The greenhouse effect of CO_2 ice clouds and climate stability on early Mars

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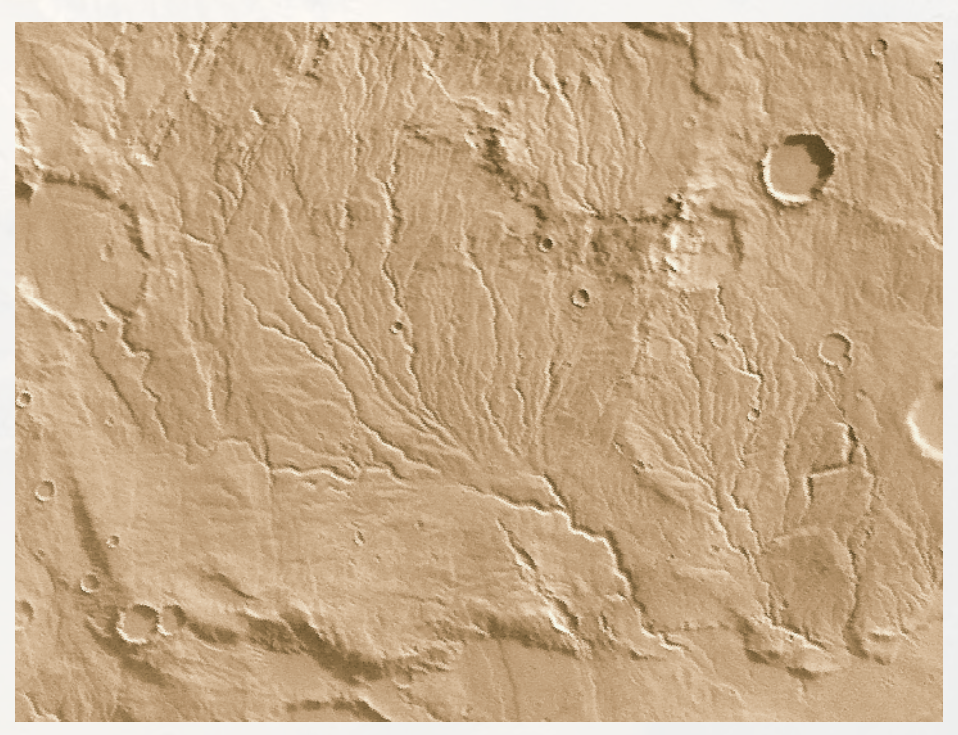
Abstract

The scattering greenhouse effect of CO_2 ice clouds has been proposed as a mechanism to make the Martian climate warm enough to support flowing water under faint young Sun. We construct a one-dimensional radiative model for the CO_2-H_2O atmosphere and analyze cloud stability on the basis of the numerical estimation of the ice condensation or evaporation rate in a cloud layer. Our numerical analysis suggests that CO_2 ice cloud layer is stabilized and the global mean surface temperature rises above melting point of H_2O when the atmospheric pressure is larger than 1 bar and the number column density of cloud condensation nuclei is kept at nearby 10^{10} m^{-2}. A negative feedback mechanism between the particle size change and the CO_2 condensation rate may stabilize warm climate on early Mars.

1. Introduction: The faint young Sun paradox on Mars

Early Mars climate : warm and wet ?

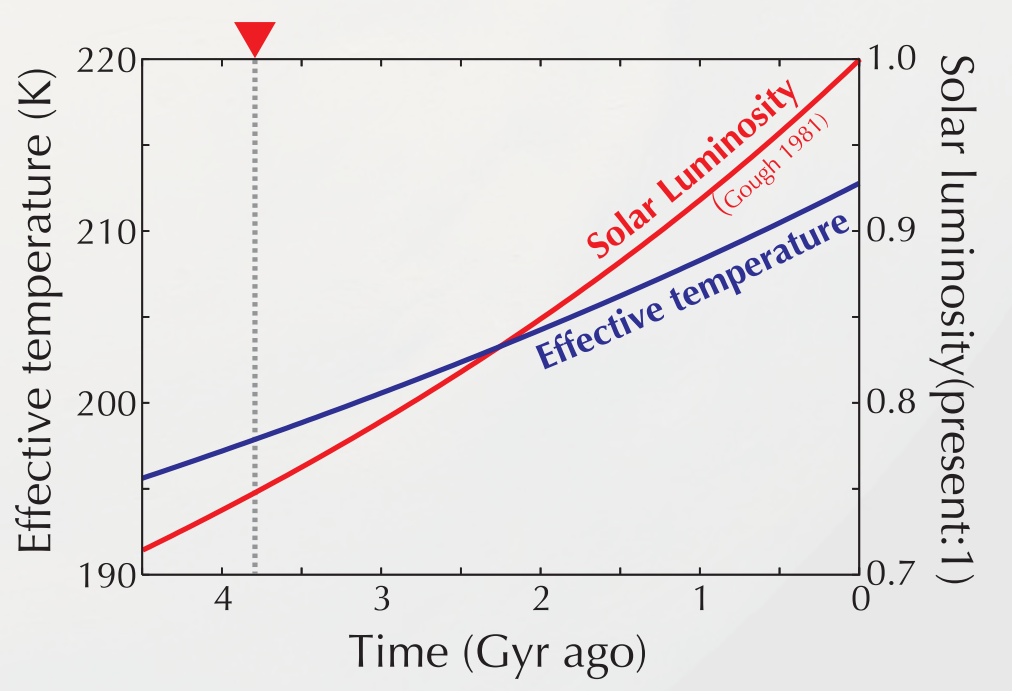
- Geomorphological evidences suggest
  - + Valley networks might be formed by groundwater supping
    - surface temperature $\gtrsim$ 273 K is required
- But **young Sun was dark** (E.g. Gough 1981)
  - + warm climate needs strong greenhouse effect: **80 K** at 3.8 Gyr ago
    - present Mars: 2 K, Earth: 24 K, Venus: 520 K (Houghton 2002)



