Deepconv, A Numerical Model for Moist Convection in Planetary Atmosphere

K. Sugiyama, M. Odaka, T.Yamashita,
K. Nakajima, Y.-Y. Hayashi,
And deepconv development group of
GFD-Dennou-Club

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History of Deepconv

- anelastic, mass stream function
    - Nakajima 1984-86 On the Earth's convective clouds
- anelastic, pressure eq
    - Nakajima 1989-94 On the Earth's convective clouds
    - Nakajima 1995-2000 application to Jupiter's H2O cloud
    - Nakajima 1998 'generic' convections with phase change in GFD
    - Odaka 1998-2002 application to dry convection on Mars

- Thermochemical package ("Oboro")
    - Sugiyama 2006, for Jupiter's H2O, NH3, NH4SH clouds
- Quasi-compressible eq. ("Arare")
    - Sugiyama 2009, on Jupiter's convective clouds
    - Odaka 2005- on Mars's convection
    - Yamashita -2015 CO2 condensation cloud on ancient Mars

Basic equations (1)

Equations of Motion

$$
\begin{aligned}
\frac{\partial u}{\partial t} &= -\left((\bar{u}+u)\frac{\partial u}{\partial x}+(\bar{v}+v)\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z})\right)-w\frac{\partial \bar{u}}{\partial z} \\
&\quad -c_{p_d}\bar{\theta}_v\frac{\partial \pi}{\partial x}+Turb.u+Turb.\bar{u} \qquad (1.1) \\
\frac{\partial v}{\partial t} &= -\left((\bar{u}+u)\frac{\partial v}{\partial x}+(\bar{v}+v)\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)-w\frac{\partial \bar{v}}{\partial z} \\
&\quad -c_{p_d}\bar{\theta}_v\frac{\partial \pi}{\partial y}+Turb.v+Turb.\bar{v} \qquad (1.2) \\
\frac{\partial w}{\partial t} &= -\left((\bar{u}+u)\frac{\partial w}{\partial x}+(\bar{v}+v)\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)-c_{p_d}\bar{\theta}_v\frac{\partial \pi}{\partial z}+Turb.w \\
&\quad +\left(\frac{\theta}{\bar{\bar{\theta}}}+\frac{\sum q_v/M_v}{1/M_d+\sum \bar{q_v}/M_v}-\frac{\sum q_v+\sum q_c+\sum q_r}{1+\sum \bar{q_v}}\right)g \qquad (1.3)
\end{aligned}
$$

Pressure Equation

$$
\begin{aligned}
\frac{\partial \pi}{\partial t} &= -\left\{\frac{\overline{C_s}^2}{c_{p_d}\bar{\theta}_v}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+\frac{\overline{C_s}^2}{c_{p_d}\bar{\rho}\bar{\theta}_v^{\,2}}\frac{\partial \bar{\rho}\bar{\theta}_v w}{\partial z}\right\} \\
&\quad -\left((\bar{u}+u)\frac{\partial \pi}{\partial x}+(\bar{v}+v)\frac{\partial \pi}{\partial y}+w\frac{\partial \pi}{\partial z}\right)+\frac{R_d\pi}{c_{vd}}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right) \\
&\quad +\frac{\overline{C_s^2}}{c_{p_d}\overline{\theta_v}}\left\{\frac{\dot{\theta}}{\bar{\bar{\theta}}}-\left(\frac{\sum \dot{q}_v+\sum \dot{q}_c+\sum \dot{q}_r}{1+\sum \overline{q_v}}.-\frac{\sum \dot{q}_v/M_v}{1/M_d+\sum \overline{q_v}/M_v}\right)\right\} \qquad (1.4)
\end{aligned}
$$

Basic equations (2)

Thermodynamic Equation

$$\begin{aligned}\frac{\partial \theta}{\partial t} &= -\left((\bar{u}+u)\frac{\partial \theta}{\partial x} + (\bar{v}+v)\frac{\partial \theta}{\partial v} + w\frac{\partial \theta}{\partial z}\right) - w\frac{\partial \bar{\theta}}{\partial x} + \frac{1}{\bar{\pi}}\left(Q_{cnd} + Q_{rad} + Q_{dis}\right) \\ &\quad + Turb.\bar{\theta} + Turb.\theta \qquad (1.5)\end{aligned}$$

Equation of state

$$\begin{aligned}\rho &= \frac{p}{R_d T}\left(\frac{1/M_d}{1/M_d + \sum q_v/M_v}\right)\left(1 + \sum q_v + \sum q_c + \sum q_r\right) \\ &= \frac{p}{R_d T_v} = \frac{p_0 \pi^{c_{vd}/R_d}}{R_d \theta_v} \qquad (1.11)\end{aligned}$$

Definition of Virtual Temperature

$$\theta_v = \frac{\theta}{\left(\frac{1/M_d}{1/M_d + \sum q_v/M_v}\right)\left(1 + \sum q_v + \sum q_c + \sum q_r\right)} \qquad (1.12)$$

Sound velocity

$$C_s{}^2 = \frac{c_{pd}}{c_{vd}} R_d \pi \theta_v \qquad (1.13)$$

Basic equations (3)

