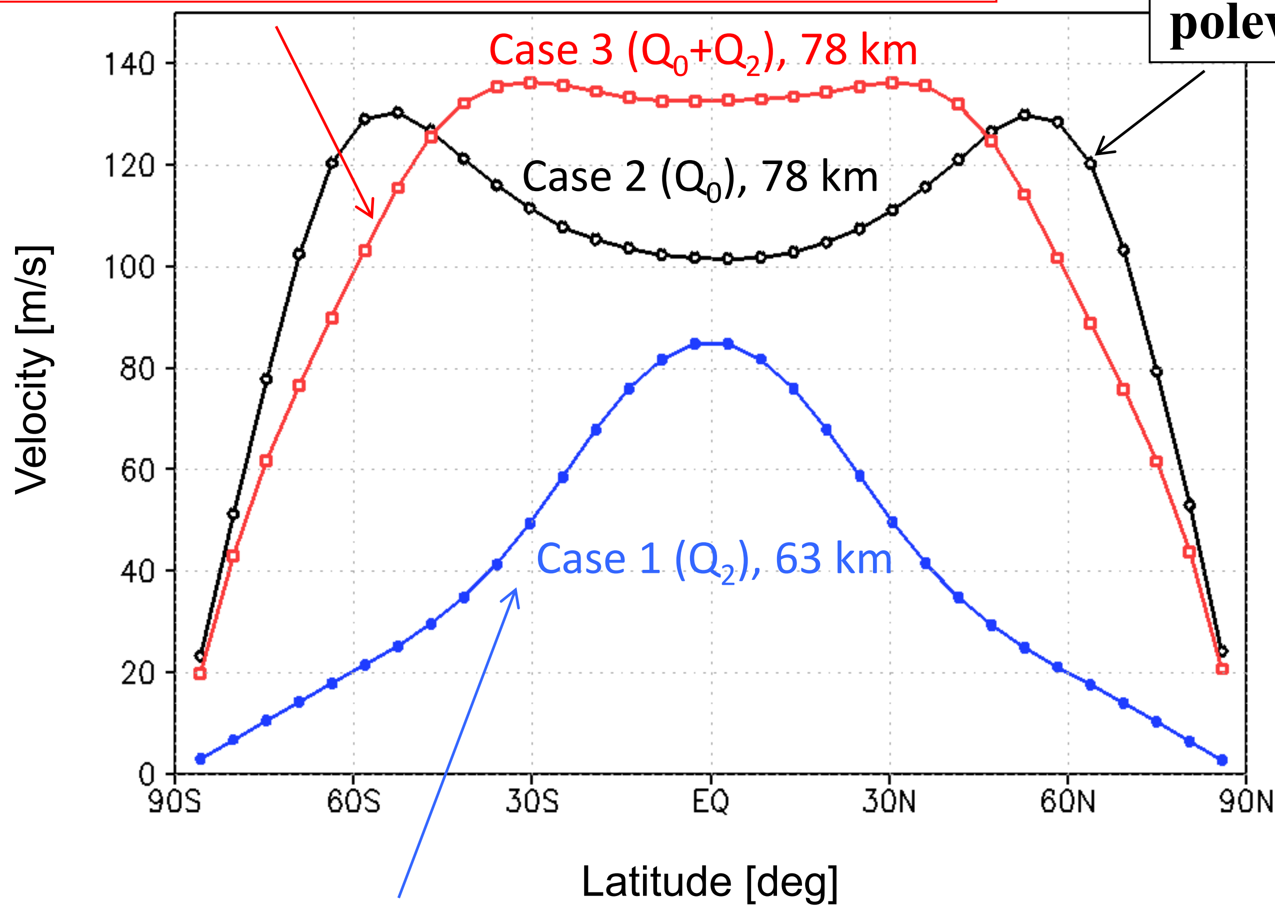
Machado et al. (2014)

Thermal tide transports angular momentum equatorward

MMC and thermal tide mechanisms

MMC and thermal tide:
Super rotation with almost constant velocity at equatorial region at the cloud top level is maintained

MMC only:
Mid-latitude jet by poleward transport



Thermal tide only: Equatorial jet by equatorward transport

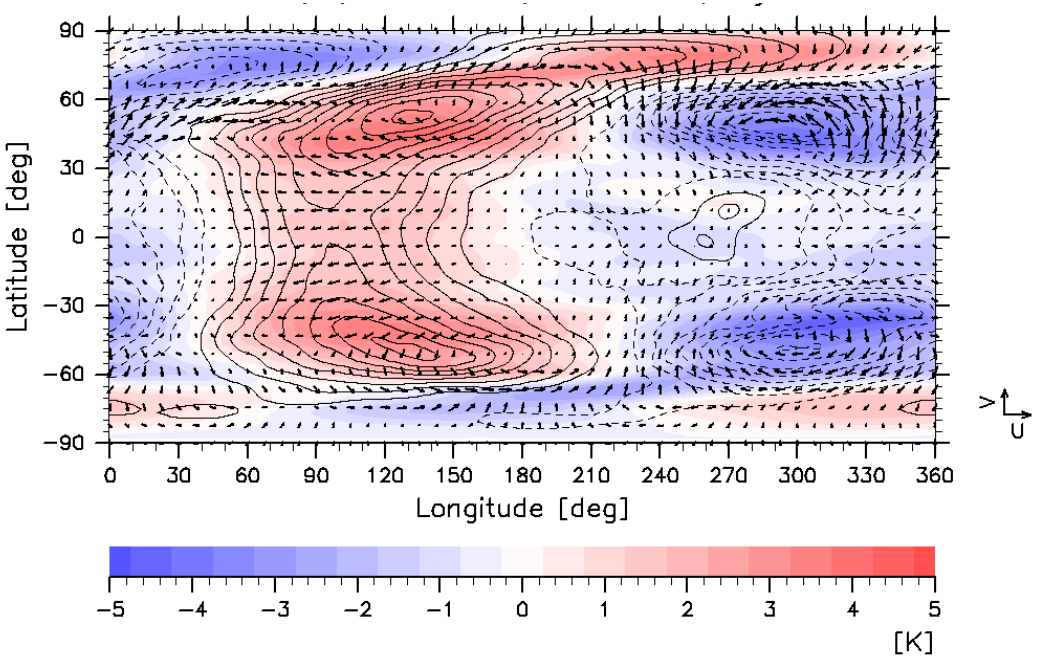
Takagi et al. (in prep)

Horizontal structure similar to obs. (cloud pattern)

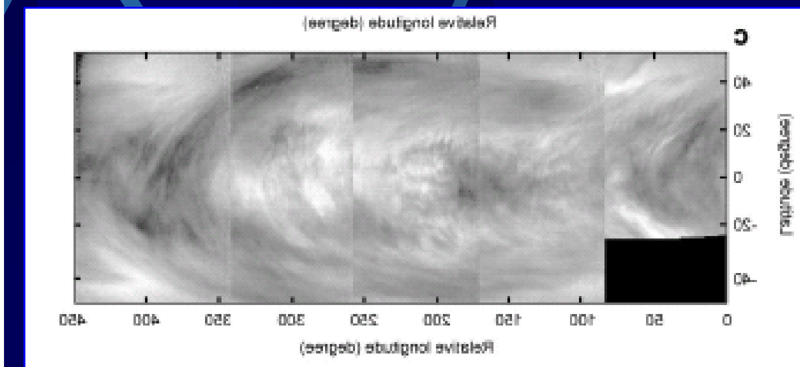
- ✓ Lifecycle of baroclinic wave appears by temperature gradient（vertical shear）

AFES results

Geopotential height (contour), wind (vector), temperature (color) at 70km



Observations: Cloud brightness distribution



Belton et al. (1991)

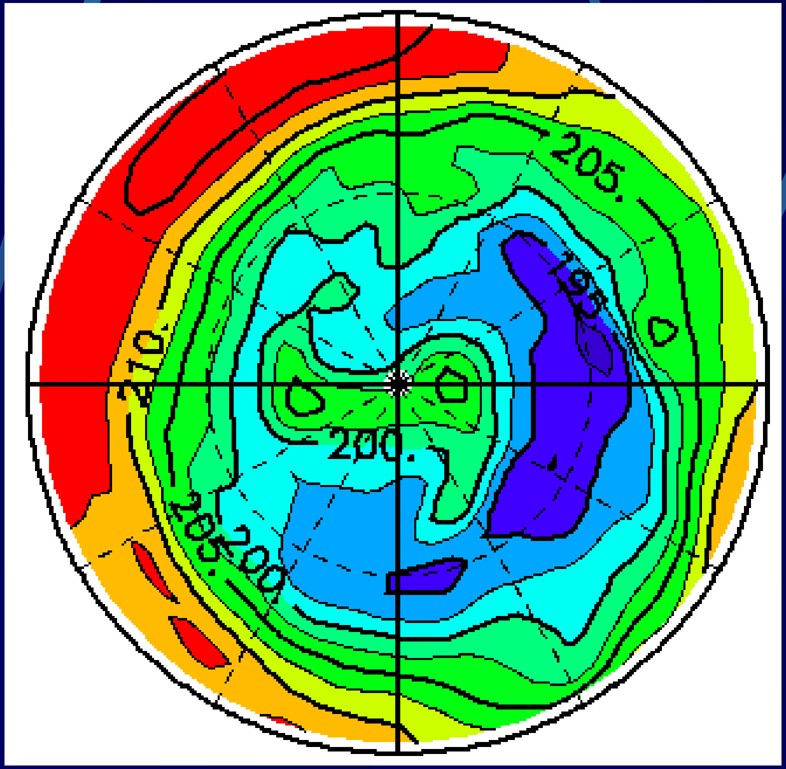
Rotation

Y-shape would be caused by baroclinic wave（Sugimoto et al., JGR2014 & GRL2014）

Polar vortex & Cold collar (T42L60 run)

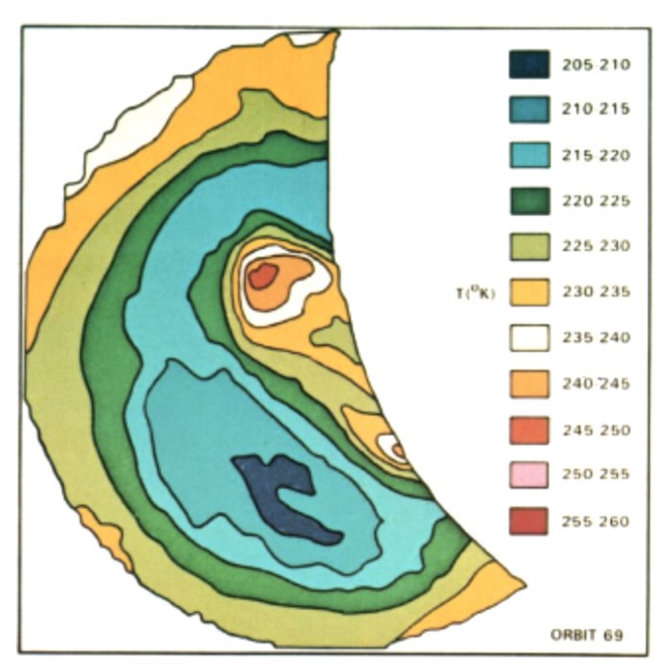
- ✓ Warm "S-shaped" polar vortex with cold latitudinal band "cold collar"

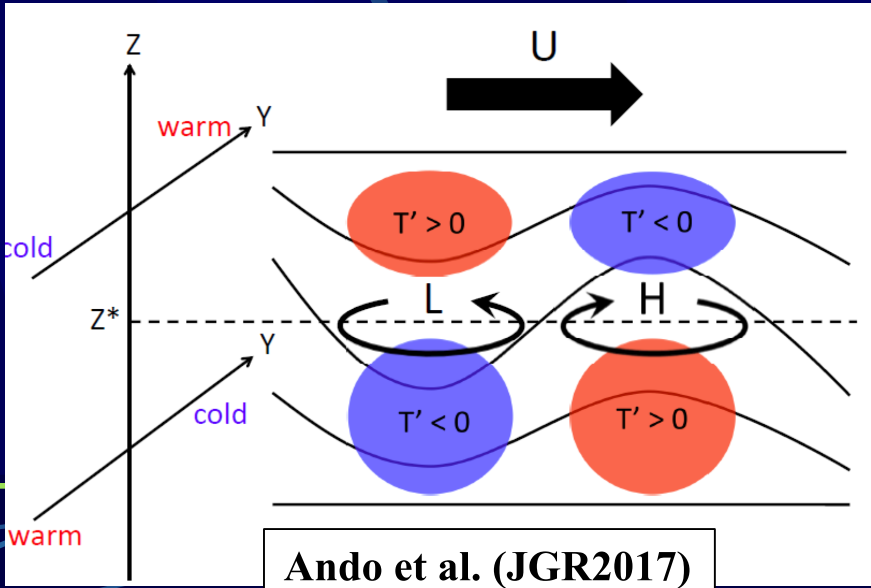
Puzzling structure is well reproduced in Venus GCM for the first time



Ando et al. (Nature Communication 2016)

Taylor et al.(1980)





Ando et al. (JGR2017)

Ando, H., N. Sugimoto, M. Takagi, H. Kashimura, T. Imamura, and Y. Matsuda,
The puzzling Venusian polar atmospheric structure reproduced by a general circulation model,
Nature Communications, Vol. 7, (2016), 10398, p1-8.

