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One-dimensional Microphysics Model of Venusian Clouds from 40 to 100 km

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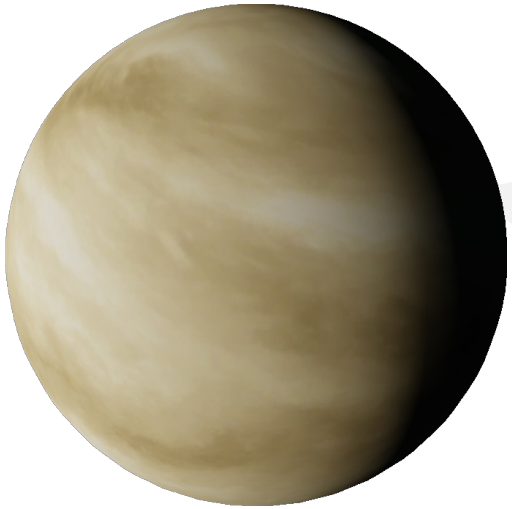
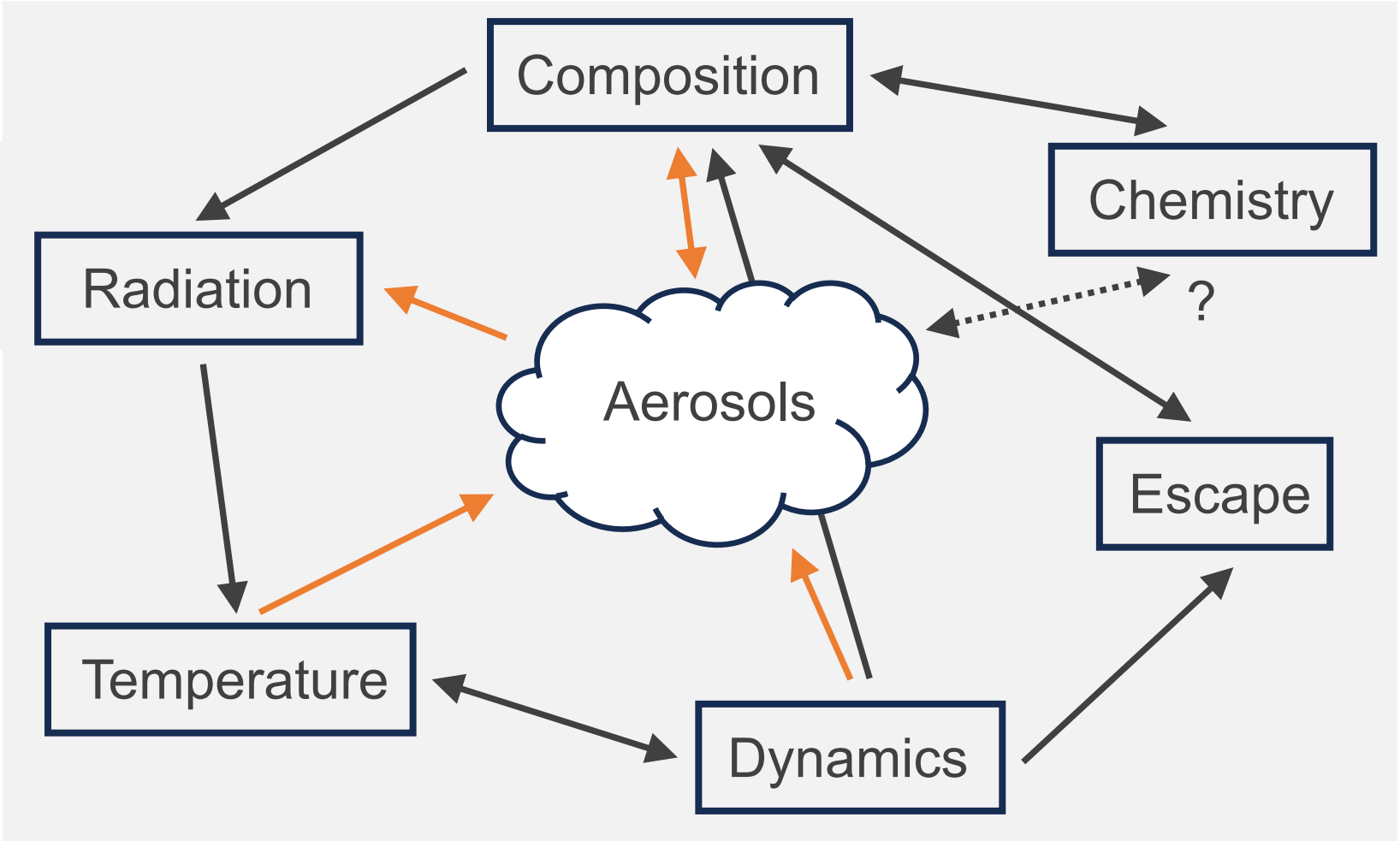
Aerosols on Venus



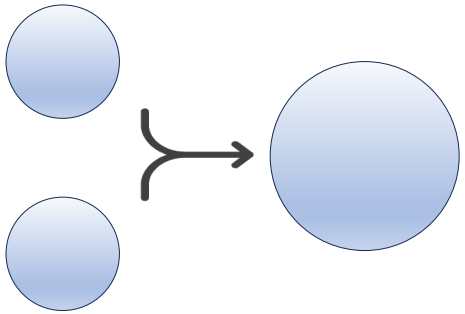
Getting realistic aerosol profile is an important first step for the atmospheric modeling on Venus
→ more complex modeling can follow after this step



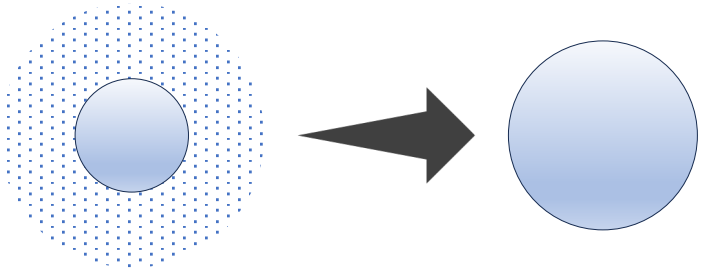
Microphysical Processes

Cloud structure evolves through the microphysical processes

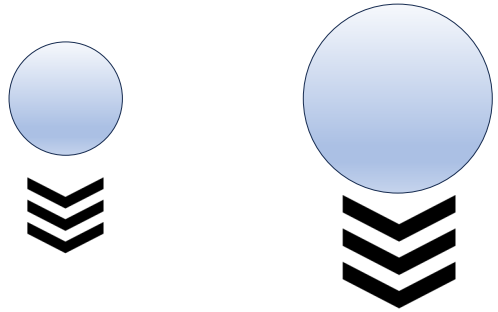
Coagulation



Condensation/evaporation



Sedimentation

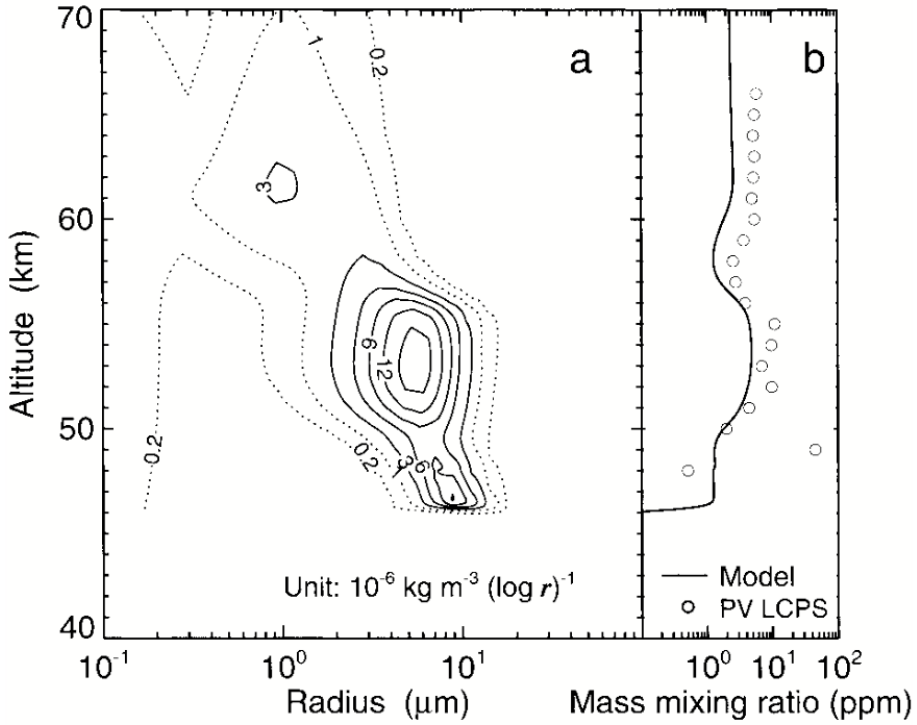


Microphysics model can simulate the cloud structure based on the most fundamental processes
→ minimal assumptions to calculate cloud profiles

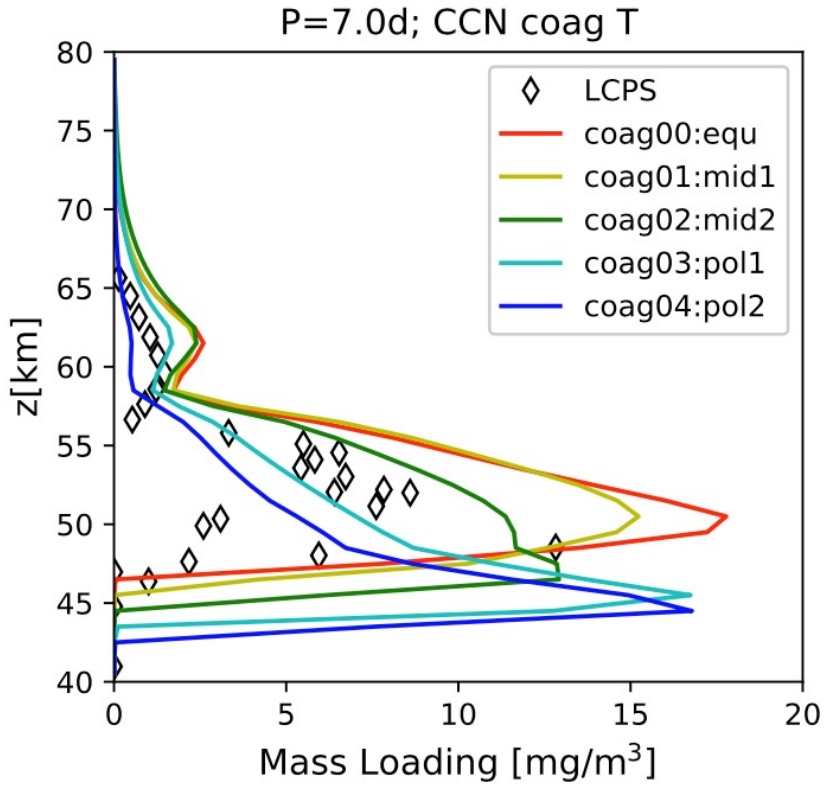
Important for cloudy atmosphere like Venus

Venus Microphysics Modeling

Imamura & Hashimoto (2001)



