

Stratospheric CO₂ ice cloud greenhouse for sporadic warming of early Mars

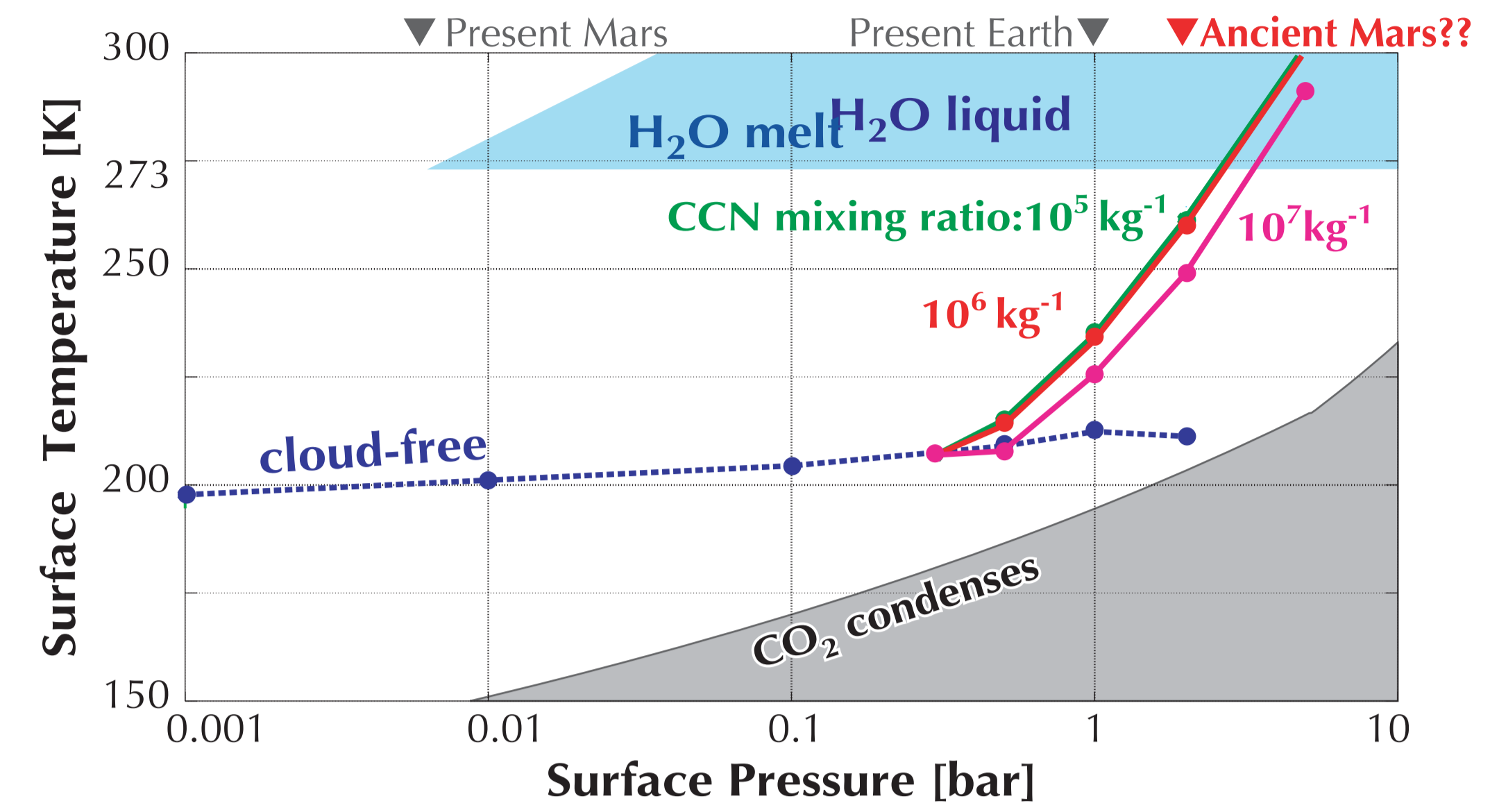
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Summary

The scattering greenhouse effect of CO₂ 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 CO₂-H₂O 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 CO₂ 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.

