Two-dimensional numerical experiments of Martian atmospheric convection with condensation of the major component

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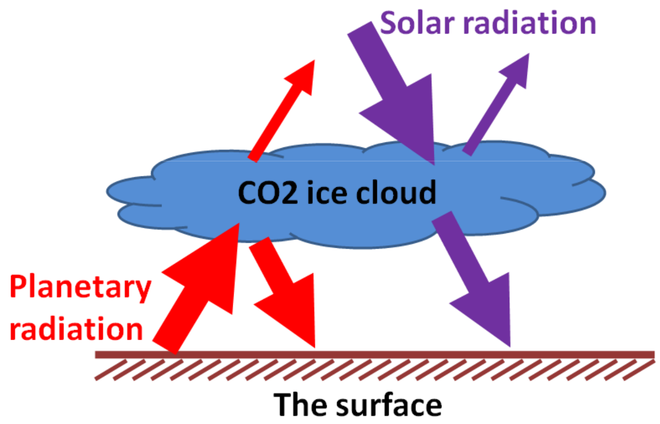
Martian atmospheric convection with condensation of the major component

- Present Martian polar region (Colaprete et al., 2003)
- Early Mars (Forget and Pierrehumbert, 1997)
  - Scattering greenhouse effect of CO_2 ice clouds may cause warm climate.

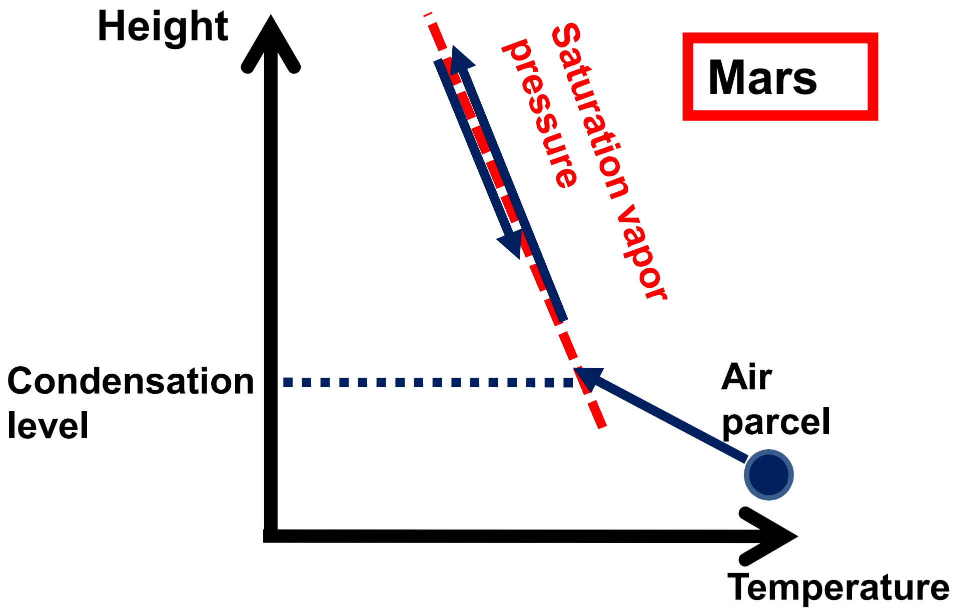
After Mitsuda(2007), Pierrehumbert and Erlick(1998)

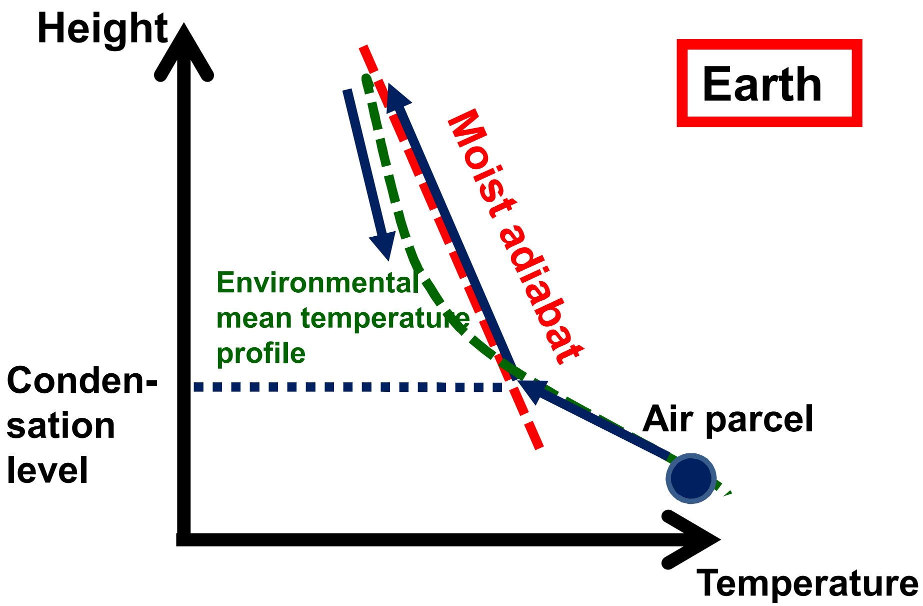


→We investigate atmospheric convection with condensation of the major component driven by a given profile of heating/cooling imitating radiative forcing.

Characteristics of convection with condensation of the major component

- Decrease of the degree of freedom for thermodynamic variables→Air parcel cannot obtain buoyancy.
  - Temperature at a given pressure level cannot deviate from the saturation value if super saturation is forbidden.
  - Temperature at ascent region must be equal to that of descent region.

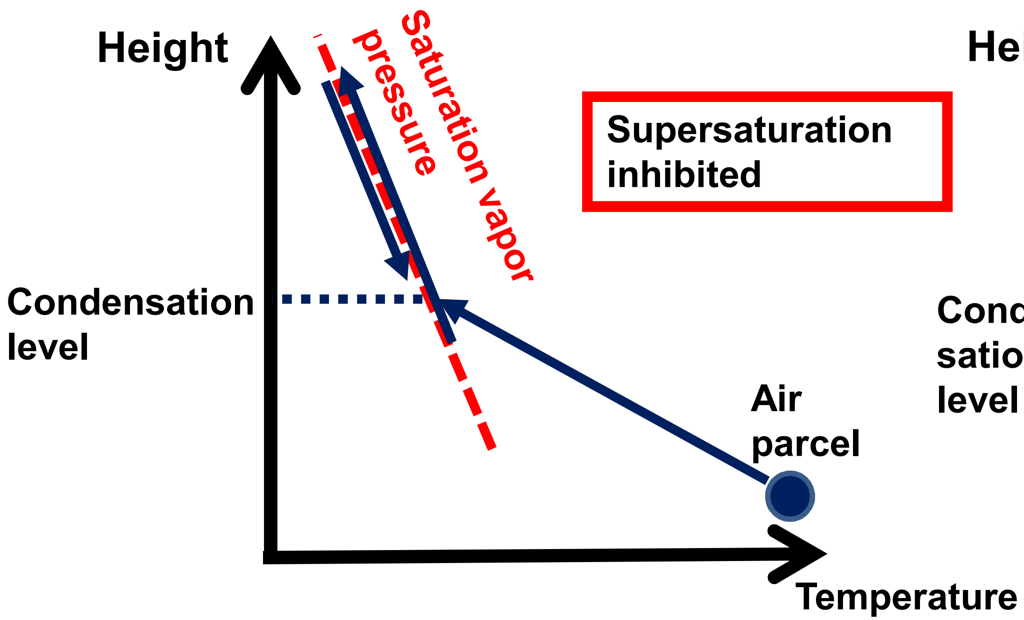


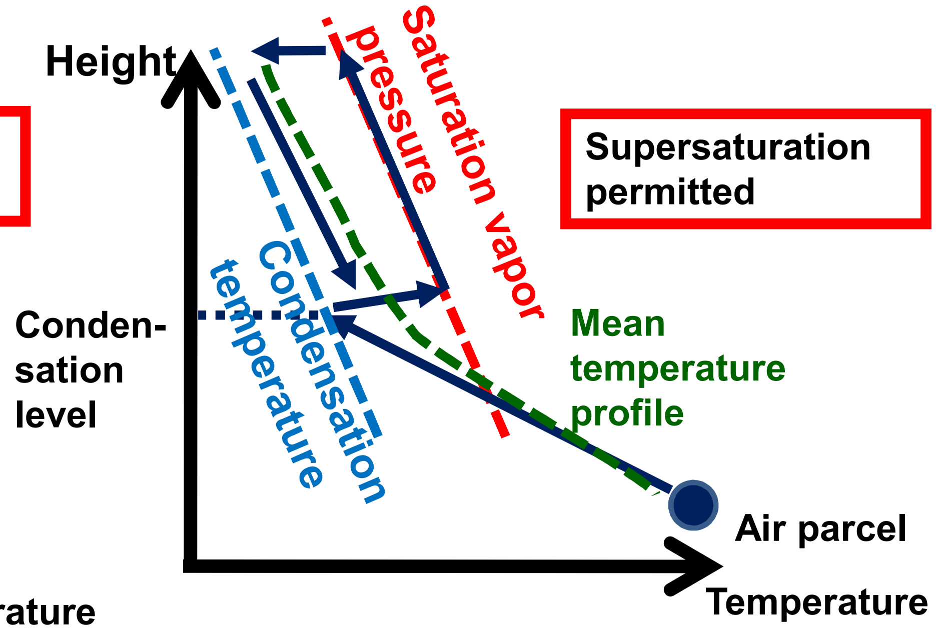


Mars where major componet condenses vs. Earth where minor component condenses.

The importance of supersaturation for moist convection with condensation of the major component

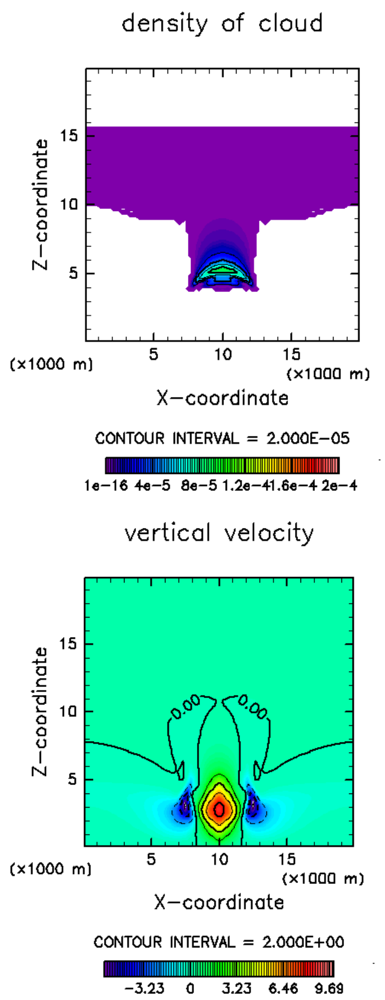
- High supersaturation (~ 0.35) is permitted in Mars(at most 0.05 in Earth).
  - Temperature of descent region can fall below the saturation temperature if supersaturation is permitted.
  - Air parcel may be buoyant.





Previous works

- Colaprete et al. (2003)
  - 1D cloud model with parameterized convection
  - Convective circulation structure cannot be described.
- We have been developing a (2D) nonhydrostatic model to calculate directly a circulation structure of convection with condensation of the major component
  - So far, we have performed several test experiments of an ascending thermal plume（Odaka et al, 2006）.
    http://www.gfd-dennou.org/library/deepconv/
- In this study,
  - We improve the condensation process etc.
  - We perform long time integration to investigate flow fields and cloud distributions in equilibrium states.