Valley networks(~ 3.8 Gyr)

What can make climate warm on early Mars ?

- Dense CO_2 atmosphere
  - + CO_2 is photochemically stable
  - + But CO_2 condensation at upper troposphere would weaken the greenhouse effect under the faint young Sun (Kasting 1991)
- Minor Components: CH_4, NH_3, SO_2 and so on
  - + But they are decomposed by photolysis rapidly (Pollack 1979)
- **The scattering greenhouse effect of CO_2 ice clouds**

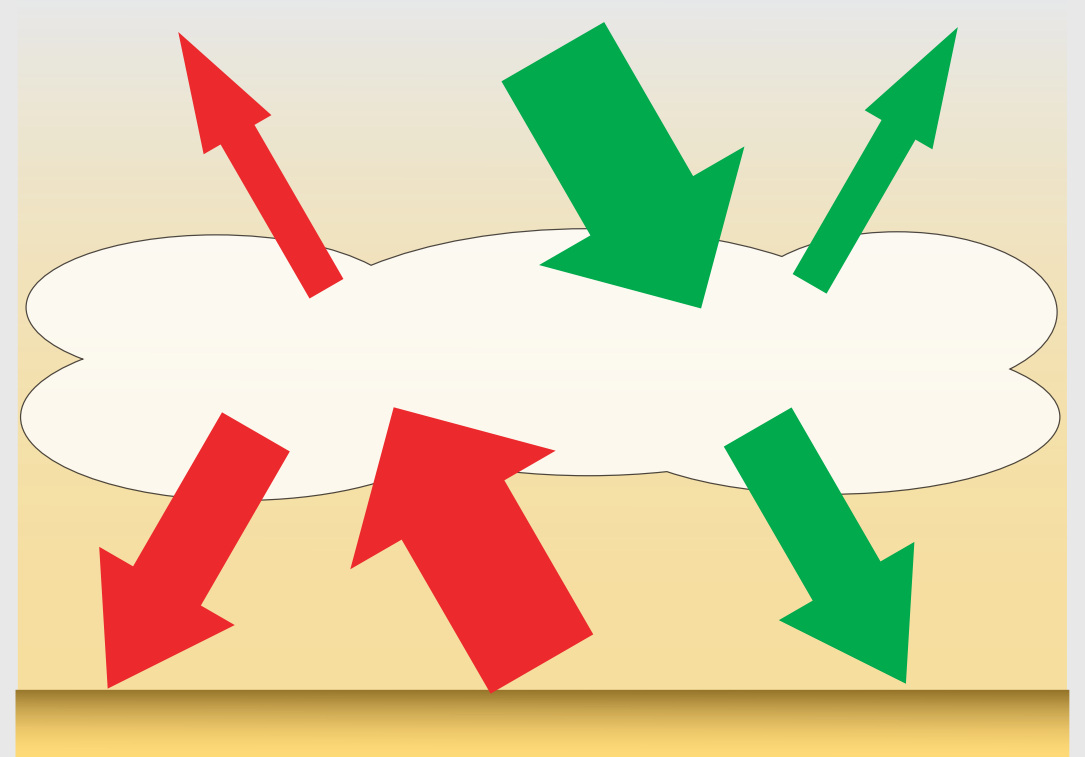


Solar luminosity and effective temperature evolution
* We assume planetary albedo have been constant, 0.216. (Kieffer *et al.* 1977)

2. The scattering greenhouse effect of CO_2 ice clouds

Mechanism

If the backward scattering of the infrared radiation is larger than that of solar radiation by the CO_2 ice clouds, climate becomes warm.



