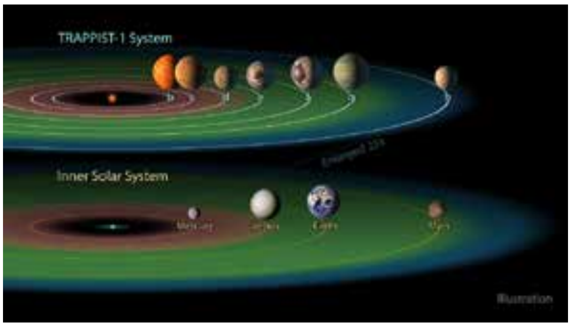
Planetary climate systems



NASA/JPL-Caltech

Inner edge of habitable zone

- Water loss limit

  Escape of water/hydrogen to space

- Runaway greenhouse limit

  Complete evaporation of ocean

→ How/when did **Venus** lose water and get the thick CO_2 atmosphere ?

Outer edge of habitable zone

- Greenhouse effect by CO_2 and other gases
- Enhancement of cloud albedo in cold, massive atmospheres

→ How/when did **Mars** lose thick atmosphere and freeze ?

Runaway greenhouse effect

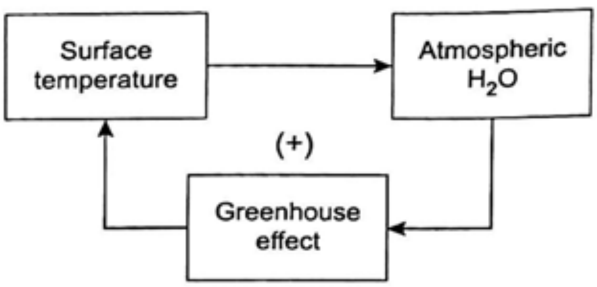
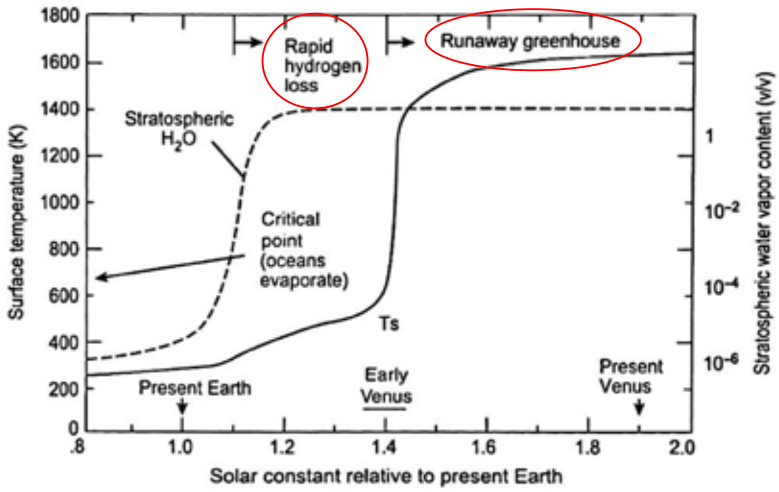


Figure 13.7 Diagram illustrating the positive feedback loop caused by water vapor.

Catling & Kasting (2017)

- An increase in surface temperature causes an increase in atmospheric water vapor, which then increases the greenhouse effect, causing a further increase in surface temperature. (Positive feedback)
- A wet atmosphere makes spectral atmospheric windows close up, and thermal infrared radiation cannot escape to cool the planet. If the absorbed solar flux exceeds the outgoing infrared limit, the surface water totally evaporates and the planet's surface heats up.

Runaway/moist greenhouse of early Venus



Albedo = 0.22 is assumed

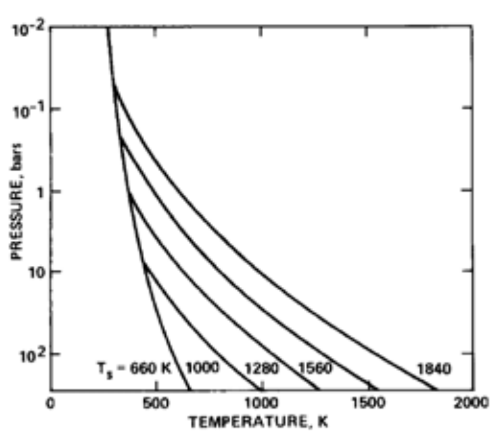
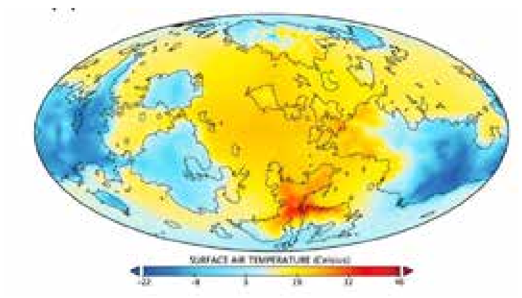


FIG. 6. Temperature versus pressure for selected runaway greenhouse atmospheres. The lower portions of the curves represent dry adiabats. The curve(s) to which they are all joined are moist pseudoadiabats, which are very nearly equivalent to the saturation vapor pressure curve for water.