Odaka et al.(2006)

Governing equations

- 2D quasi-compressible equations by Klemp and Wilhelmson (1978) with additional terms representing major component condensation (Odaka et al.,2005)

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \bullet \nabla \mathbf{u} - C_p \bar{\theta} \nabla \Pi' + \mathbf{D}_\mathbf{u} + \frac{\theta'}{\bar{\theta}} \mathbf{g}$$

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

Thermal expansion

Pressure reduction due to decreasing of gas mass

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

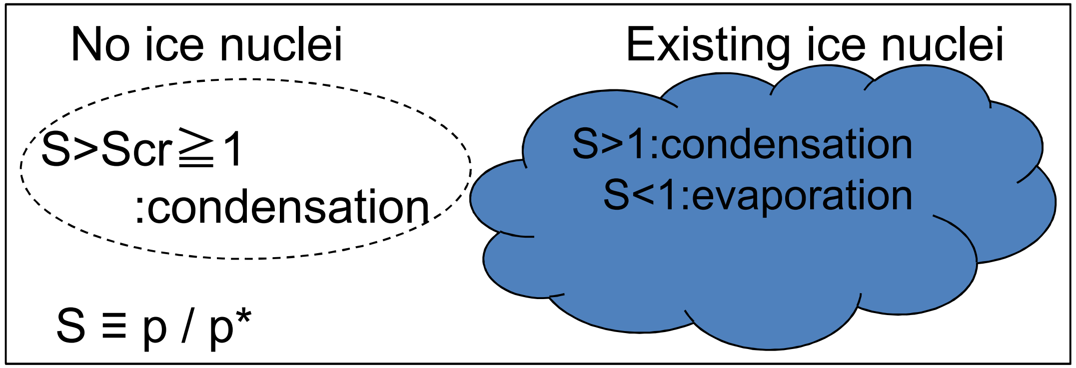
$$\frac{\partial \rho_s}{\partial t} = -\nabla \bullet \left(\rho_s \mathbf{u} \right) + M_{cond} + D_{\rho_s}$$

Overbar denotes basic state, prime denotes perturbation components.

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

Condensation and evaporation of clouds

- Only CO2 ice clouds are considered.
- Cloud particles are assumed to grow by diffusion process.
- Condition of condensation and evaporation follows Tobie et al. (2003)



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

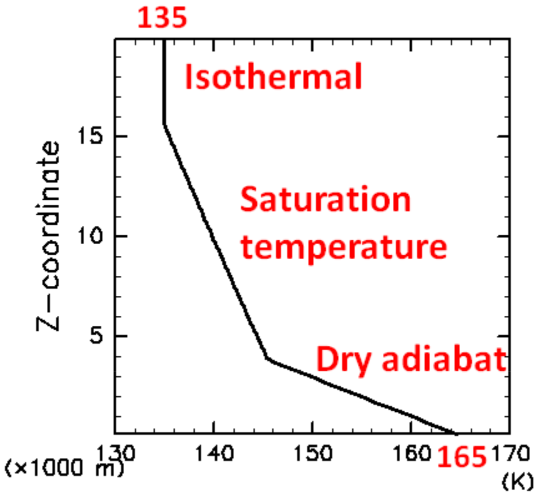
Scr : Critical saturation ratio

p : Pressure p_* : Saturation pressure

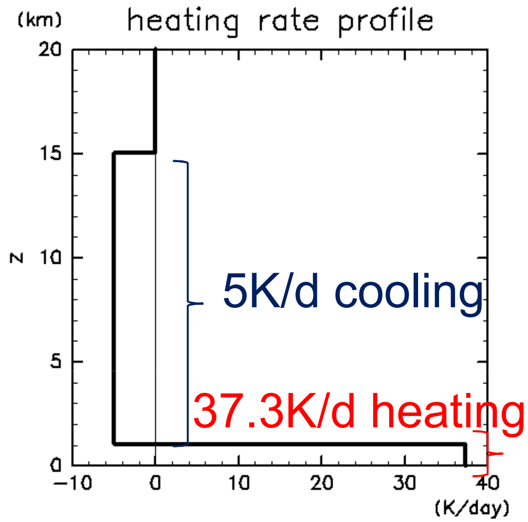
- Adopted values of Critical saturation ratio (Scr)
  - Scr=1.0
  - Scr=1.35 : Laboratory experiments by Glandorf et al.(2002)
- Falling of cloud particles is not considered(We are calculating now!).
- Drag force due to cloud particles is not also considered.

Numerical configuration

- Computational domain, integration time
  - 50 km in the horizontal direction, 20 km in the vertical direction(Grid spacing: 200 m)
  - 50 days
- Boundary condition
  - Periodic
    in the horizontal direction
  - Stress free
    at vertical boundaries
  - Surface fluxes of momentum
    and heat are not considered.



Initial temperature profile

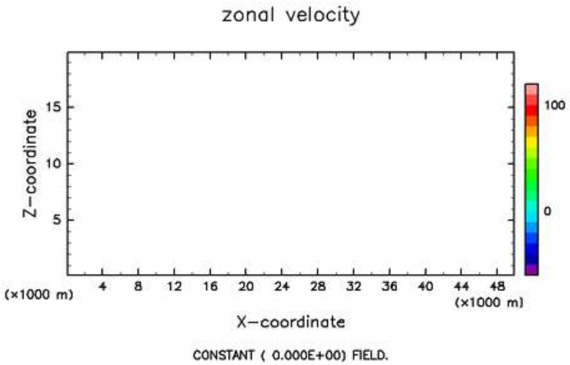


Heating rate

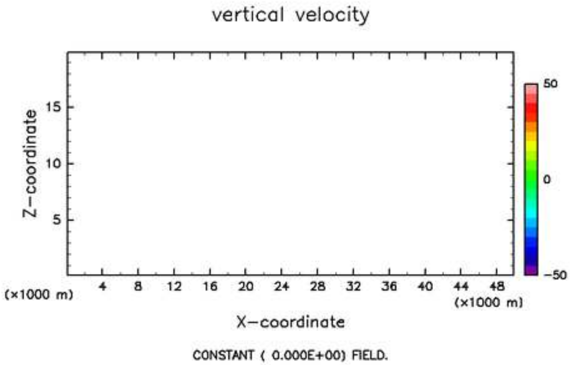
- Initial condition
  - Temperature profile : left panel
  - Random noise of potential temperature with amplitude of 1 K is added in the lowest layer.
- Heating rate : right panel
  - Uniform body cooling(5K/day for 1 – 15 km height) and heating(0 – 1 km height)
  - Heating rate are adjusted to retain heat balance of the entire system.

Results : Scr = 1.0

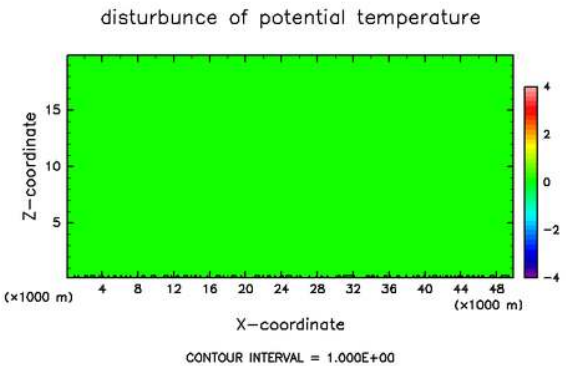
Horizontal component of velocity



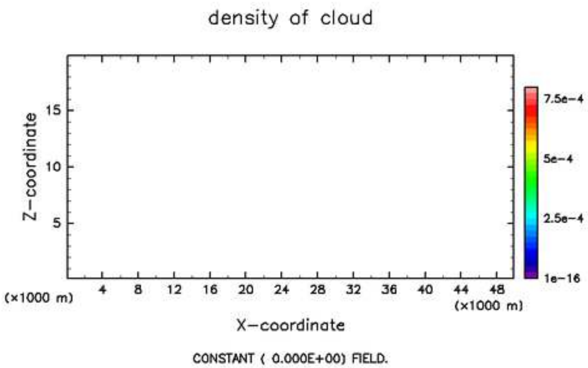
Vertical component of velocity



- Strong dry convection with one cell develops.
  - Maximum values of |u| and |w| are 110 m/s, 40 m/s, respectively.
- Clouds disappear.



Deviation of potential temperature

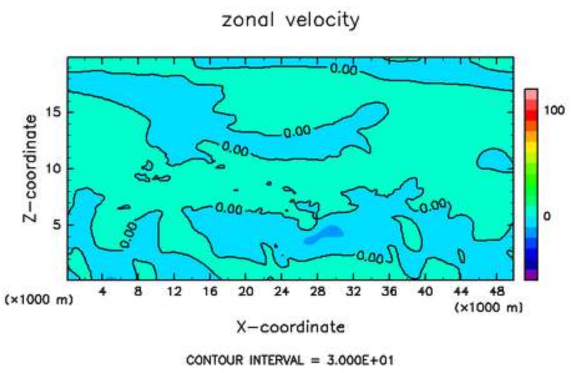


Cloud density

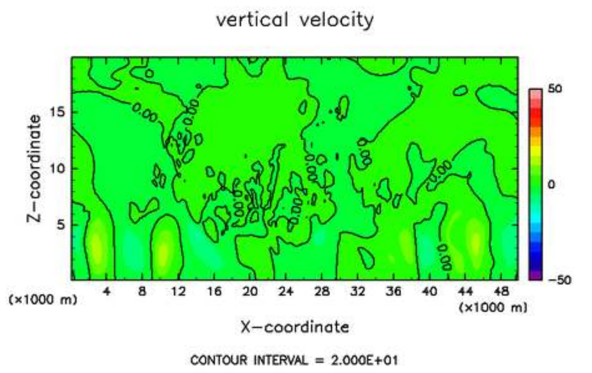
Initial state

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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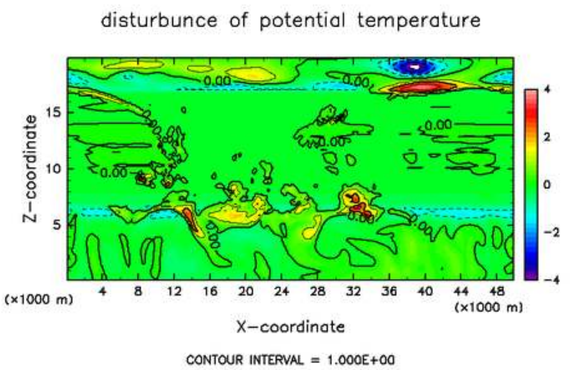
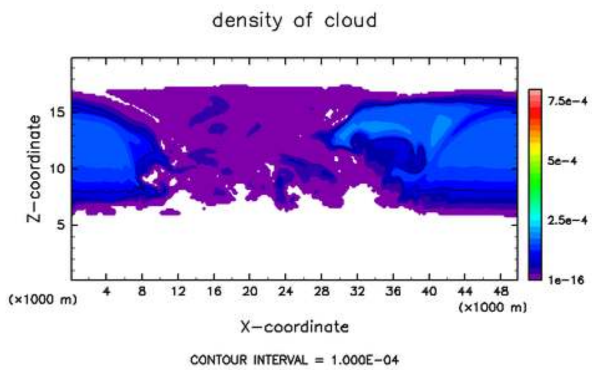