慶應義塾
Keio University

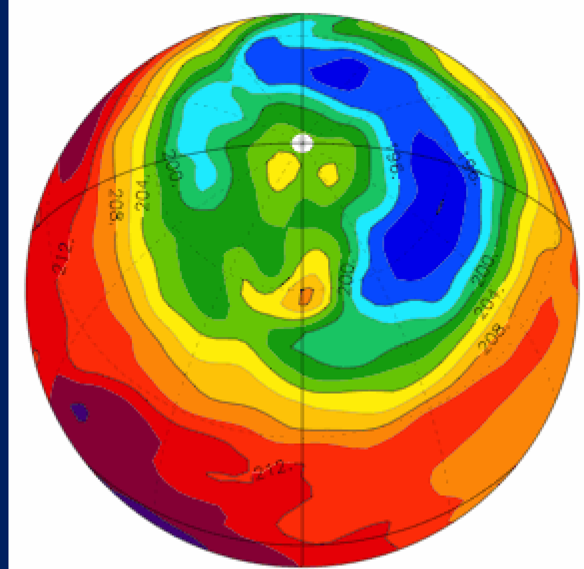
2016/02/02 Press release

[プレスリリース]
金星極域の高温の生成・維持メカニズムを理論的に解明

研究

2016/02/01 国立研究開発法人 宇宙航空研究開発機構
慶應義塾大学
京都産業大学

国立研究開発法人宇宙航空研究開発機構（JAXA）の安藤紘基宇宙航空プロジェクト研究員および慶應義塾大学の杉本憲彦准教授らによる研究チームは、大規模なコンピュータシミュレーションから、金星の極域上空の大気に生じている特異な気温分布を世界で初めて再現し、その生成・維持メカニズムを理論的に解明することに成功しました。



Asahi newspaper

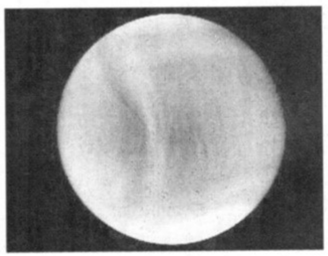
Morning newspaper 2016/02/02

金星上空 赤道から南北に気流

探査機「あかつき」で観測へ

金星の北極や南極の上空の気温が周りより高いのはなぜか。謎に迫るシミュレーション結果を宇宙航空研究開発機構（JAXA）の安藤紘基研究員らがまとめた。赤道から南北に向かう大きな大気の流れがあり、これが影響しているとみられるという。４月から本格的に始まる金星探査機「あかつき」の観測で実際の大気の流れを確かめる。１日付の英科学誌ネイチャーコミュニケーションズに発表した。

金星の大気は二酸化炭素が多くを占め、星全体を巡る高速の風が吹くなど気象は地球と大きく異なる。1970年代の探査で、高度60～70㌔の気温は、北極や南極のほうが周囲よりも20度ほど高い零下30度ほどであることが分かっていた。研究チームが高度120㌔までの大気の動きをコンピューターで再現したところ、高度80㌔以上に赤道から南北に向かう大きな流れがあり、北極と南極の上空で強い下降気流を起こし、温度を上げているとみられるという。（奥村輝）



あかつきが撮影した金星の赤外線画像。北極や南極が白く写り、周辺より温度が高いことが分かる＝JAXA提供

Nikkei newspaper

金星極域の高温解明

ＪＡＸＡなど 大気圧縮で加熱

宇宙航空研究開発機構（ＪＡＸＡ）などは1日、金星の北極と南極が高温になる仕組みをコンピューターシミュレーションで解明したと発表した。

金星の軌道には昨年12月、日本の探査機「あかつき」が到着しており、4月からの本格観測で裏付けを目指す。論文は1日付の英科学誌ネイチャー・コミュニケーションズに掲載された。

地球の極域は寒冷だが、金星の極域は温度が高いことが観測で判明している。赤道などに比べ、極域は太陽からのエネルギーが少なく寒冷になるはずなのに、なぜ金星では温度が高いのか分かっていなかった。

ＪＡＸＡの安藤紘基研

探査機「あかつき」が撮影した金星。画面下の南極域など温度の高い部分が白く写っている（昨年12月7日）＝宇宙航空研究開発機構提供

Energy Spectra (T159L120 run)

$$E_n = \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}\left(|\tilde{\zeta}_m^n|^2 + |\tilde{D}_m^n|^2\right)$$

✓ Rotational & divergent component

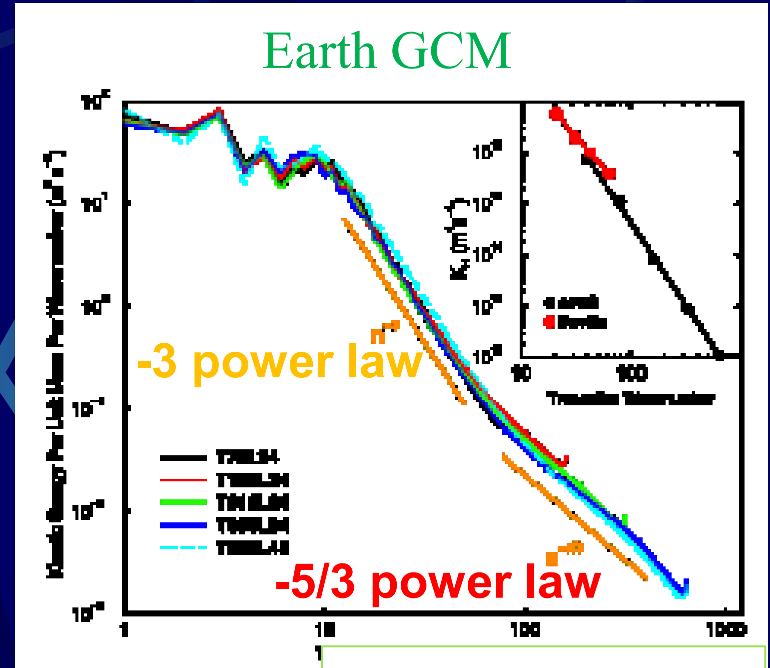
$$E_n^{\mathrm{R}} \equiv \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}|\tilde{\zeta}_m^n|^2$$

balanced flow; Rossby waves

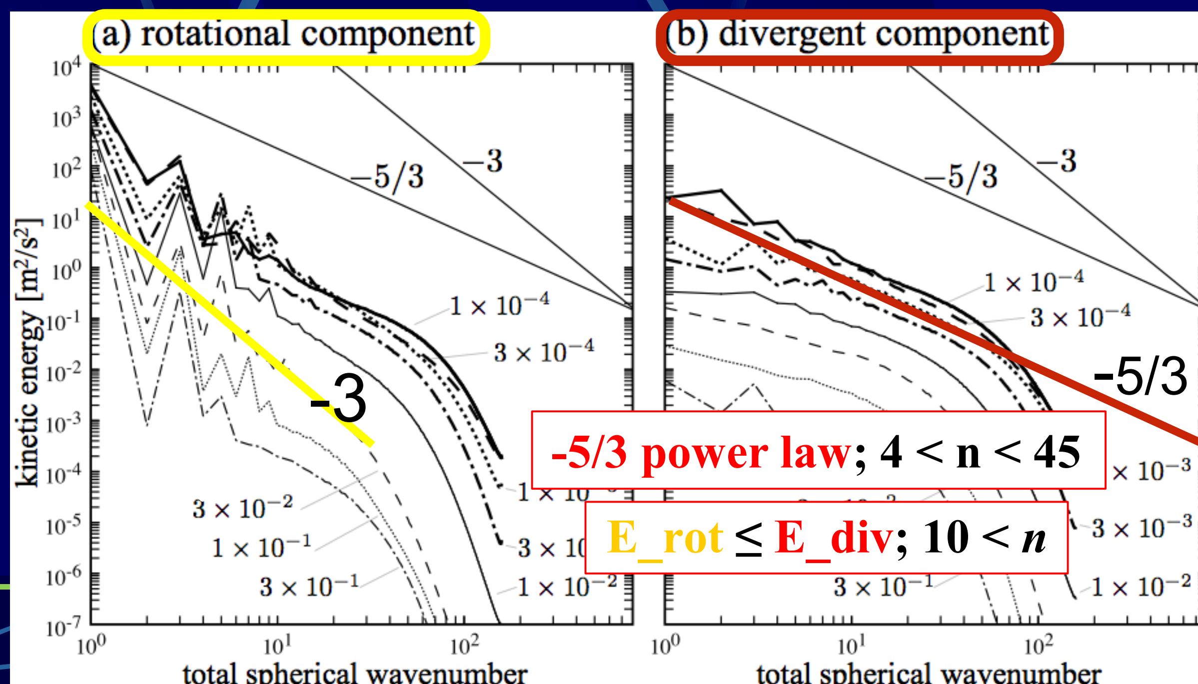
$$E_n^{\mathrm{D}} \equiv \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}|\tilde{D}_m^n|^2$$

unbalanced flow;
gravity waves

Gravity waves are more important than Earth



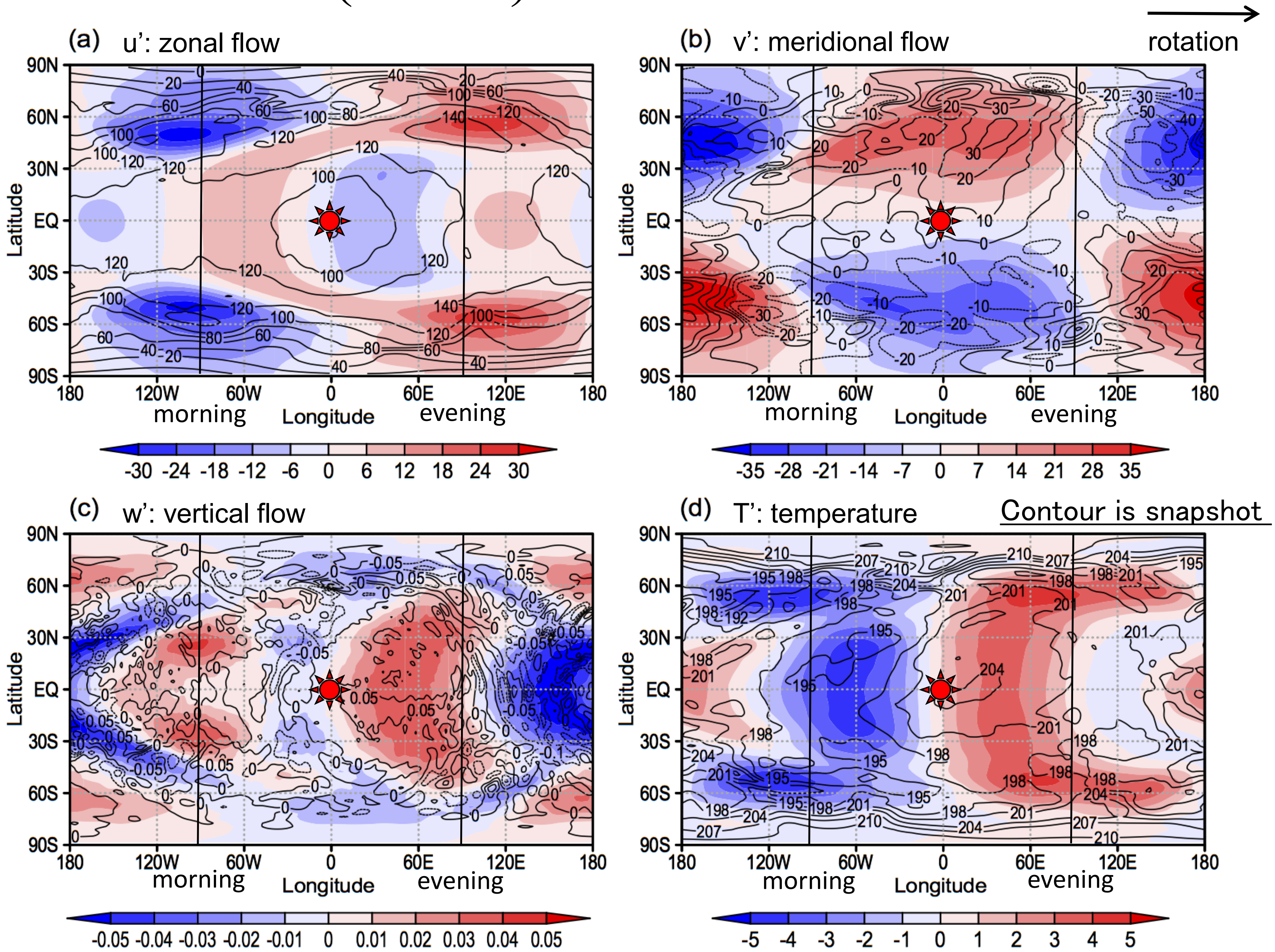
Takahashi et al.(2006)



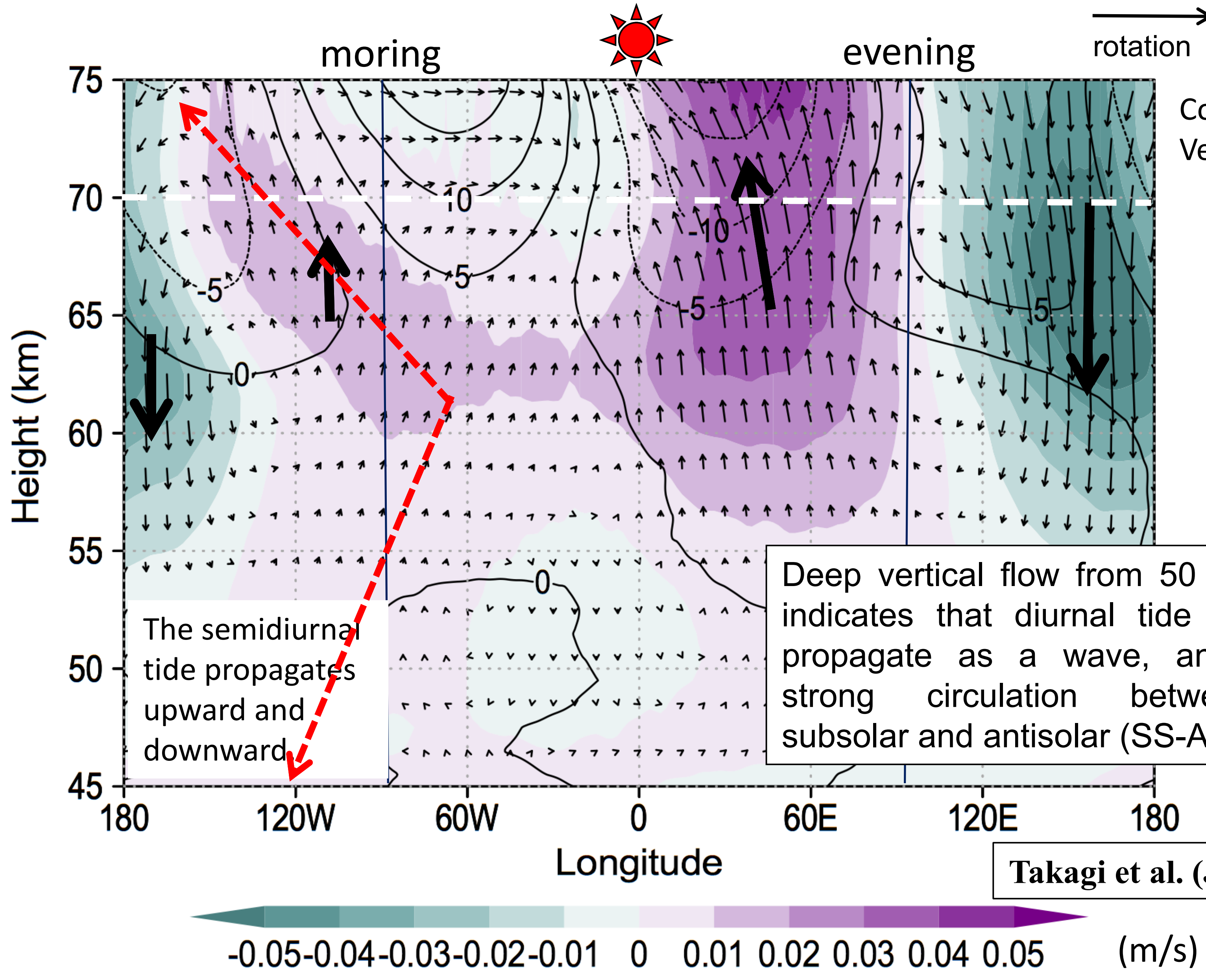
Kashimura et al. (in preparation)

Thermal tide (70 km)

Takagi et al. (JGR2018)



