Development of a Venus' cloud formation scheme for a convection resolving model

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Summary

- We develop a new cloud formation scheme for a convection resolving model based on Imamura and Hashimoto (1998).
- Our cloud formation scheme represents formation and decomposition of H_2SO_4-H_2O solution successfully.
- The convection resolving model in which our cloud formation scheme is implemented represents the distribution of H_2SO_4-H_2O solution droplets associated with convection.

Introduction

- Although convection has been suggested to occur in the lower part of Venus' cloud layer by some observational evidences, its structure remains to be clarified.
- In the previous studies, Baker et al. (1998, 2000), Imamura et al. (2014), and Lefevre et al. (2017) try to simulate Venus' cloud-level convection, but their models they utilized do not consider cloud formation process.
- Our purpose is to develop new cloud formation scheme and to perform numerical simulation using the scheme in order to investigate a possible structure of Venus' cloud-level convection and clouds distribution.

Our cloud formation scheme and settings of calculations

- Our cloud formation scheme is based on Imamura and Hashimoto (1998).
  - The number densities of sulfuric acid (H_2SO_4) and water (H_2O) in the gas and liquid phases are calculated.
  - Sedimentation of H_2SO_4-H_2O solution droplets and chemical reactions of sulfuric acid are also considered.

$$\frac{\partial n_i^{total}}{\partial t} = -\boxed{\frac{\partial}{\partial z}\left(w_{sed} n_i^{liq}\right)} + \boxed{P_i} - \boxed{L_i} \qquad (1)$$

n_i^{total}	: number density (gas + liquid)
n_i^{gas}	: number density (gas)
n_i^{liq}	: number density (liquid)
P_i	: production rate
L_i	: loss rate
i	: $i = 1$ H2SO4, $i = 2$ H2O
w_{sed}	: sedimentation velocity
x_i	: concentration of H2SO4 solution
p_1^{sat}	: saturation vapor pressure
k	: Boltzmann constant
T	: temperature
μ_i	: chemical potential

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

H2SO4 production / H2O loss: Chemical Reaction $SO_2 + O + H_2O \rightarrow H_2SO_4$

$$P_1 = -L_2 = -3.5\times10^{16} \times \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(z-z_0)^2}{2\sigma^2}\right) cos\,\varphi$$

H2SO4 loss / H2O production: Chemical Reaction $H_2SO_4 + CO \rightarrow SO_2 + CO_2 + H_2O$

$$L_1 = -P_2 = \frac{f_{CO}^* k_{13} K_p}{(kT)^2}\frac{n_1^{total}}{n_2^{total}} p$$

  - Partitioning of H_2SO_4 and H_2O between gas and liquid is determined using saturation vapor pressure of H_2SO_4-H_2O solution which is the function of concentration x_1.

$$n_i^{total} = n_i^{gas} + n_i^{liq}$$

$$n_i^{gas} = \frac{p_i^{sat}(T, x_1)}{kT}$$

$$n_i^{liq} = n_i^{total} - \frac{p_i^{sat}(T, x_1)}{kT}$$

$$\left.\begin{aligned} \ln p_1^{sat}(T,x_1) &= \ln \dot{p}_1^{sat}(T) + \frac{\mu_1(T,x_1) - \dot{\mu}_1(T)}{RT} \\ \ln p_2^{sat}(T,x_1) &= \ln \dot{p}_2^{sat}(T) + \frac{\mu_2(T,x_1) - \dot{\mu}_2(T)}{RT} \\ n_1^{total} &= \frac{p_1^{sat}(T,x_1)}{kT} + x_1 n^{liq} \\ n_2^{total} &= \frac{p_2^{sat}(T,x_1)}{kT} + (1-x_1) n^{liq} \end{aligned}\right\}$$

x_1 is calculated numerically by Newton method

Note: $\frac{\mu_i(T,x_i)-\dot{\mu}_i(T)}{RT}$ can be calculated based on the equations of Zeleznik(1991).

