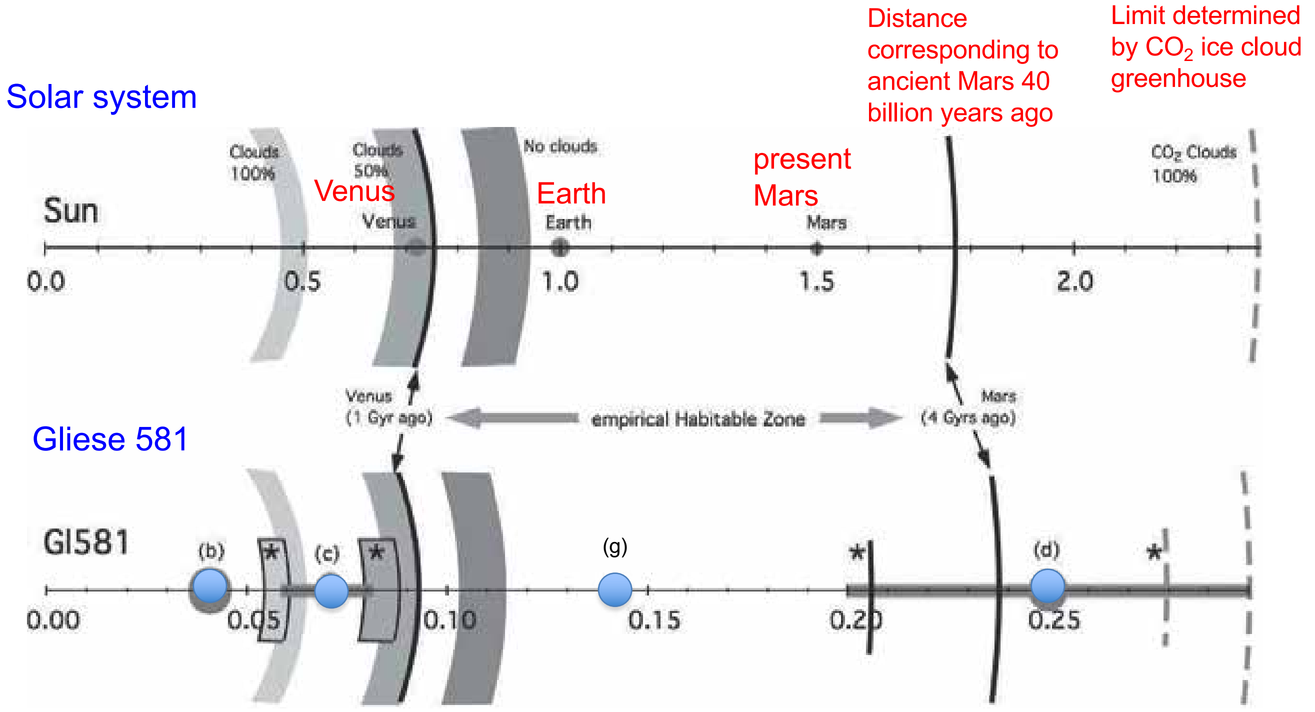
Planetary climate systems I

Diagrams depicting the habitable zone around the Sun and Gliese 581 (Selsis et al. 2007)



Solar system

Gliese 581

Venus

Earth

present Mars

Distance corresponding to ancient Mars 40 billion years ago

Limit determined by CO_2 ice cloud greenhouse

Inner edge of habitable zone

- Runaway greenhouse limit

  Complete evaporation of ocean
- Water loss limit

  Escape of water/hydrogen to space

→ 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

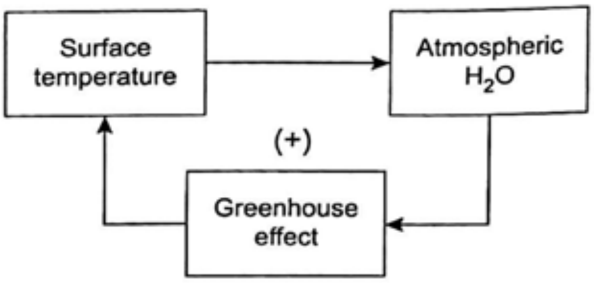


Figure 13.7 Diagram illustrating the positive feedback loop caused by water vapor.

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)
- More precisely, 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.

Classical runaway greenhouse effect

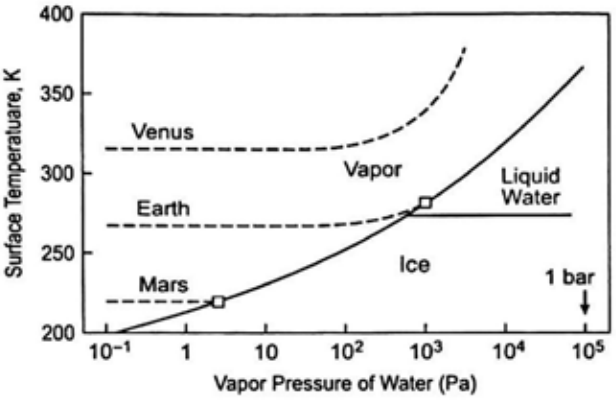


Figure 13.8 Diagram illustrating the "classical" runaway greenhouse effect. The solid curve represents the saturation vapor pressure of water. The three dashed curves show surface temperature of three initially airless planets as they outgas an atmosphere of pure water vapor. Atmospheric radiative transfer is gray, i.e., with a single broadband infrared absorption coefficient. (From Goody and Walker, (1972). Reproduced with permission of Pearson Education, Inc., New York. Copyright 1973. Adapted originally from Rasool and DeBergh, 1970.)

Catling & Kasting (2017)

- Initially airless planets
- Outgas of pure H_2O atmosphere

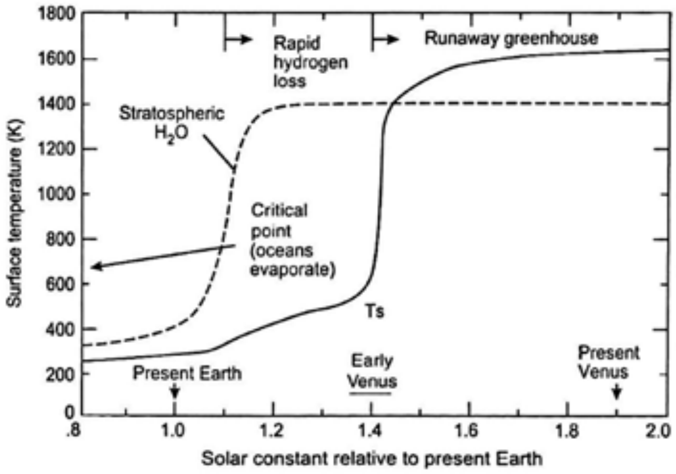
→ All of H_2O released from Venus's interior would have remained in the vapor phase. With a sufficient amount of H_2O, runaway greenhouse state is reached.

→ Mars is basically a frozen desert.

However,

- H atoms can be lost to space.
- Clouds form.
- Other greenhouse gases exist.

Runaway/moist greenhouse of early Venus



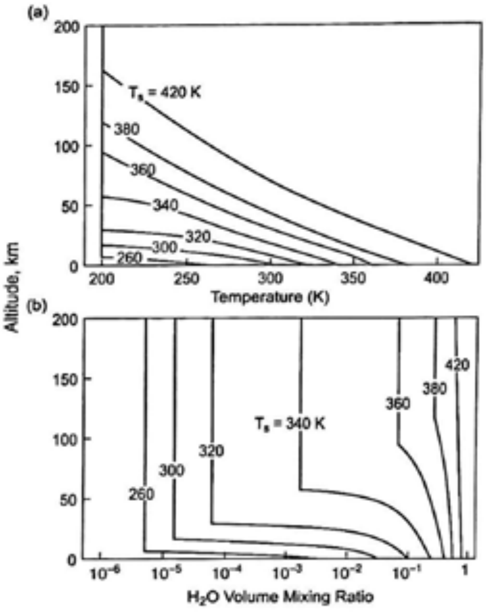


Figure 13.13 Vertical profiles of temperature (a) and water vapor mixing ratio (b) for atmospheres with different surface temperatures, T_s. A 1-bar N_2/O_2 background atmosphere is assumed. (From Kasting, (1988). Reproduced with permission from Elsevier. Copyright 1988.)

Kasting 1988; Catling & Kasting 2017

Earth’s CO_2 cycle (carbon cycle)

- CO_2 dissolves in the ocean and buried in the crust.
- CO_2 buffer may have stabilized the Earth’s climate.