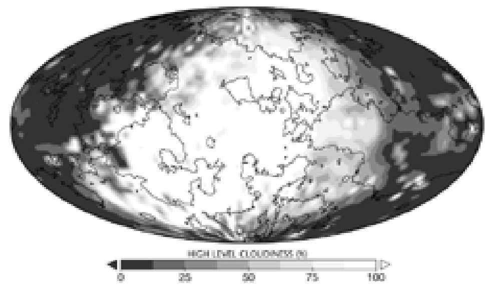
Kasting 1988; Catling & Kasting 2017

Could ancient Venus be habitable ? (Way et al. 2016)

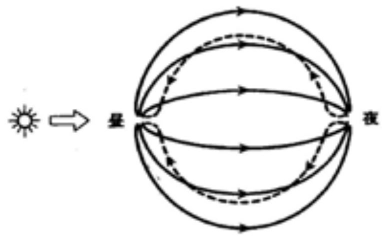
Surface air temperature



Cloudiness

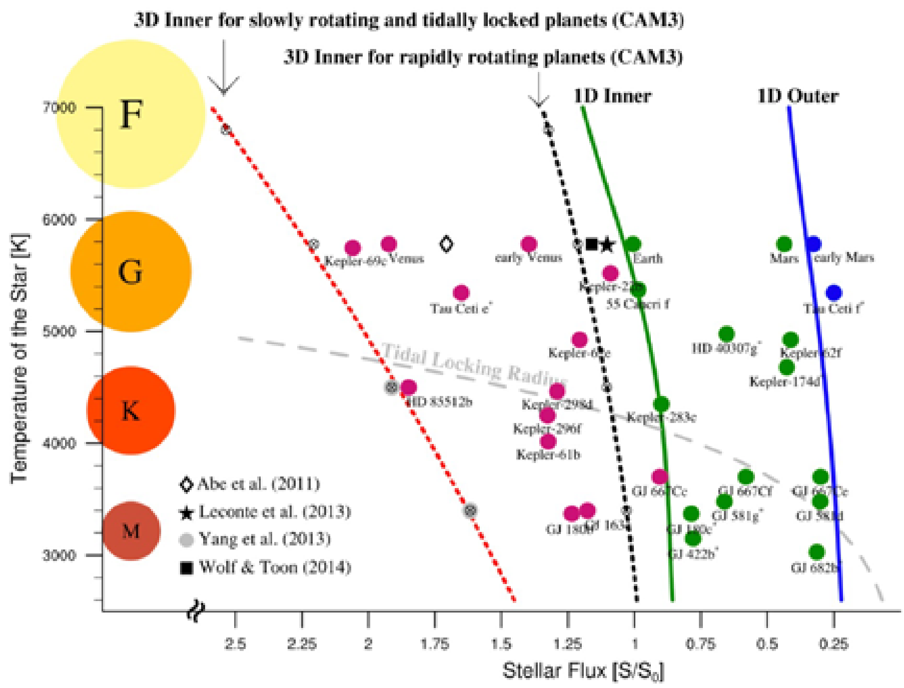


- Low CO_2 density like Earth is assumed, with CO_2 being fixed in the crust as carbonate rocks.
- Global mean surface air temperature of 11℃ despite an incident solar flux at Venus's orbit ~46% higher than that received by modern Earth
- The dayside of the planet is almost completely cloudy, as a result of this world's slow rotation which generates a strong circulation with rising motion and accompanying high thick clouds on the dayside.



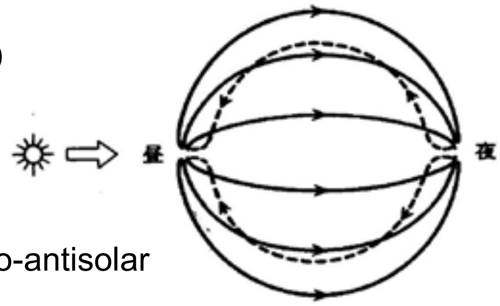
subsolar-to-antisolar circulation
(Y. Matsuda)

Habitable zone for tidally-locked exoplanets (Yang et al. 2014)



Rotation period >> Radiative relaxation time

(Earth : 100 Earth days)



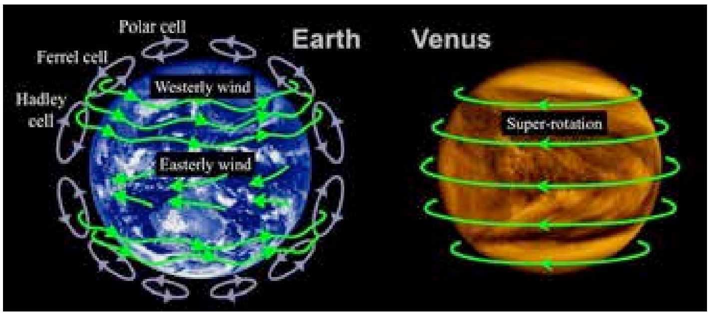
Subsolar-to-antisolar circulation

（松田 2000）

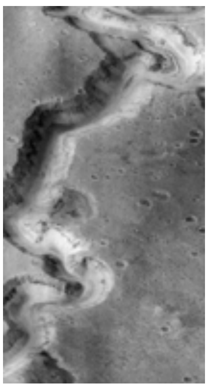
Rotation period << Radiative relaxation time

(Venus : 50 Earth years)