- To verify our scheme, we perform some tests.
  - We check the included parameters in our scheme (see Fig.1 – Fig.4) .
  - We check condensation level of H_2SO_4-H_2O solution (see Fig.5).
    - An air parcel is assumed to rises from the bottom (z = 30 km) in a process that condensate is removed as soon as it is formed. H_2SO_4 and H_2O mole fractions at bottom are 10 ppm and 30 ppm, respectively. Temperature and pressure profiles are adopted from Venus international reference atmosphere (Sieff et al. 1985).
  - We also check time evolution of vertical profiles of H_2SO_4 and H_2O (see Fig.6).
    - The initial profiles of H_2SO_4 and H_2O are the same as those shown in Fig.5.

Results of test calculations

Checks on the included parameters

- Sedimentation Velocity W_{sed} and chemical properties are consistent with previous studies.

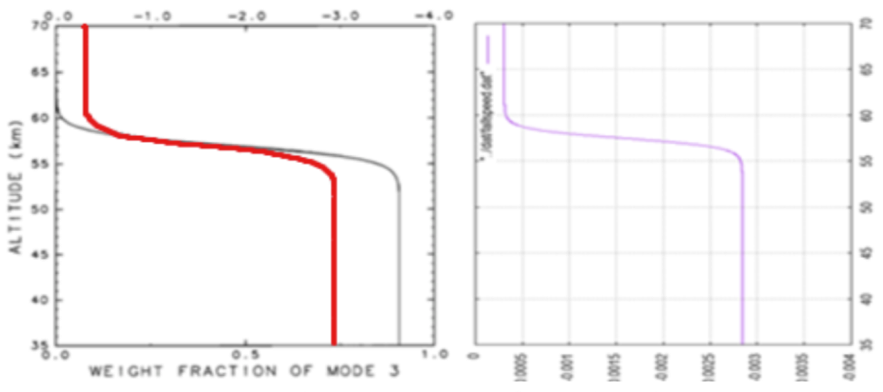

Fig. 1: Comparison about W_{sed}. Left and right panels mean original and our results, respectively. Left panel is taken from Imamura and Hashimoto, 1998).

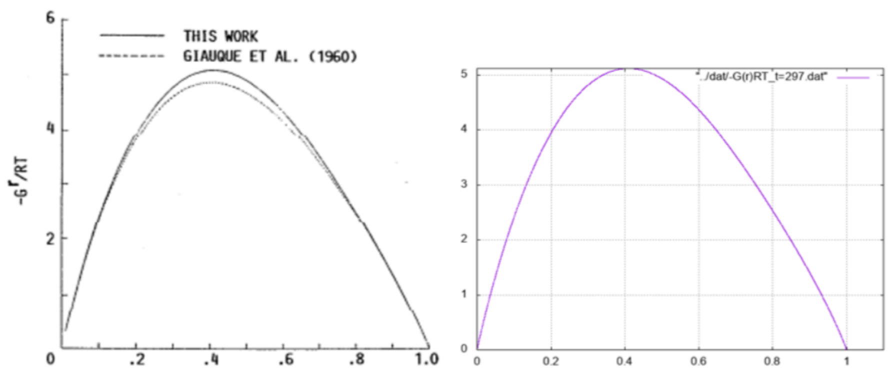

Fig. 2: Comparison about $-G^{(r)}(T,x_1)/RT$. Left and right panels mean original and our results, respectively. Left panel is taken from Zeleznik (1991).