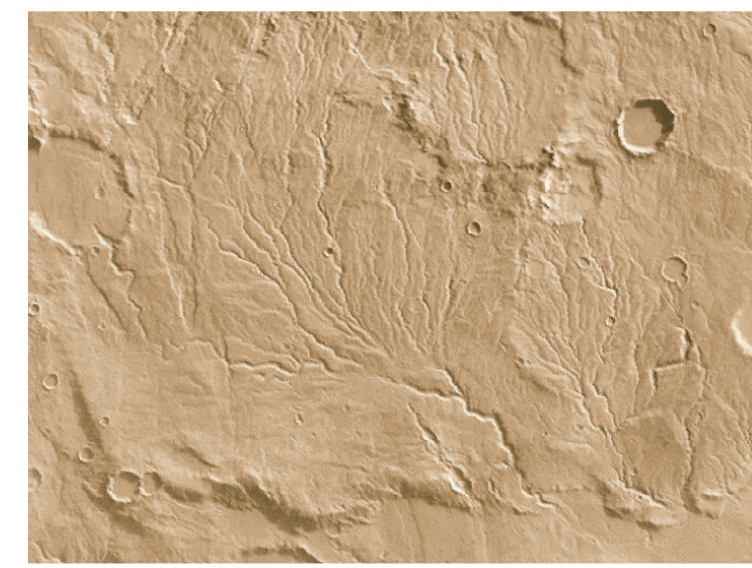


Relationship between the surface pressure and temperature of CO₂-H₂O atmosphere on early Mars. The solid curves include cloud formation owing to radiative cooling and the dash curve neglects it. The dot curve represents the saturation temperature of CO₂. The aqua region in the upper-right of figure represents the condition that liquid water exists stably.

Introduction

The scattering greenhouse effect of CO₂ ice cloud

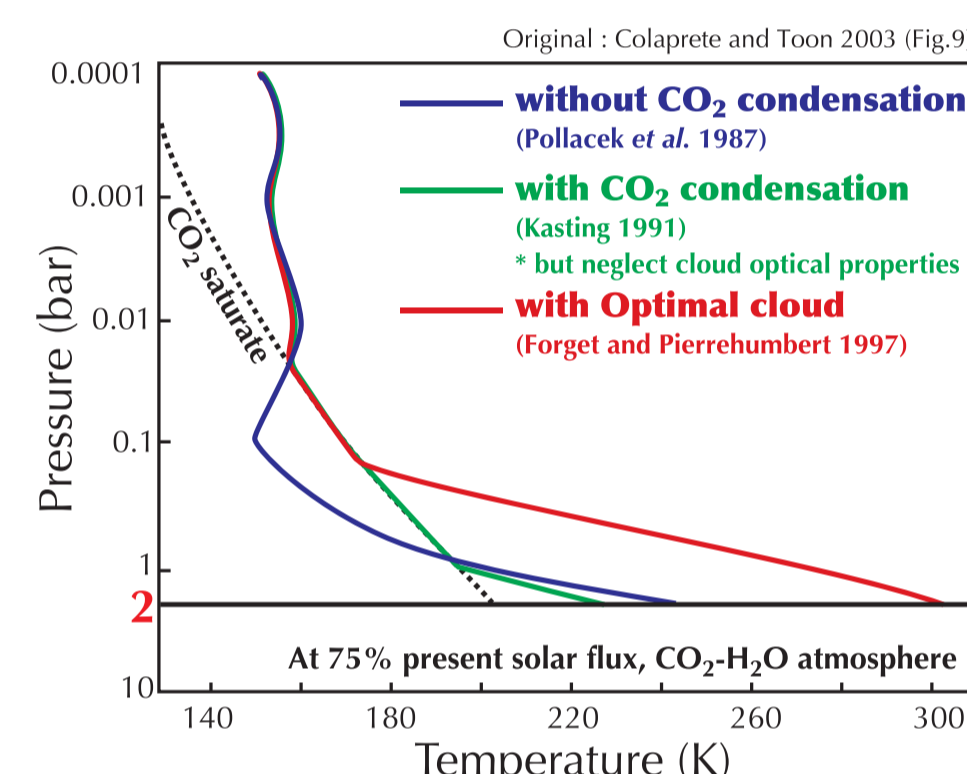
- is candidate mechanism to explain the warm climate which allows valley networks to form on early Mars.
- + The greenhouse effect of dense CO₂-H₂O atmosphere cannot simply explain the warm climate because the increase in temperature at upper troposphere due to CO₂ condensation would significantly weaken the greenhouse effect (Kasting 1991).