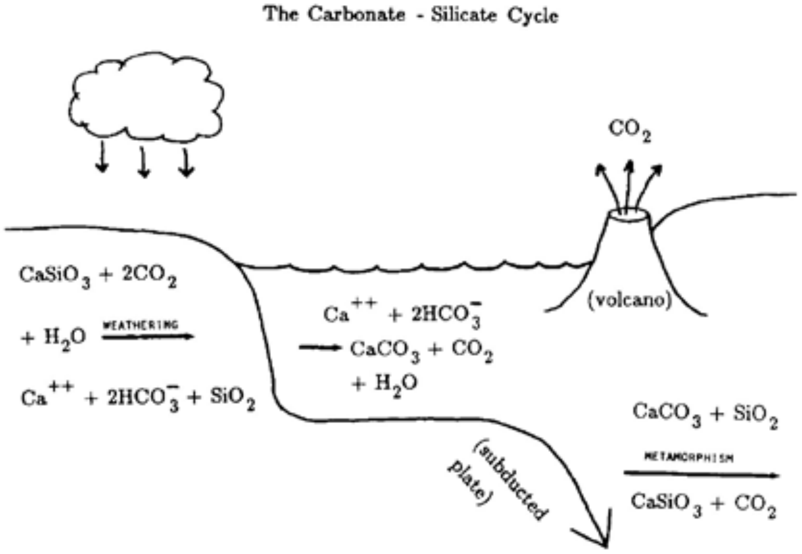
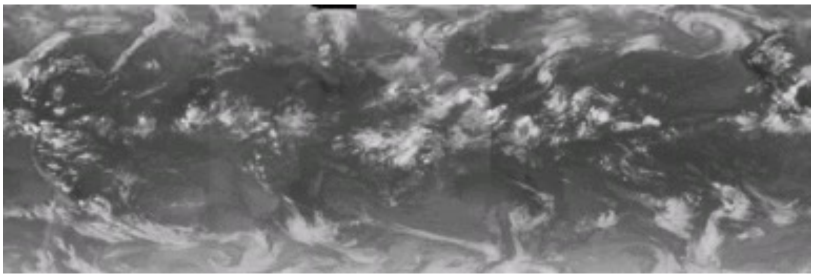


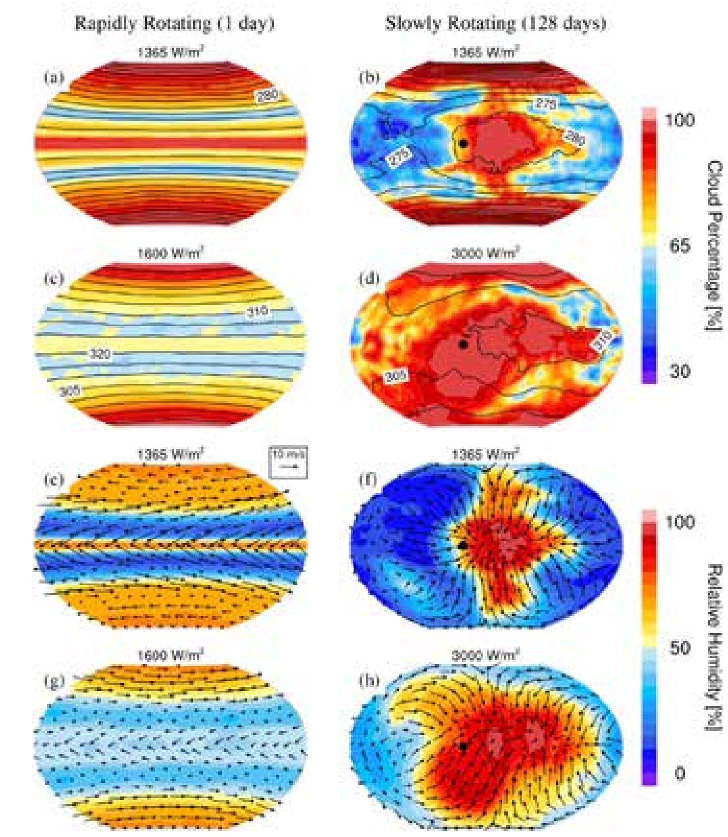
Fig. 5. A schematic representation of chemical weathering reactions of terrestrial continental silicate rocks by CO_2 dissolved in water, the subduction of the resultant carbonate rocks, their thermal decomposition at depth, and the outgassing of the released CO_2.

Effect of H_2O clouds on the inner edge of the habitable zone

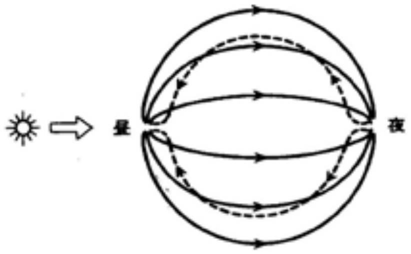
- Clouds increase the planetary albedo, thereby cooling the planet.
- When the cloud cover is 100%, the albedo becomes 0.8. This shifts the runaway greenhouse limit to 0.46 AU. When the cloud cover is 50%, the albedo becomes 0.6, and the runaway greenhouse limit comes to 0.68 AU. (Selsis et al. 2007)



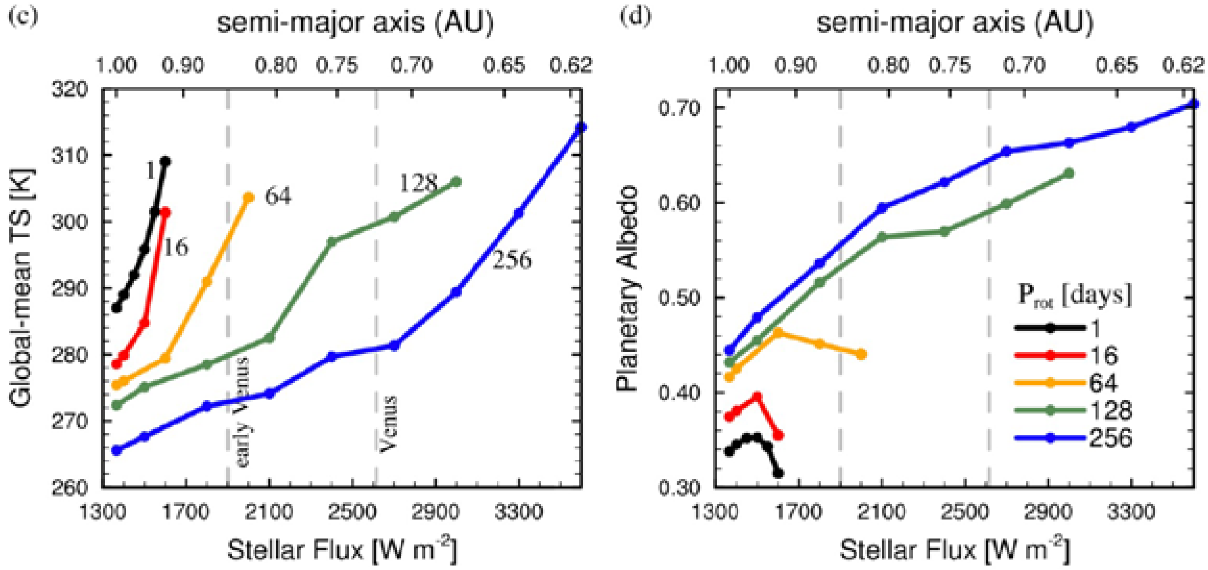
STRONG DEPENDENCE OF THE INNER EDGE OF THE HABITABLE ZONE ON PLANETARY ROTATION RATE (Yang et al. 2014, ApJ)



- Atmospheric circulation affects the albedo
- subsolar-to-antisolar circulation on slow rotators can generate thick clouds on the illuminated side



subsolar-to-antisolar circulation
(Y. Matsuda)



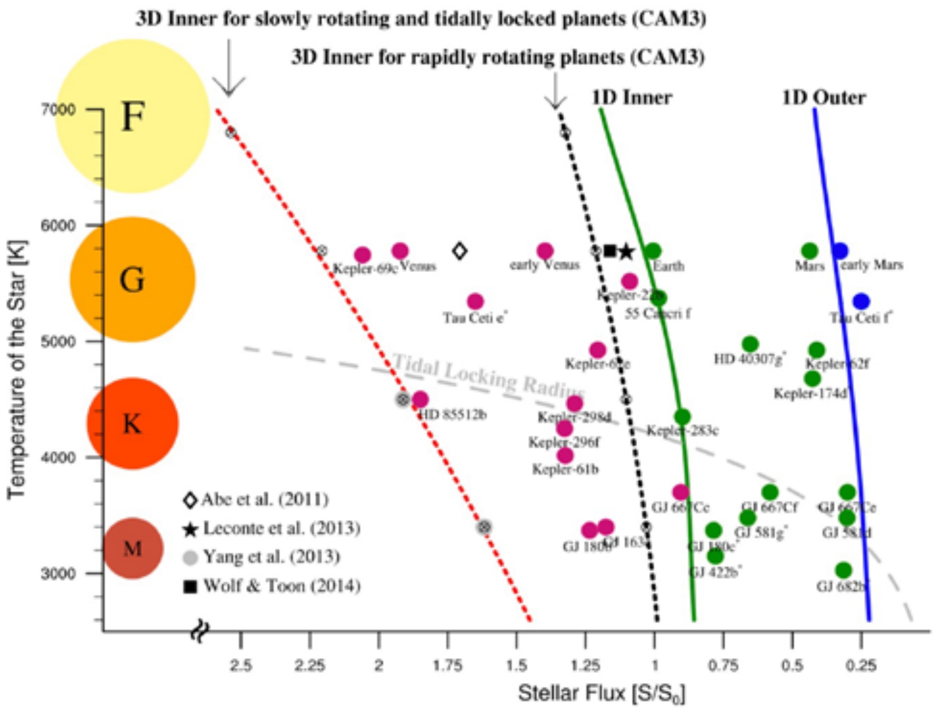


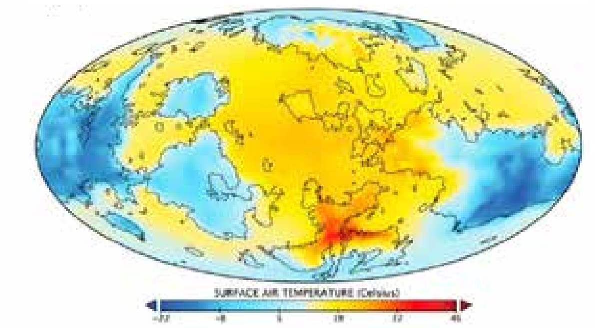
Figure 3. Habitable zone boundaries as a function of stellar type and planetary rotation rate for a 1D radiative–convective model and for the 3D general circulation model CAM3. Blue line: the 1D outer edge (maximum greenhouse; Kopparapu et al. 2013); green line: the 1D inner edge (runaway greenhouse; Kopparapu et al. 2013); black line: the 3D inner edge for rapidly rotating planets in CAM3 (rotation period of 1 day); red line: the 3D inner edge for slowly rotating planets in CAM3 (rotation period of 128 days for G and F stars, and tidally locked with an orbit of 60 days for M and K stars); gray line: the tidal locking radius (Kasting et al. 1993). The CAM3 simulations used to calculate the 3D inner edge lines are denoted by ⊗. We also plot the inner edge of the habitable zone for rapidly rotating dry planets (Abe et al. 2011), for Earth obtained in generic-LMD (Leconte et al. 2013a) and CAM3 with a modified radiative-transfer module (Wolf & Toon 2014). Finally, we plot solar system planets and discovered exoplanets (unconfirmed exoplanets are marked by *).

