What controls the tropopause level of the Jovian atmosphere?

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1. Introduction

1-1. Why we study Jupiter?

- Characterization of planetary atmosphere, including those of exoplanets is necessary to know planetary formation and/or evolution.
- Jupiter is the most familiar H_2-rich planet for us, and many of observed exoplanets likely have such atmosphere. We are developing a numerical model to reproduce the thermal structure of H_2-rich atmosphere and have carried out calculation for the Jovian atmosphere as the first step.

1-2. Jovian cloud structure

- Cloud formation is important for Jupiter because cloud covers Jupiter globally and affects planetary spectrum and albedo.
- Equilibrium Cloud Condensation Model (ECCM) [1,2] predicts 3 layered cloud (H_2O, NH_4SH, NH_3) from thermochemical calculations, but it assume a simple adiabatic air uplift (fig. 1).
- Cloud convection model [3] with micro cloud physics and dynamical processes indicates that cumulonimbus cloud activity could have intermittency under some radiative cooling settings, but assuming a simple cooling profile (fig. 2).
- Radiative-convective equilibrium model [4] predicts that the boundary of radiative equilibrium and convective (tropopause) one occurs around 0.5bar, almost the same level for the initiation of NH_3 condensation in an adiabatically uplifted air parcel.

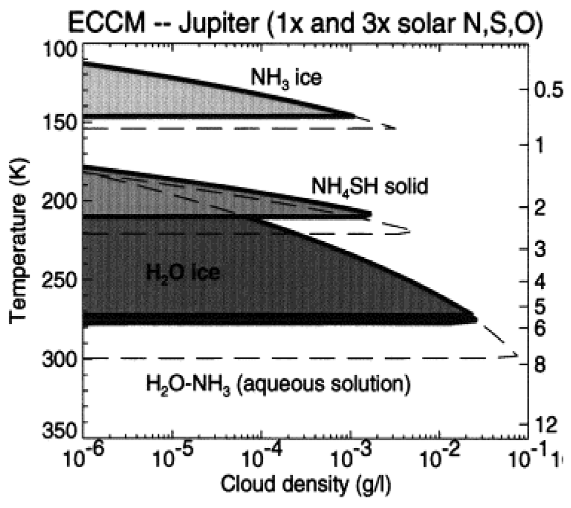


fig. 1 : Cloud distribution with ECCM. [2]

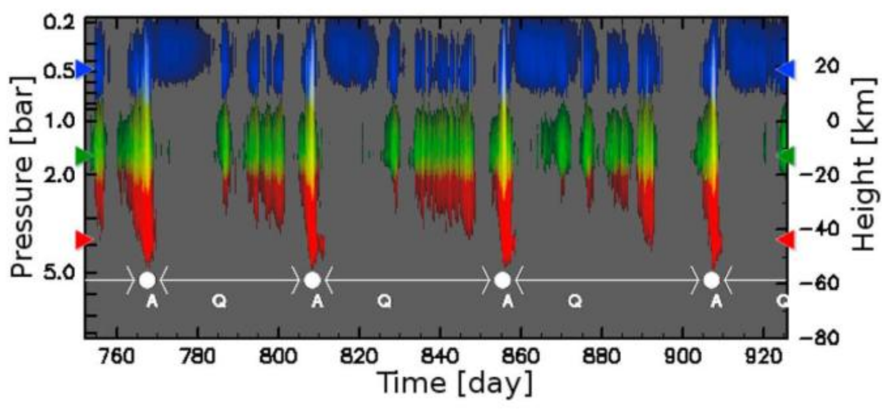


fig. 2 : Time varying cloud distribution. each color shows NH_3(blue), NH_4SH(green), H_2O(red) cloud, respectively. [3]

2. Purpose

2-1. Revisit the level of tropopause

- Cloud top of the Jovian atmosphere is thought as NH_3 cloud from estimated temperature profile, but it remains unclear whether it is stratospheric or convective cloud. This issue is revisited with our model.

2-2. Estimate the cooling rate in troposphere

- Radiative cooling drives convection in troposphere. We calculate its rate and discuss about cloud convection intermittency.

3. Model

3-1. Assumptions & settings

- 1D radiative-convective equilibrium model
- Transfer of thermal radiation is solved with given the potential temperature of troposphere.
- Neglects solar irradiation and the opacity due to condensates.
- Calculated wavenumber range is 0 – 10,000 cm^{-1} (10,000 cm^{-1} = 1 μm), with 10 cm^{-1} band.
- Gravity is 24.82ms^{-2} (Jovian equator)
- Volume Mixing Ratio (VMR) is changed along saturation vapor pressure.

