Venusian cloud physics simulated by a general circulation model

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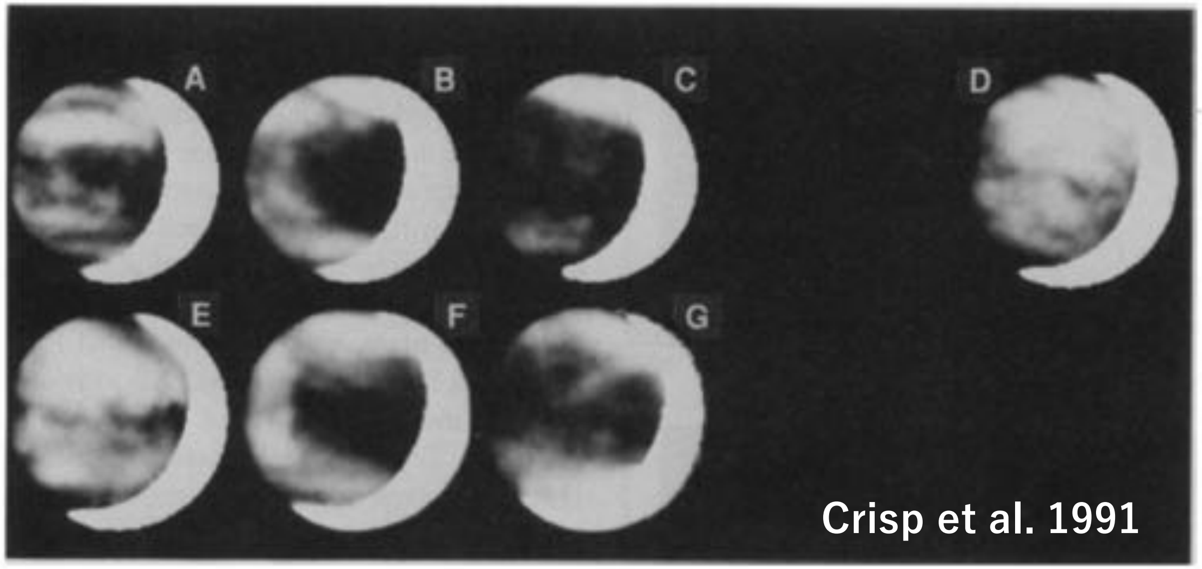
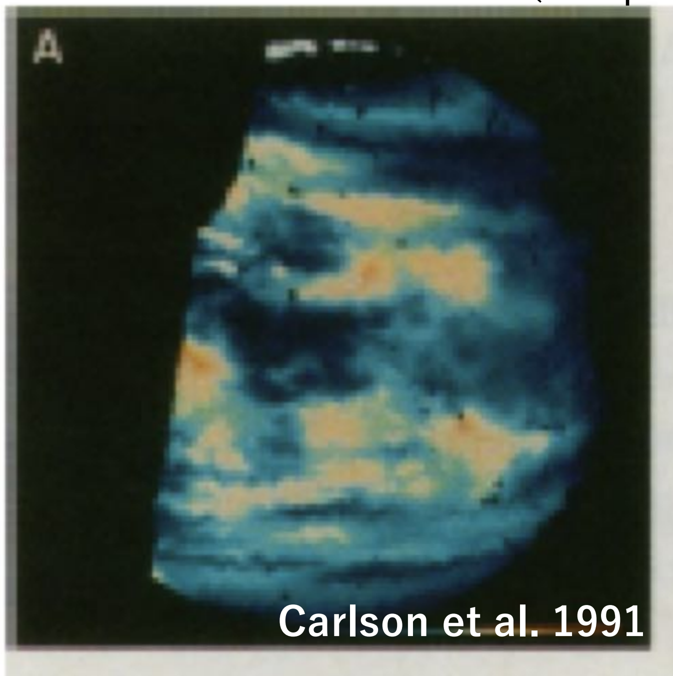
Previous infrared measurements of the Venus cloud

Ground-based observation（2.36μm）



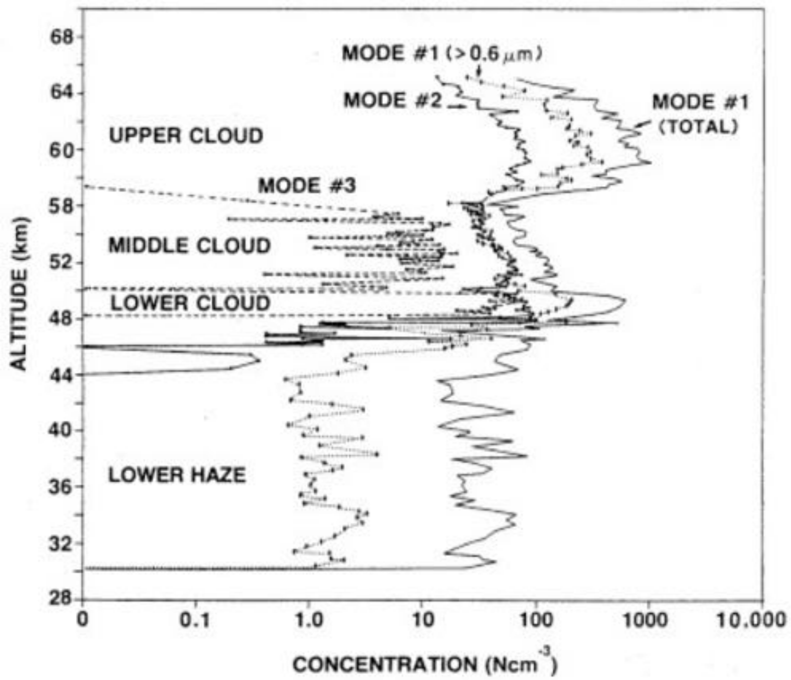
Galileo infrared camera（2.3μm）



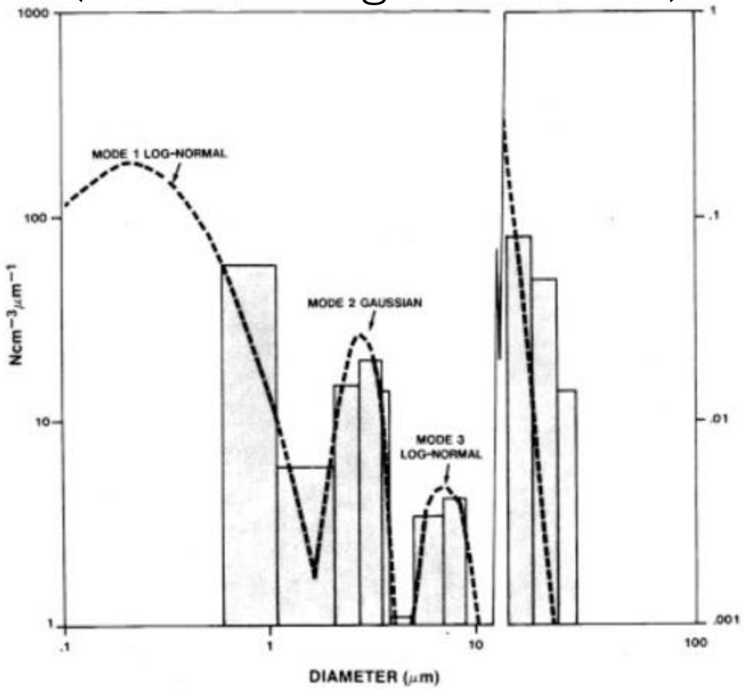
- Both bright and dark parts are seen in the low latitude region.
- Middle latitude region mainly has a bright place, implying that the cloud is thin.
- Polar latitude region is basically dark, suggesting that the cloud is thickest there.

Previous in-situ measurements of the Venus cloud

Number density of the cloud particle (Knollenberg et al. 1980)



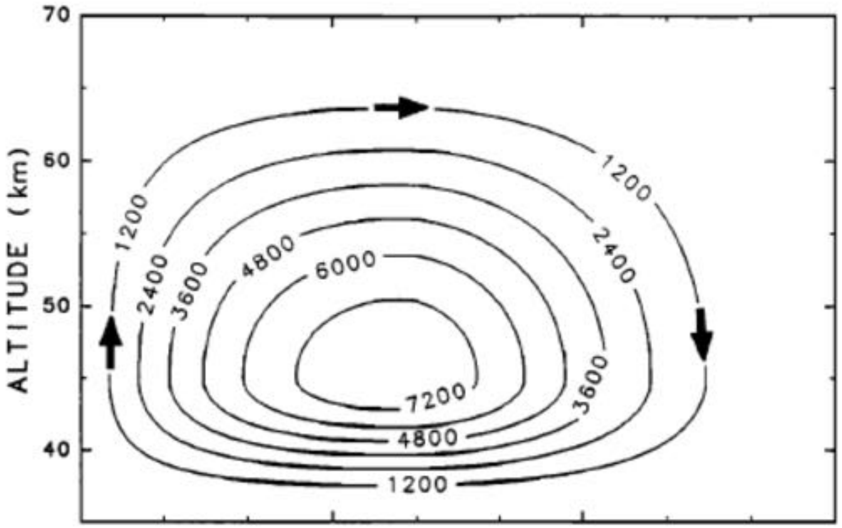
Particle radius distribution (Knollenberg et al. 1980)



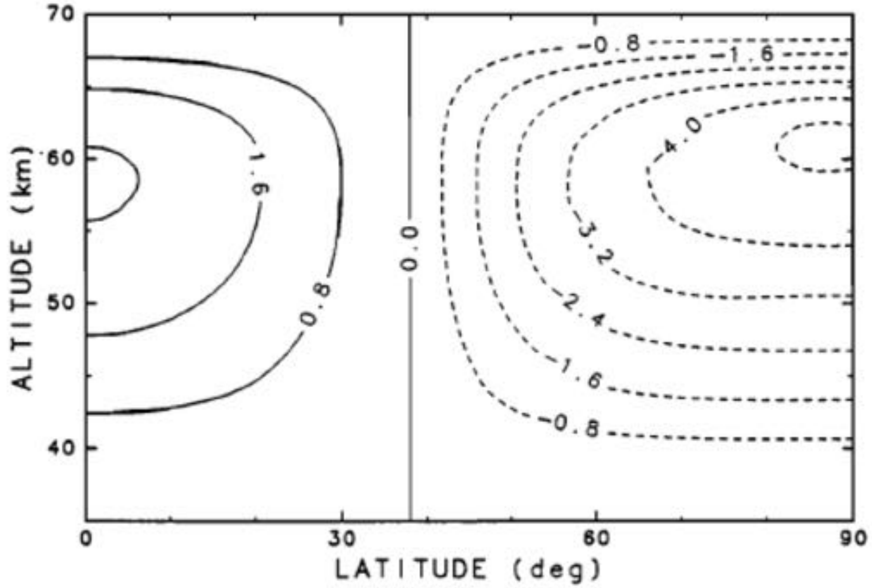
- Cloud has a three-layer structure.
- Cloud particles are classified into three modes: Mode1 ($r<1\mu m$), Mode2 ($1<r<5\mu m$), and Mode3 ($r>5\mu m$).
- It is thought that Mode1 is haze, Mode2 is H_2SO_4 liquid and Mode3 is crystal or does not exist.