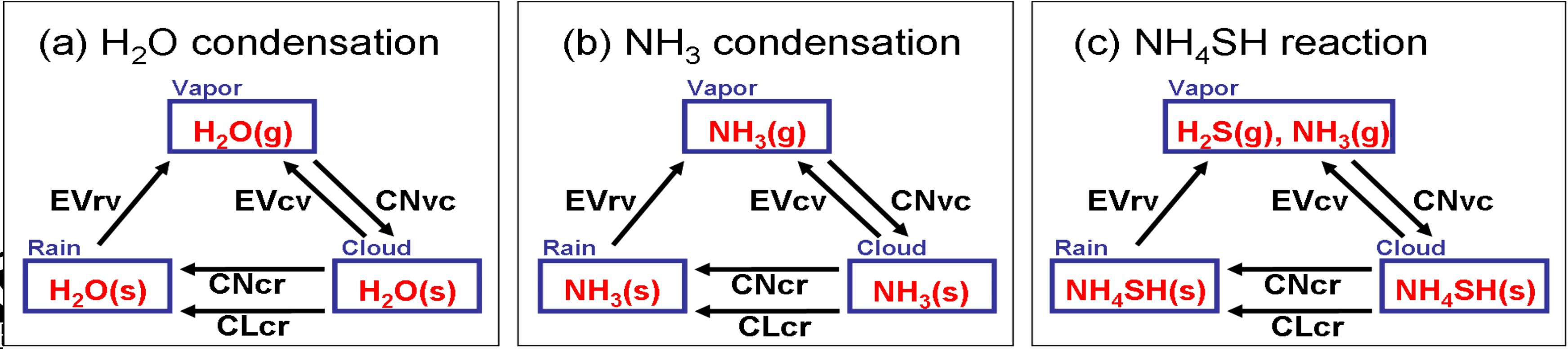
Thermodynamic eq

$$
\begin{aligned}
\frac{\partial \theta}{\partial t} &= -\left((\bar{u}+u)\frac{\partial \theta}{\partial x} + (\bar{v}+v)\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z}\right) - w\frac{\partial \bar{\theta}}{\partial x} + \frac{L}{c_{pd}\bar{\pi}}(CN_{vc} - EV_{cv} - EV_{rv}) \\
&\quad + \frac{1}{\bar{\pi}}(Q_{rad} + Q_{dis}) + Turb.\bar{\theta} + Turb.\theta \qquad (1.14)
\end{aligned}
$$

Conservation eq. for vapor, cloud, and rain

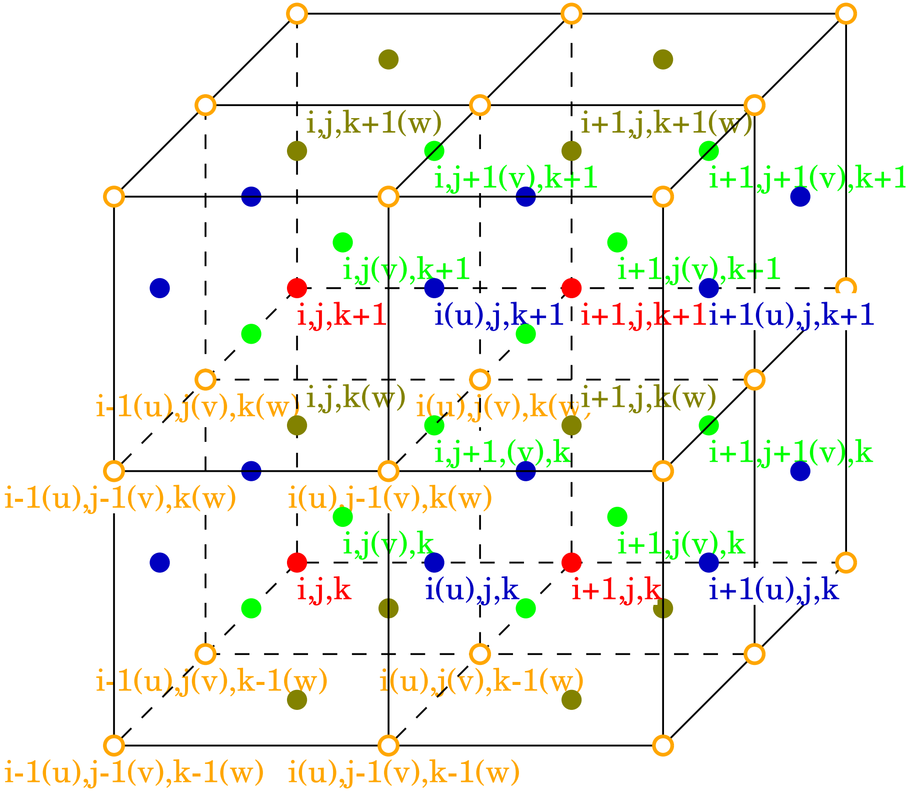
$$
\begin{aligned}
\frac{\partial q_v}{\partial t} &= -\left((\bar{u}+u)\frac{\partial q_v}{\partial x} + (\bar{v}+v)\frac{\partial q_v}{\partial y} + w\frac{\partial q_v}{\partial z}\right) - w\frac{\partial \bar{q_v}}{\partial x} - (CN_{vc} - EV_{cv} - EV_{rv}) \\
&\quad + Turb.q_v + Turb.\bar{q_v}, \qquad (1.15) \\
\frac{\partial q_c}{\partial t} &= -\left((\bar{u}+u)\frac{\partial q_c}{\partial x} + (\bar{v}+v)\frac{\partial q_c}{\partial y} + w\frac{\partial q_c}{\partial z}\right) + (CN_{vc} - EV_{cv} - CN_{cr} - CL_{cr}) \\
&\quad + Turb.q_c, \qquad (1.16) \\
\frac{\partial q_r}{\partial t} &= -\left((\bar{u}+u)\frac{\partial q_c}{\partial x} + (\bar{v}+v)\frac{\partial q_c}{\partial y} + w\frac{\partial q_c}{\partial z}\right) + (CN_{cr} + CL_{cr} - EV_{rv}) + PR_r
\end{aligned}
$$

Thermodynamic quantities are provided by Oboro (thermochemical package) automatically.