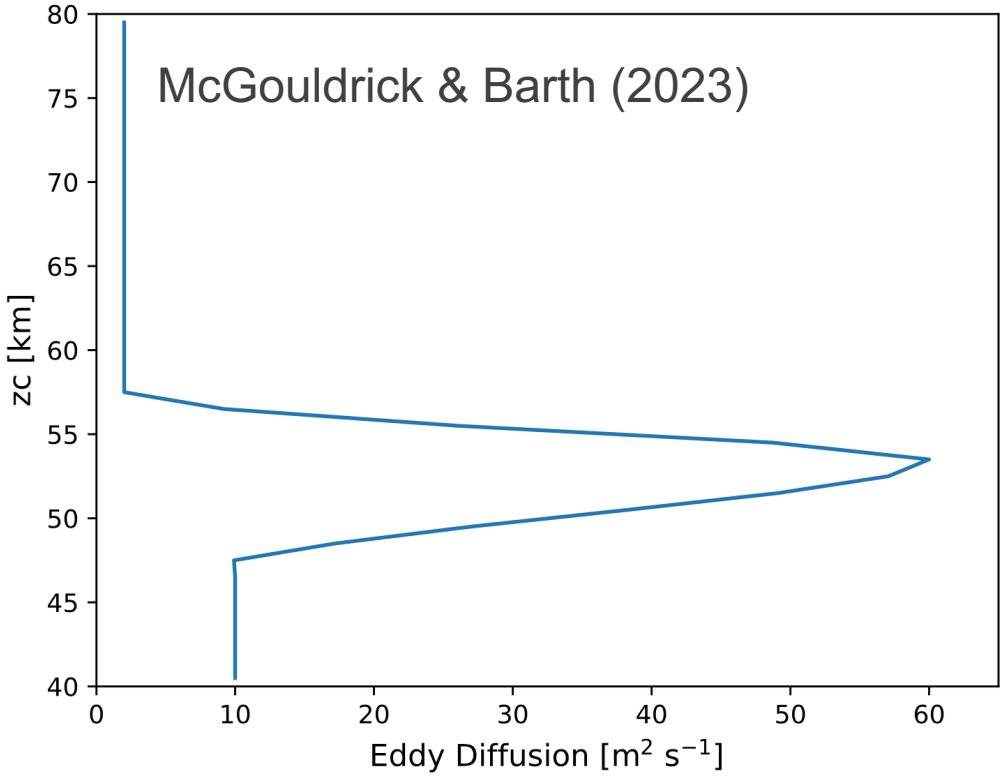
CARMA Model (e.g., McGouldrick & Barth, 2023)

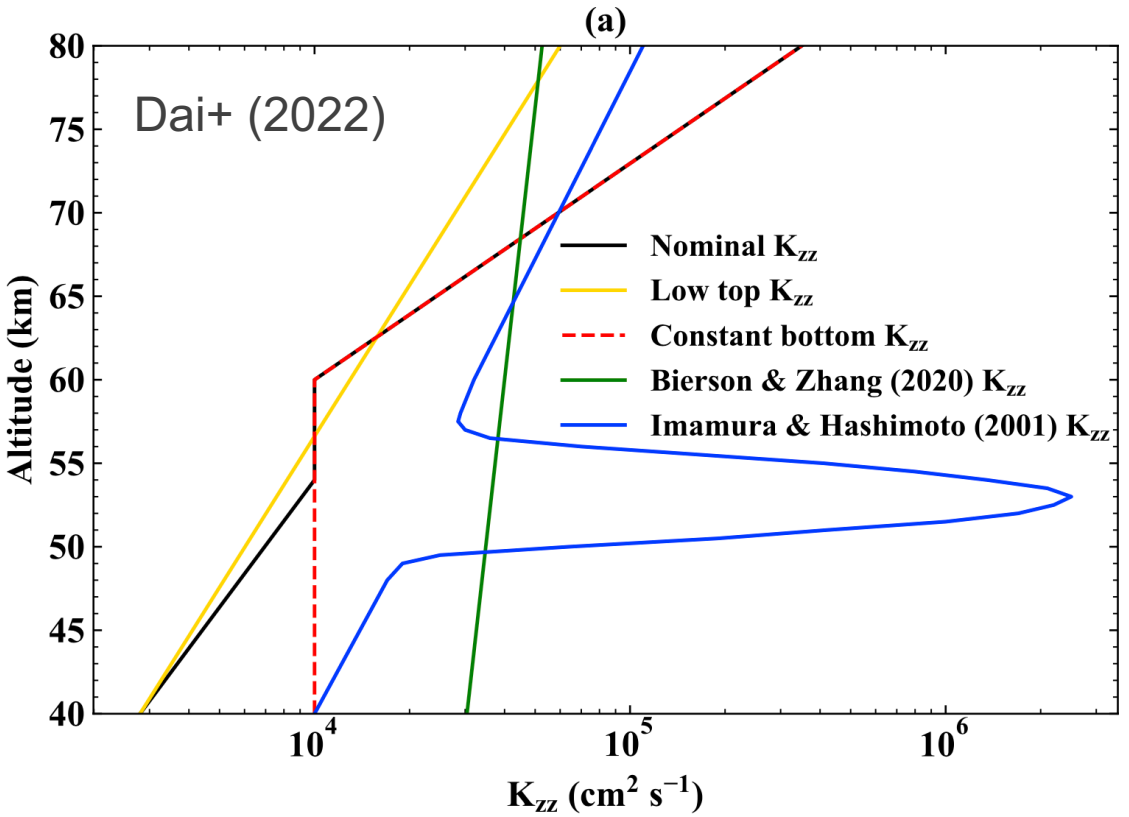


Previous models obtained observed cloud structures

Challenges in Microphysics Modeling 1/3

Eddy diffusion is chosen for better representation of the observed cloud structure and there are many standards

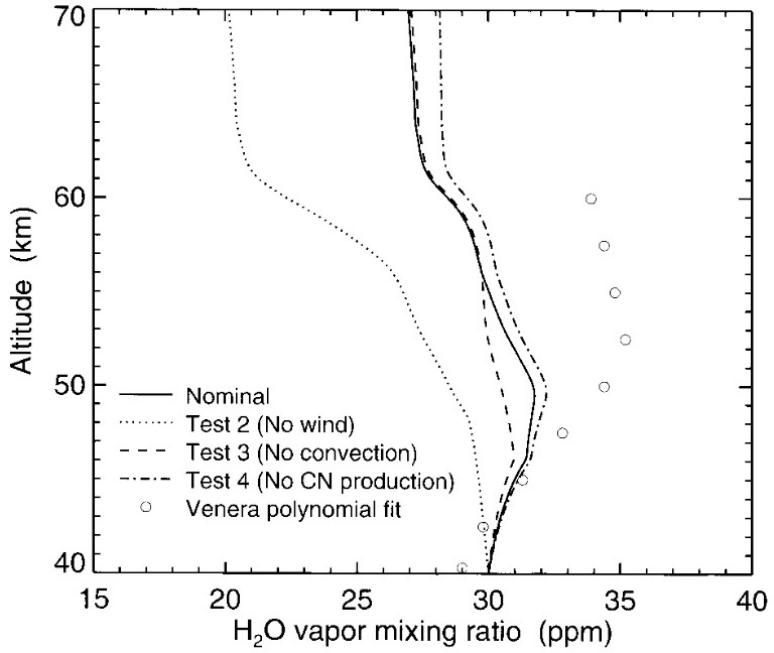




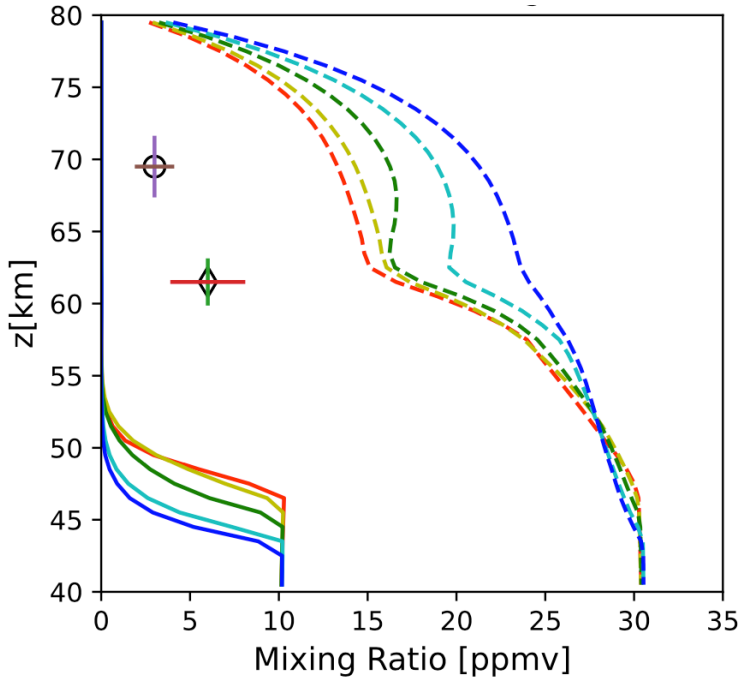
Challenges in Microphysics Modeling 2/3

H_2O VMR tends to be overestimated around the cloud top

Imamura & Hashimoto (2001)



McGouldrick & Barth (2023)



Observations

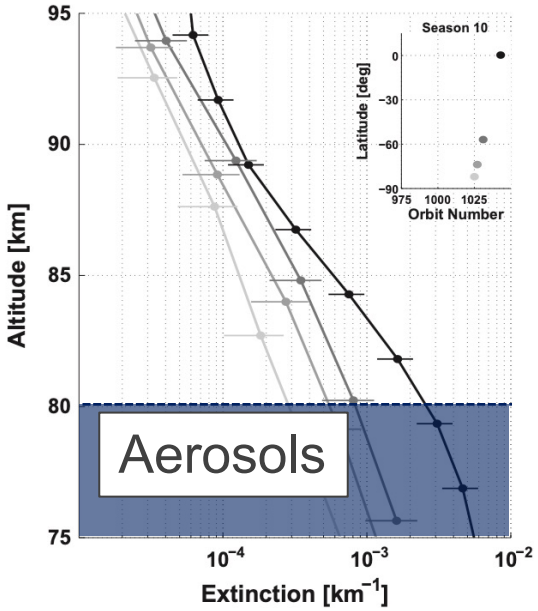
H_2O VMR is ~1 ppm above the cloud top altitude (~70 km)

Fedorova+ (2008)
Chamberlain+ (2020)
Mahieux+ (2023)

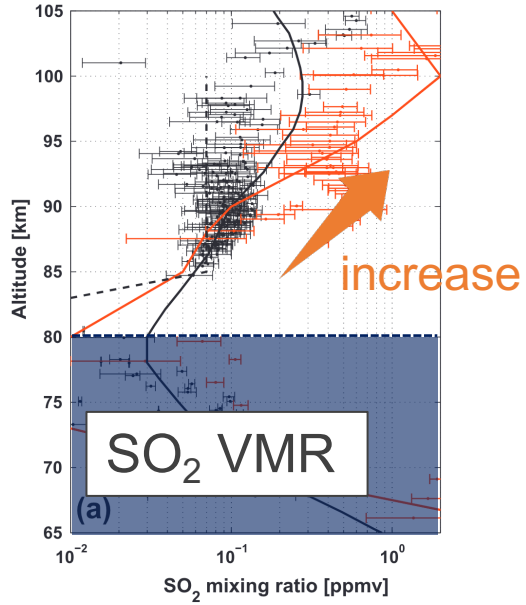
Microphysics models overestimate the H_2O VMR by ~10 times at the cloud top
→ related to eddy diffusion profiles chosen in the model?

