Two-dimensional simulation of Early Martian atmospheric convection with the major component condensation – Parameter experiments on critical saturation ratio and number density of condensation nuclei –

Tatsuya YAMASHITA

M. ODAKA, K. SUGIYAMA, K. NAKAJIMA,

M. ISHIWATARI, Y.-Y. HAYASHI

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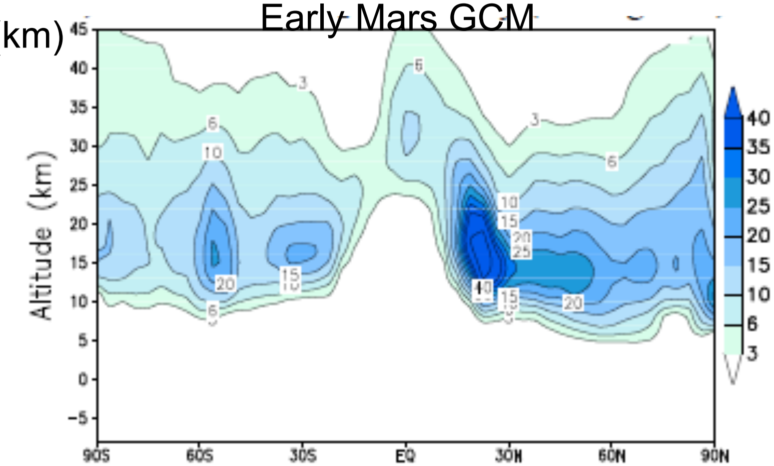
Major component condensation in Martian atmosphere

- Major component, CO_2, condenses in Martian atmosphere
  - Present Mars: Clouds in the polar region (Pettengill and Ford, 2000)
  - Early Mars: Clouds in wider area(Kasting,1991: Mitsuda, 2007:Forget et al., 2013), Scattering greenhouse effect (Forget and Pierrehumbert, 1997)
- Structures of convection with major component cc … nderst

Density of CO2 cloud obtained by Early Mars GCM

Height(km)

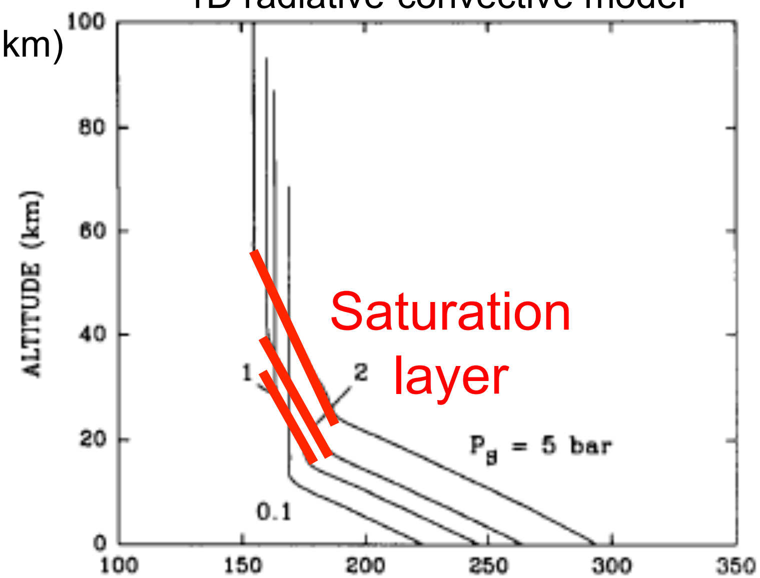


Latitude

Forget et al. (2013)

Temperature obtained by 1D radiative-convective model

Height(km)

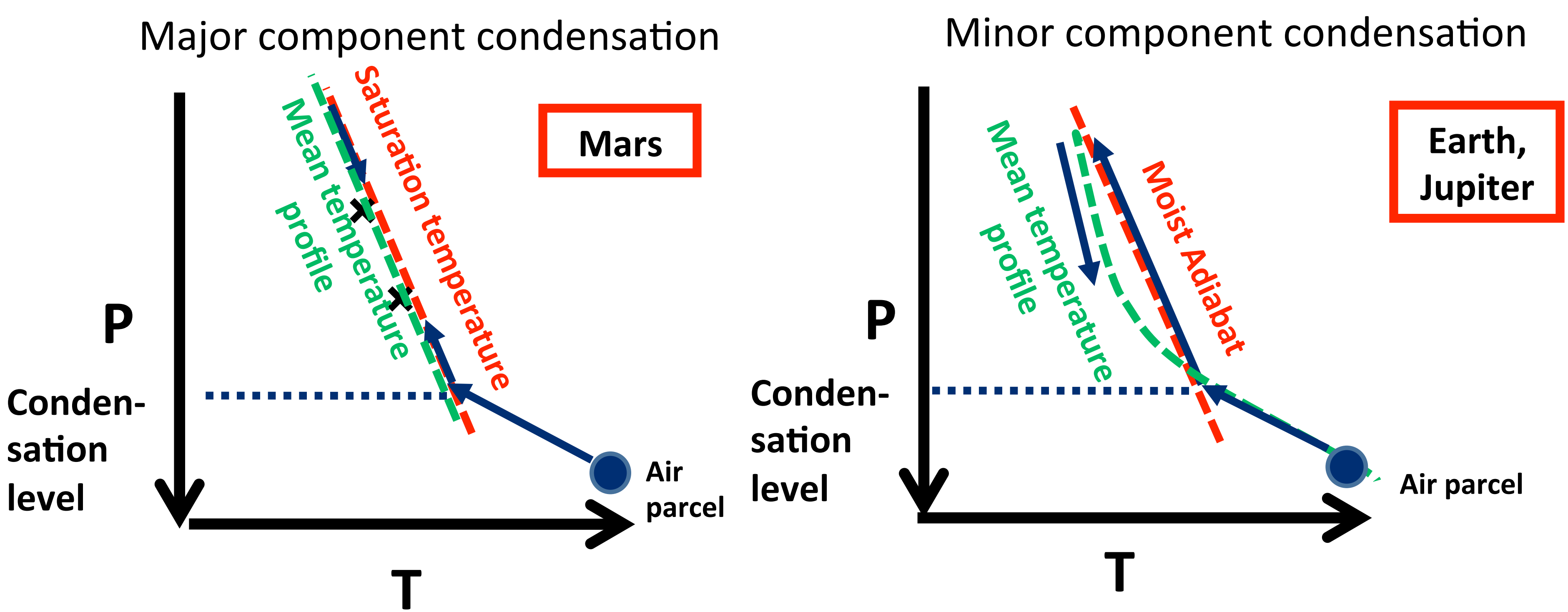


Temperature(K)