Deviation of potential temperature

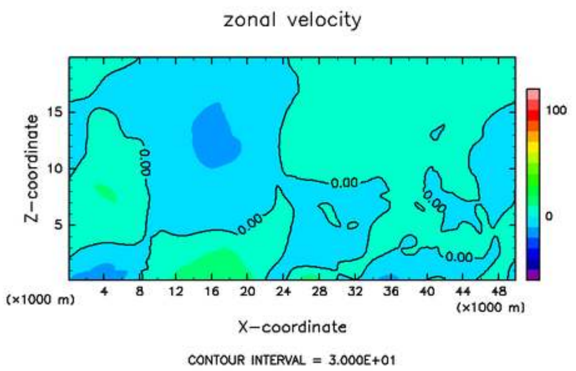


Cloud density

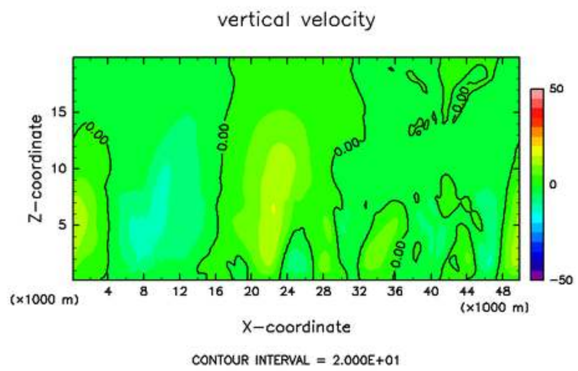
1 st day

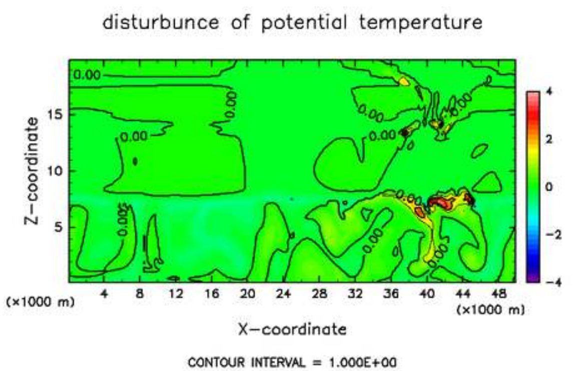
Results : Scr = 1.0

Horizontal component of velocity

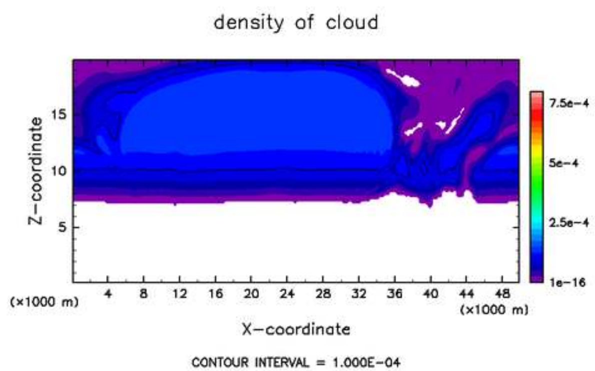


Vertical component of velocity





Deviation of potential temperature



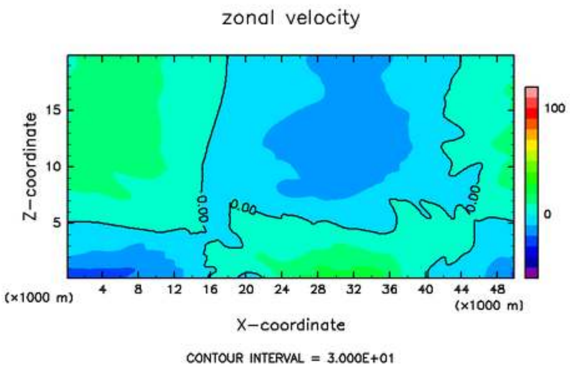
Cloud density

- Strong dry convection with one cell develops.
  - Maximum values of |u| and |w| are 110 m/s, 40 m/s, respectively.
- Clouds disappear.

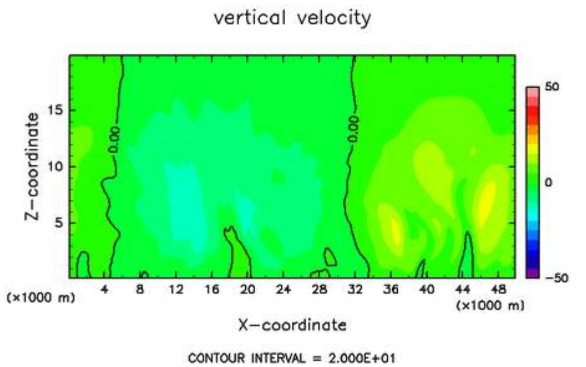
2 nd day

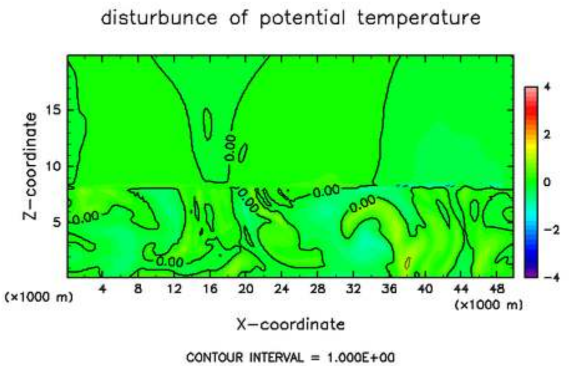
Results : Scr = 1.0

Horizontal component of velocity

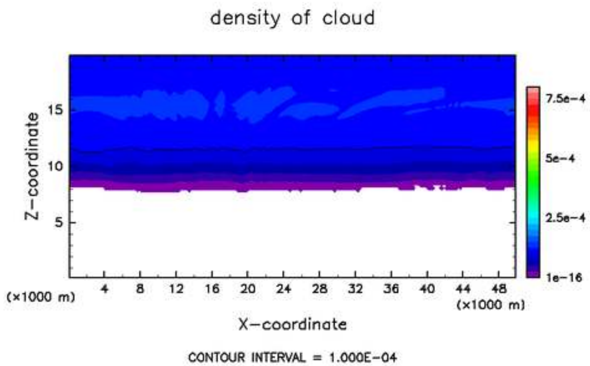


Vertical component of velocity





Deviation of potential temperature



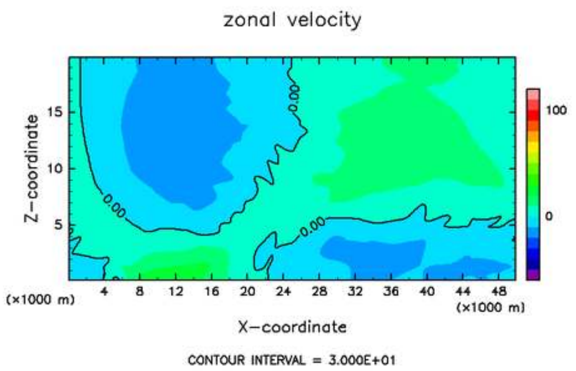
Cloud density

- Strong dry convection with one cell develops.
  - Maximum values of |u| and |w| are 110 m/s, 40 m/s, respectively.
- Clouds disappear.

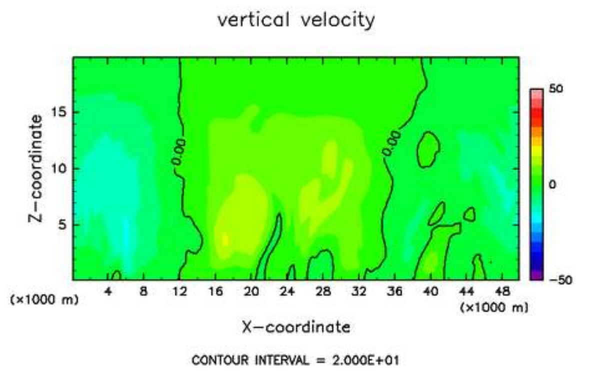
3 rd day

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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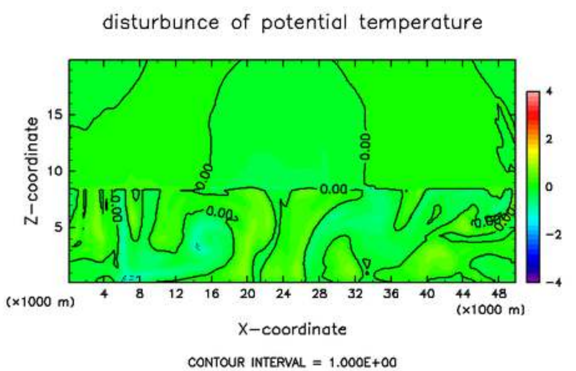
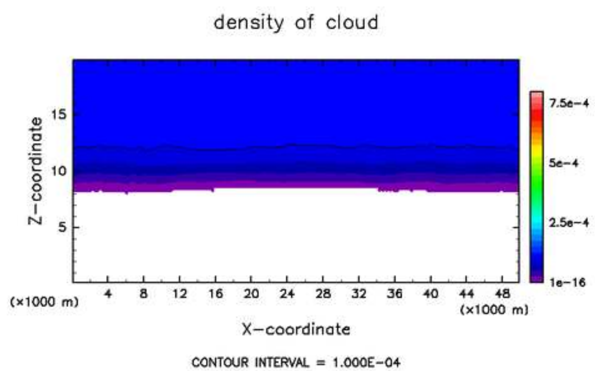


Deviation of potential temperature

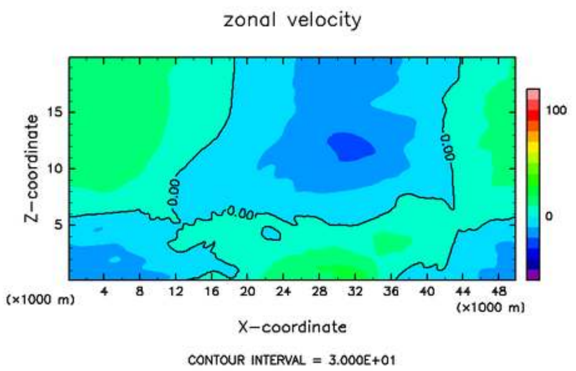


Cloud density

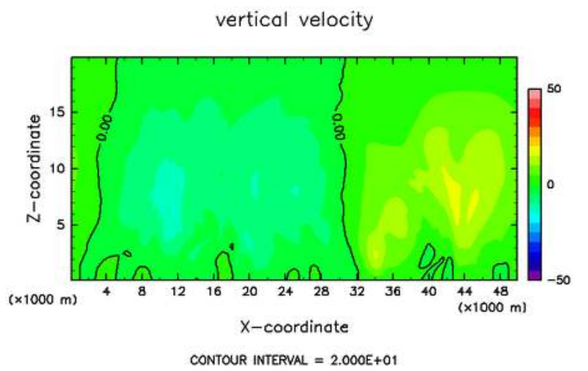
4 th day

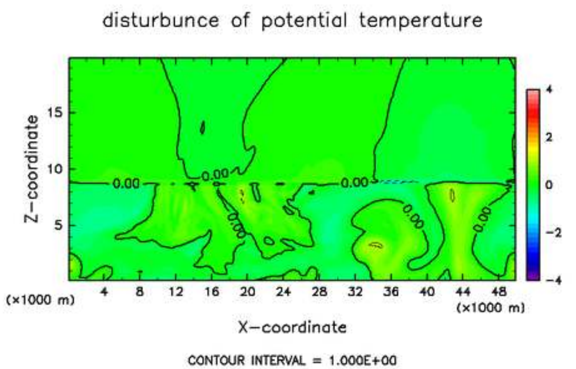
Results : Scr = 1.0

Horizontal component of velocity

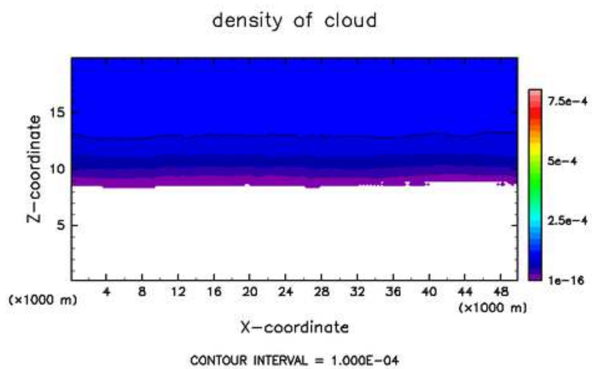


Vertical component of velocity





Deviation of potential temperature



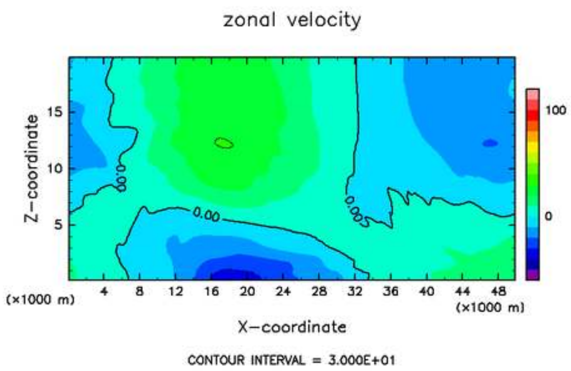
Cloud density

- Strong dry convection with one cell develops.
  - Maximum values of |u| and |w| are 110 m/s, 40 m/s, respectively.
- Clouds disappear.

