Maintenances of Venusian Sulfuric Acid Clouds due to Chemistry and Dynamics Simulated by a General Circulation Model

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Introduction

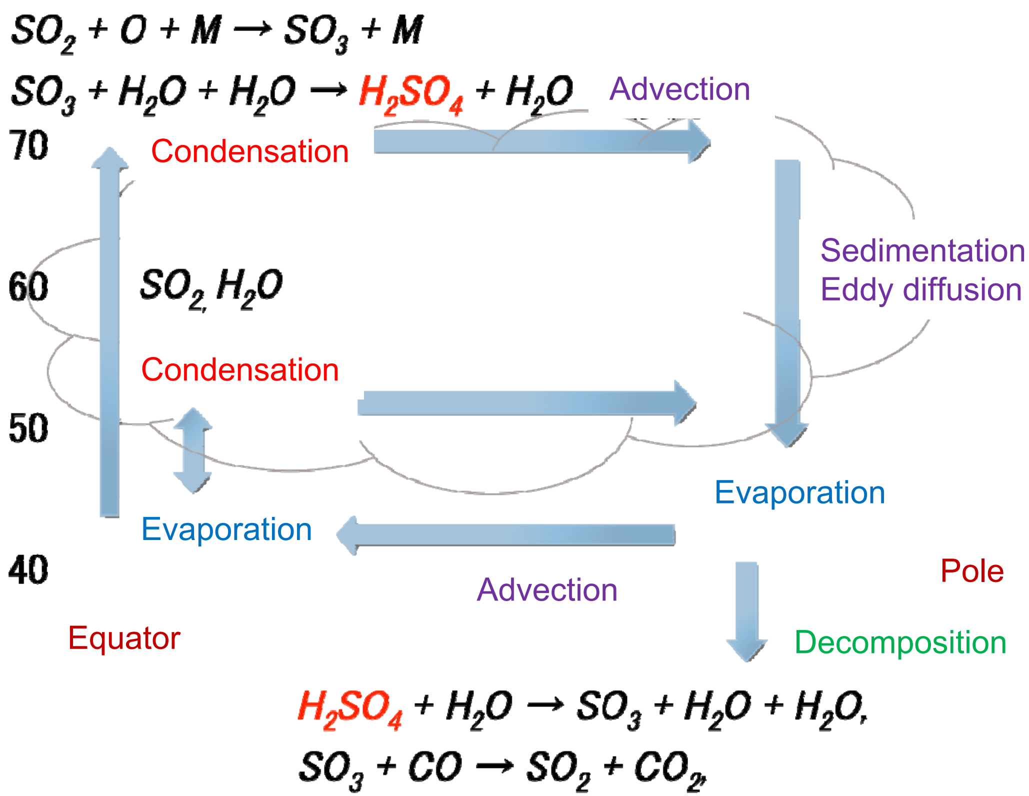
Venusian cloud formation

(Knollenberg and Hunten, 1980; Imamura and Hashimoto, 1998)

✓ *Imamura and Hashimoto* (1998), using a 2-D model including advection, sedimentation, condensation/evaporation suggested the cloud formation.

⇩

＊The meridional circulation under the clouds is unknown.



The schematic view of H_2SO_4 in the Venus atmosphere based on *Imamura and Hashimoto* (1998).

What would drive the meridional circulation?

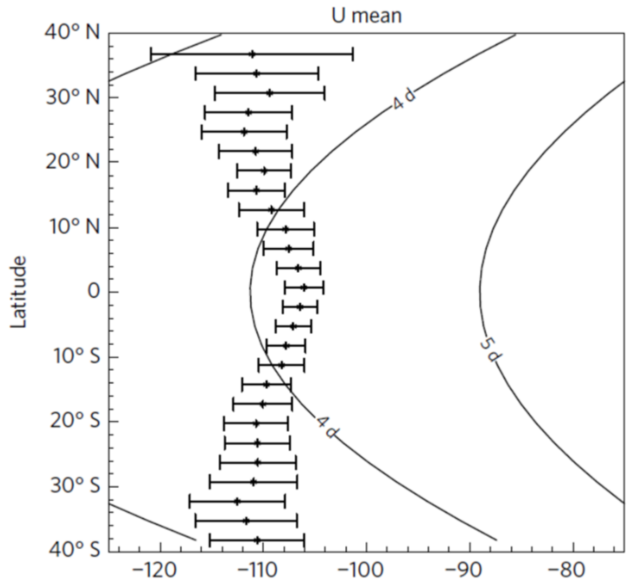
- Radiative effects (gases/clouds)?

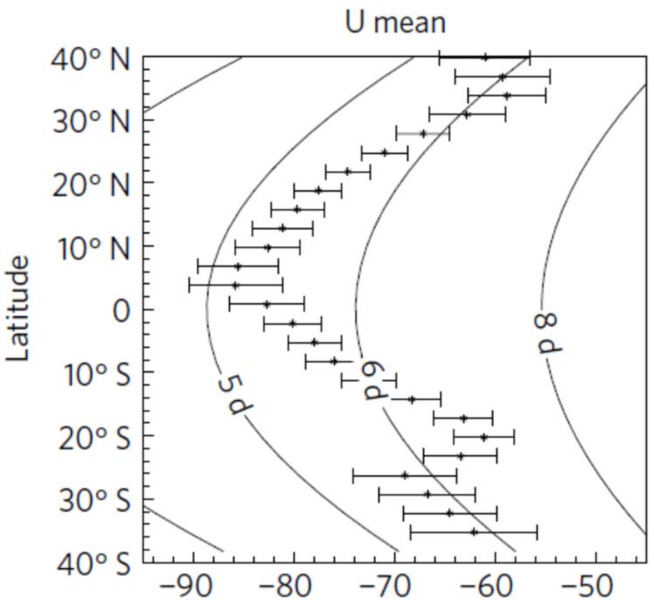
- Eddies (planetary waves/tides)?

And how the wind structures would be?