"Was Venus the first habitable world of our solar system?"

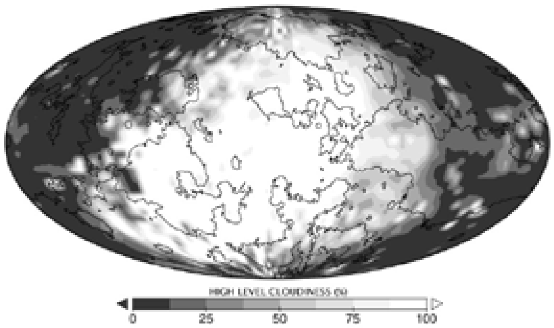
Way et al. (2016)

(Sim A) Solar flux: 1.46 x Earth, Rot. period: Modern Venus

Surface air temperature

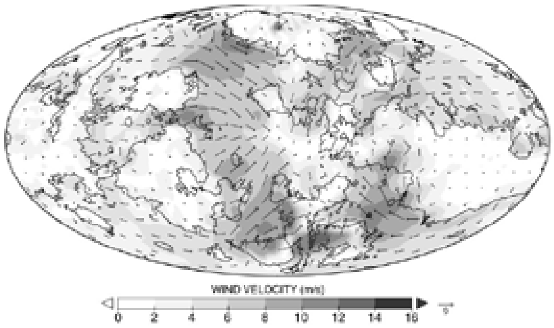


Cloudiness



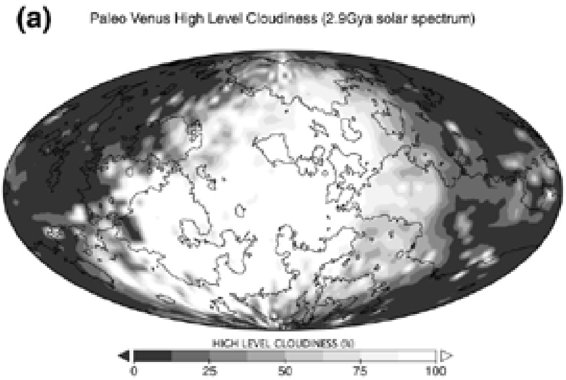
- Global mean surface air temperature of 11° C despite an incident solar flux at Venus's orbit ~46% higher than that received by modern Earth
- The dayside of the planet is almost completely cloudy.

Surface level winds

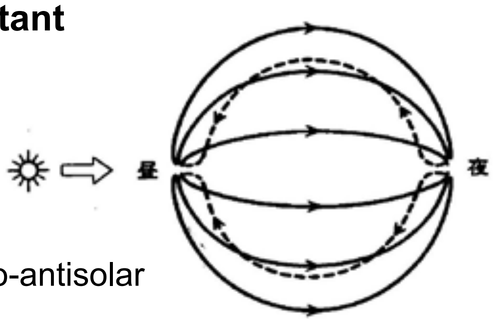


What is happening in the model ?

- The high-level cloudiness on the dayside has values as high as 100%. This is the result of this world's slow rotation which generates a strong circulation with rising motion and accompanying high thick clouds on the dayside that reflect a substantial fraction of the incident sunlight.



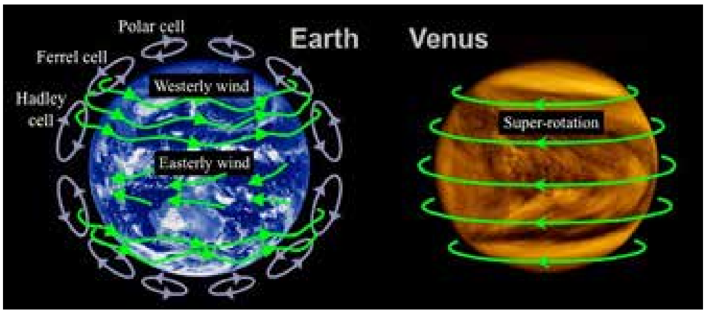
Rotation period >> Radiative time constant



Subsolar-to-antisolar circulation

（松田 2000）

Rotation period << Radiative time constant

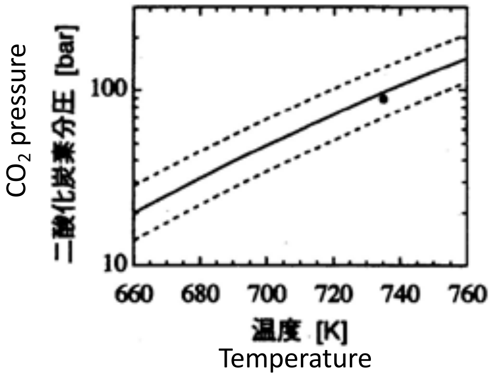


Axi-symmetric circulation

Carbonate buffer hypothesis

The observed surface condition coincides with the CO_2 equilibrium partial pressure over the calcite–quartz–wollastonite assemblage. (Urey 1952)

$$\underset{\text{(calcite)}}{CaCO_3} + \underset{\text{(quartz)}}{SiO_2} = \underset{\text{(wollastonite)}}{CaSiO_3} + CO_2$$



(はしもと・阿部、1998)

(Stabilization?)
When volcanism increases atmospheric CO_2, carbonate formation is enhanced due to the increases in CO_2 pressure, leading to the removal of CO_2.

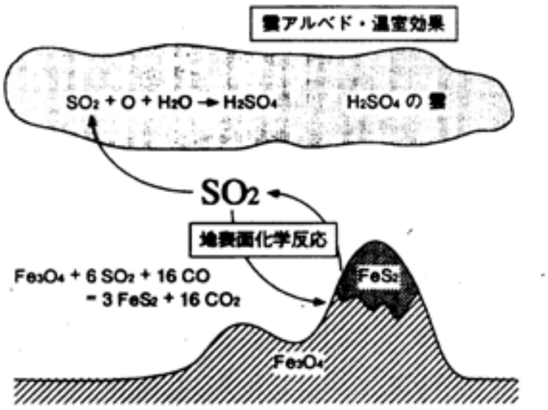
(Destabilization?)
An increase of CO2 leads to an increase in temperature via greenhouse effect, which enhances carbonate decomposition. The positive feedback destabilizes the system. (Hashimoto et al. 1997)

Stabilization of Venus' climate by a chemical-albedo feedback

(Hashimoto & Abe, 2000)

The atmospheric SO_2 abundance might be controlled by the equilibria with the pyrite-magnetite assemblage.

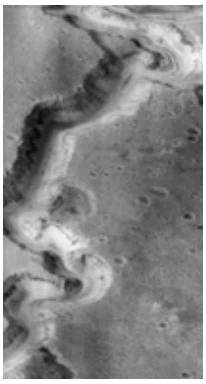
$$3\,\underset{\text{(pyrite)}}{FeS_2} + 16\,CO_2\text{(gas)} = \underset{\text{(magnetite)}}{Fe_3O_4} + 6\,SO_2\text{(gas)} + 16\,CO\text{(gas)}$$



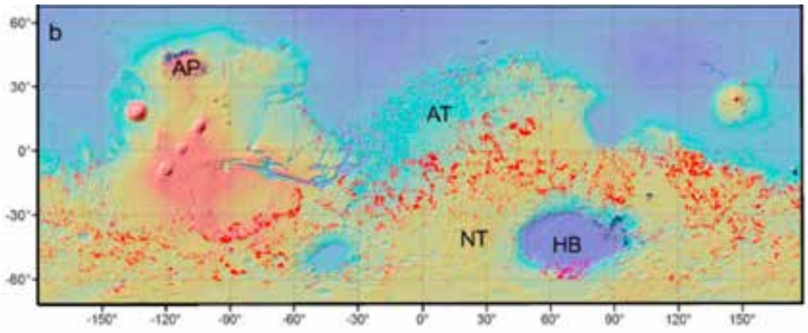
(はしもと・阿部、1998)

A decrease in surface temperature removes some atmospheric SO_2. This reduces the photochemical production of H_2SO_4 clouds, leading to a decrease of the cloud albedo and a resultant increase of the temperature. This negative feedback stabilizes the system. (Hashimoto & Abe, 2000)

Ancient Martian climate



Valley network distribution (Ramirez & Craddock 2018)