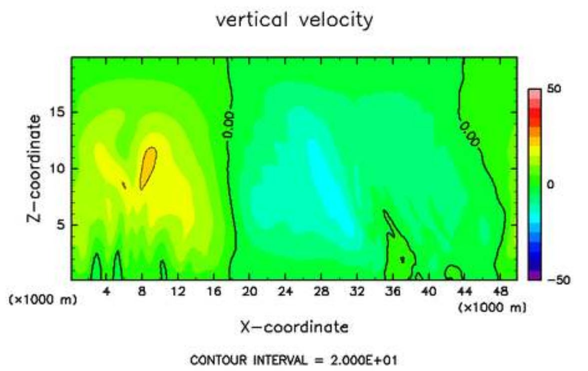
5 th day

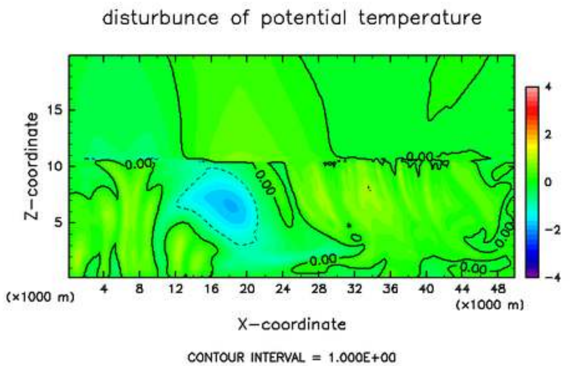
Results : Scr = 1.0

Horizontal component of velocity

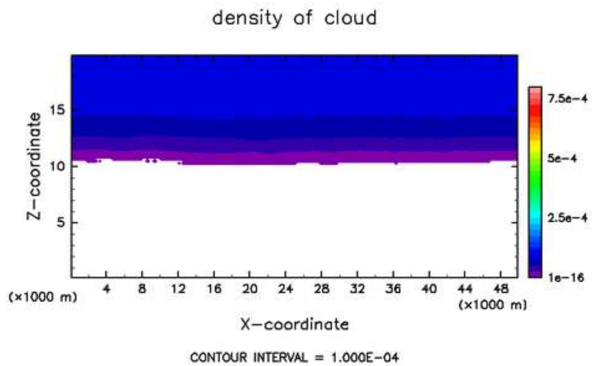


Vertical component of velocity





Deviation of potential temperature



Cloud density

- Strong dry convection with one cell develops.
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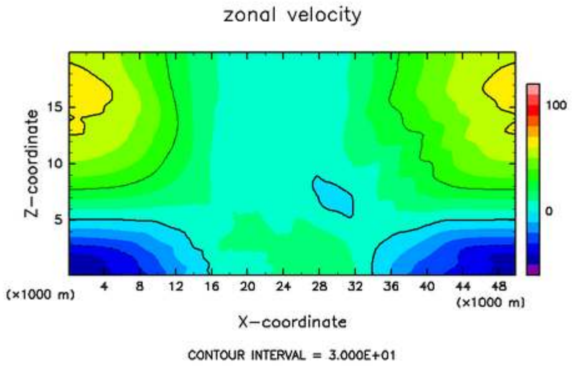
- Clouds disappear.

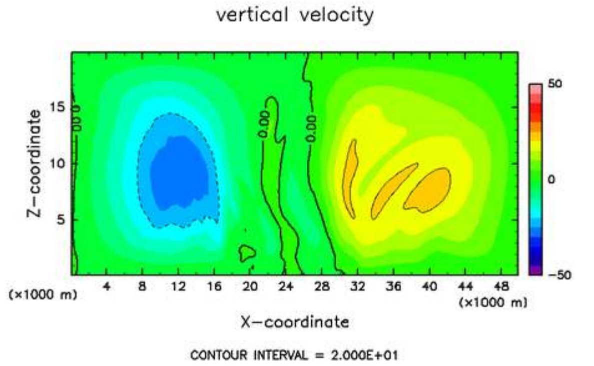
10 th day

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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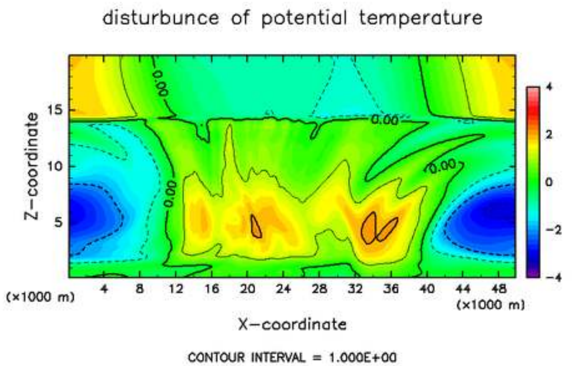
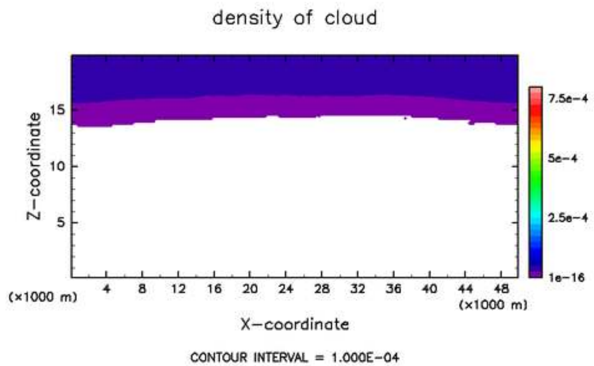


Deviation of potential temperature

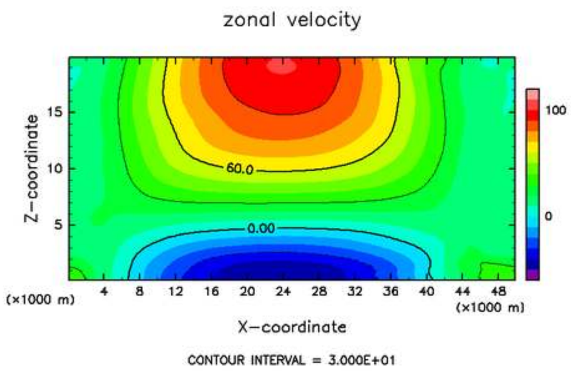


Cloud density

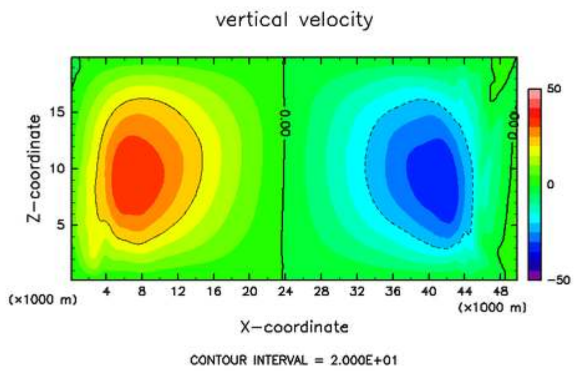
20 th day

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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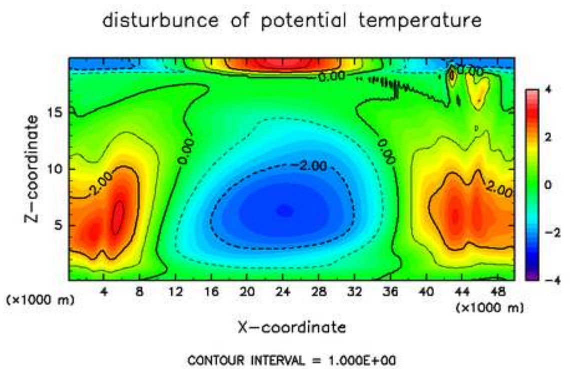
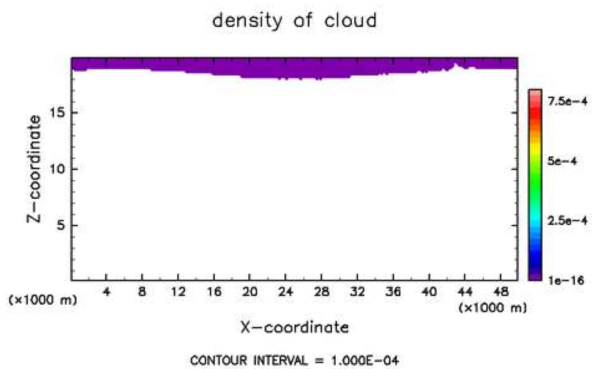


Deviation of potential temperature

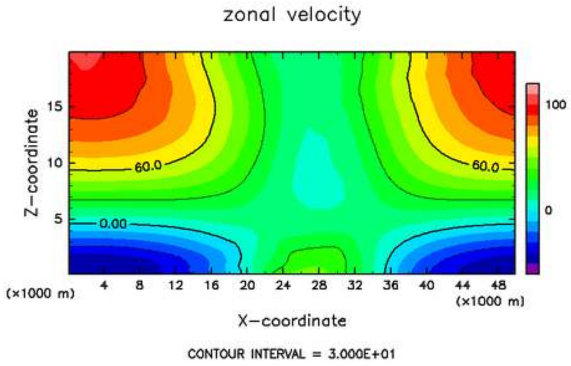


Cloud density

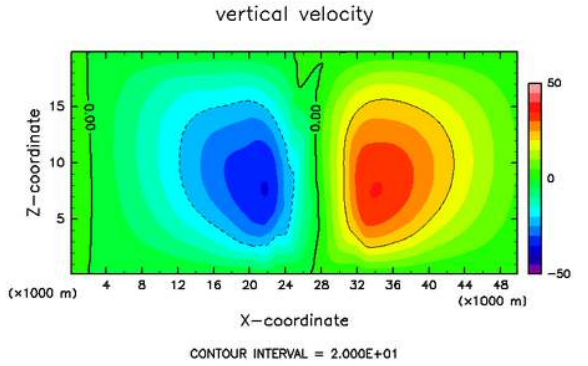
30 th day

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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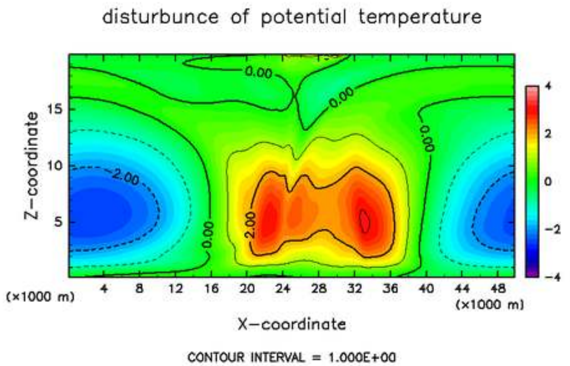
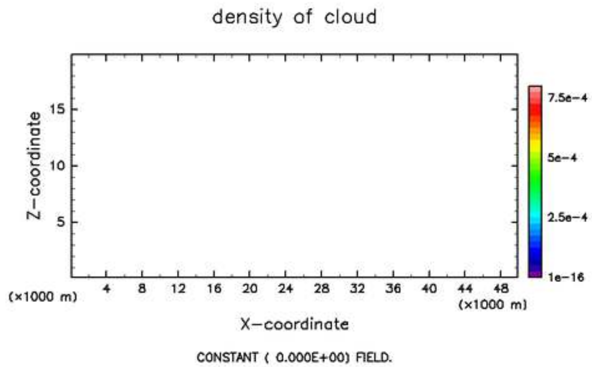


