# A numerical study on convection of a condensing $CO_2$ atmosphere under an early Mars like condition

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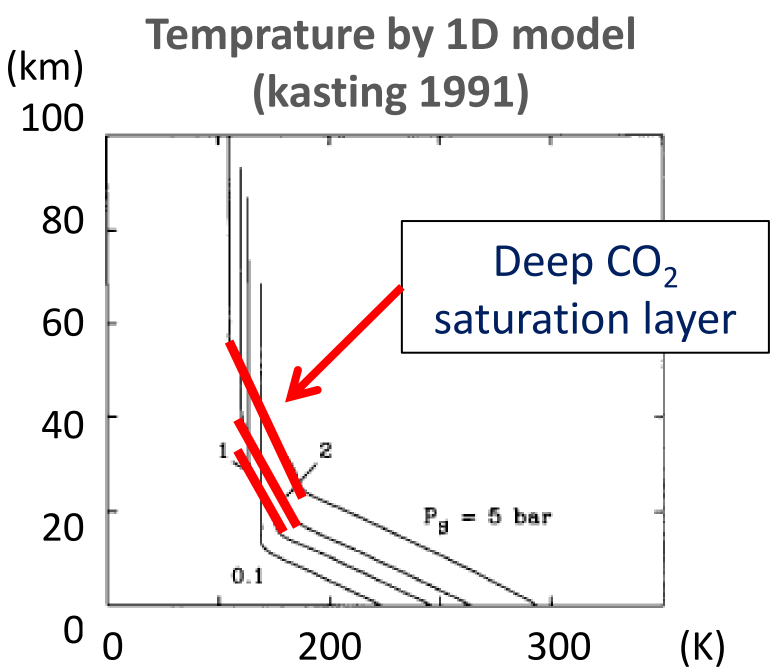
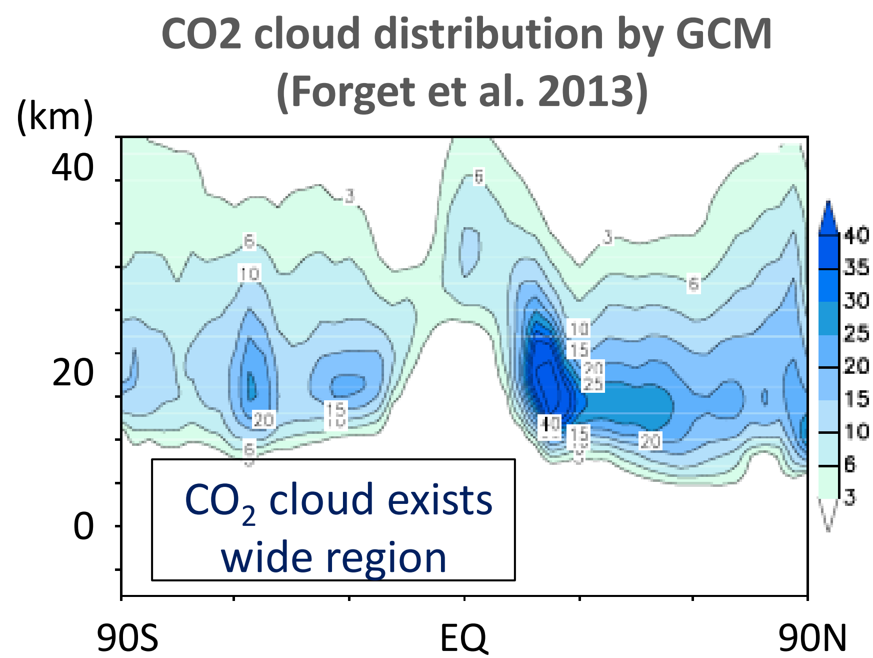
# Warm climate and $CO_2$ ice cloud in Early Mars

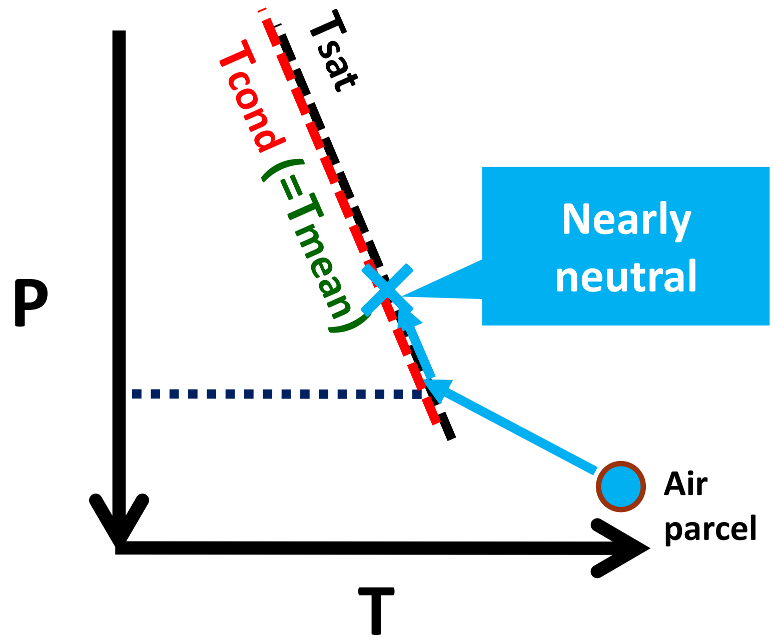
- Major atmospheric component, $CO_2$, condenses, and the ice clouds are widely distributed.
- In Early Martian climate study, <u>stratiform cloud</u> is assumed.
  - The nature of convective $CO_2$ cloud is not studied well.

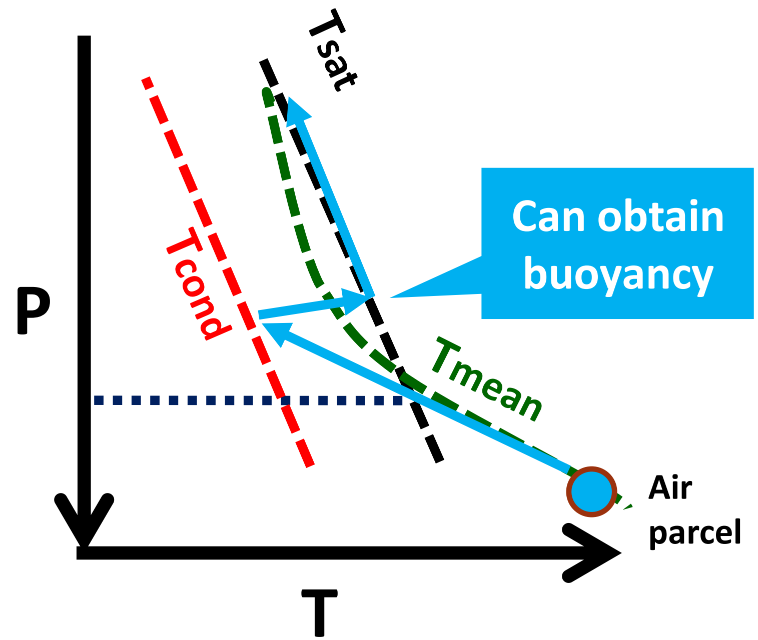


# Condensation convection of $CO_2$ and cloud type
(Colaprete et al. 2003)

- Whether supersaturation is allowed or not is key point.
  - No: Stratiform cloud Yes: Convective cloud




- However, circulation features and cloud distribution due to condesation convection of $CO_2$ are not examined.
  - Results of Colaprete et al.(2003) is based on 1D cloud model.