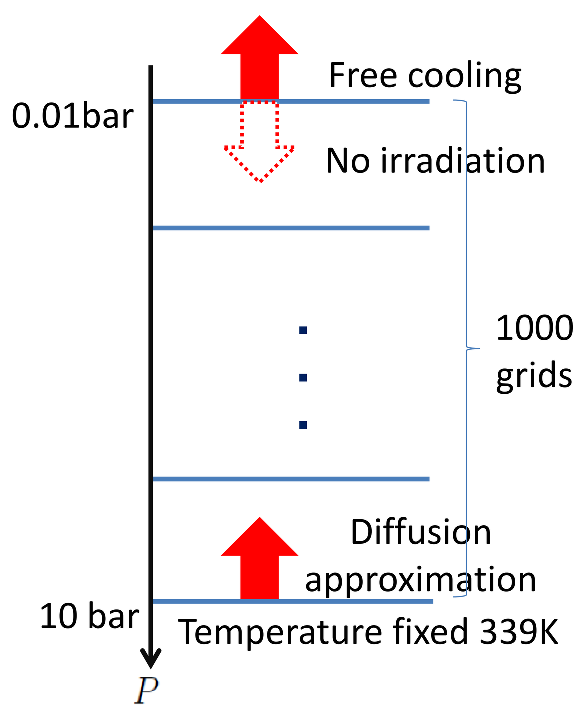


fig. 3 : Conceptual diagram of model

3-2. Line & CIA absorption

-H_2O, CH_4, NH_3 line absorption from HITRAN2008 [6].
Line by line calculation is reduced to wavenumber resolution to 10cm^{-1}.
-H_2-H_2, H_2-He Collision induced absorption from Borysow 1989, 2002 [7,8].

3-3. Radiative transfer & convective adjustment

$$F_\nu^{\downarrow}(z) = \int_z^\infty \pi B_\nu(T(z'))\frac{\partial}{\partial z'}\exp\left(-\frac{5}{3}(\tau_\nu(z)-\tau_\nu(z'))\right)dz'$$

$$F_\nu^{\uparrow}(z) = \int_0^z \pi B_\nu(T(z'))\frac{\partial}{\partial z'}\exp\left(-\frac{5}{3}(\tau_\nu(z')-\tau_\nu(z))\right)dz'$$

$$F_\nu^{surface}(z) = \pi B_\nu(T_s)\exp\left(-\frac{5}{3}(\tau_\nu(0)-\tau_\nu(z))\right)$$