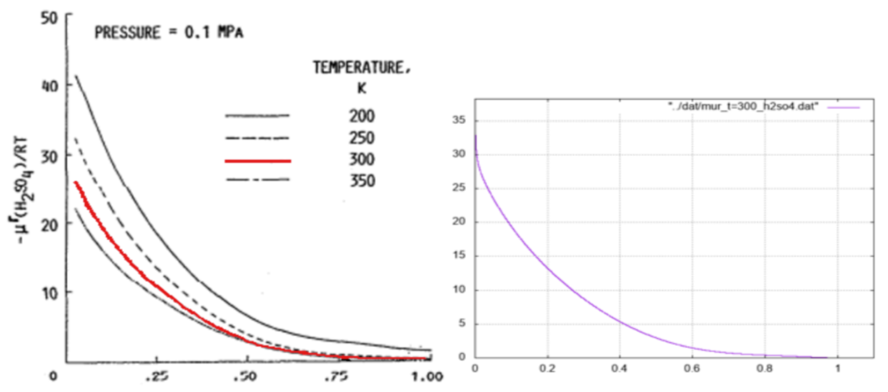

Fig. 3: The same figure of Fig.2 but for $\mu_1(T,x_1)-\dot{\mu}_1(T)$.

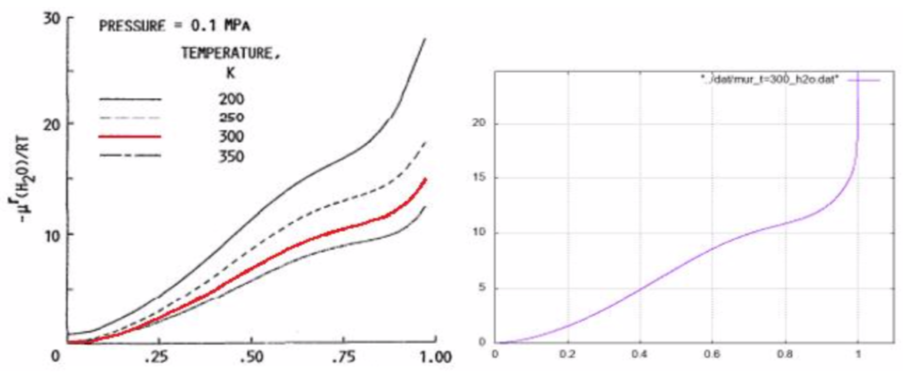

Fig. 4: The same figure of Fig.2 but for $\mu_2(T,x_1)-\dot{\mu}_2(T)$.

Condensation level (1-D calculation)

- Obtained profiles mean that condensation occurs successfully. H_2SO_4 is almost saturated (x_1 is almost 1) near the cloud base.

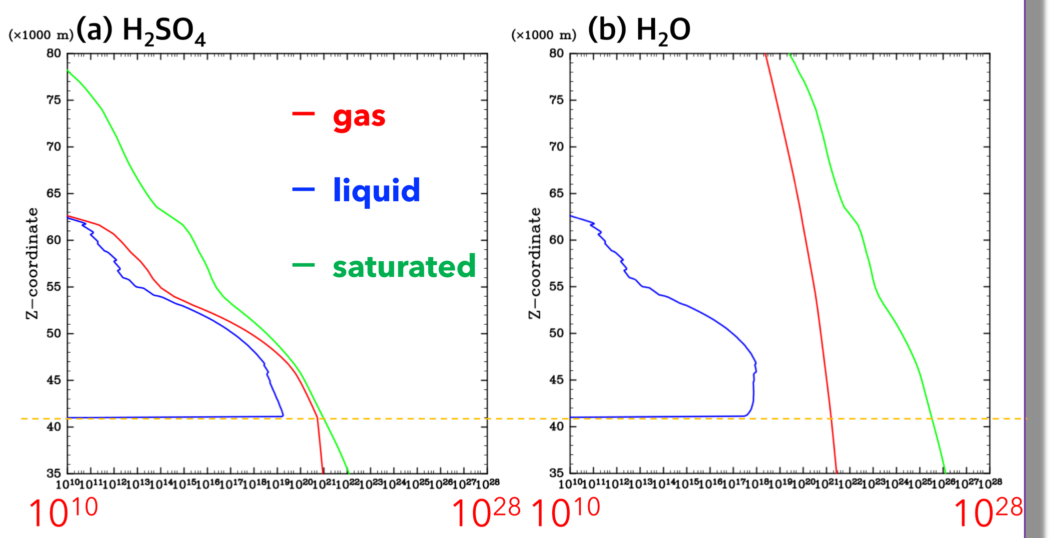

Fig. 5: Number density profiles of H_2SO_4 (left) and H_2O (right). Note that green lines mean the number density obtained by saturated vapor pressure of pure H_2SO_4 and H_2O.