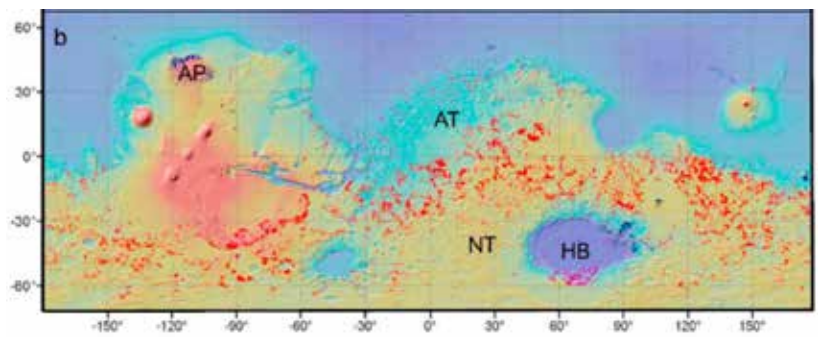
Axi-symmetric circulation



Ancient Martian climate: clue to the outer edge of the habitable zone



Valley network distribution (Ramirez & Craddock 2018)



Three possibilities

- The greenhouse effect was bigger in the past because of a thicker atmosphere that contained higher concentrations of greenhouse gases.

- The fluvial features were caused by many temporary warm episodes associated with impacts. The energy released from impacts would have heated the surface of early Mars, vaporized ice into steam, and produced rainfall that eroded river valleys.

- The fluvial features were produced in a rather cold environment. Fluvial erosion might be produced in response to fortuitous combinations of orbital parameters, allowing localized snowmelt. Brines can exist as liquids at temperatures below 273 K.

(Catling and Kasting 2017)

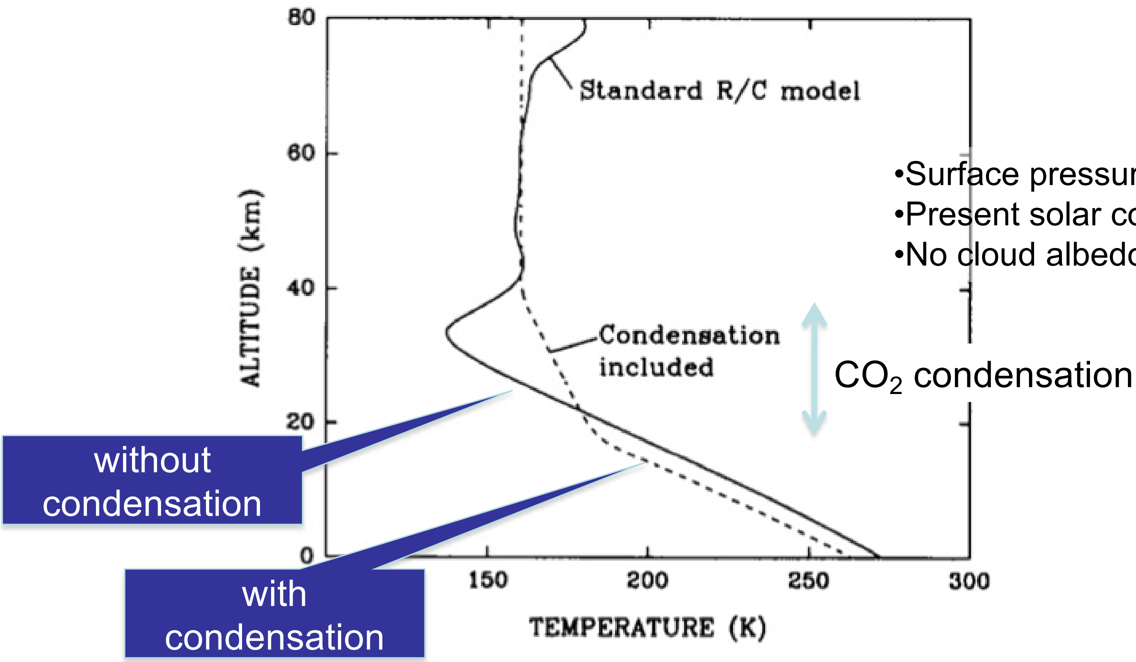
Can the ancient Mars be warm with CO_2 greenhouse effect ?

Kasting (1991)

- The ancient Sun was 25% dimmer than the present
- CO_2 greenhouse has been expected to warm the ancient Mars

- Warm lower atmosphere causes convection, which induces condensation of CO_2 in the upper atmosphere. The associated latent heating raises the temperature at upper levels, and at the same time cools the lower atmosphere so that the net energy balance is maintained.

Effect of CO_2 condensation



- Surface pressure of 2 bar
- Present solar constant
- No cloud albedo

→When the solar constant is less than 86% of the present value, the surface temperature cannot exceed 273 K.

CO_2 ice clouds traveling above the Mars Curiosity rover on December 12th, 2021

Greenhouse effect due to CO_2 ice clouds

Forget & Pierrehumbert (1997)

- CO_2 ice clouds scatter infrared radiation emitted from the surface, thereby causing greenhouse effect.
- CO_2 ice clouds also have cooling effect via increase of the planetary albedo. However, thick CO_2 atmosphere itself has a high albedo even when no cloud exists, and thus the effect of cloud albedo is relatively minor.
  - For example, cloud-free 2-bar CO_2 atmosphere has an albedo of 0.38. Addition of CO_2 clouds increases the albedo to 0.65, thereby reducing the solar absorption by 40%. At the same time the clouds absorbs 60% of the infrared radiation emitted from the surface.