$$\frac{dT(z)}{dt} = -\frac{1}{\rho C_P}\frac{dF(z)}{dz}$$

$$T = T_0\left(\frac{P}{P_0}\right)^{\frac{\gamma-1}{\gamma}}$$

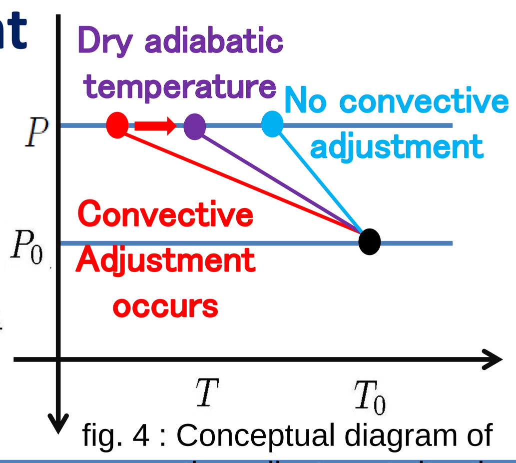
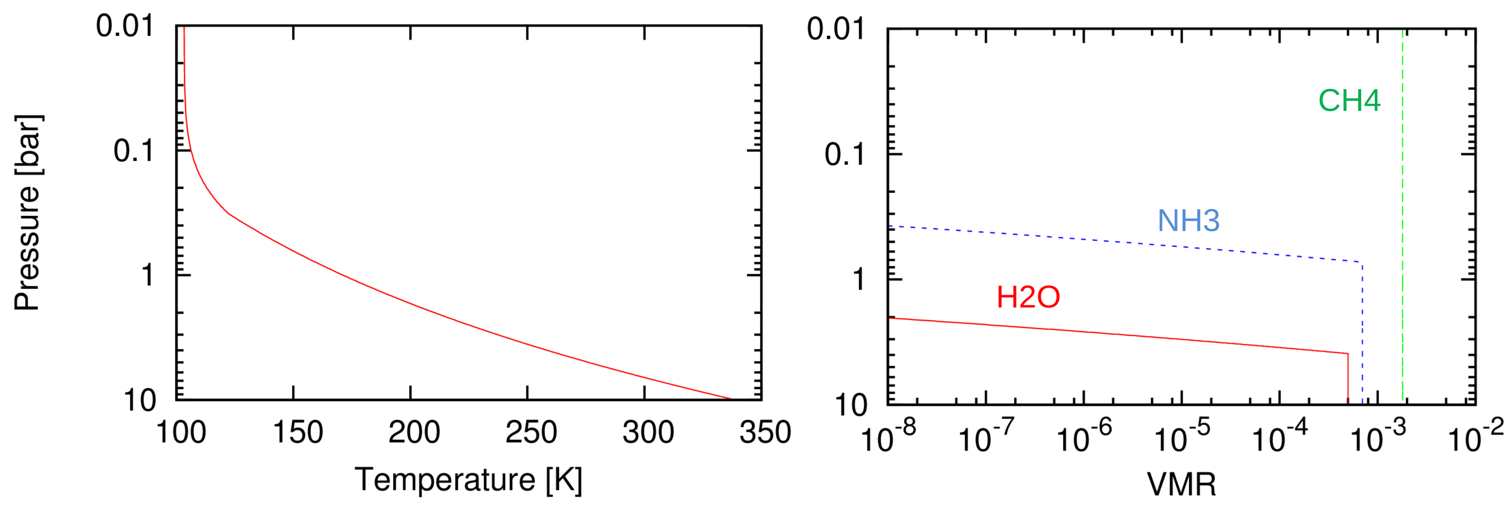


fig. 4 : Conceptual diagram of convective adjustment situation

4. Results

4-1. Temperature profile & Volume mixing ratio

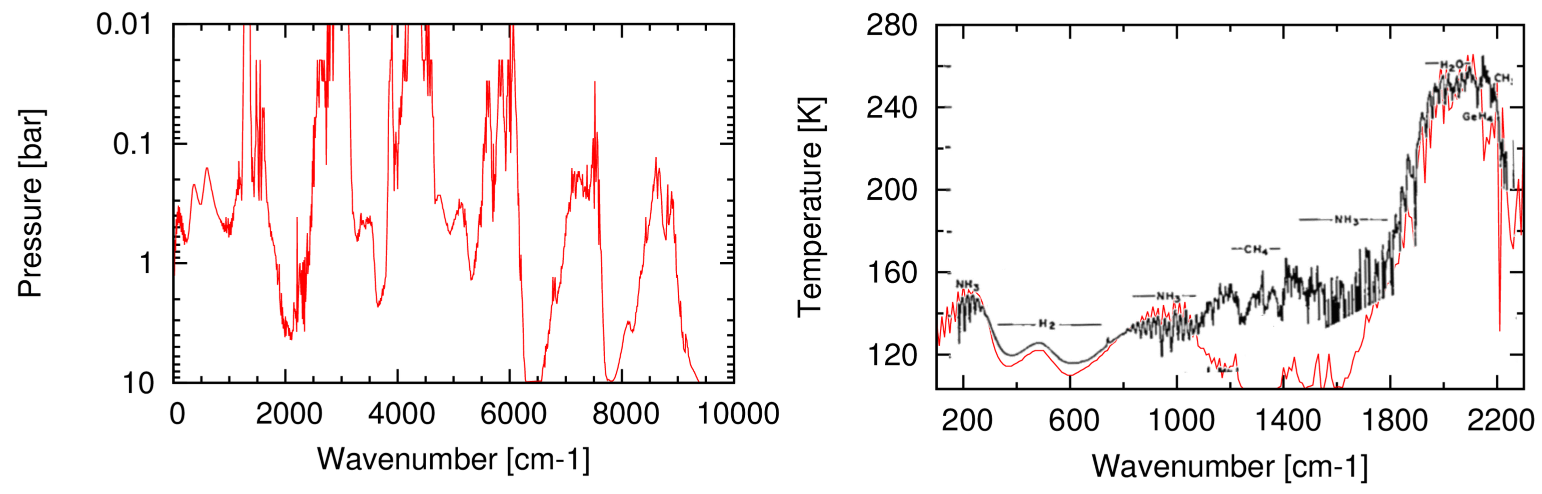
No thermal inversion occurs because of no solar irradiation.