Challenges in Microphysics Modeling 3/3

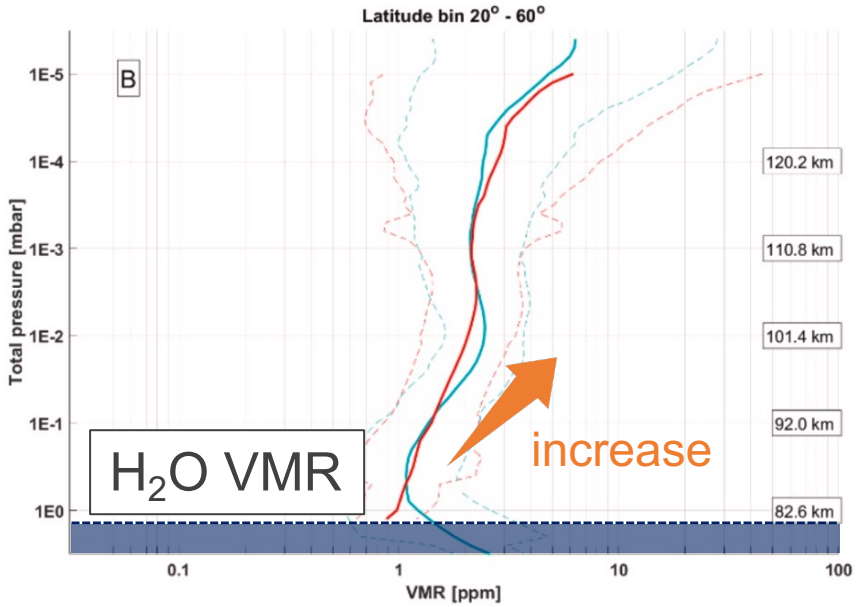
No simultaneous simulation of H_2O, H_2SO_4, and aerosol profiles above 80 km



Wilquet+ (2012)



Belyaev+ (2012)



Chamberlain+ (2020)

SOIR observed haze layer and unexpected increase of trace gas VMR
→ Aerosols may contirbute to the material transport from the middle to upper atmosphere, and chemistry of these altitudes (Zhang+ 2010)

Motivations

Challenges of microphysics modeling include

1. Choosing realistic eddy diffusion coefficient
2. Reproducing aerosol, H_2SO_4, and H_2O distributions simultaneously up to 100 km altitude

- **Eddy diffusion sensitivity study**: We revisit the sensitivity of H_2O, H_2SO_4, and aerosol profiles to eddy diffusion → a new standard for cloud modeling
- **Temperature sensitivity study**: We study the effects of aerosol evaporation on H_2O and H_2SO_4 VMR variability to better understand SOIR observation with the obtained eddy diffusion coefficients

Method

1-D Cloud Microphysics Model

Governing equation for aerosol particles

$$\frac{\partial C(m,z,t)}{\partial t} = \frac{\partial}{\partial z}\left(K_{zz}(z)\,\rho(z)\,\frac{\partial}{\partial z}\left[\frac{C(m,z,t)}{\rho(z)}\right]\right)$$
$$-\frac{\partial}{\partial z}[w_{\mathrm{sed}}(m,z)\,C(m,z,t)] - \frac{\partial}{\partial m}[G(m,z,t)\,C(m,z,t)]$$
$$+\frac{1}{2}\int_{m_{\mathrm{cn}}}^{m} K_{\mathrm{coag}}(m',m-m')\,C(m',z,t)\,C(m-m',z,t)\,dm'$$
$$-C(m,z,t)\int_{m_{\mathrm{cn}}}^{m_{\max}} K_{\mathrm{coag}}(m',m)\,C(m',z,t)\,dm',$$

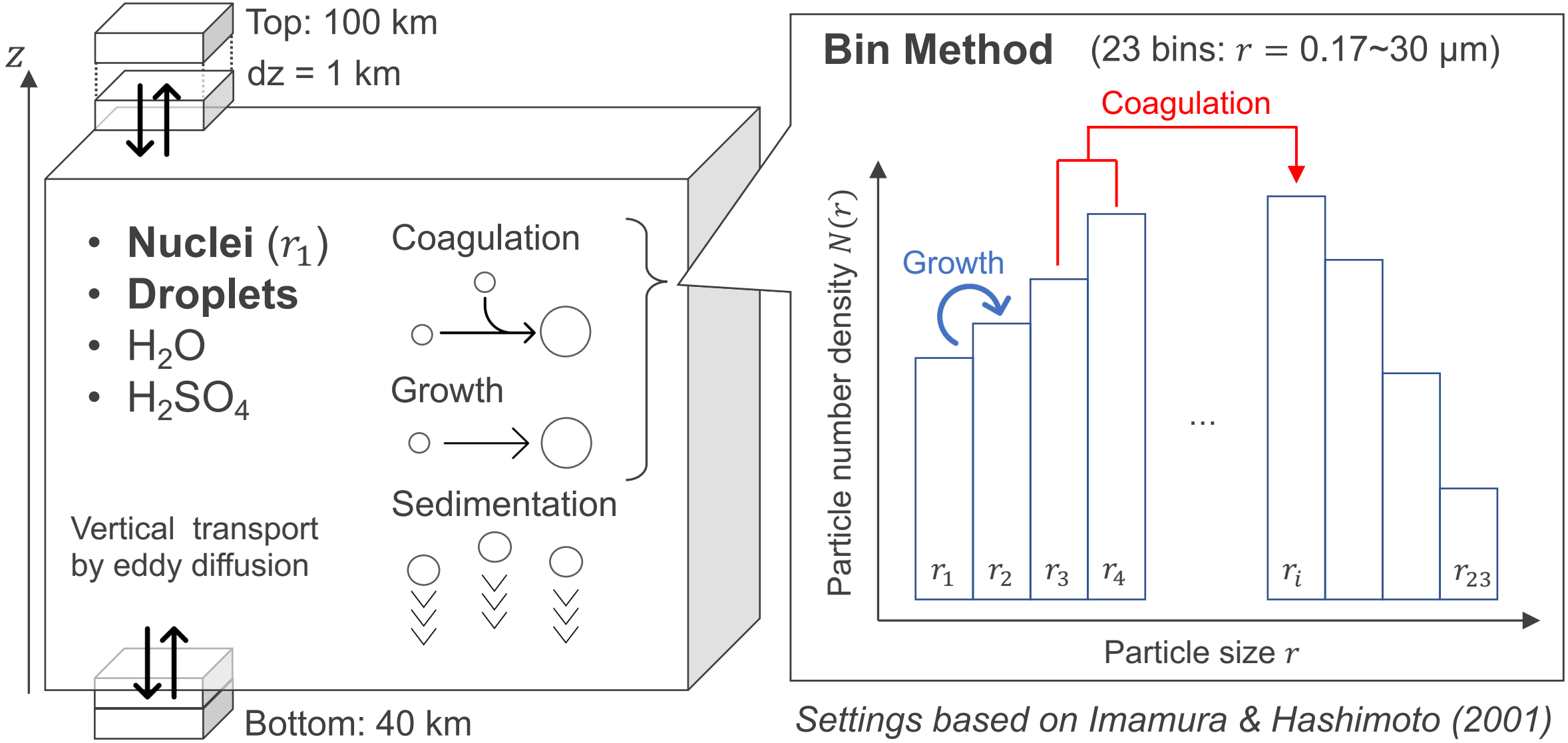
Process of each term

1st: diffusion transport
2nd: sedimentation
3rd: condensation/evaporation
4th, 5th: coagulation

C: cloud number density, K_{zz}: eddy diffusion coefficient, ρ: atmospheric density, w_{sed}: sedimentation velocity, G: particle growth rate, K_{coag}: coagulation efficiency

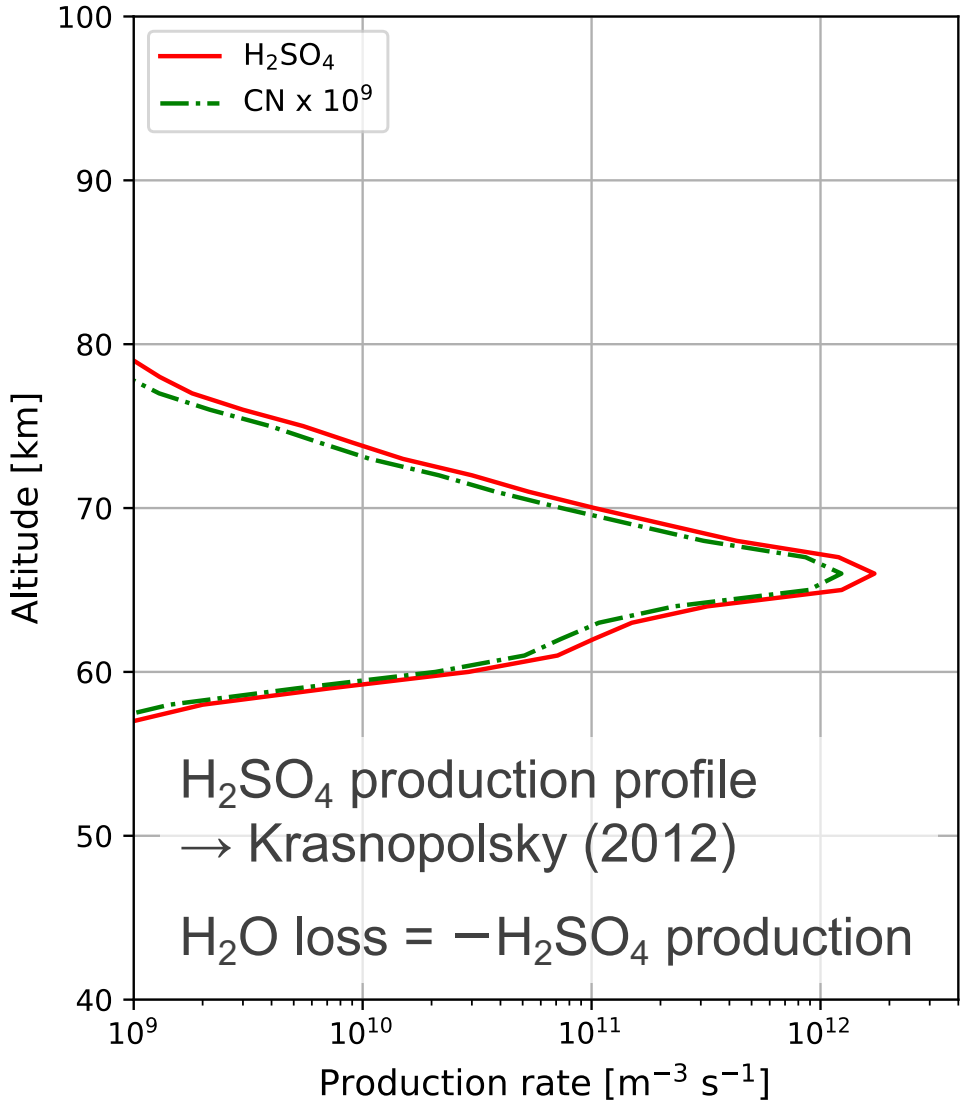
The model also calculates transport equation for H_2O and H_2SO_4 vapors

1-D Cloud Microphysics Model



Settings based on Imamura & Hashimoto (2001)

Chemical Cycle Assumed in the Model



Assumed chemical cycle

$$\mathrm{SO_2} + \mathrm{h}\nu \rightarrow \mathrm{SO} + \mathrm{O},$$

$$\mathrm{SO} + \mathrm{h}\nu \rightarrow \mathrm{S} + \mathrm{O}.$$

$$\mathrm{SO_2} + \mathrm{O} + M \rightarrow \mathrm{SO_3} + M,$$

$$\mathrm{SO_3} + \mathrm{H_2O} \rightarrow \mathrm{H_2SO_4}.$$

→ Net: $3\mathrm{SO_2} + 2\mathrm{H_2O} \rightarrow \mathrm{S} + 2\mathrm{H_2SO_4}.$

Chemical cycle is not complete
→ H_2O and H_2SO_4 vapor VMRs are set to constant values at the bottom boundary

Simulation Settings

Altitude range: 40-100 km

Latitude: 45°

H_2SO_4 production / H_2O loss rate: Photochemical model results (Krasnopolsky 2012)

Boundary conditions: observational constraints

Altitude	CN Number Density	Droplet Number Density	H_2SO_4 VMR	H_2O VMR
40 km (bottom)	4×10^7 m^{-3}	0 m^{-3}	4 ppm	30 ppm
100 km (top)	$\frac{df_{CN}}{dz} = 0$	$\frac{df_{droplet}}{dz} = 0$	$\frac{df_{H2SO4}}{dz} = 0$	$\frac{df_{H2O}}{dz} = 0$

Note. The mixing ratio is expressed as f.