Scattering greenhouse effect of clouds
Clouds reflect IR radiation > Solar radiation

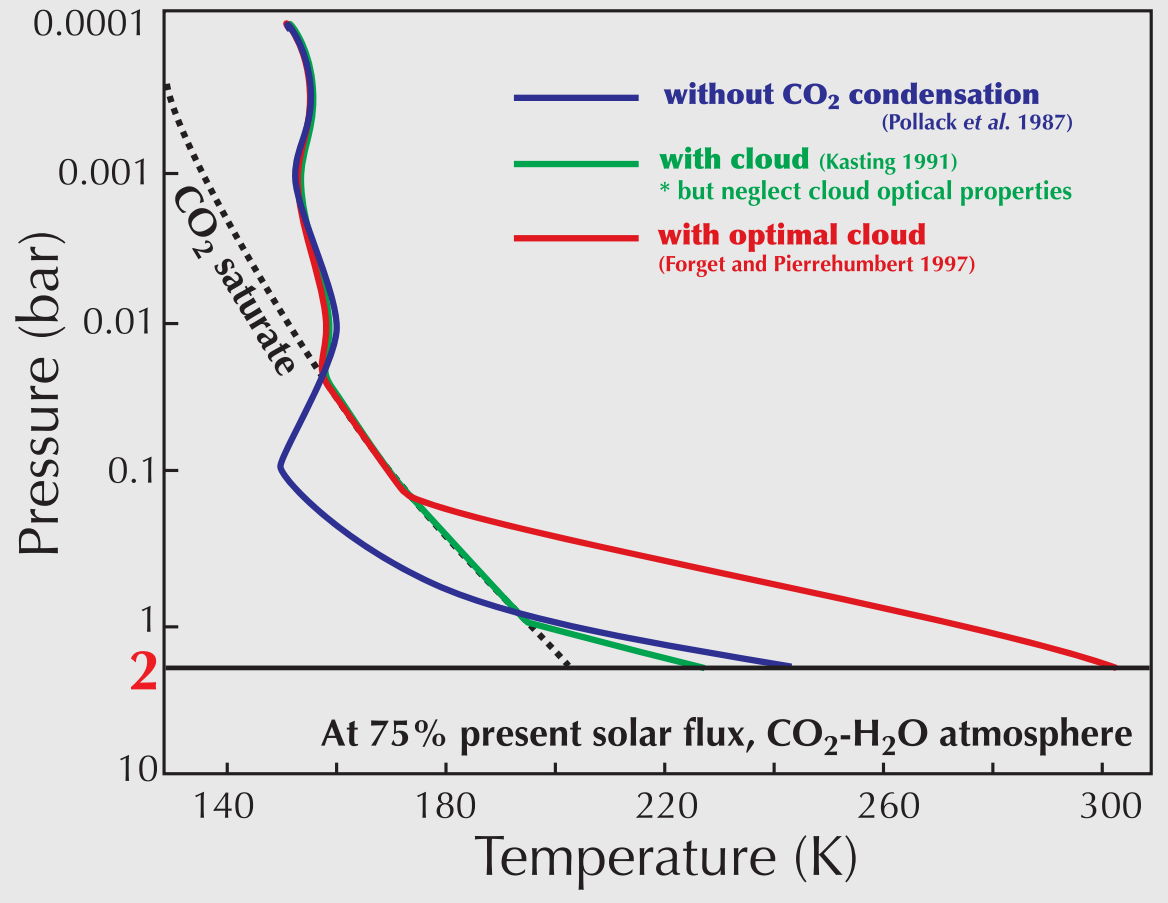
Previous studies have shown (Mischna *et al.* 2000, Yokohata *et al.* 2002)

- the strength of greenhouse effect strongly depends on the cloud parameters such as particle size, optical depth and so on.
- **warm climate is possibly achieved** for suitable ranges of cloud parameters
  - + cloud particle size : 7.5 - 20 μm (effectively reflect IR radiation)
  - + cloud column mass density : 10^{-1} – 1 kg m^{-2}

HOWEVER,

it has been poorly examined whether or not such the suitable cloud layer could exist stably

Original : Colaprete and Toon 2003 (Fig.9)



Calculated vertical temperature profile

What make cloud status change ?

- collision and coalescence of particles
- evaporation as settling of particles
- **evaporation (condensation) by radiative heating (cooling)**

In this study :

We focus on the influence of radiative heating on CO_2 ice clouds especially and estimate cloud particle size and optical depth to examine the scattering greenhouse effect of CO_2 ice clouds