# The purpose of this study

- We investigate circulation features and cloud distribution associated with condensation convection of $CO_2$ under Early Mars condition
  - Use 2D cloud resolving numerical model, implemented $CO_2$ ice cloud physics considering supersaturation
  - Perform long-term numerical simulations until statistical equilibrium states are reached.

- In this presentation…
  - We show dependencies of critical saturation ratio(Scr) on the circulation features and cloud distribution.
    - Scr is the saturation ratio for the onset of condensation.

# Outline of numerical model

- Dynamics: 2D Quasi-compressible fluid
  - Pure $CO_2$ atmosphere and its condensation is considered
- $CO_2$ ice cloud microphysics (Tobie et al. 2003)
  - Diffusional growth, gravitational settling of cloud particles
  - Number density of condensation nuclei is constant
- Radiation
  - Only IR is considered, given as a horizontal uniform cooling
- Surface  flux (Louis, 1979)
  - Estimated from bulk formula with fixed surface temperature
- Subgrid scale turbulence (Klemp and Wilhelmson, 1978)
  - Turbulent flux is calculated by using urbulent kinetic energy.

# Governing equations

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

**Momentum equation:**

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

**Pressure equation:**

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

**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:**

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

**Condensation /evaporation term**

$\mathbf{u} = (u, w)$ : Velocity, $\theta$ : Potential temperature,
$\Pi$ : The Exner function, $\rho$ : Density of vapor,
$\rho_s$ : 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,
$\mathbf{D_u} = (D_u, D_w)$, $D_\theta$, $D_{\rho_s}$ : Turbulent diffusion term,
$\mathbf{g} = (0, g)$ : Gravitational accerelation

# $CO_2$ ice cloud microphysics

- Condensation/Evaporation rate (Tobie et al., 2003)

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

  - For 1<S<Scr, condensation does not occur if cloud density is less than a threshold value
  - We assume the value of threshold as $1.0^{-6}$ kg/$m^3$

- Gravitational settling rate

$$M_{fall} = \frac{\partial}{\partial z}(\rho_s V_{term})$$

$$V_{term} = \left(1 + \frac{4}{3}K_n\right)\frac{2r^2 g \rho_I}{9\eta}$$

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

$p$ : Pressure $\quad p_*$ : Saturation vapor pressure

$\rho$ : Gas density $\quad \eta$ : viscosity coefficient

$N*$ : Number density of condensation nuclei

$r$ : Radius of cloud particle $\quad \rho_I$ : CO2 ice density

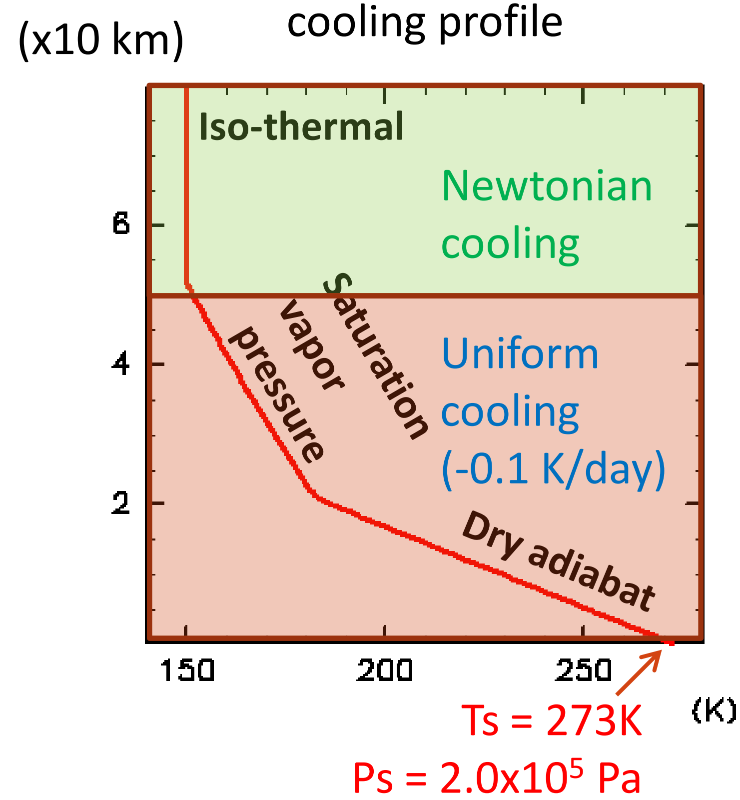
$Kn$ : Knudsen number for cloud particle

$k$ : Thermal diffusion coefficient $\quad R$ : Gas constant

# Setup of experiments

- Domain size:
  - 100km in horizontal direction (grid spacing: 500m)
  - 80km in vertical direction (grid spacing: 400m)
- Initial temperature and cooling profile
  - Based on Kasting (1991)