Initial conditions: same as the boundary conditions for all vertical grids

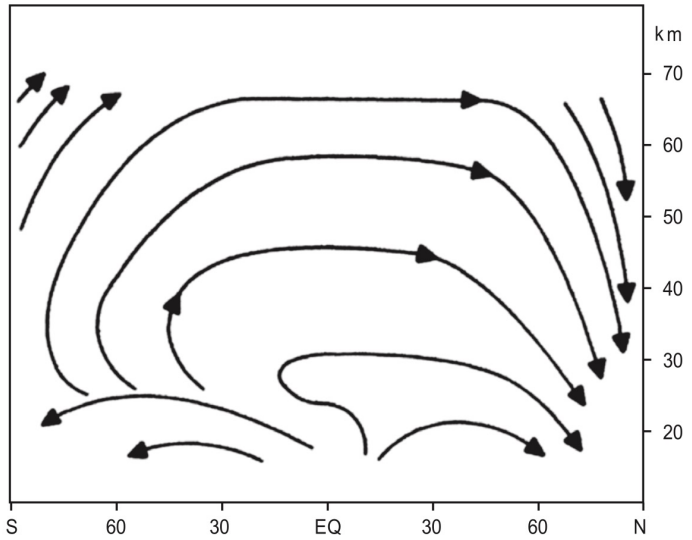
Eddy Diffusion Sensitivity Study

Assumed Transport Processes

- Mechanism of vertical transport in the planetary atmosphere is not well understood

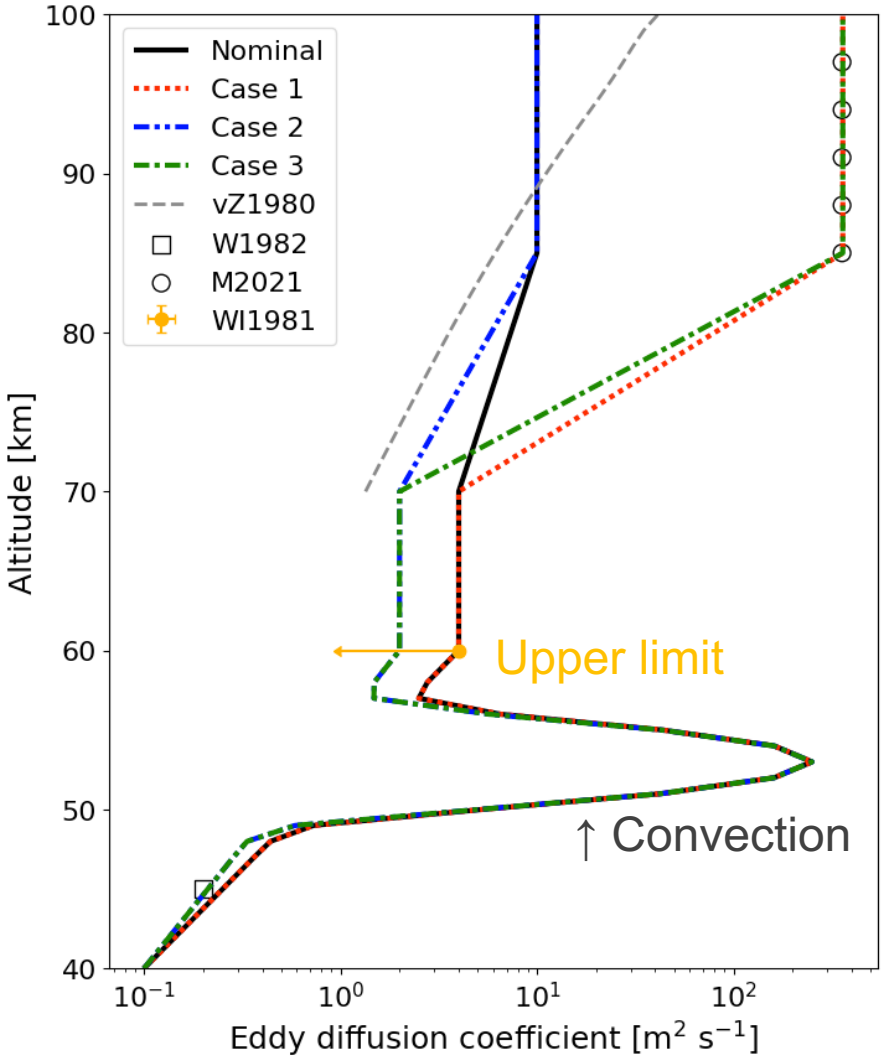
→ most 1D models assume eddy diffusion coefficient to employ the vertical transport

- This is simplified but the most practical



We focus on globally averaged structure (~45˚) by representing all vertical transport processes combined with eddy diffusion coefficients
(overturning circulation, wave breaking, etc → conceptual quantity)

Eddy Transport Sensitivity Studies



Case Name	Eddy Diffusion Coefficient at 60–70 km (m^2 s^{-1})	Eddy Diffusion Coefficient at 85–100 km (m^2 s^{-1})	Temperature Profile
Nominal	4 (a)	10 (b)	VIRA (d)
Case 1	4 (a)	360 (c)	VIRA (d)
Case 2	2	10 (b)	VIRA (d)
Case 3	2	360 (c)	VIRA (d)

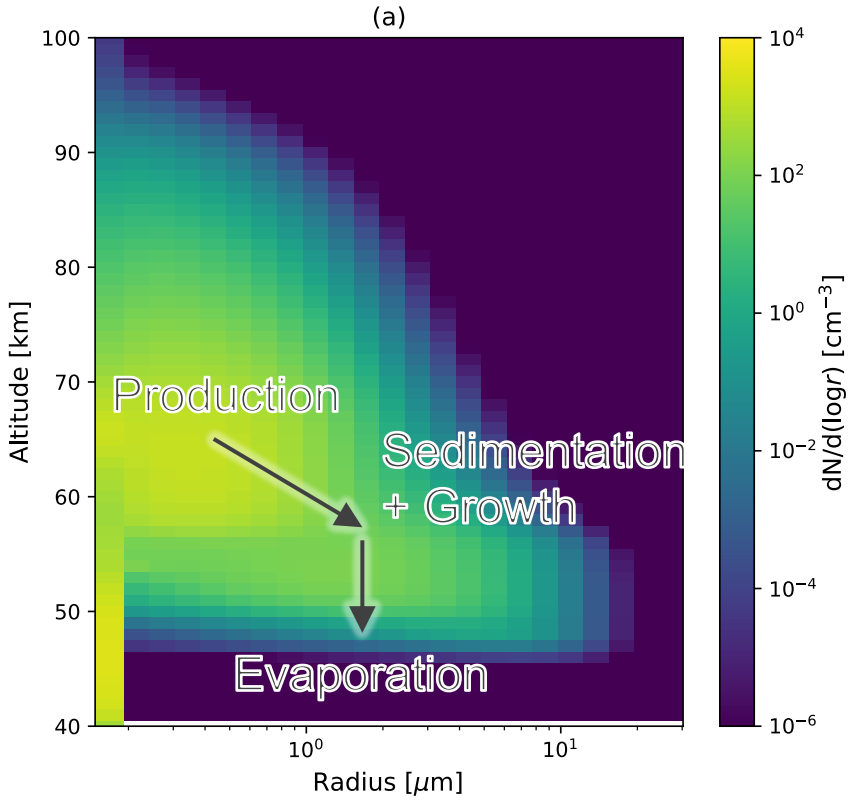
References. (a) Woo & Ishimaru (1981); (b) von Zahn et al. (1980); (c) Mahieux et al. (2021); (d) Seiff et al. (1985)

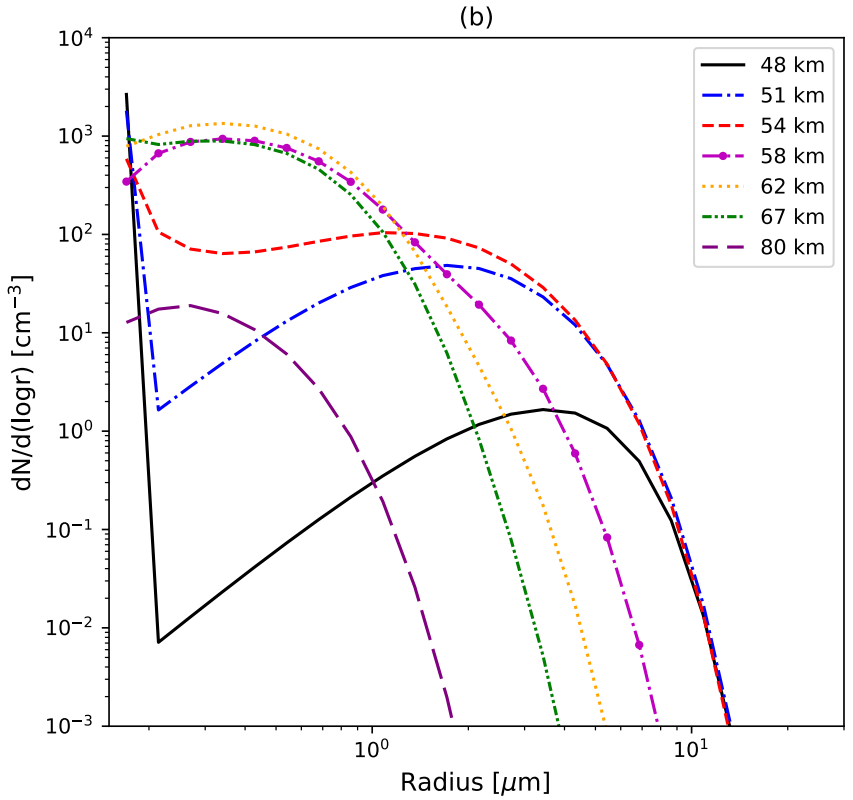
Only the *Nominal case* (**black line**) and *Case 3* (**green line**) are shown for today