Deviation of potential temperature

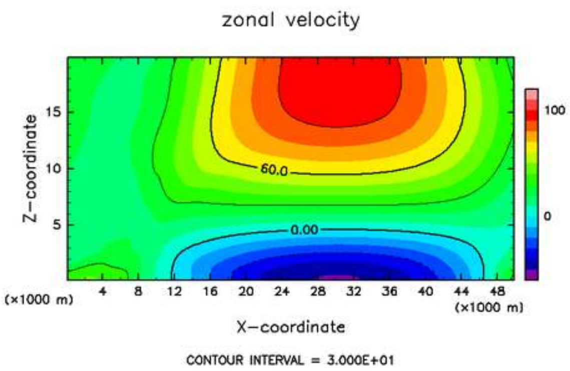


Cloud density

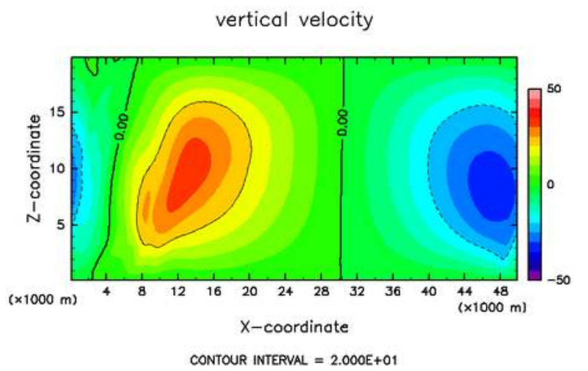
40 th day

Results : Scr = 1.0

Horizontal component of velocity



Vertical component of velocity



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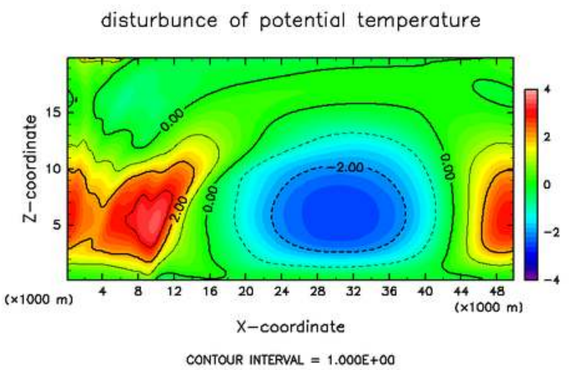
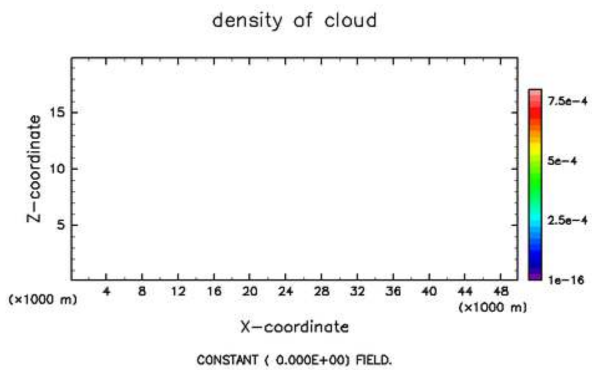


Deviation of potential temperature

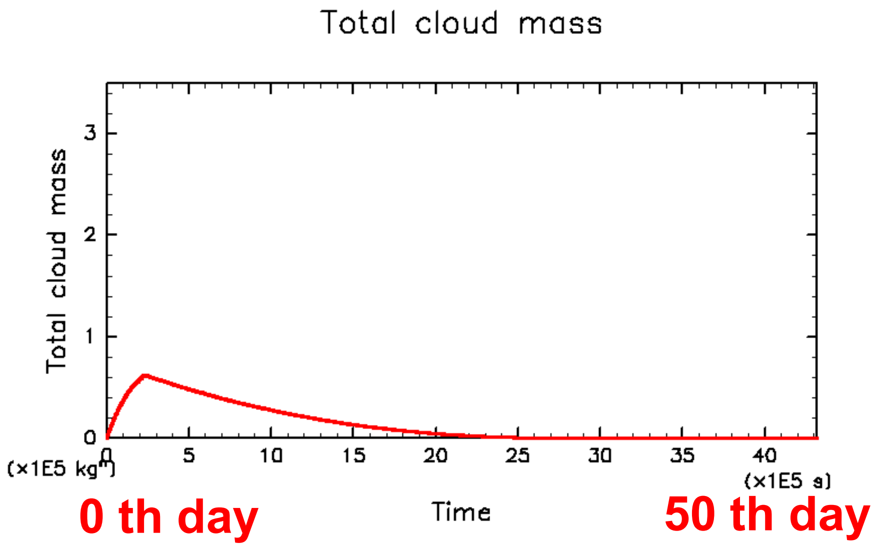


Cloud density

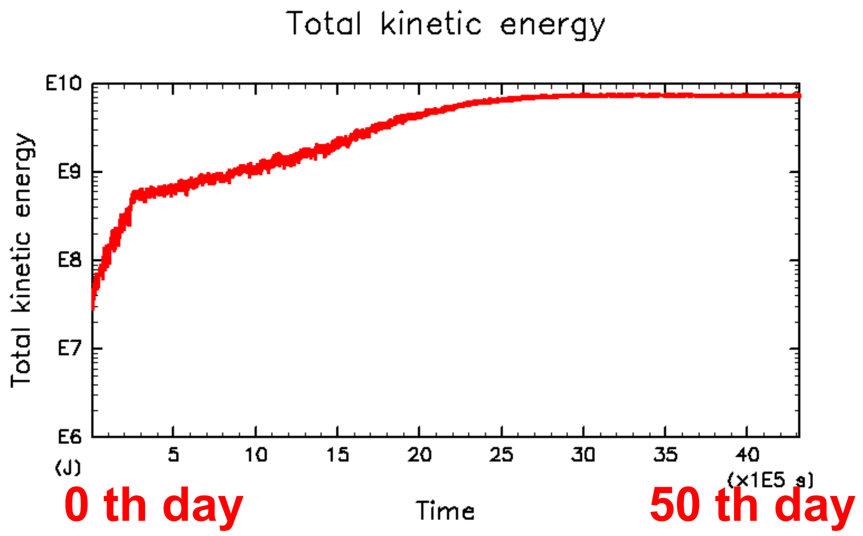
50 th day

Results : Scr = 1.0

Total cloud mass



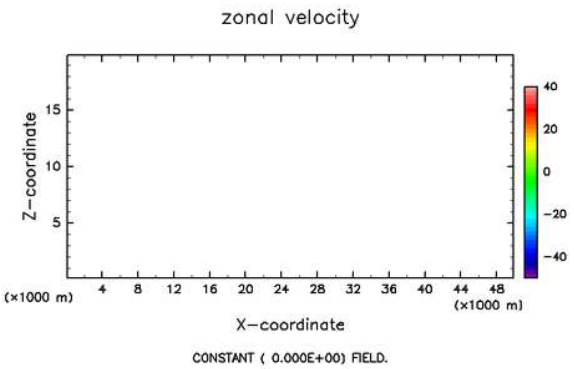
Total kinetic energy



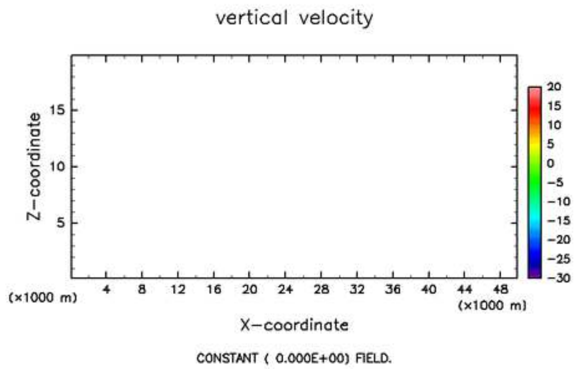
- Total cloud mass
  - increases until 2.5 th day, and then decreases to zero in about 34 th day.
- Total kinetic energy
  - increases until 34 th day, and then becomes nearly constant.
- Quasi-equilibrium state is established.

Results : Scr = 1.35

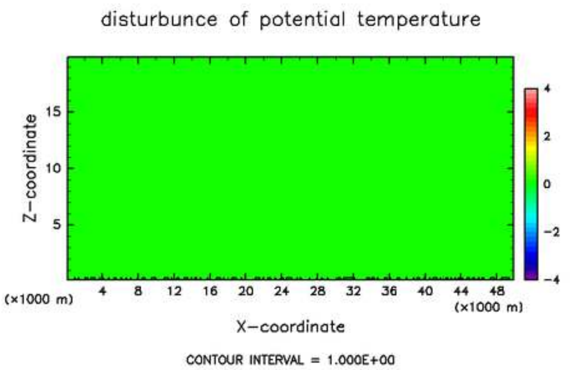
Horizontal component of velocity



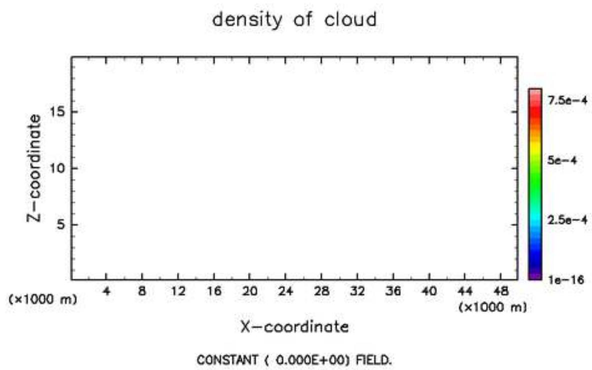
Vertical component of velocity



- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.