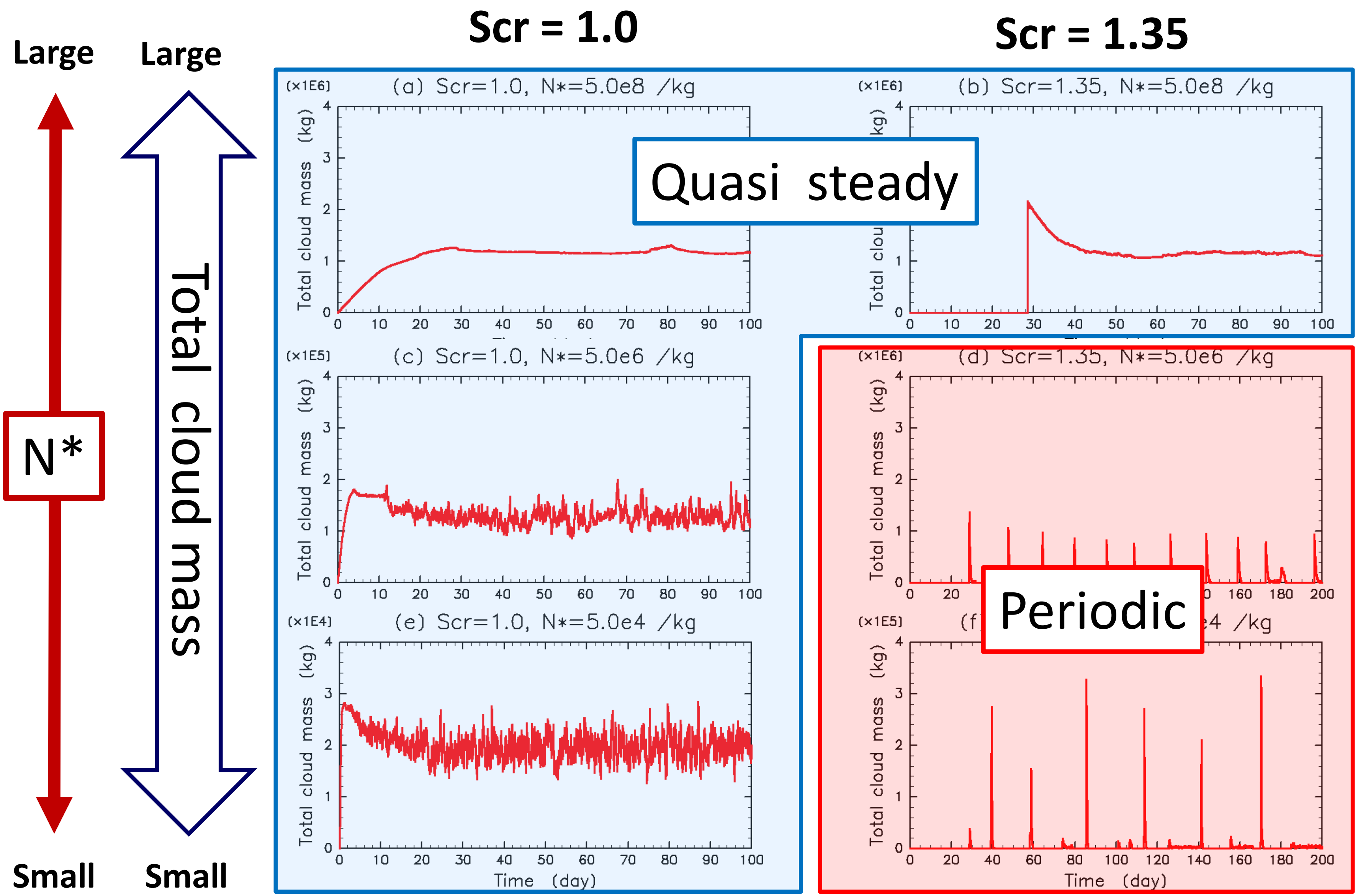
Initial temperature and cooling profile




- Critical saturation ratio (Scr): 1.0, 1.35
  (Glandorf et al., 2002)
- Number density of condensation nuclei (N*): 5.0x10$^4$, 5.0x10$^6$, 5.0x10$^8$ /kg
  (Tobie et al.,2003: Forget et al., 2013)

