Scattering greenhouse effect of radiatively controlled CO_2 ice cloud layer in a Martian paleoatmosphere

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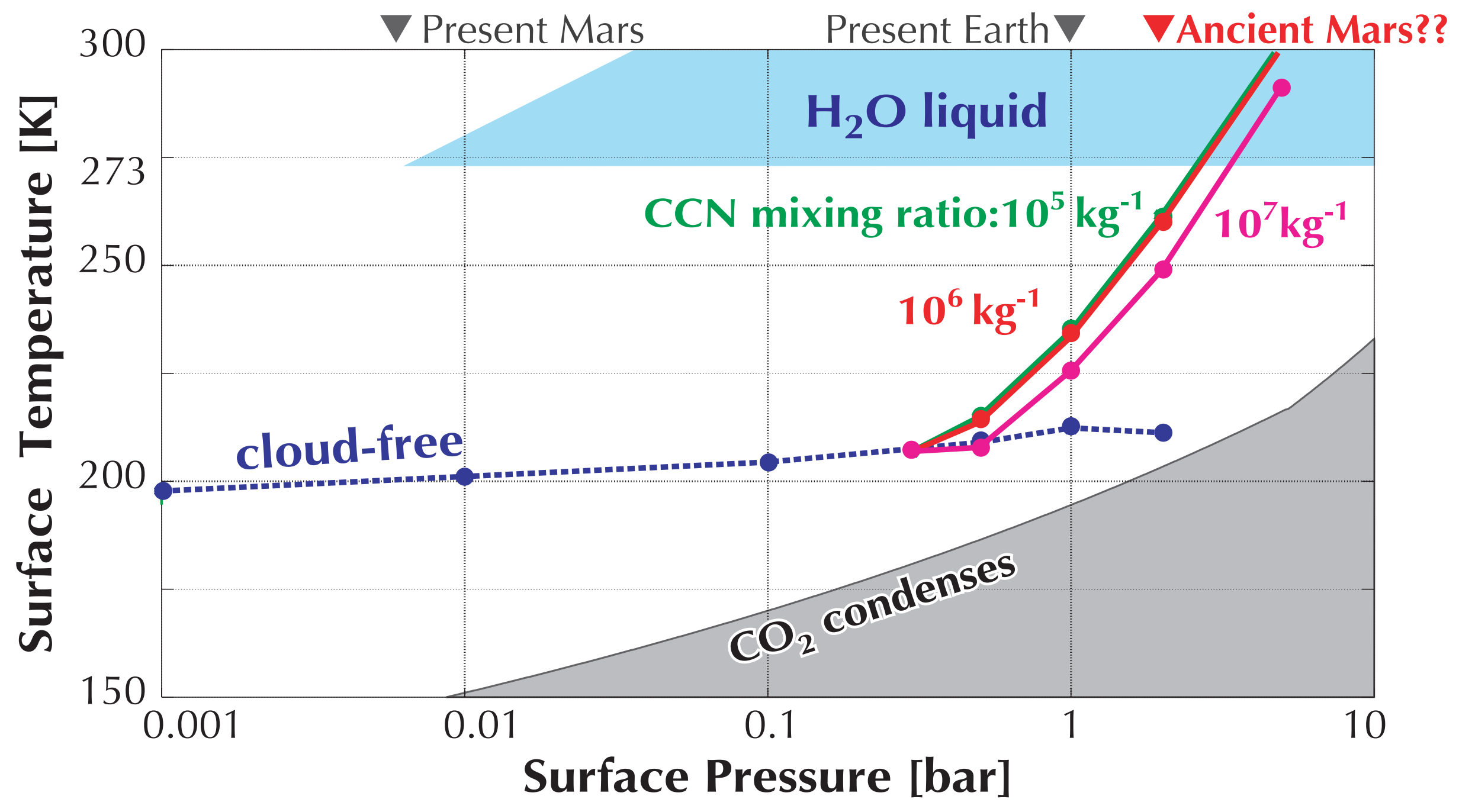
AGU 2006 fall meeting, 12 December 2006, Planetary sciences, Martian atmosphere, P23A-0042

Summary

The scattering greenhouse effect of CO_2 ice cloud has been proposed as a potential mechanism for keeping the Martian climate warm enough to support flowing water under a faint young Sun. Previous studies have shown that such warm climate is possibly achieved if a cloud layer with optimal ranges of particle size and optical depth is placed in dense CO_2-H_2O atmosphere. However, it has not been examined how such an optimal cloud layer could be formed.