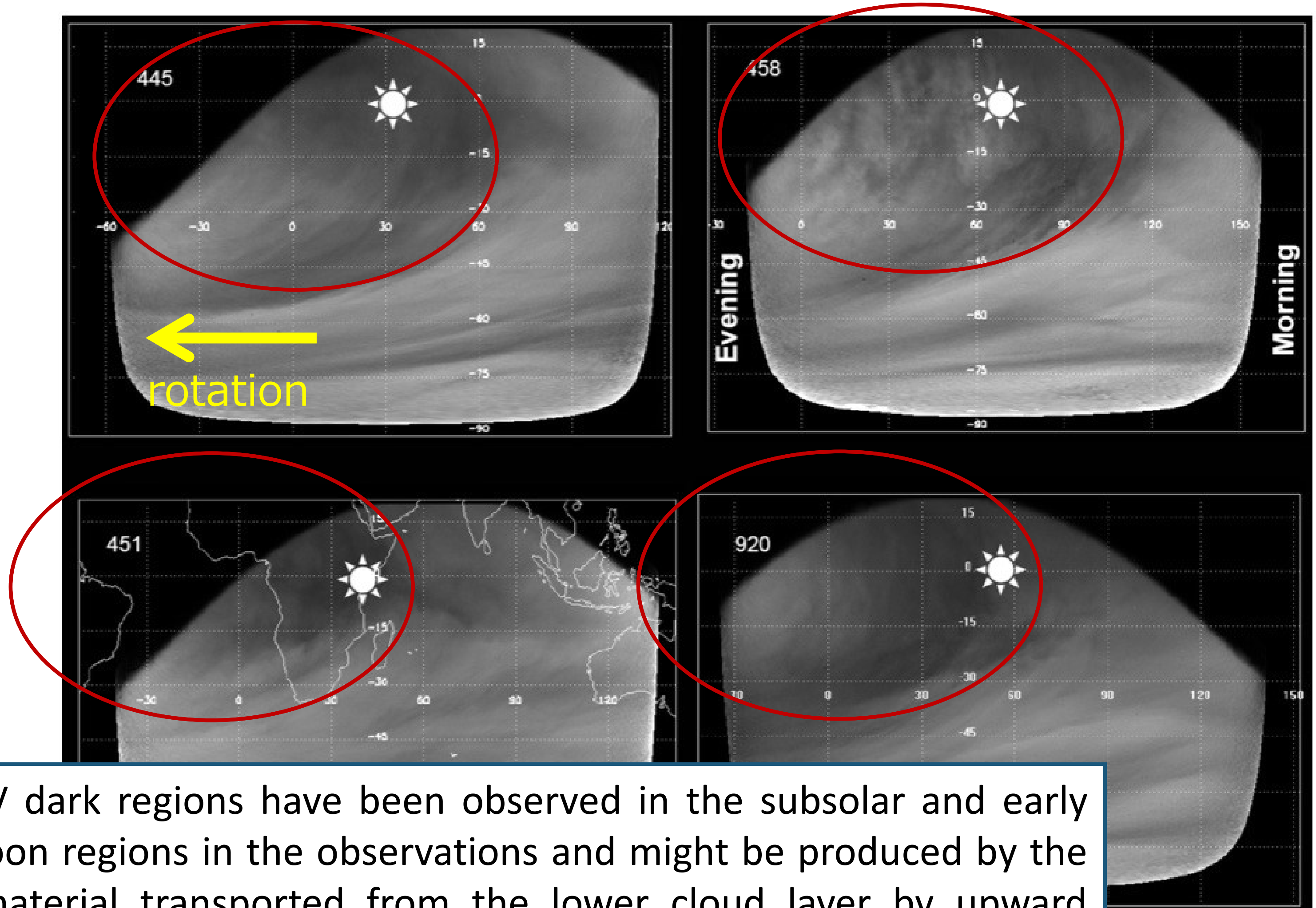
Vertical flow of thermal tide (at the equator)



Deep vertical flow from 50 to 80 km indicates that diurnal tide does not propagate as a wave, and has a strong circulation between the subsolar and antisolar (SS-AS) points.

Takagi et al. (JGR2018)

Dark region observed by UV



The UV dark regions have been observed in the subsolar and early afternoon regions in the observations and might be produced by the dark material transported from the lower cloud layer by upward motions. This is consistent with AFES-Venus results and indicates that the upward motions are caused by SS-AS circulation (of diurnal tide).

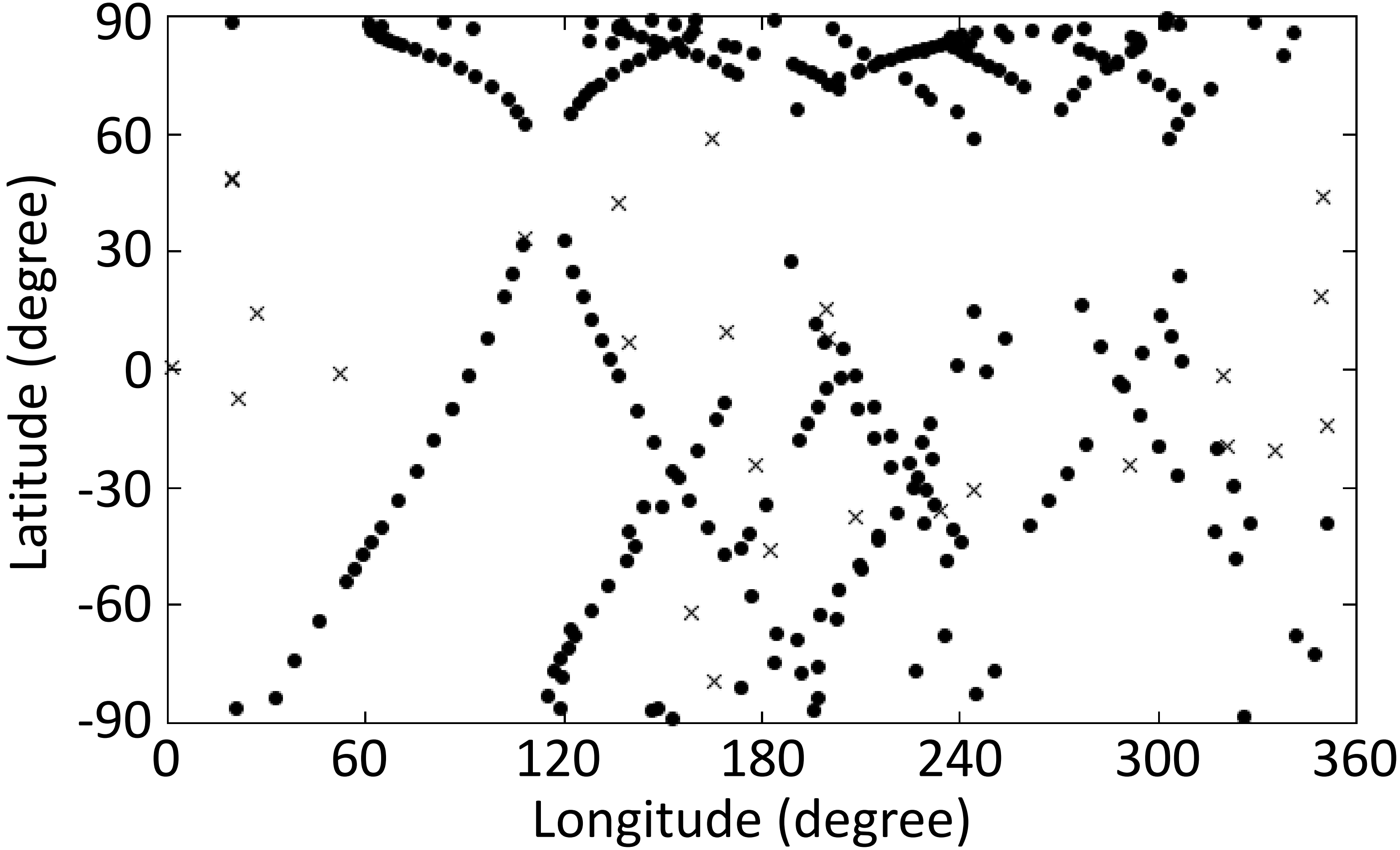
...e atmosphere rotates from right to
...tours of the Earth's continents are

Titov et al. (2012)

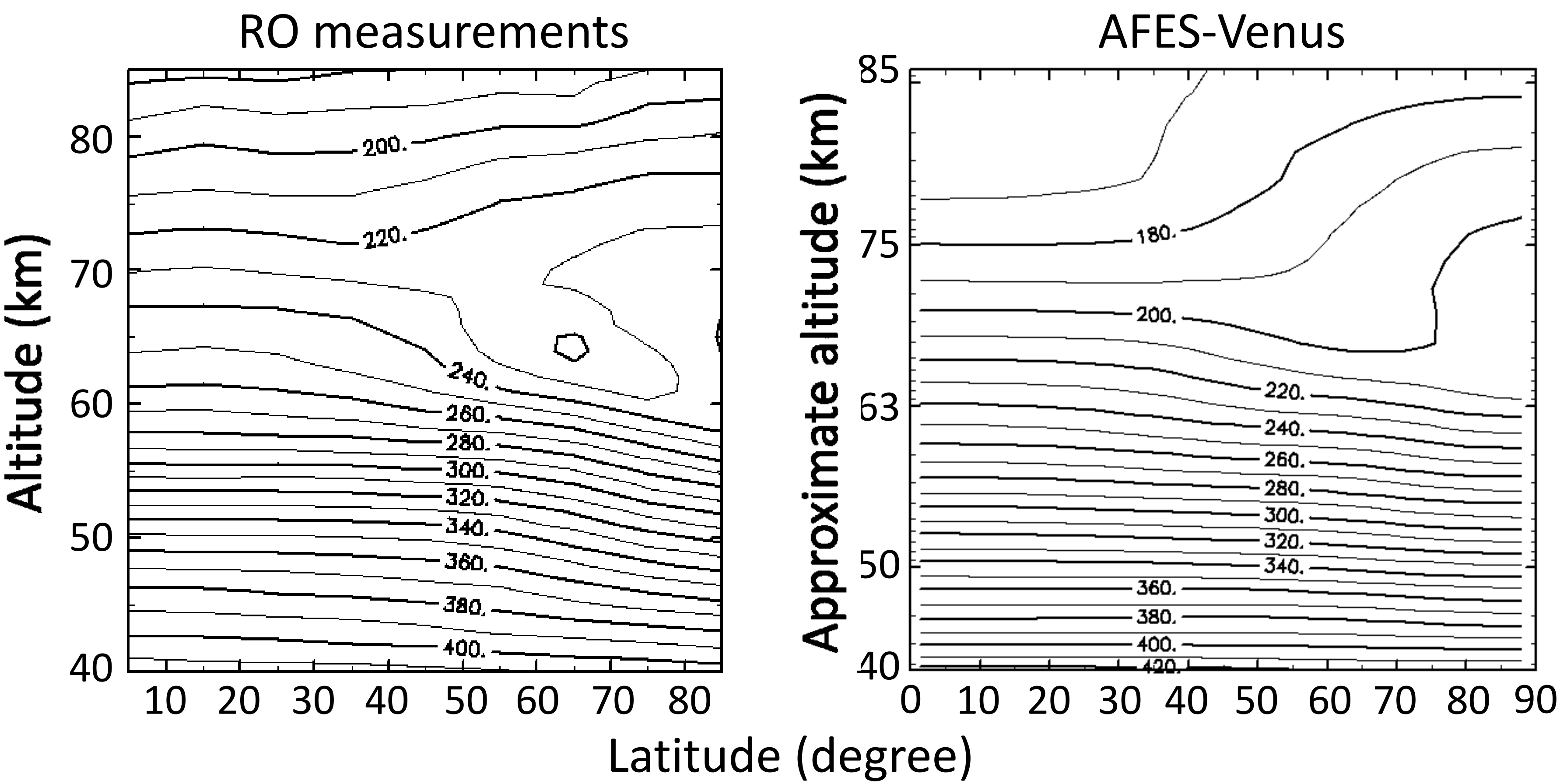
Data used in this study

- Venus Express open-loop data obtained in 2006–2010
- Akatsuki open-loop data obtained in 2016–2017