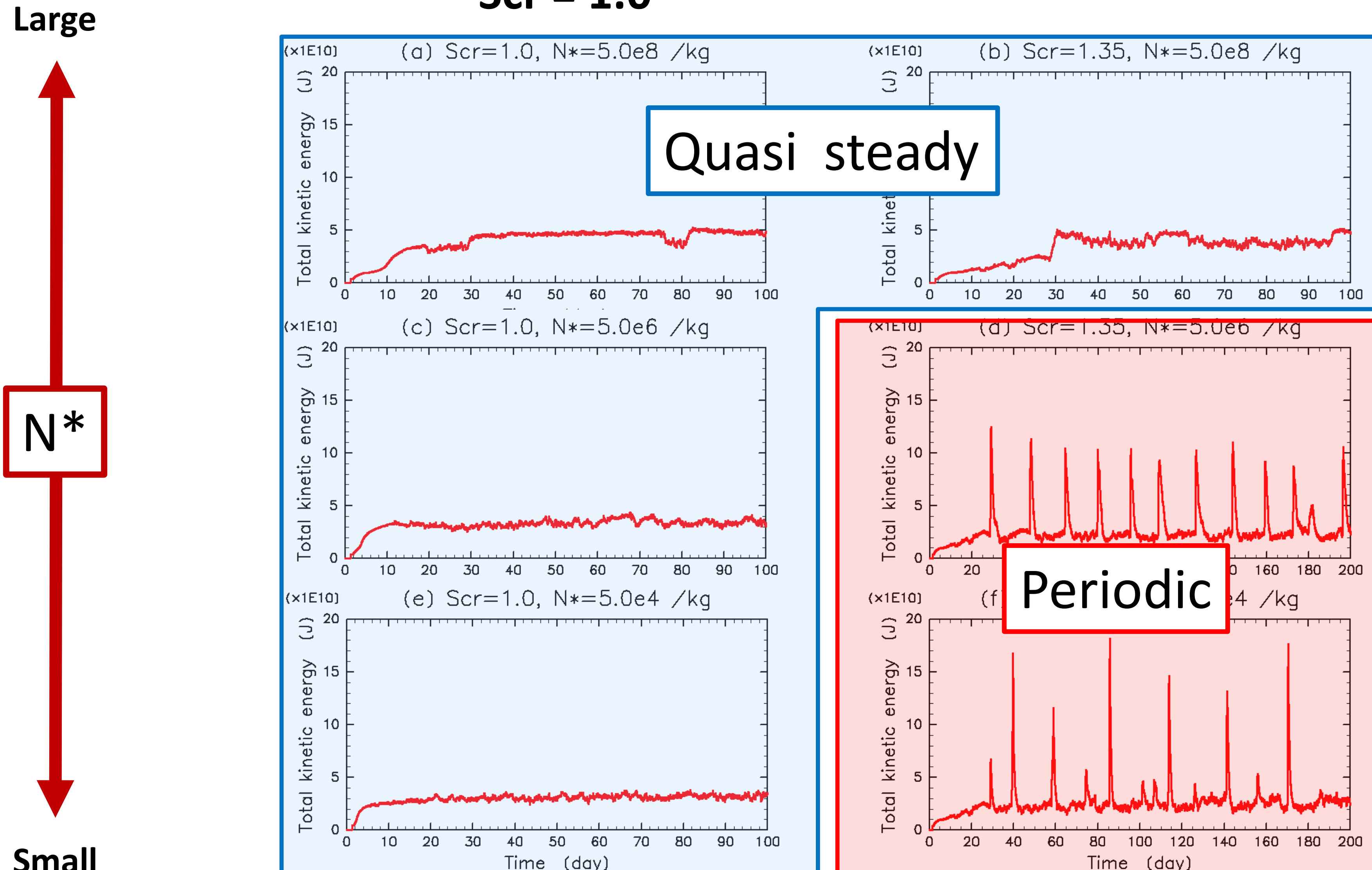
# Results

# Parameter dependence: time evolution of total cloud mass



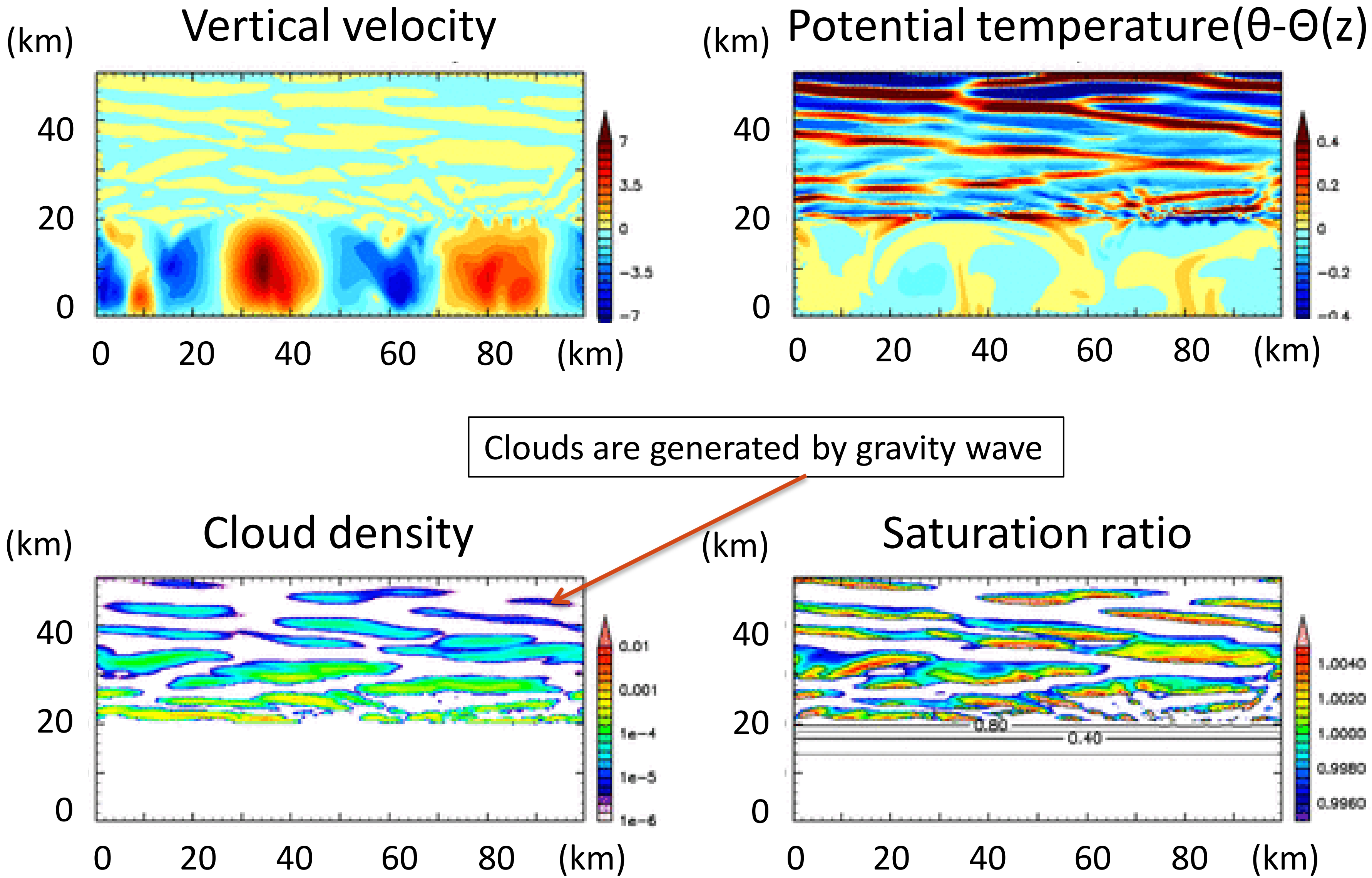
# Parameter dependence: time evolotion of total kinetic energy

**Scr = 1.0**



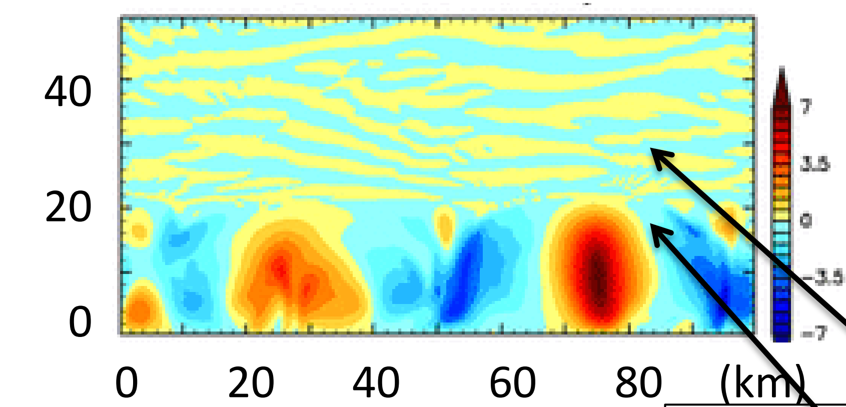
# Circulation features and cloud distribution: Scr=1.0

(100 days)

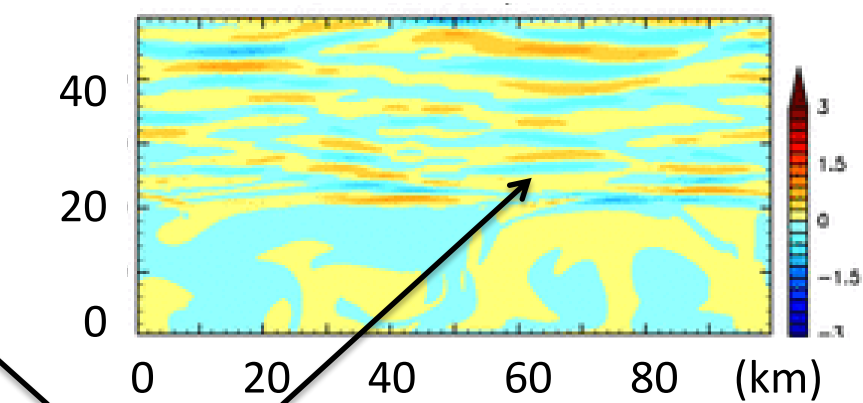


# Circulation features and cloud distribution: Scr=1.35
(143 days)

## Vertical velocity



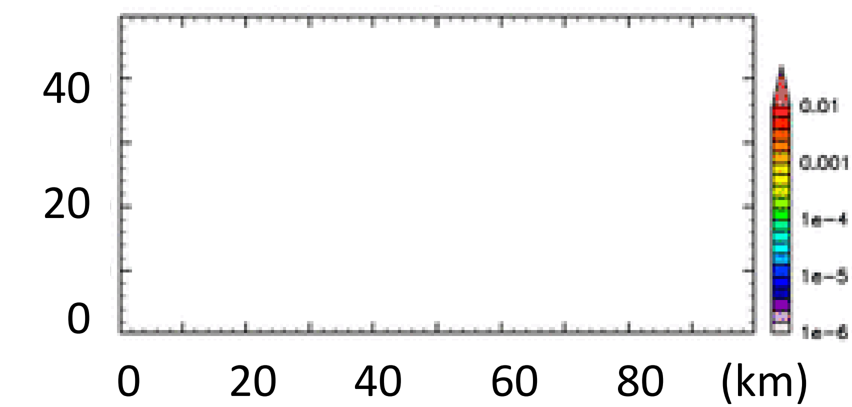

## Potential temperature(θ-Θ(z))



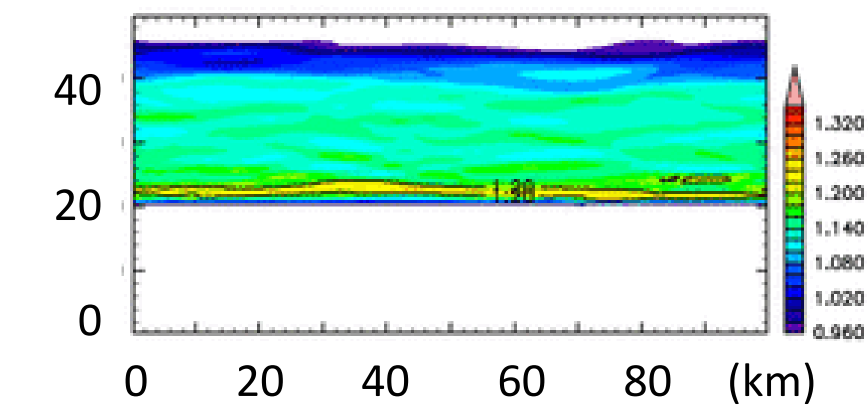

Buoyancy flow occurs above condensetion region

The dry convection is activated due to evaporation cooling of dropped cloud particle