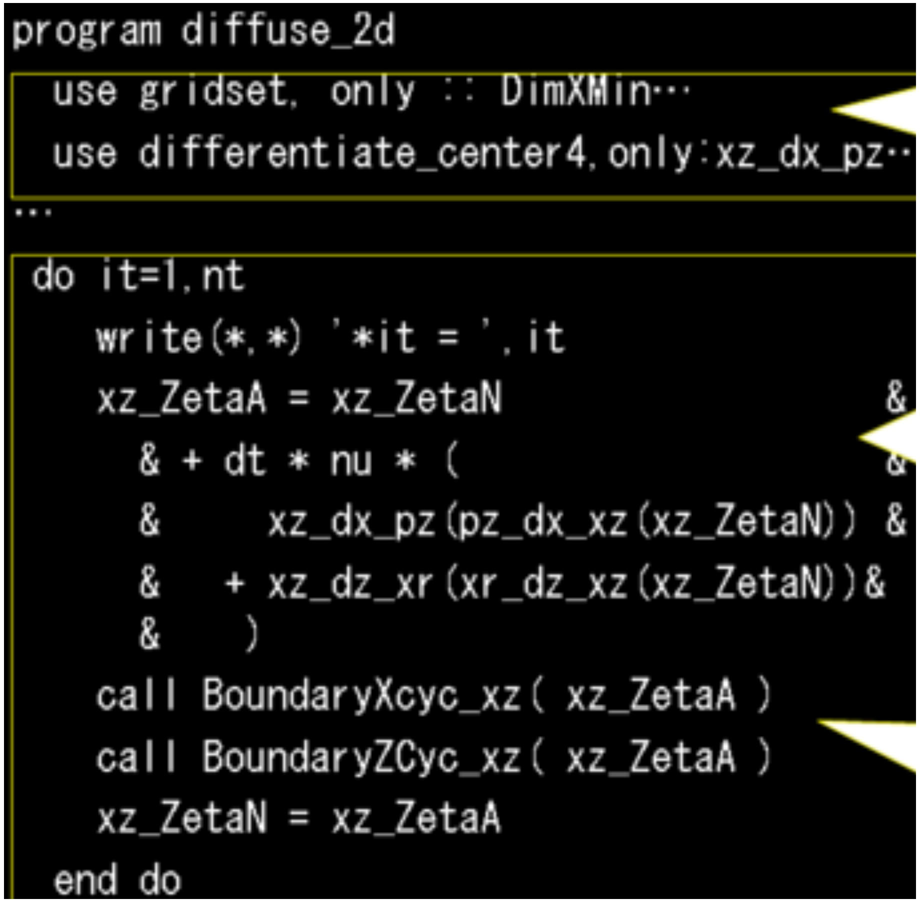


Grid configuration

- Horizontal Arakawa-C grid
- Vertical Lorenz grid
- Centered difference
  - 2nd / 4th order



Coding style : use F90 array functions



```
program diffuse_2d
  use gridset, only :: DimXMin…
  use differentiate_center4,only:xz_dx_pz…
…
 do it=1,nt
    write(*,*) '*it = ',it
    xz_ZetaA = xz_ZetaN                &
      & + dt * nu * (                  &
      &       xz_dx_pz(pz_dx_xz(xz_ZetaN)) &
      &     + xz_dz_xr(xr_dz_xz(xz_ZetaN))&
      &     )
    call BoundaryXcyc_xz( xz_ZetaA )
    call BoundaryZCyc_xz( xz_ZetaA )
    xz_ZetaN = xz_ZetaA
  end do
```

$$\pi_{i(u),j,k} \equiv \frac{\pi_{i+1,j,k} + \pi_{i,j,k}}{2}$$

$$u_{i,j,k} \equiv \frac{u_{i(u),j,k} + u_{i-1(u),j,k}}{2}$$

$\zeta \downarrow t = \nu(\partial \uparrow 2\ \zeta / \partial x \uparrow 2\ + \partial \uparrow 2\ \zeta / \partial z \uparrow 2\ )$

Back to ”moderate” way

- With extensive usage of F90 array functions, the model runs like a turtle.
  - Back to more F77 like style
  - Improve the speed by 100 times

- With extensive dependence of Oboro thermodynamic package, the model loses flexibility.
  - “molecular weight of non-condensible component” can be specified again.
  - Helpful for “mechanistic experiments.”

Example 1 : Jupiter clouds of three components: H2O, NH3, NH4SH

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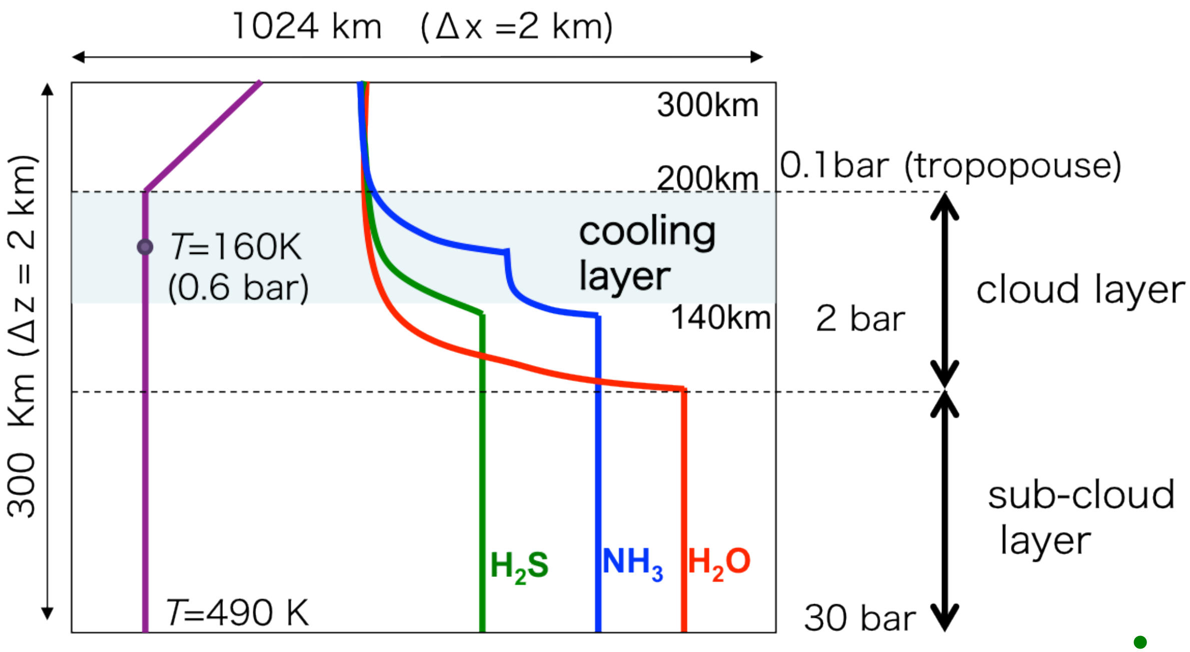
Set-up of the experiments