In this study, we suggest that cloud particle size is automatically adjusted so the cloud layer as to satisfy radiative equilibrium assuming cloud formation by radiative cooling instead of moist convection. Adjusted CO_2 ice cloud layer can induce strong greenhouse effect with strong dependency on mixing ratio of cloud condensation nuclei (CCN). This seems consistent with intermittent warming suggested by modest erosion of ancient cratered terrain because Martian paleoclimate might fluctuate between warm and cold states induced by the variation of nuclei mixing ratio.

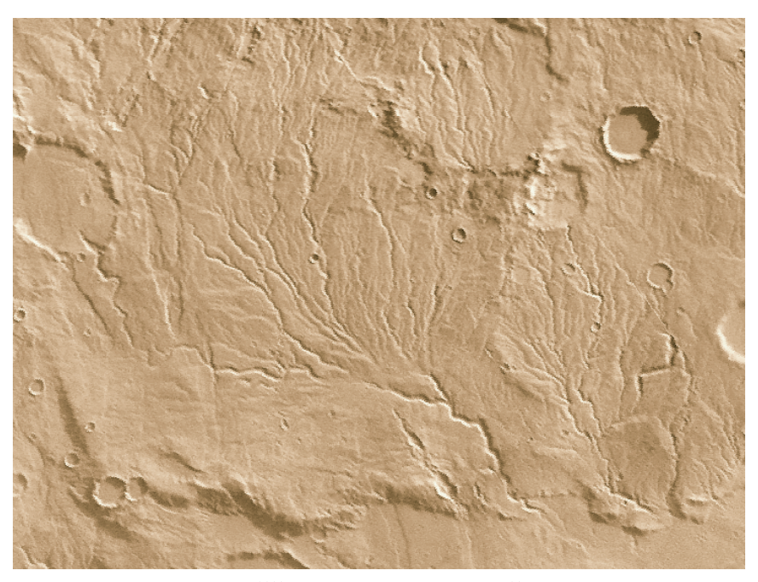


Relationship between the surface pressure and temperature of CO_2-H_2O atmosphere on early Mars. The solid curves include cloud formation owing to radiative cooling and the dash curve neglects it. The dot curve represents the saturation temperature of CO_2. The aqua region in the upper-right of figure represents the condition that liquid water exists stably.

Introduction

The scattering greenhouse effect of CO_2 ice cloud

- is candidate mechanism to explain the warm climate which allows valley networks to form on early Mars.
  - + The greenhouse effect of dense CO_2-H_2O atmosphere cannot simply explain the warm climate because the increase in temperature at upper troposphere due to CO_2 condensation would significantly weaken the greenhouse effect (Kasting 1991).