Previous theoretical study of the Venus cloud (Imamura & Hashimoto 1998)

Stream function



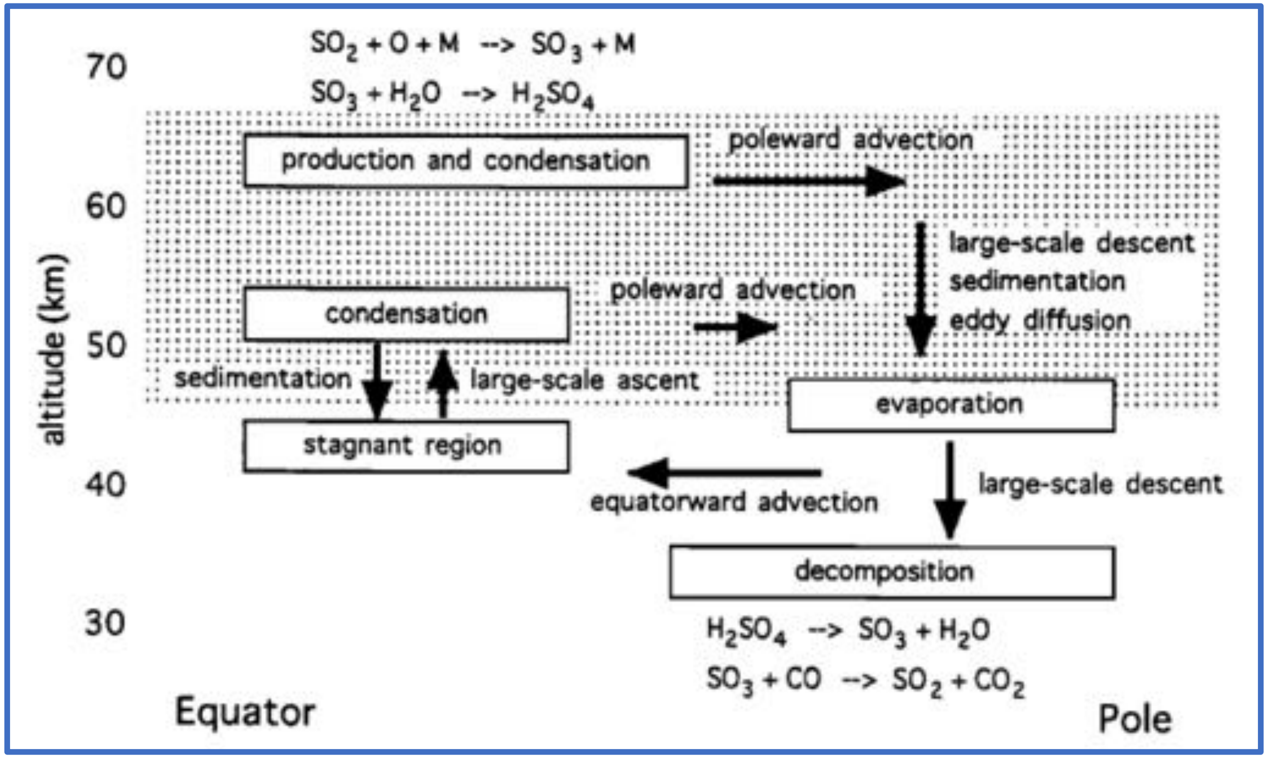
Vertical wind (mm/s)



- Two-dimensional (Latitude-height) calculation was conducted.
- Mode2 and Mode3 particles are considered as the cloud particles and assumed to be H_2SO_4 liquid. Chemical processes are also included.
- It is assumed that the meridional circulation has one cell.

→ Meridional distributions of the mixing ratios of H_2SO_4 and H_2O gases and mass loading are obtained.

Venus cloud physics suggested in Imamura & Hashimoto (1998)



- Both the mixing ratios of H_2SO_4 and H_2O vapors have local maxima in the equatorial region.
- Mass Loading has also maximum in the equatorial region. This is associated with the upward vertical wind of the mean meridional circulation.

Previous theoretical study of the Venus cloud （Hashimoto & Abe 2001）

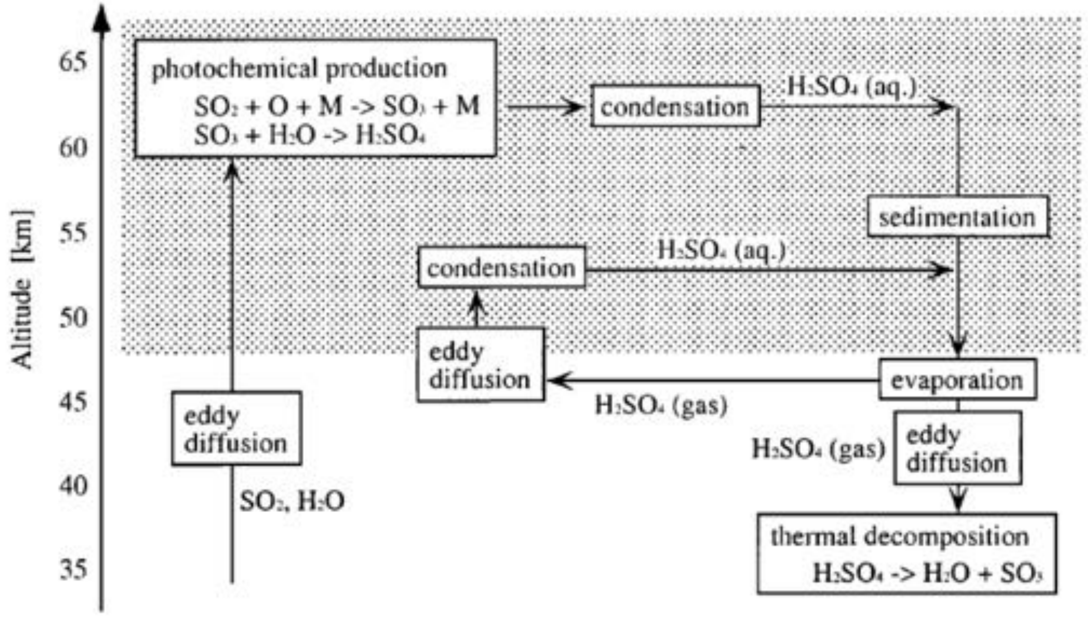


Figure 1. Schematic picture of H_2SO_4 cycle in Venus' cloud. Shaded area indicates the cloud layer.

- Vertical one-dimensional calculation
- Only H_2SO_4 and H_2O vapors are included and chemical processes are not included. Mode2 (H_2SO_4 liquid) is only considered.
- When both the partial pressures of H_2SO_4 and H_2O vapors reach those saturated pressures, the cloud can be created.

→ Vertical distributions of H_2O and H_2SO_4 vapor mixing ratios, mole concentration, cloud density are calculated.

Motivation of the present study

- There are no previous theoretical studies of the Venus cloud conducted in the realistic three-dimensional distributions of the wind and temperature.
- Venusian general circulation model named AFES-Venus have succeeded in reproducing various atmospheric structures （Sugimoto et al. 2014, 2017, 2019; Ando et al. 2016, 2017, 2018; Takagi et al. 2018; Kashimura et al. 2019）.

- The cloud physics processes shown in Hashimoto & Abe (2001) are simplified and implemented to AFES-Venus.
- We analyzed the calculation data and investigated the three-dimensional distributions of the cloud and cloud materials. And then, we examined how these distributions were induced.

Setup of AFES-Venus

(Sugimoto et al. 2014a, 2014b, 2017; Ando et al. 2016, 2017, 2018; Takagi et al. 2018)

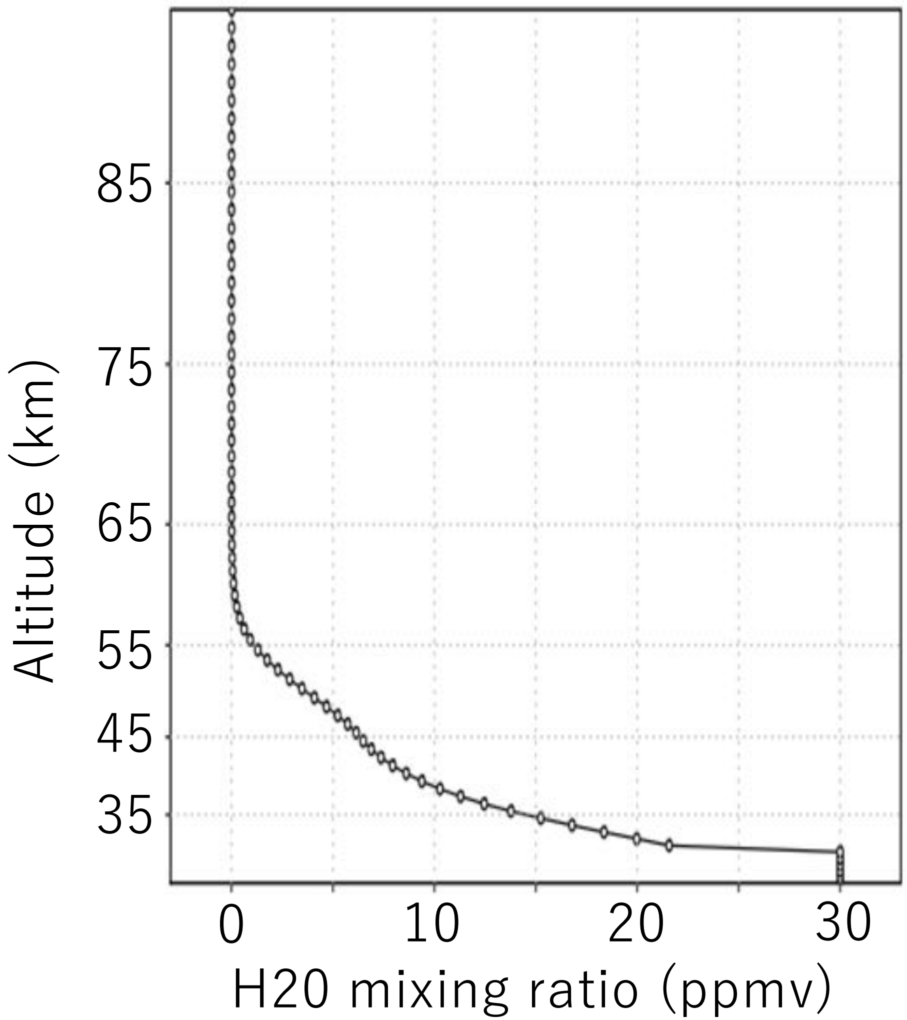
- Atmospheric GCM For Earth Simulator
  - Three-dimensional primitive equation （spectral model）
  - Resolution：T42L120 (Horizontal : 128 × 64 grids, Vertical : 0-120km, $\Delta z \sim 1$km)
  - Specific heat： 1000 J/(kg・K)
  - Horizontal hyper viscosity：∇^4 (relaxation time for the maximum wavenumber = 0.1 day)
  - Vertical eddy diffusion： 0.15 m^2/s
  - Rayleigh friction is included at the bottom layer and above 90 km altitude. (It acts on all the components except for zonal wavenumber-0.)
- Radiative processes
  - Solar heating：zonal mean (Qz) + diurnal (Qt) （Tomasko et al. 1980）
  - Newtonian cooling：$dT/dt = -\kappa\,(T - T_{ref}(\theta, z))$