Kasting (1991)

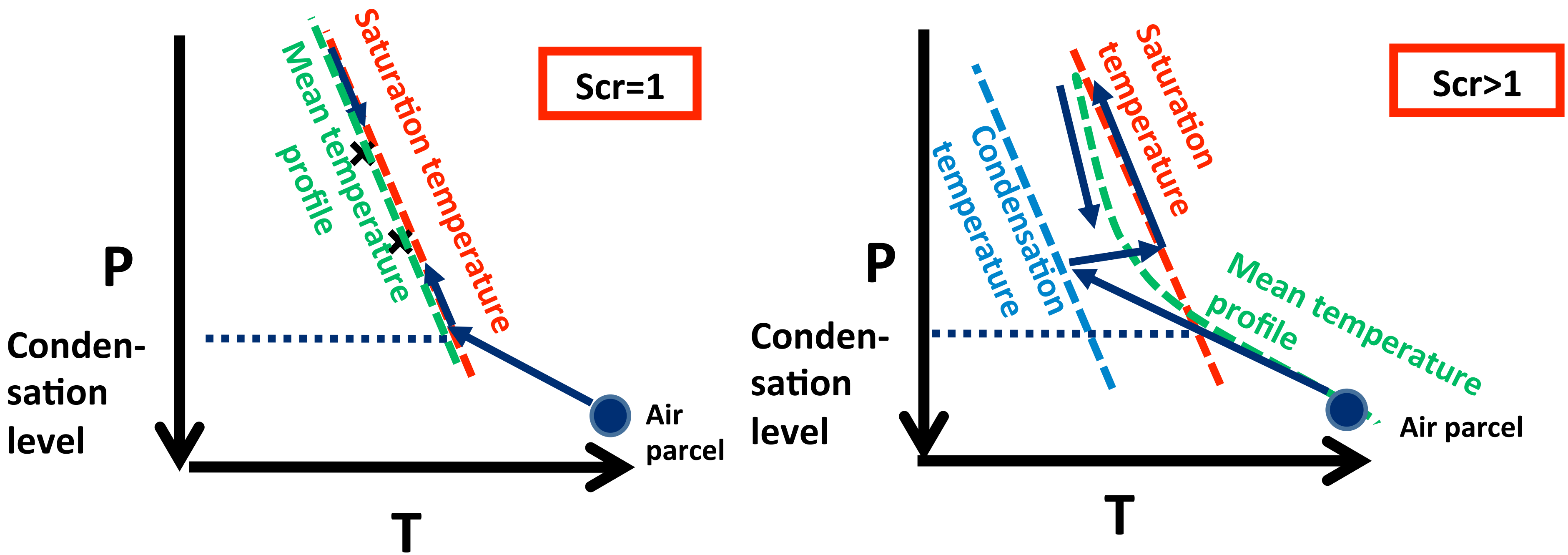
Little buoyancy is obtained when major component condenses

- Little buoyancy force acts to the vertically displaced air parcel because temperature and pressure are constrained to the saturation relation (Colaprete et al., 2003)



Buoyancy can be obtained if critical saturation ratio(Scr) is greater than 1

- Temperature and pressure are not constrained to the saturation relation (Colaprete et al., 2003)
- But Colaprete et al.(2003) simulates by 1D cloud model
  - It is unclear whether mean temperature profile become supersaturated



In this study

- We investigate whether convection with major component condensation occur and how it behaves asymptotically
  - Specifically, we investigate distribution of cloud and flow field such as vertical velocity in Early Martian atmosphere
  - As a first step, we do not solve radiation transfer explicitly, and focus on interaction between dynamics and cloud microphysics
  - In the future, we consider interaction among dynamics, radiation and cloud microphysics explicitly, and approach the warm climate problem on Early Mars

Outline of model description

- Quasi-compressible equations (Klemp and Wilhelmson, 1978)
  - 2D in horizontal and vertical directions
  - Pure CO_2 atmosphere
- CO_2 cloud microphysics
  - Diffusional growth and gravitational settling of cloud particles
- Radiative transfer: horizontally uniform cooling
- Surface flux: Louis (1979)
- Turbulent mixing: 1.5 order closure model (Klemp and Wilhelmson, 1978)

Governing equations

- Quasi-compressible equations(Klemp and Wilhelmson, 1978) and conservation equation for CO2 ice

Momentum equation:

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \bullet \nabla \mathbf{u} - C_p \bar{\theta} \nabla \Pi' + \mathbf{D_u} + \frac{\theta'}{\bar{\theta}} \mathbf{g} - \underline{\frac{R}{p_0} \frac{\bar{\theta}}{\bar{\Pi}^{c_v/R}} \rho_s \mathbf{g}}$$

Drag force

Pressure equation:

$$\frac{\partial \Pi'}{\partial t} = -\frac{\bar{c}_s^{\,2}}{C_p \bar{\rho} \bar{\theta}^2} \nabla \bullet (\bar{\rho} \bar{\theta} \mathbf{u}) + \frac{\bar{c}_s^{\,2}}{C_p \bar{\theta}^2 \bar{\Pi}} (Q_{dis} + Q_{rad}) + \frac{\bar{c}_s^{\,2} L}{C_p^{\,2} \bar{\rho} \bar{\theta}^2 \bar{\Pi}} M_{cond} - \frac{\bar{c}_s^{\,2}}{C_p \bar{\rho} \bar{\theta}} M_{cond}$$