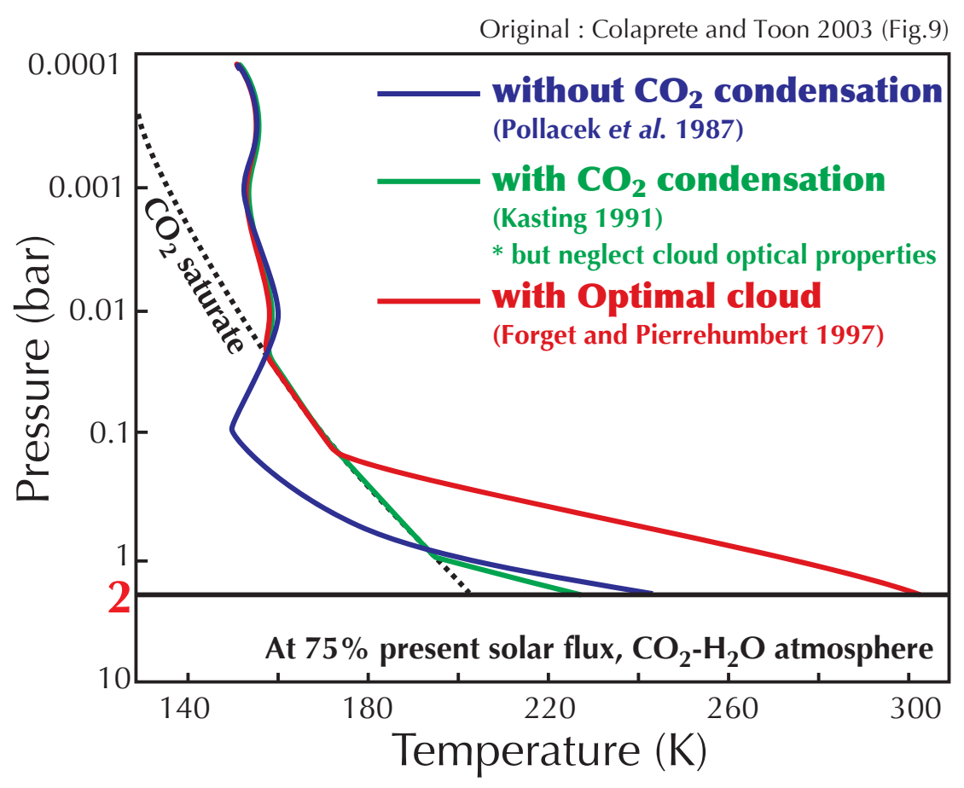


Valley networks

In previous studies (Pierrehumbert and Erlick 1998, Mischna *et al.* 2000)

- The strength of greenhouse effect strongly depends on the cloud parameters such as particle size and optical depth.
- However, the estimation of cloud parameters have been considered as a difficult problem so far
  - + supposing that cloud formation is mainly driven by **moist convection** like that in the terrestrial troposphere.

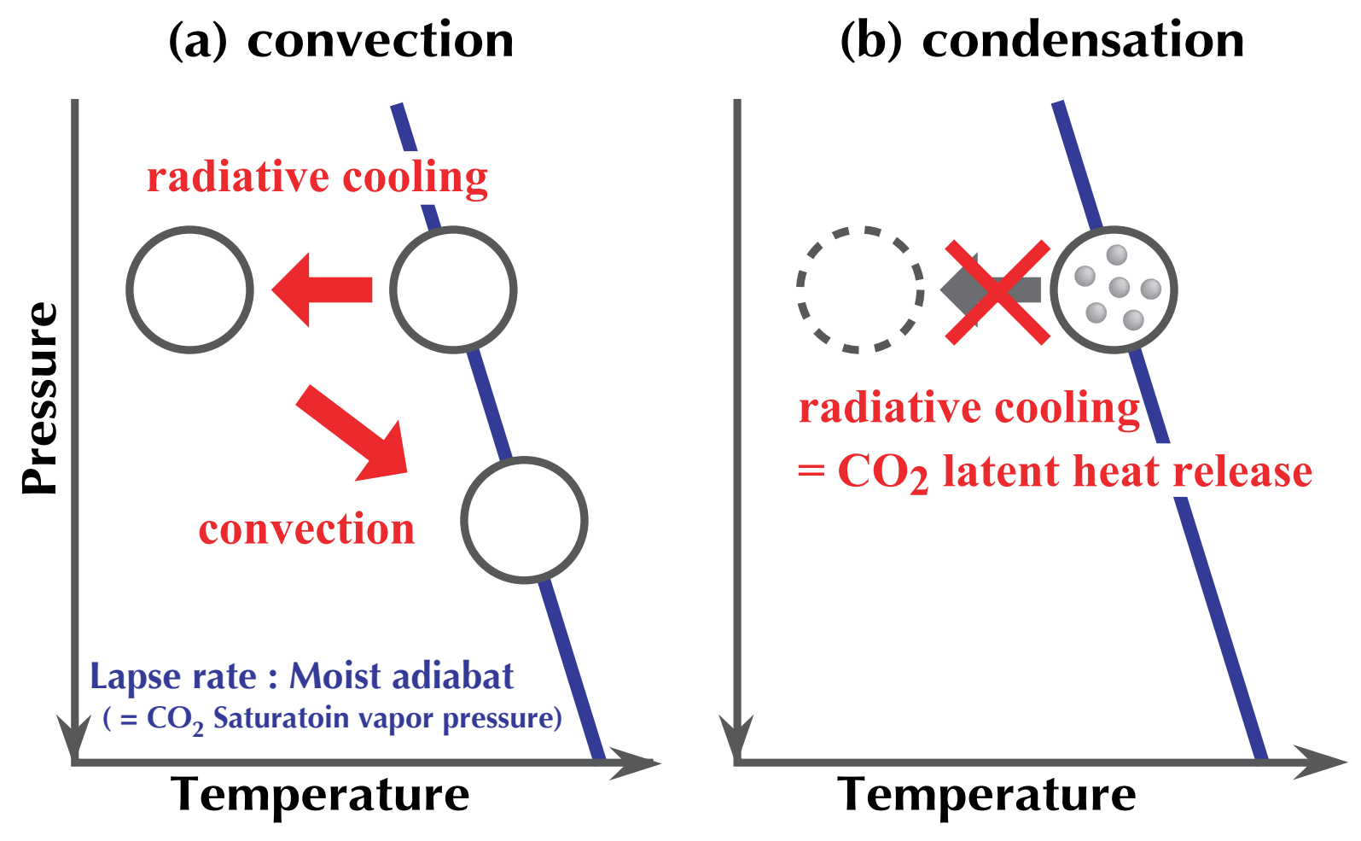
Original : Colaprete and Toon 2003 (Fig.9)