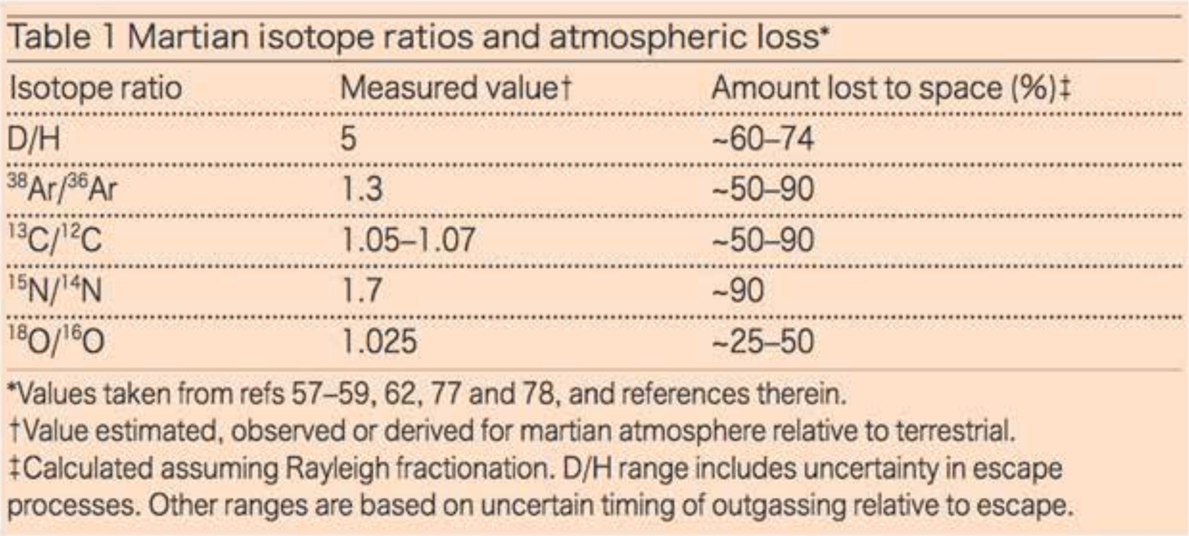


Table 1 Martian isotope ratios and atmospheric loss*

Isotope ratio	Measured value†	Amount lost to space (%)‡
D/H	5	~60–74
$^{38}Ar/^{36}Ar$	1.3	~50–90
$^{13}C/^{12}C$	1.05–1.07	~50–90
$^{15}N/^{14}N$	1.7	~90
$^{18}O/^{16}O$	1.025	~25–50

*Values taken from refs 57–59, 62, 77 and 78, and references therein.

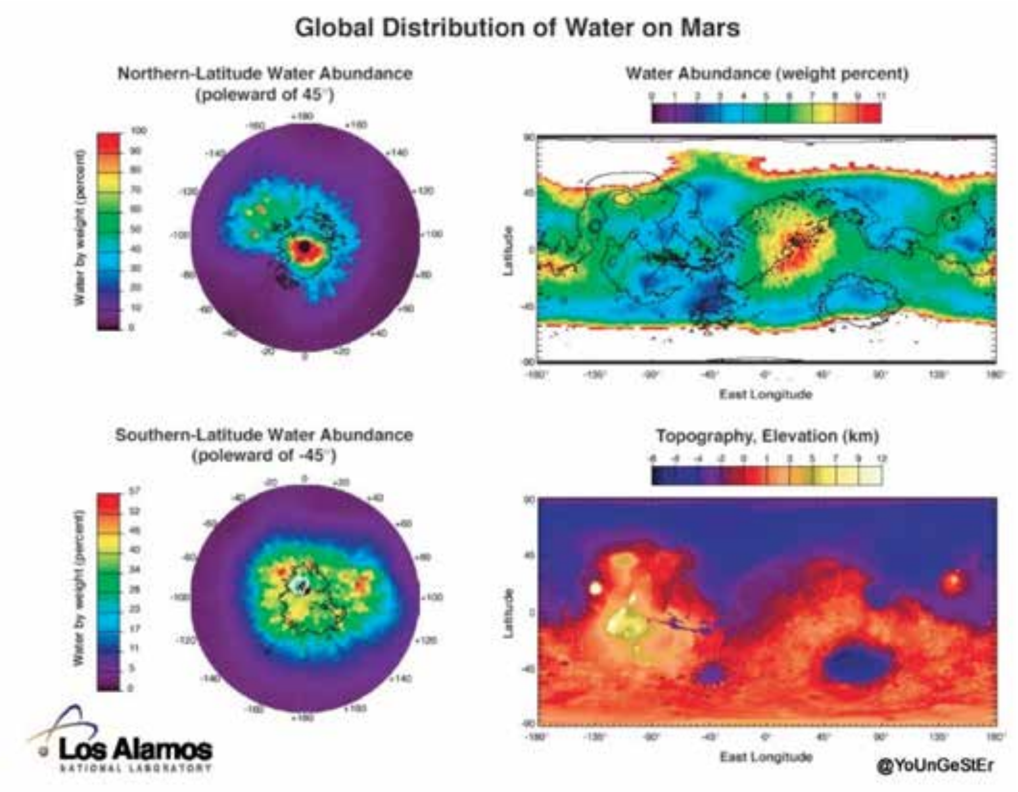
†Value estimated, observed or derived for martian atmosphere relative to terrestrial.

‡Calculated assuming Rayleigh fractionation. D/H range includes uncertainty in escape processes. Other ranges are based on uncertain timing of outgassing relative to escape.

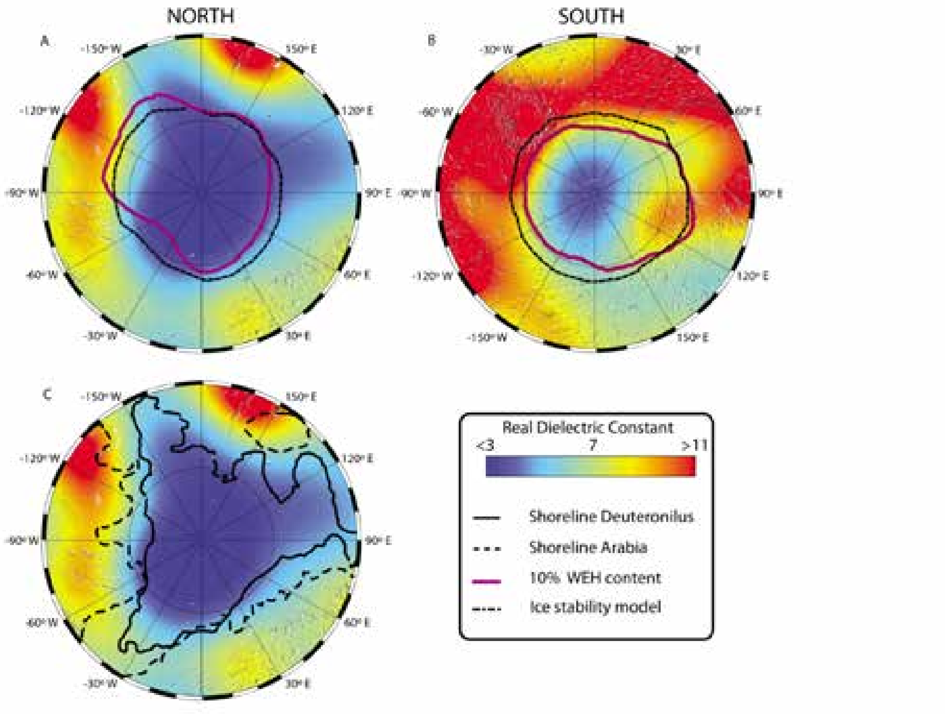
Jakosky & Phillips (2001)

Subsurface water on Mars

Mars Odyssey Neutron Spectrometer (NS) and High-Energy Neutron Detector (HEND)



Dielectric constant of subsurface material
(Mouginot et al. 2012)



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)

Possible evolution of Martian climate

Chassefiere et al. (2007)

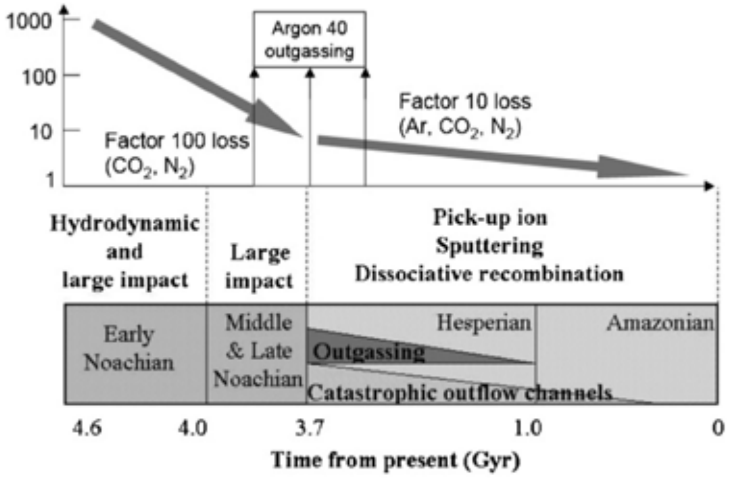


Fig. 3. Schematic chronology of atmospheric escape on Mars. A factor of 100 loss is expected to have occurred during the heavy bombardment period, by impact loss and possibly hydrodynamic escape. In the subsequent period, by using radiogenic argon as a tracer of sputtering escape, an additional loss by a typical factor of 10 occurred.

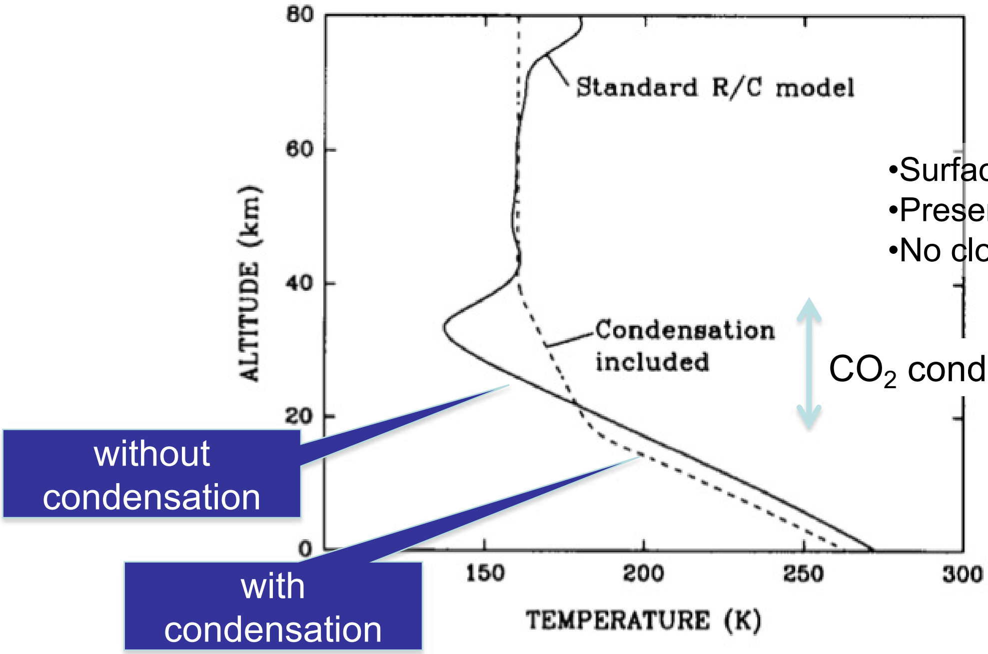
Can the ancient Mars be warm with CO_2 greenhouse effect ?