3. 1-D radiative transfer model

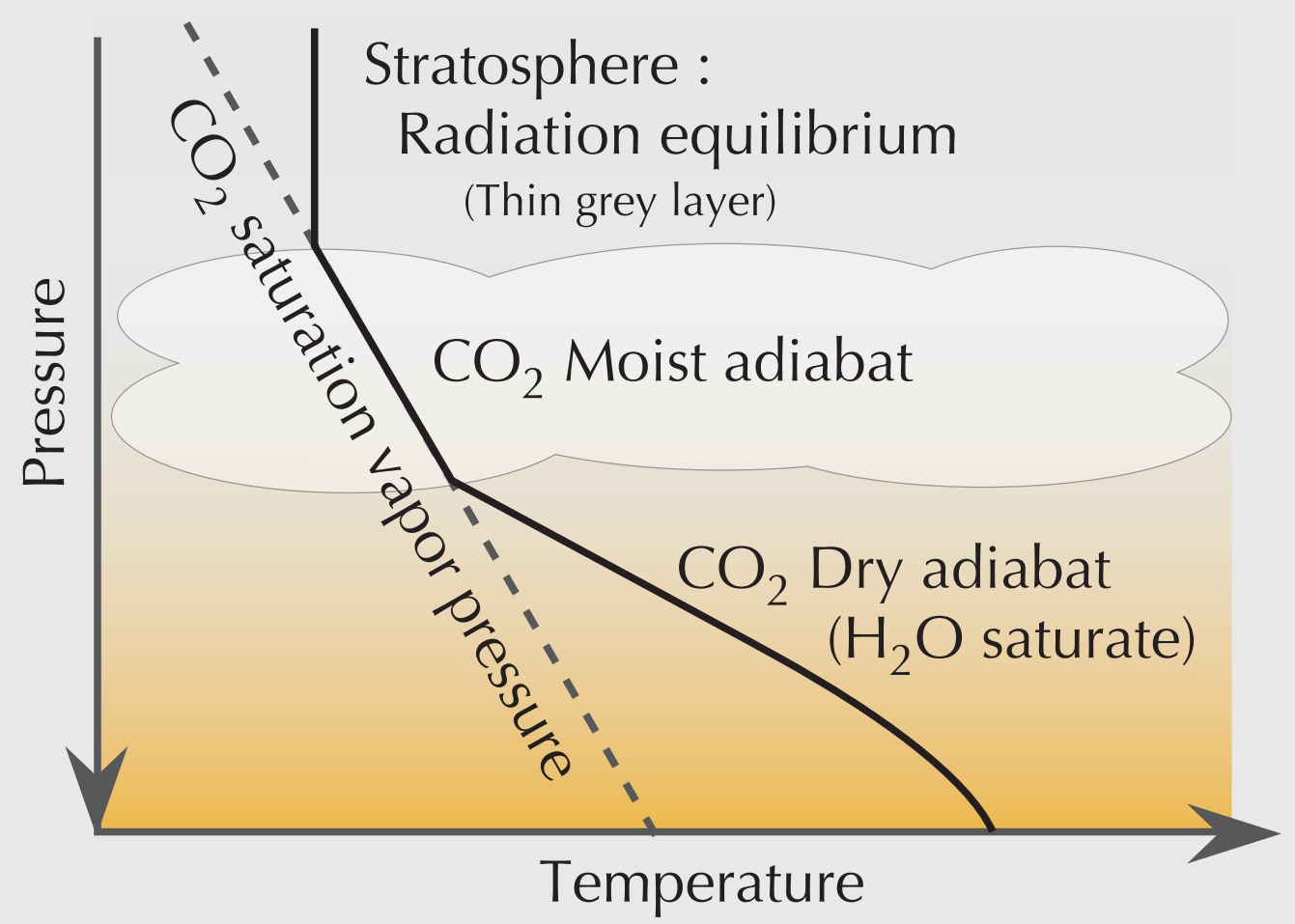
Atmospheric components : CO_2, H_2O

Radiative transfer

- Two-streem approximation
  - δ-Eddington approximation for scattering layer
- gaseous absorption for infrared radiation
  - Line-by-line method
    - absorption line parameters : HITRAN2000
  - Random model (for cloud layer)
    - band parameter : Houghton 2002
- cloud scattering and absorption
  - Mie scattering theory
    - complex indices of CO_2 ice : Warren 1986

Given variables

- Atmospheric pressure, Surface temperature
- Cloud
  - uniform particle size
  - column number density of condensation nuclei
    -> cloud column mass density



Assumed vertial temperature profile
(refer to result of I-D radiative-convective model calculation, Kasting 1991)

Input parameters

- Solar luminosity : 75 % as present (Gough 1981)
- Surface albedo : 0.216 (Kieffer *et al.* 1977)