Calculated vertical temperature profile

In this study

- We estimate cloud parameters and induced greenhouse effect assuming cloud formation by **local radiative cooling** instead of moist convection.
  - + Unstable stratification is not necessary to be formed by radiative cooling because the major atmospheric component CO_2 is condensable.
    - Latent heat release with CO_2 condensation can inhibit it.
  - + Furthermore, if cloud becomes to receive net radiative heating as it grows, **the cloud parameters would be autonomously adjusted** to achieve the radiative equilibrium in each CO_2 cloud layer.



Inhibition of unstable stratification by condensation of major atmospheric component

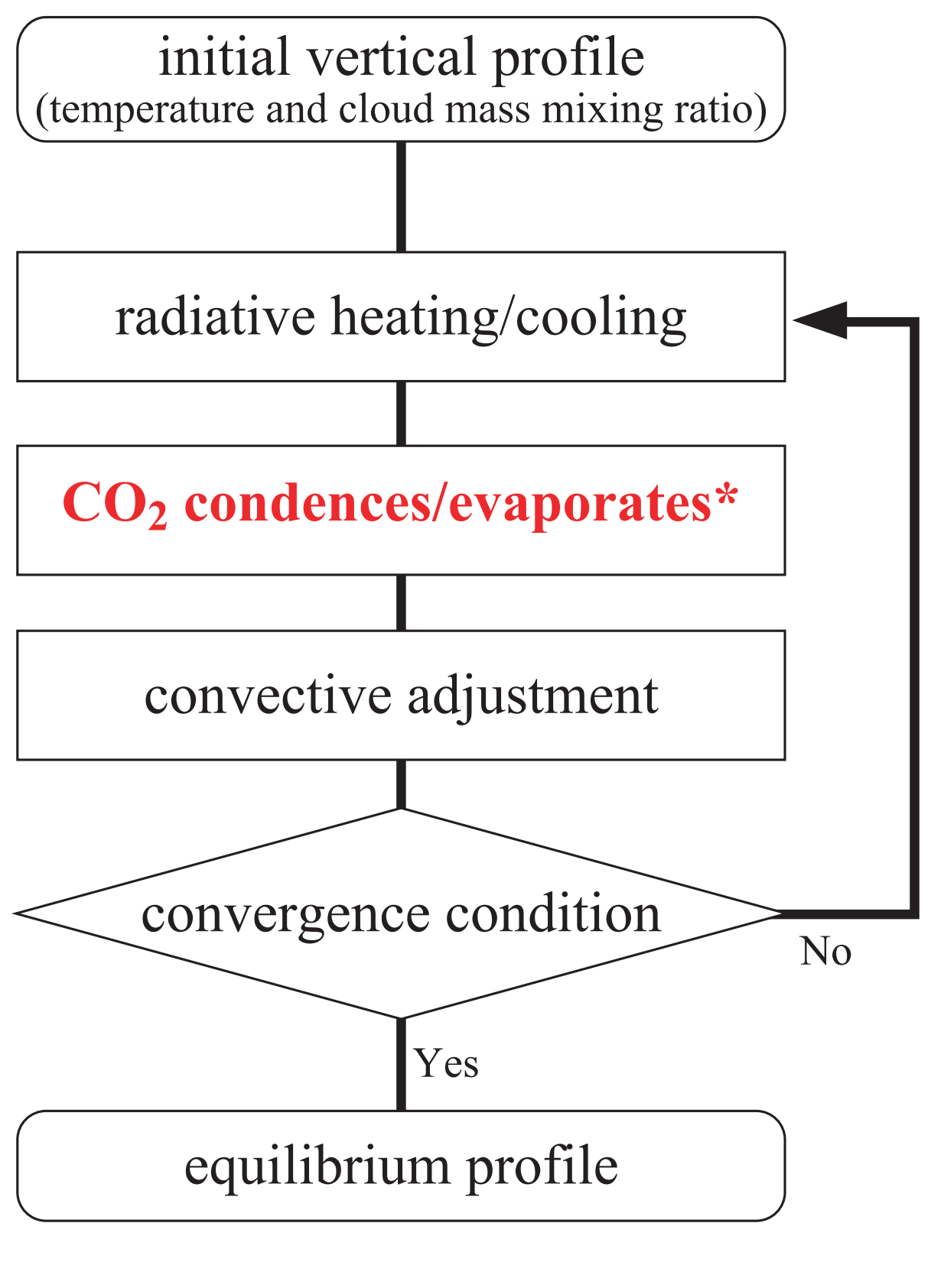
1-D radiative-convective model with cloud formation

Assumptions

- **condensation time << convective time**
  - + unstable stratification is inhibited by condensation
- **Cloud particles stay each level and do not coagulate each other.**
  - + CCN mixing ratio is kept constant in a run.
- Cloud particle size is uniform in each layer.