Longitude-latitude distribution of the data points

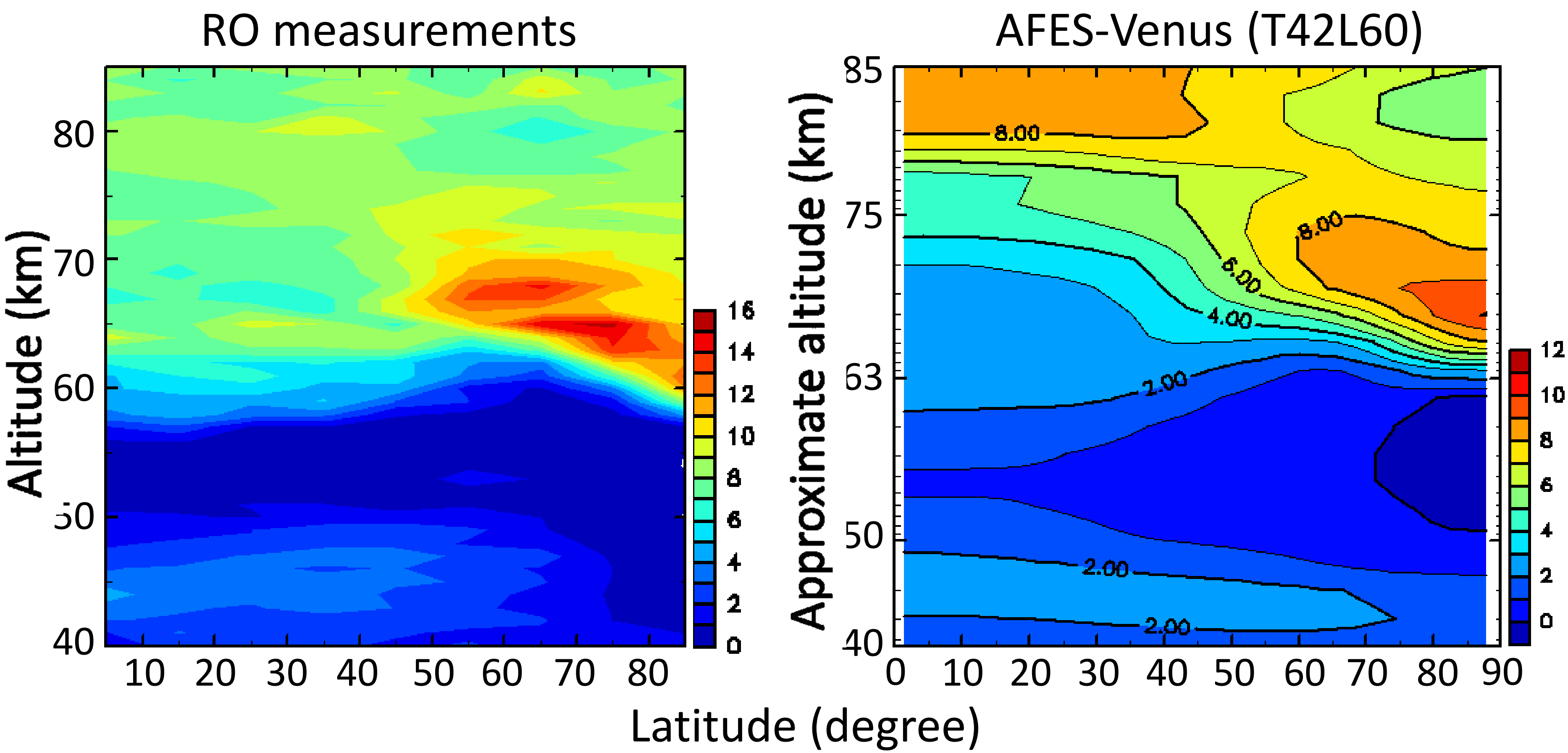


Latitude-height distribution of the zonally and temporally averaged temperature



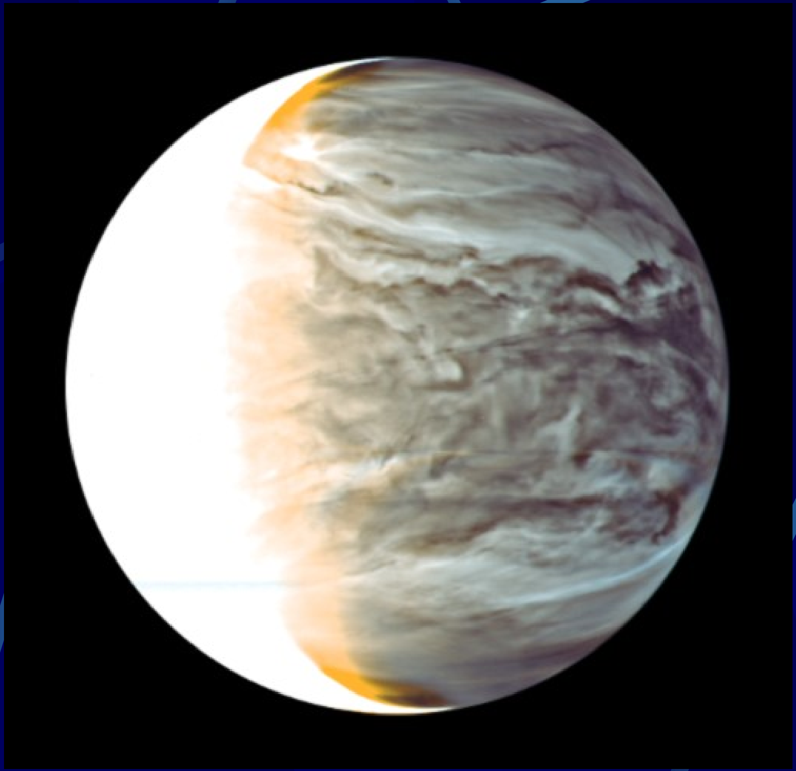
Temperature distributions obtained by RO and AFES-Venus are qualitatively consistent with each other.

Latitude-height distribution of the zonally and temporally averaged static stability



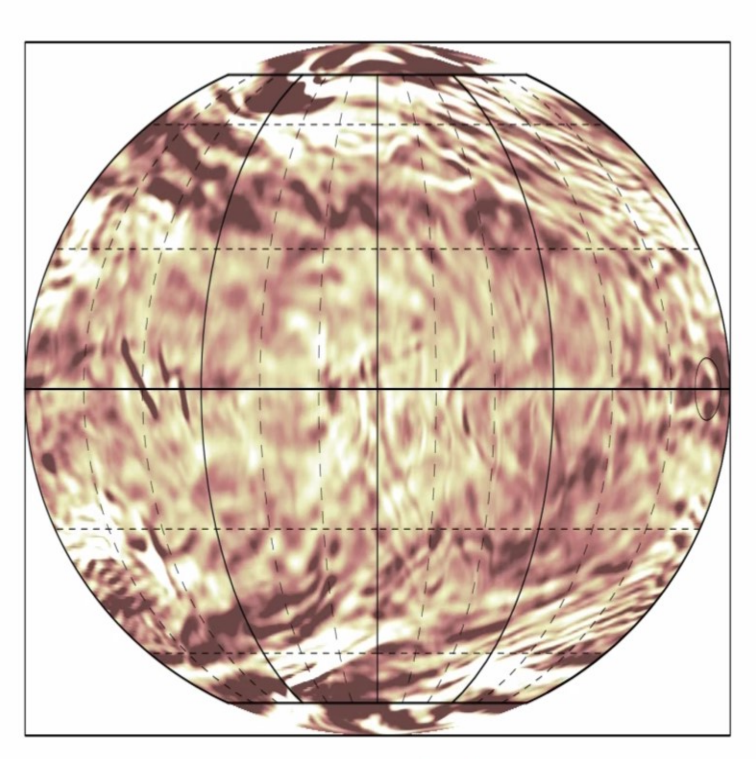
Static stability distributions obtained by RO and AFES-Venus are also qualitatively consistent with each other.

Akatsuki IR2 images and AFES-Venus (T159L120 run)



A synthesized false color image of Venus using 1.735-µm and 2.26-µm images taken by IR2 camera. Images are colorized as follows: 1.735 µm → red; 2.26 µm → blue; average of both → green. At 1.735 µm, dayside brightness is strong and considerable amounts of light are running into the nightside. This is why the border between dayside and nightside looks orangeish in color. The slight color variations on the nightside are believed to indicate the difference in size of cloud particles.

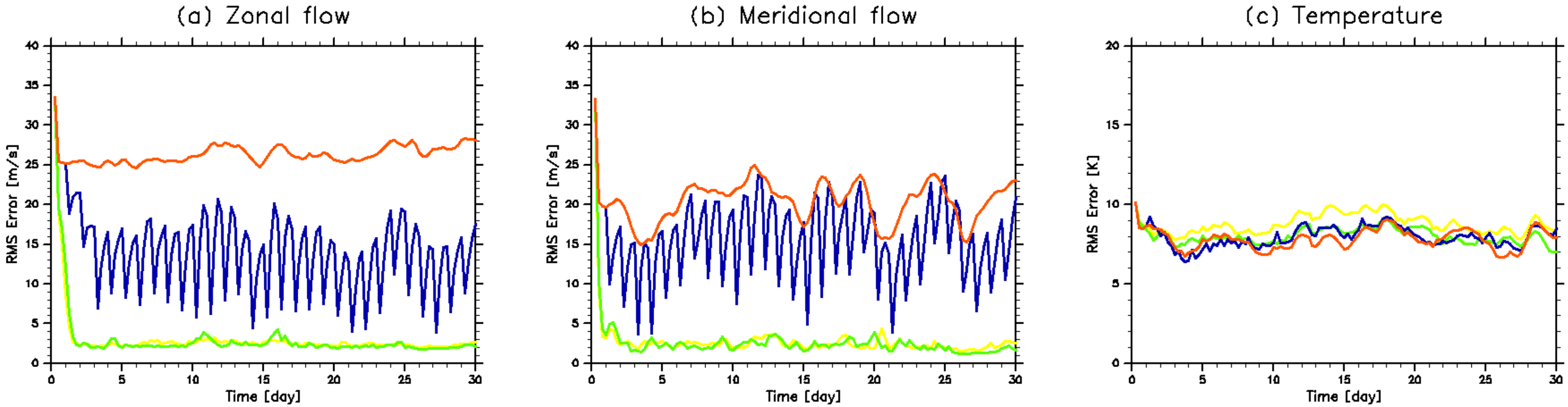
http://akatsuki.isas.jaxa.jp/en/gallery/data/001056.html



T159L120 run: vertical p-velocity

Results

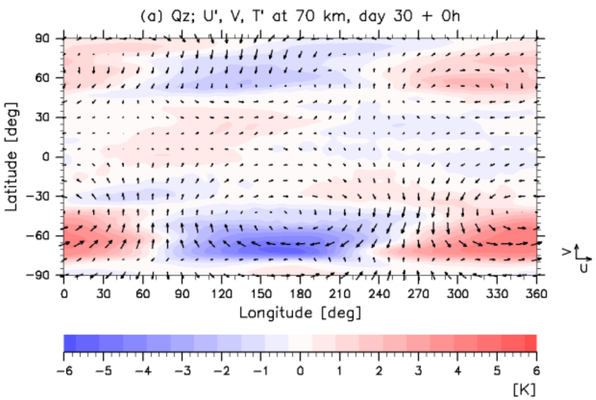
- **Root-mean-square error (U, V, T) at 70 km**

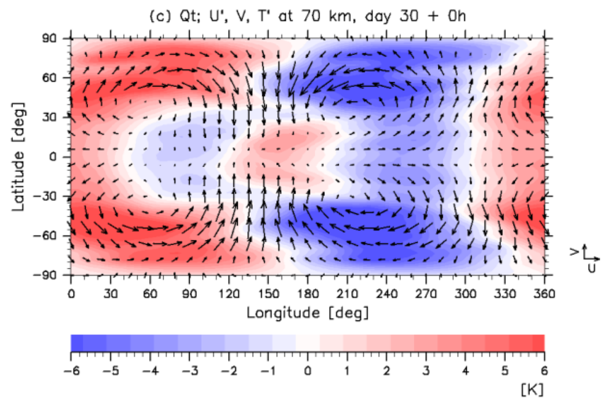


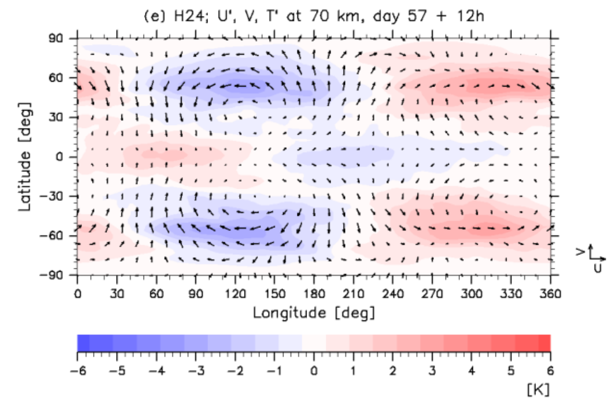
Red: Frf Blue: H24 Green: H6 Yellow: H1

Cases H1 and H6 converge quickly.
Assimilation cycle can be seen in Case H24 (once per day).
Temperature field does not converge.

Horizontal structures (Cases Qz, Qt, H24) at 70 km







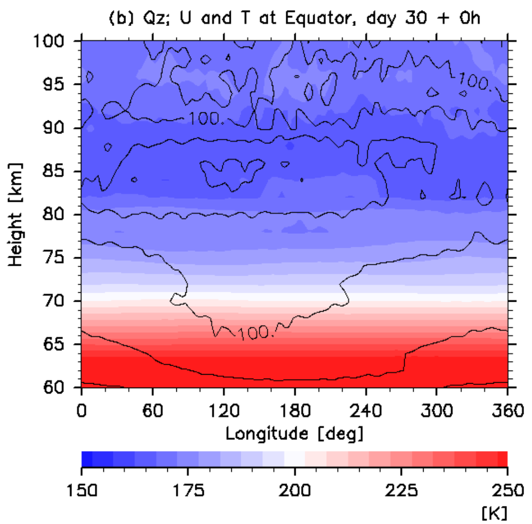
Qz; zonal mean only
~ Frf

Qt; including diurnal variation
~ Obs.

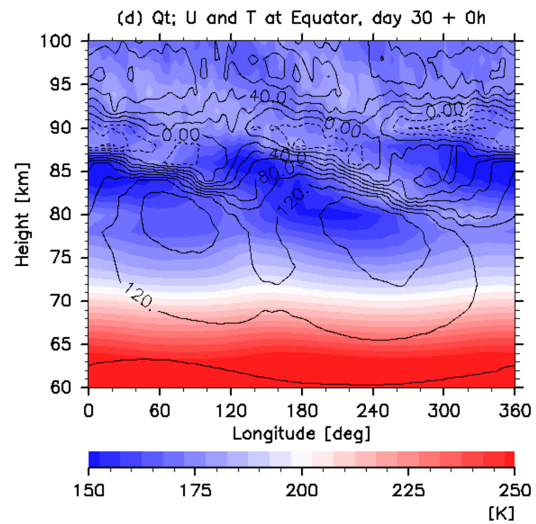
H24; result of VALEDAS

Thermal tide appears in Case H24 (once per day)
not only for the horizontal flows but <u>temperature field</u>.

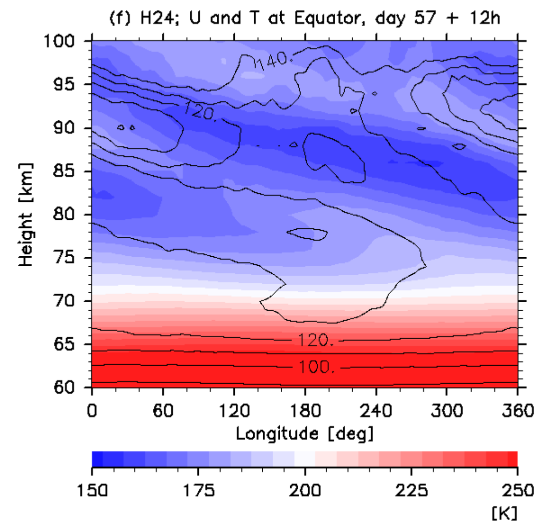
Vertical structures (Cases Qz, Qt, H24) at the equator



Qz; zonal mean only
~ Frf



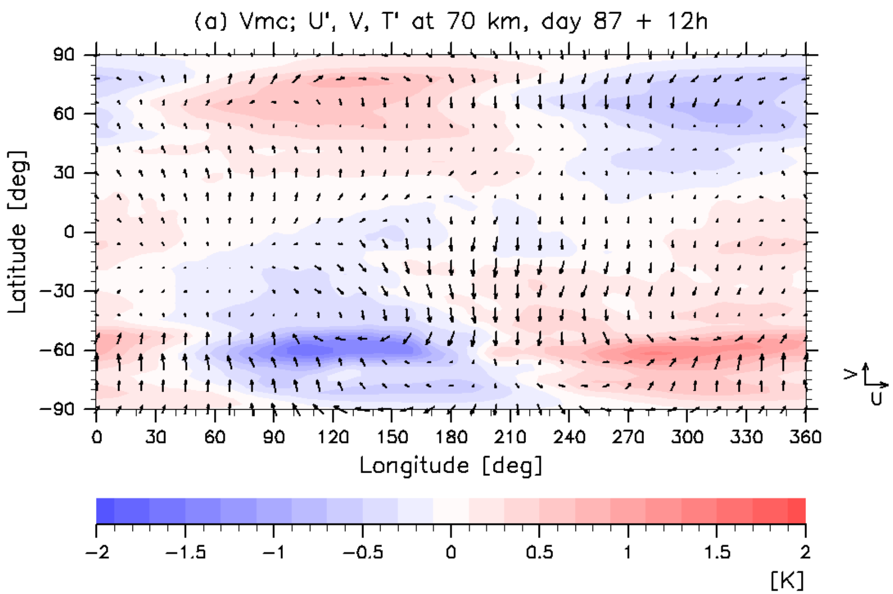
Qt; including diurnal variation
~ Obs.