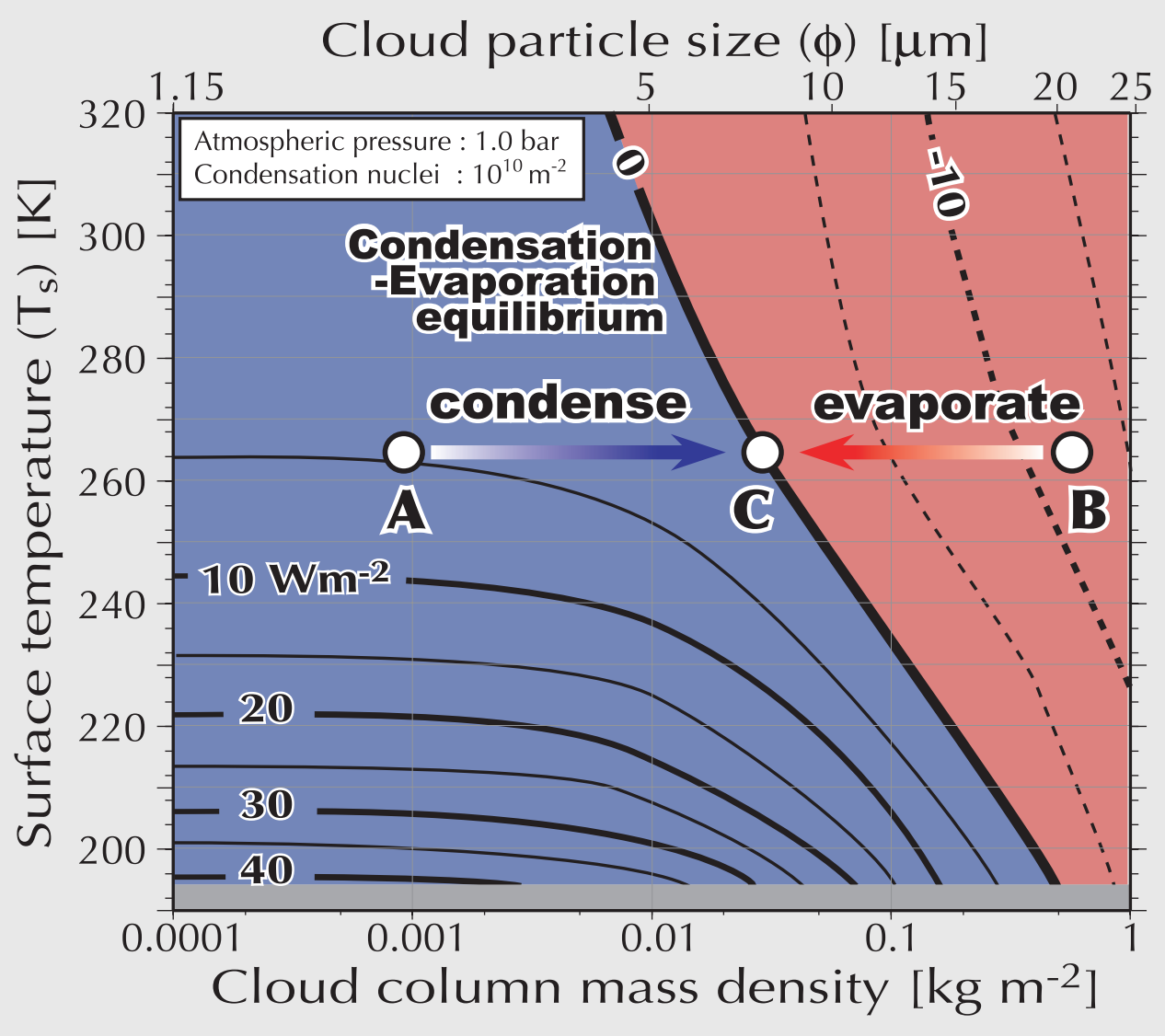
We estimate the CO_2 condensation rate which is balanced with the radiative cooling rate in the cloud layer and examine the diretion of cloud particle size change

4. Results and Discussion

4.1 The CO_2 condensation rate

An inverse correlation between the particle size and the codensation rate is observed

- denser clouds receive stronger radiative heating
- This correlation is important.
  - + **a negative feedback mechanism between the particle size and the condensatoin rate is expected** if surface temperature changes are neglected
    - If cloud particles are small (Ex. Point A), the particles grow owing to radiative cooling.
    - If cloud particles are large (Ex. Point B), the particles evaporate owing to radiative heating.



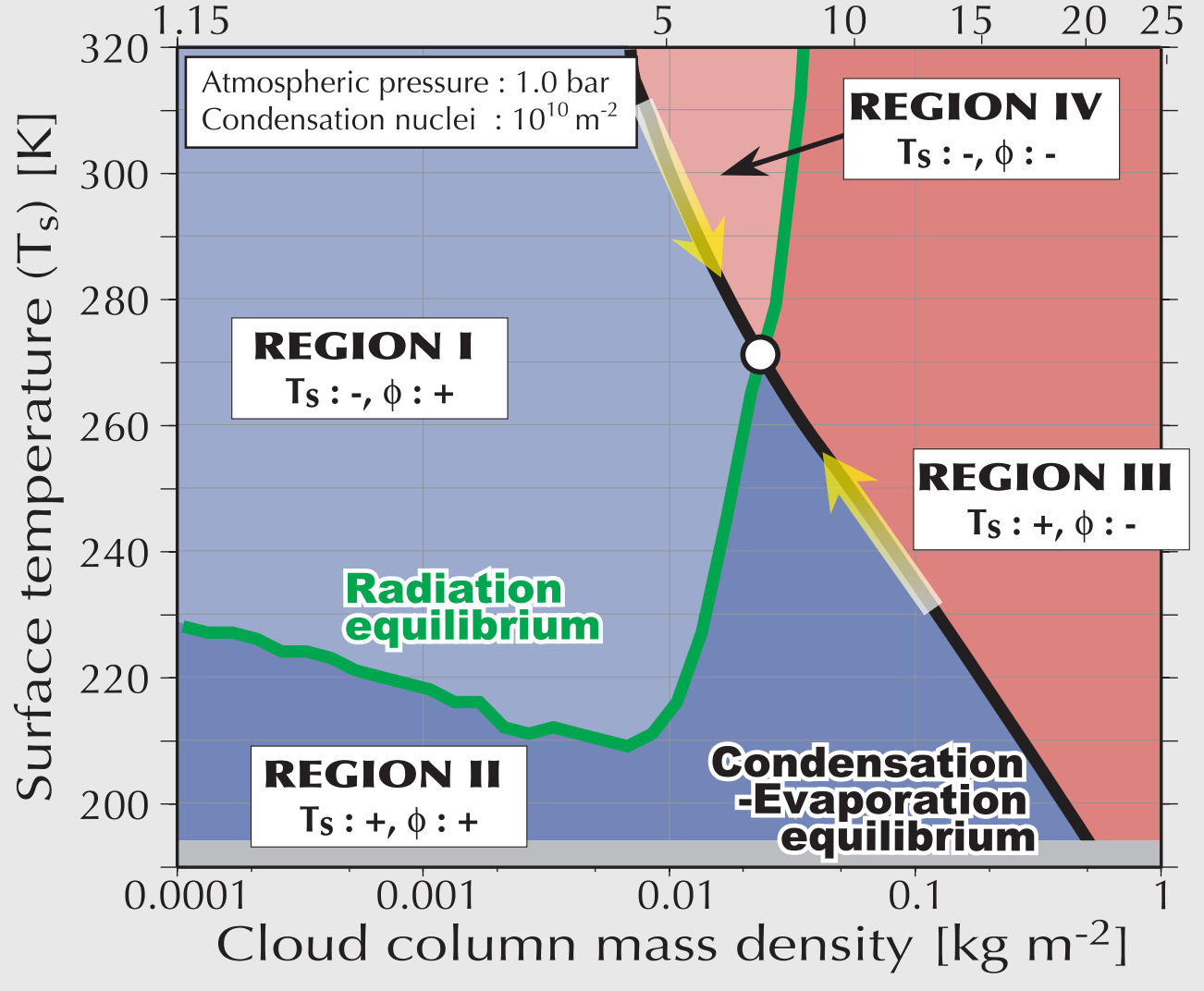
The CO_2 condensation rate at various surface temperature and cloud particle size calculated.