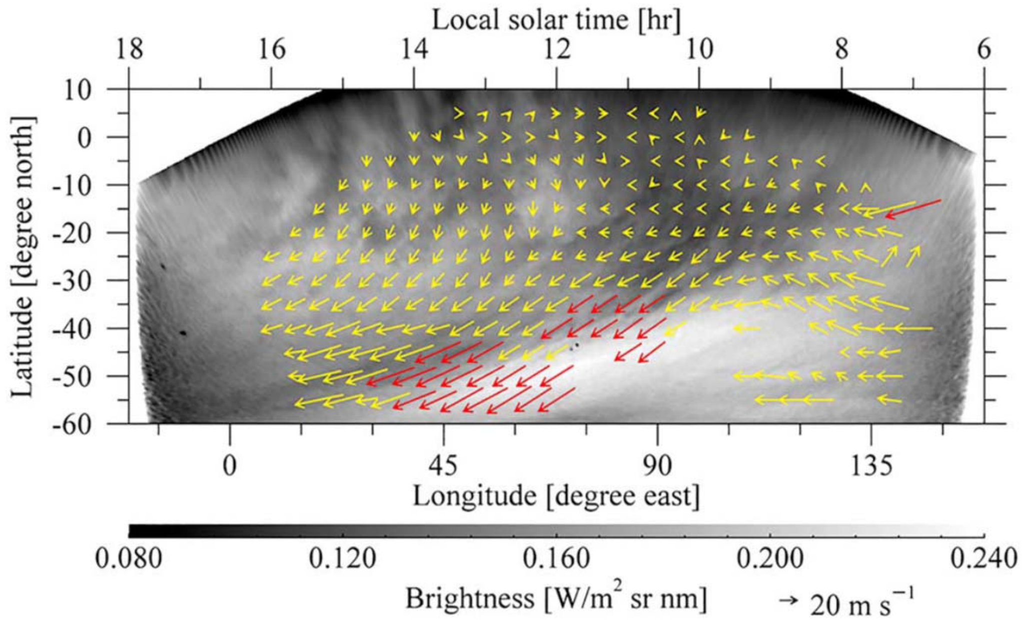
3D information in Venusian cloud layer

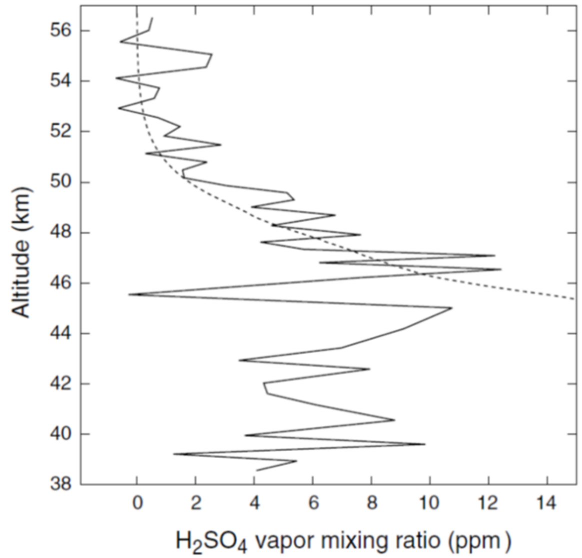
Upper (~70km) and Lower (~50km) zonal wind by Akatsuki [Horinouchi et al., 2017]





Wind vectors to make the upper Y-feature from VMC images [Nara et al., 2019]





Equatorial H_2SO_4 vapor by Akatsuki RO [Imamura et al., 2017]

We are getting quite a lot of information!

Venus GCMs

(teams which have recent publications, as far as I know)

AFES [Sugimoto et al., 2014a, 2014b, 2019; Ando et al., 2016, 2017, 2018; Takagi et al., 2018; Kashimura et al., 2019]

- Collaborations with Akatsuki project
- Horizontally high resolution (0.75 degs in highest)
- <u>Simplified radiation (Newtonian cooling)</u>

LMD/IPSL [Lebonnois et al., 2010, 2015, 2016; Gilli et al., 2017; Lebonnois and Schubert, 2017; Navarro et al., 2018; Garete-Lopez and Lebonnois, 2018]

- <u>Gas-cloud radiation (sulfuric acid clouds spatially fixed)</u>
- Up to thermosphere (~150 km)
- Photochemistry
- Implementation of topography

AORI [Yamamoto and Takahashi, 2003-2018; Yamamoto et al., 2019]

- <u>Simplified/gas-cloud radiation</u>
- Implementation of topography

No Venus GCMs have achieved <u>a cloud-radiation interactive simulation (realistic radiation)</u> as far as I know on publication!

Our activities

Step by step, as master/bachelor theses of students

- VGCM on base: AORI with gas-cloud radiation (Ikeda, 2011)
  (same as Yamamoto et al., 2019)
- Implementation of sulfuric acid cloud formation, sedimentation and advection (Kuroda M., 2013; Nitta, 2013; Kato, 2014)
- Implementation of chemical processes for the production/loss of H_2SO_4 vapor (Itoh, 2016)
- Test of a cloud-radiation interactive simulation (Akiba, 2019)

Final goal

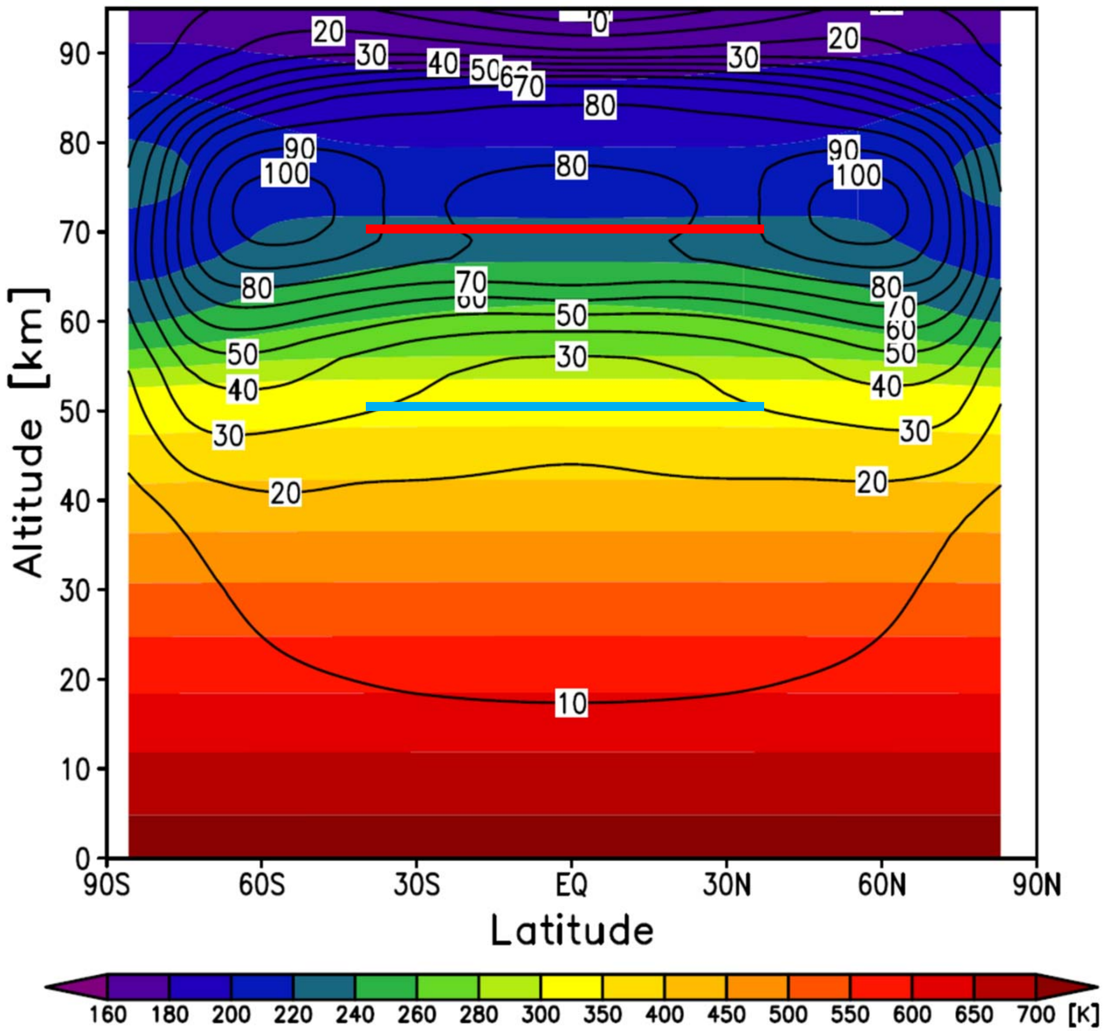
Development of a VGCM including realistic cloud distribution and feedback to the atmospheric radiation for the elucidation of the mechanism of the Venusian atmospheric structures (e.g., polar vortex) and the cloud formation system -> Contribute to Akatsuki project