Radiative model (in detail; Mitsuda *et al.* 2006)

- Two-stream approximation (Toon *et al.* 1989)
  - + δ-Eddington approximation @solar radiation
  - + Hemispheric mean approximation @IR radiation
- Gaseous absorption: correlated k-distribution method
  - + CO_2, H_2O line absorption (HITRAN 2004 + HITEMP)
  - + CO_2 pressure-induced absorption (Kasting *et al.* 1984)
  - + H_2O continuum absorption (Roberts *et al.* 1976)
  - + CO_2 contiuum absorption (Mitsuda *et al.* 2006)
- Cloud absorption & reflection : Mie theory
  - + CO_2 pure ice (Warren 1986)



initial vertical profile
(temperature and cloud mass mixing ratio)

radiative heating/cooling

CO_2 condences/evaporates*

convective adjustment

convergence condition

No

Yes

equilibrium profile

Settings

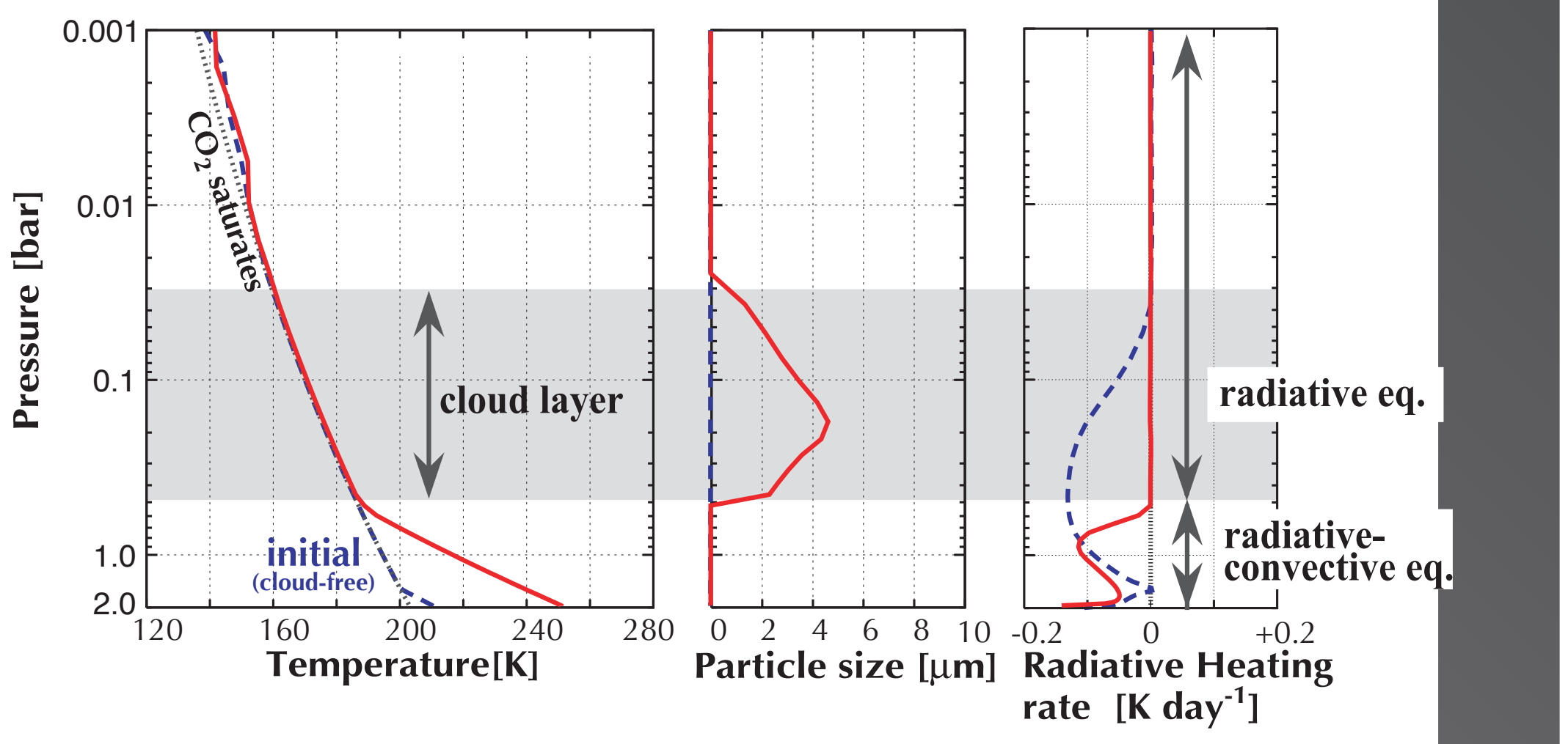
- atmospheric components: CO_2 and saturated H_2O
- layer number: 50
- surface albedo: 0.2
- solar luminosity: 75 % of the present value (Gough 1981)
- time step: 25 - 10^4 sec
- convergence condition: maximum dT/dt $< 10^{-8}$ K sec^{-1}
- parameters: surface pressure and CCN mixing ratio
- initial vertical profile:
  - + radiative-convective equilibrium profile at cloud-free condition