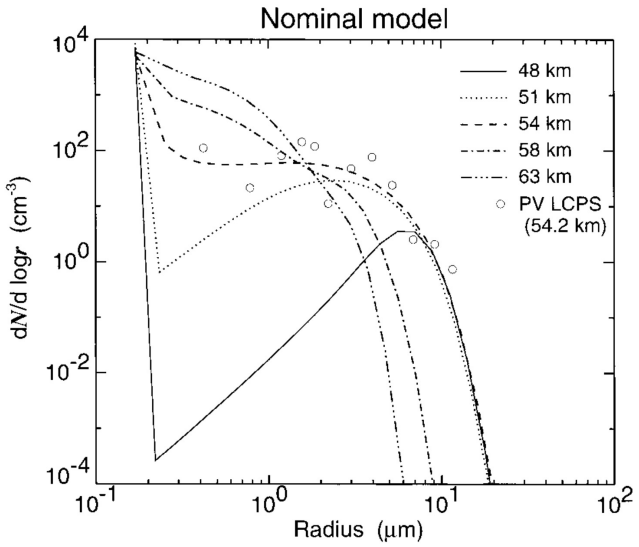
Nominal → conventional eddy diffusion case

Case 3 → high above 85 km and decreased by half between 60-70 km compared to the Nominal case

Nominal case: Size Distribution



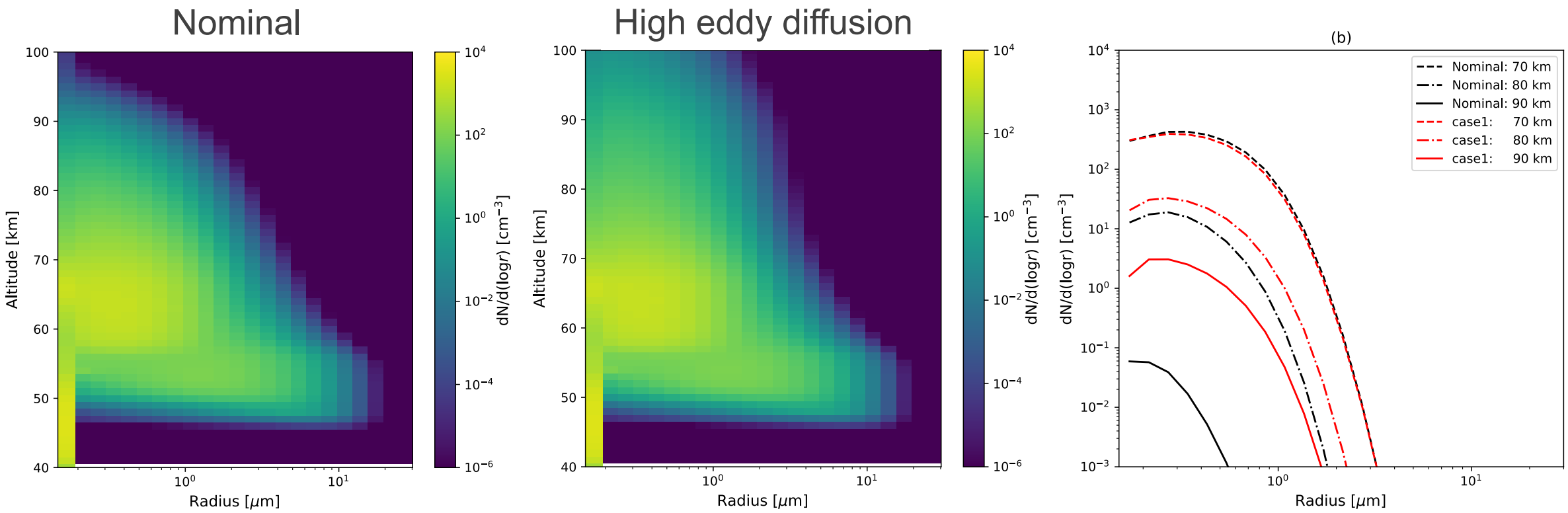




Imamura & Hashimoto (2001)