Deviation of potential temperature

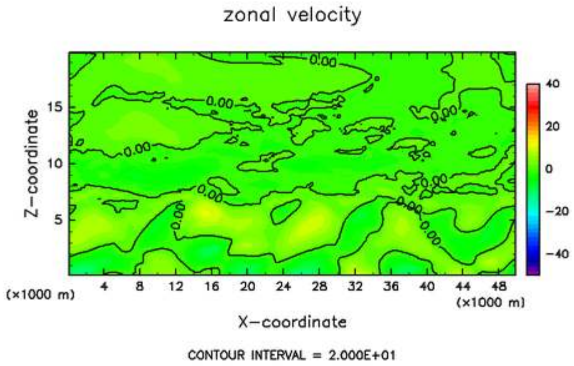


Cloud density

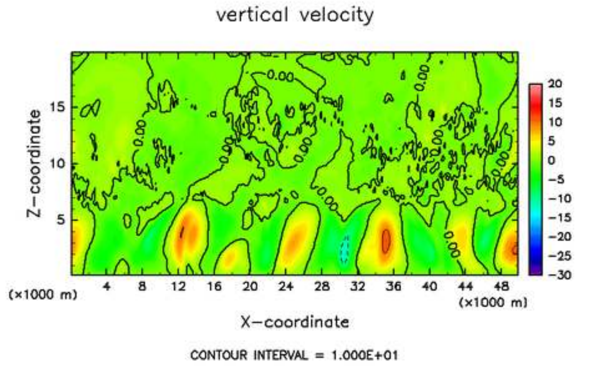
Initial state

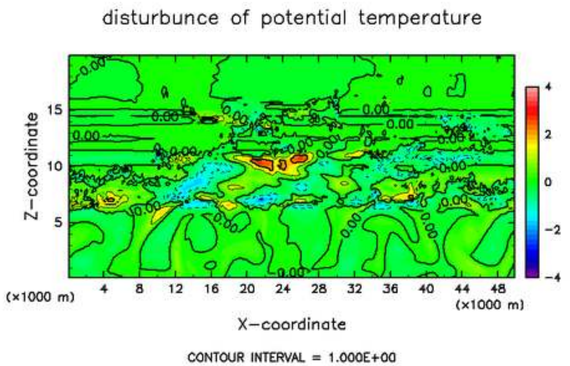
Results : Scr = 1.35

Horizontal component of velocity

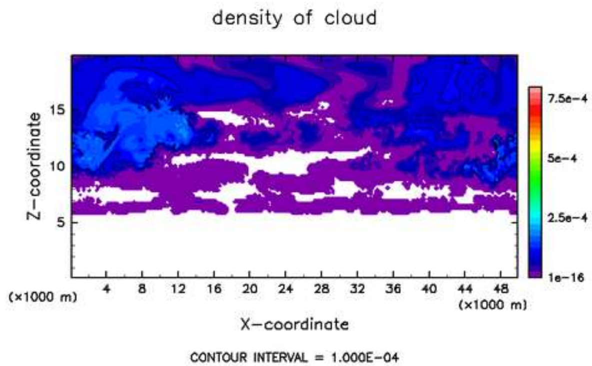


Vertical component of velocity





Deviation of potential temperature



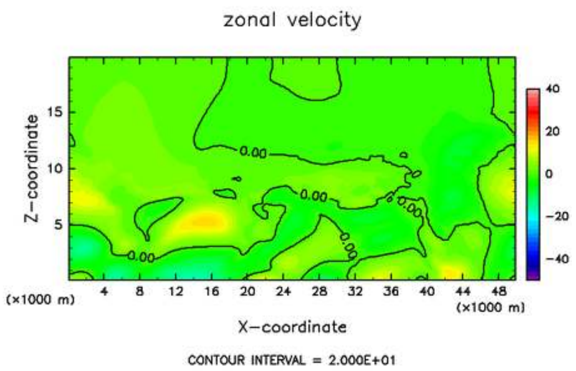
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

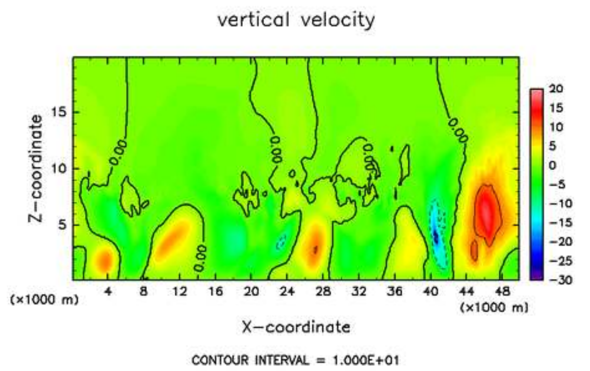
1 st day

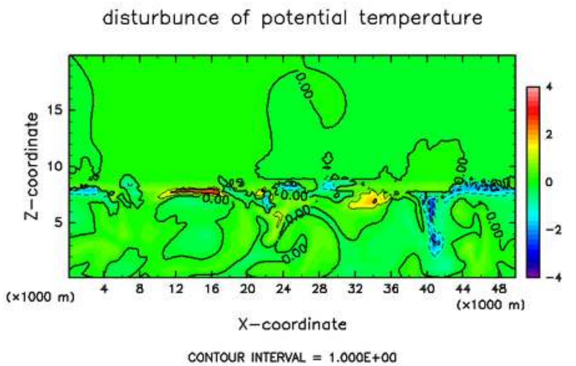
Results : Scr = 1.35

Horizontal component of velocity

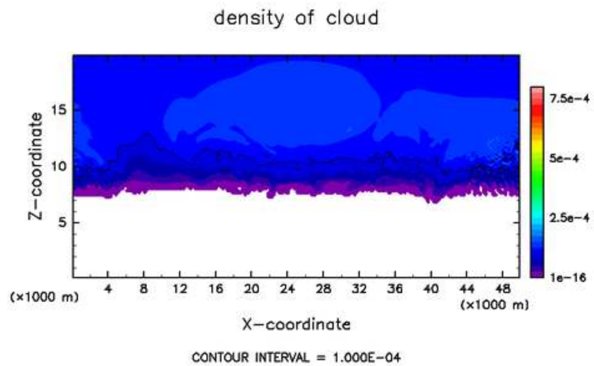


Vertical component of velocity





Deviation of potential temperature



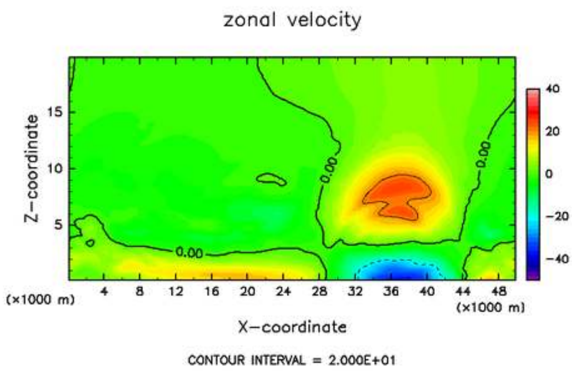
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

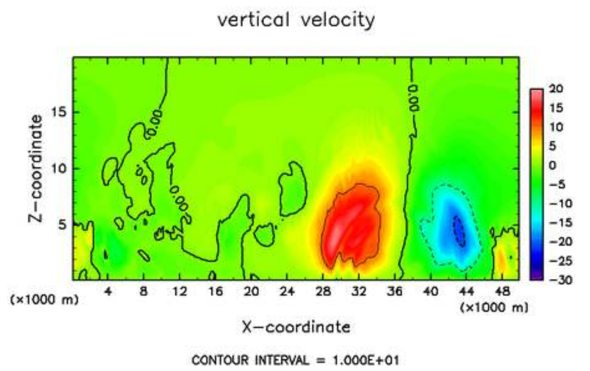
2 nd day

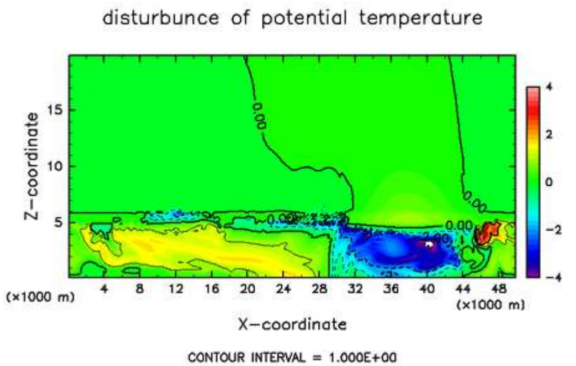
Results : Scr = 1.35

Horizontal component of velocity

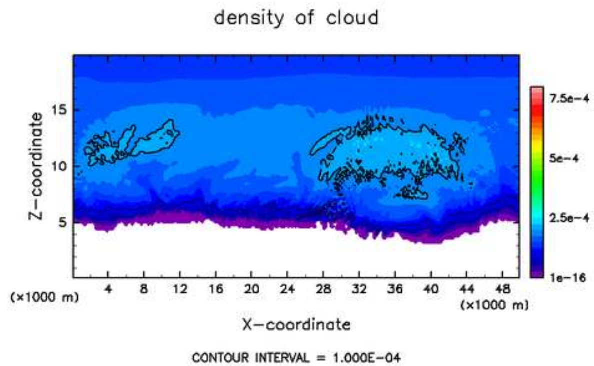


Vertical component of velocity





Deviation of potential temperature



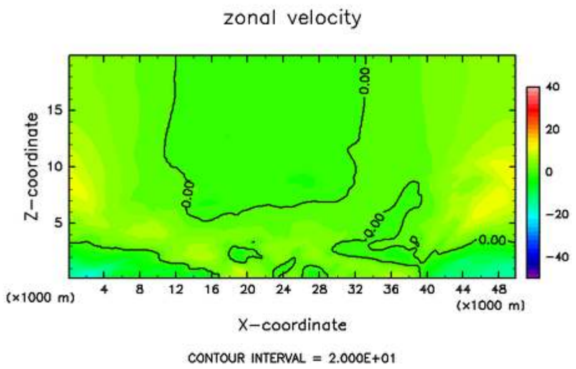
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

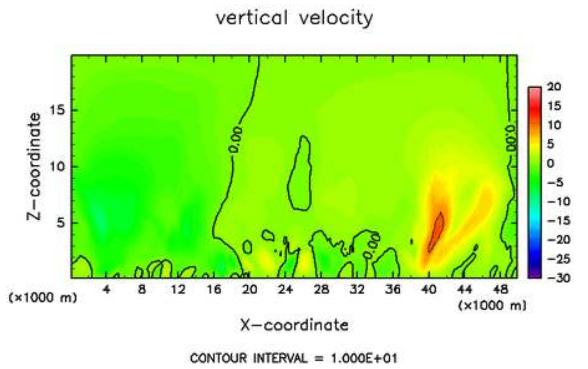
3 rd day

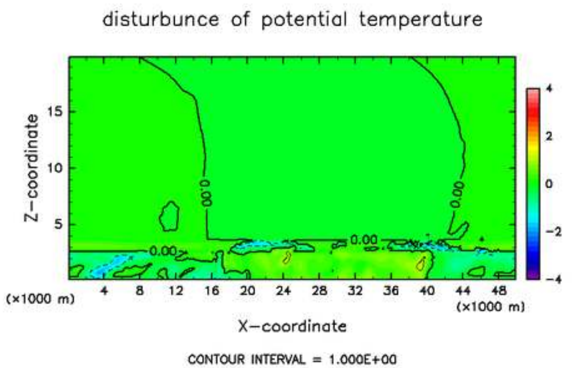
Results : Scr = 1.35

Horizontal component of velocity

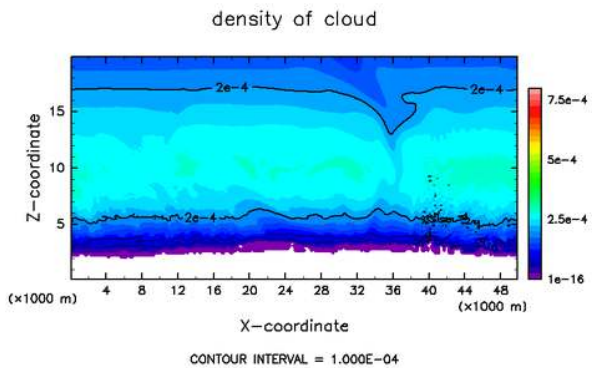


Vertical component of velocity





Deviation of potential temperature



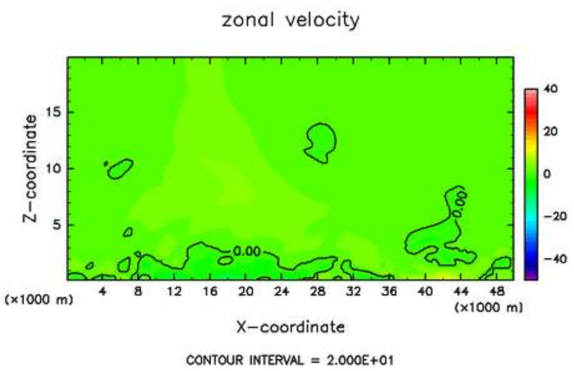
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