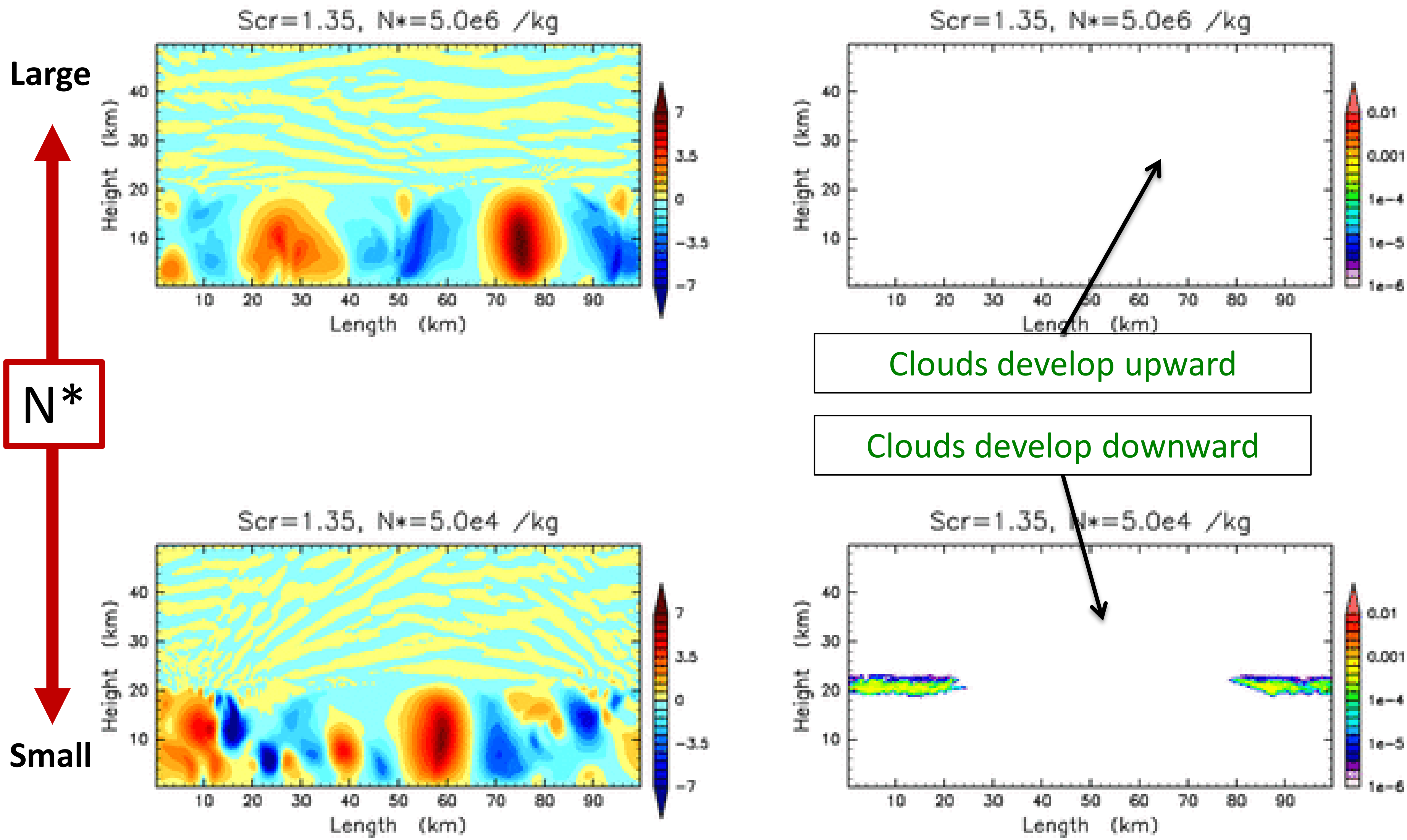
## Cloud density




## Saturation ratio



# Dependency of number density of condensation nuclei: Scr=1.35



# Estimation of radius of cloud particles and cloud optical depth

| $S_{cr}$ | $N_*$ ($kg^{-1}$) | radius of cloud particles($\mu m$) | | | optical depth | | |
|---|---|---|---|---|---|---|---|
| | | all | non cond. | cond. | all | non cond. | cond. |
| 1.0 | $5.0 \times 10^4$ | 35 | – | – | 5 | – | – |
| 1.0 | $5.0 \times 10^6$ | 15 | – | – | 70 | – | – |
| 1.0 | $5.0 \times 10^8$ | 5 | – | – | 1500 | – | – |
| 1.35 | $5.0 \times 10^4$ | 5 | 5 | 30 | 1 | 0.5 | 10 |
| 1.35 | $5.0 \times 10^6$ | 2 | 0.1 | 10 | 15 | 0.01 | 100 |
| 1.35 | $5.0 \times 10^8$ | 5 | – | – | 1500 | – | – |

- Suitable combination of cloud particle radius and optical depth for “scattering green house effect” does not occur.
  - The estimation of optical depth is following to Petty (2006)
  - The scattering green house effect is effective when **cloud particle radius is 10 µm and its optical depth is about 10.**