The particle size may approach an equilibrium value at which the condensation-evaporation equilibrium is achieved.

4.2 Estimation of equilibrium surface temperature

The equilibrium surface temperature

- is estimated assuming that the condensation-evaporation (CE) equilibrium and the radiative balance of Mars are simultaneously satisfied
- is uniquely determined if surface pressure and the number of condensation nuclei are kept to be constant
- **is actually achieved**
  - + relaxation time : CE equilibrium << radiative equilibrium
    - First, particle size approaches the state where CE equilibrium is achieved owing to the positive or negative condensation rate
    - Next, the particle size and surface temperature change to state which radiative equilibrium is achieved owing to radiative equilibrium of Mars
    - Finally, the equilibrium surface temperature is archived



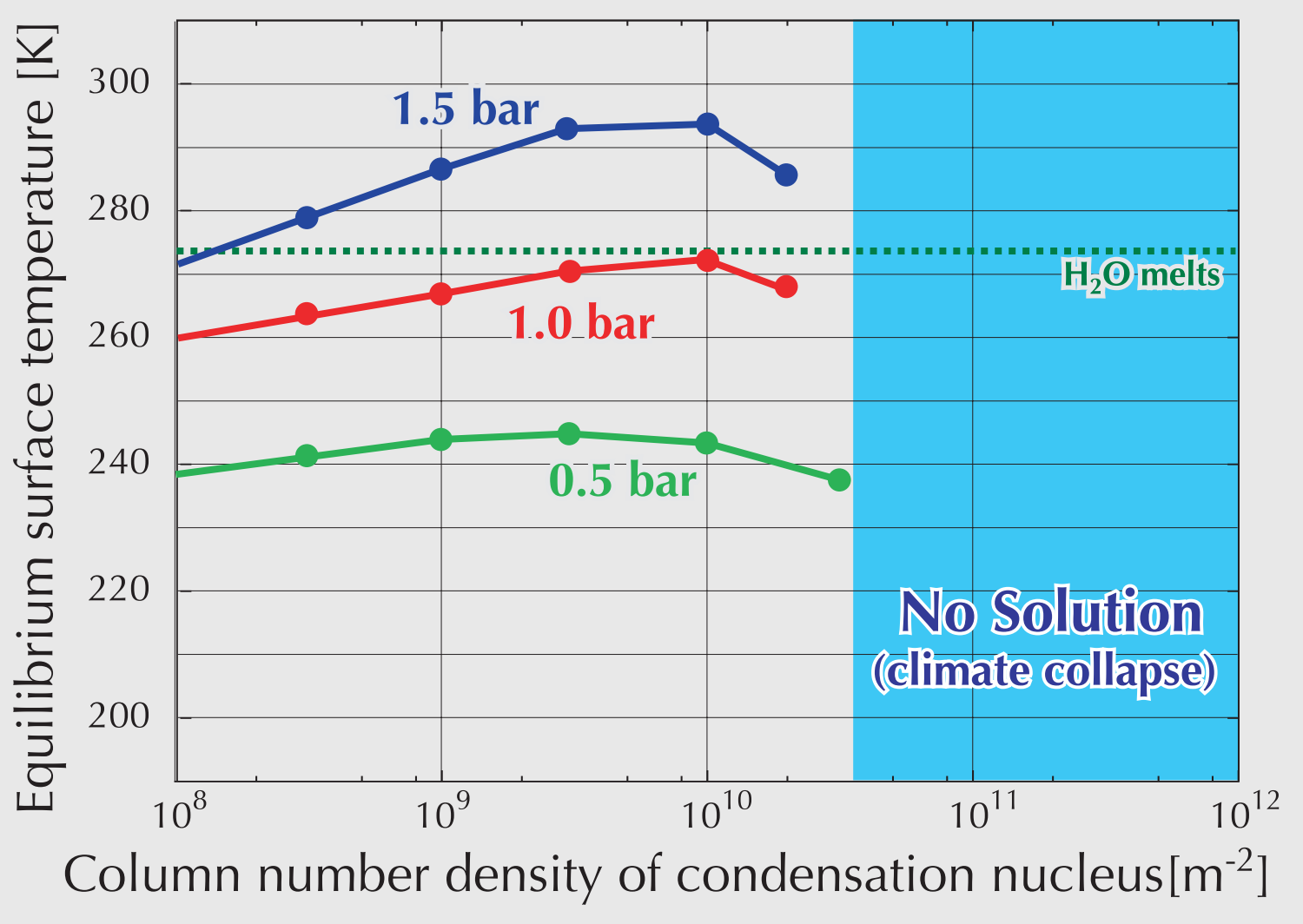
The cloud particle – surface temperature condition for each of equilibriums. We show directions of change in the cloud particle size (ϕ) and surface temperature (T_S) which are estimated by CO_2 condensation rate and radiation budget of Mars, respectively.