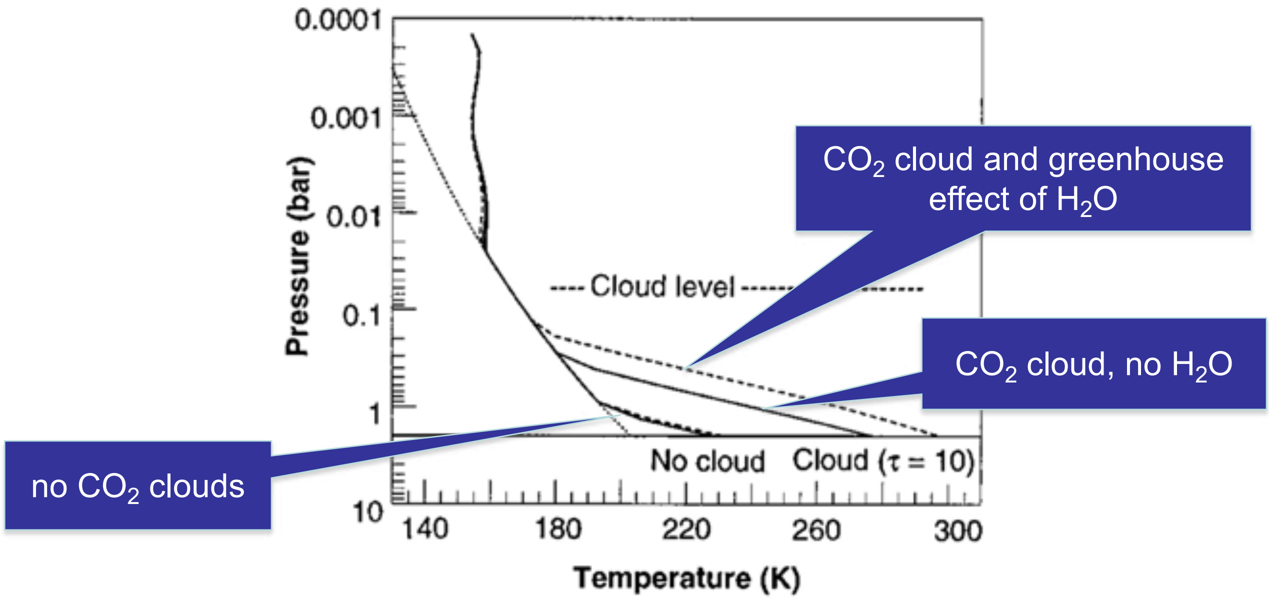


Fig. 2. Calculated mean temperature profiles for a 2-bar CO_2 atmosphere, assuming a 25% reduced solar luminosity corresponding to the early Mars conditions. The effect of the cloud from Fig. 1 (τ = 10, r = 10 μm) is shown in the cases of a wet (fully saturated troposphere; dashed curves) and a dry (solid curves) atmosphere. The dotted curve shows the CO_2 condensation temperature profile.

3D modelling of the early Martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds

(Forget et al. 2013)

- 3D global climate simulations of the early martian climate performed assuming a faint young Sun and a CO_2 atmosphere with surface pressure between 0.1 and 7 bars
- Previous studies had suggested that CO_2 ice clouds could have warmed the planet thanks to their scattering greenhouse effect. However, even assuming parameters that maximize this effect, it does not exceed +15 K. As a result, a CO_2 atmosphere could not have raised the annual mean temperature above 0 deg C anywhere on the planet.
- This is consistent with a cold early Mars scenario in which nonclimatic mechanisms must occur to explain the evidence for liquid water.

Mean surface temperature vs. Surface pressure (column CO_2 amount)

- Surface temperature increases up to 2 bar. Above 2– 3 bar, bar Rayleigh scattering by CO_2 gas more than compensates for the increased thermal infrared opacity of the atmosphere. Increasing the atmospheric thickness does not result in an increase of the mean surface temperature.
- Taking into account the radiative effect of CO_2 ice clouds results in a global warming of the surface by more than 10 K resulting from the CO_2 ice cloud scattering greenhouse effect.
- The collapse of the atmosphere into permanent CO_2 ice caps is predicted for higher pressures.

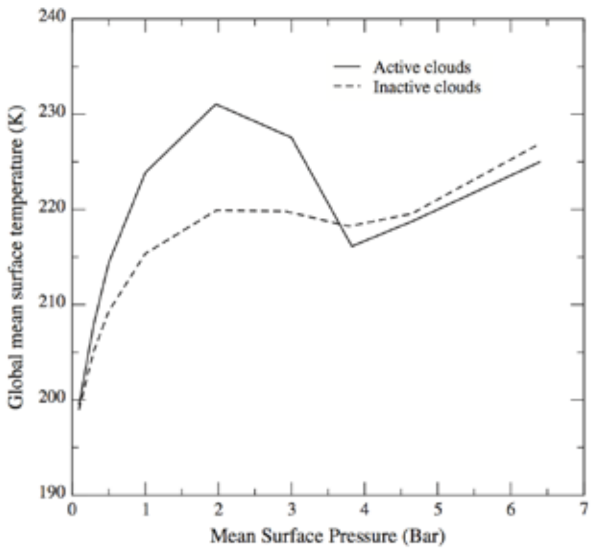
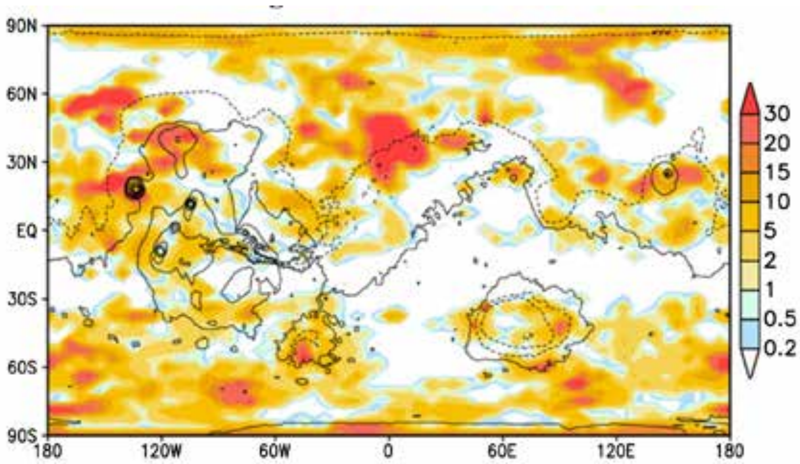