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



without condensation

with condensation

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

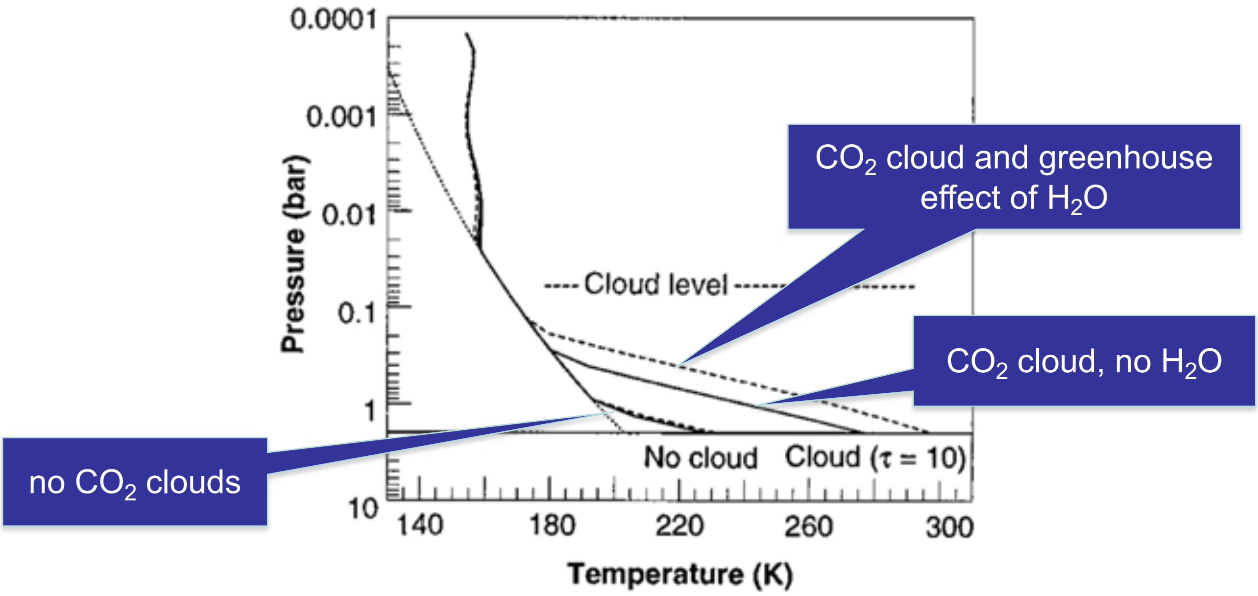
↕ CO_2 condensation

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

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.



CO_2 cloud and greenhouse effect of H_2O

CO_2 cloud, no H_2O

no CO_2 clouds

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° 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 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 pressures higher than 3 bar.

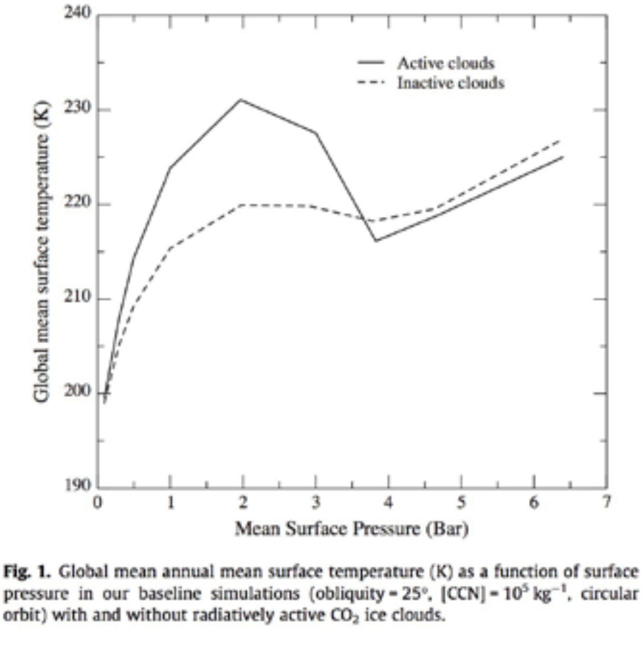
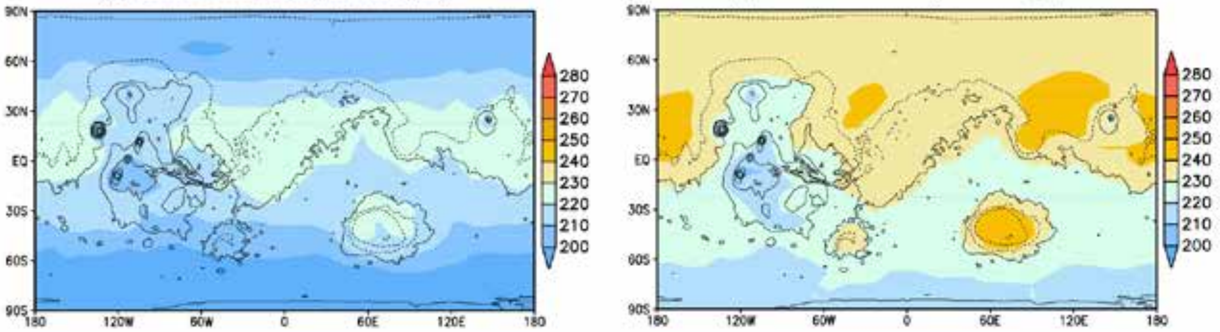
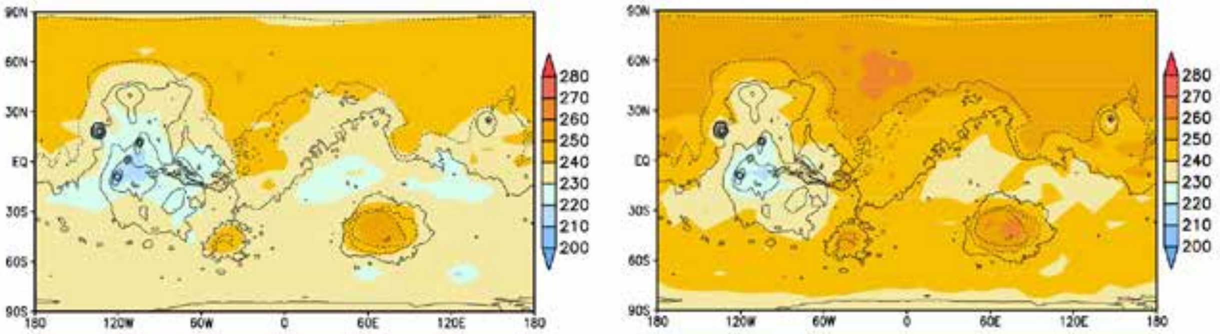


Fig. 1. Global mean annual mean surface temperature (K) as a function of surface pressure in our baseline simulations (obliquity = 25°, [CCN] = 10^5 kg^{-1}, circular orbit) with and without radiatively active CO_2 ice clouds.

Surface temperature
(for present-day ground albedo of 0.22)


Ps=0.5 bars (a) Annual mean temperatures (K)

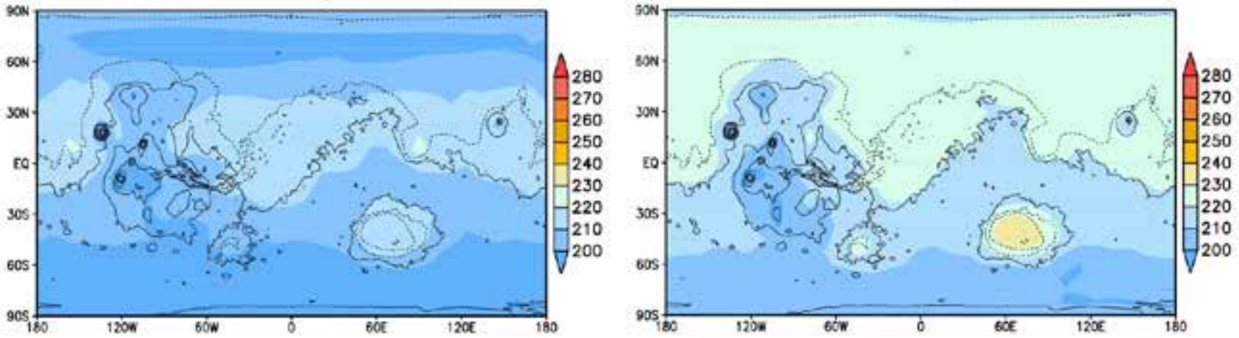
Ps=2 bars (b) Annual mean temperatures (K)


(c) Max daily mean temperatures (K)

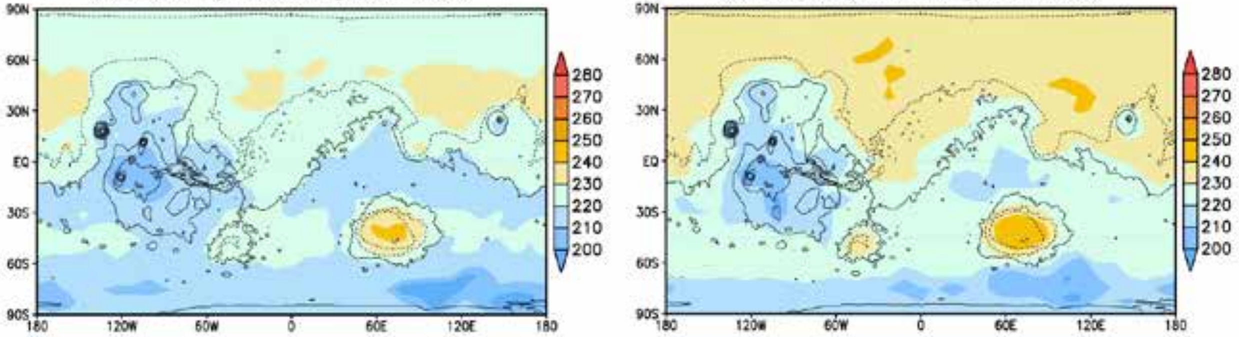
(d) Max daily mean temperatures (K)

- annual mean surface temperatures are always significantly below 0° C.