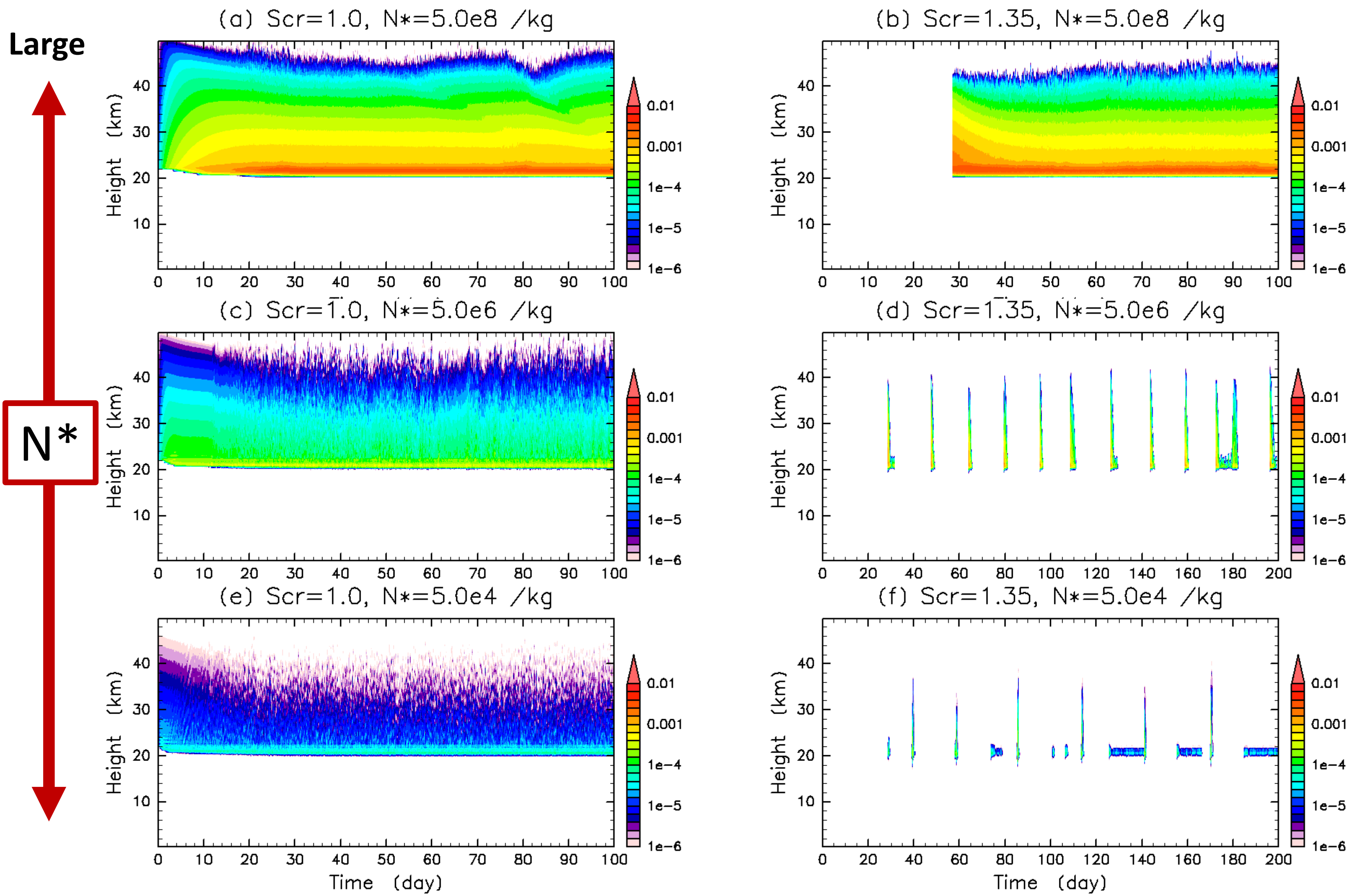
# Concluding remarks

- Circulation features and cloud distributions associated with condensation convection of $CO_2$ vary greatly with the values of Scr.
- Scr=1.0: No supersaturation case
  - Condensation occurs continuously
  - Stratiform clouds is generated by gravity wave
- Scr=1.35: Supersaturation case
  - Non-condensation and condensation periods occur alternately
  - In condensation periods, convective clouds forms
- Note: In any cases, suitable combination of cloud particle radius and optical depth for scattering green house effect does not occur.

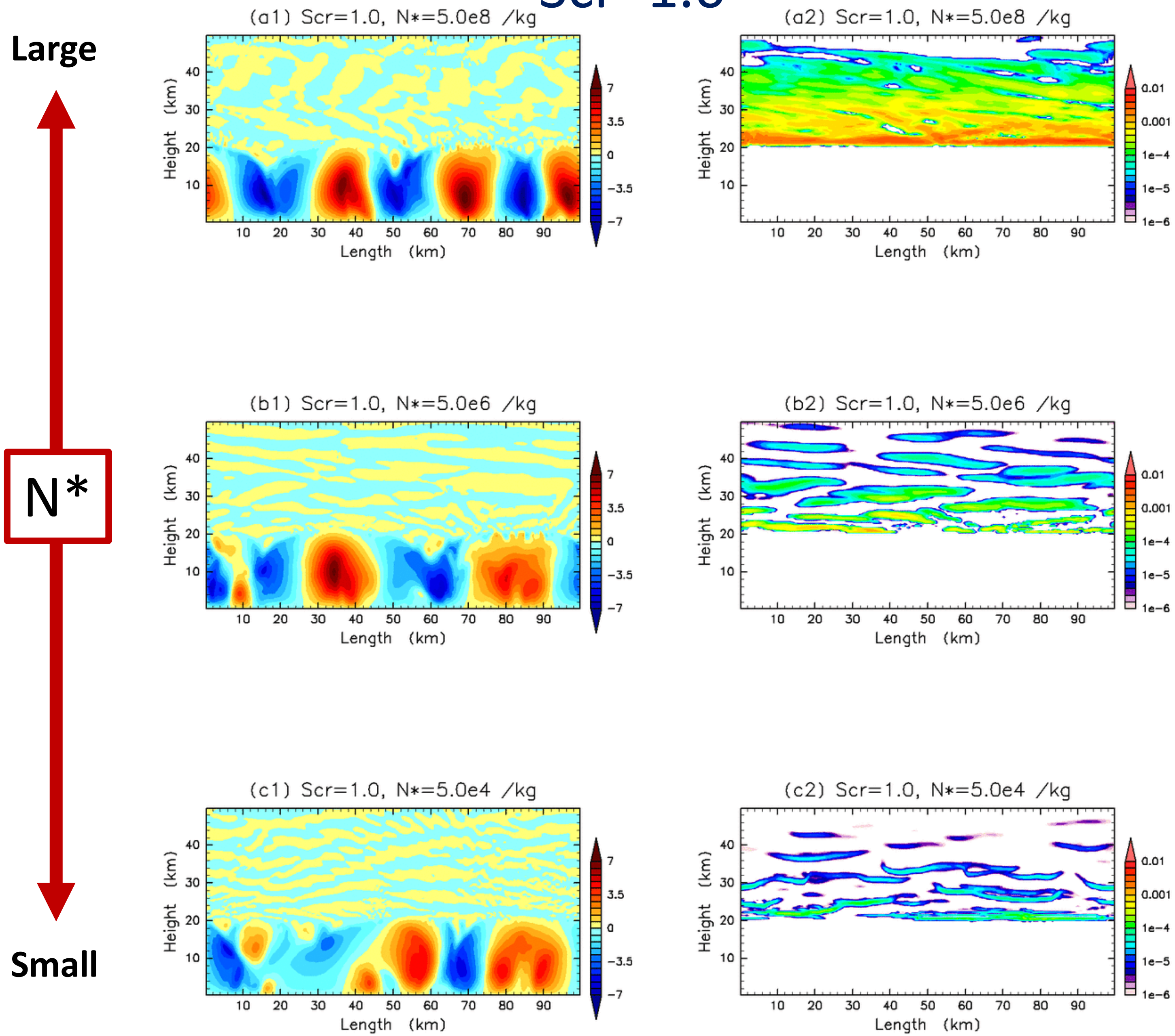
This study is submitted to Journal of the Atmospheric Sciences.