Fig. 1. Global mean annual mean surface temperature (K) as a function of surface pressure in our baseline simulations (obliquity = 25°, [CCN] = 10^5 kg^{-1}, circular orbit) with and without radiatively active CO_2 ice clouds.

An example of the instantaneous CO_2 ice clouds coverage for a mean surface pressure 2 bar



- CO_2 ice clouds cover a major part of the planet but not all. Their behavior is controlled by a combination of large scale ascents and descents of air, stationary and travelling waves, and resolved gravity waves related to the topography.
- The mean cloud warming remains lower than 15 K because of the partial cloud coverage and the limited cloud optical depth.

Other greenhouse gases?

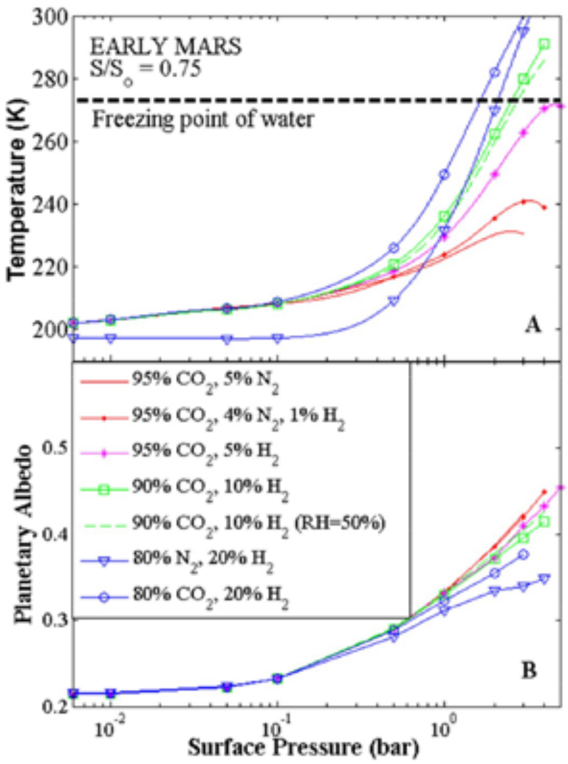
- Ammonia (NH_3) : 500 ppm of NH_3 in a 4–5 bar CO_2 atmosphere could raise surface temperatures to 273 K. However, NH_3 is photochemically unstable and would require shielding to survive.

- Methane (CH_4) : even at concentrations of 500 ppm CH_4 does not significantly boost the greenhouse effect of a pure CO_2/H_2O atmosphere. CH_4 would require strong sources to sustain the above concentrations.

- Sulfur dioxide (SO_2) & hydrogen sulfide (H_2S) : An obvious source for these gases is volcanic activity. SO_2 needs to build up to concentrations around the 10 ppm level or higher. SO_2 readily converts to aerosols, and these aerosols should have a net cooling effect on surface temperatures. Furthermore, SO_2 is highly soluble and will washout quickly when conditions become warm enough for rainfall.

(Forget et al. 2013)

H_2–CO_2 greenhouse ? (Ramirez et al. 2014)



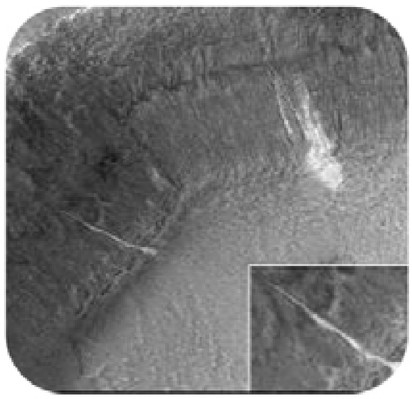
Collision-induced absorption (CIA) band of H_2 caused by the foreign-broadening by the background CO_2 atmosphere

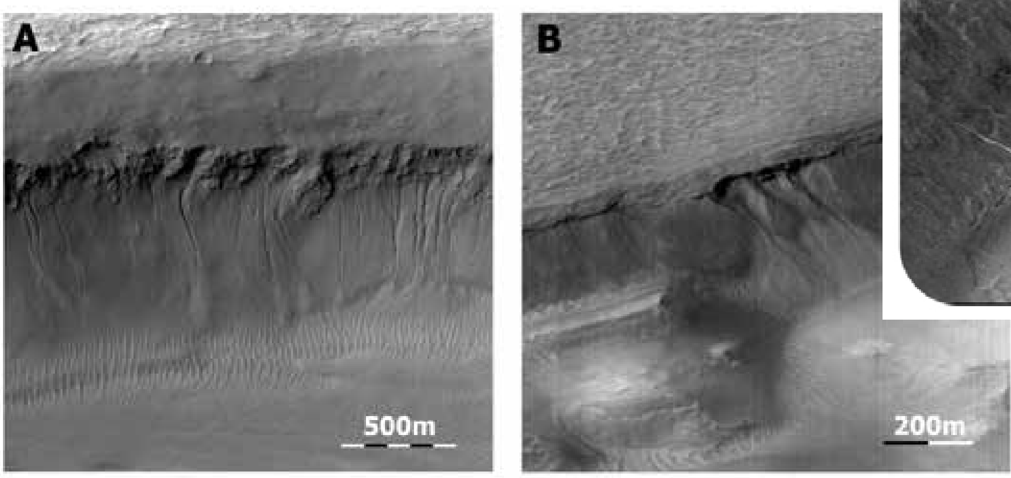
Reduced mantle conditions could have favored enhanced outgassing of H_2 over long timescales. Hydrogen is continuously replenished by volcanism that offsets losses to space.