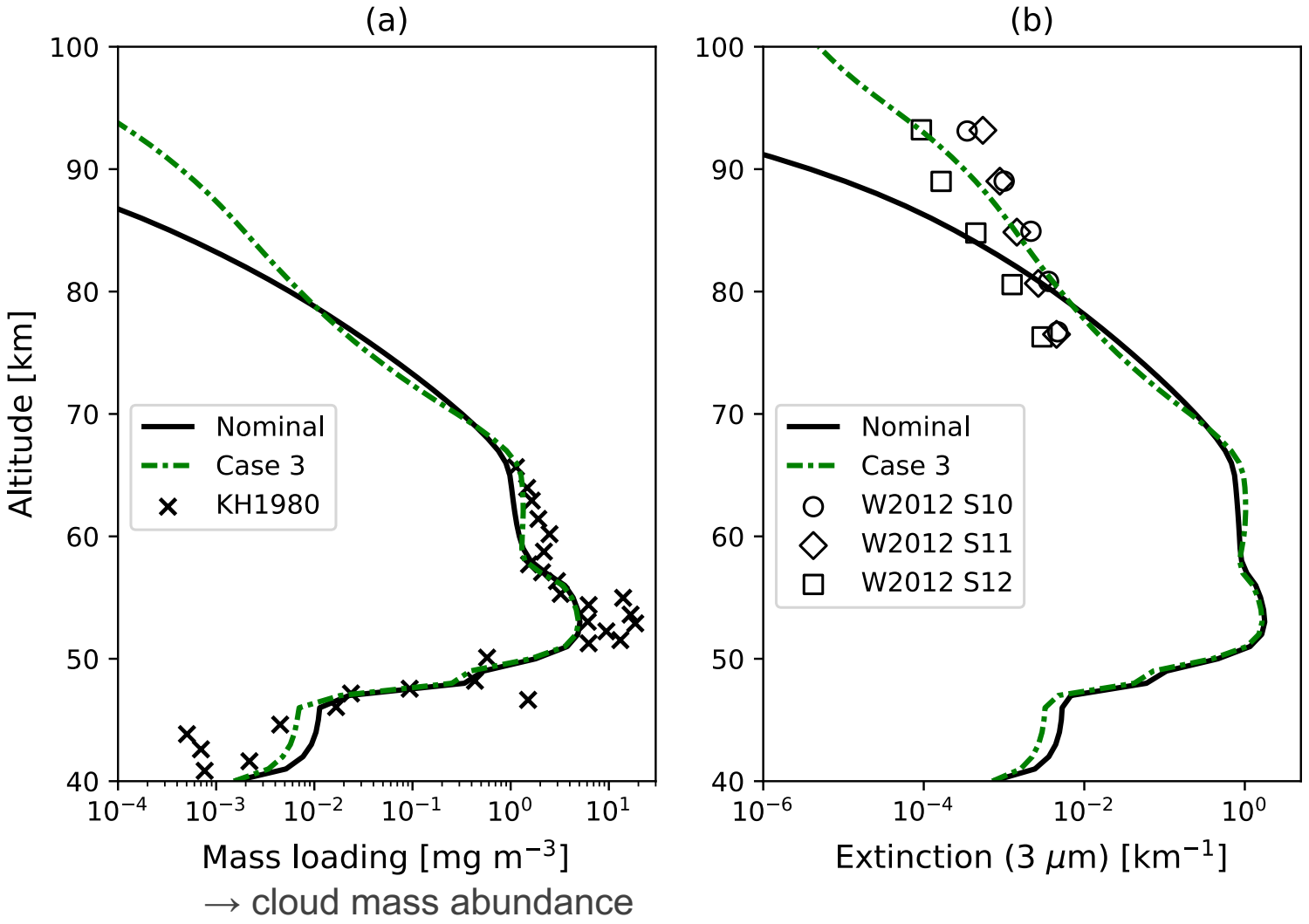
Consistent with the earlier work

Case 3: Size Distribution



- The upper haze is extended in high eddy diffusion cases

Cloud Profiles

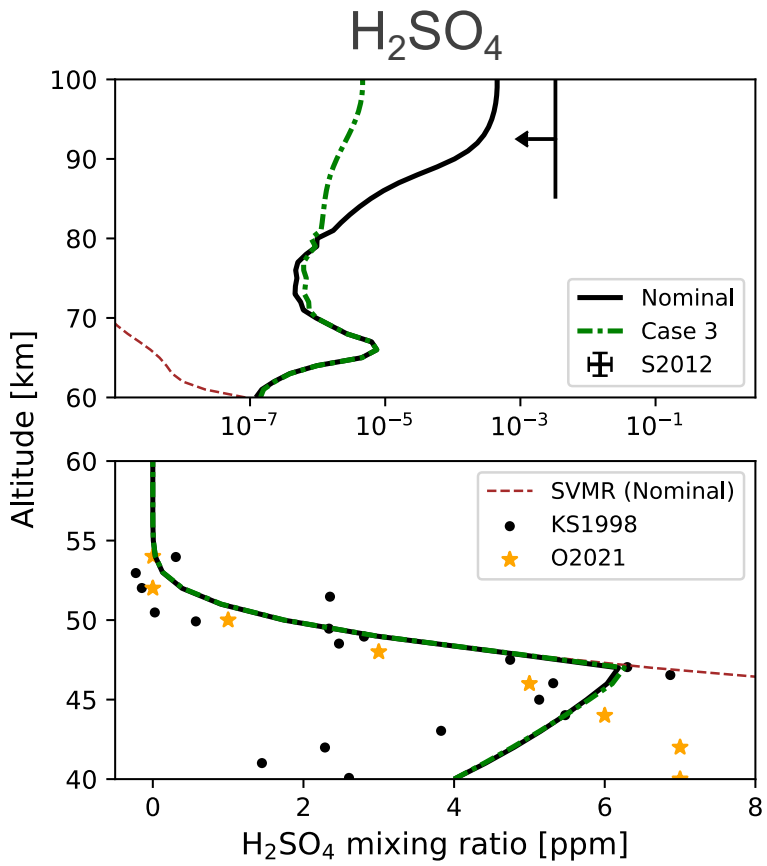


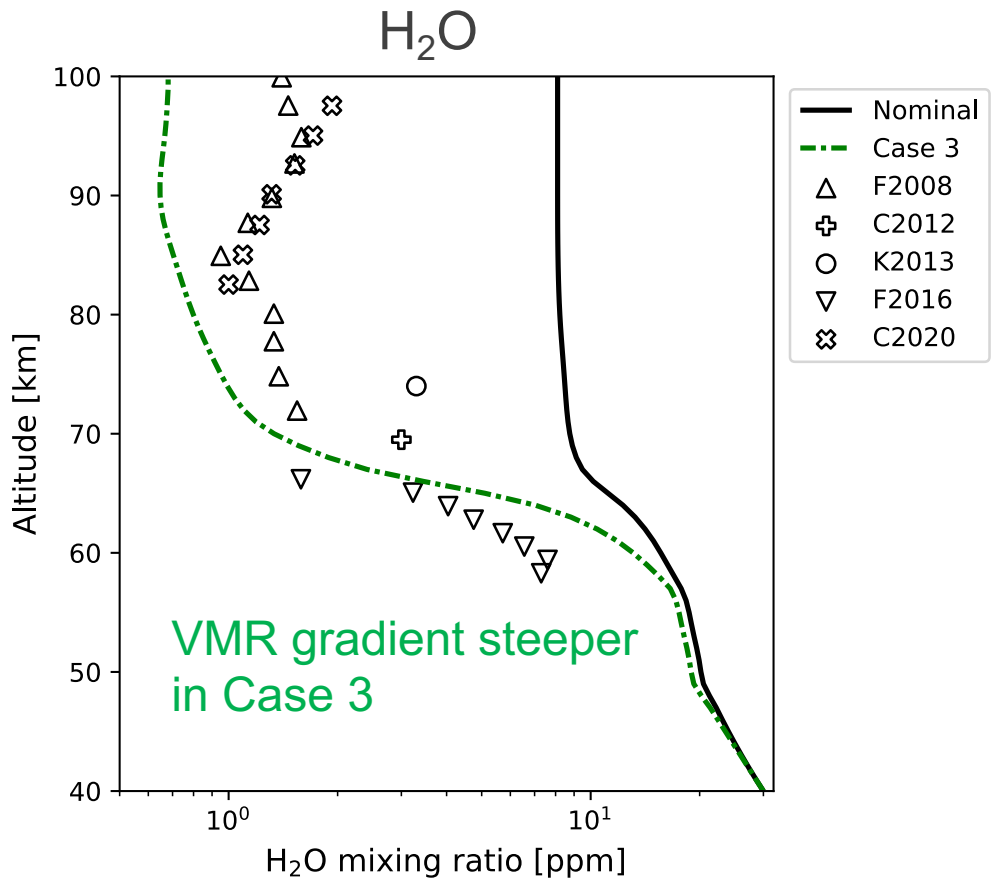
→ cloud mass abundance

Mass loading is consistent with the in-situ observation

The upper haze layer is extended in Case 3 due to efficient eddy transport
→ quantitatively consistent with the SOIR observations

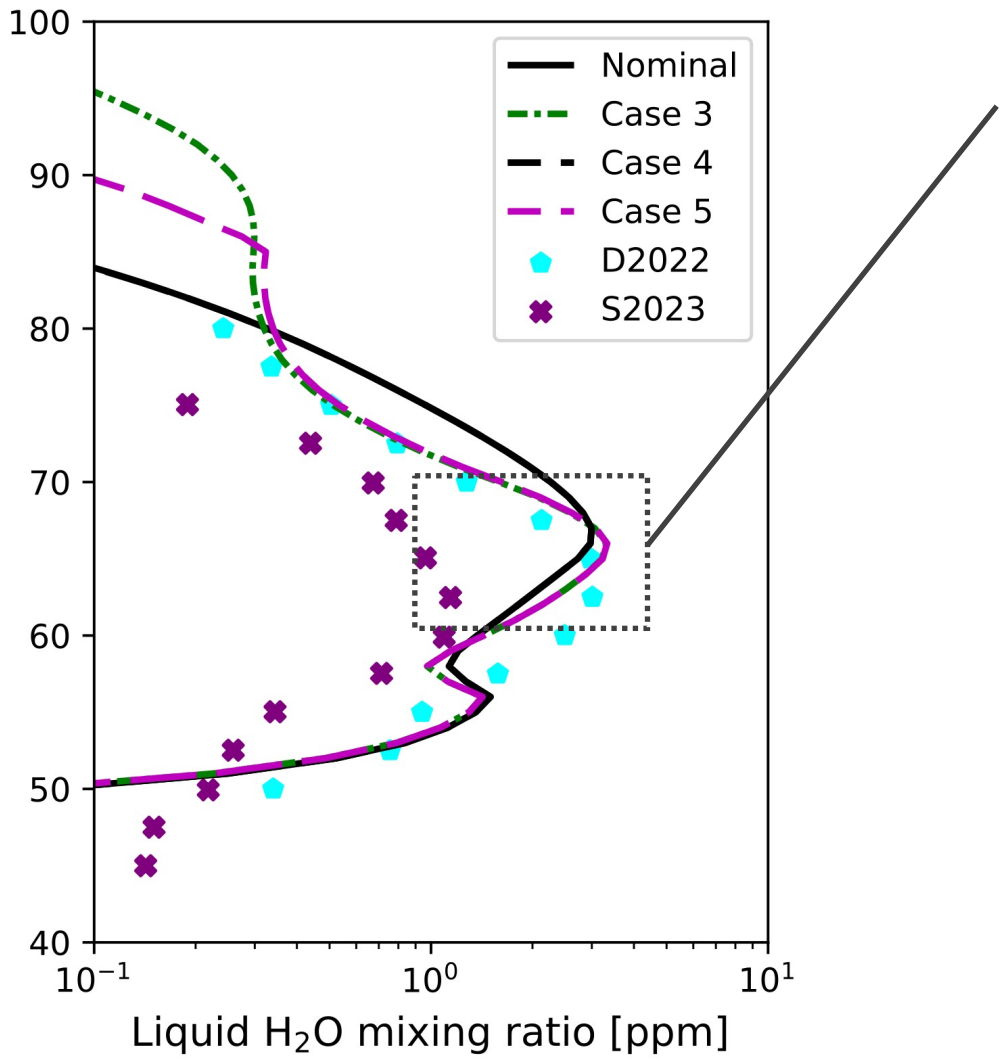
H_2SO_4 and H_2O Profiles





- H_2SO_4 is highly supersaturated above 60 km (also reported by Dai et al. 2021)
- H_2O profile is sensitive to eddy diffusion coefficient between 60-70 km

Mechanism of H_2O Depletion



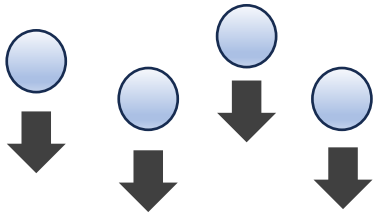
Cloud structure is almost determined by chemical production of H_2SO_4

→ similar liquid H_2O VMR in all cases
→ similar H_2O sedimentation flux in all cases

chemical loss
+ liquid flux
→ $\Phi_{H2O,down}$

=

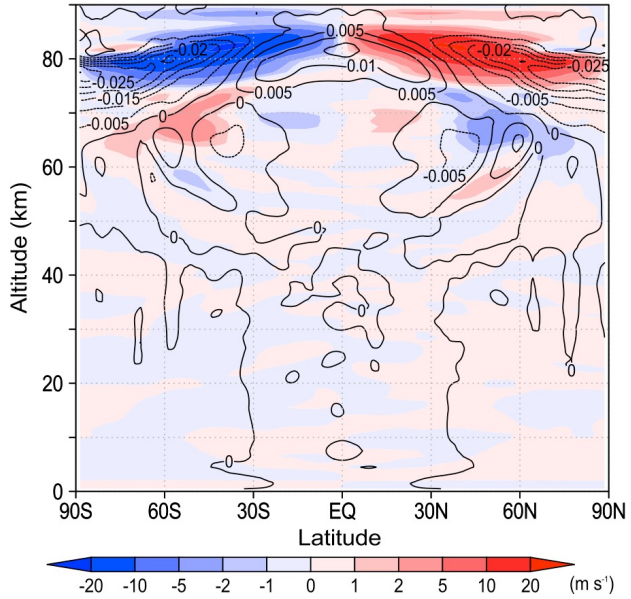
upward vapor flux
→ $K_{eddy}\frac{\partial f_{H2O}}{\partial z}$

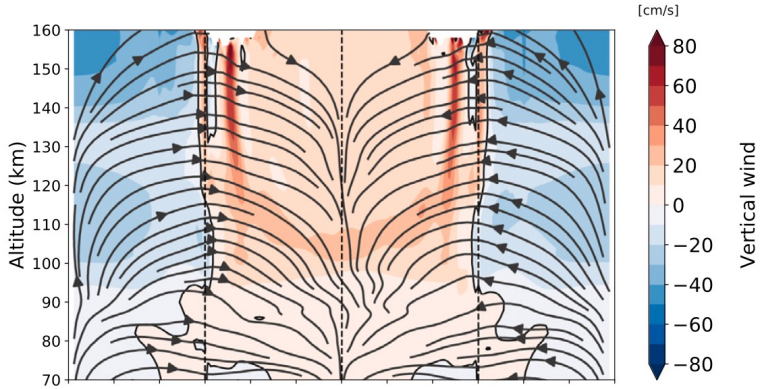


$$\Phi_{H2O,down} \sim const = K_{eddy}\frac{\partial f_{H2O}}{\partial z} \rightarrow \frac{const}{K_{eddy}} = \frac{\partial f_{H2O}}{\partial z}$$

VMR gradient varies significantly with transport efficiency between 60-70 km

Comparison with GCM





Simple comparison using transport timescale

Assuming the transport timescales are similar in both 1D and 3D models

$\tau \sim H/w$, $\tau \sim H^2/K_{eddy} \rightarrow K_{eddy} \sim wH$ (in GCM)