    κ ：cooling rate (Crisp 1986)， $T_{ref}(\theta, z)$：reference temp. based on VIRA

Cloud physics processes considered in AFES-Venus

- Generation and loss processes of the cloud are based on Hashimoto & Abe (2001);
  - Only H_2O and H_2SO_4 vapors are considered as the cloud material, and chemical processes are not considered.
  - It is assumed that the cloud is composed of H_2SO_4 liquid particles with Mode1 ($r = 0.5$ μm) and Mode2 ($r = 1.0$ μm). Mole concentration is fixed to be 85%.
  - Cloud particle is generated when **both** partial pressures of H_2O and H_2SO_4 vapors reach their saturation vapor pressures. Otherwise, it evaporates.
  - H_2SO_4 vapor is generated around 62 km altitude in the dayside region and thermally decomposed above 480 K.
- At initial state, the mixing ratio of H_2O vapor is decided by the saturation vapor pressure for H_2SO_4 liquid with the mole concentration of 85% above 30 km altitude. Below that level, it is always fixed to be 30ppmv (e.g., Pollack et al. 1993).
- The maximum of H_2O vapor mixing ratio is limited by the saturation vapor pressure of pure H_2O vapor.
- Above 90 km altitude, H_2SO_4 vapor is artificially removed with the appropriate time constant (e.g., Sandor et al. 2012). It is infinite Earth days at 90 km altitude and 0.1 Earth days at 120 km altitude, and they are connected with a tangent hyperbolic function.
- The calculation runs for 40 Earth years, and we mainly analyze the data within the last 2 Venus days.

Initial distribution of H_2O vapor mixing ratio



Saturation vapor pressure of H_2O gas

$$\ln p_2^{sat}(T, x_1) = \ln {}^\circ p_2^{sat}(T) + \frac{\mu_2(T, x_1) - {}^\circ\mu_2(T)}{RT}, \quad \text{(A2)}$$

Saturation vapor pressure of pure H_2O gas

$$\ln {}^\circ p_2^{sat} = \alpha - \frac{\beta}{T} + \frac{\gamma\xi}{T + 0.01}[\exp(\delta\xi^2) - 1] - \epsilon \exp(-\eta\zeta) \quad \text{(A4)}$$

x_1 : mole concentration (= 0.85), T : temperature,
R : gas constant, T_0 = 385K

$\xi = (T+0.01)^2 - 293700$, $\zeta = (647.26 - T)^{5/4}$,
$\alpha = 24.021415$, $\beta = 4616.9134$, $\gamma = 3.1934553\times10^{-4}$
$\delta = 2.7550431\times10^{-11}$, $\varepsilon = 1.0131374\times10^{-2}$,
$\eta = 1.3158813\times10^{-2}$

Saturation vapor pressure of H_2SO_4 gas

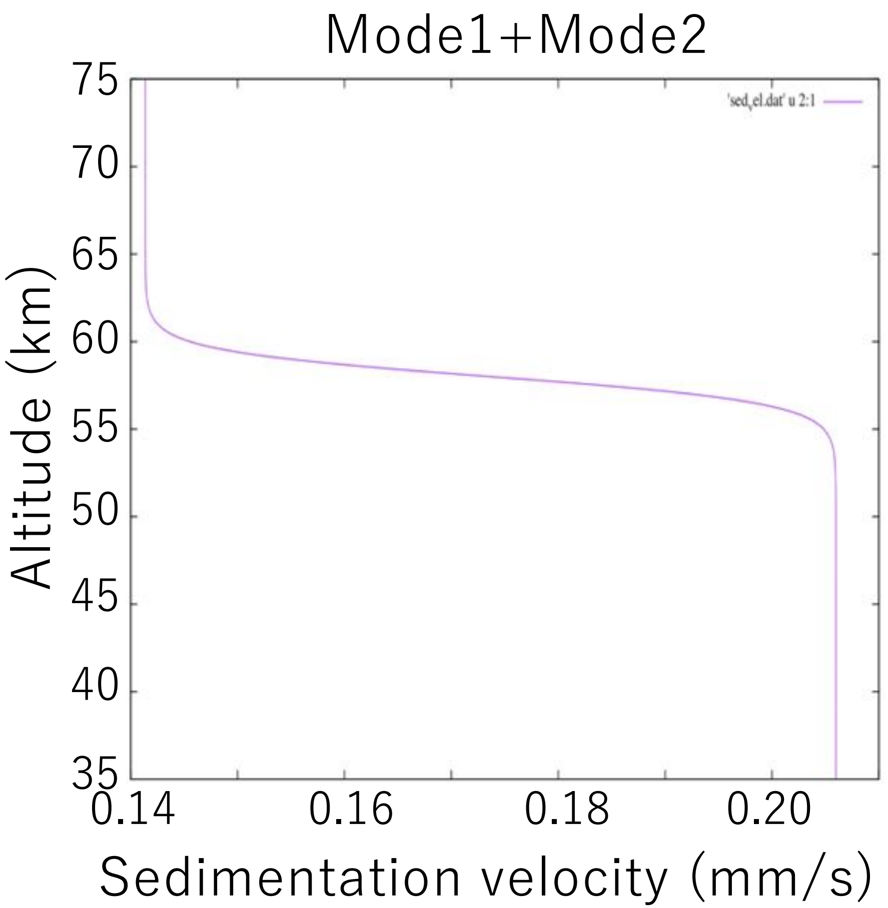
$$\ln p_1^{sat}(T, x_1) = \ln {}^\circ p_1^{sat}(T) + \frac{\mu_1(T, x_1) - {}^\circ\mu_1(T)}{RT}, \quad \text{(A1)}$$

Saturation vapor pressure of pure H_2SO_4 gas

$$\ln {}^\circ p_1^{sat} = 16.259 - \frac{10156}{T} + 7.42\left(1 + \ln\frac{T_0}{T} - \frac{T_0}{T}\right) \quad \text{(A3)}$$

Please see also Imamura & Hashimoto (1998) in more detail.

Sedimentation velocity distribution assumed in our model



Based on Imamura & Hashimoto (1998), sedimentation velocity is given by Stokes velocity:

$$w_{sed} = -\frac{2}{9}\frac{g\rho r^2}{\eta}$$

g = 8.87 m/s^2, ρ =1.8x10^3 kg/m^3, η = 1.5x10^{-5} kg/m/s,
r : particle radius（Mode1 : 0.5μm, Mode2 : 1.0μm）

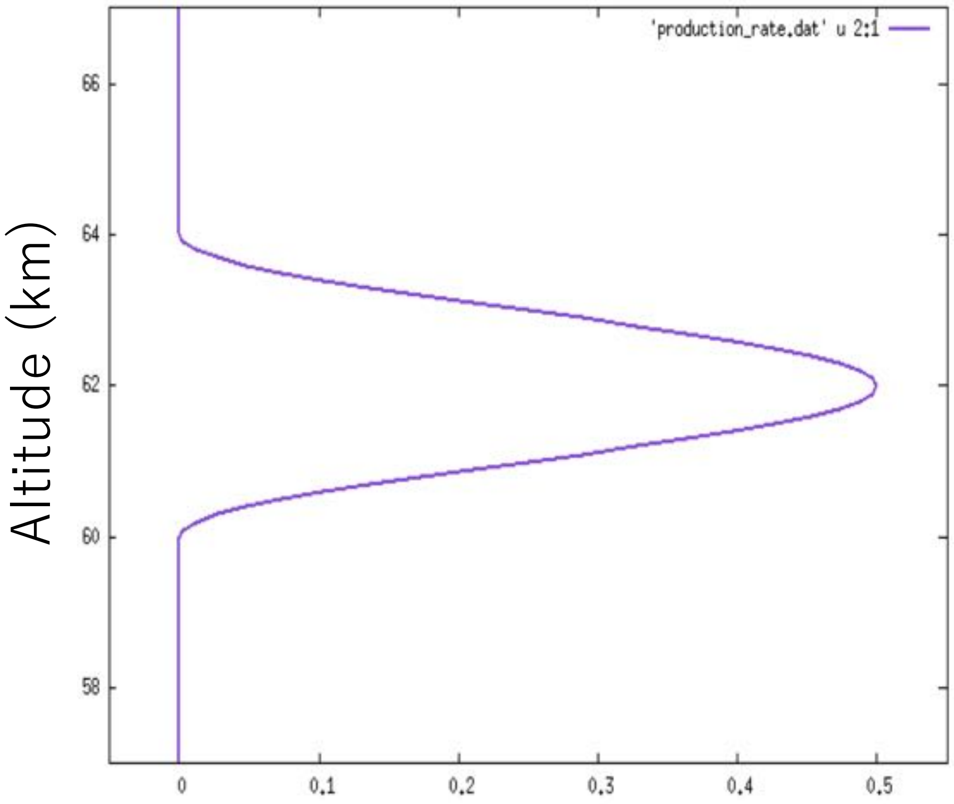
Based on Knollenberg et al. (1980), considering the number densities of Mode1 (N_1) and Mode2 (N_2),

- Above 58km altitude, N_1 = 1000 cm^{-3}, N_2 = 100 cm^{-3}
- Below 58km altitude, N_1 = 100 cm^{-3}, N_2 = 50 cm^{-3}

weighted sedimentation velocity distribution is given.