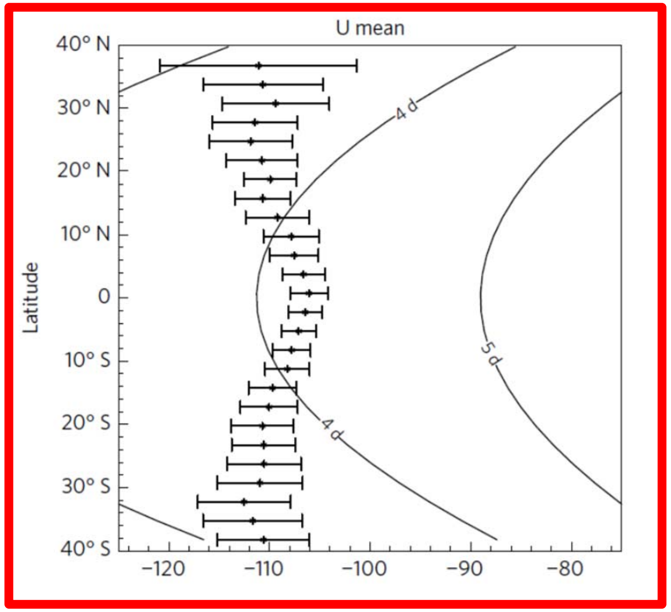
Tohoku/AORI VGCM

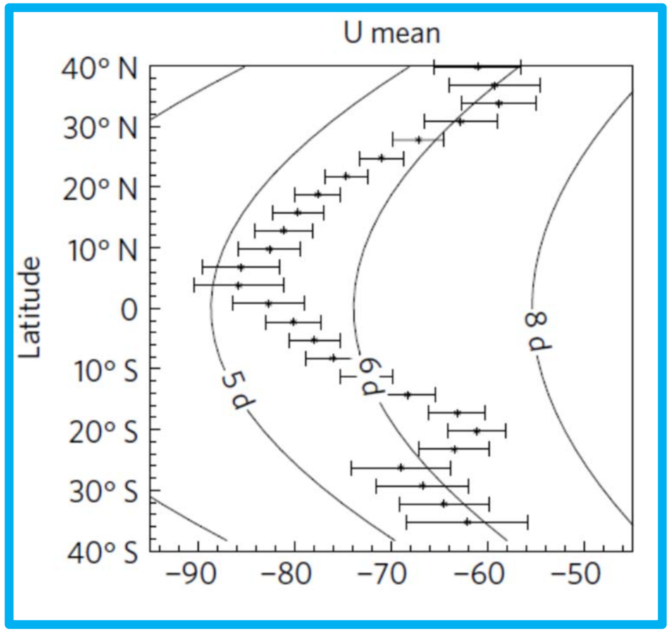
- Dynamical core of CCSR/NIES/FRCGC MIROC model (spectral solver for the three-dimensional primitive equations)
- Horizontal resolution: 5.6° × 5.6° (~600 km at equator), vertical 52 pressure levels with the top of the model at about 95 km
- A circular orbit with no inclination, and topography is neglected (i.e. the model is symmetric across the equator)
- A comprehensive radiative transfer model considering the effects of molecules: CO_2 (including CIA), H_2O, CO, SO_2, OCS and sulfuric acid clouds (75% H_2SO_4): for 4 size modes (after Crisp 1986) + unknown UV absorber
  Distributions of these species are fixed in time and space (Originally by Ikeda, 2011)
- Inertial gravity wave forcings (Hou and Farrell, 1987) for the acceleration of superrotation wind *Note: excluded on Yamamoto et al. (2019)
- 4th-order horizontal diffusion with a e-folding time of 4 (terrestrial) days for the maximum wavenumber
- The vertical eddy diffusions for momentum and heat are set to 0.8 $m^2 s^{-1}$ (constant)
- No Rayleigh friction
- Dry convective adjustment

Mean temperature and zonal wind

(Calculated for hundreds of Venusian days
from the isothermal state)