# Appendices

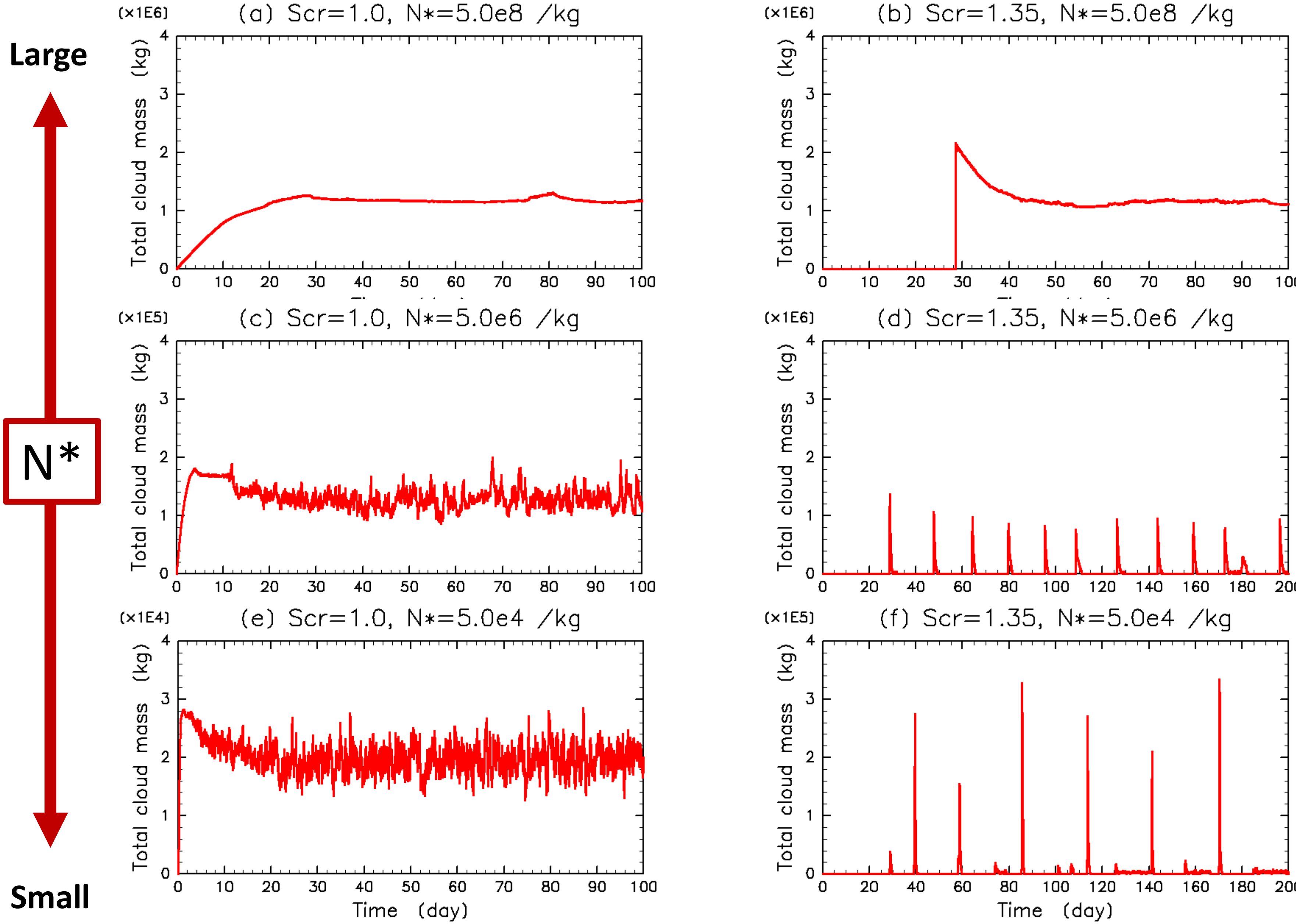
# Horizontal mean cloud distribution



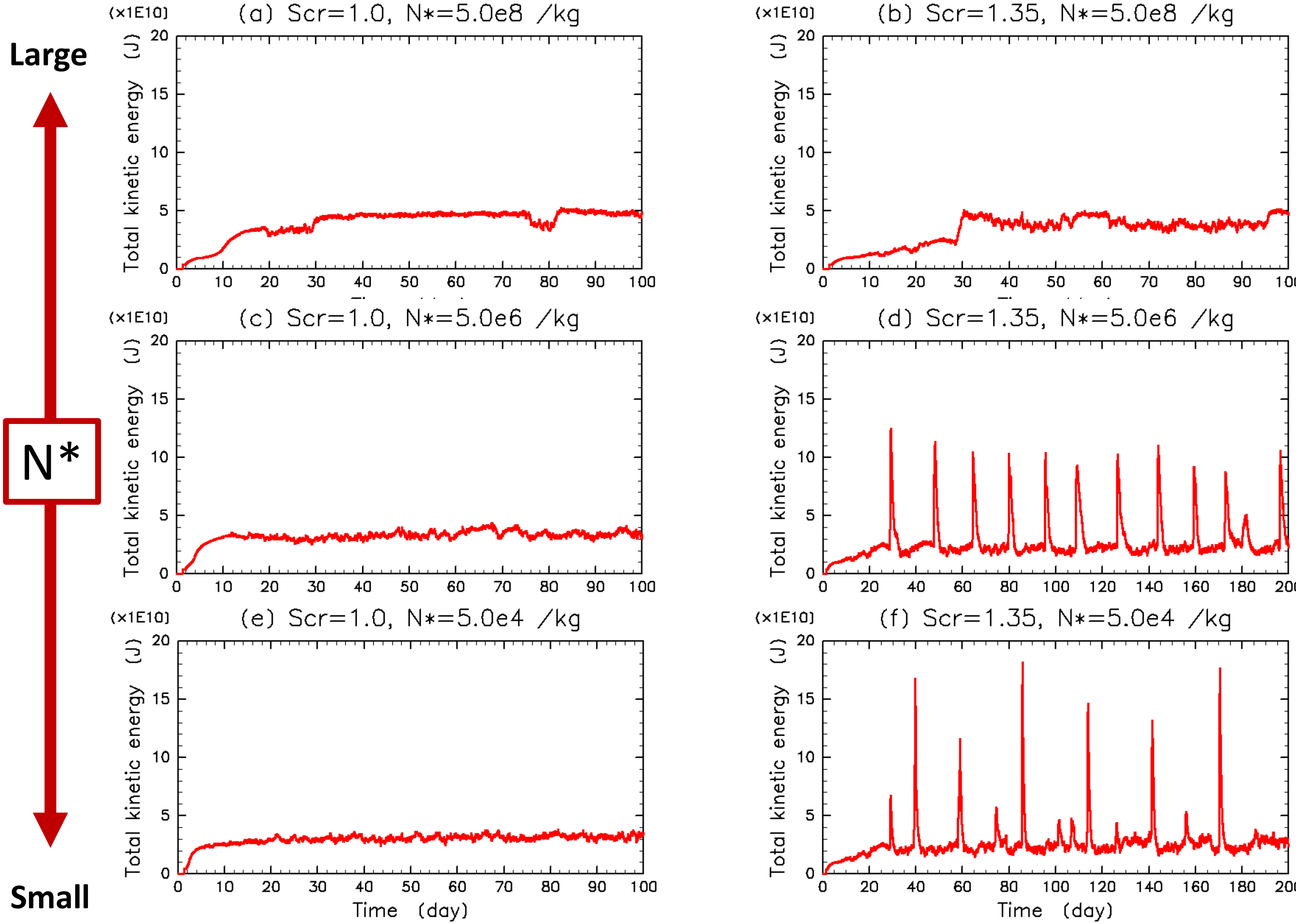
# Dependency of number density of condensation nuclei: Scr=1.0