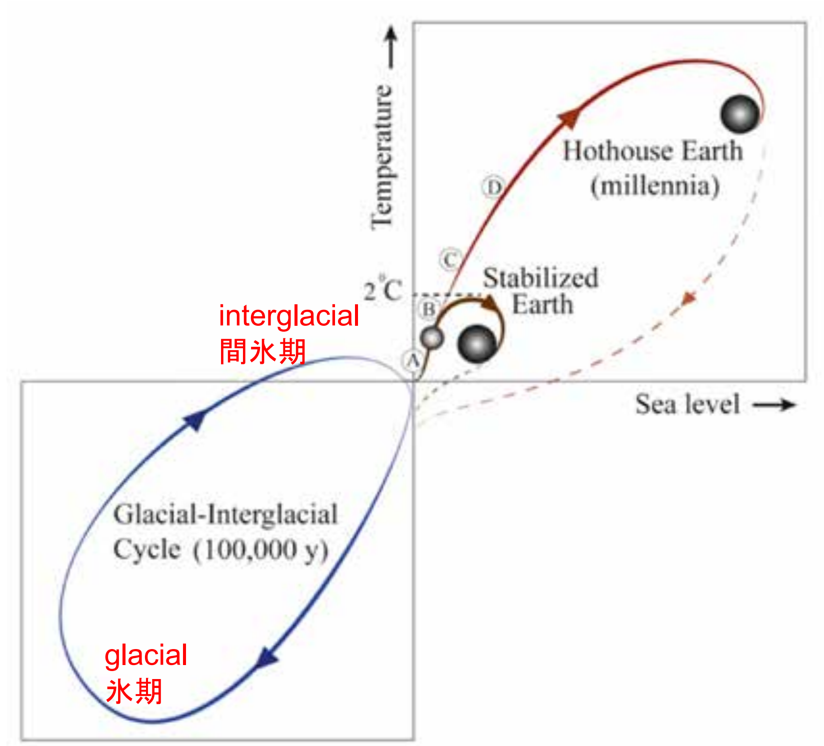
An atmosphere containing -4 bar of CO_2 and 5% H_2 would have brought Mars' average surface temperature up to the freezing point of water.

recurrent slope lineae

- transition between different climate regimes ?







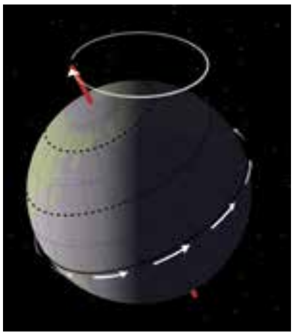
Steffen et al. (PNAS, 2018)