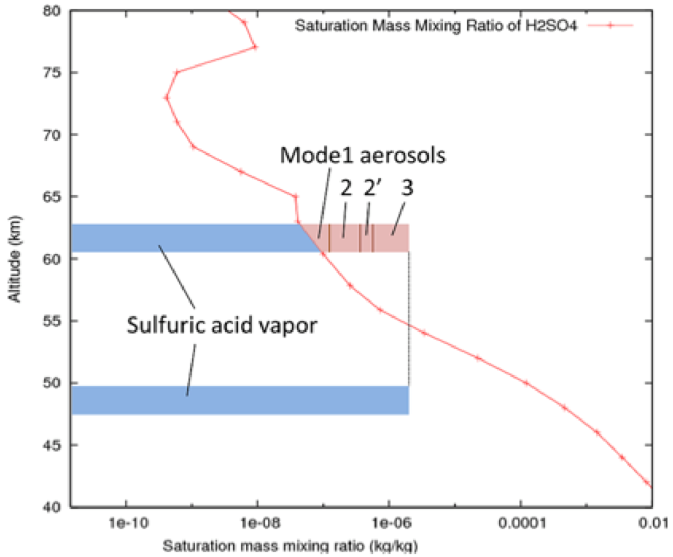


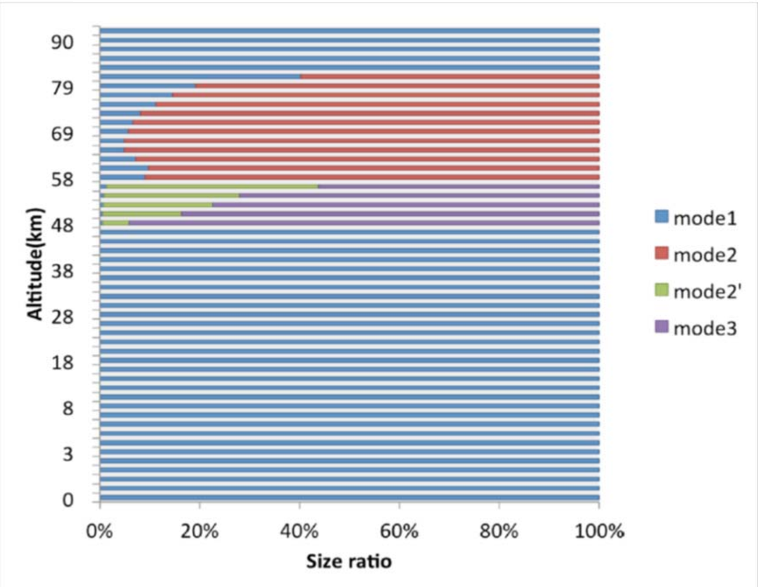


[Horinouchi et al., 2017]

Cloud condensation/evaporation

Mode	1	2	2’	3
Effective radius (μm)	0.46	1.04	1.46	3.65





- Calculate the mixing ratio of sulfuric acid q_a for each grid and layer.
- Supersaturation is not considered.

For $q_a > q_{saturation}$, $q_{cloud} = q_a - q_{saturation}$

For $q_a < q_{saturation}$, $q_{cloud} = 0$

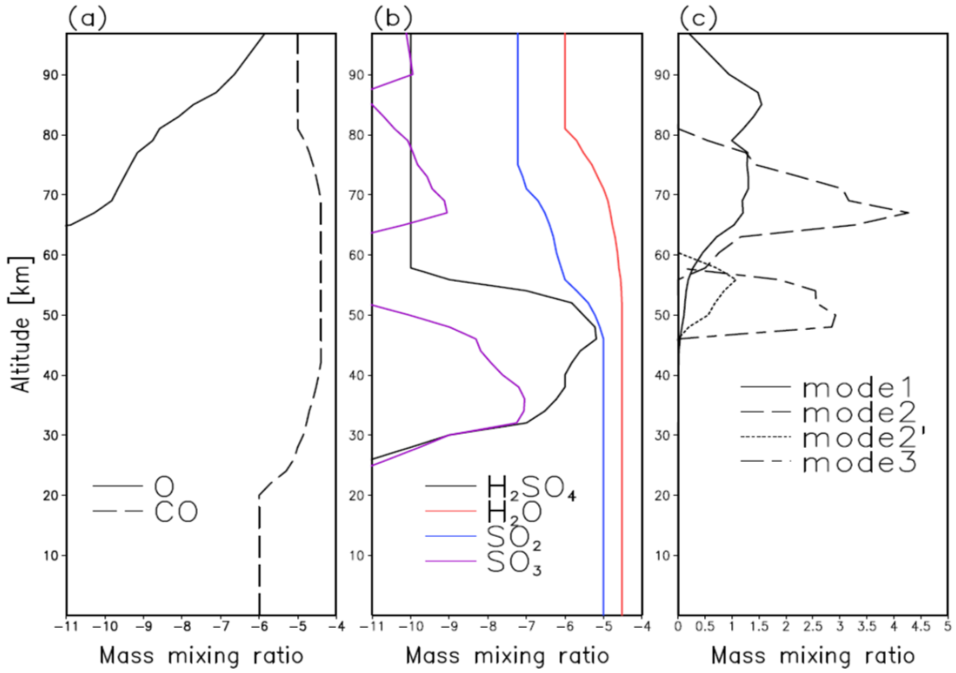
- Condensation/evaporation processes of 75% H_2SO_4 with the exchange of latent heat
- Saturation mixing ratio of H_2SO_4 vapor: Kulmala and Laaksonen (1990)’s formula
- Radius of clouds are assumed to be divided into 4 modes along with the cloud model of Haus and Arnold (2010), keeping the ratios at each height on formation

$q_n = r_n \times q_{cloud}$ n : mode r_n : mode ratio

- Sedimentation velocity: from Kasten (1968)

<- r_n for each height

Chemical processes



[log10 of the ratio] [ppm]

4 chemical reactions have been implemented:

- SO_2 + O + M(CO_2) → $\mathbf{SO_3}$ + M(CO_2)
- $\mathbf{SO_3}$ + H_2O + H_2O → $\mathbf{H_2SO_4}$ + H_2O
- $\mathbf{H_2SO_4}$ + H_2O → $\mathbf{SO_3}$ + H_2O + H_2O
- $\mathbf{SO_3}$ + CO → SO_2 + CO_2

<- Initial vertical profiles (horizontally uniform)