Best-fit eddy diffusion

K_{eddy} = 2 m²/s @60-70 km

K_{eddy} = 360 m²/s @85-100 km

AFES GCM (Takagi+ 2018) @60-70 km

w ~1 mm/s

$K_{eddy} \sim wH$: 5 m²/s

IPSL GCM (Navarro+ 2022) @85-100 km

w ~0.1 m/s

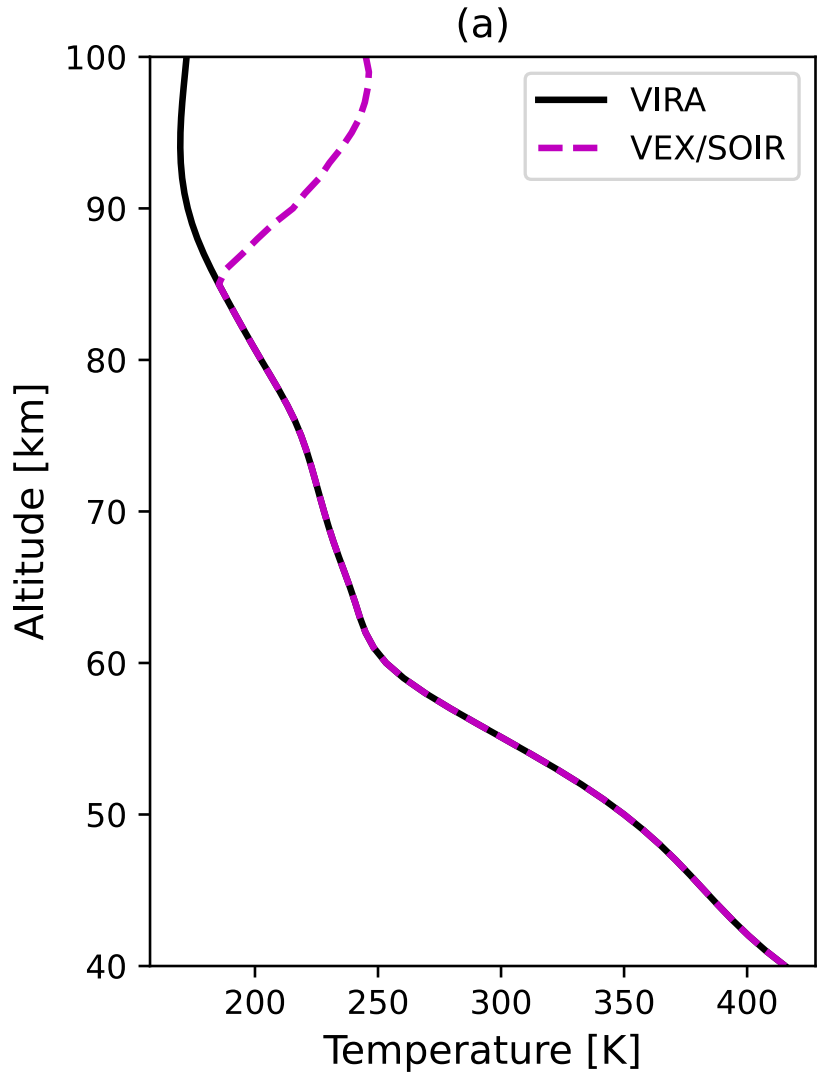
$K_{eddy} \sim wH$: 370 m²/s

These values agree within a few factors of degrees

Good approximation of transport in 1D

Temperature Sensitivity Study

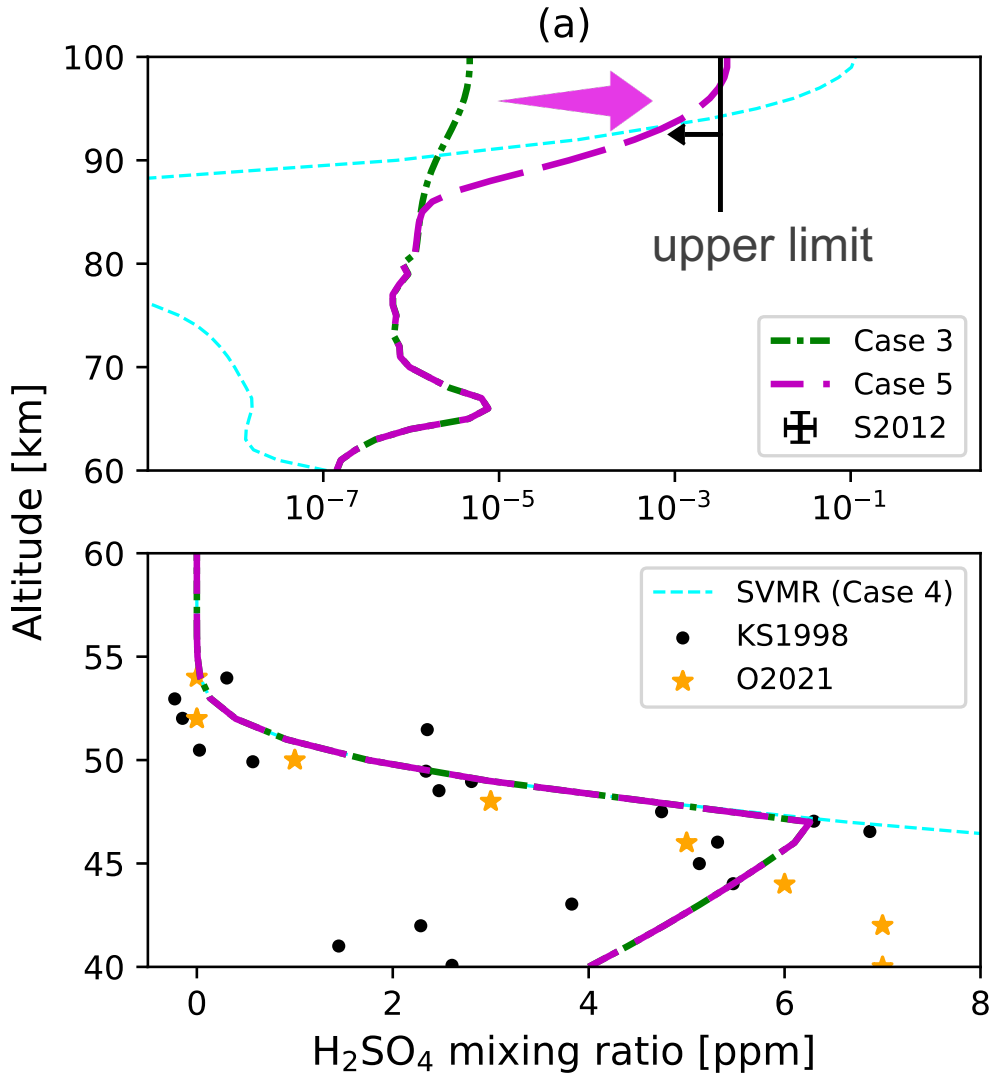
Temperature Sensitivity Studies



We extrapolated temperature profiles SOIR observations to see the effect of temperature condition on the cloud structure
(Mahieux+ 2015)
→ Case 5 (terminator condition)

Case 3 eddy diffusion is also used for Case 5

H_2SO_4 Profiles

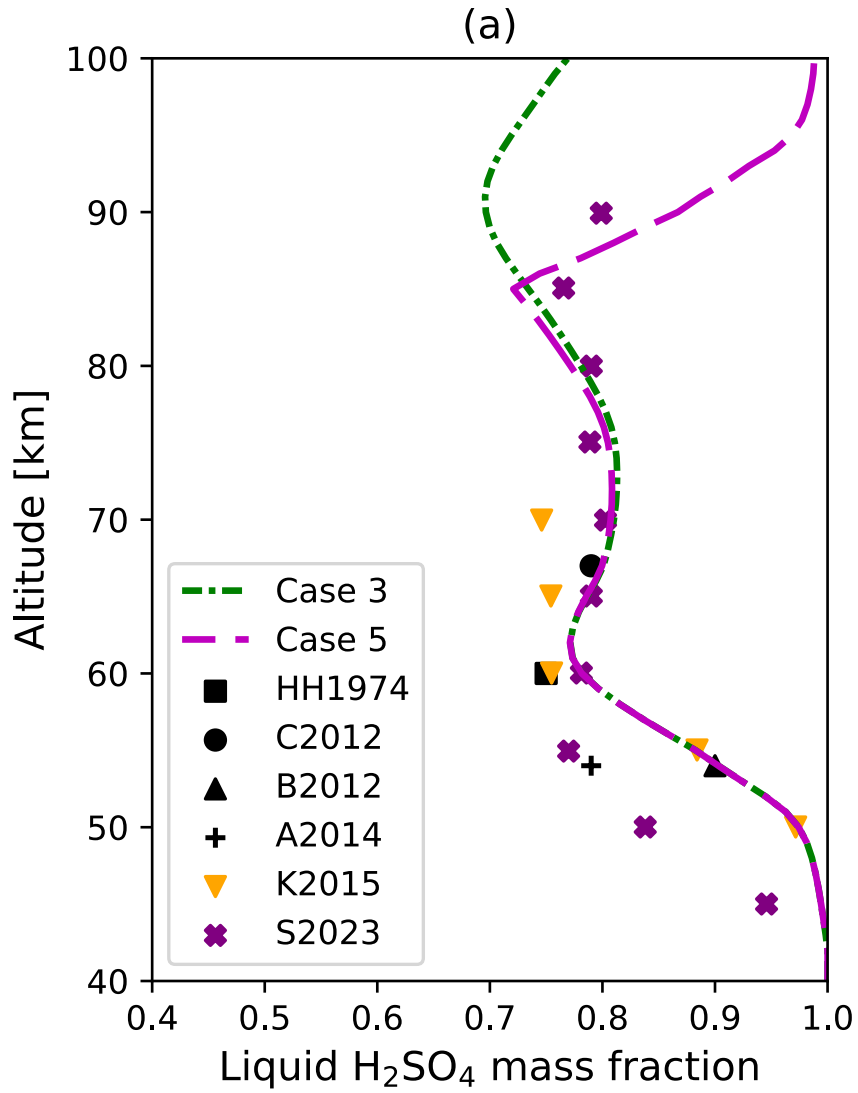


1. SVP is elevated by high temperature (cyan line)

2. H_2SO_4 is subsaturated above 90 km
→ aerosol evaporation

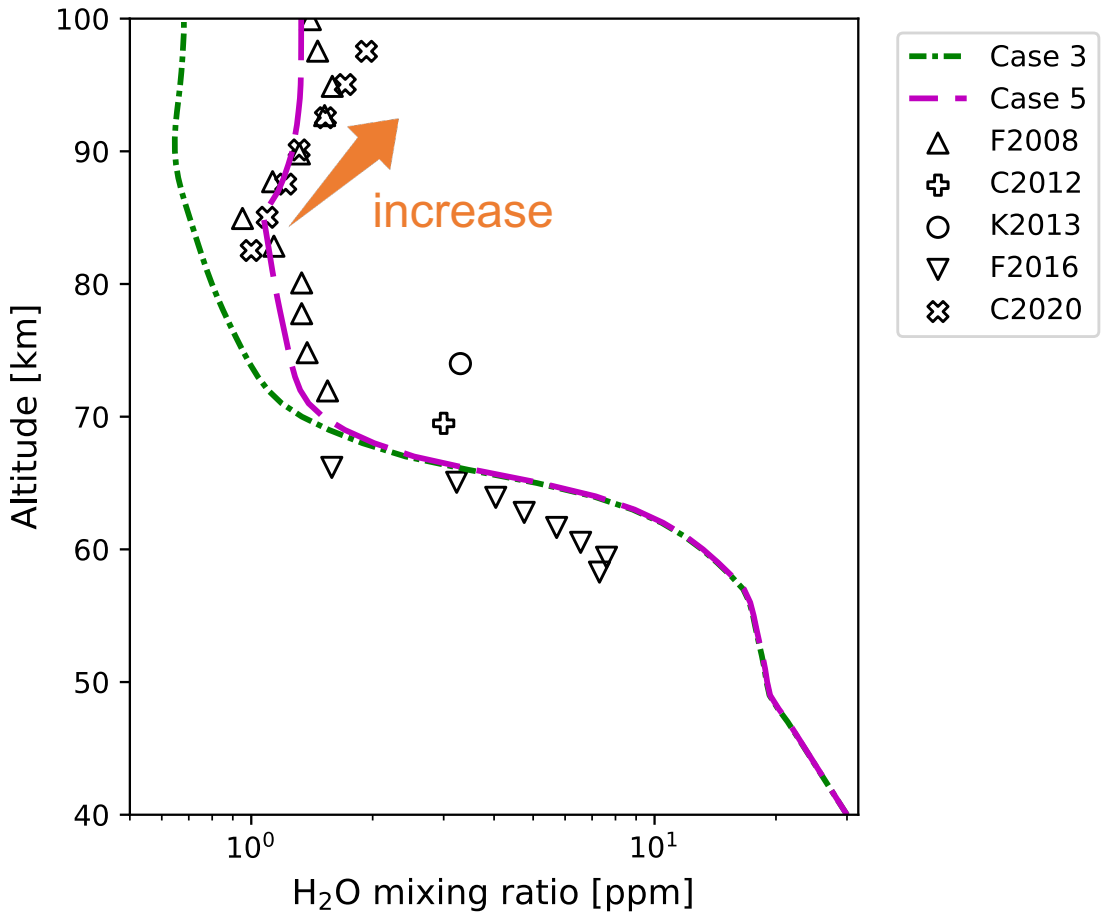
H_2SO_4 VMR increases to ~3 ppb
→ equivalent to the upper limit suggested by Sandor+ (2012)

Aerosol Acidity Profiles



1. High mesospheric temperature changes the thermal equilibrium condition for aerosols
2. Water is removed from the aerosols
3. The aerosol acidity significantly increases