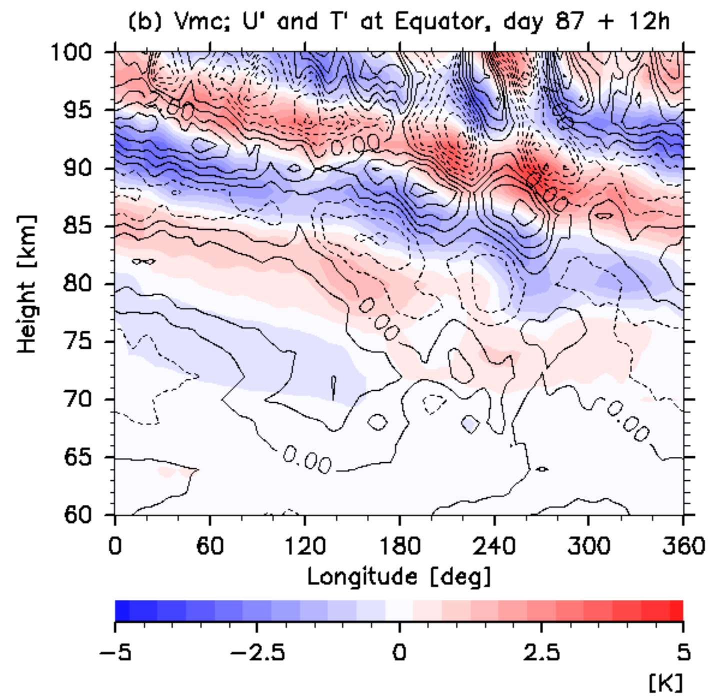


H24; result of VALEDAS

Thermal tide propagates in the vertical direction in Case H24
(once per day only for horizontal flows) even for the temperature field.

Horizontal and vertical structures for Case Vmc

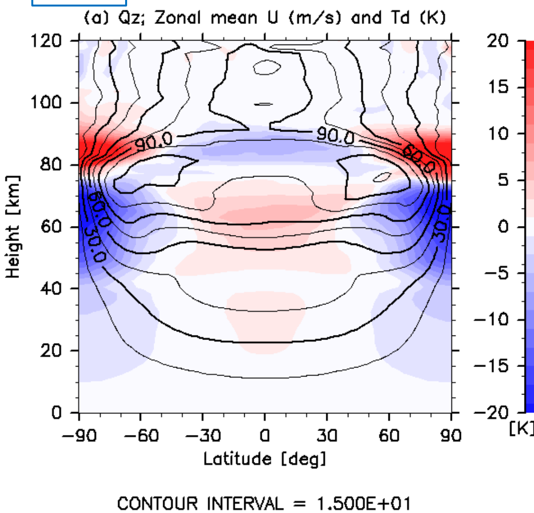




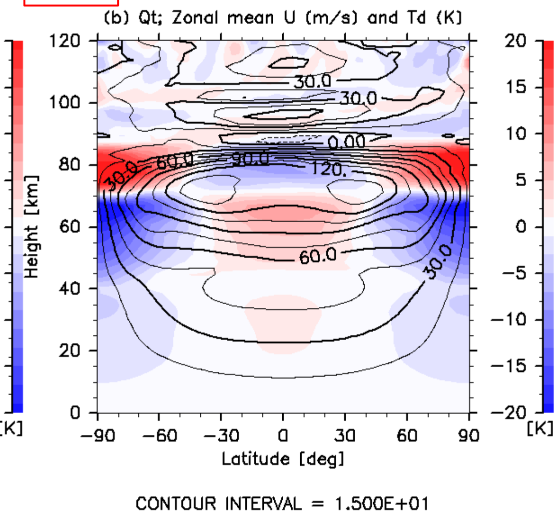
Thermal tide appears in Case VMC even though horizontal flows in dayside region once per day *but amplitude is small*.

Latitude-height cross sections (Cases Qz, Qt, H24, Vmc)

Qz



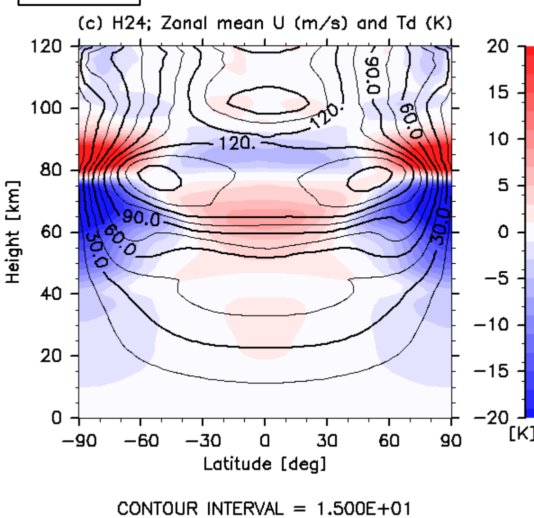
Qt



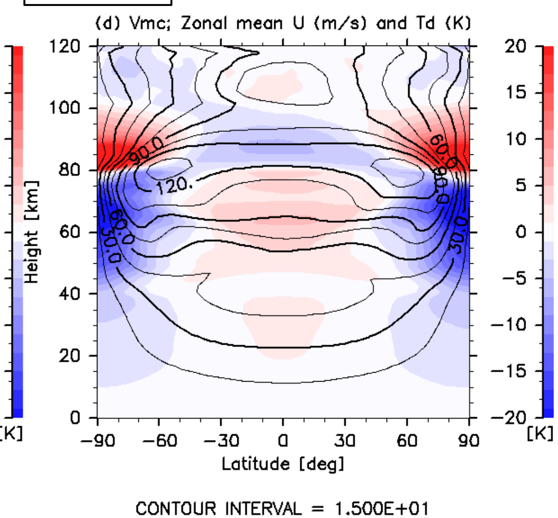
Contour: zonal mean zonal flow

Color : temperature deviations from the horizontally averaged temperature

H24

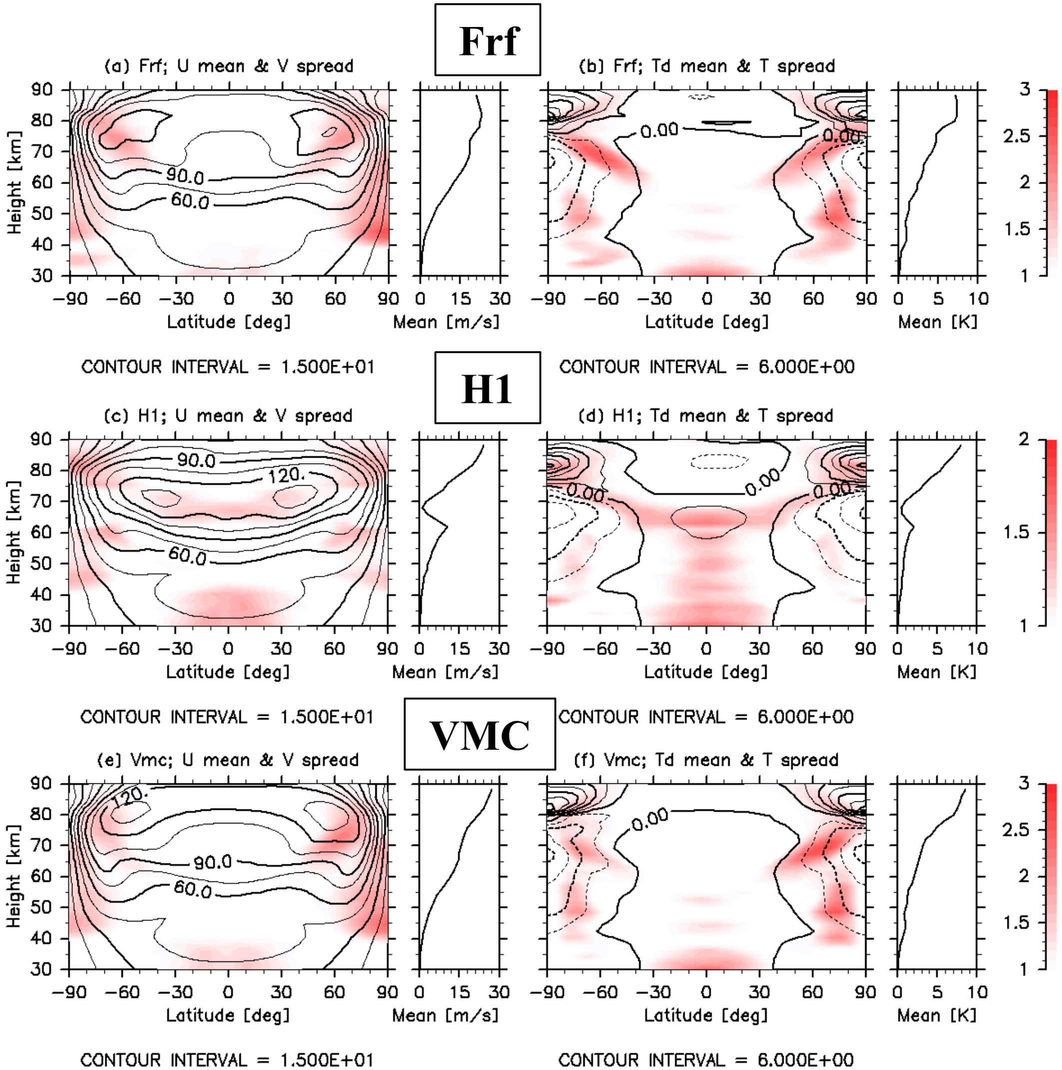


VMC



Zonal mean zonal flow *does not change largely* for both Cases Vmc and H24 because of **Qz forcing.**

Latitude-height cross sections (Cases Frf, H1, Vmc)



Left red shade: Spread of V
Right red shade: Spread of T
Left contour: zonal mean zonal flow
Right contour: temperature deviations from the horizontally averaged temperature
Line plots (right panel): horizontal average of these spread

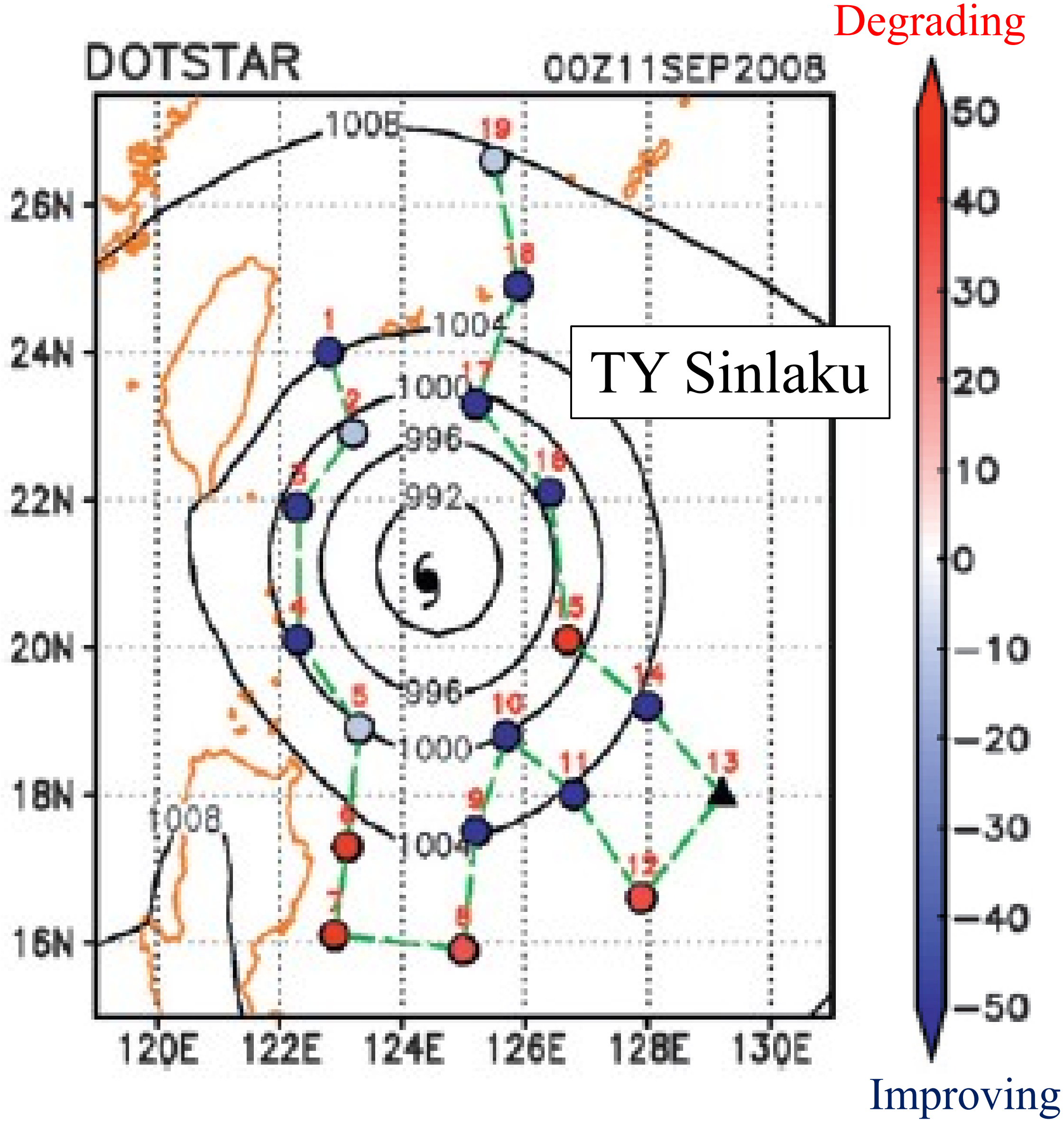
- Mid-latitudes: Baroclinic instability (Rossby-type waves)
- High-latitudes: Barotropic instability
- Low-latitudes: Thermal tides (H1)

Zonal mean zonal flow changes significantly for Case H1.

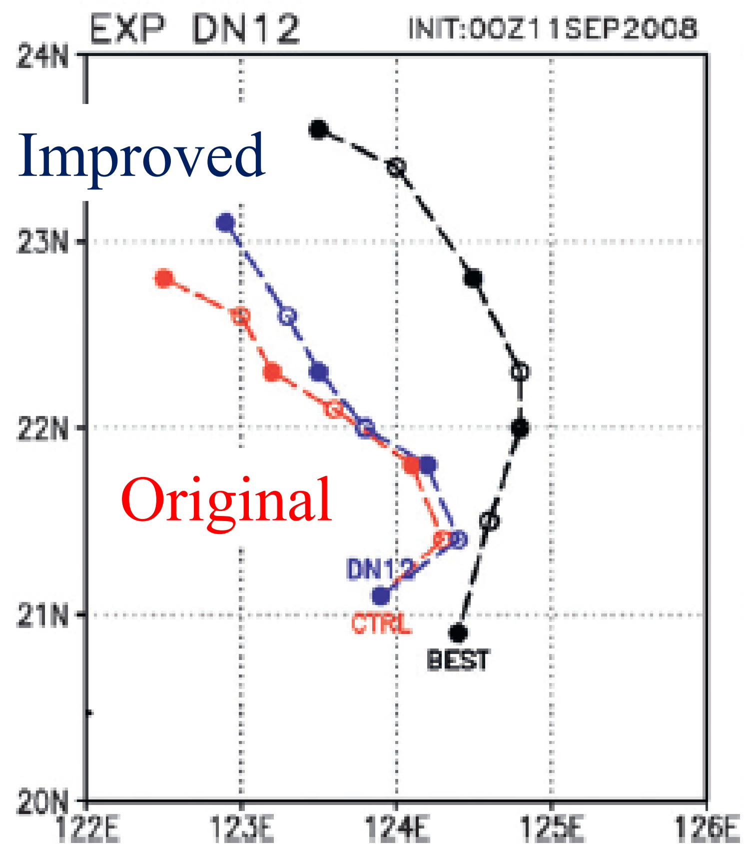
General circulation could be changed by frequent observations.