Valley networks

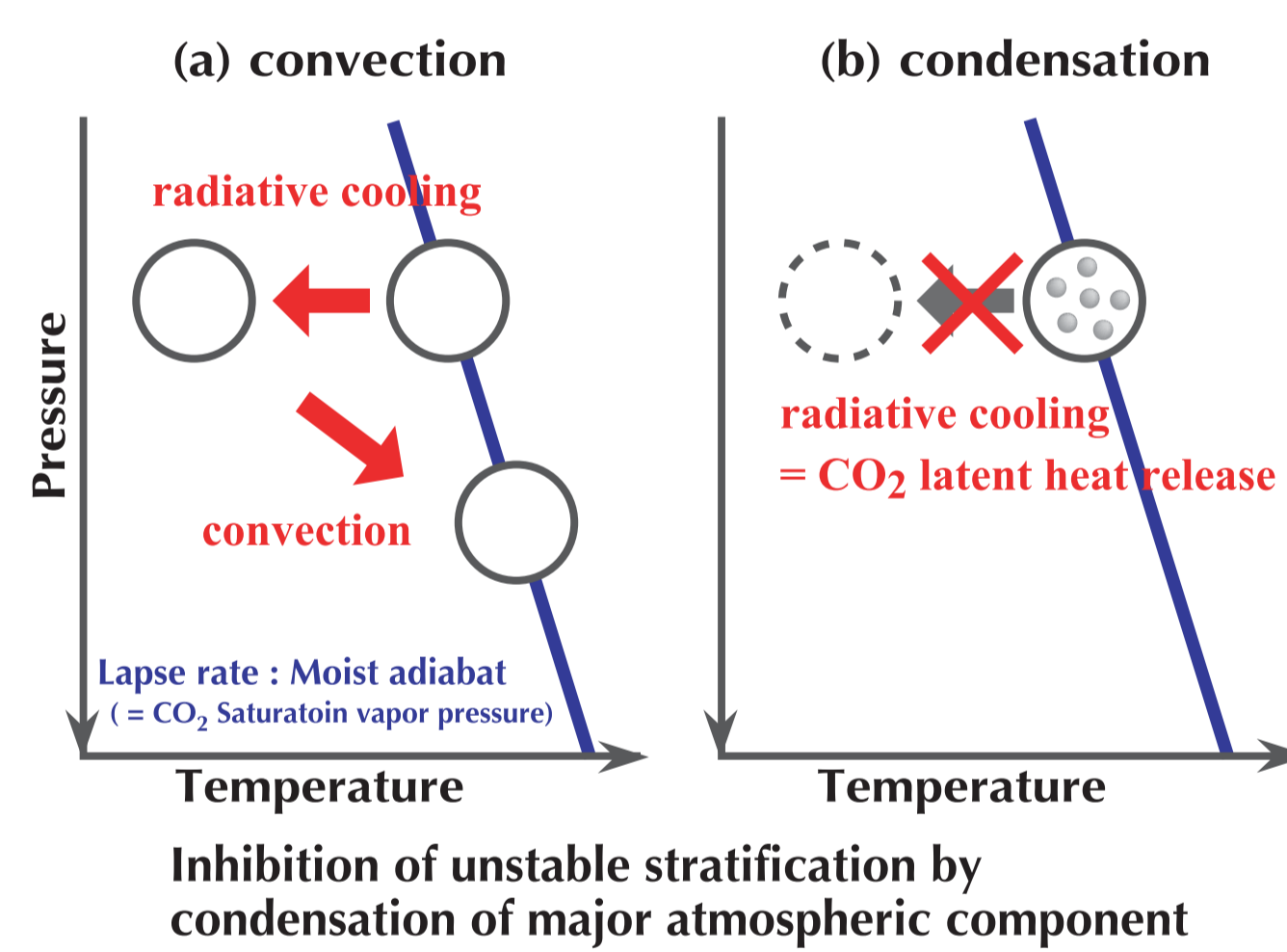
In previous studies (Pierrehumbert and Erlick 1998, Mischna et al. 2000)

- 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.



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 CO₂ is condensable.
- Latent heat release with CO₂ 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 CO₂ cloud layer.