Thermodynamic equation:

$$\frac{\partial \theta'}{\partial t} = -\mathbf{u} \bullet \nabla \theta' - w \frac{\partial \bar{\theta}}{\partial z} + \frac{1}{\bar{\Pi}} \left(\frac{L M_{cond}}{C_p \bar{\rho}} + Q_{dis} + Q_{rad} \right) + D_\theta$$

Conservation equation for CO2 ice:

$$\frac{\partial \rho_s}{\partial t} = -\nabla \bullet (\rho_s \mathbf{u}) + \underline{M_{fall}} + \underline{M_{cond}} + D_{\rho_s}$$

Gravitational settling term

Condensation term

$\mathbf{u} = (u, w)$: Velocity, θ : Potential temperature,
Π : The Exner function, ρ : Density of vapor,
ρ_s : Density of cloud, T : Temperature,
c_s : Sound speed,
C_p : Specific heat at constant pressure,
L : Latent heat, M_{cond} : Condensation rate,
Q_{dis} : Dissipative heating rate,
Q_{rad} : Radiative heating rate,
$\mathbf{D_u} = (D_u, D_w)$, D_θ, D_{ρ_s} : Turbulent diffusion term,
$\mathbf{g} = (0, g)$: Gravitational acceleration

Formulation of condensation/evaporation

- We include the threshold of cloud density, ρt, which corresponds to critical radius of nucleation

	S<1	1≦S<Scr	S≧Scr
ρs > ρt (activated)	Evaporation	Condensation	Condensation
0≦ρs<ρt (not activated)		No Condensation, no evaporation	

  - We assume ρt=1.0e-6 kg/m^3

- Condensation / evaporation rate (e.g., Tobie et al., 2003)