Surface temperature
(for ice-covered ground albedo of 0.4)


Ps=0.5 bars (a) Annual mean temperatures (K)

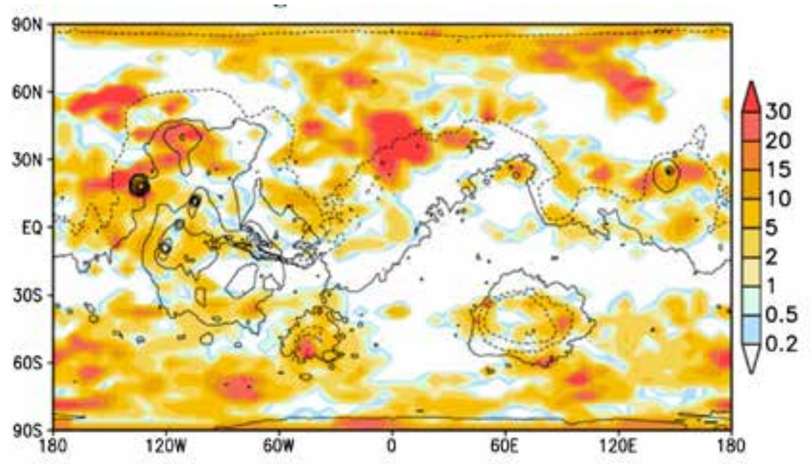
Ps=2 bars (b) Annual mean temperatures (K)


(c) Max daily mean temperatures (K)

(d) Max daily mean temperatures (K)

- annual mean surface temperatures are always significantly below 0° C.

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.

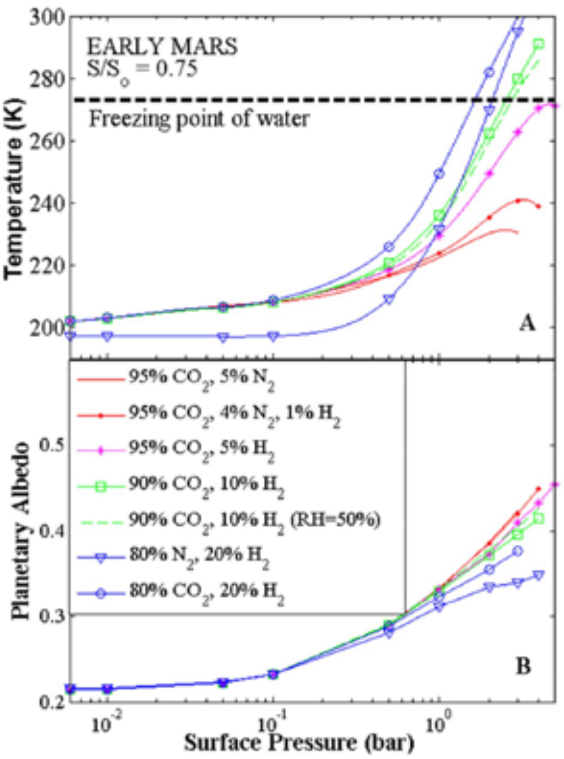
- Methane (CH_4) : even at concentrations of 500 ppm CH_4 does not significantly boost the greenhouse effect of a pure CO_2/H_2O atmosphere. CH_4 would require strong sources to sustain the above concentrations.

- 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 CO2 and 5% H_2 would have brought Mars' average surface temperature up to the freezing point of water.

(Ramirez & Kaltenegger 2017)

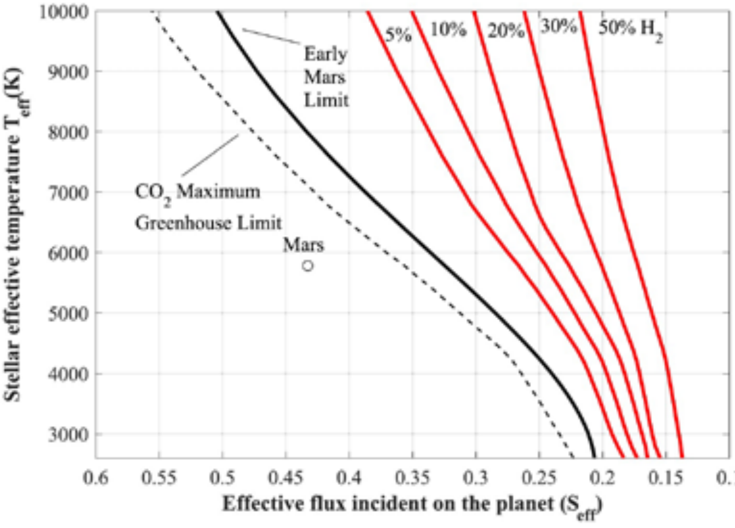
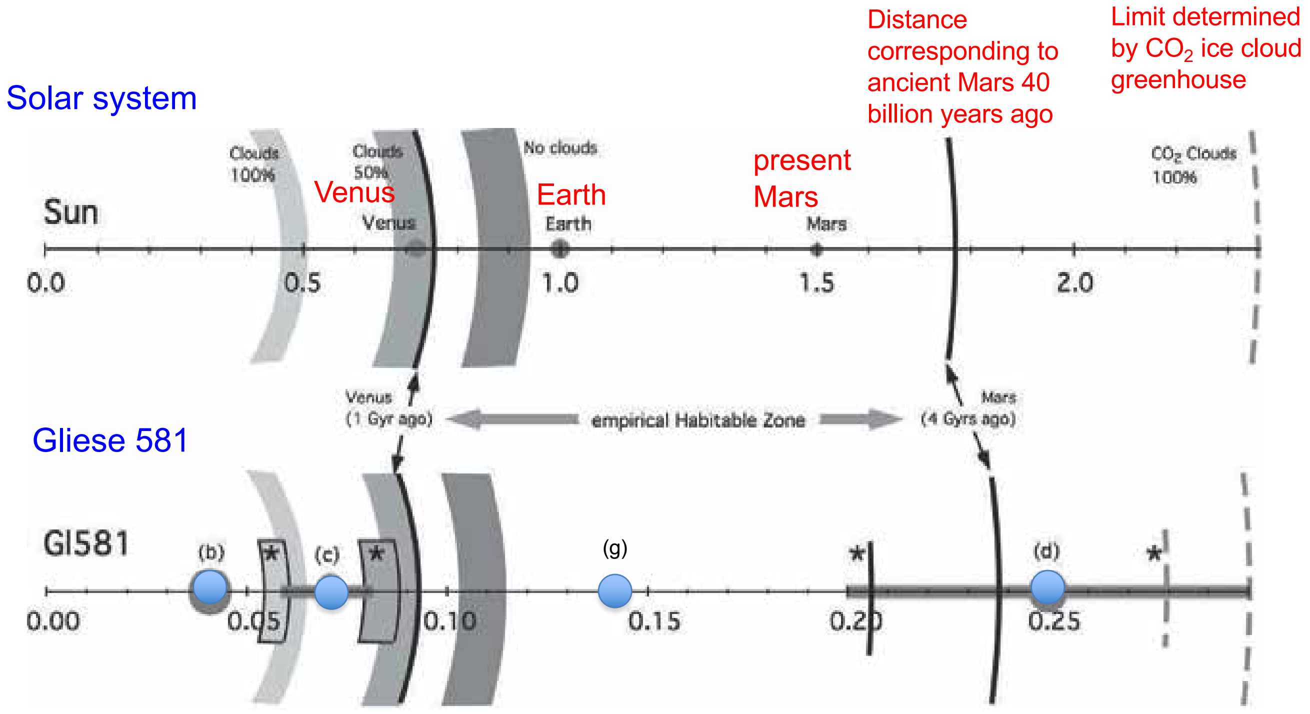


Figure 1. Effective stellar temperature vs. incident stellar flux (S_{eff}) for the outer edge. The CO_2 maximum greenhouse limit (dashed) is shown along with the empirical outer edge (solid black) and outer edge limits containing 5%, 10%, 20%, 30%, and 50% H_2 (red solid).