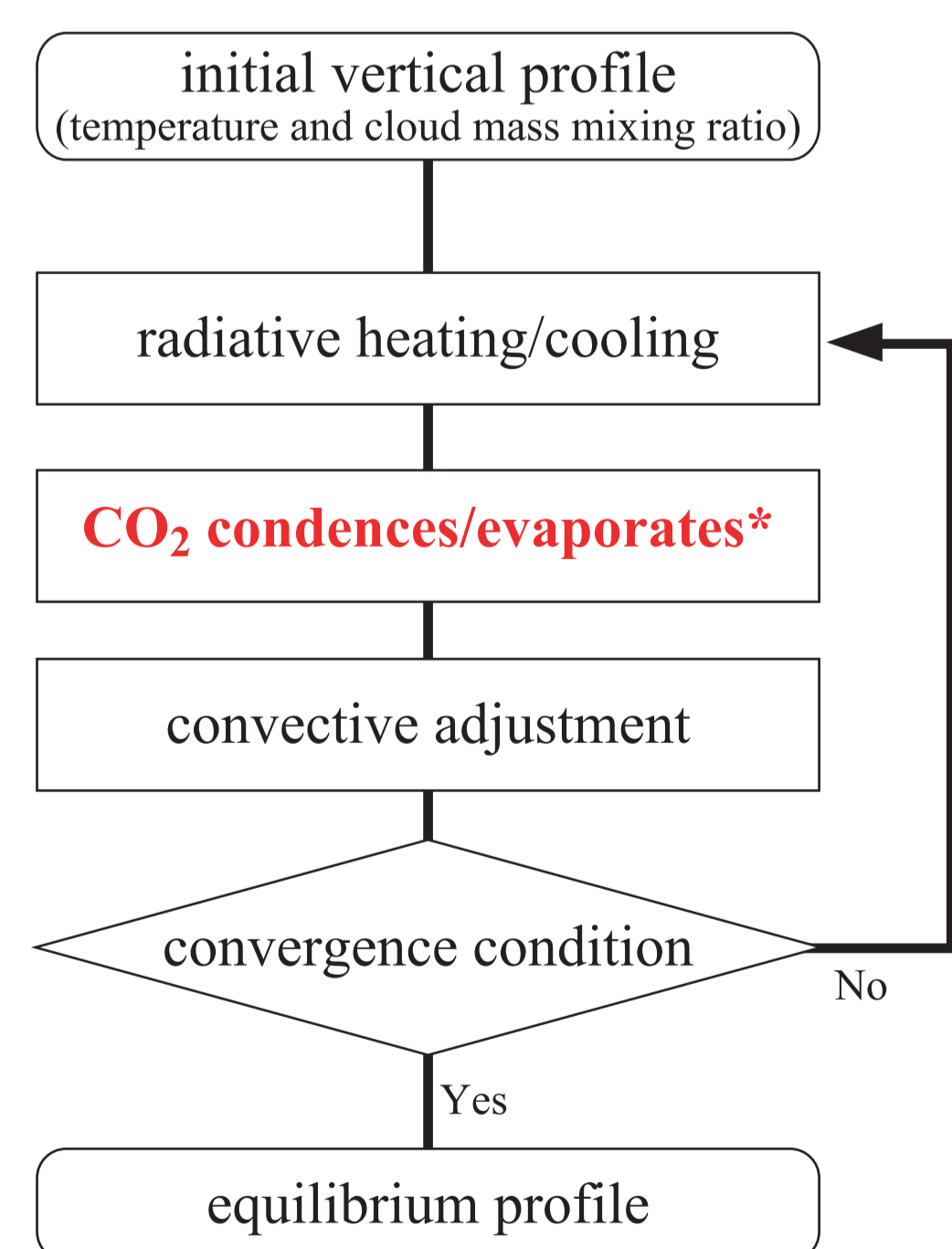
1-D radiative-convective model with cloud formation

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
- + CO₂, H₂O line absorption (HITRAN 2004 + HITEMP)
- + CO₂ pressure-induced absorption (Kasting et al. 1984)
- + H₂O continuum absorption (Roberts et al. 1976)
- + CO₂ continuum absorption (Mitsuda et al. 2006)
- Cloud absorption & reflection : Mie theory
- + CO₂ pure ice (Warren 1986)