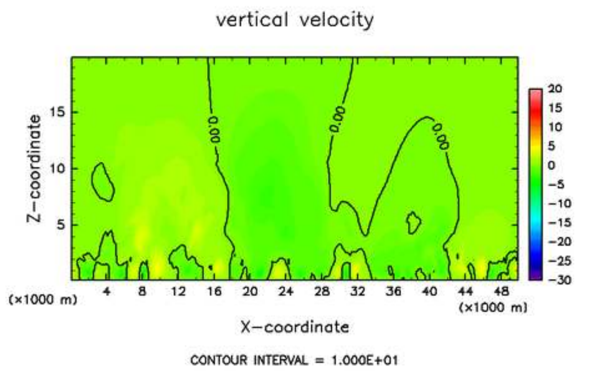
4 th day

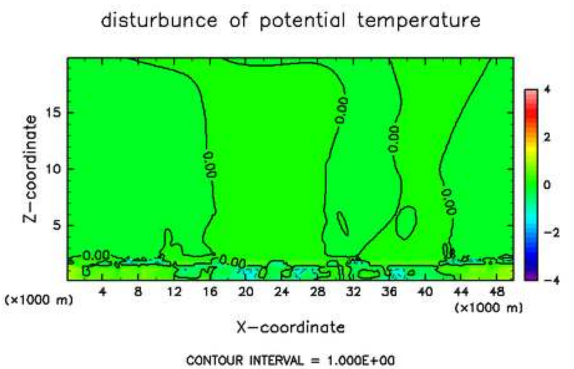
Results : Scr = 1.35

Horizontal component of velocity

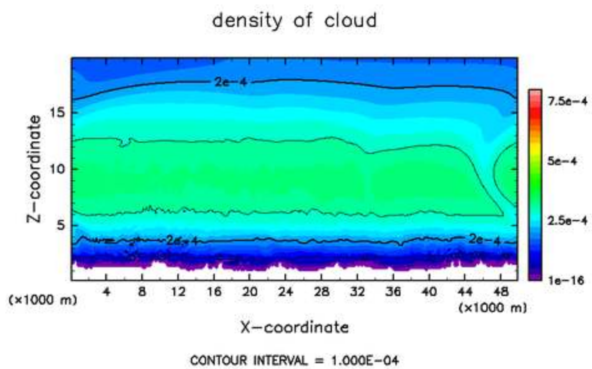


Vertical component of velocity





Deviation of potential temperature



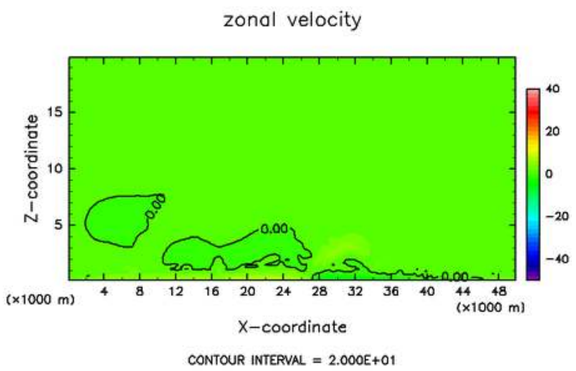
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

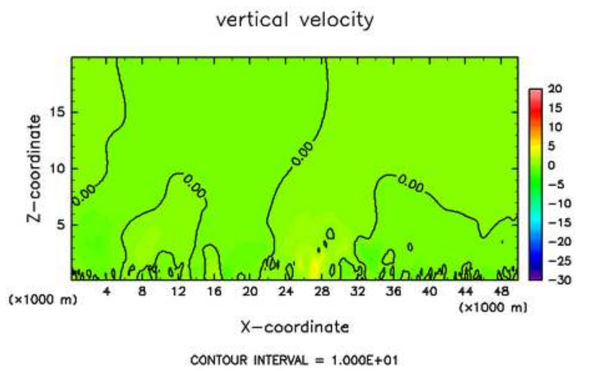
5 th day

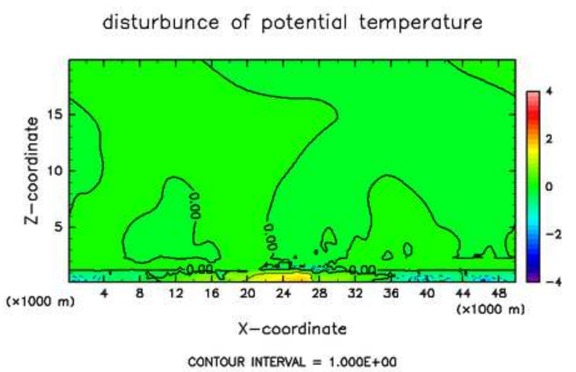
Results : Scr = 1.35

Horizontal component of velocity

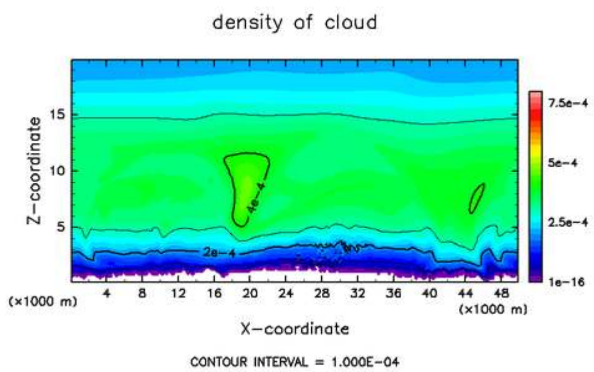


Vertical component of velocity





Deviation of potential temperature



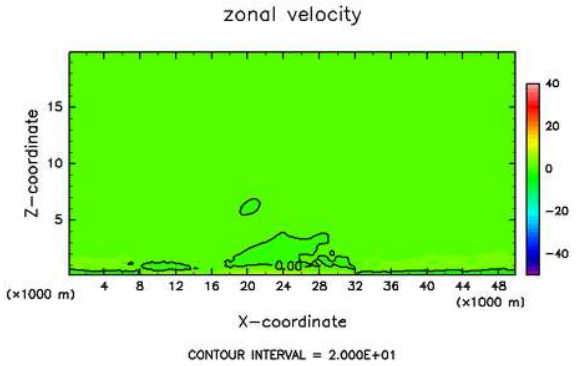
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

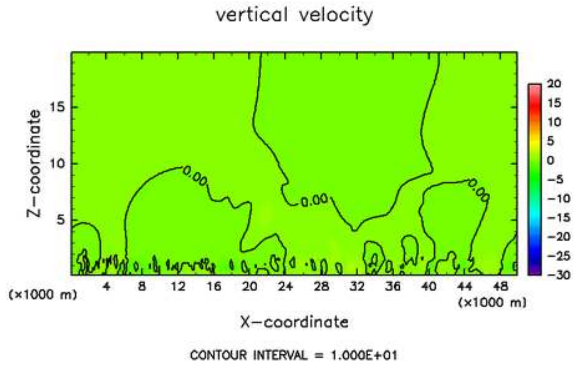
10 th day

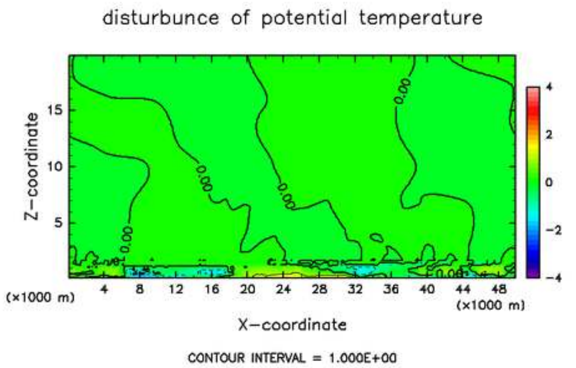
Results : Scr = 1.35

Horizontal component of velocity

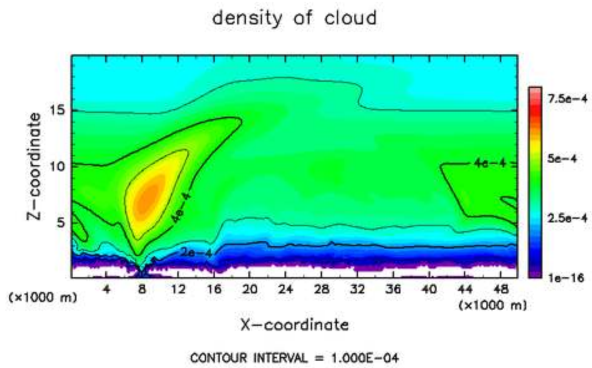


Vertical component of velocity





Deviation of potential temperature



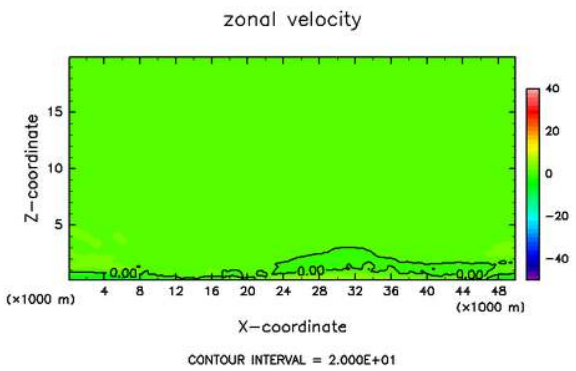
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