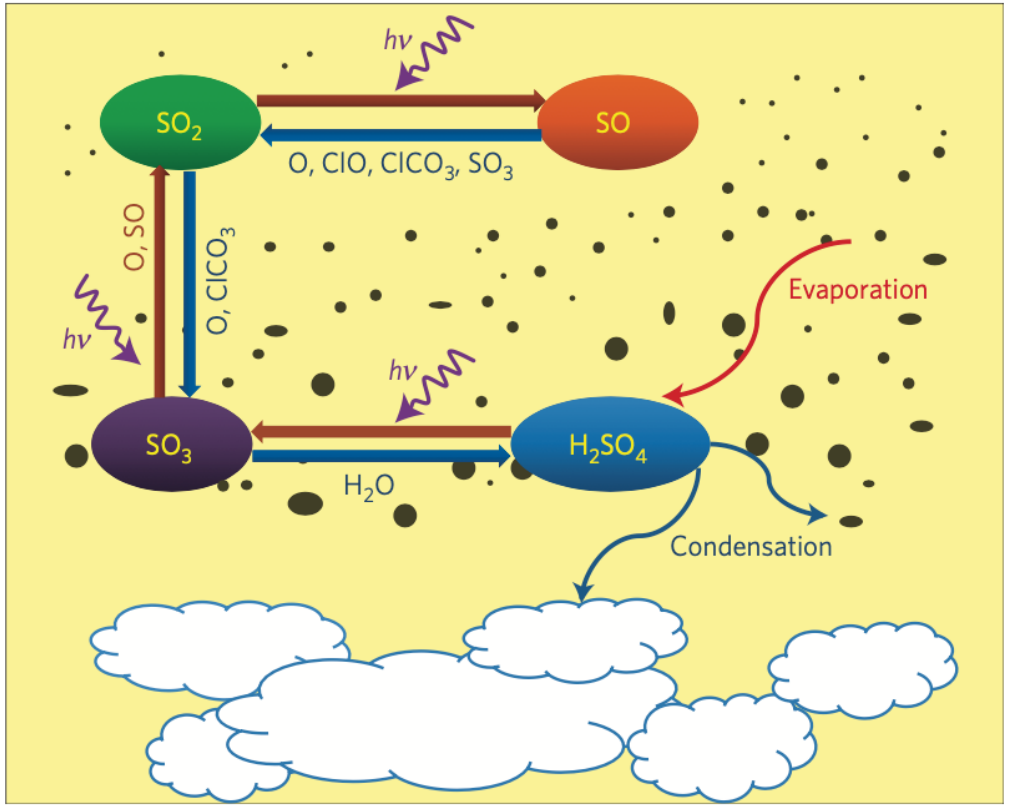
H_2O Profiles

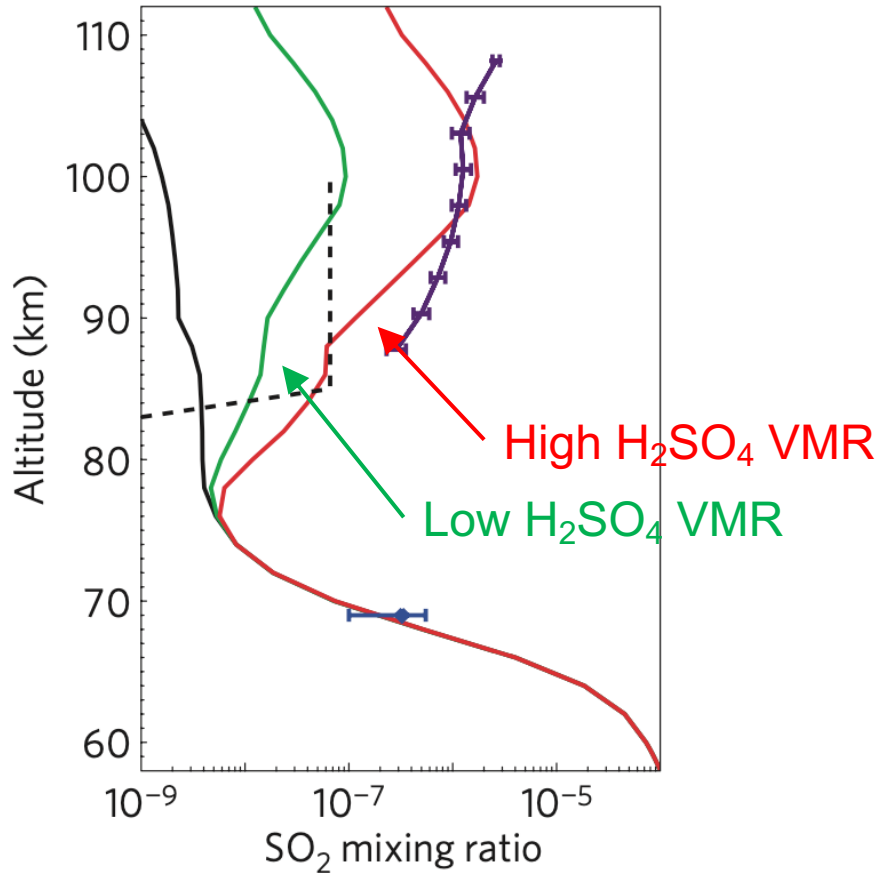


Water is removed from the liquid phase due to the equilibrium condition change
→ The H_2O VMR increases above 85 km

The aerosol-atmosphere interaction can cause the H_2O VMR increase observed by the SOIR

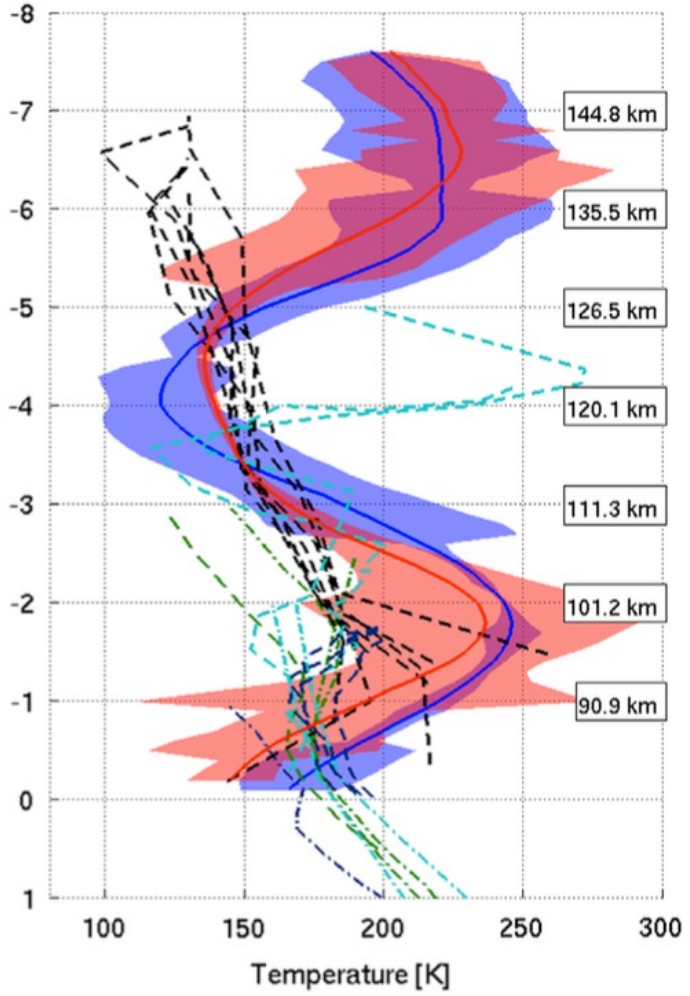
Discussion: Aerosols as a Sulfur Source

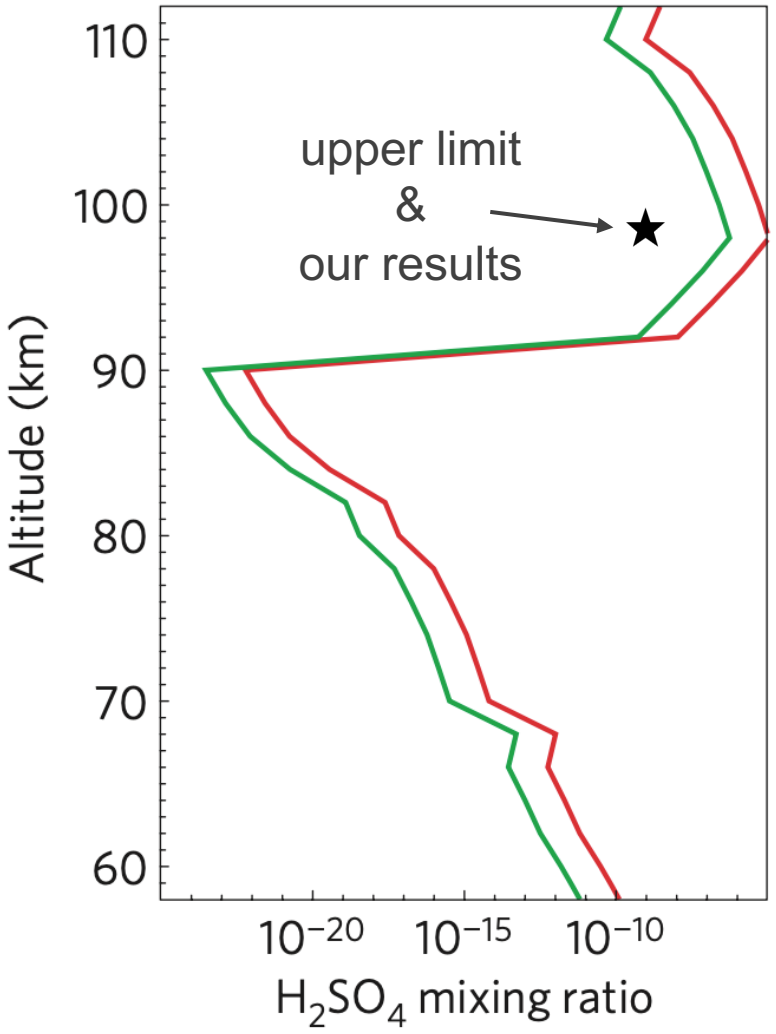




Zhang+ (2010) proposed that evaporation of sulfuric acid aerosols can provide the sulfur source

H_2SO_4 Profiles Assumed in Zhang+ (2010)





Zhang+ (2010) assumed the *supersaturated* H_2SO_4 vapor profile to reproduce the SOIR observation
→ ~5 ppm above 90 km

Previous observation and our results suggest ~3 ppb

H_2SO_4 vapor from aerosols is not suitable for the source of SO_2

Summary & Future Prospects

Summary of Karyu+ (2024) PSJ

- We performed microphysics simulation with a set of different eddy diffusion profiles and temperature profiles based on previous observations
- The obtained H_2SO_4, H_2O, and aerosol profiles agree with observations when the eddy diffusion coefficient is 2 $m^2\ s^{-1}$ at 60-70 km and 360 $m^2\ s^{-1}$ above 85 km
- The transport timescale of the eddy diffusion coefficient roughly agrees with those simulated by GCM
- Aerosols can increase VMR of H_2O and H_2SO_4 above 85 km with SOIR temperature profile, but the H_2SO_4 is not sufficient enough to increase SO_2 VMR around the same altitude

Future prospects

- Taking acount condensation nuclei size distribution
- Coupling with photochemistry
- Coupling with atmospheric radiation