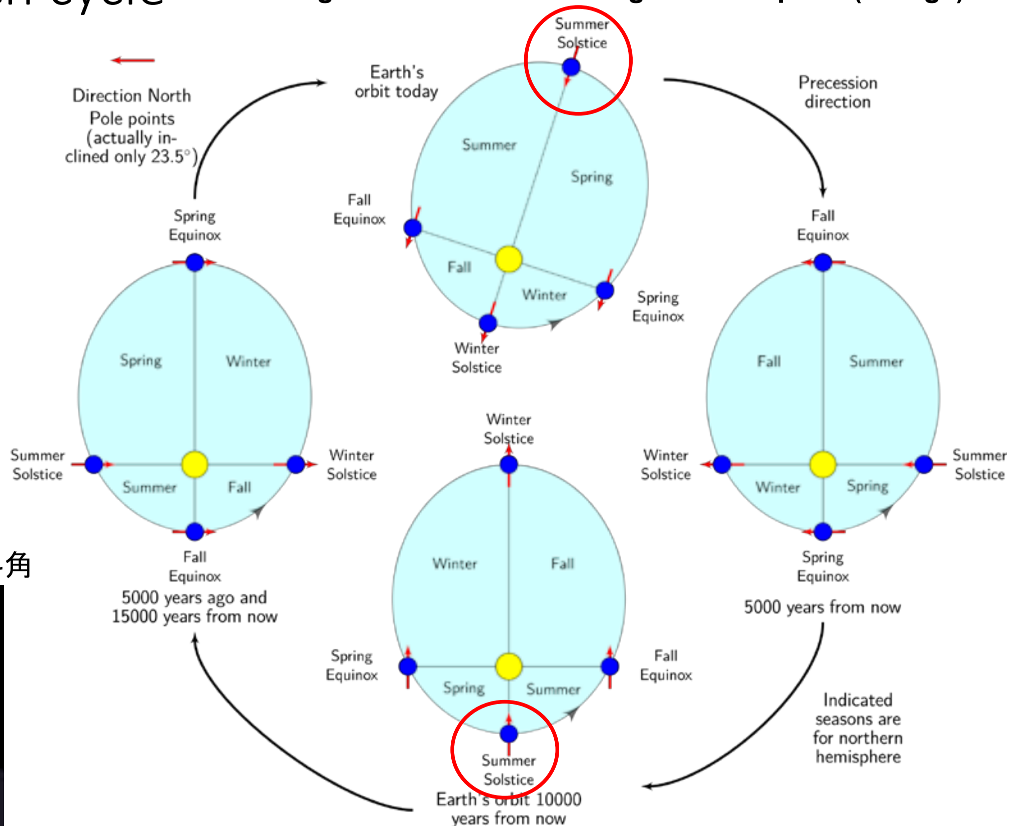
Milankovitch cycle

from Wikipedia

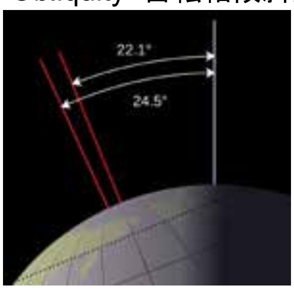
low summer insolation in the northern high latitude
→ growth of ice sheets → glacial inception (ice age)

Precession 歳差





Obliquity 自転軸傾斜角



high summer insolation in the northern high latitude
→ decay of ice sheets → Interglacial (warm interval)

Milankovitch cycles on Mars and Earth

Table 12.10 The orbital elements of Mars and the Earth and their variability.

Parameter	Present Mars	Martian variability: Range	Martian variability: Cycle (years)	Present Earth	Terrestrial variability: Range	Terrestrial variability: Cycle (years)
Obliquity (°)	25.19	0–85*	120 000**	23.45	22–24	41 000
Eccentricity	0.093	0–0.12	120 000***	0.017	0.01–0.04	100 000
Longitude of perihelion (°)	250	0–360	51 000	285	0–360	21 000

* Before ~10 Ma, obliquity variations are chaotic. While unpredictable at an exact time, statistically they would have varied between 0 and 85° (Laskar *et al.*, 2004; Touma and Wisdom, 1993).
** The amplitude of obliquity oscillation is modulated with a ~1.2 Myr period envelope.
*** The amplitude of eccentricity oscillation is modulated with a ~2.4 Myr period envelope.