At the equilibrium states clouds are stable against the disturbances of the particle size and surface temperature.

4.3 Effect of number of condensation nuclei and atmospheric pressure

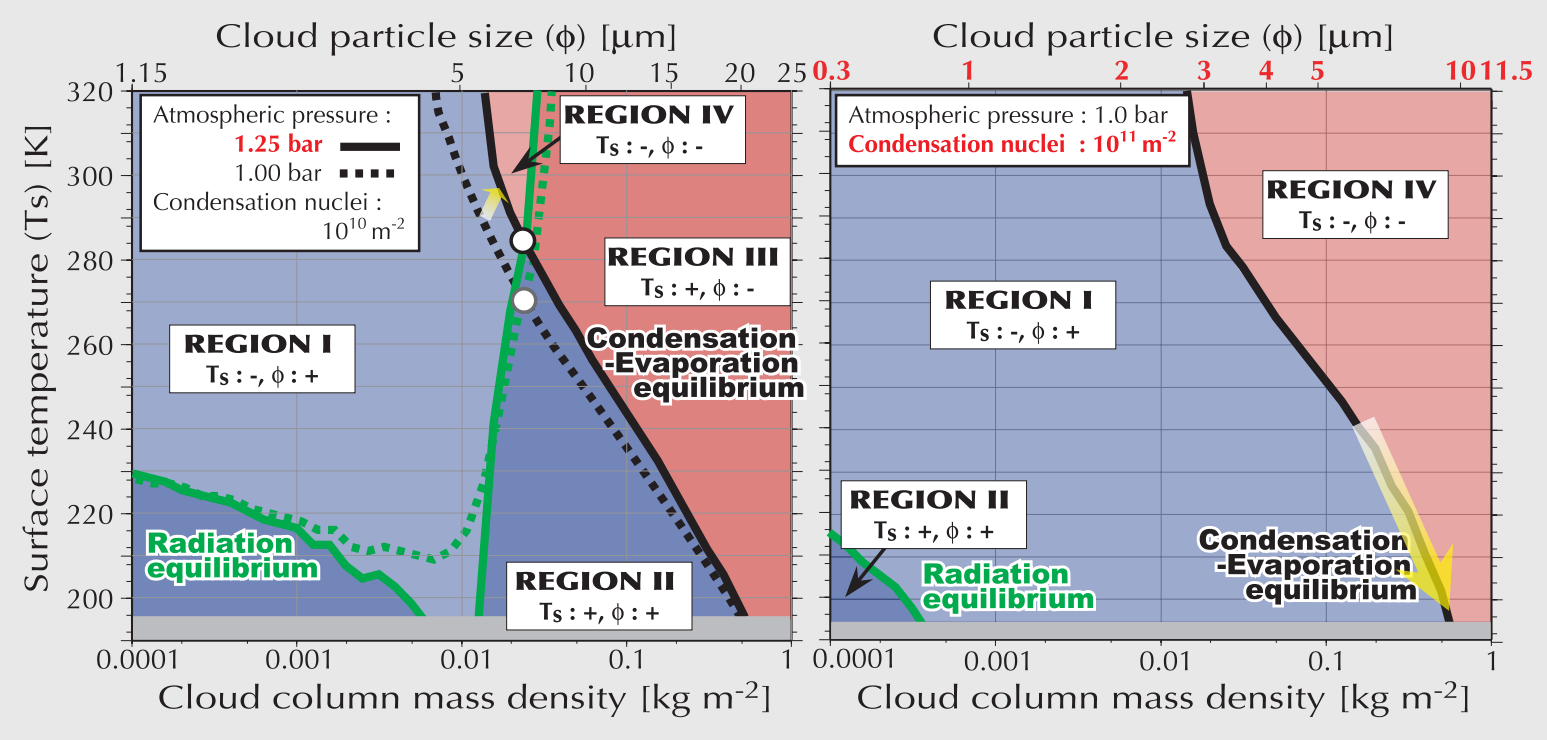
Dependency on atmospheric pressure

- The greenhouse effect is intensified with increasing the surface pressure from 0.5 to 1.5 bar
- As the surface pressure increases under the fixed surface temperature and the particle size, the condensation rarte tends to increase because the thermal emission from a cloud layer increases
- The conditions for CE equilibrium shift to those with denser clouds and higher surface temperature