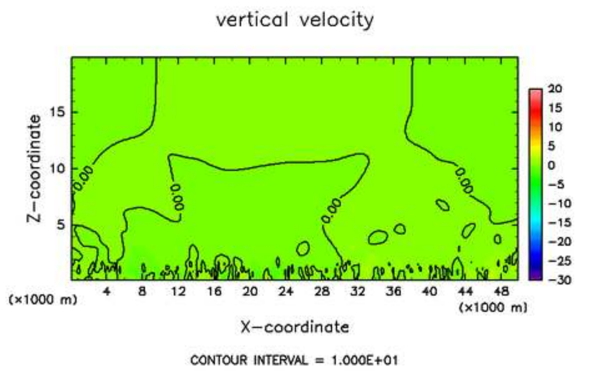
20 th day

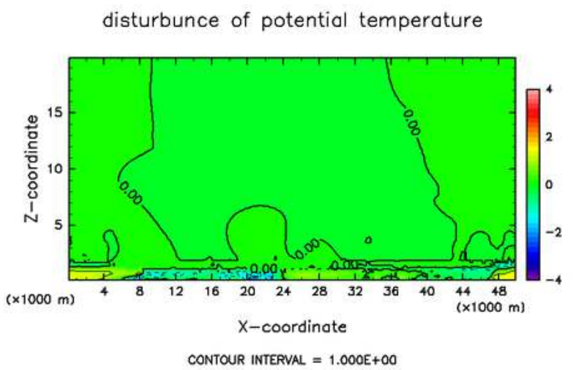
Results : Scr = 1.35

Horizontal component of velocity

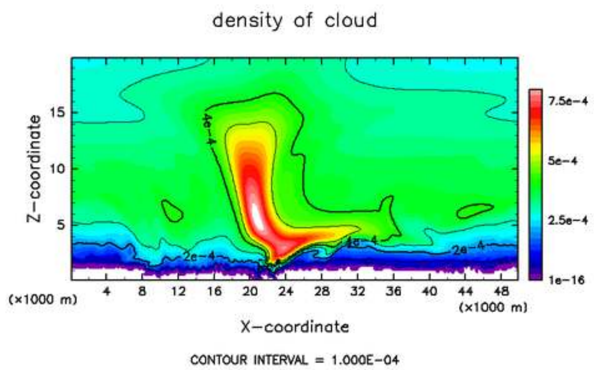


Vertical component of velocity





Deviation of potential temperature



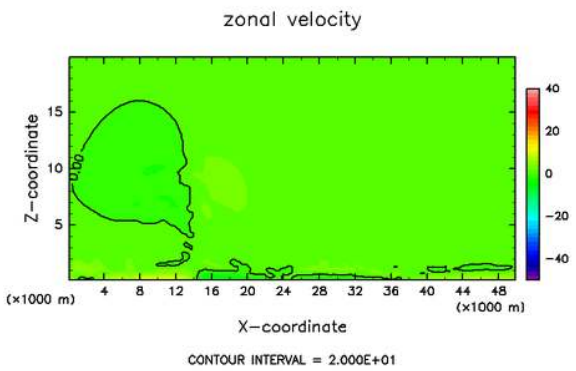
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

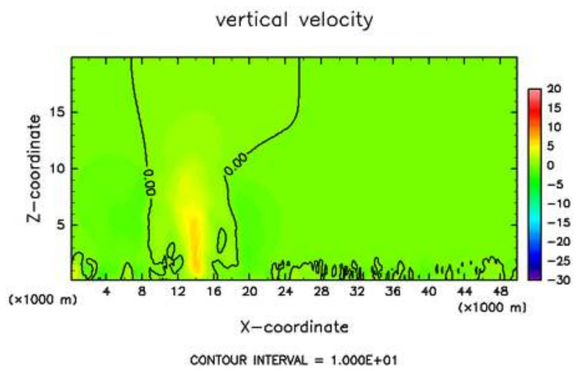
30 th day

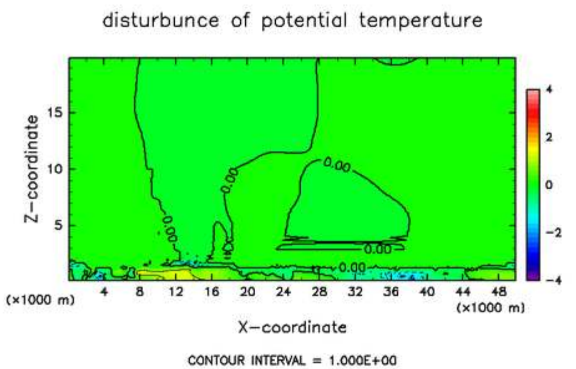
Results : Scr = 1.35

Horizontal component of velocity

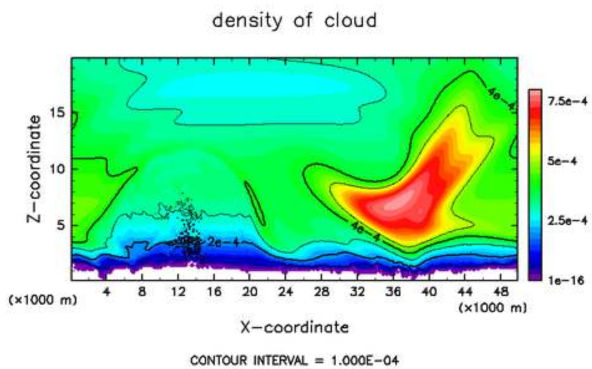


Vertical component of velocity





Deviation of potential temperature



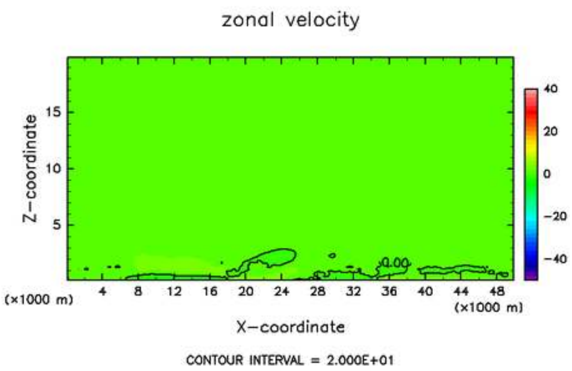
Cloud density

- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.

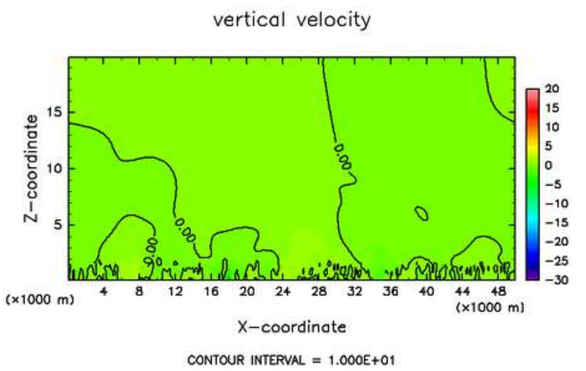
40 th day

Results : Scr = 1.35

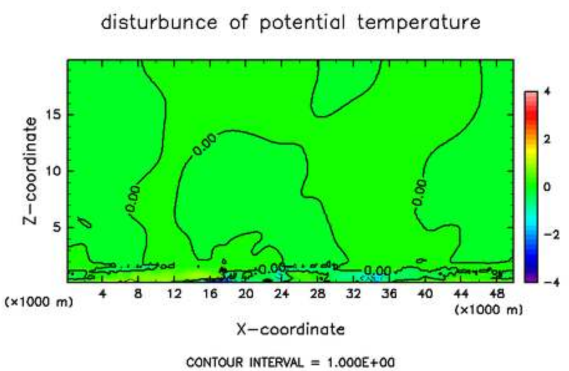
Horizontal component of velocity



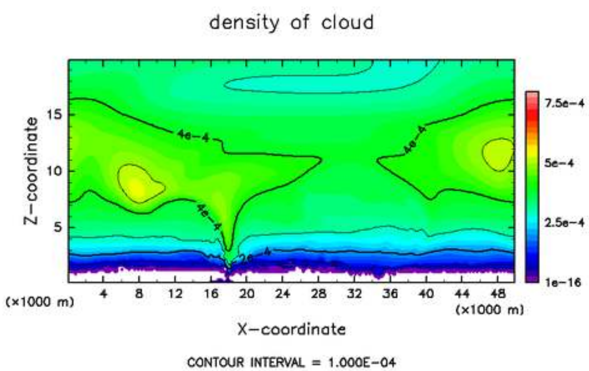
Vertical component of velocity



- Weak circulation develops.
  - Maximum values of |u| and |w| are 10 m/s.
- All the domain except for the shallow layer near the surface is covered with clouds.



Deviation of potential temperature

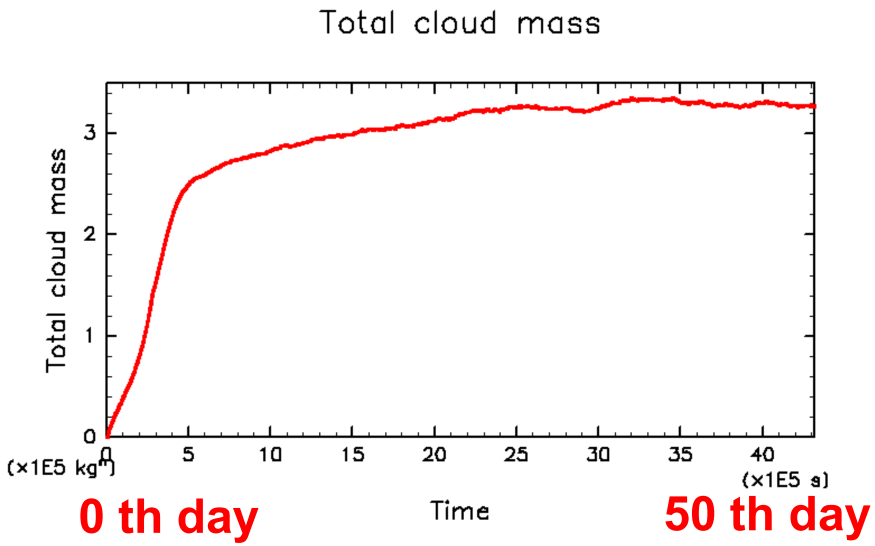


Cloud density

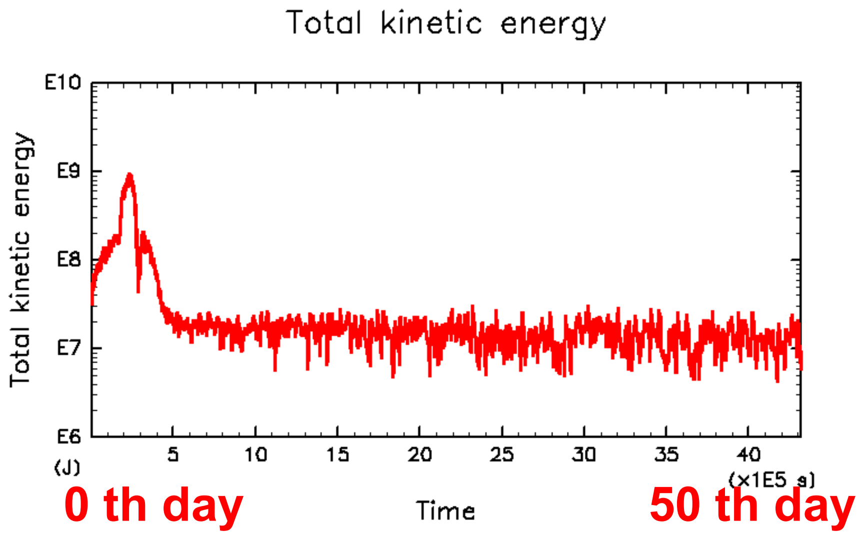
50 th day

Results : Scr = 1.35

Total cloud mass



Total kinetic energy



- Total cloud mass
  - increases until about 38 th day, and then becomes nearly constant.
- Total kinetic energy
  - also becomes nearly constant after 6 th day.
- Quasi-equilibrium state is established.

Summary

- Results
  - We could perform time integration long enough to obtain quasi-equilibrium states by using our nonhydrostatic model.
  - It is suggested that the difference of Scr produces significant difference of structure of moist convection and cloud distribution in equilibrium state .
- Future works
  - Calculation with the falling of cloud particles
  - Calculation with the drag force due to cloud particles
    - Numerical experiments for terrestrial cloud convection(e.g. Nakajima et al.(1998)) show that the falling of cloud particles and the drag force affect the convective structure significantly.

Acknowledgement

- This study uses following software developed and maintained by GFD Dennou Club (http://www.gfd-dennou.org/index.html.en):
  - gtool5,
    - http://www.gfd-dennou.org/library/gtool/gtool5.htm.en,
  - Dennou Ruby software,
    - http://www.gfd-dennou.org/library/ruby/.