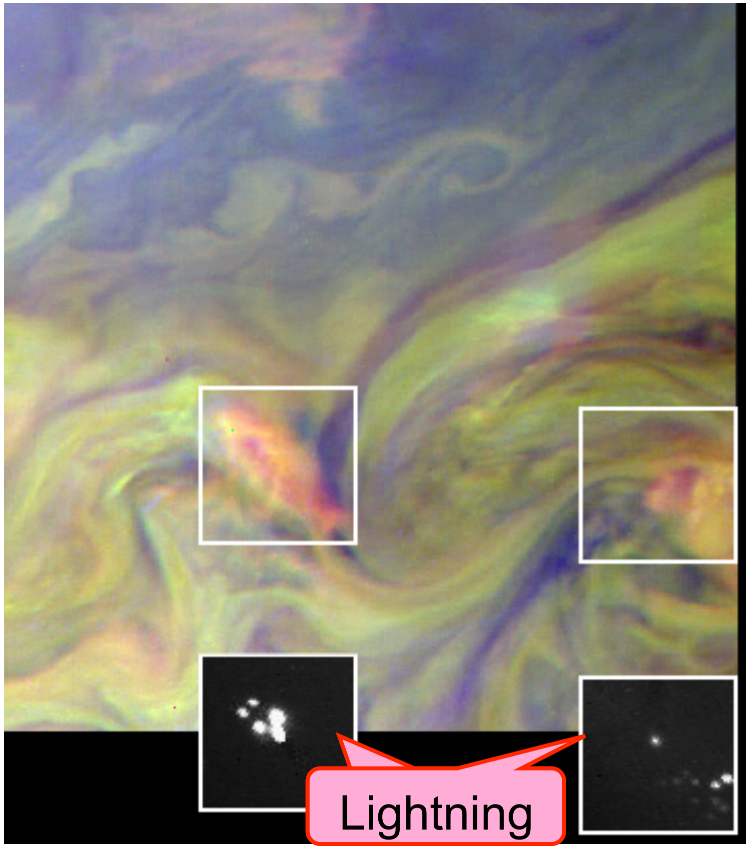


Initial potential temperature（θ）

Initial mixing ratios (1 x solar)

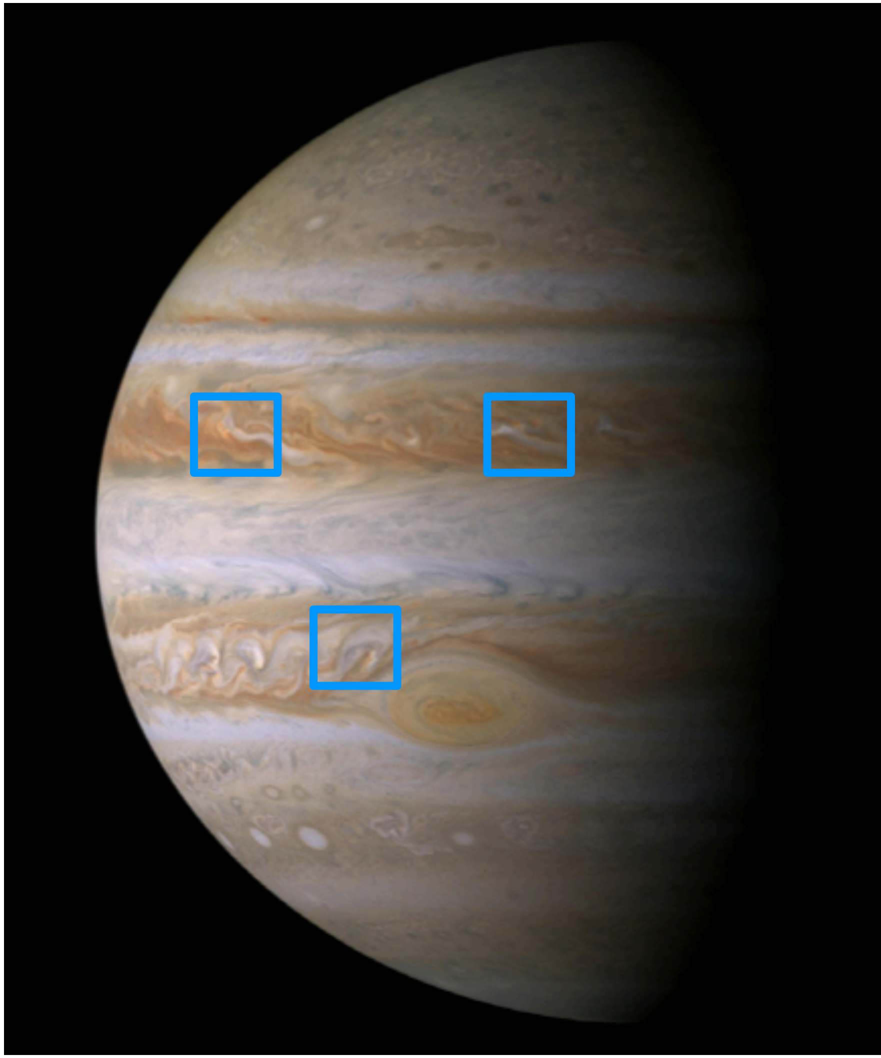
- Boundary conditions
  - Horizontal boundary is cyclic. Stress free condition and $w = 0$ are given at the lower and upper boundaries.
  - Temperature and mixing ratios of vapor at the lowest level are fixed.
- Initial condition
  - Random potential temperature perturbation ($\Delta\theta_{max} = 0.1$ K) is given to seed convective motion.