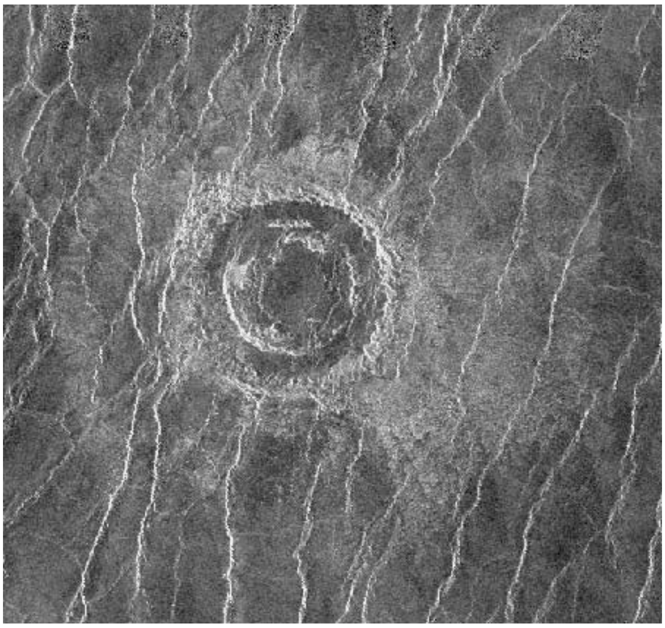
The model atmospheres contain 1 bar of N_2, H_2 with concentrations of 1%, 5%, 10%, 20%, 30% and 50%, and CO_2 with the saturation partial pressure at 273 K.

Diagrams depicting the habitable zone around the Sun and Gliese 581 (Selsis et al. 2007)



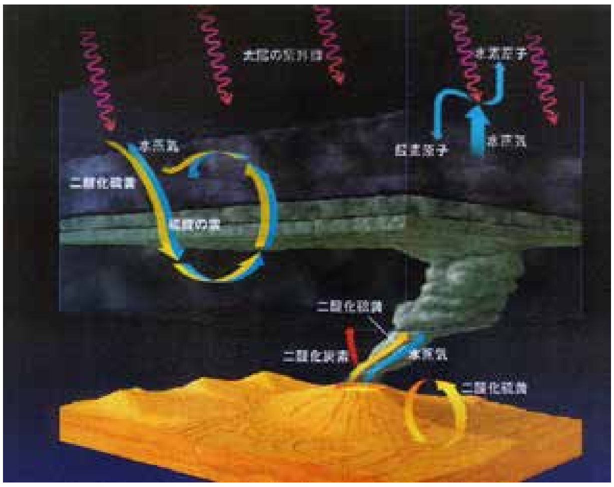
Venus:

Massive eruptions several hundred million years ago ?



Radar image of Venus surface by NASA's Magellan spacecraft

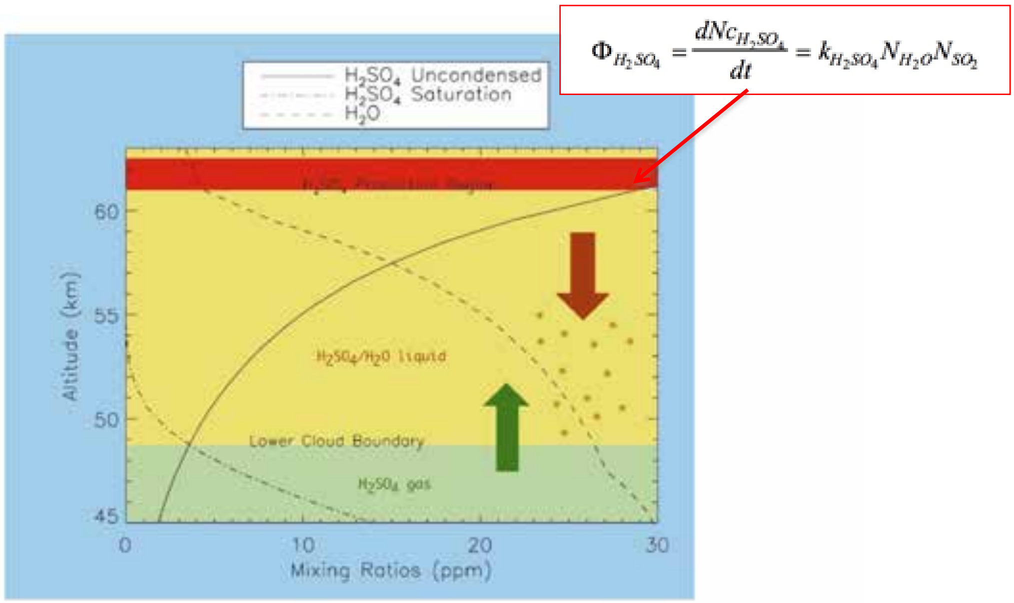
Wrinkle ridges may have been formed by thermal stress caused by a sporadic enhancement of greenhouse effect (H_2O?) in the past.



“The Recent Evolution of Climate on Venus“

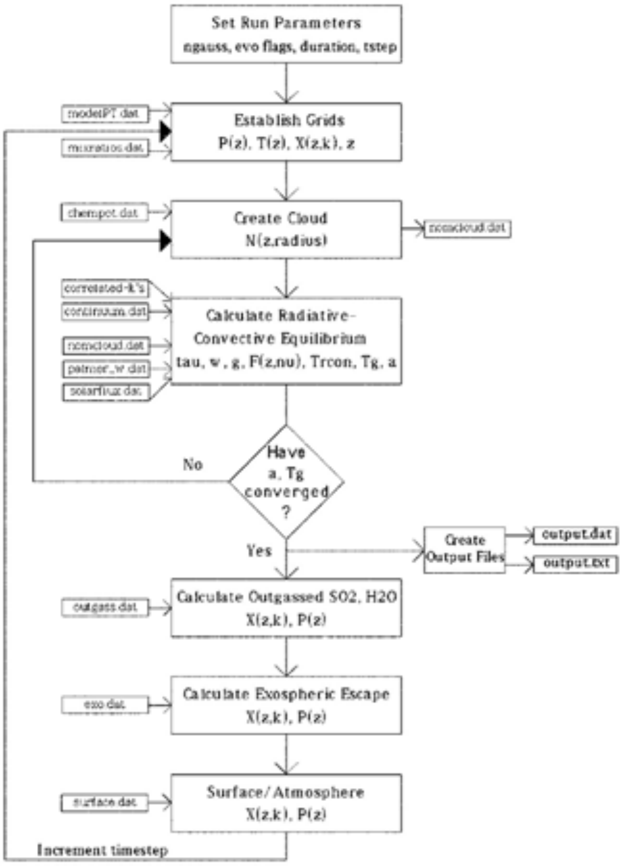
Bullock and Grinspoon (2001)

One-dimensional radiative-convective model coupled with cloud formation

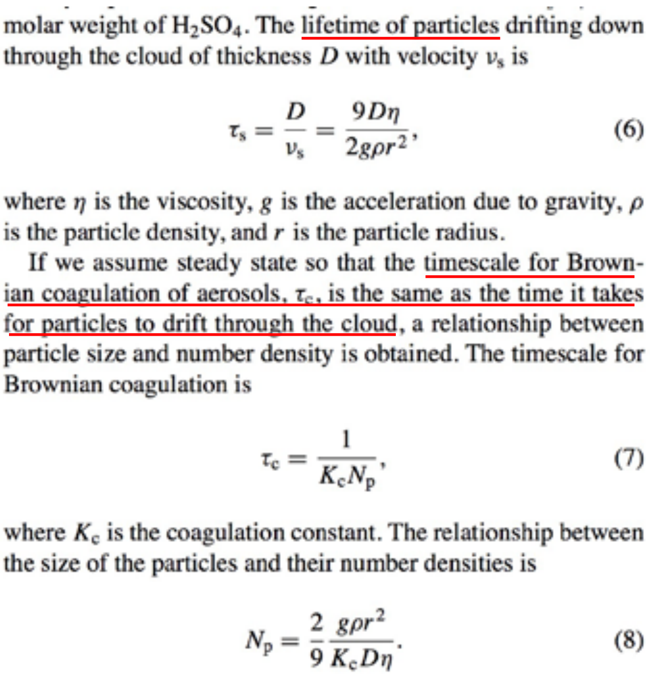


$$\Phi_{H_2SO_4} = \frac{dNc_{H_2SO_4}}{dt} = k_{H_2SO_4} N_{H_2O} N_{SO_2}$$

FIG. 4. H_2O and H_2SO_4 abundances within the nominal cloud model. The mixing ratio of H_2SO_4 in the absence of condensation is shown by the solid line. The saturation mixing ratio of H_2SO_4 over H_2SO_4/H_2O solution for the calculated weight fractions is shown with the dot-dashed line. The lower cloud boundary, z_{lcb}, is where these two curves intersect. The H_2O mixing ratio within the cloud, calculated from the conservation of hydrogen, is shown with the dashed curve.



Cloud process



molar weight of H_2SO_4. The lifetime of particles drifting down through the cloud of thickness D with velocity v_s is

$$\tau_s = \frac{D}{v_s} = \frac{9D\eta}{2g\rho r^2}, \quad (6)$$

where η is the viscosity, g is the acceleration due to gravity, ρ is the particle density, and r is the particle radius.

If we assume steady state so that the timescale for Brownian coagulation of aerosols, τ_c, is the same as the time it takes for particles to drift through the cloud, a relationship between particle size and number density is obtained. The timescale for Brownian coagulation is

$$\tau_c = \frac{1}{K_c N_p}, \quad (7)$$

where K_c is the coagulation constant. The relationship between the size of the particles and their number densities is

$$N_p = \frac{2}{9} \frac{g\rho r^2}{K_c D\eta}. \quad (8)$$

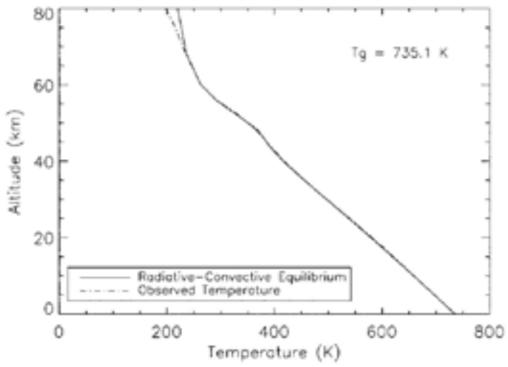


FIG. 2. Temperature profile calculated from the Venus radiative transfer model (solid line). For comparison, the Venus International Reference Atmosphere is plotted with a dashed line (Kliore *et al*. 1986).