$$M_{cond} = 4\pi r \rho N_* k R \theta^2 \Pi^2 / L^2 \; (S-1)$$

  - We consider diffusional growth of cloud particle
  - N*, k, L are constant

$S = \frac{p}{p_*}$: Saturation ratio

p : Pressure p_* : Saturation pressure

N^* : Number density of condensation nuclei

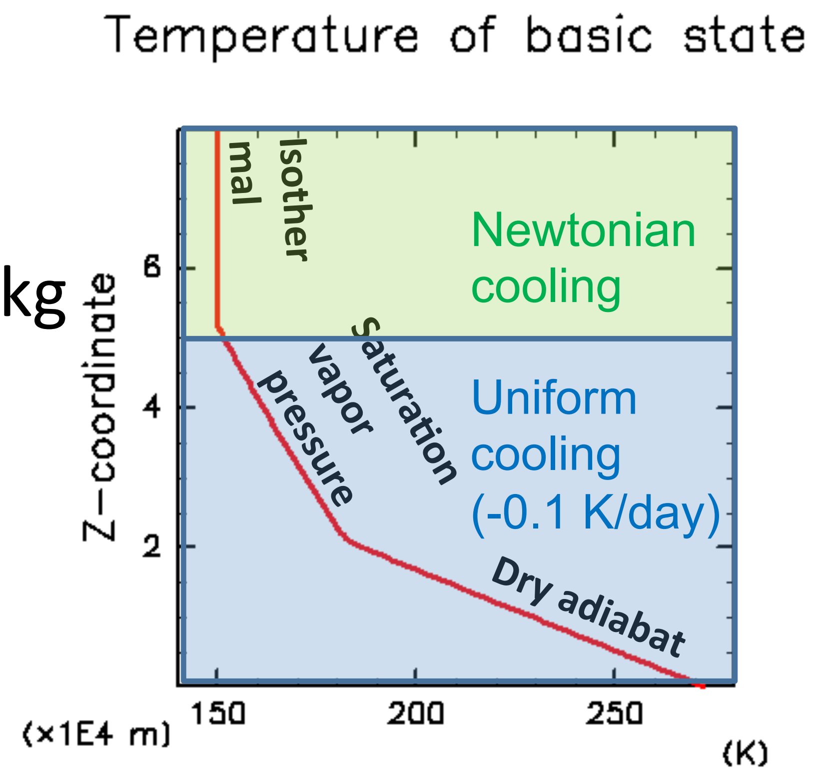
r : Radius of cloud particle

k : Thermal diffusion coefficient

L : latent heat

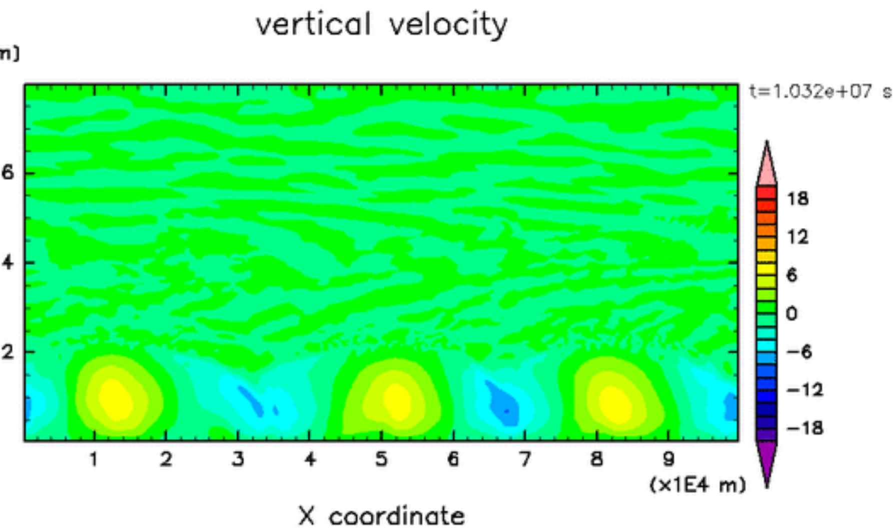
Setup of baseline experiment

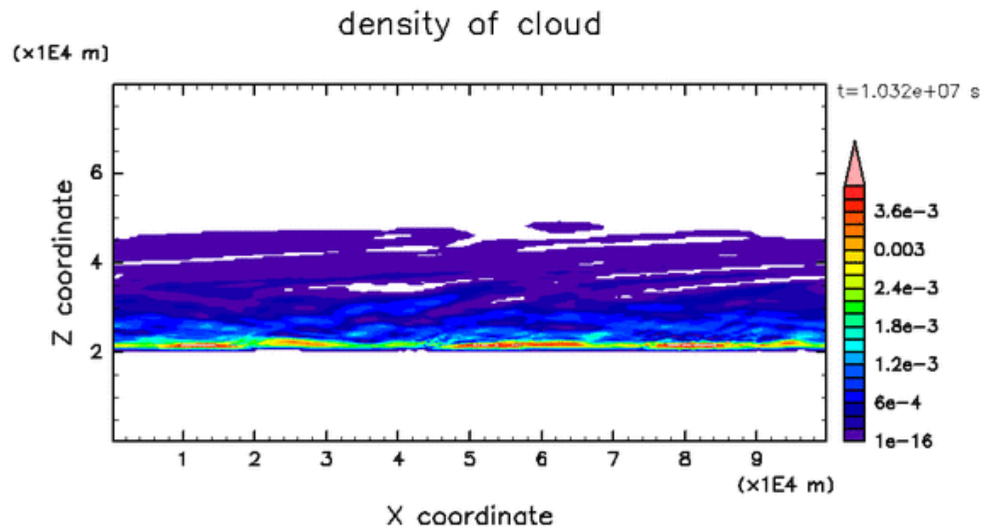
- Initial temperature: right figure
- Cooling rate: right figure
- Critical saturation ratio(Scr): 1.0
- Number density of condensation nuclei (N*): 5.0e8 /kg
  - follows Tobie et al.(2003)
- Surface pressure: 2.0e5 Pa
- Surface temperature: 273K
- Integration time: 120 days
- Domain size:
  - 100km in the horizontal direction(grid spacing: 500m)
  - 80km in the vertical direction (grid spacing: 400m)



Baseline experiment

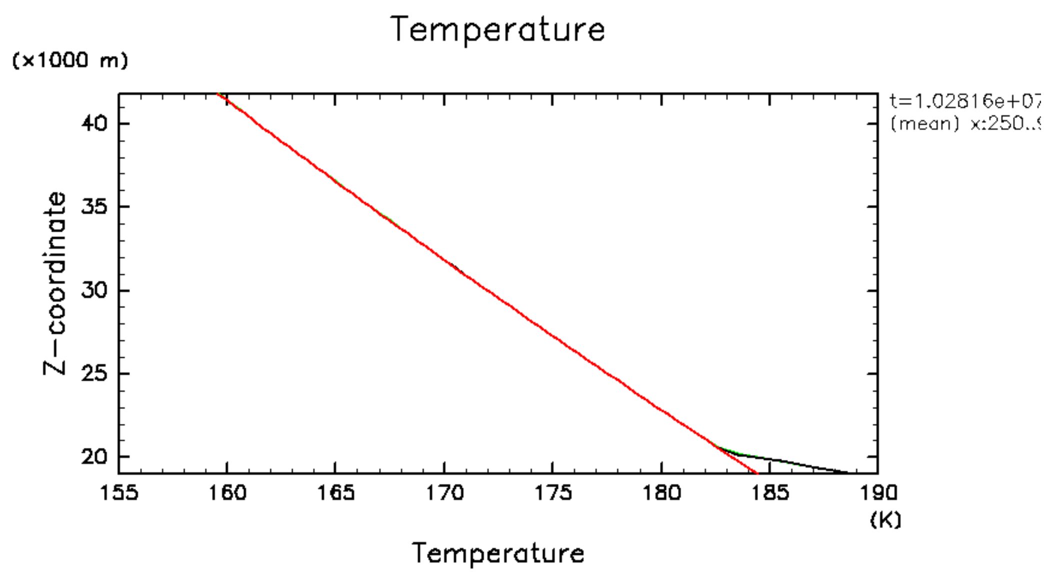
A statistical equilibrium solution

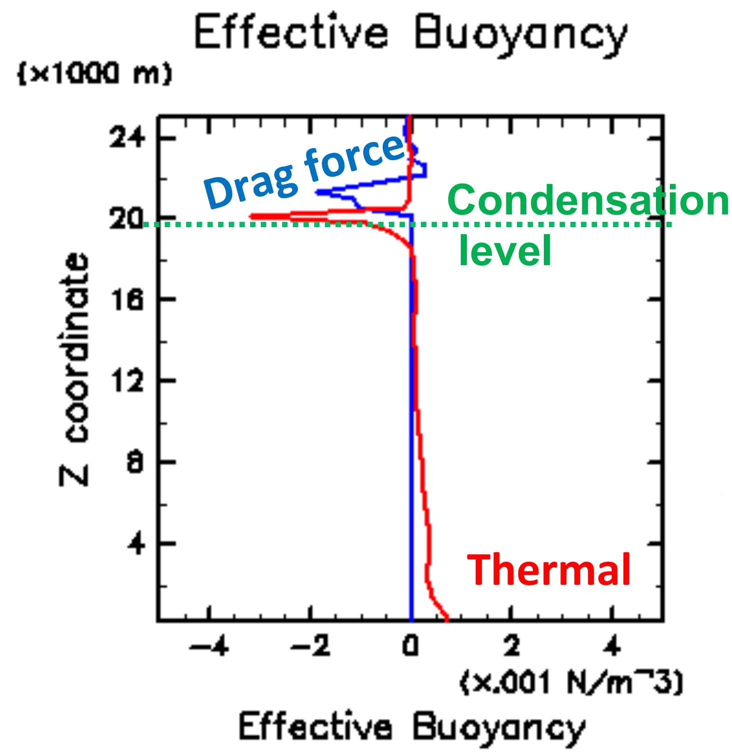




- Cloud layer forms between 20 km and 50 km altitude
- Most of cloud mass is distributed near the condensation level(20 km)
- Vertical velocity in cloud layer is much smaller than those below the condensation level, and is 0.5 m/s at a maximum