*CO₂ condensation scheme

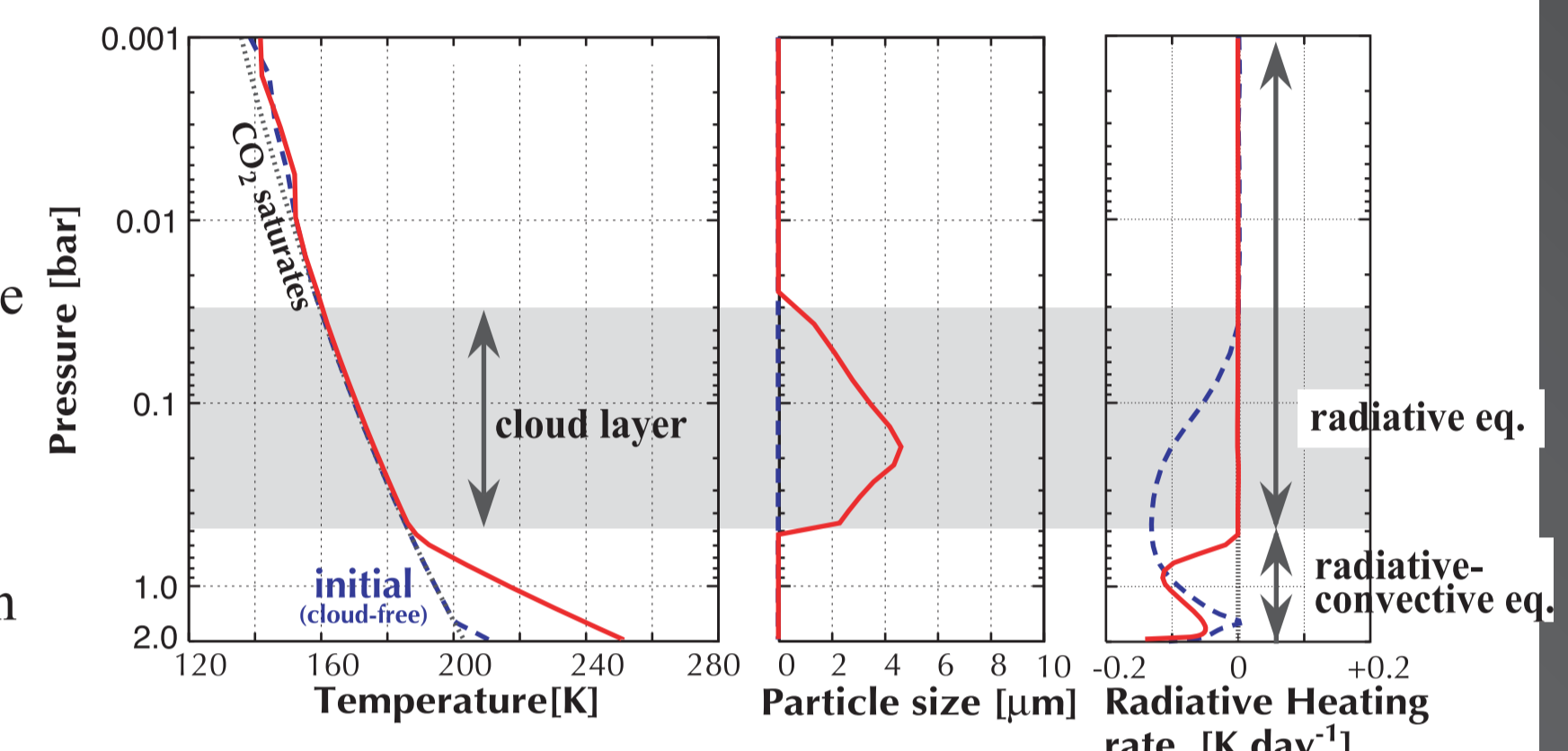
- adjusts atmospheric temperature and cloud mass density to satisfy CO₂ gas-solid equilibrium.
- Condensed CO₂ is left at each altitude with forming CO₂ ice cloud.