*CO_2 condensation scheme

- adjusts atmospheric temperature and cloud mass density to satisfy CO_2 gas-solid equilibrium.
- Condensed CO_2 is left at each altitude with forming CO_2 ice cloud.

Results1: temperature and cloud particle size profile

- Parameter set
  - + Surface pressure: 2 bar
  - + CCN mixing ratio: 10^7 kg^{-1}
- The cloud layer reaches the terminal state which satisfies radiative equilibrium
  - + cloud particle size (ave.) : 3.5 micron
  - + CO_2 icepath : 0.036 kg m^{-2}
    - Optical depth : 1.4 @ λ = 20 micron
  - + altitude : 15 – 40 km
  - + **Induced surface warming : 40 K**

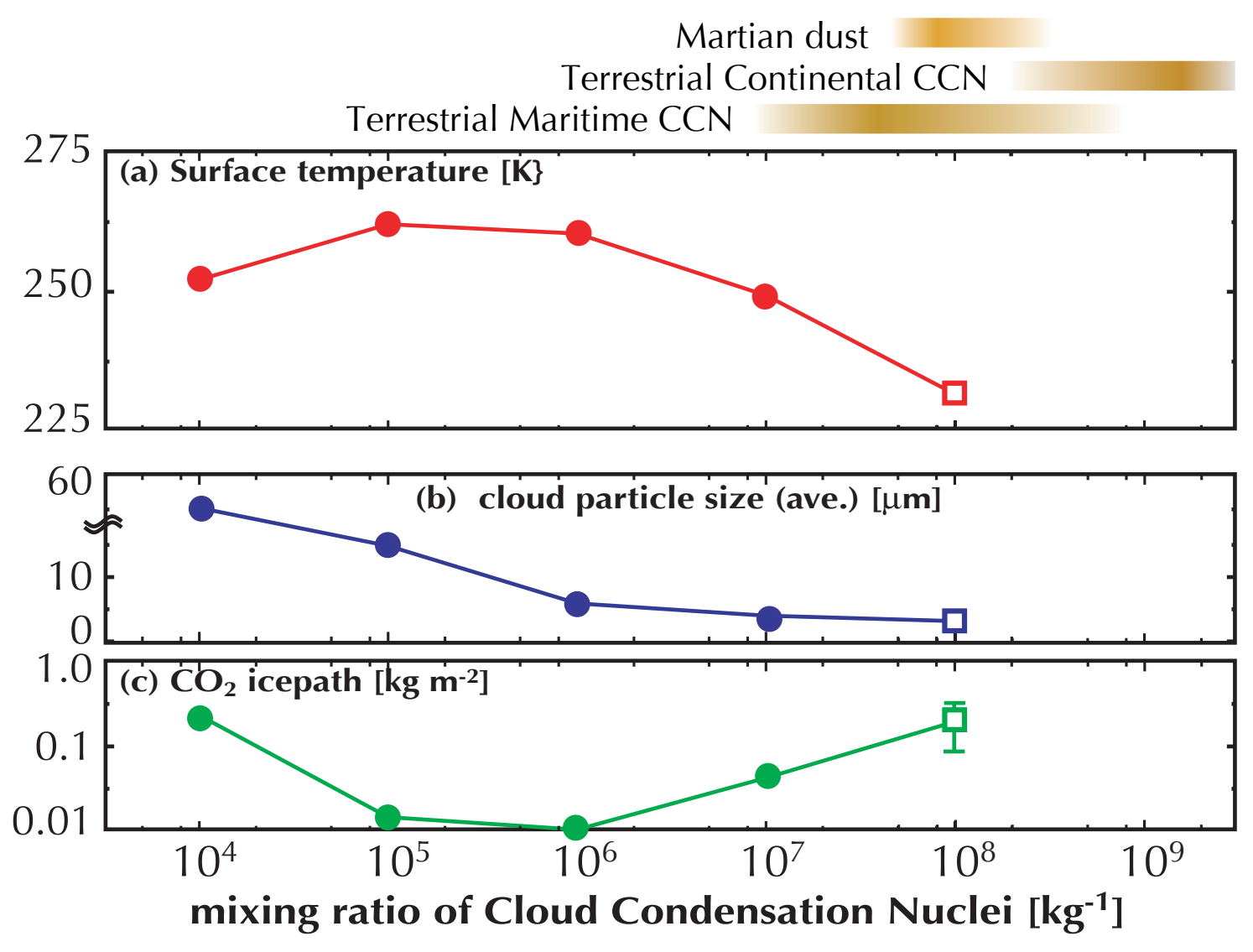


- **The negative feedback mechanism between the cloud particle size growth and cloud radiative cooling controls terminal particle size.**
- This feedback is caused by
  - + increase in the absorbance of the cloud layer with size growth,
  - + increase in incident infrared radiation to cloud from lower atmosphere.
    - As cloud particles grow over 2 up to 15 micron in size, the cloud induces stronger warming.