A statistical equilibrium solution





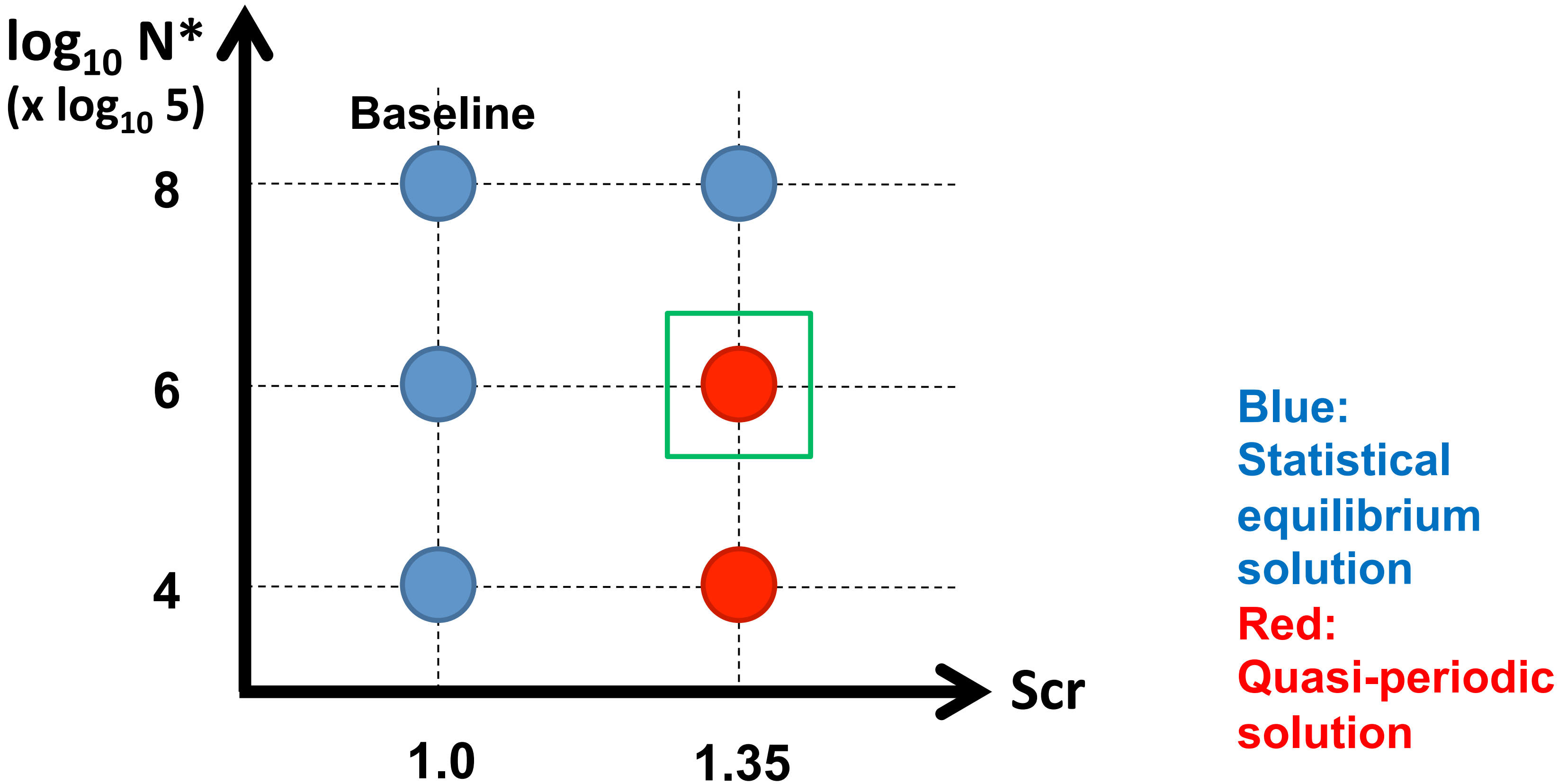
Black: Temperature of ascent region,
Green: mean temperature profile,
Red: Saturation temperature

- Temperature of ascent region and mean temperature approximately equals to saturation temperature
- An air parcel does not obtain buoyancy in the cloud layer, and strong vertical motion does not occur
- It is consistent with Colaprete et al.(2003)