Please see Imamura & Hashimoto (1998) in more detail.

Generation rate of H_2SO_4 gas



Vertical distribution of generation rate [m^{-1} s^{-1}]

Vertical distribution of generation rate is described as follow:

$$\varphi(z) = \frac{1}{2\Delta z}\left\{\cos\left(\frac{z-z_c}{\Delta z}\pi\right)+1\right\}$$

$z_c - \Delta z < z < z_c + \Delta z$

where z_c = 62 km, Δz = 2km.

Then the formula of generation rate of H_2SO_4 vapor is

$$Q_{H2SO4} = (Q_{peak} \times \varphi(z) \times m)/(\rho \times N_A)$$

$Q_{peak} = 1.0\text{x}10^{16}\ m^{-2}\ s^{-1}$

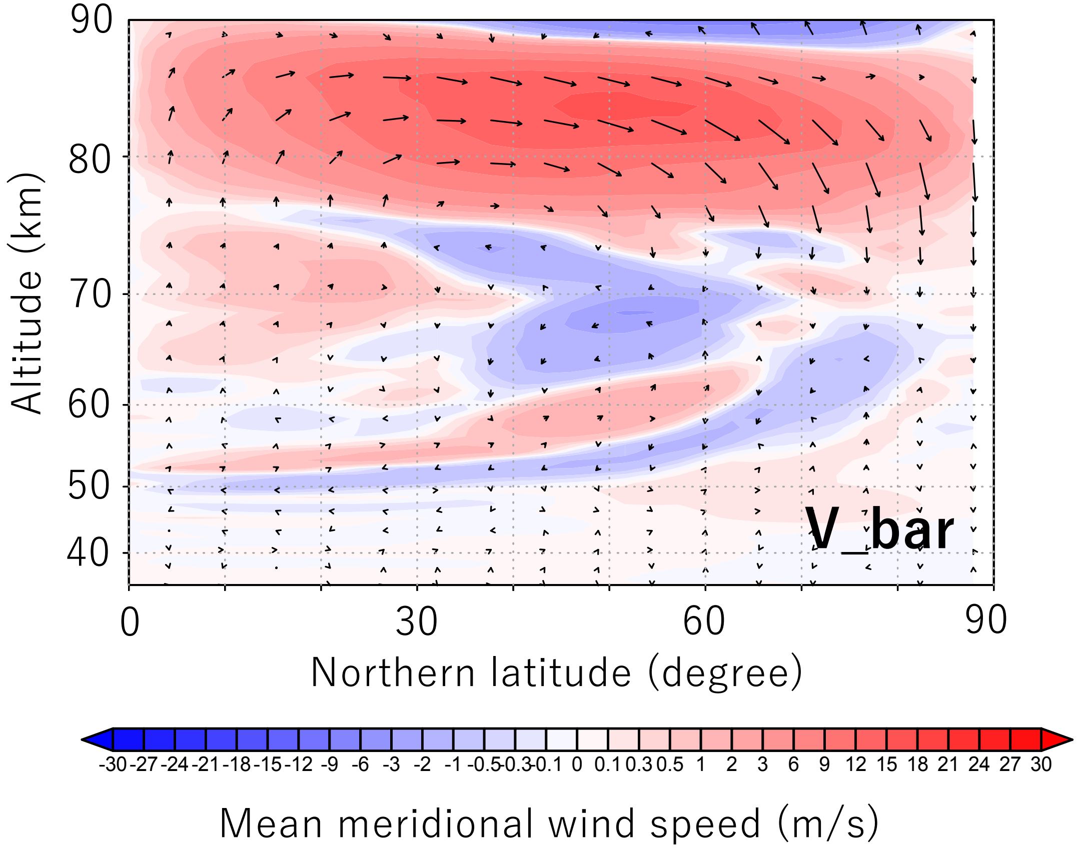
$m = 98.1\ g\ mol^{-1}$

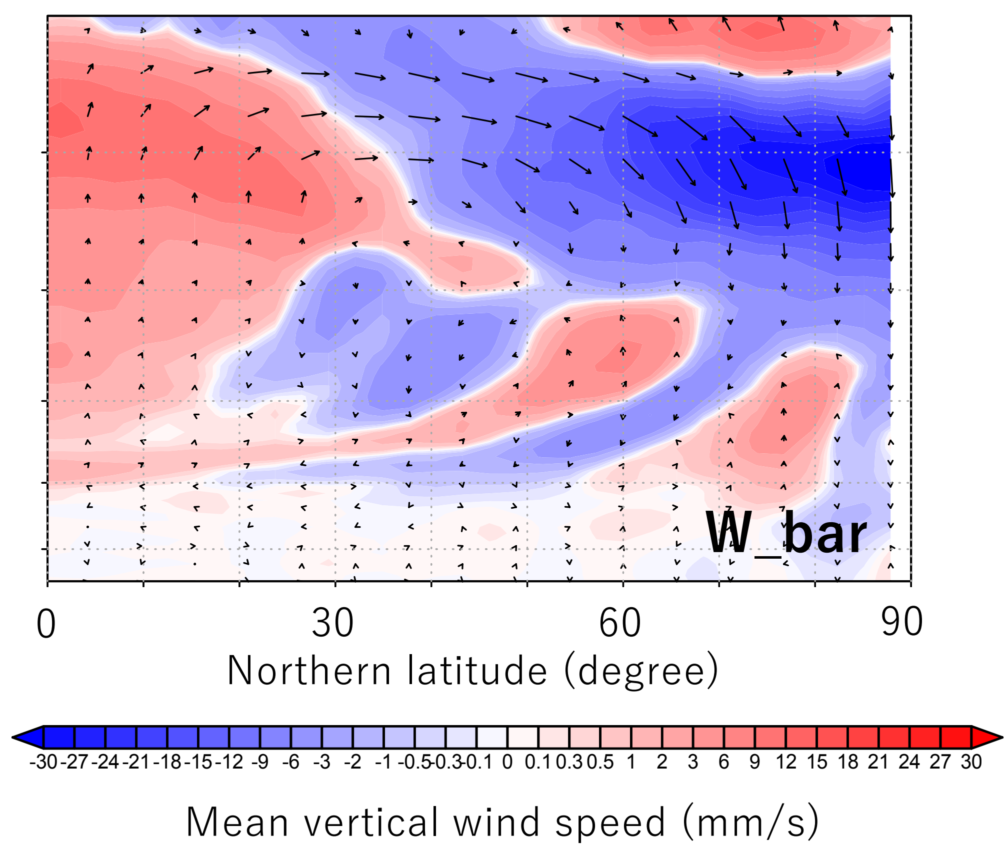
ρ : density, N_A : Avogadro's constant

＊Dependence of generation rate on solar zenith angle is also considered.

Please see also Hashimoto & Abe (2001) in more detail.

Structure of mean meridional circulation

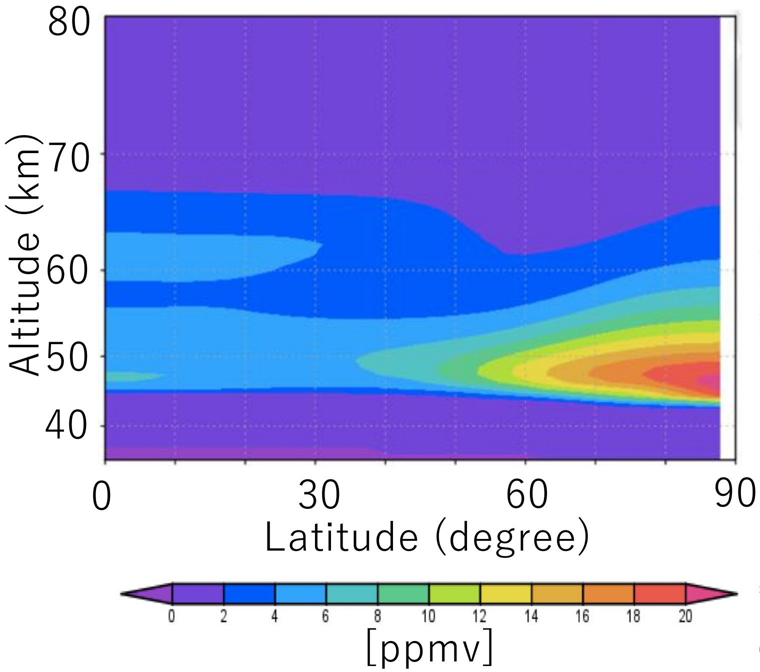




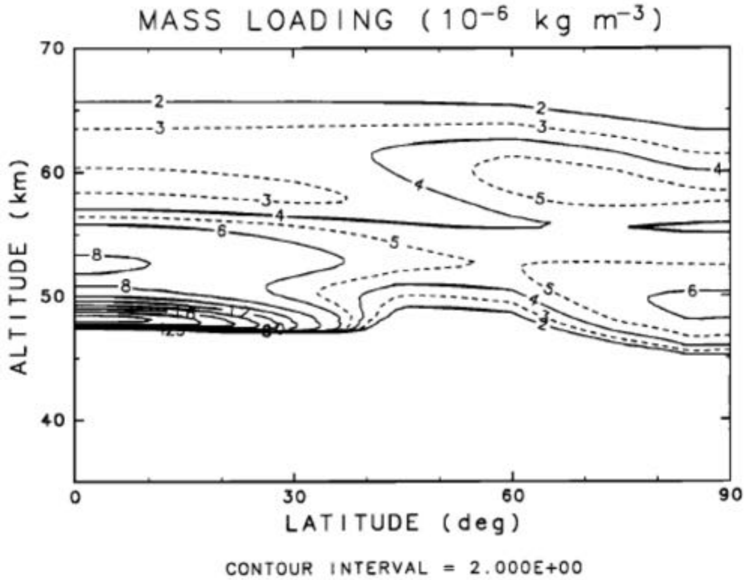
*Zonal and temporal (for 2 Venus days) average were conducted.