Time evolution (1-D calculation)

- Sedimentation, production, and loss terms in eq. (1) are calculated successfully.

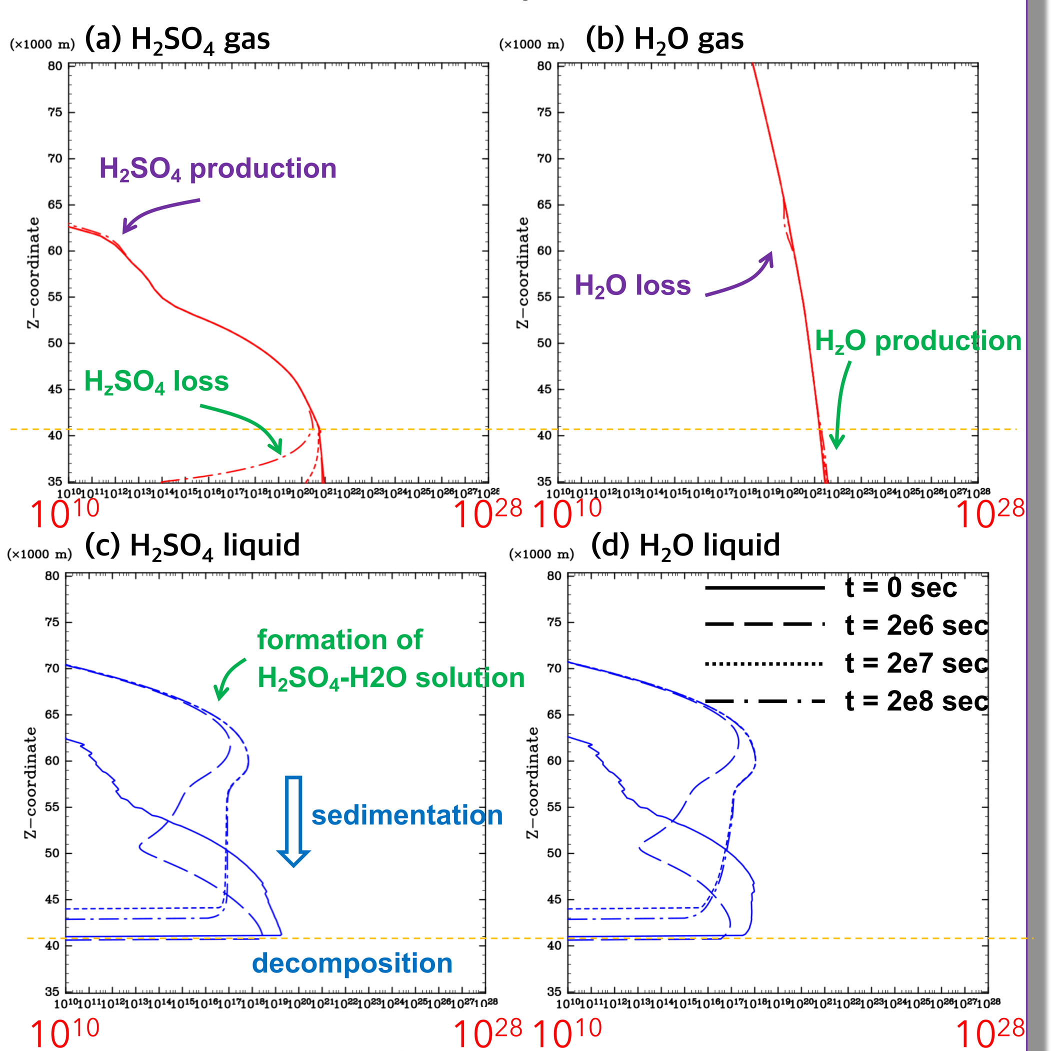

Fig. 6: Time evolution of number density profiles.