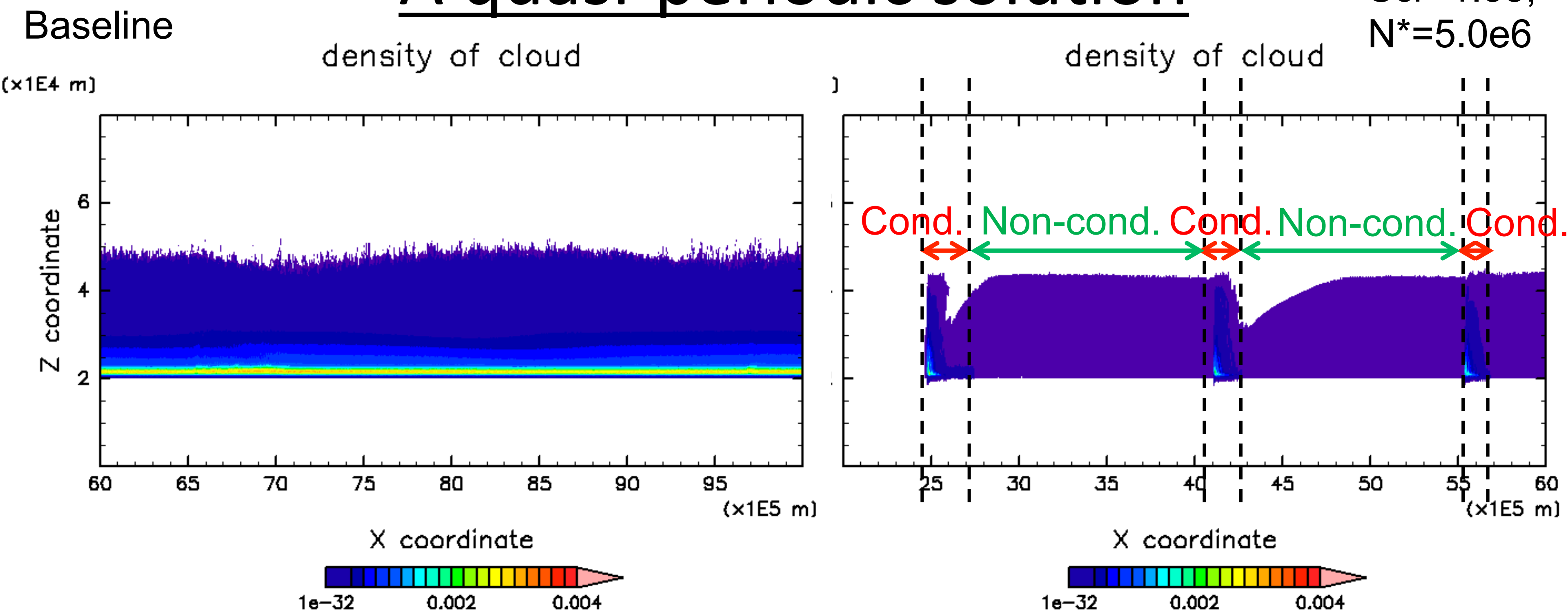
Parameter experiments

Parameter experiments

- Scr = 1.0 or 1.35
  - The value of Scr=1.35 is based on Glandorf et al.(2002)
- N*=5.0e4 or 5.0e6 or 5.0e8 /kg
  - The range of N* is based on Tobie et al.(2003), Forget et al.(2013)



A quasi-periodic solution

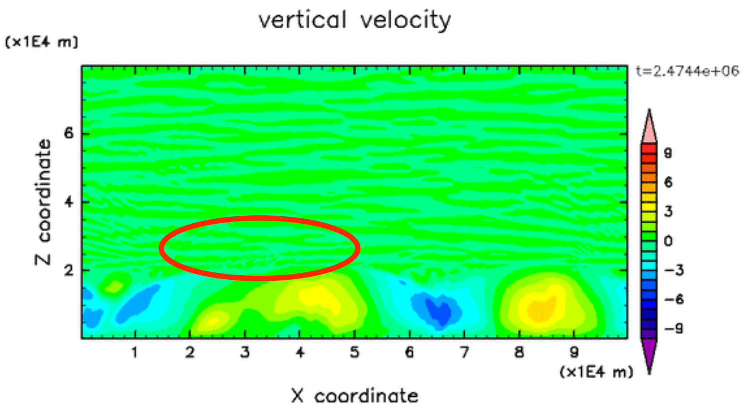


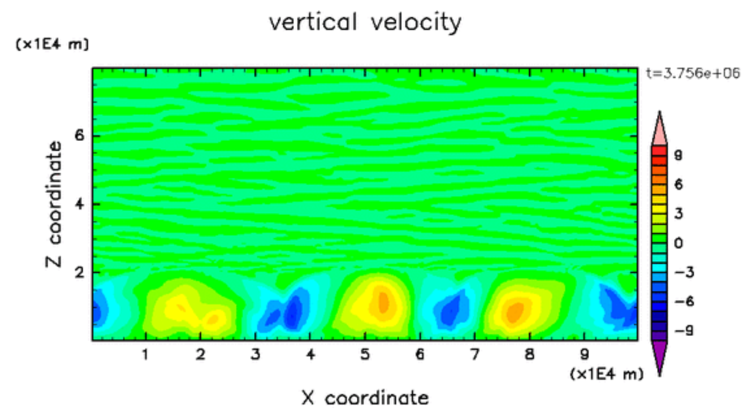
- Condensation and non-condensation periods occur alternately