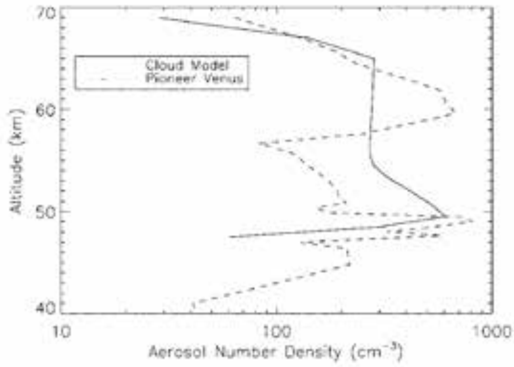


FIG. 5. Nominal cloud number densities as a function of altitude (solid line). Results for the real Venus cloud from the *Pioneer Venus* nephelometer are shown with the dashed line.

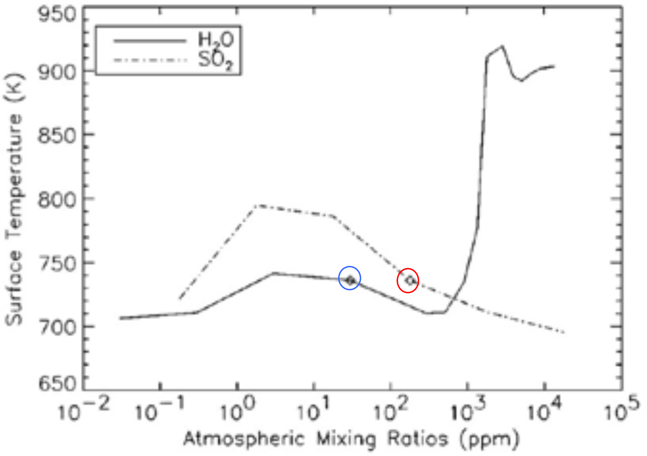
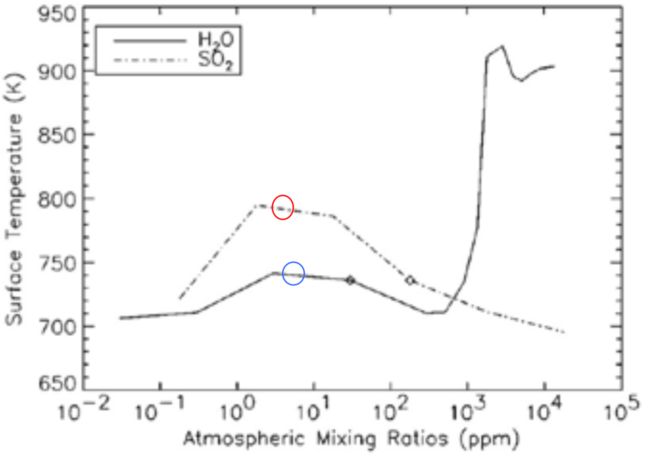


FIG. 6. Surface temperature as a function of the abundance of atmospheric SO_2 and H_2O for the coupled Venus radiative transfer/cloud model. The solid line is for H_2O, the dot–dashed line is SO_2. Diamonds indicate the current atmospheric abundances and surface temperature. Surface temperatures stay between 700 and 800 K until abundances are greater than about 1000 ppm. As H_2O increased beyond that, the surface temperature reaches 900 K. Further increases in surface temperature as H_2O mixing ratio is increased are limited by emission from the atmosphere in the window 2.1–2.7 μm. As SO_2 is increased beyond 1000 ppm, surface temperatures cool below 700 K (due to increased cloudiness).

As these abundances drop, the clouds become thinner, increasing the available solar flux.

Lowering cloud albedo dominates, and the atmosphere becomes hotter. Because it becomes hotter, the cloud base is shifted upward, and the clouds become thinner still.



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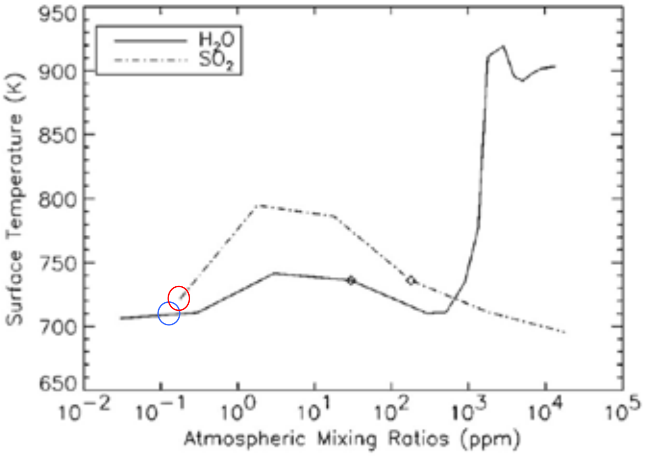
For very low abundances of H_2O and SO_2 (0.3 and 0.2 ppm, respectively), no clouds exist but the surface temperature is about 725 K, slightly cooler than present conditions.

There is a lower infrared gaseous opacity, there is no cloud infrared opacity, and the cloud-free planetary albedo is relatively high (0.4) due to Rayleigh scattering.



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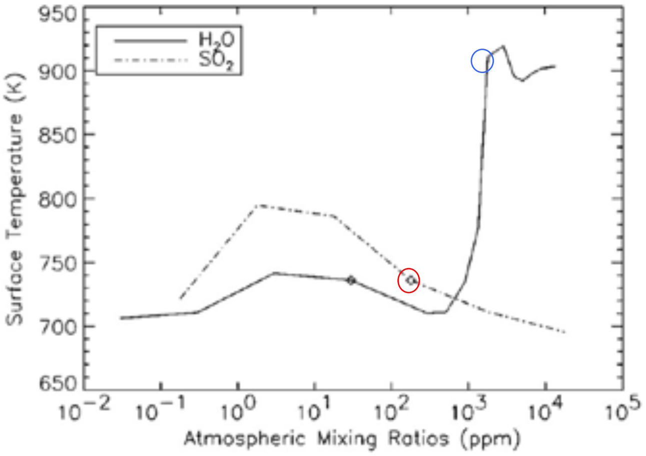
An interesting transition occurs when atmospheric H_2O is increased to more than about 50 times its current value. Because the Venus greenhouse effect is so sensitive to H_2O abundance, the atmosphere heats up sufficiently to overcome the effects of increased cloud albedo.

The result is a rapid decrease in cloud thickness and albedo, as the rising atmospheric temperatures erode the cloud base from below, leaving a high, thin cloud.



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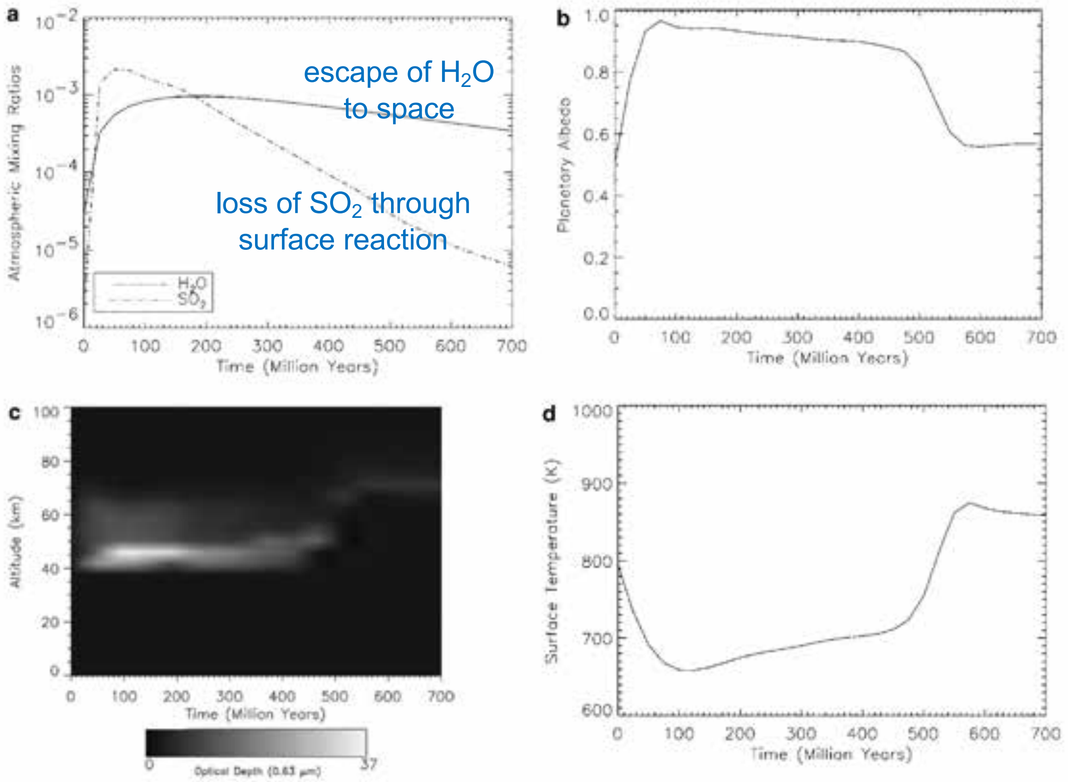
Temporal development including H_2O/SO_2 loss



escape of H_2O to space

loss of SO_2 through surface reaction

FIG. 10. Case 2: Rapid outgassing (100 Myr, 10 km), with exospheric escape (160 Myr) and SO_2 reactions with the surface. (a) is the evolution of atmospheric mixing ratios as a function of time. The solid line is for H_2O, dot–dashed line is for SO_2. (b) is the evolution of planetary albedo. (c) shows the evolution of cloud optical depths as a function of time. (d) shows the evolution of surface temperature as a function of time.