Jupiter's “Convective” clouds

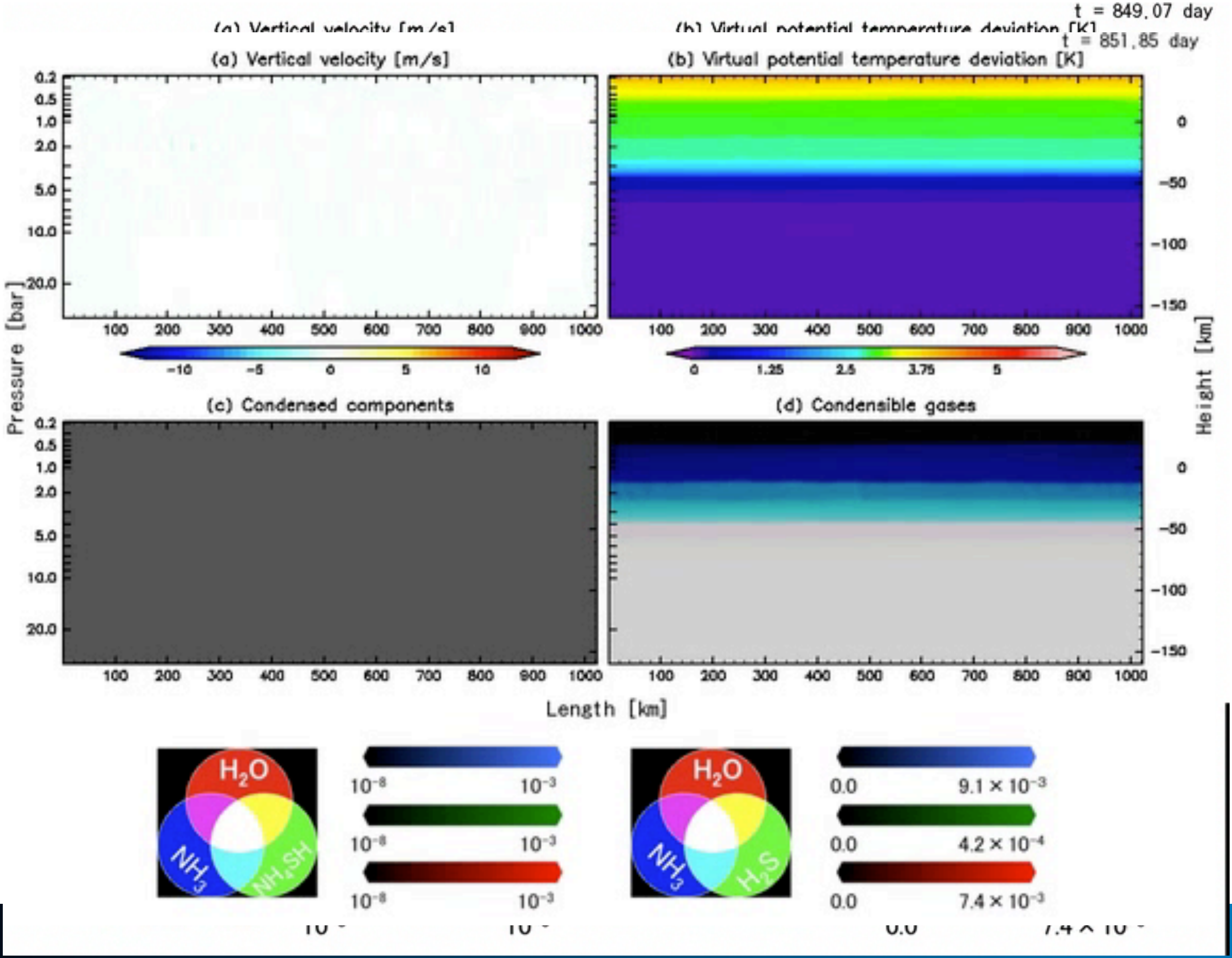


Convective clouds

(Vasavada and Showman, 2005)



Results: Animation

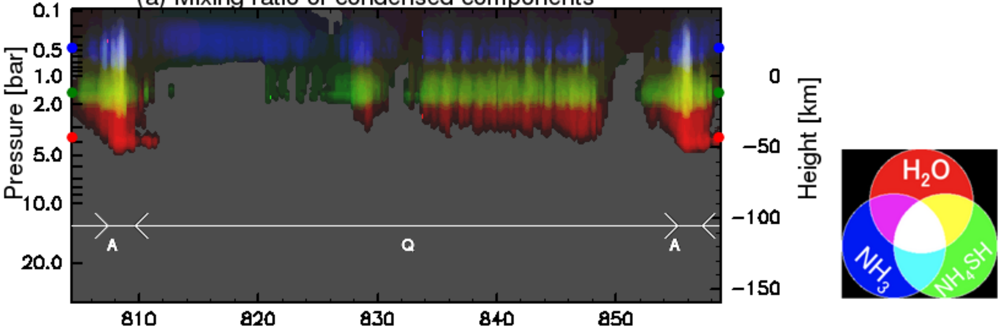


Temporal variation

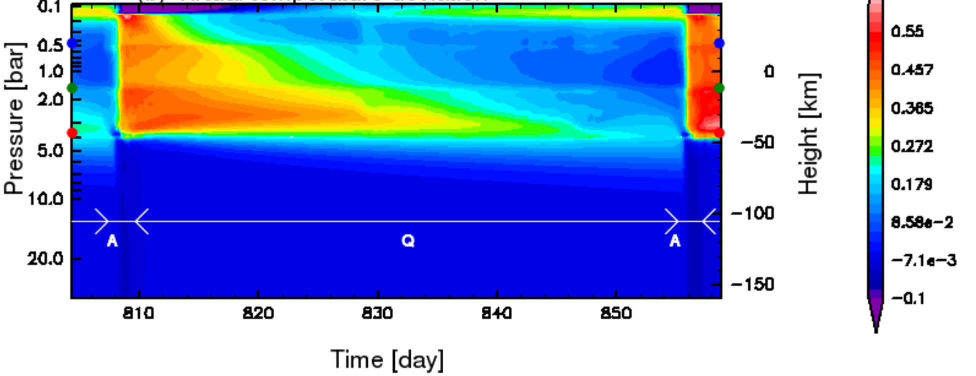
- The convective activity of the whole layer is not steady but quasi-periodic with a period of about 40 days.

- Overall temperature of the cloud layer synchronizes with the intermittent convective activity.
  - We will refer the time when the active cloud convection occurs as `active period' (A) and the other as `quiet period’ (Q).