Results2: parameter dependency

on CCN mixing ratio

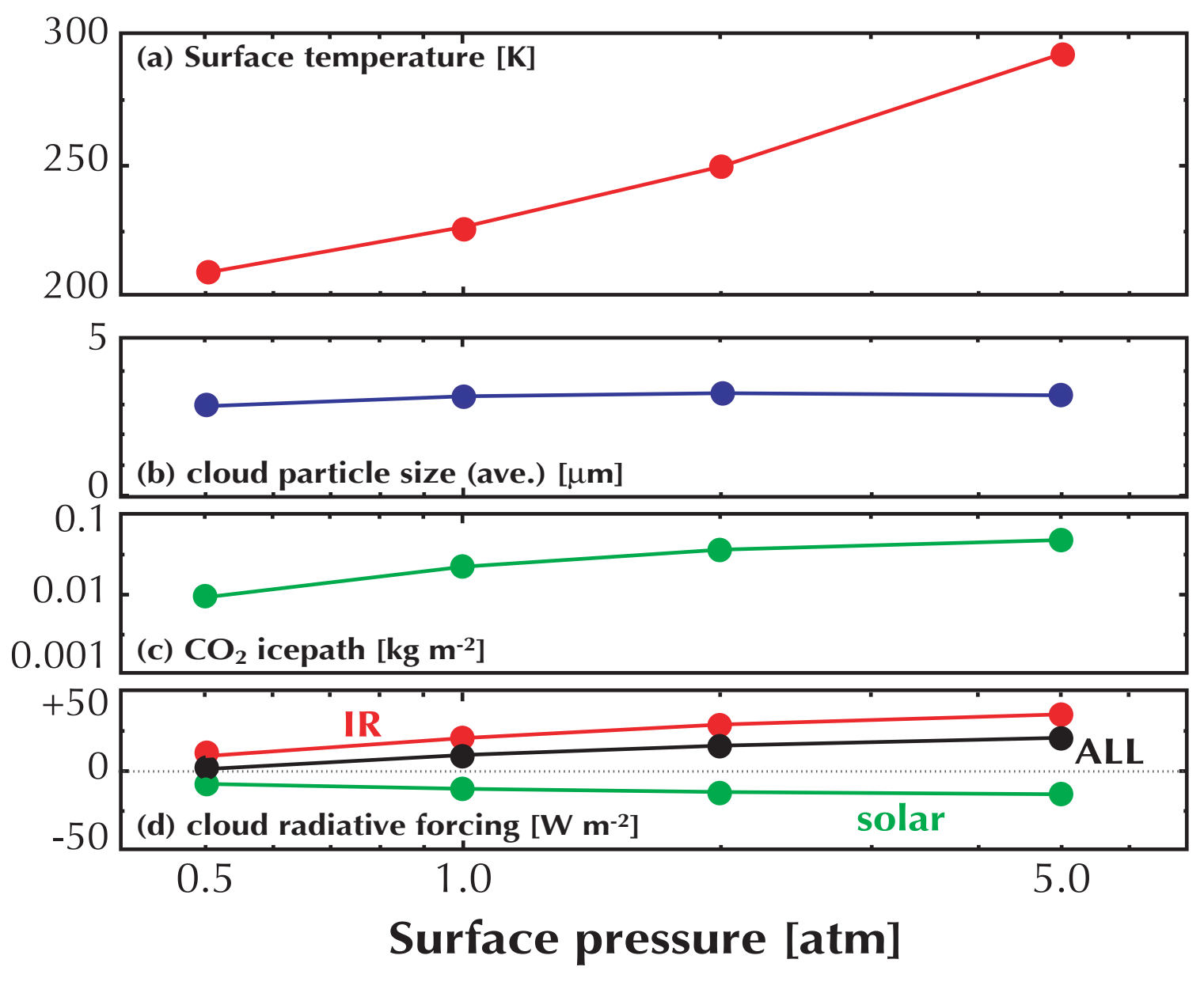
- With increasing the mixing ratio, terminal particle size decreases owing to increase in feedback response.
- Surface temperature takes maximal value at 10^5 kg^{-1}.
  - + Cloud has particle size adequate to reflect 20 micron band, one of the atmospheric window.
- CCN mixing ratio < 10^8 kg^{-1}
  - + **Atmosphere and cloud converge into terminal state.**
- CCN mixing ratio > 10^8 kg^{-1}
  - + **Cloud has oscillatory solution.**
    - Cloud becomes too optically thick to converge into terminal state.
    - Cloud oscillation little influences the temperature profile because oscillation period is much shorter than radiative relaxation time of troposphere.
- CCN mixing ratio > 10^9 kg^{-1}
  - + **CO_2 atmosphere condenses onto the surface resulting in the climate collapse.**
    - Cloud particle becomes too small to cause greenhouse effect.
    - The surface temperature cannot approach equilibrium value if it decreases to CO_2 condensation temperature.