Impact of dropsondes on a Typhoon (example of the Earth)

Estimated observation impact



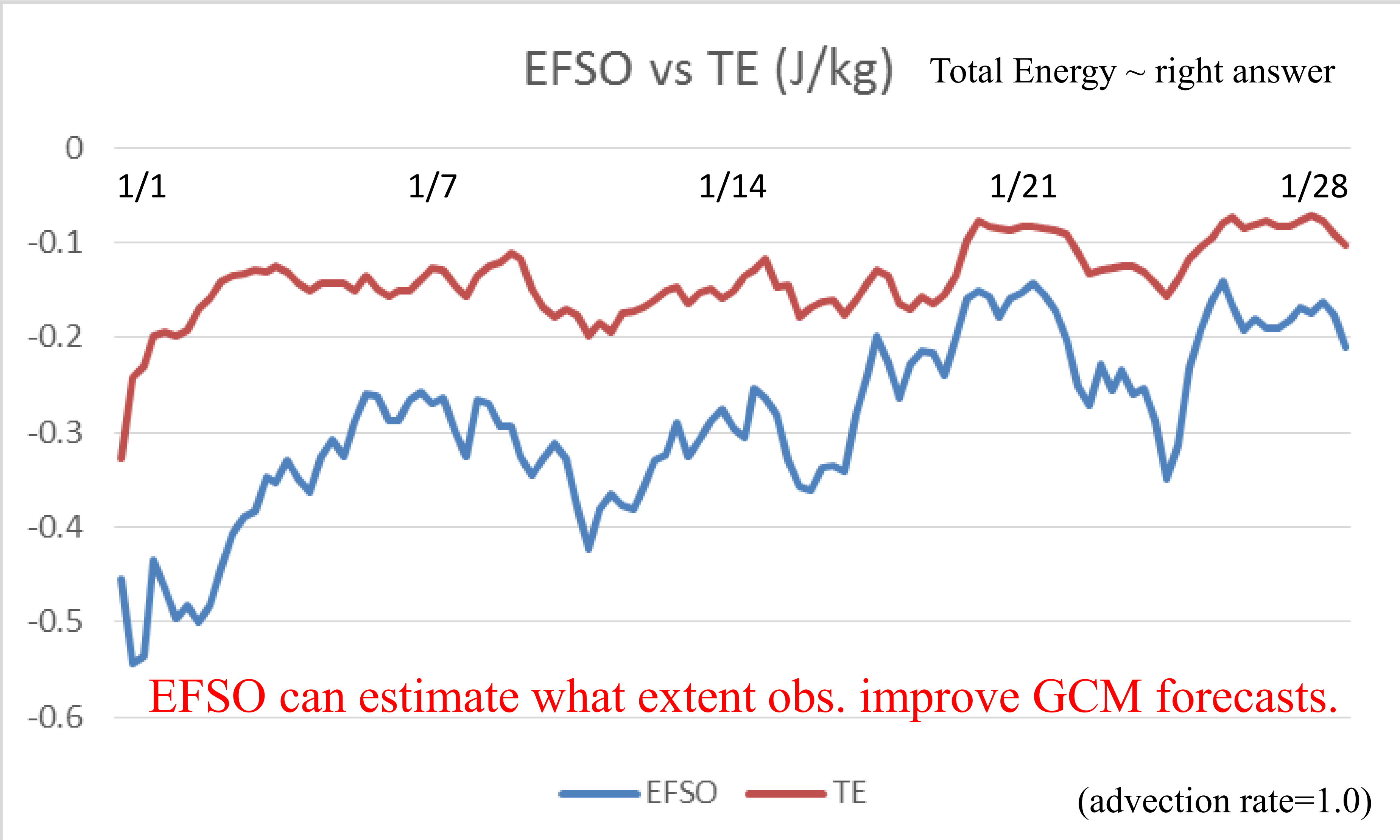
Typhoon track forecast actually improved.



Kunii et al. (2012MWR)

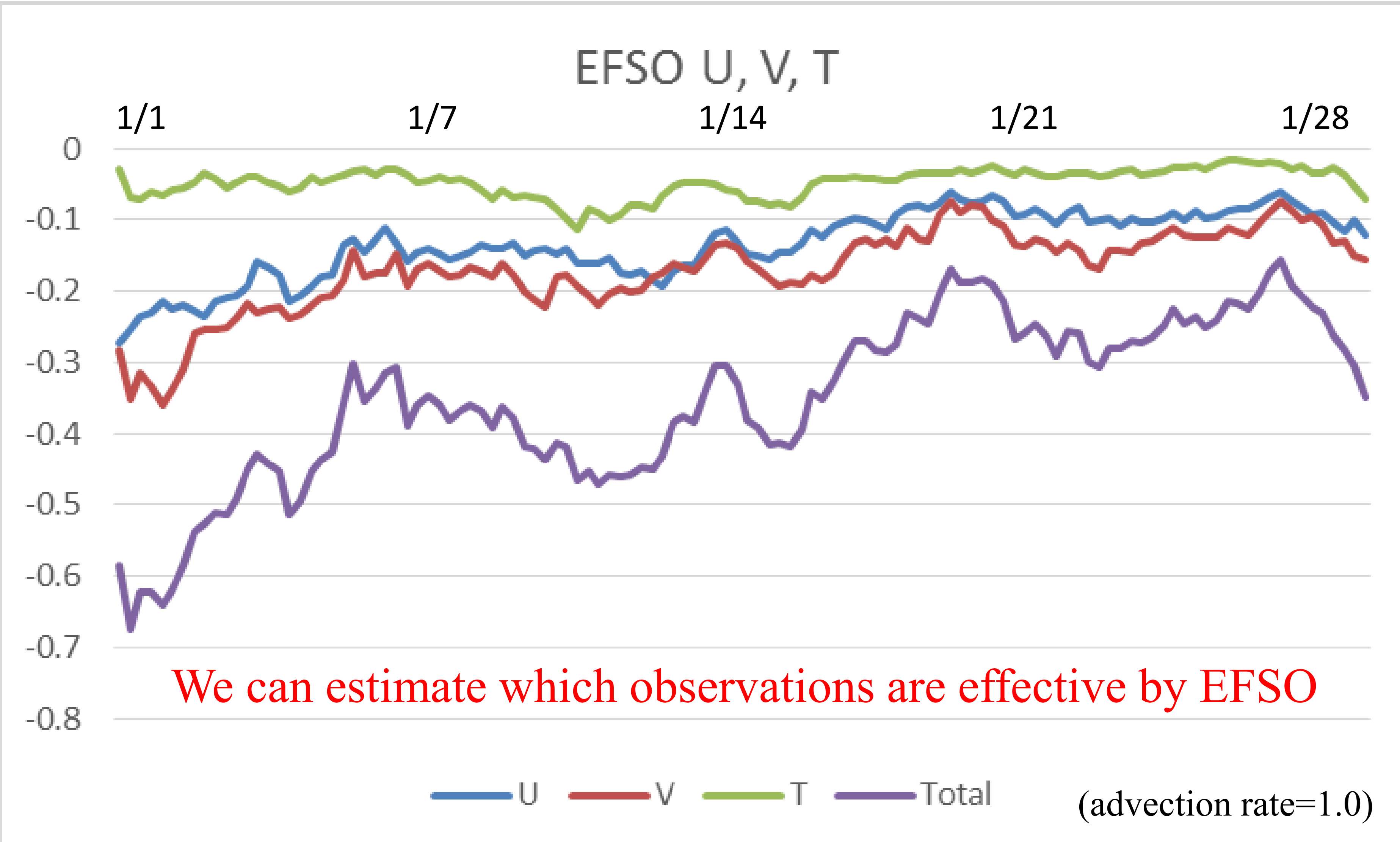
Test of EFSO (Case H1)

✓ Correlation 80.64%; EFSO works well *but overestimates a little*



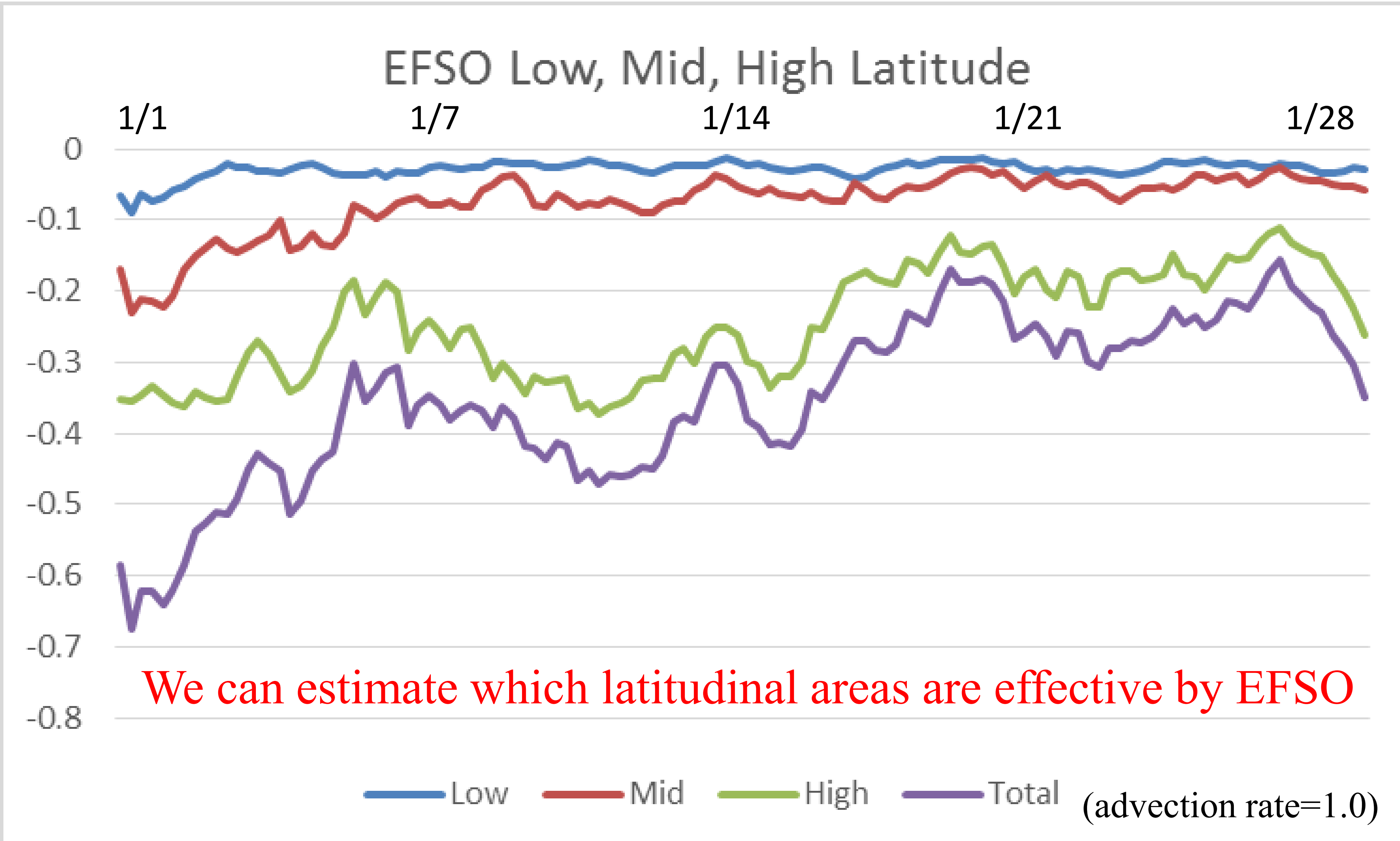
Test of EFSO (Case H1+T; Case H1 with temperature obs.)

- ✓ EFSO values divided into U, V, and T components.



Test of EFSO (Case H1+T; Case H1 with temperature obs.)

- ✓ EFSO values at the area of low-, mid-, and high-latitudes.



Summary

- Data assimilation system for the Venusian atmosphere has been developed (VALEDAS; VAFES-LETKF data assimilation system).

- Test observations; horizontal flows at the cloud top level

①Idealized: AFES-Venus runs (1, 6, 24-hourly)

②Real: VMC/VEX (~24-hourly and dayside region only)

Both observations include thermal tide but **AFES-Venus forecasts forced with solar heating exclude thermal tide.**

⇒ Thermal tide appears and propagates vertically in temperature field

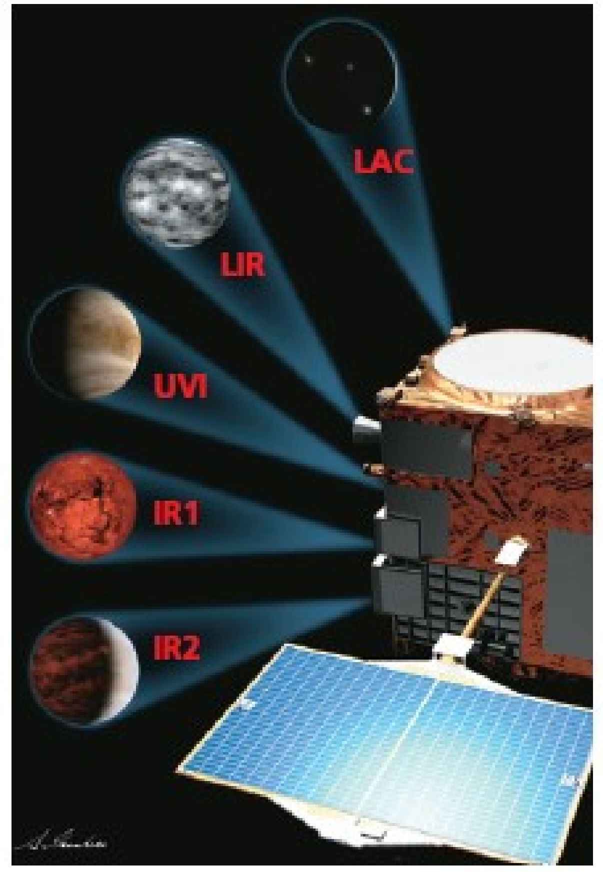
We also perform sensitivity experiments: ensemble size of 63-member (to confirm convergence), localization and observation error (to confirm that the effect is small), Qt (solar heating Including diurnal variation) run, data assimilation for temperature observation data...