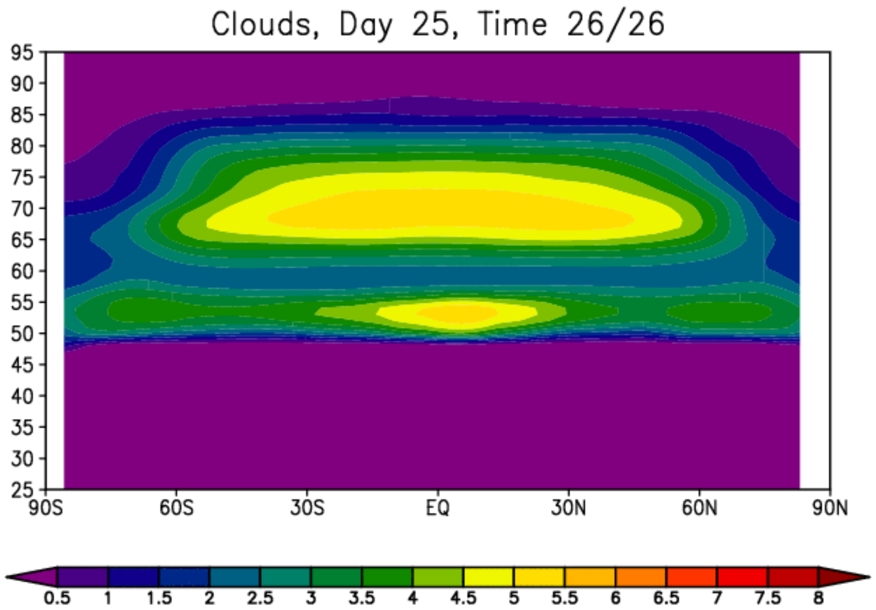
- H_2SO_4 and SO_3 distributions are calculated from the reactions above.
- H_2O and SO_2 distributions are defined with linear relaxation as the substitute of all other effective chemical reactions including photolysis (Marcq and Lebonnois 2013).

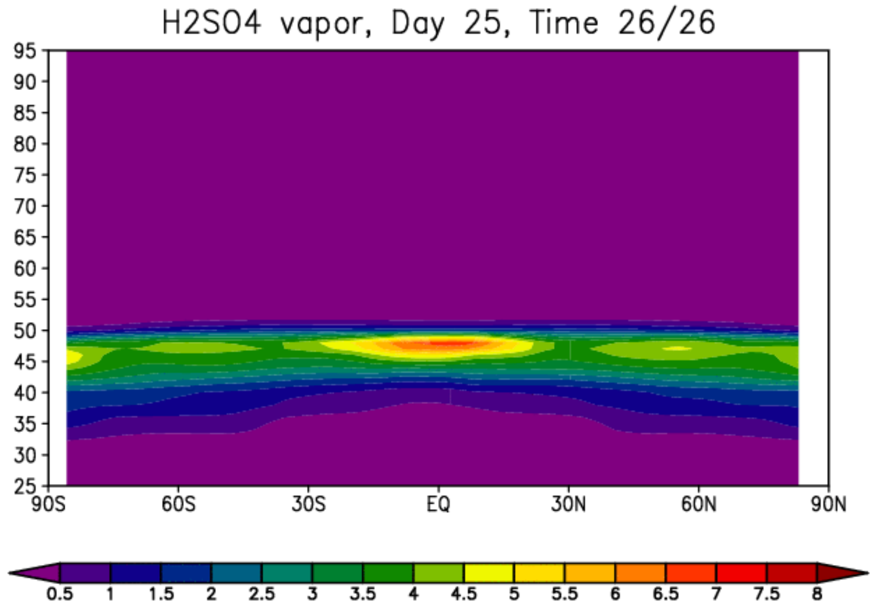
$$\frac{dq}{dt} = \frac{q_0 - q}{\tau}$$

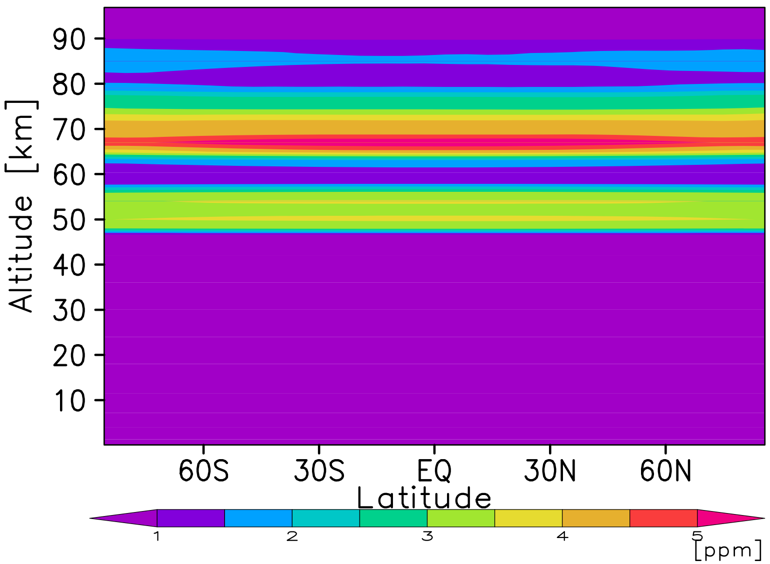
q_0 : Standard mixing ratio (Krasnopolsky 2012, as shown on the profiles above)
τ : relaxation time (s) τ_{SO2} : 5×10^5
τ_{H2O} : 10^6

- O and CO distributions are temporally fixed.

Simulated cloud & H_2SO_4 vapor distributions



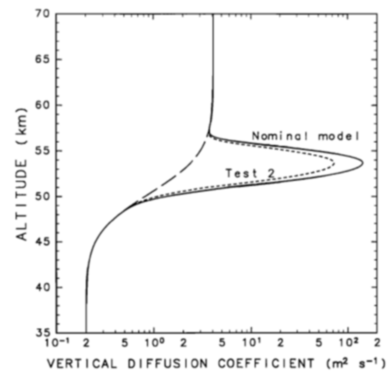




- Unit: ppm of mass
- Note that clouds are radiatively-passive

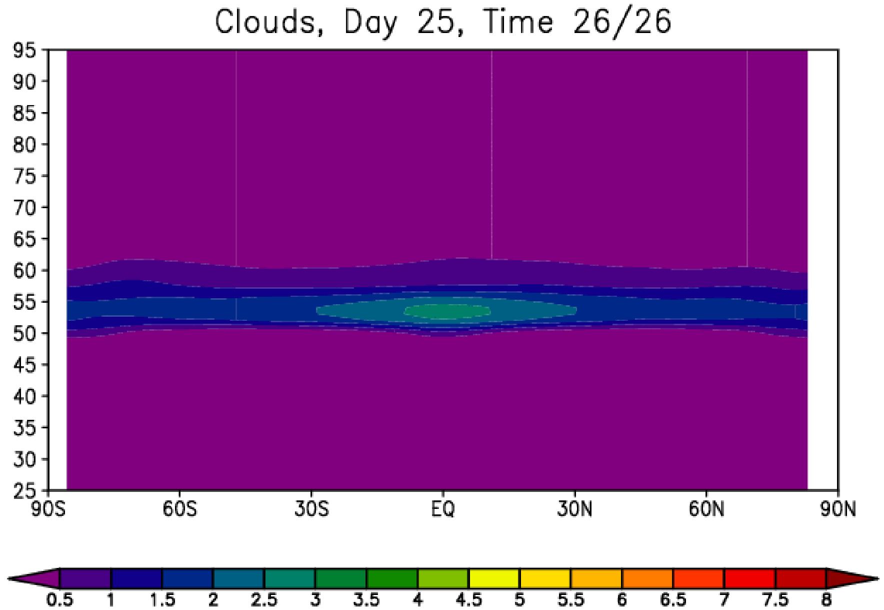
The vertical eddy diffusion for material transport is defined along with the vertical profile of Imamura and Hashimoto (1998) ->