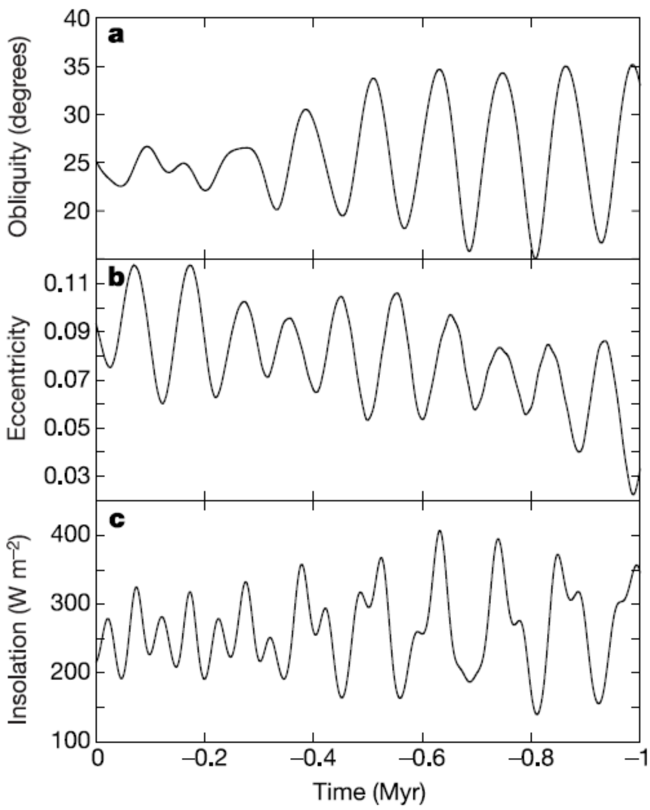
Catling & Kasting 2017

Milankovitch cycles on Mars

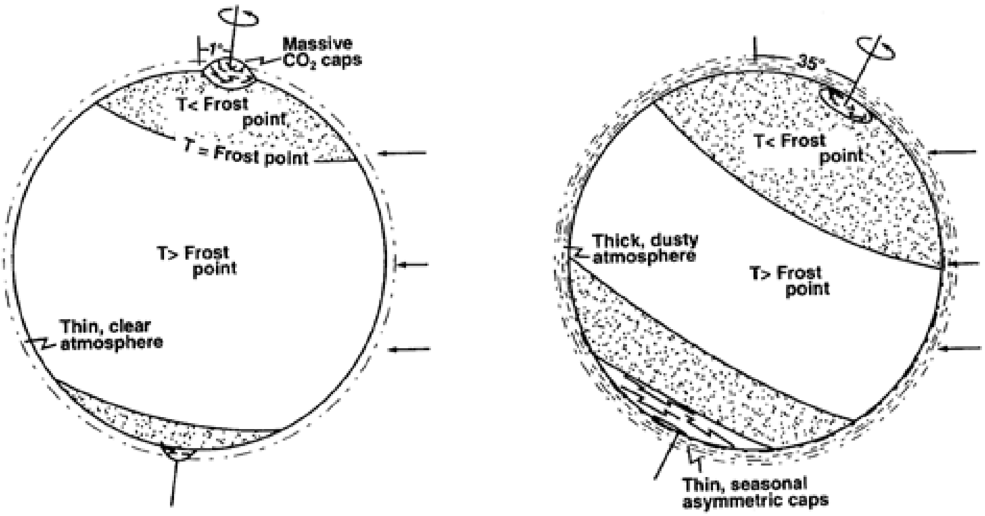
自転軸傾斜角

軌道離心率

北極域の夏至の日射



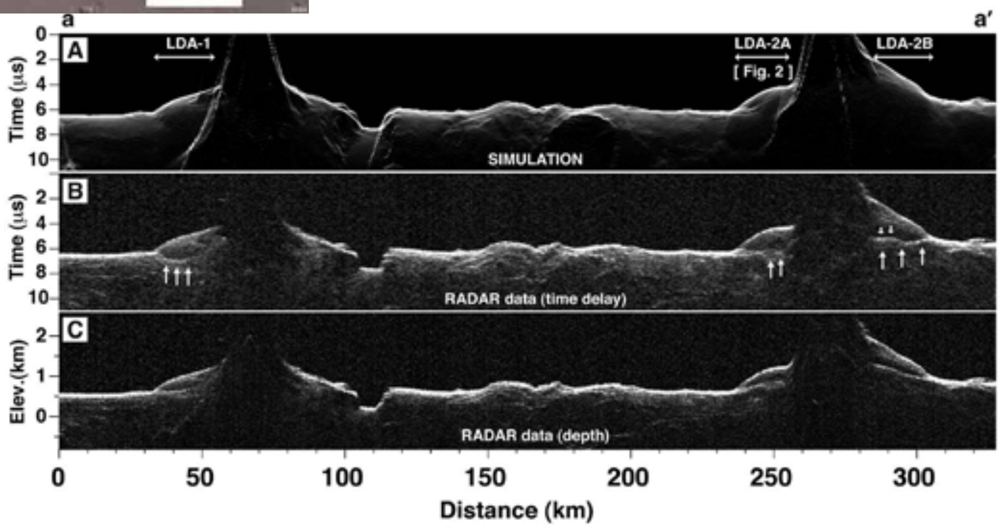
Laskar et al. (2002)



- low obliquity → cold pole → massive polar cap → dry atmosphere → retreat of ice sheet

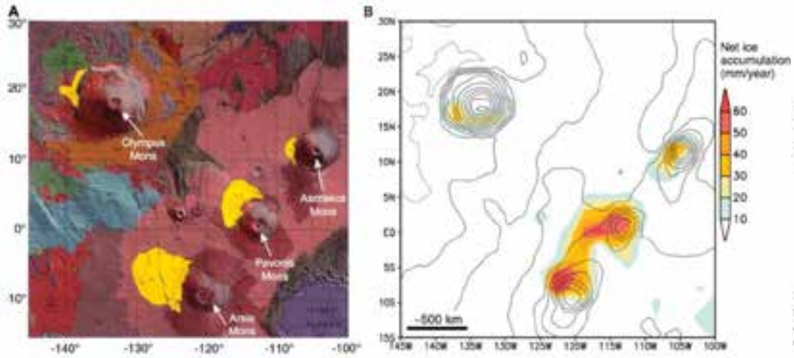
- high obliquity → warm pole → thin polar cap → moist atmosphere → growth of ice sheet, ice accumulation in the tropics

Buried glaciers



Formation of glaciers on Mars by atmospheric precipitation at high obliquity Forget et al. (2006)

- The model predicts ice accumulation in regions where glacier landforms are observed, on the western flanks of the great volcanoes and in the eastern Hellas region



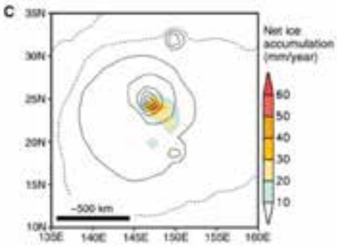


Fig. 1. (A) Geologic map modified from (30) of the Tharsis region showing the location of fan-shaped deposits of Amazonian age (yellow) located on the northwest slopes of the Tharsis Montes and Olympus Mons. (B) Net surface water ice accumulation in the Tharsis region simulated with 45° obliquity and assuming that surface water ice is present on the northern polar cap. Superimposed Mars Orbiter Laser Altimeter (MOLA) topography contours are at 2000-m intervals. (C) Same as (B) but for the Elysium Mons region. Outside the Tharsis and Elysium areas, no net ice accumulation is predicted.

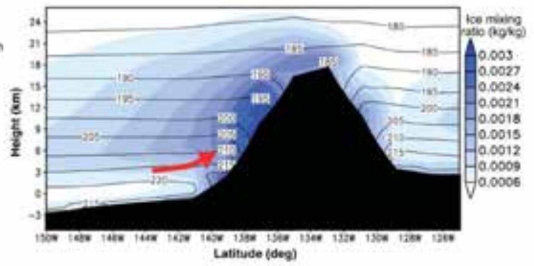


Fig. 3. Cross section of Olympus Mons along the 16°N latitude showing the mean atmospheric ice mass mixing ratio (shaded blue) and the atmospheric temperature (contour, K) averaged over the period of ice accumulation Ls = 125° to 155° (northern summer). The strong northwesterly winds induce adiabatic cooling on the flank of the volcanoes and atmospheric condensation and precipitation.