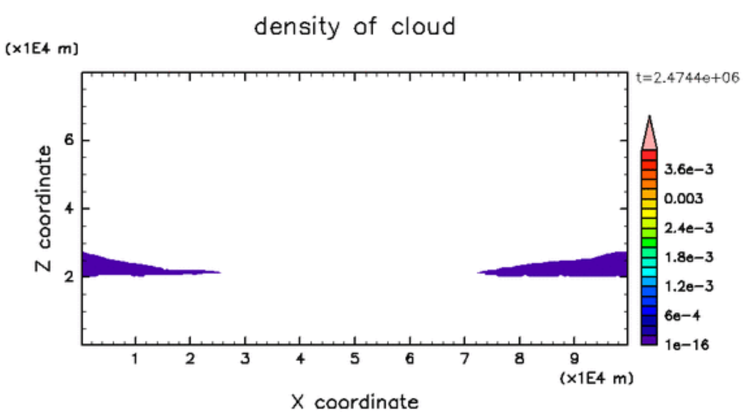
A quasi-periodic solution

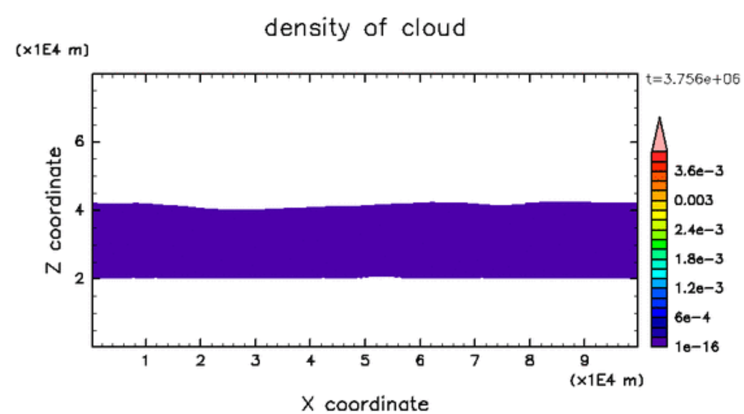
Condensation period

Non-condensation period





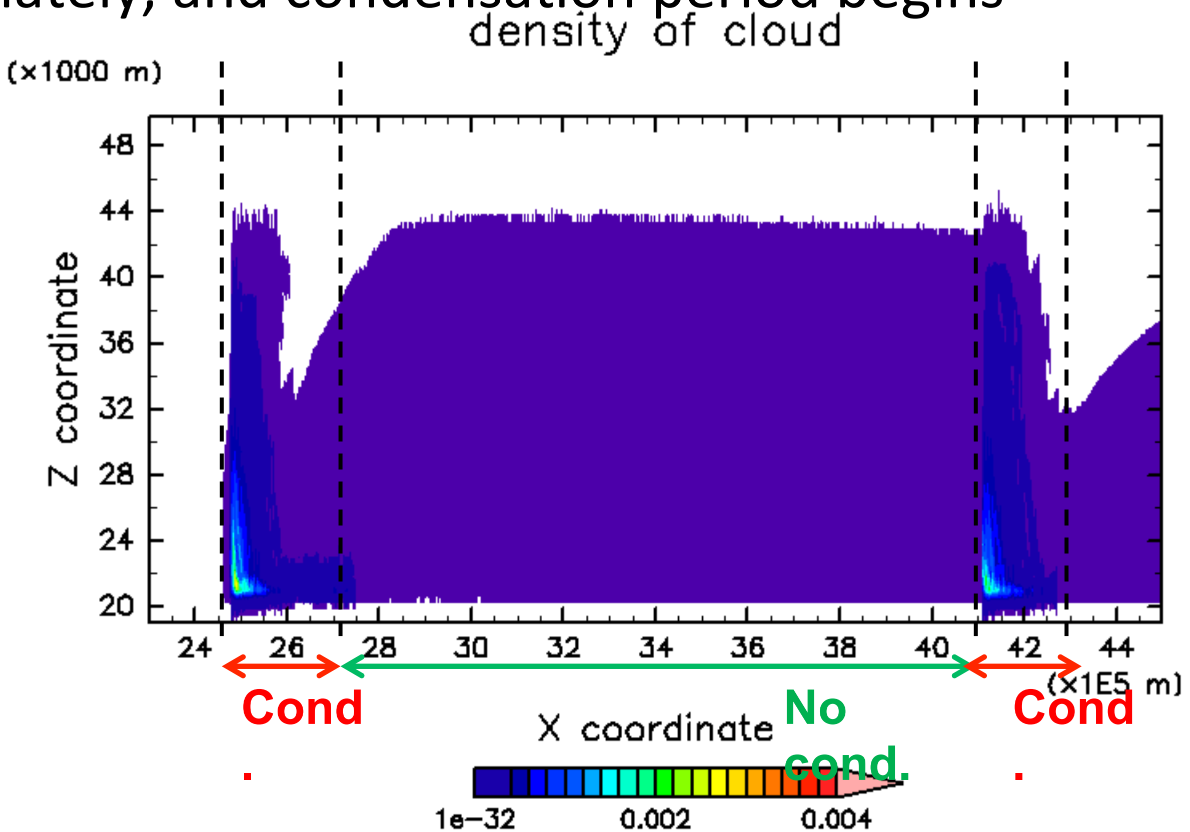




- Condensation period: vertical velocity of 2-3m/s in the cloud
- Non-condensation period: wispy cloud layer, small velocity (<0.5m/s) in the cloud layer

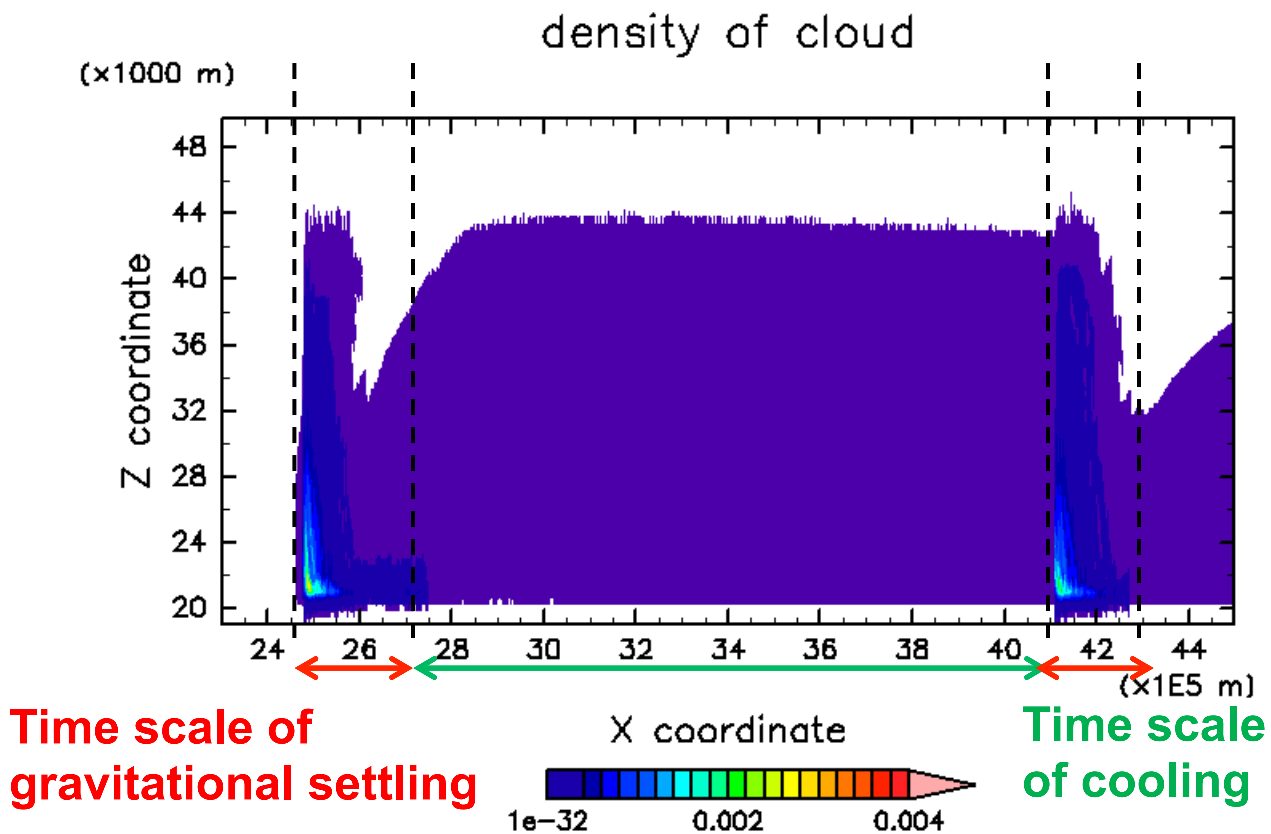
Why can the solution be periodic?