(a) Mixing ratio of condensed components



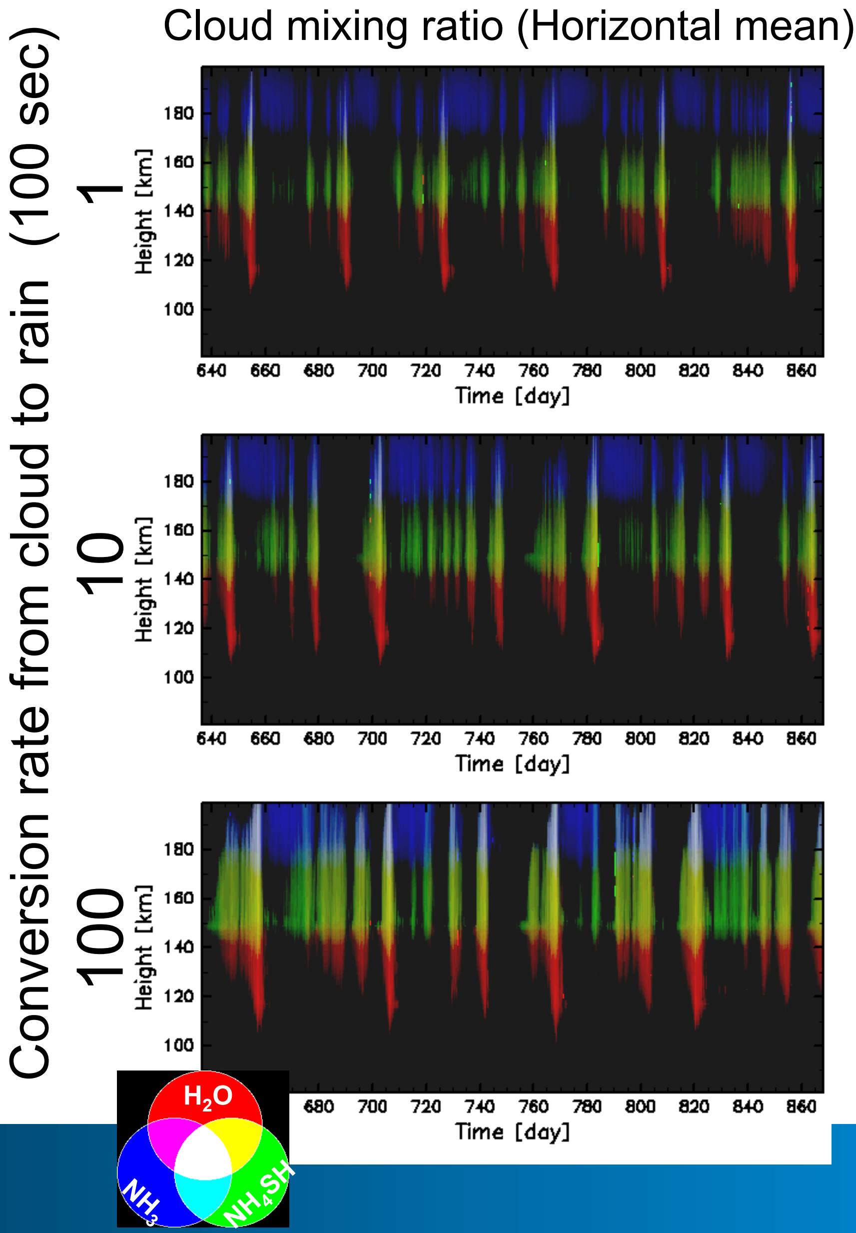
(b) Virtual temperature deviation



Period of the intermittency

- The period of the quasi-periodic cycle is about 2 times larger than that of the previous study.

Conversion rate from cloud to rain (100 sec)	period in the numerical experiment (day)	ratio
1	36.4	1
10	60.2	1.80
100	62.5	1.85


Cloud mixing ratio (Horizontal mean)

Example 2 : Mars condensation of major component (CO2)

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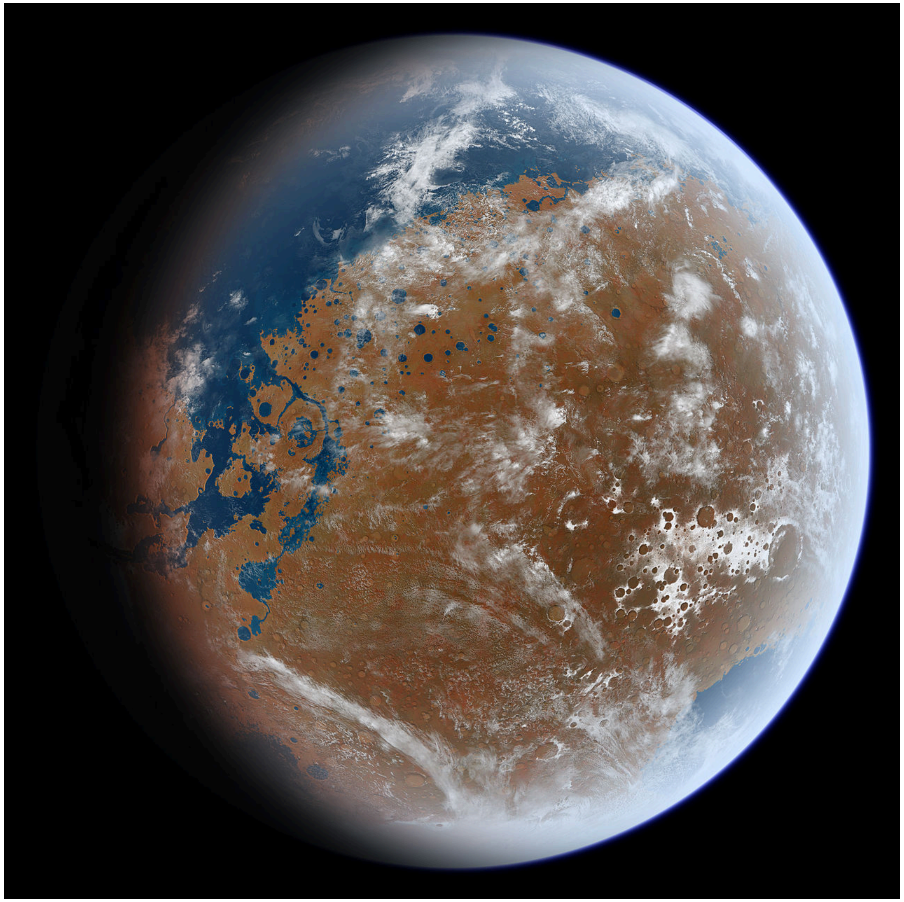
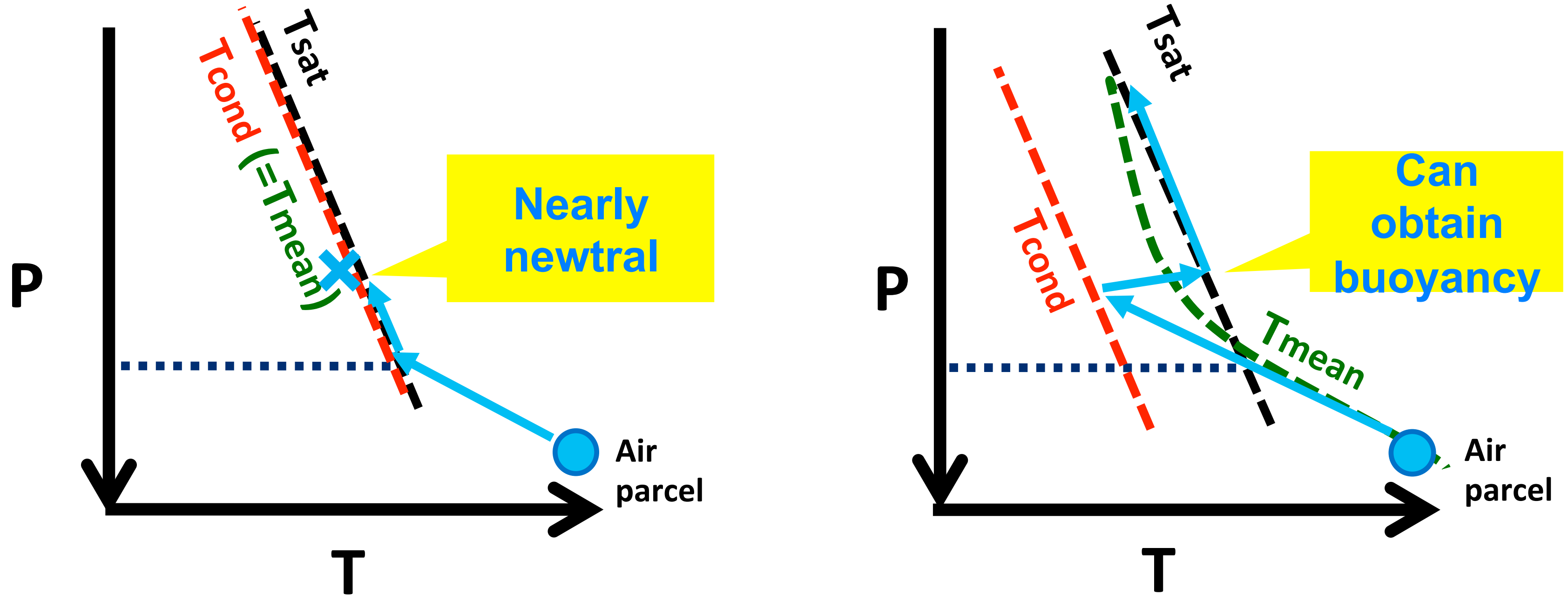
- Ancient warm and moist Mars?