Settings

- atmospheric components: CO₂ and saturated H₂O
- layer number: 50
- surface albedo: 0.2
- solar luminosity: 75 % of the present value (Gough 1981)
- time step: 25 - 10⁴ 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

Results1: temperature and cloud particle size profile

- Parameter set
 - + Surface pressure: 2 bar
 - + CCN mixing ratio: 10⁷ kg⁻¹
- The cloud layer reaches the terminal state which satisfies radiative equilibrium
 - + cloud particle size (ave.): 3.5 micron
 - + CO₂ icepath : 0.036 kg m⁻²
 - Optical depth : 1.4 @ λ = 20 micron
 - + altitude : 15 - 40 km
 - + **Induced surface warming : 40 K**



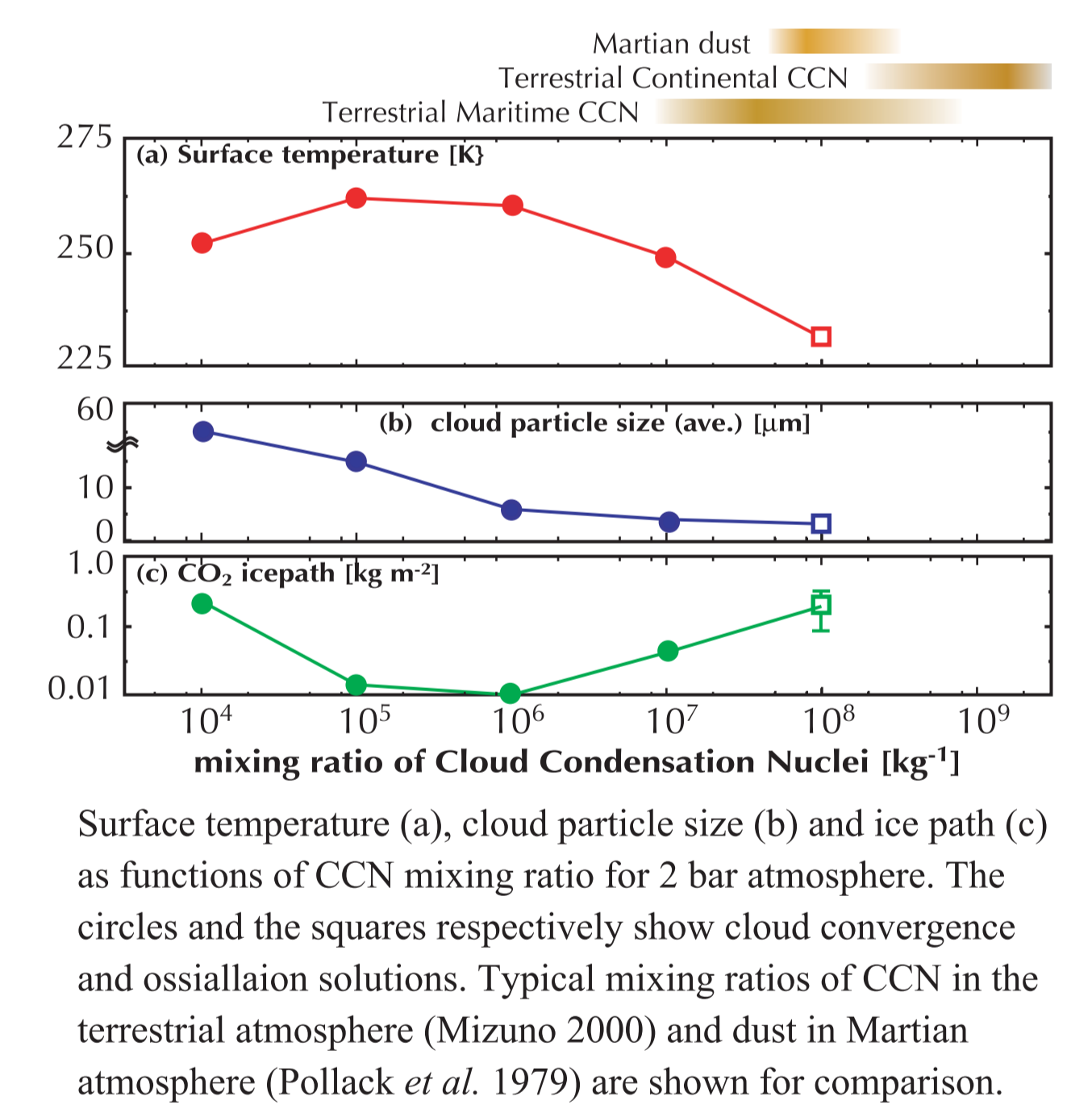
- The negative feedback mechanism between the cloud particle size growth and cloud radiative cooling controls terminal particle size.