- Cloud density falls below the threshold of condensation due to gravitational settling, and non-condensation period begins
  - “ ■ “ represents the region in which cloud density falls below the threshold
- Cloud layer is cooled until saturation ratio equals to Scr approximately, and condensation period begins
- …



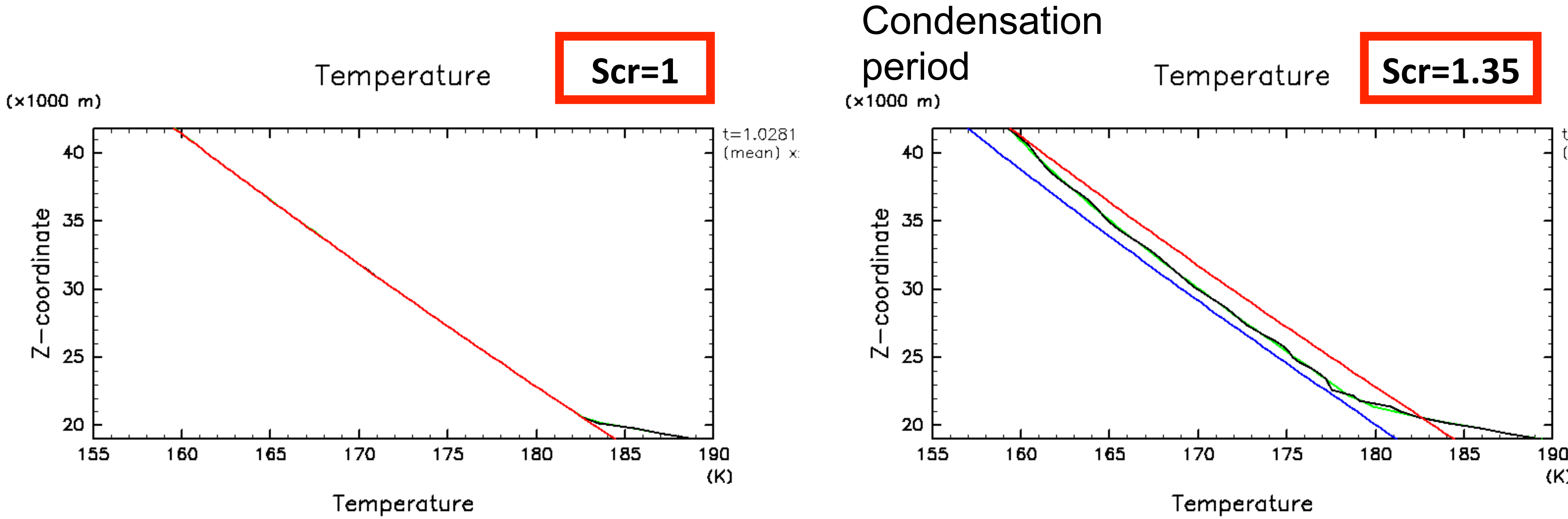
Time scale of gravitational settling and cooling determines period of solution

- Time scale of gravitational settling ~ (10000 m) / (0.1m/s) ~ 1.0e5 s
- Time scale of cooling ~ (2 K) / (0.1 K/ day) ~ 2.0e6 s
- The period ~ 1.5e6 s



Our study supports Colaprete et al.(2003)

- In the condensation period, mean temperature profile become supersaturated
  - When condensation occurs in ascent region, the difference of temperature of ascent region and mean temperature occurs, and air parcel can obtain buoyancy



Black: Temperature of ascent region, Green: mean temperature, Red: Saturation temperature, Blue: Temperature of S=1.35

Summary

- We obtain statistical equilibrium and quasi-periodic solutions
  - Scr=1.0: Statistical equilibrium solutions
  - Scr=1.35: Quasi-periodic solutions except for case of high N*
- Statistical equilibrium solutions
  - Cloud layer forms between 20 km and 50 km altitude
  - Most of cloud mass is distributed near the condensation level
  - Vertical velocity in cloud layer is much smaller than those below the condensation level, and is 0.5 m/s at a maximum
- Quasi-periodic solutions
  - Condensation and non-condensation periods occur alternately
  - Condensation period: vertical velocity of 2-3m/s in the cloud
  - Non-condensation period: wispy cloud layer, small velocity (<0.5m/s) in the cloud layer