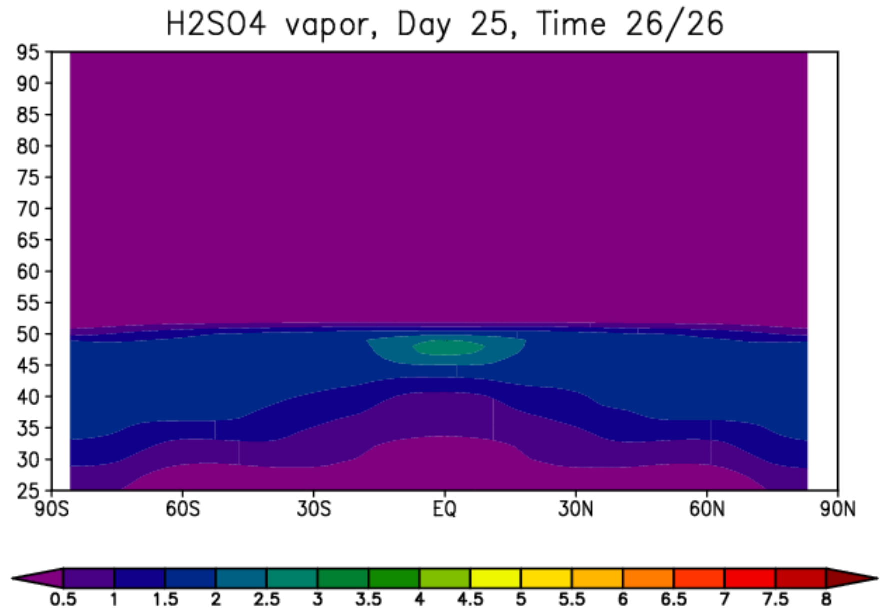
<- Initial state of clouds



Simulated cloud & H_2SO_4 vapor distributions

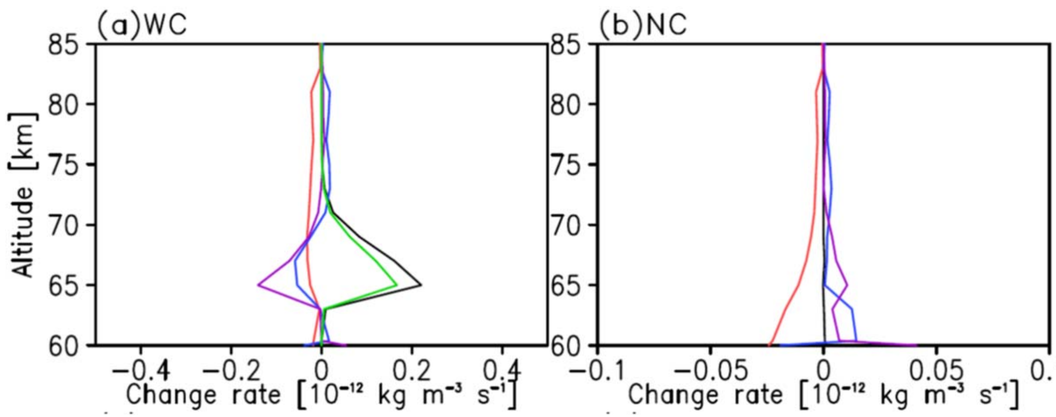
(Without chemical reactions)





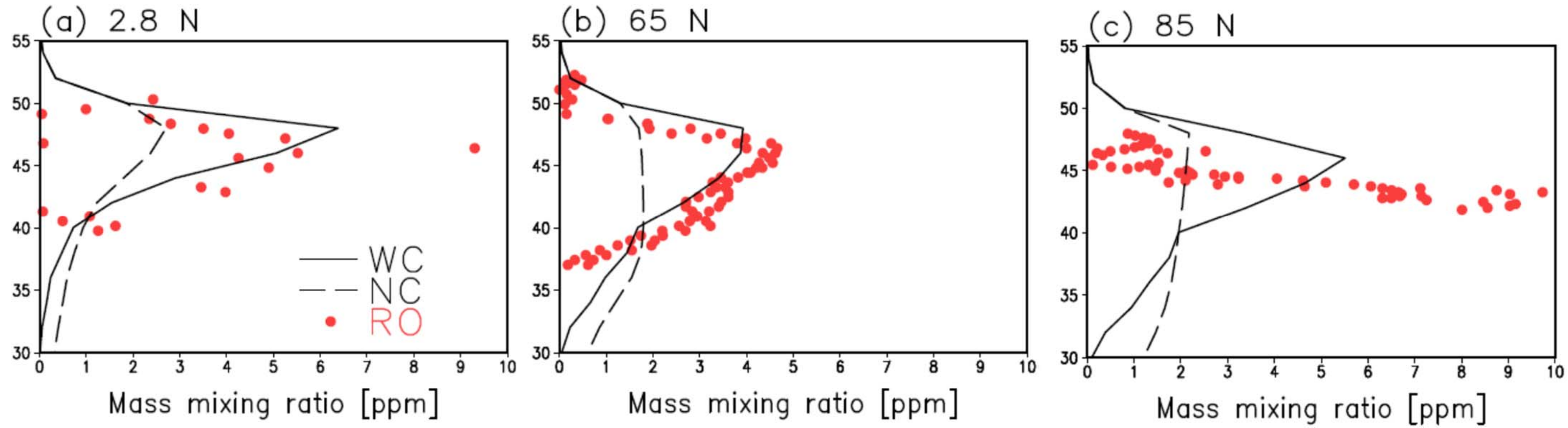
Chemical reactions are critical for cloud simulation!