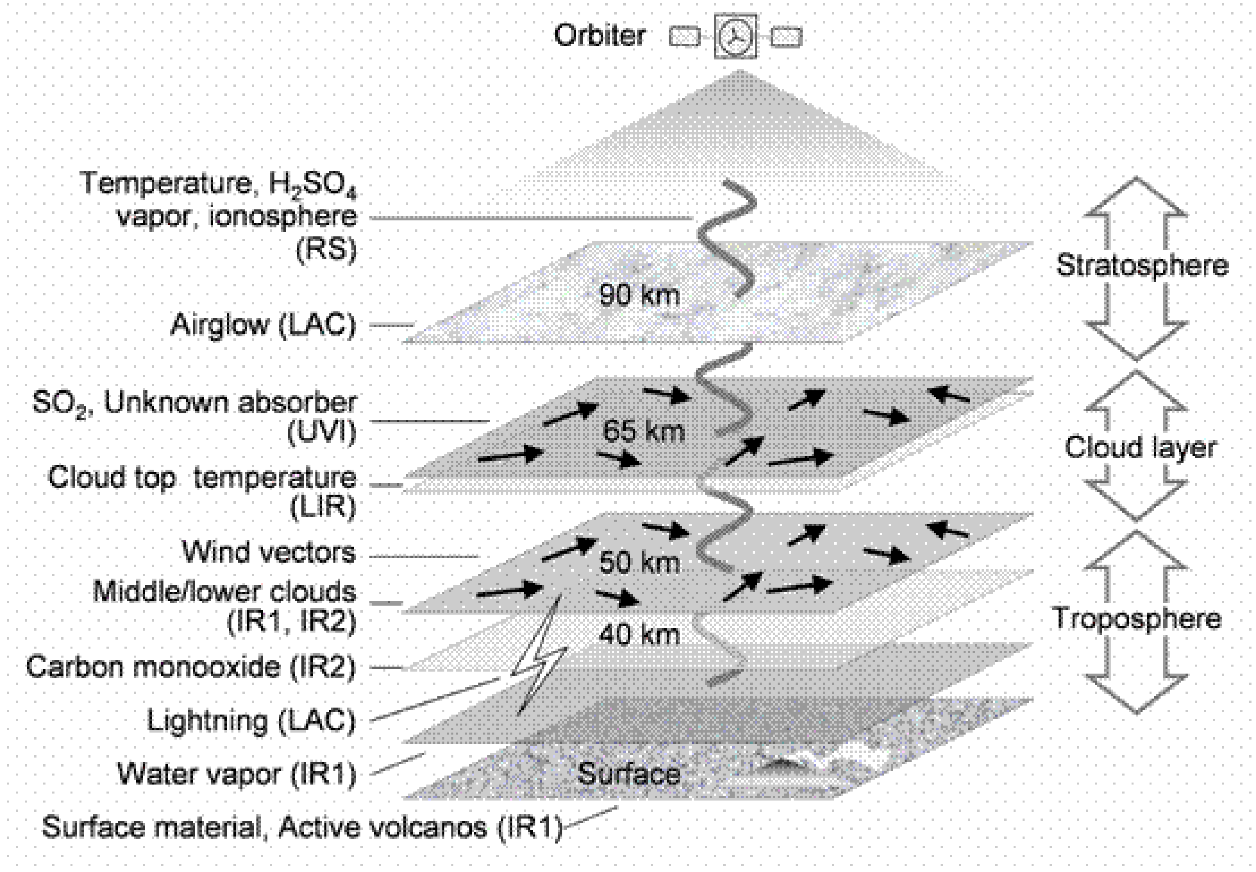
- EFSO (Ensemble Forecast Sensitivity to Observations) has been implemented.

Impacts of specific observations can be estimated diagnostically and automatically without OSSE (Observation System Simulation Exp.).

2. VALEDAS (VAFES-LETKF data assimilation system)

- **Data assimilation system for Akatsuki obs.**
  - ✓ Frequent meteorological observations at multiple altitudes (Nakamura et al., 2011, 2014…)

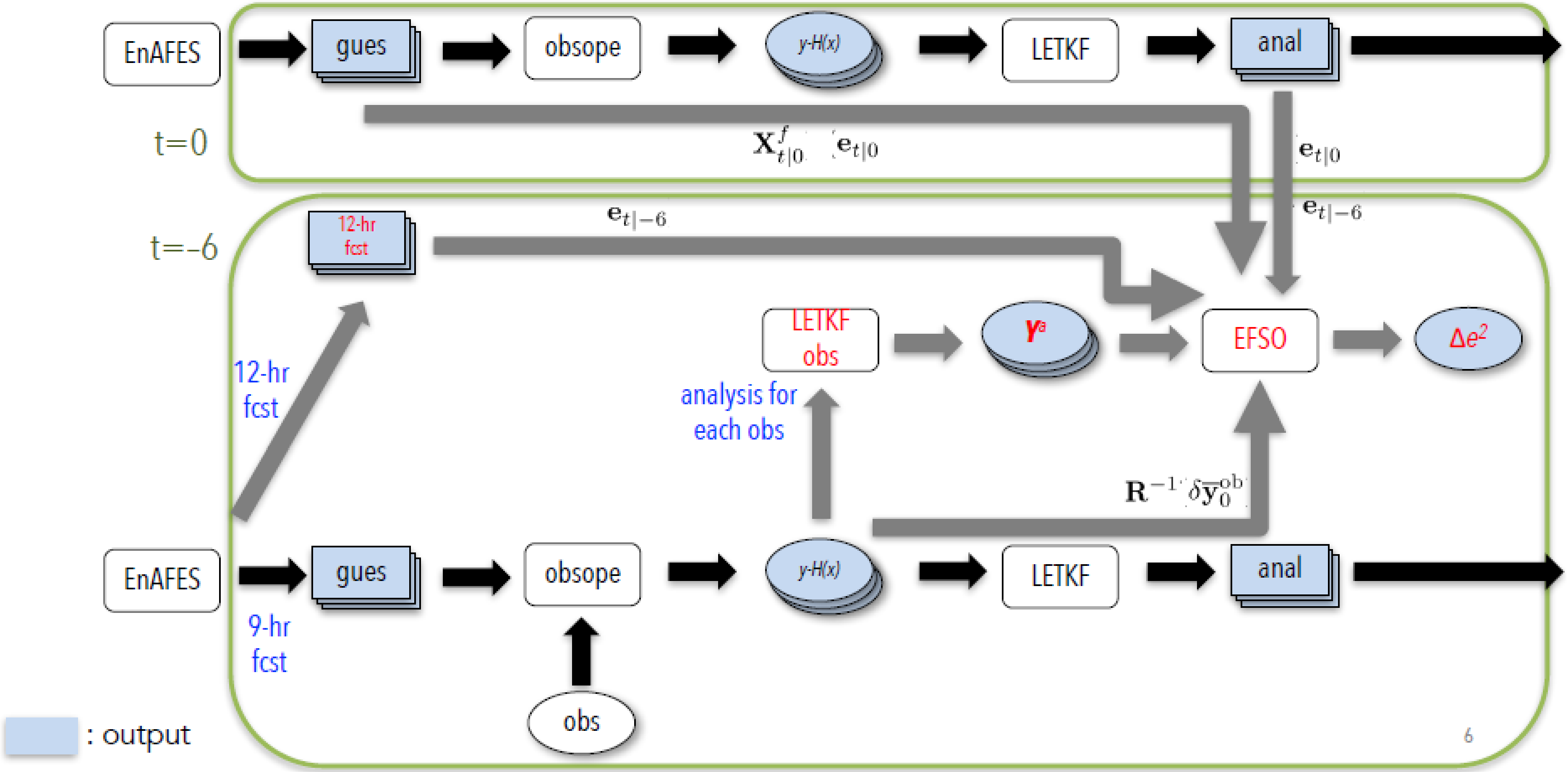




http://global.jaxa.jp/projects/sat/planet_c/

Forecast-analysis cycle w/ EFSO

$$\Delta e^2 = (\delta \bar{\mathbf{y}}_0^{\mathrm{ob}})^{\mathrm{T}} \frac{1}{K-1} \mathbf{R}^{-1} \mathbf{Y}^a (\mathbf{X}_{t|0}^f)^{\mathrm{T}} \mathbf{C}(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6})$$



Yamazaki et al. (2018?)

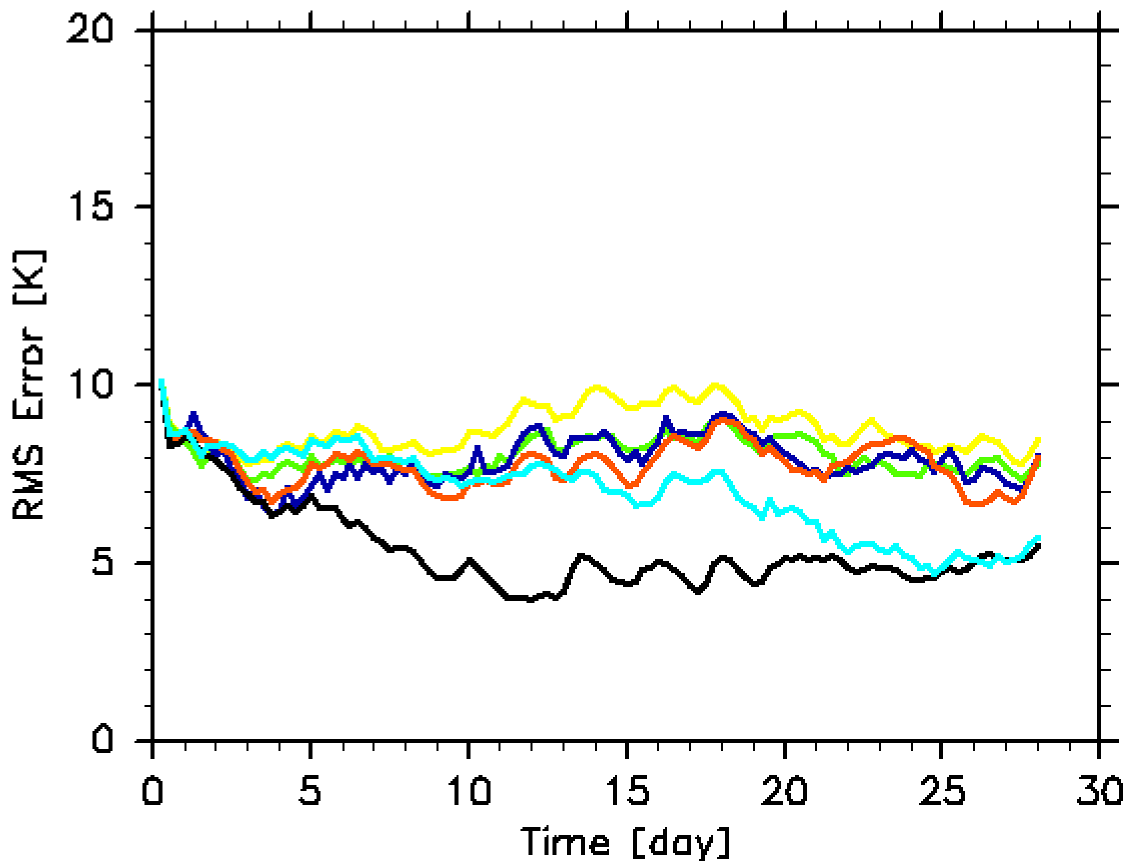
Two types of ensemble runs are performed to estimate impacts of observations.

Test assimilation of idealized temperature by Radio-Oc.

- ✓ Cases T15; 1-hourly temperature data for 15 points
- ✓ Cases UVT15; 1-hourly temperature data for 15 points with horizontal flows at the cloud top level (70 km)

Red: Frf
Blue: H24
Green: H6
Yellow: H1
Right Blue: UVT15
Black: T15

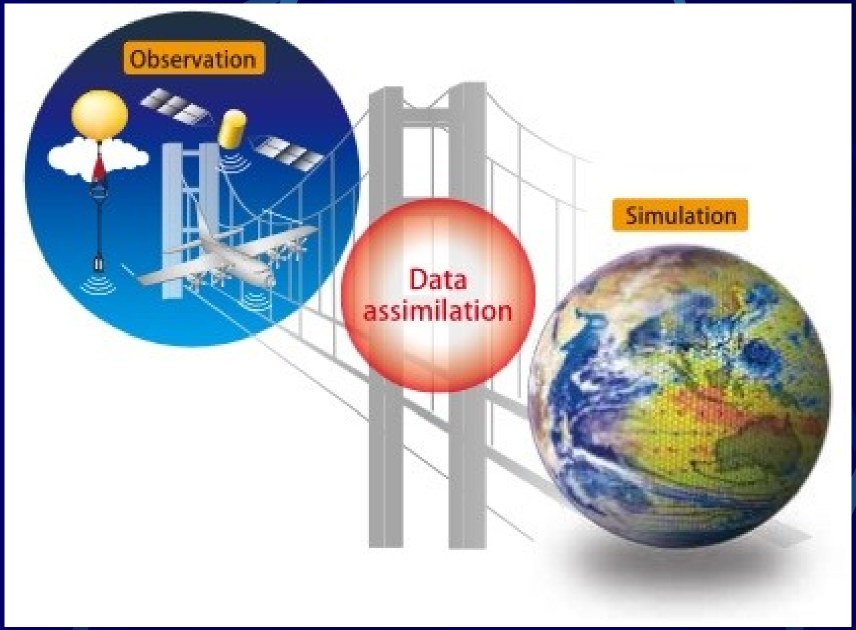
Root-mean-square error T at 70 km



Error of the temperature field reduces gradually.

1. Introduction Data assimilation

Data assimilation fills in the gaps by integrating actual observation data into simulations, which enhances a simulation's accuracy.



Data assimilation is like a bridge between observation and simulations. In the case of weather forecasting, observations from radiosondes (weather balloons) and weather-observation satellites, for example, are integrated into numerical weather prediction simulations. As a result, we obtain more accurate weather forecasts.

We have to reproduce phenomena in a model similar to observations.

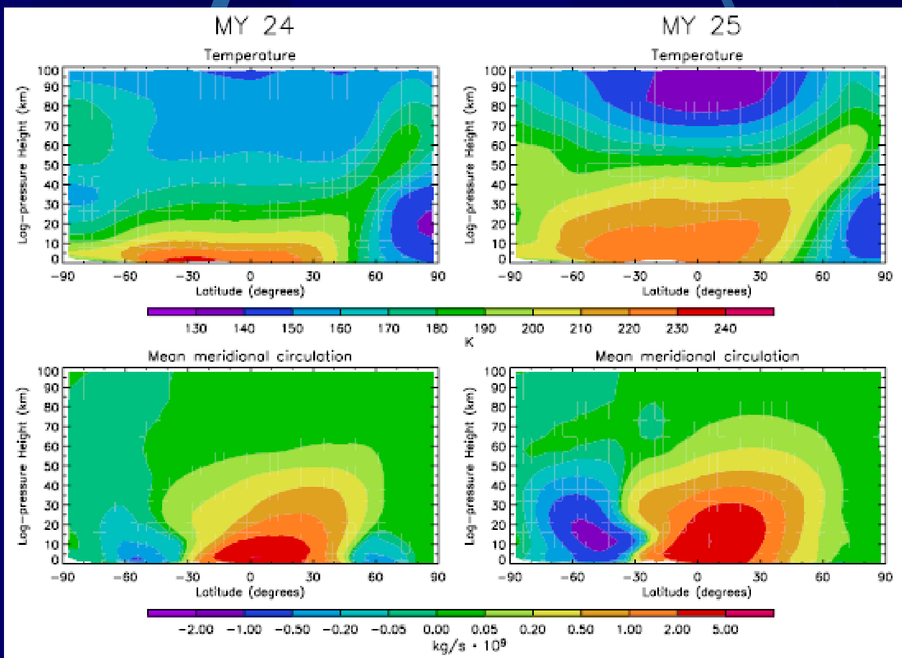
http://www.data-assimilation.riken.jp/jp/research/research.html

For Earth：NCEP-Reanalysis, ERA-interim, JRA-55 ...