- 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

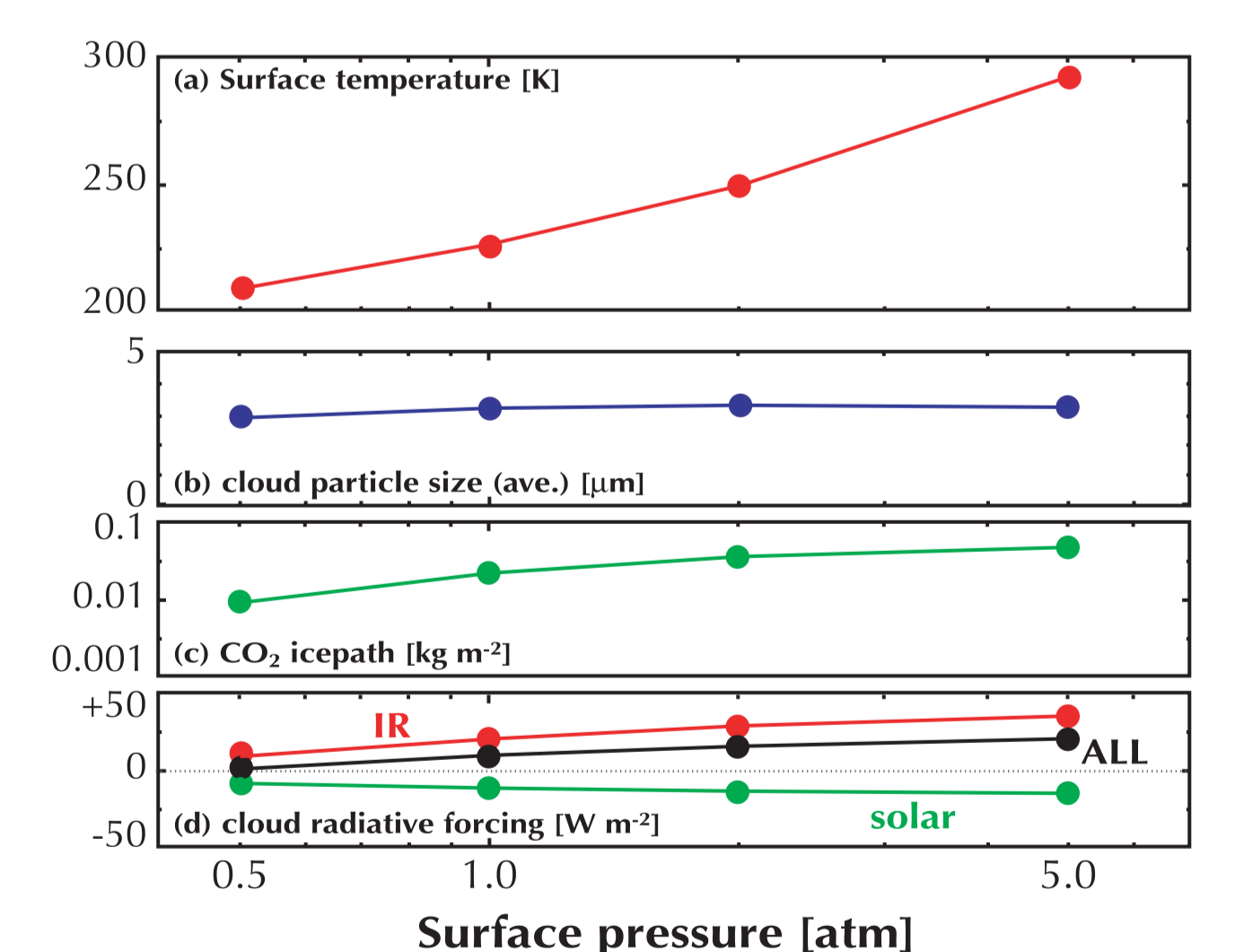
- With increasing the mixing ratio, terminal particle size decreases owing to increase in feedback response.
- Surface temperature takes maximal value at 10⁵ kg⁻¹.
 - + Cloud has particle size adequate to reflect 20 micron band, one of the atmospheric window.
- CCN mixing ratio < 10⁸ kg⁻¹
 - + **Atmosphere and cloud converge into terminal state.**
- CCN mixing ratio > 10⁸ 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 > 10⁹ kg⁻¹
 - + **CO₂ 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 CO₂ 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 oscillation 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 CO₂ 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 pressure under constant CCN mixing ratio of 10⁷ kg⁻¹. The format of this figure is same as upper one except the horizontal axis.

References

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