Zonally and temporally averaged mass loading

AFES-Venus



Imamura & Hashimoto (1998)



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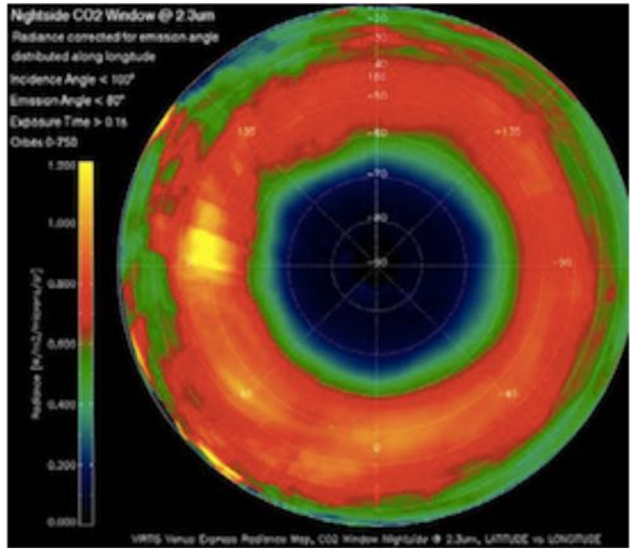
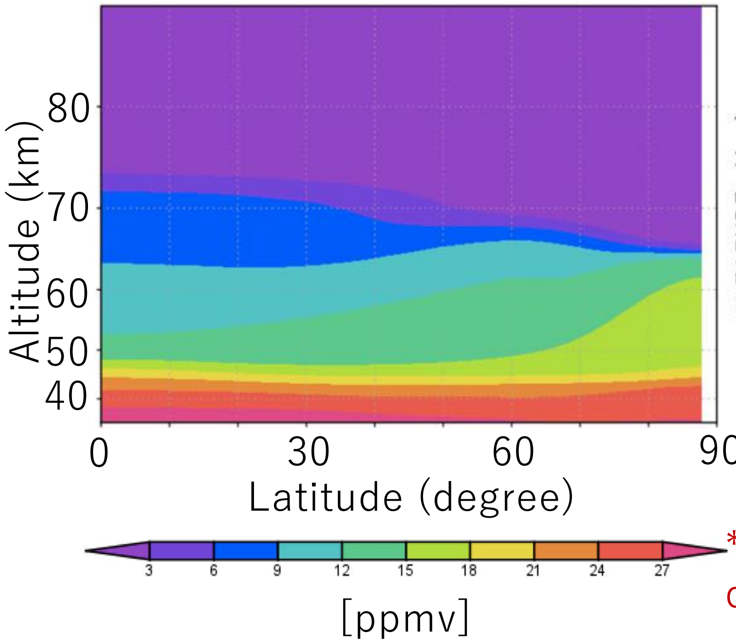


*Zonal and temporal (for 2 Venus days) average were conducted.

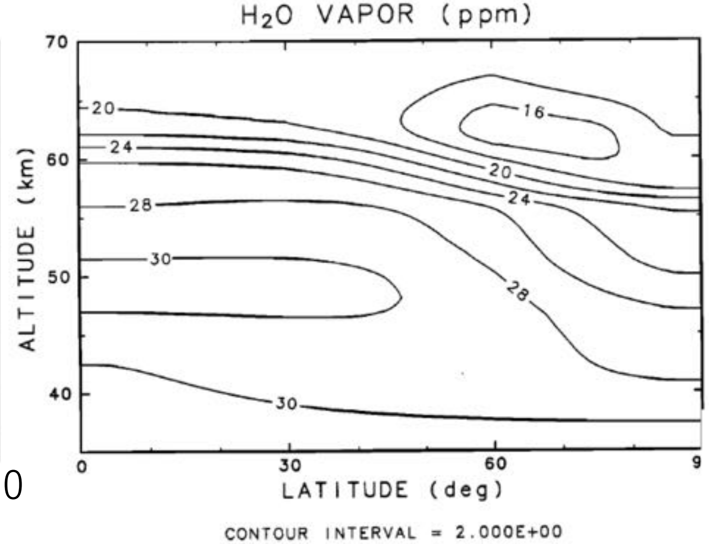
- In our model, mass Loading has maximum in the polar region. It becomes large in the equatorial region. These are qualitatively consistent with the previous infrared measurements. (Please see also my movie of the horizontal distribution of the vertically integrated mass loading.)
- Our results are opposite to Imamura & Hashimoto (1998).

Zonally and temporally averaged H_2O vapor mixing ratio

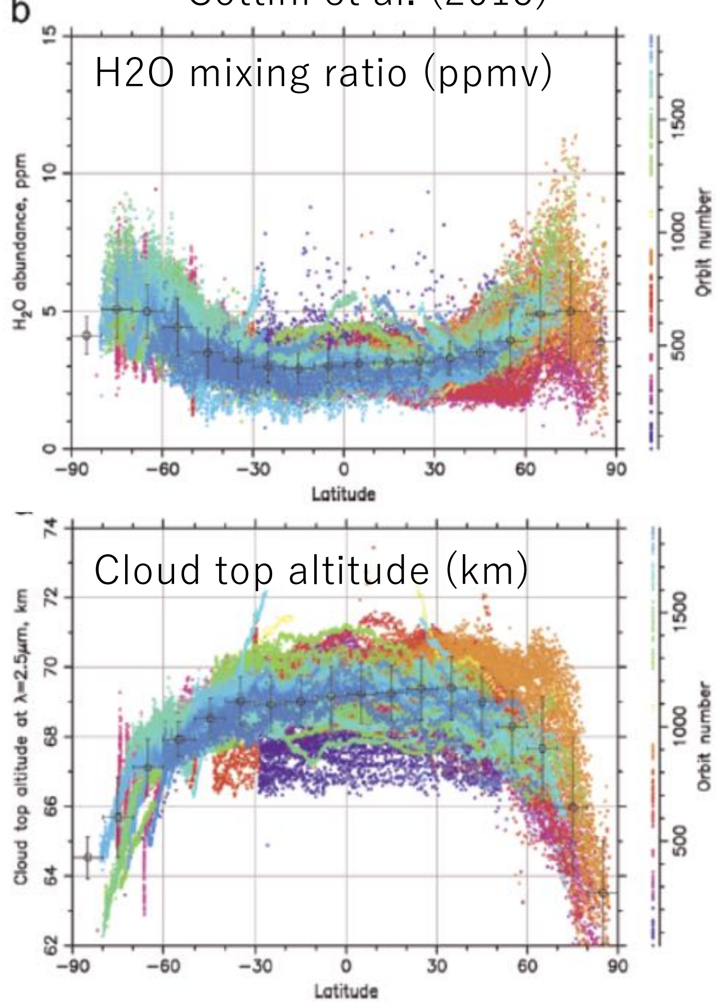
AFES Venus



Imamura & Hashimoto (1998)



Cottini et al. (2015)

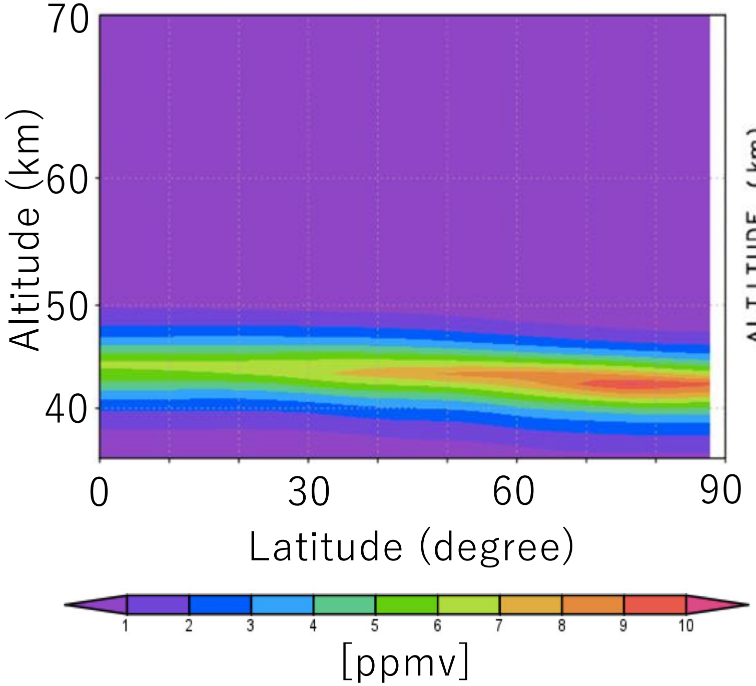


*Zonal and temporal (for 2 Venus days) average were conducted.

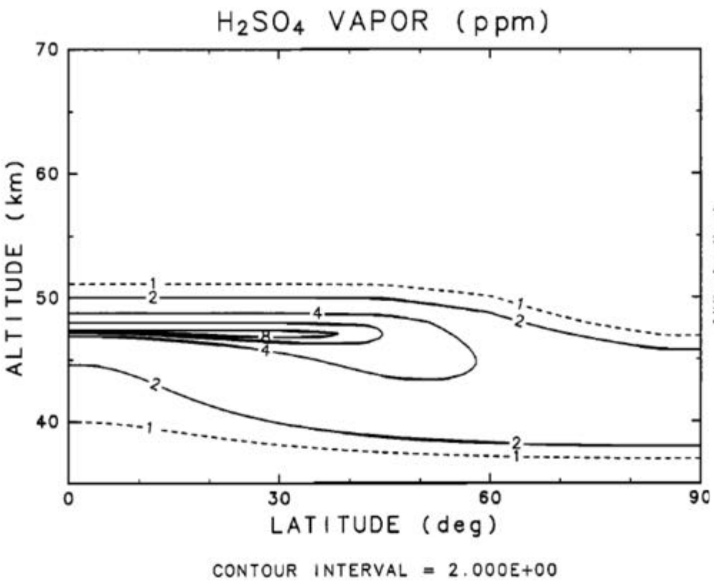
- In our model, the mixing ratio of water vapor increases with latitude. This is qualitatively consistent with the previous infrared measurements.
- Our results are opposite to Imamura & Hashimoto (1998).