Green: Change rate of H_2SO_4 vapor by chemistry
Black: change rate of clouds by condensation

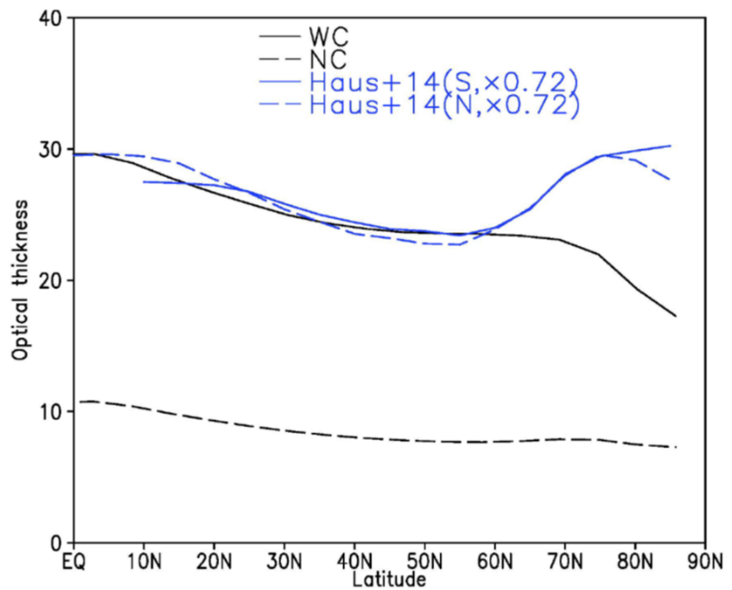


Comparison with observations

Sulfuric acid vapor (with Mariner 10/Magellan radio occultation)



Cloud opacity (with VEx/VIRTIS)

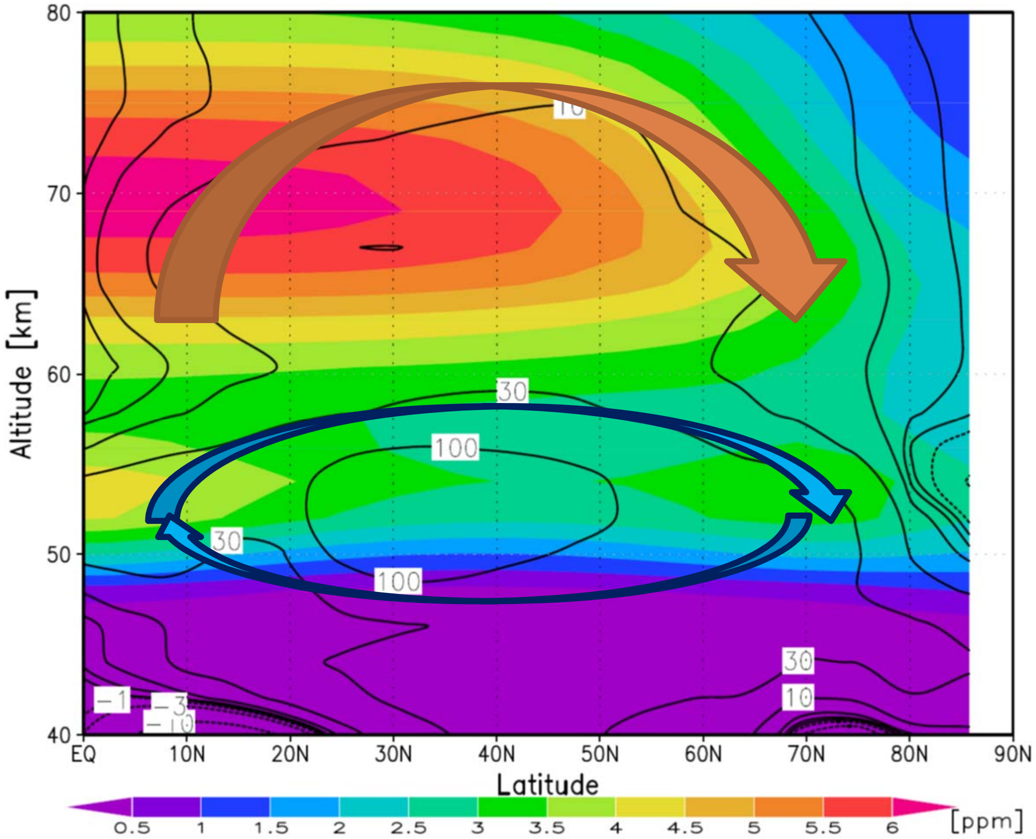


WC = With Chemistry
NC = No Chemistry
Note that clouds are radiatively-passive

The simulated results are qualitatively consistent with observations, but only in low- and mid-latitudes.

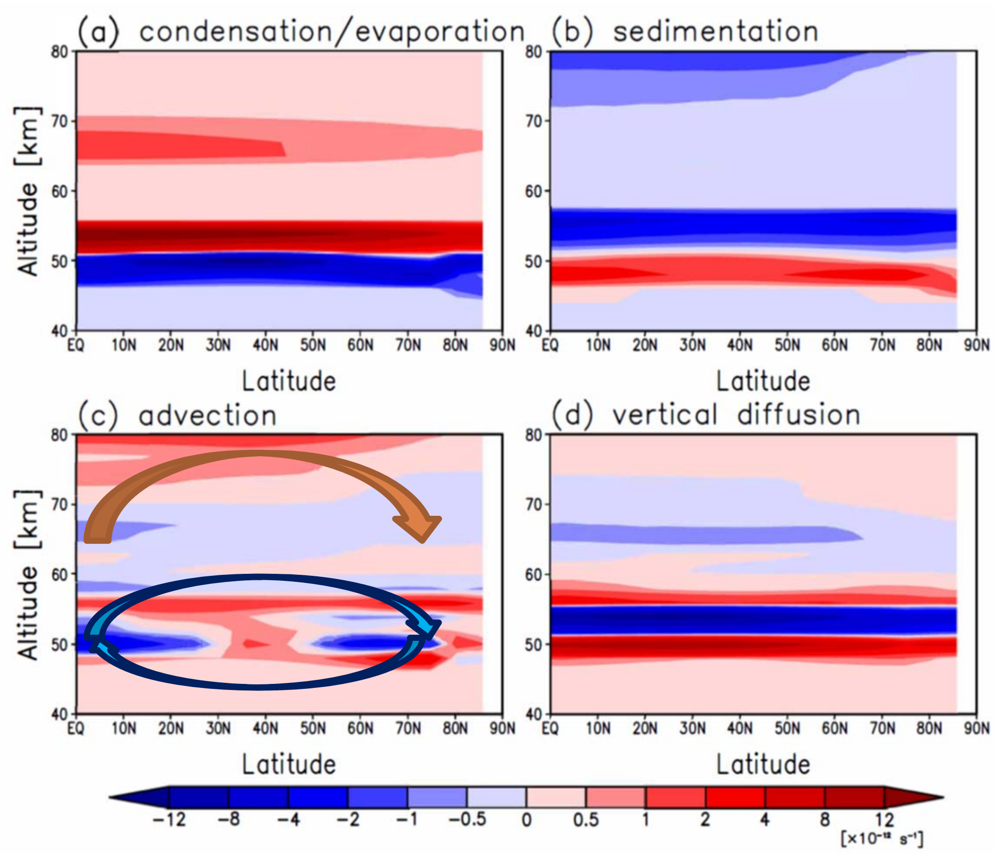
Cloud distribution and meridional transport