Surface temperature (a), cloud particle size (b) and ice path (c) as functions of CCN mixing ratio for 2 bar atmosphere. The circles and the squares respectively show cloud convergence and ossiallaion solutions. Typical mixing ratios of CCN in the terrestrial atmosphere (Mizuno 2000) and dust in Martian atmosphere (Pollack *et al.* 1979) are shown for comparison.

on surface pressure

- The surface temperature increases with increasing the surface pressure.
  - + The CO_2 condensation level expands and the thicker cloud is formed.



Surface temperature (a), cloud particle size (b), ice path (c) and cloud radiative forcing (d, IR: < 4000 cm^{-1}, SLR: > 4000 cm^{-1}) as functions of surface puressure under constant CCN mixing ratio of 10^7 kg^{-1}. The format of this figure is same as upper one except the horizontal axis.

References

Colaprete, A. and Toon, O. B., 2003, *J. Geophys. Res.*, **108**, E4, 5025-5047
Gough, D. O., 1981, *Sol. Phys.*, **74**, 21–34
HITRAN2004/HITEMP, http://www.hitran.com
Jakosky, B. M. and Phillips, R. J., 2001, *Nature*, **412**, 237–244
Kasting, J. F., 1991, *Icarus*, **91**, 1–13
Kasting, J. F., Pollack, J. B. and Crisp, D., 1984, *J. Atmos. Chem.*, **1**, 403–428
Mischna, M. A., Kasting, J. F. and Freedman, R., 2000, *Icarus*, **145**, 546–554
Mitsuda, C., Yokohata, T. and Kuramoto, K., 2006, *Proc. of the 39th ISAS Lunar and Planetary Sympsium*, in press
Pierrehumbert, R. T. and Erlick, C., 1998, *J. Atmos. Sci.*, **55**, 1897–1903
Pollack, J. B., Colburn, D. S., Flasar, F. M., Kahn, R., Carlston, C. E. and Pidek, D., 1979, *J. Geophys. Res.*, **84**, 2929–2945
Pollack, J. B., Kasting, J. F., Richardson, S. M. and Polokaoff, K., 1987, *Icarus*, **71**, 203–224
Roberts, R. E., Biberman, L. M. and Selby, J. E. A., 1976, *Appl. Opt.*, **15**, 2085–2090
Toon, O. B., McKay, C. P., Ackerman, T. P. and Santhanam, K., 1989, *J. Geophys. Res.*, **94**, 16287-16301
Warren, S. G., 1986, *Appl. Opt.*, **25**, 2650–2674
Yokohata, T., Kosugita, K., Odaka, M. and Kuramoto, K., 2002, *Proceedings of the 35th ISAS Lunar and Planetary Syposium,* 13–16