Zonally and temporally averaged H_2SO_4 vapor mixing ratio

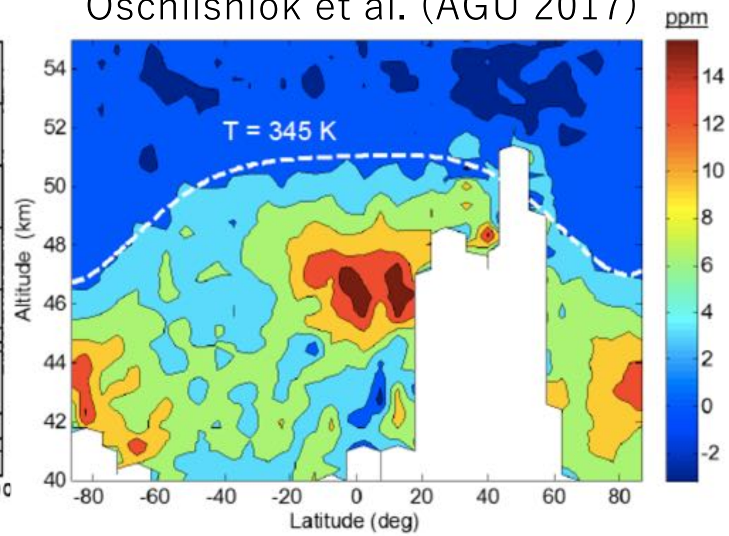
AFES Venus



Imamura & Hashimoto (1998)



Oschlisniok et al. (AGU 2017)

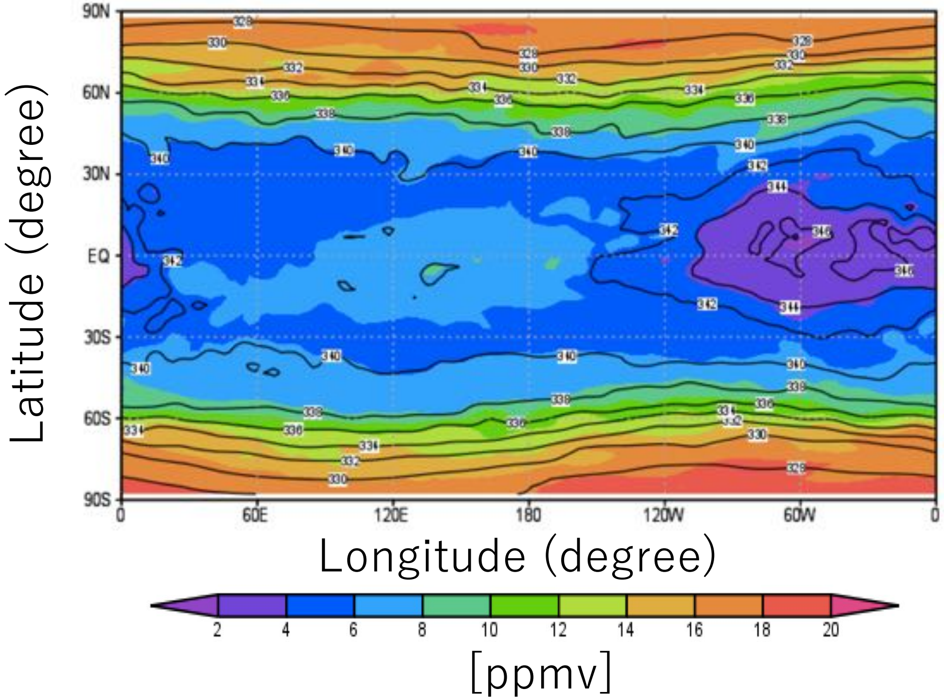


*Zonal and temporal (for 2 Venus days) average were conducted.

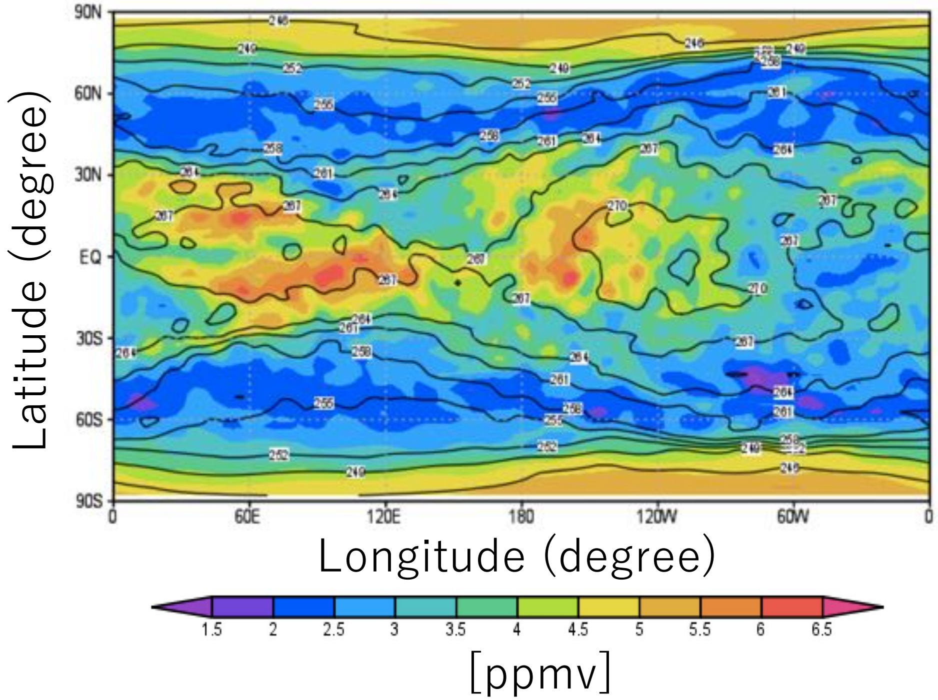
- In our model, the mixing ratio of H_2SO_4 vapor becomes large in the polar region. This is partly consistent with radio occultation measurements.
- Our results are opposite to Imamura & Hashimoto (1998).

Horizontal distribution of the mass loading

At 50 km altitude (around cloud bottom level)

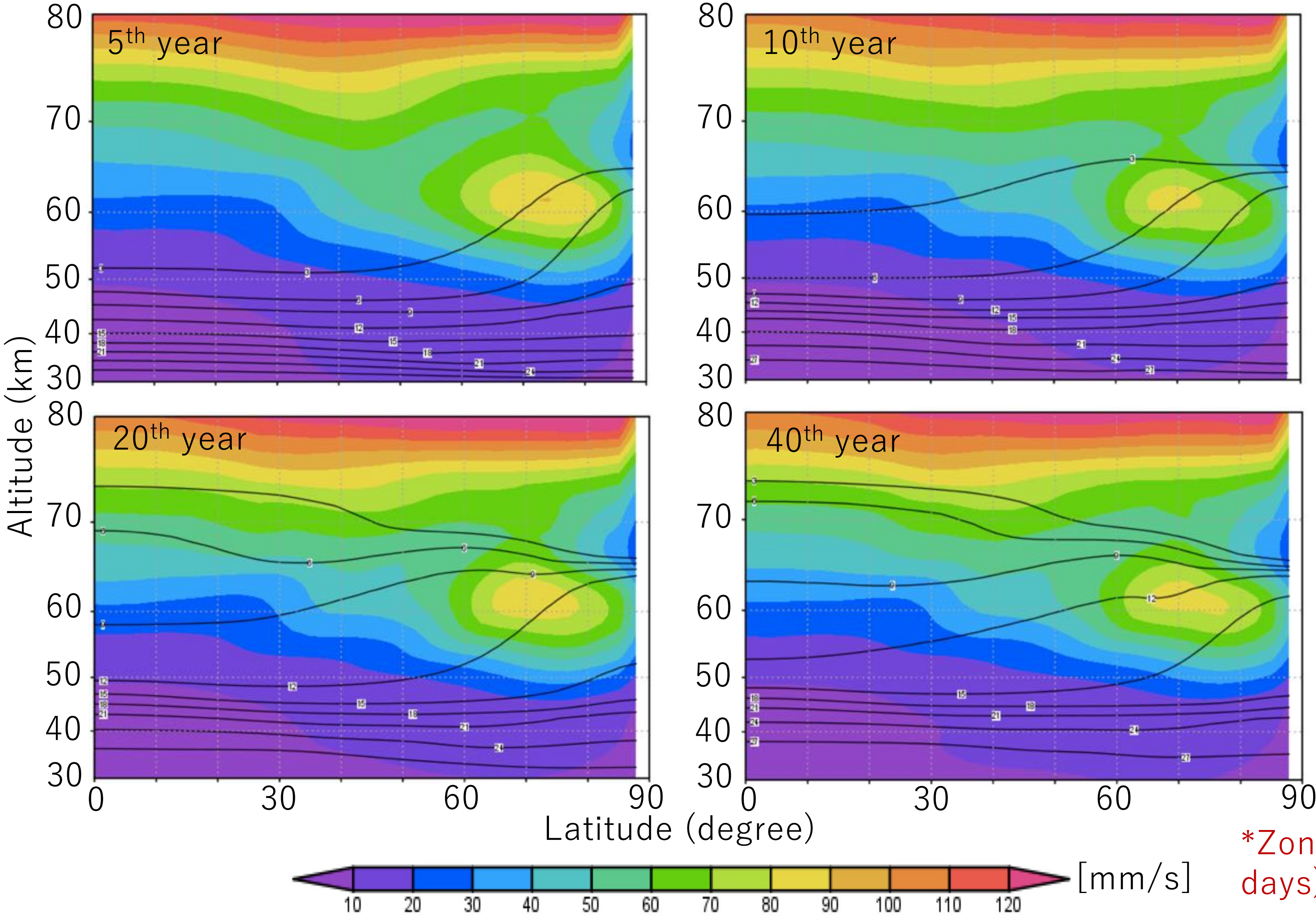


At 60 km altitude



- Cloud distribution at 50 km altitude seems to be closely related to the temperature distribution. Zonal wavenumber-1 structure can be seen and might be associated with Kelvin wave (Sugimoto et al. 2014b).
- Cloud distribution at 60 km altitude shows that zonal wavenumber-1 and -2 structures, which might be associated with thermal tides (Takagi et al. 2018), are mixed.
- Please see also my movie of the horizontal distribution of the vertically integrated mass loading.