Our convection resolving model and settings of calculations

- Our cloud formation scheme is implemented into our convection resolving model developed by Sugiyama et al (2009).
  - The model is used in the simulations of the atmospheric convections of Jupiter (Sugiyama et al., 2011,2014) and Mars (Yamashita et al., 2016).
  - The basic equations is the quasi-compressible system (Klemp and Wilhelmson, 1978).
    - Turbulence: 1.5-order closure (Klemp and Wilhelmson, 1978).
- We perform 2-D calculation. Our Settings of calculation is similar to those of Imamura et al (2014) but the diurnal change of solar heating is not considered.
  - The model atmosphere is subject to externally given body heating that are substitute for the solar and long-wave heating (Fig.1)
  - Domain size: 128 km x 30 km (z = 35 km ~ 65 km)
  - Resolution: dx = 200 m, dz = 125 m
  - Time Integration: 2,000,000 sec (~23 day) (Amount of computation time is about 32 core × 12 hours)
  - Number density profiles of H_2SO_4 and H_2O gases are same as those of t = 0 shown by Fig.6 (a,b).
  - Number densities of H_2SO_4 and H_2O liquids are set to be zero at the initial time.
  - In order to seed a convective motion, a small random potential temperature perturbation is added in the neutral layer.

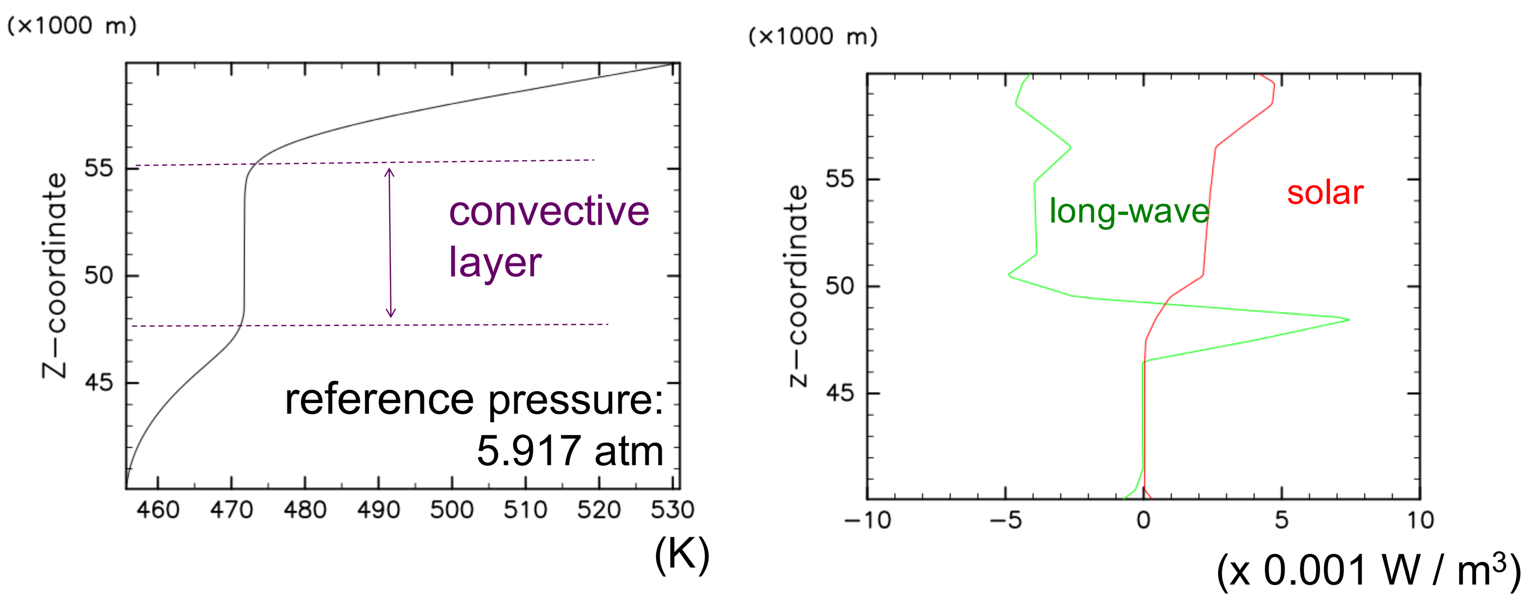

Fig. 7: Initial potential temperature and heating profiles .

Results of 2-D calculation

- The distribution of H_2SO_4 and H_2O associated with convective motion are obtained successfully.
  - Convective layer is covered with H_2SO_4-H_2O solution droplets (Fig. 8)
  - H_2SO_4-H_2O solution droplets are trapped In the convective layer (z = 49 ~ 56 km) (Fig. 9).
    - The number density of H_2SO_4 liquid is almost zero just below the convective layer .
    - The number density of H_2SO_4 liquid in the convective layer increases with time.
    - The vertical profile of H_2SO_4 gas is similar to that obtained by 1-D calculation.