Dependency on number of condensation nuclei

- column number density < 10^{10} m^{-2}
  - + The equilibrium surface temperature can rise nearby H_2O melting point at the atmospheric pressure 1 bar
- column number density > 10^{11} m^{-2}
  - + There is no equilibrium surface temperature
    - The cloud particles becomes too small to cause greenhouse effect
    - In this case, a CO_2 atmosphere condenses on the surface and the atmospheric pressure decrease



Necessary conditions for the warm and wet climate on early Mars :
- **The atmospheric pressure > 1 bar**
- **Column number density of condensation nuclei $\lesssim 10^{10}$ m^{-2}**

4.4 Influence of minor gases

CH_4 is the most important minor gas for early Martian climate

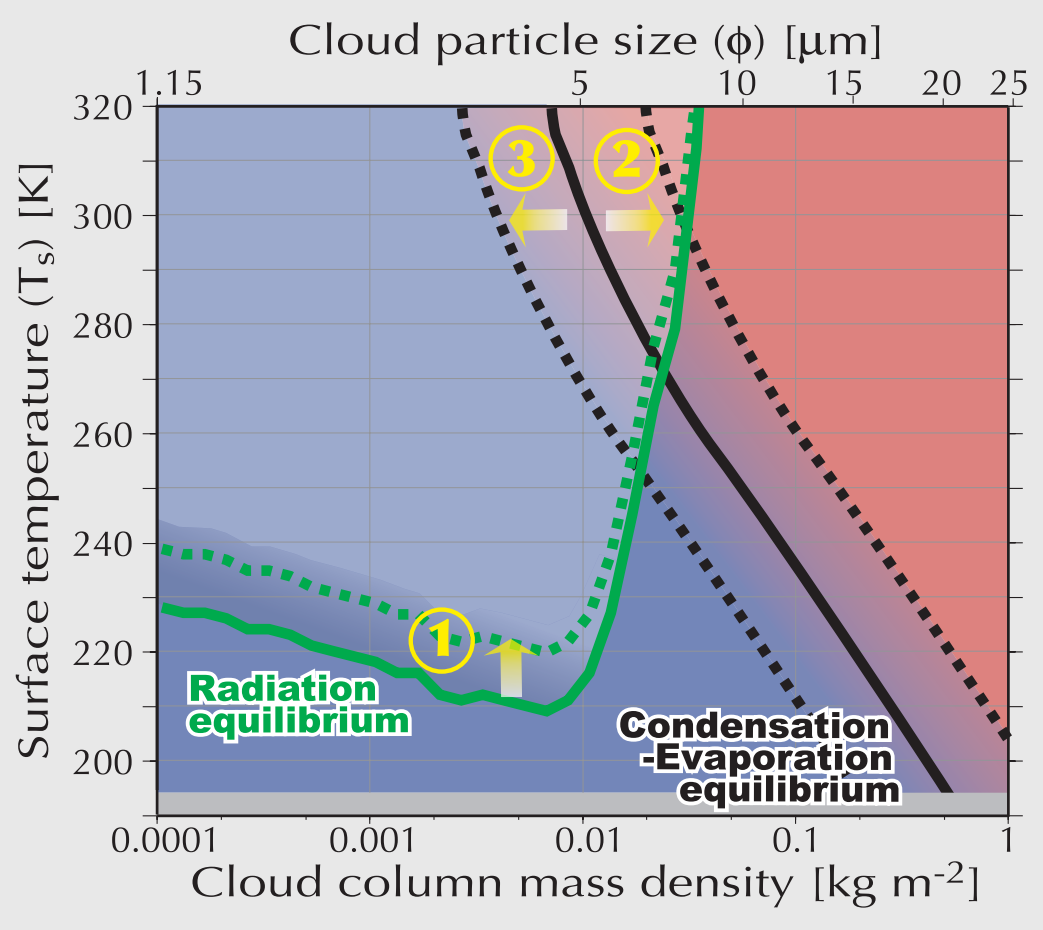
- originated by volcanic process, biological source and so on (e.g. Kasting, 1997)
- optically active in both infrared radiation and solar radiation and may have a large impact on climate

CH_4 absorption band for infrared radiation

- strengthens greenhouse effect of gases by shadowing upward infrared radiation (①)
- might strengthen greenhouse effect of clouds by increasing thermal emission from the cloud layer (②)

CH_4 absorption band for solar radiation

- weakens greenhouse effect of clouds by clouds evaporation (③)



It is not clear whether CH_4 causes stronger greenhouse effect or not.

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