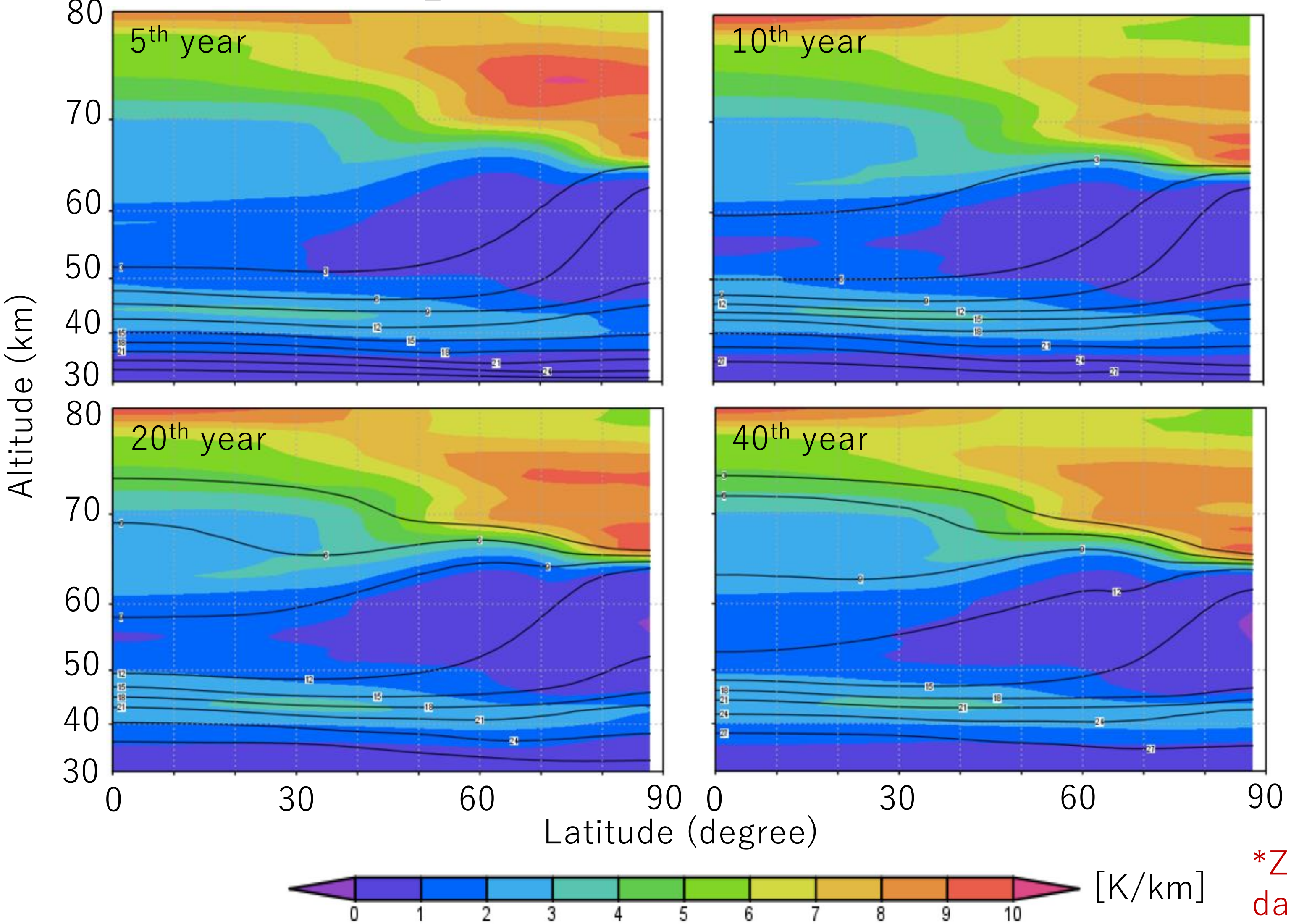
H_2O vapor mixing ratio and RMS of w’



- As time passes, H_2O vapor comes from the polar lower atmosphere.
- This is attributed to the strong vertical motion in the polar region, where static stability is low there.

*Zonal and temporal (for 2 Venus days) averages were conducted.

H_2O vapor mixing ratio and static stability

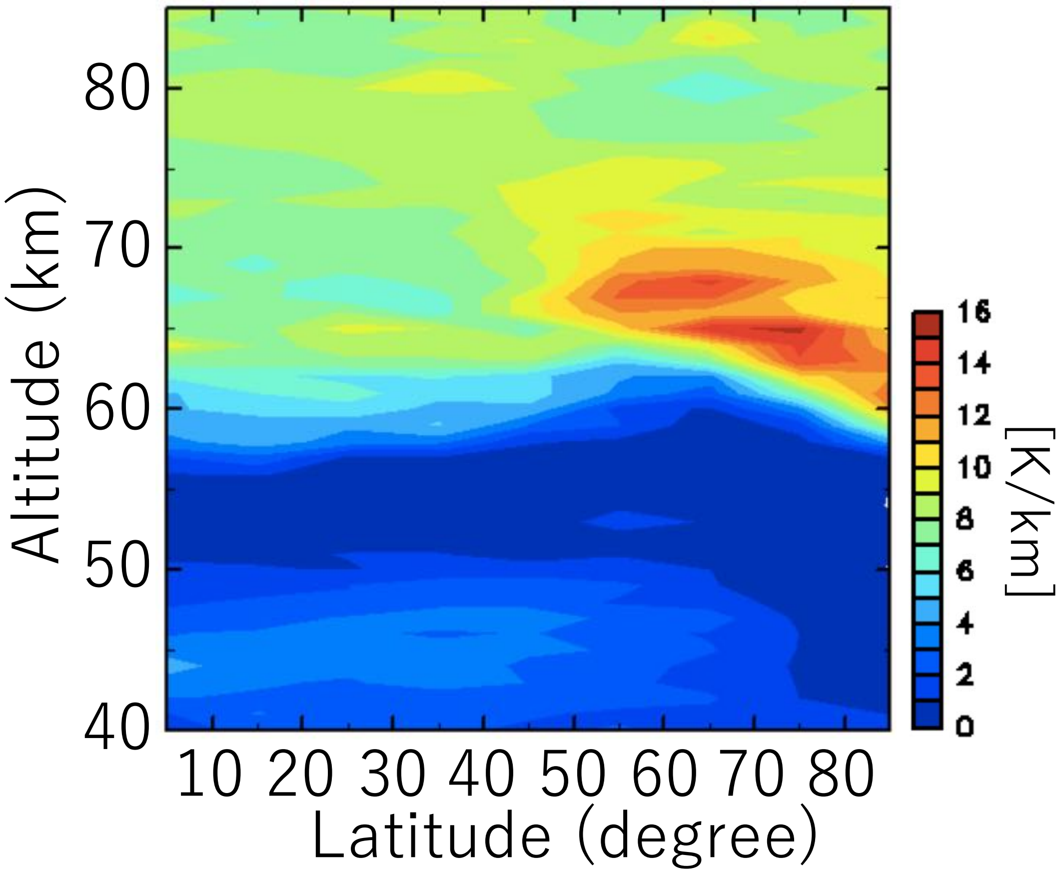


- Static stability in the polar region is lower than those in the low and middle latitude regions.
- Static stability distribution reproduced in our model is qualitatively consistent with radio occultation measurements.

*Zonal and temporal (for 2 Venus days) averages were conducted.

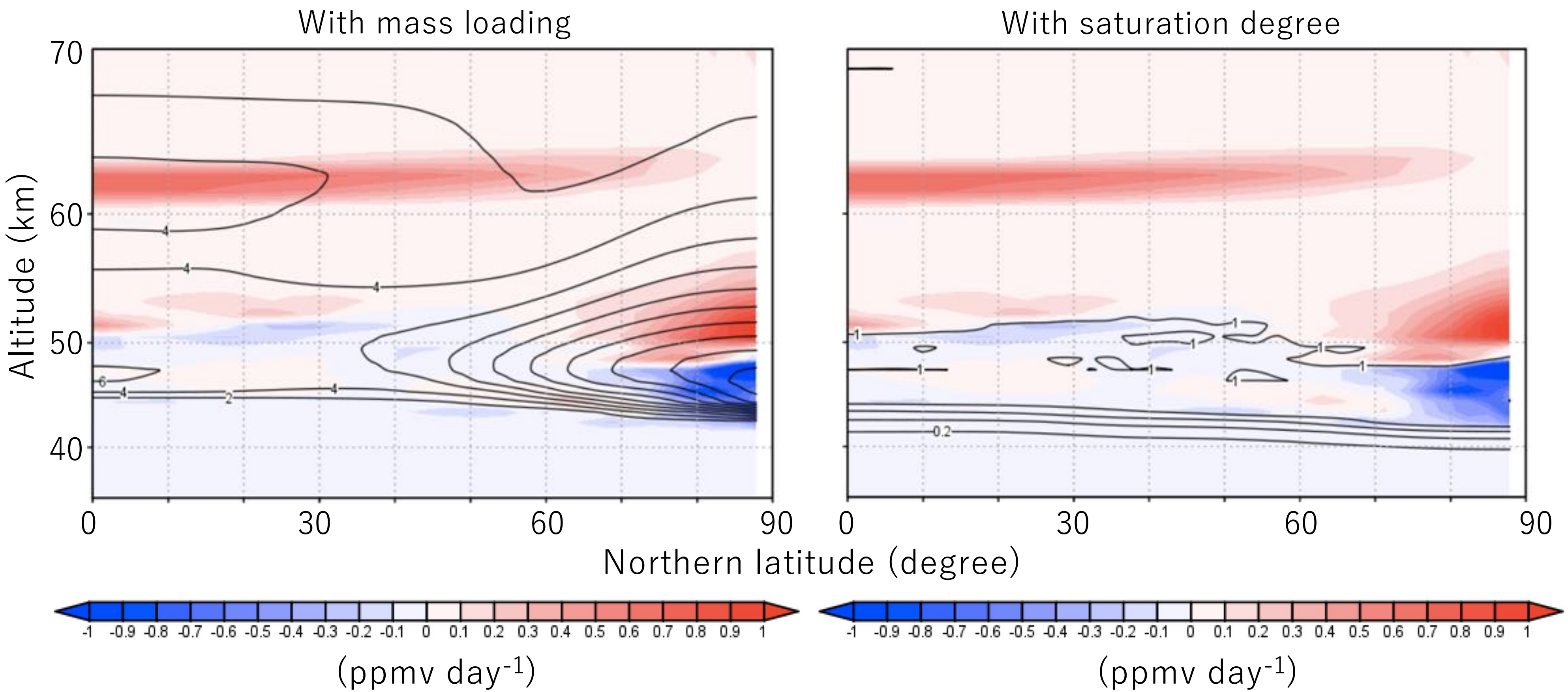
Static stability distribution obtained by radio occultation measurements

Ando et al. (under review)