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



CO_2 ice cloud microphysics

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

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

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

- **Gravitational settling rate**

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

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

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

p : Pressure p_* : Saturation vapor pressure

ρ : Gas density η : viscosity coefficient

$N*$: Number density of condensation nuclei

r : Radius of cloud particle ρ_I : CO2 ice density

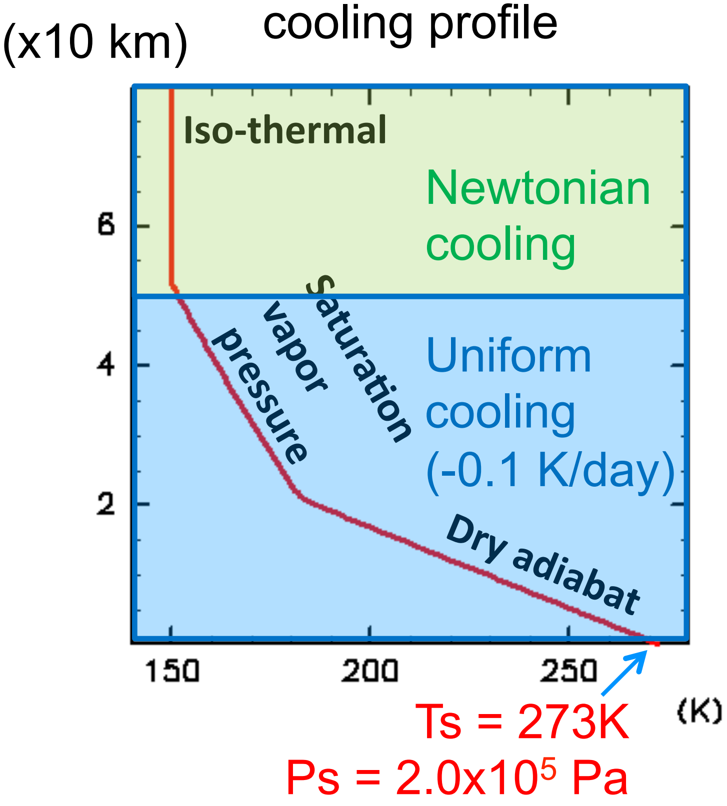
Kn : Knudsen number for cloud particle

k : Thermal diffusion coefficient R : Gas constant

Setup of experiments

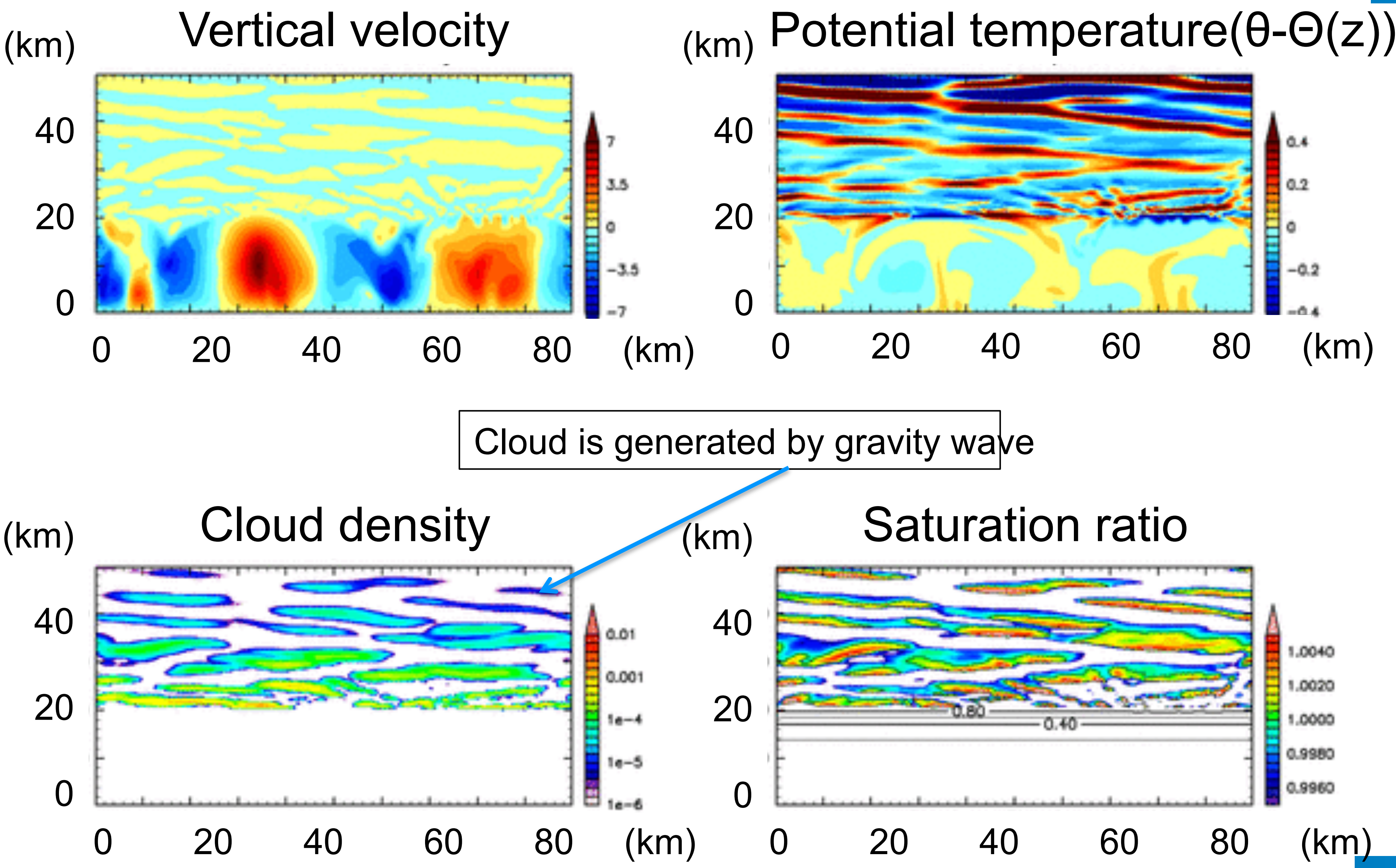
- Domain size:
  - 100km in horizontal direction (grid spacing: 500m)
  - 80km in vertical direction (grid spacing: 400m)
- Initial temperature and cooling profile
  - Based on Kasting (1991)
- Critical saturation ratio (Scr): 1.0, 1.35 (Glandorf et al., 2002)
- Number density of condensation nuclei 5.0×10^8 /kg (Tobie et al.,2003: Forget et al., 2013)

Initial temperature and cooling profile



Circulation features and cloud distribution: Scr=1.0

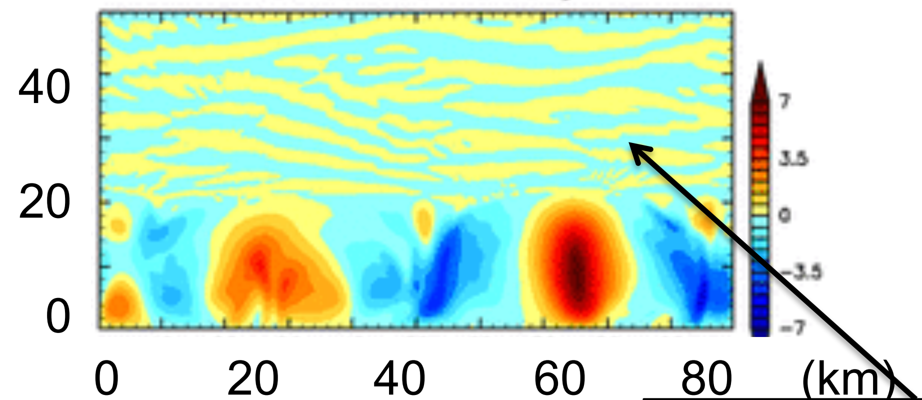
(100 days)



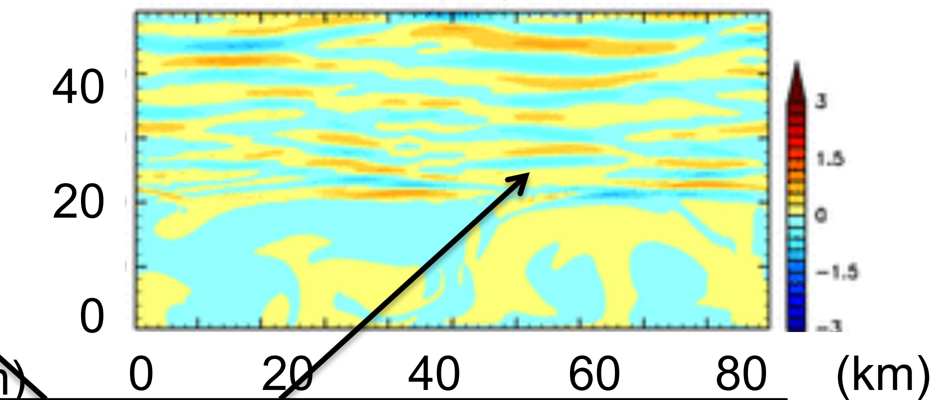
Cloud is generated by gravity wave

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

Vertical velocity



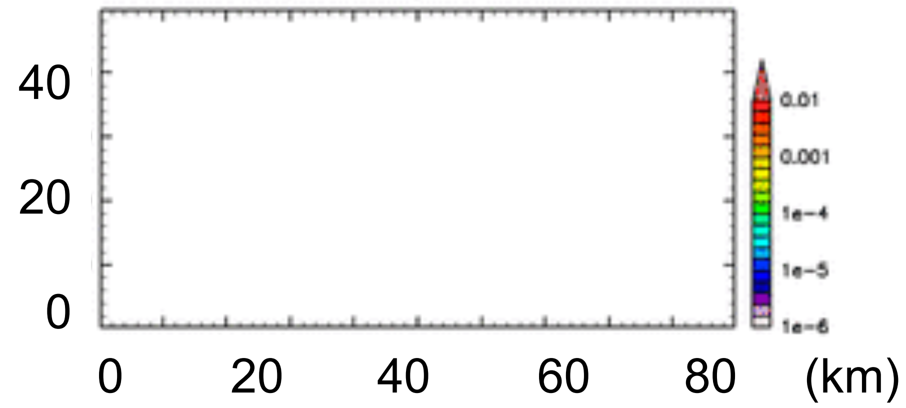
Potential temperature(θ-Θ(z))



Buoyancy flow occurs above condensetion region

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

Cloud density



Saturation ratio