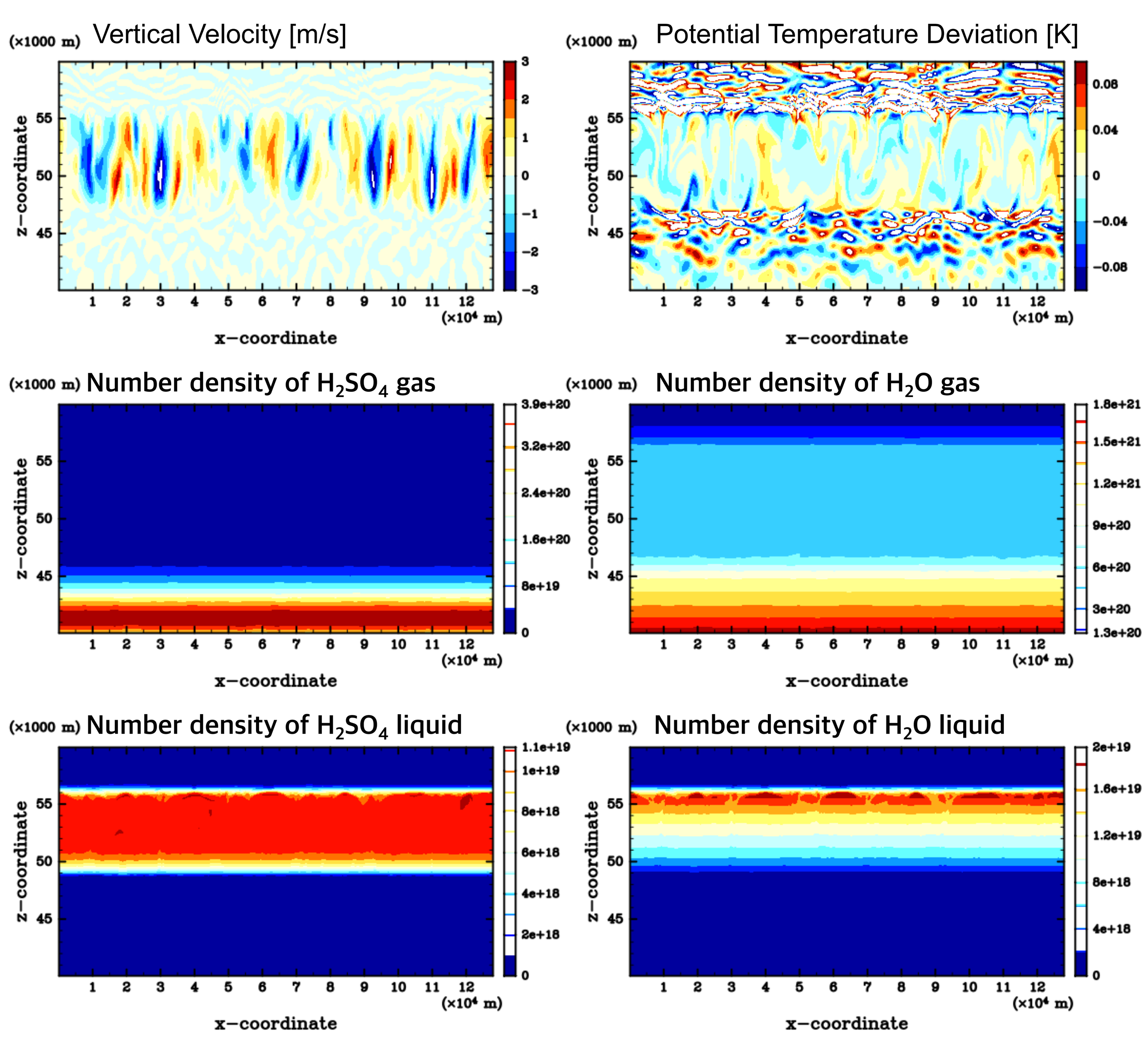

Fig. 8: X-Z cross section of vertical velocity, potential temperature deviation from horizontal mean, and number densities