Left : Thermal profile under radiative-convective equilibrium.
Right : Volume mixing ratio of major heavy gases.

4-2. Optical depth

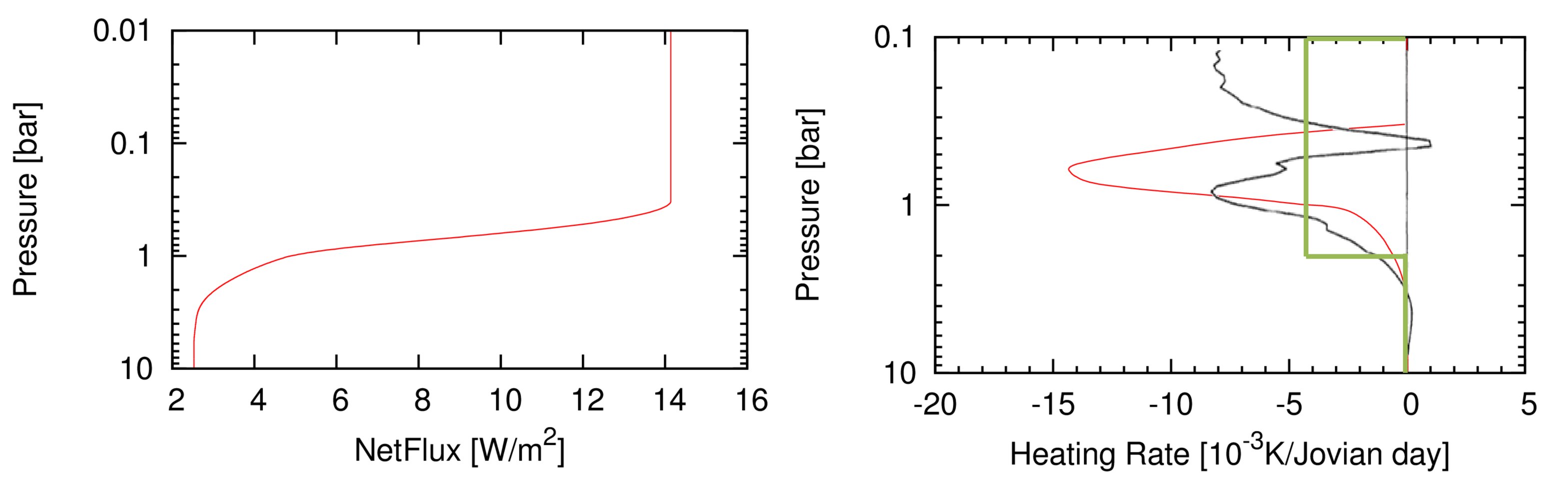
Significant mismatch from the observation between 1,100 to 1,800 cm^{-1} may be caused by solar irradiation, because it makes the thermal inversion in the stratosphere.



Left : The level where optical depth reaches 2/3.
Right : Brightness temperature (red) compared with the observation by IRIS on Voyager [9].

4-3. Net upward flux & Radiative heating rate

Net upward flux at the atmospheric top is almost the same with Jovian mean heat flux 13.59+-0.14 W/m^2 observed by Voyager [10].



Left : Net upward flux on each altitude.
Right : Radiative heating rate. Black and green curves show the observed cooling rate by Galileo probe [11], and simplified cooling rate profile in [3], respectively.

5. Discussions & Conclusions

5-1. Tropopause is formed on 0.33bar level

- This suggests that convective NH_3 cloud would be ubiquitously formed. But note that this calculation neglects some potentially important factors including the solar heating which would stabilize the upper atmospheric layer .

5-2. Heat flux and Cooling rate profile

- Good agreement between calculated and observed heat flux (4-3) means the total amount of radiative cooling is well reproduced by our model. Total energy loss 11.4 W/m^2 assumed for convective layer in [3] is also near that of our model while the calculated peak cooling rate is twice larger than the observed value at the Galileo prove entry site.
- The cloud convection intermittency by [3] is supported from our results.
- Further modelling study is needed to clarify how the realistic cooling profile affects cloud formation.

References

[1] Weidenschilling and Lewis 1972, [2] Atreya et al. 1999, [3] Sugiyama et al. 2011, [4] Appleby and Hogan 1984, [5] Taylor et al. 2004, [6] Rothman et al. 2009, [7] Borysow 2002, [8] Borysow 1989, [9] Hanel et al. 1992, [10] Hanel et al. 1981, [11] Sromovsky et al. 1999.