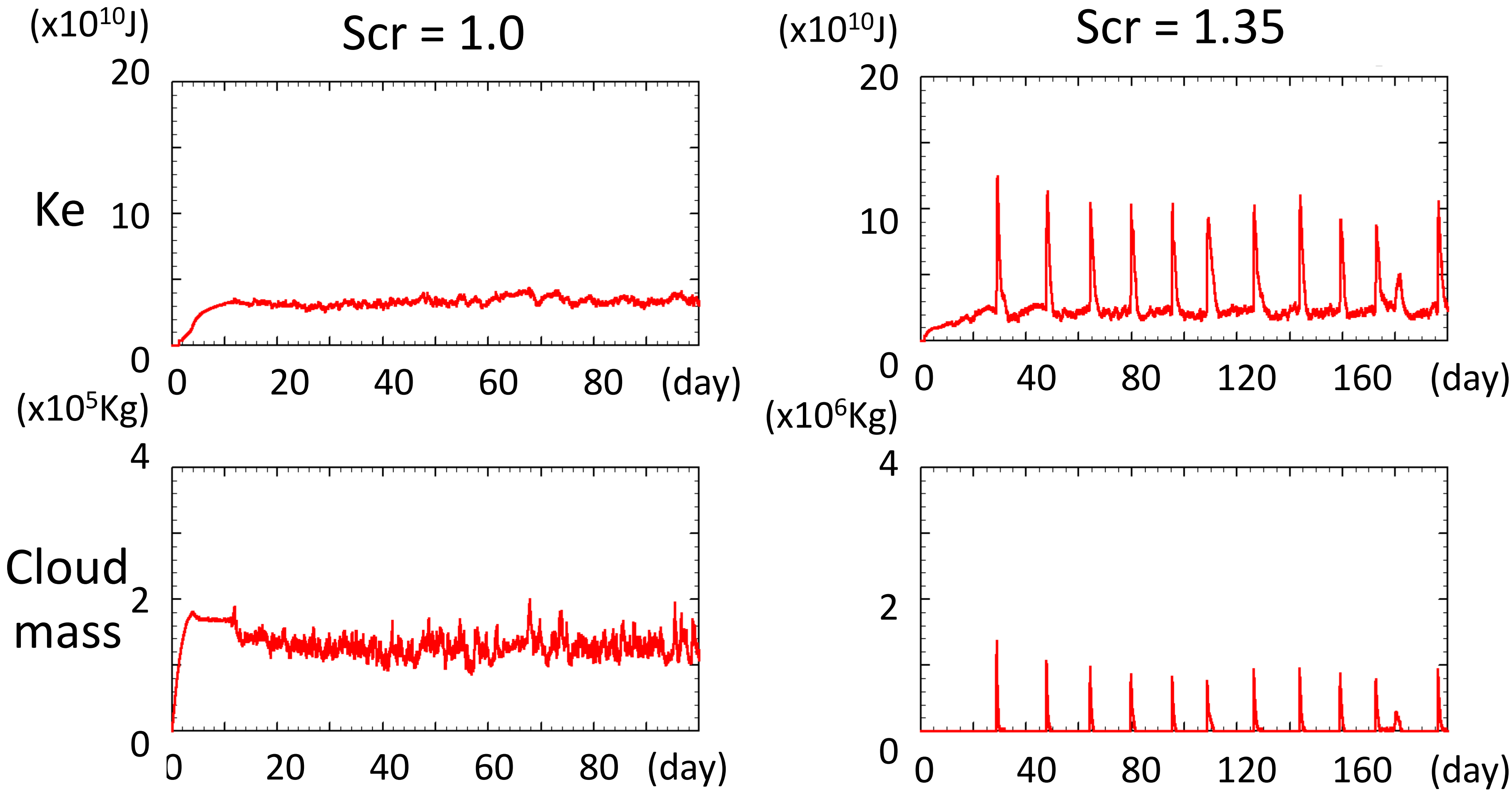
# Total cloud mass



# Total kinetic energy



# Total kinetic enregy and cloud mass

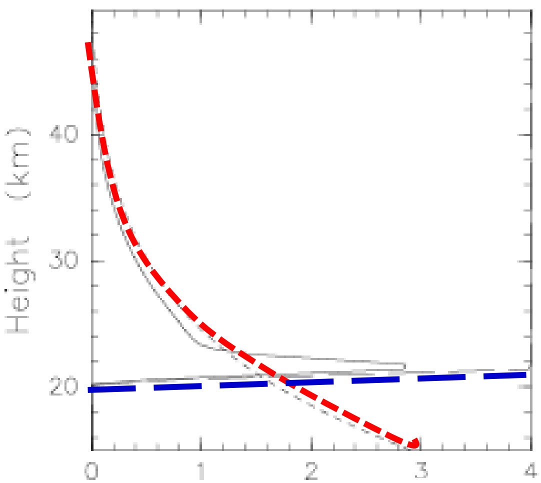



Total energy and cloud mass
are quasi-steady

non-condensation and
condensation periods
occur alternately

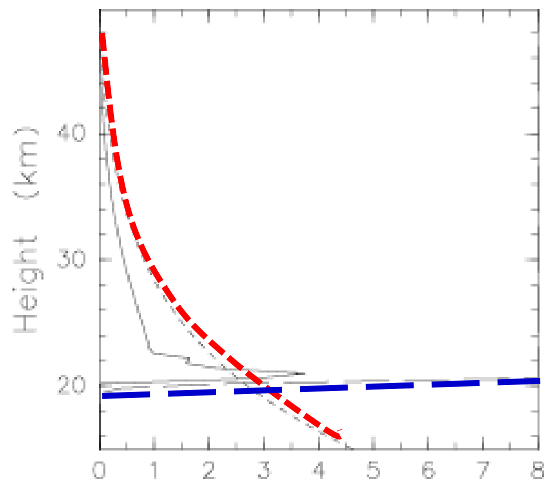
# Vertical profiles of cloud mass density in no supersaturation case

$N^* = 5.0 \times 10^8\ kg^{-1}$



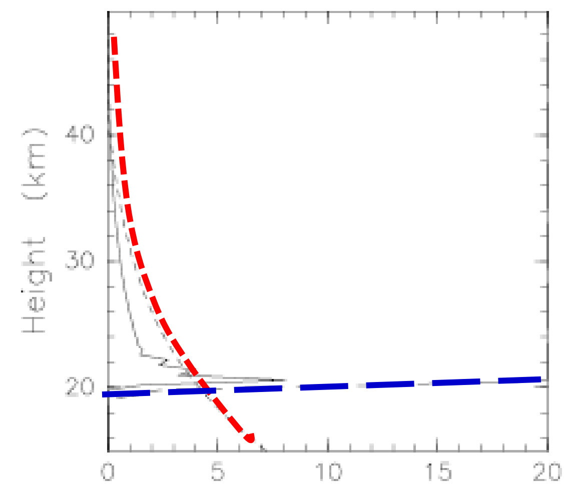

$(\times 10^{-3}\ kg\ m^{-3})$

$N^* = 5.0 \times 10^6\ kg^{-1}$




$(\times 10^{-4}\ kg\ m^{-4})$

$N^* = 5.0 \times 10^4\ kg^{-1}$




$(\times 10^{-5}\ kg\ m^{-5})$

- Vertical profiles of cloud mass density is determined by
  - In the Uppper part: balances between radiative cooling and condensation heating, and condensation rate and gravitational setteling (red dot line)
  - In the lower part: conservation of liquid water static energy (blue dush line)