of H_2SO_4 and H_2O for z = 40 km – 60 km

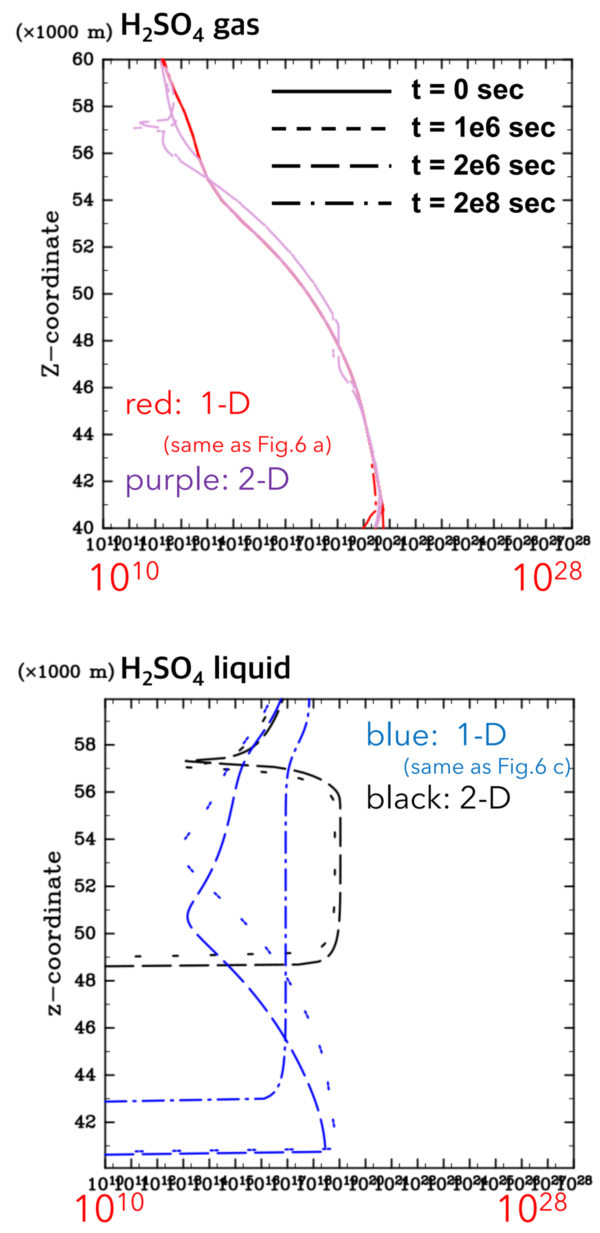

Fig. 9: Comparison with the profiles obtained by 1-D calculation (Fig.6 a,c).