Data assimilation for Mars

Assimilate observations of the Mars mission
Oxford Univ./Open Univ./LMD/Caltech/Maryland Univ...

- ✓ More observations than Venus.
- ✓ Good reproducibility of Mars GCM.

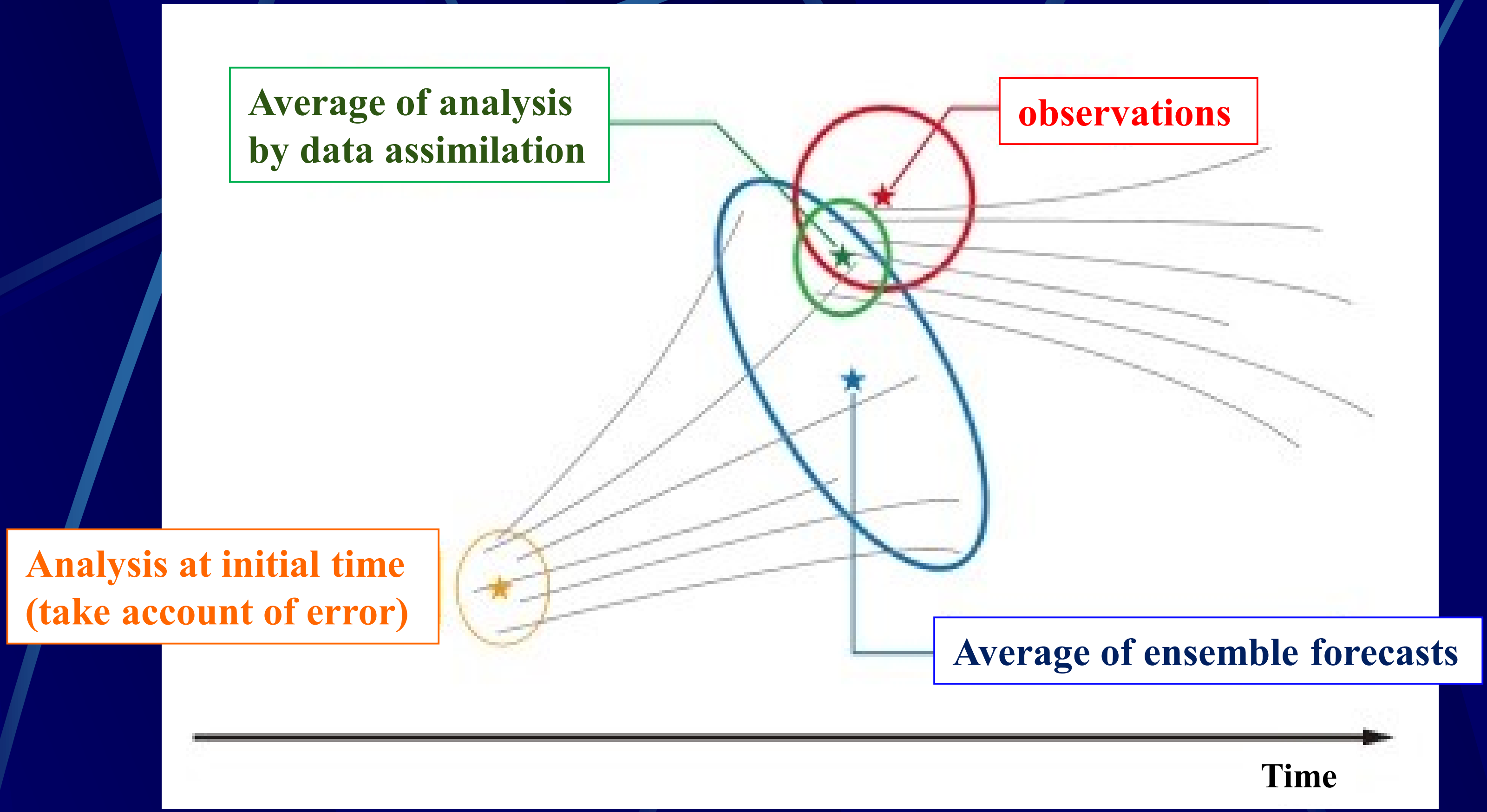


Temp. and dust by MGS are assimilated into Mars GCM: Temp. (top) and Mass stream function (bottom). (Montabonne et al., 05)

Mars Atmosphere Data Assimilation workshop on August 29-31, 2018, at Savoie, France.

Data assimilation of planetary atmosphere has become realistic

Schematic of LETKF

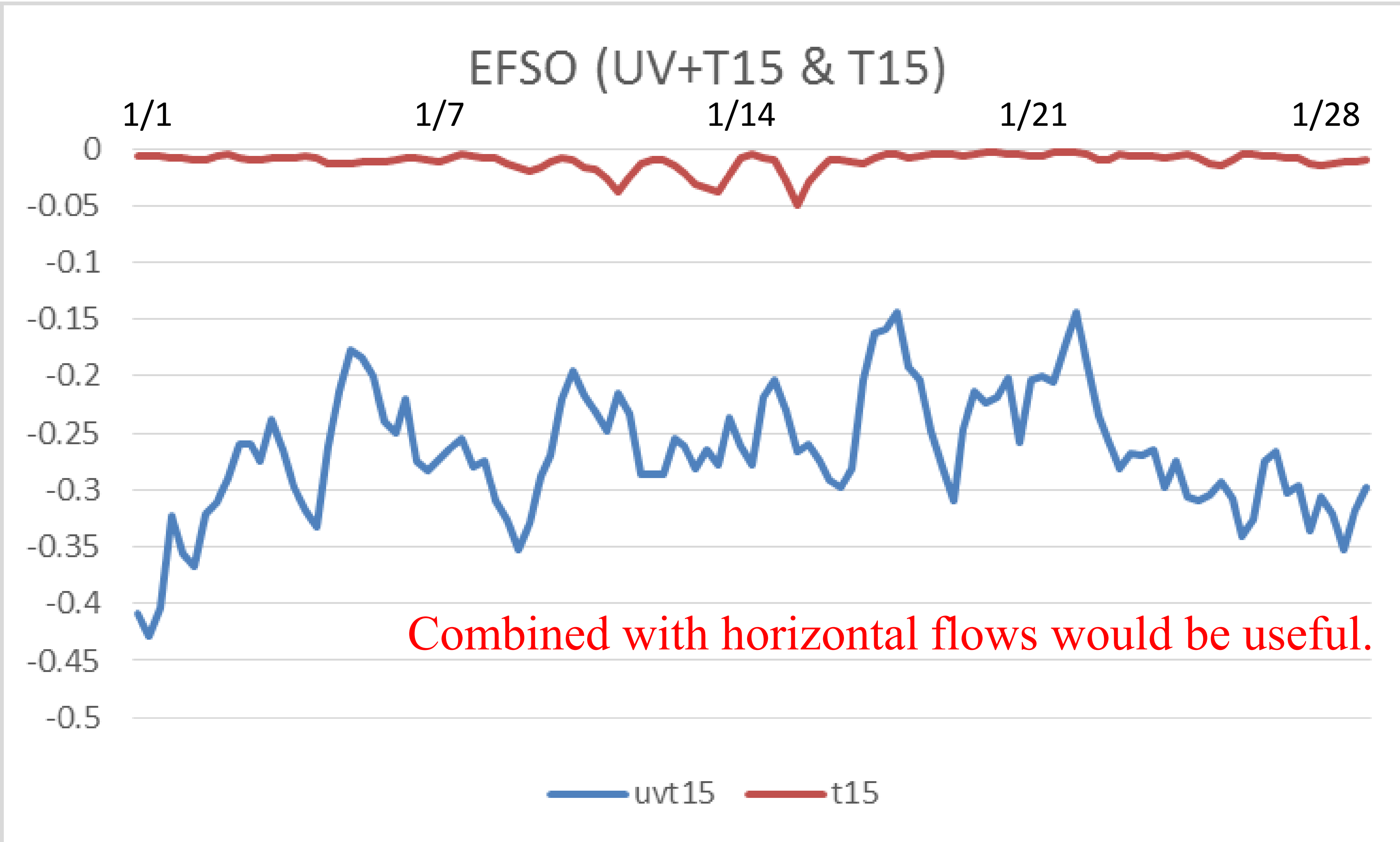


LETKF: Simulation from initial analysis with variation (orange) produce large ensemble forecasts (blue). Assimilation of observations (red) makes these forecasts confined and produces new balanced (i.e., dynamically consistent) analysis for next forecast (green).

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

Test assimilation of idealized temperature by Radio-Oc.

- ✓ EFSO is small because of a limited number of observations; T15



- **Test assimilation of idealized temperature by Radio-Oc.**
  - ✓ Cases TE3; 1-hourly temperature data for 3 points at the eq.
  - ✓ Cases TL5; 1-hourly temperature data for 5 points at lon=0

Red: Frf

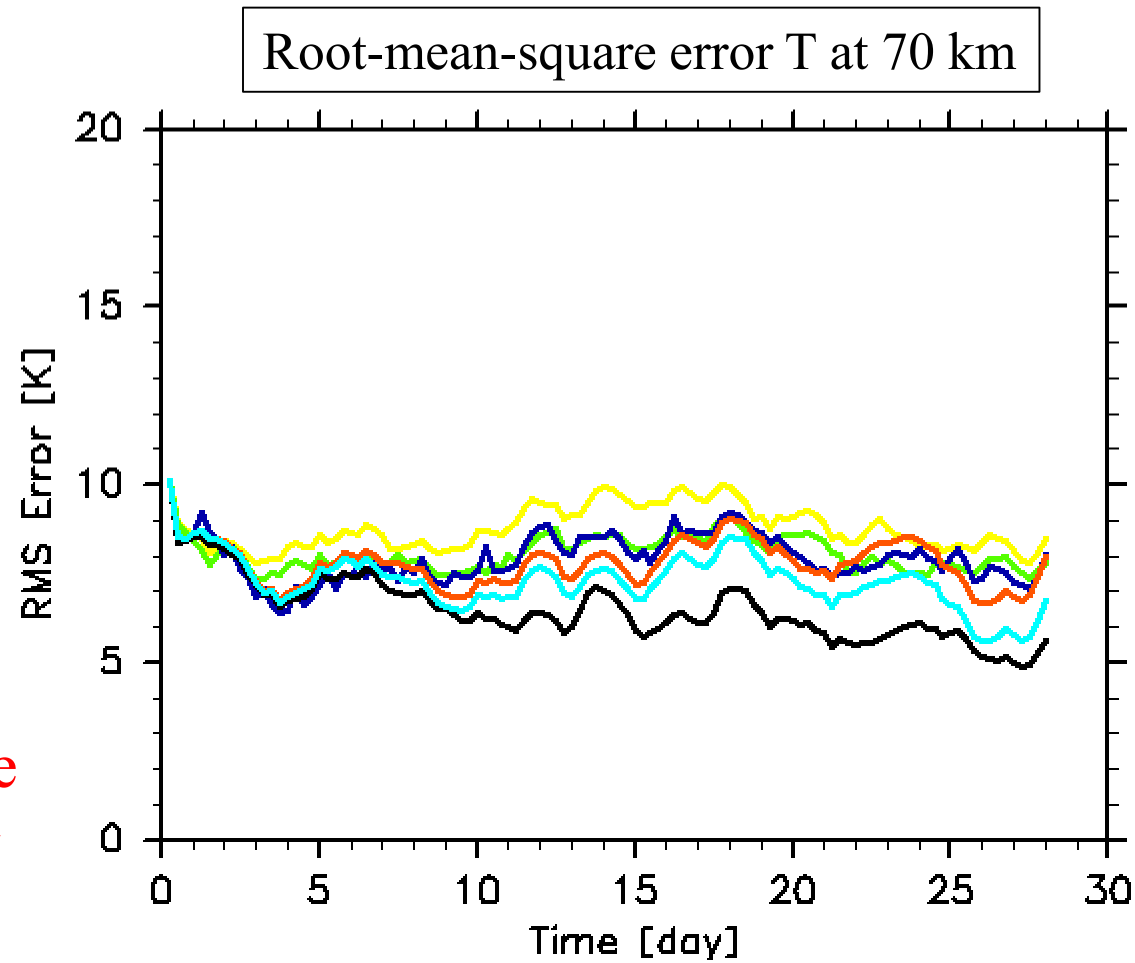
Blue: H24

Green: H6

Yellow: H1

Right Blue: TE3

Black: TL5

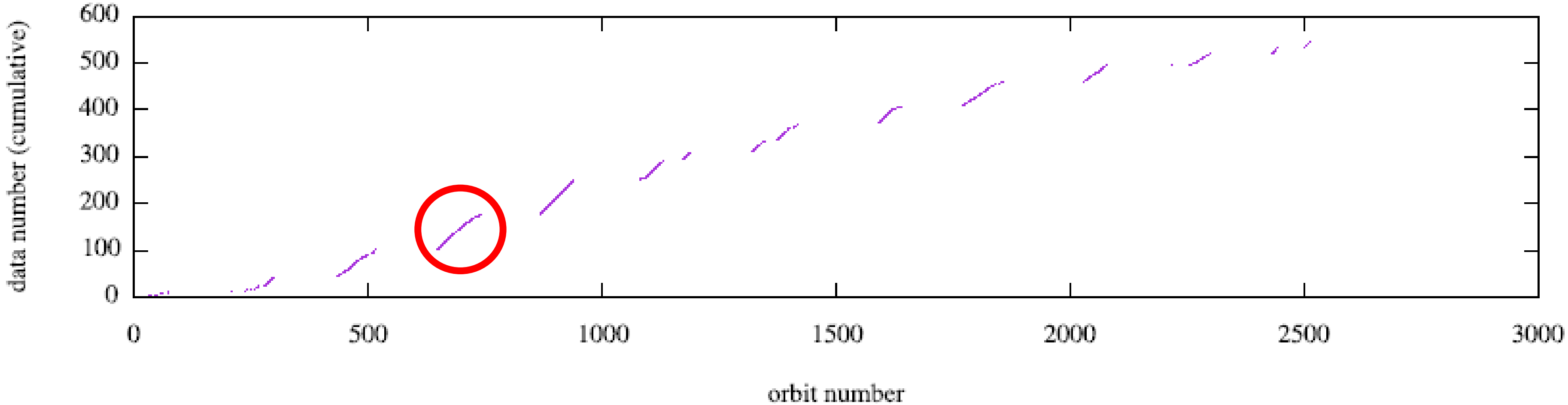


Error of the temperature field reduces gradually

Observations by VMC/VEX

Table 1. Definition of Epochs

Epoch	Period	Orbit No.	Number of Orbits
1	20 May 2006 to 3 Jul. 2006	30–74	13
2	15 Nov. 2006 to 13 Feb. 2007	208–298	30
3	30 Jun. 2007 to 17 Sep. 2007	436–515	62
4	28 Jan. 2008 to 1 May 2008	648–741	77
5	6 Sep. 2008 to 16 Nov. 2008	869–940	74
6	6 Apr. 2009 to 22 Jul. 2009	1082–1189	64
7	30 Nov. 2009 to 11 Mar. 2010	1320–1420	61



Kouyama et al. (JGR2013)