Shades: cloud abundance
Black contours: residual circulation



Note that clouds are radiatively-passive

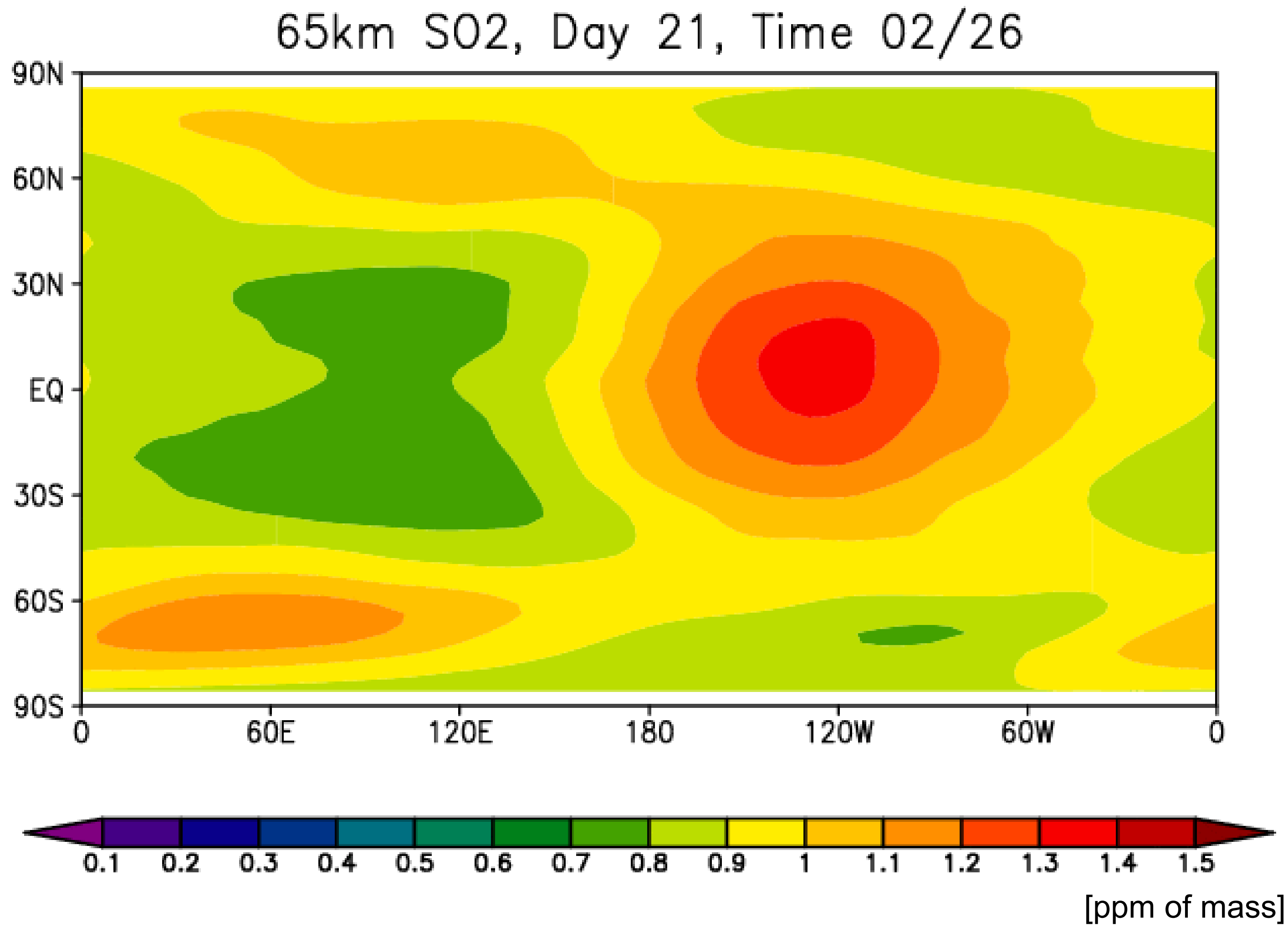
Formation rates of clouds



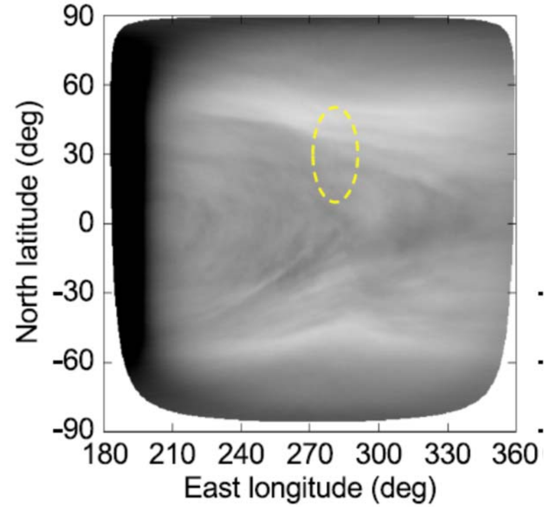
Looks like those features…?

Investigations are ongoing…
(needs a radiatively-active simulation for the accurate evaluation)

Animation of SO_2 distributions at 65km height



[Kitahara et al., 2019]



For good comparisons with Akatsuki UVI 283nm images!

Summary and future plans

- Model development is still ongoing, and we have a lot of things to consider.
  - Make the model with radiatively-active clouds (still under tests…)
  - Validation of model results (wind, temperature, cloud and H_2SO_4 vapor distributions) with observations
- Improvement of cloud formation scheme, and comparison with the AFES scheme (cf. the poster by Dr. Ando) for evaluation
- Implementation of CO-related chemistry and extend the model to upper altitude, for the comparison with telescope observations
- Possible collaborations with Akatsuki team
- Commonalize the radiation code with present-Mars (Kuroda et al., 2005-2019) and paleo-Mars (Kamada et al., Icarus, under revision) GCMs, for the investigations of the climate changes of CO_2-rich planets