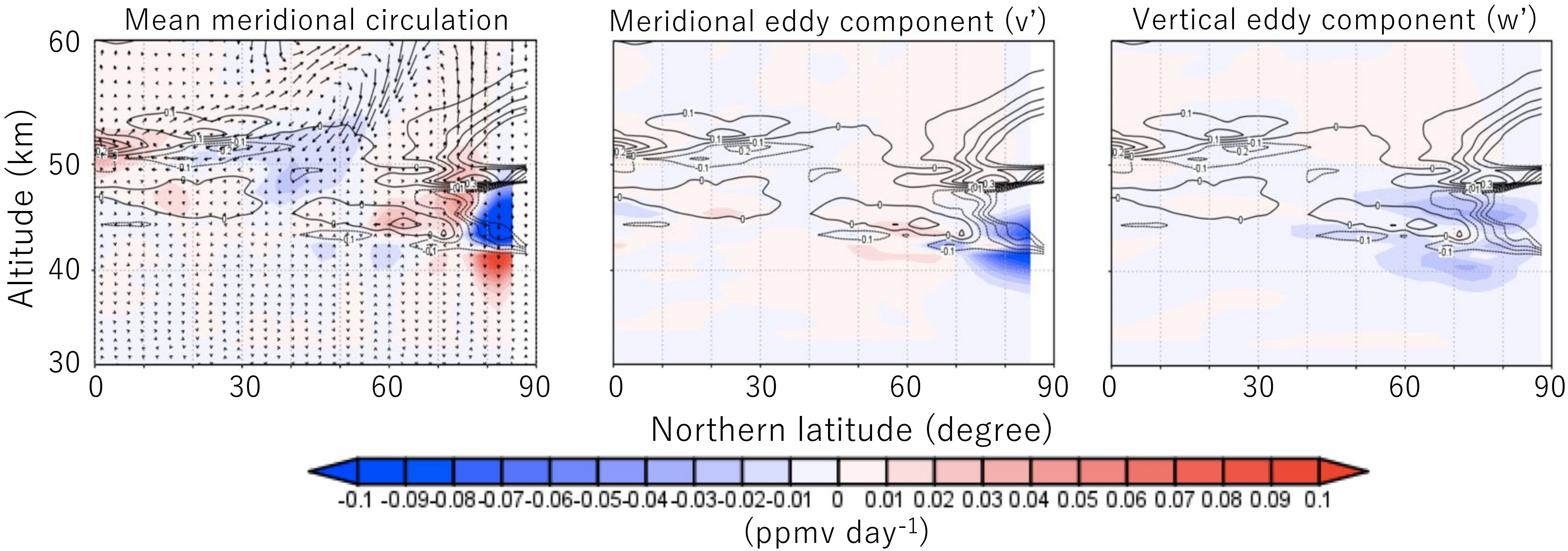
- In the polar region, low static stability layer continuously extends below 60 km altitude.
- Static stability distribution reproduced in AFES-Venus is qualitatively consistent with radio occultation measurements.
- Latitude-height distribution of H_2O vapor mixing ratio seems to be closely related to the static stability distribution.

Latitude-height distribution of the generation rate of cloud



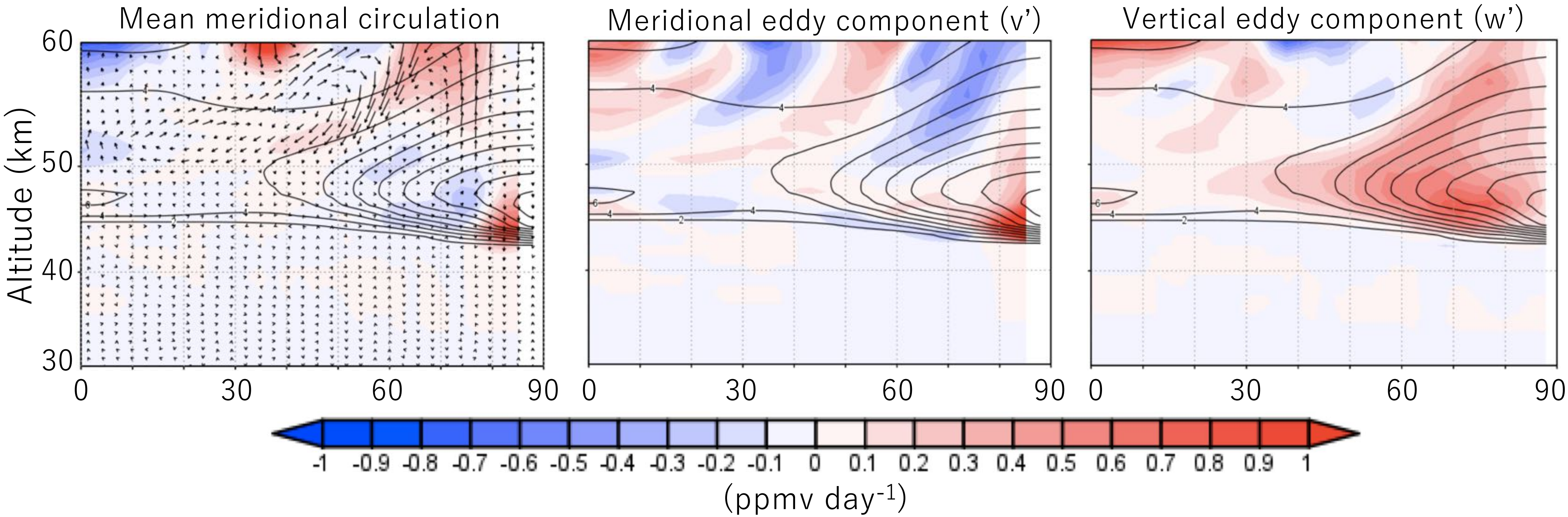
- Large generation rates can be seen at 62 km altitude and 50–55 km altitudes.
- Moderately large generation rates are also seen at 50-55 km altitudes in the low latitude region.

Convergence of H_2SO_4 vapor flux and cloud generation rate



- H_2SO_4 vapor is accumulated around 50 km altitude and 45–48 km altitudes in the low latitude region by the mean meridional circulation. This induces the cloud generation in these regions.
- H_2SO_4 vapor is taken away from the middle latitude region (to the low latitude region) by the mean meridional circulation. This reduces the cloud generation rate and makes the cloud thin there.

Convergence of cloud flux and mass loading

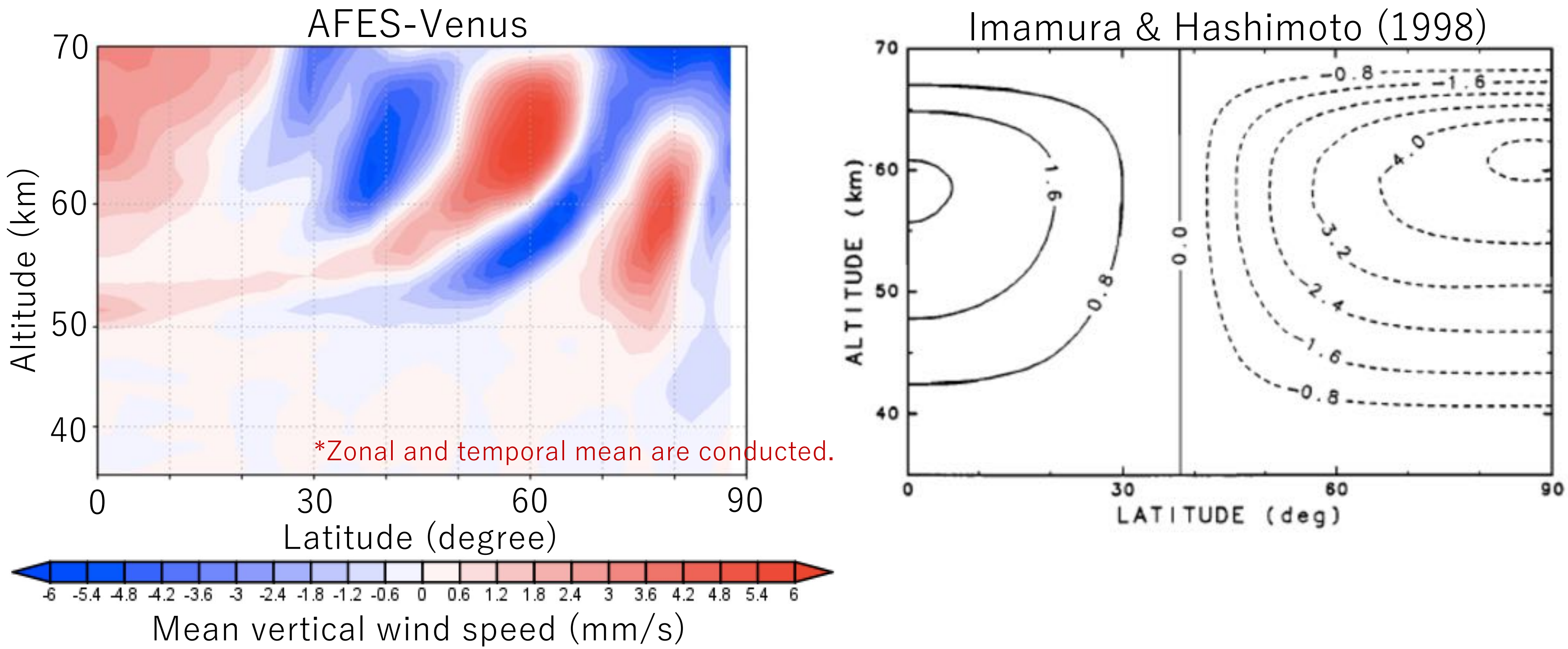


- Cloud particles are taken away from the low latitude region and accumulated in the middle latitude region by the mean meridional circulation. This compensates for the reduction of the cloud generation rate associated with the removal of H_2SO_4 vapor by the mean meridional circulation in the middle latitude region.
- Large mass loading in the high latitude region is attributed to the vertical eddy wind, which might be associated with barotropic and/or baroclinic instability generated in the high latitude region (e.g. Garate-Lopez et al. 2013; Sugimoto et al. 2014b; Lebonnois et al. 2016; Ando et al. 2017).

Summary

- Based on Hashimoto & Abe (2001), the simplified cloud physics processes were implemented into AFES-Venus. And then, three-dimensional calculation was conducted.
- Mixing ratio of H_2O vapor increases with latitude. This is attributed to the strong vertical motion in the polar region, where static stability is low. (These are qualitatively consistent with the previous measurements.)
- Mass Loading becomes maximum in the polar region because H_2O vapor comes from the polar lower atmosphere and H_2SO_4 vapor is transported from the equatorial region to the polar region by the mean meridional circulation. (These are qualitatively consistent with the previous measurements.)
- Mixing ratio of H_2SO_4 vapor also increases with latitude because the cloud is thick in the polar region and the sedimentation amount of the cloud is also large. （This is partly consistent with the recent measurements.)

Comparison of the mean vertical wind between AFES-Venus and Imamura & Hashimoto (1998)



- Mean vertical wind is much weaker than Imamura & Hashimoto (1998) below 50 km altitude. This is the reason why the cloud and H_2SO_4 vapor are not accumulated in the equatorial region.