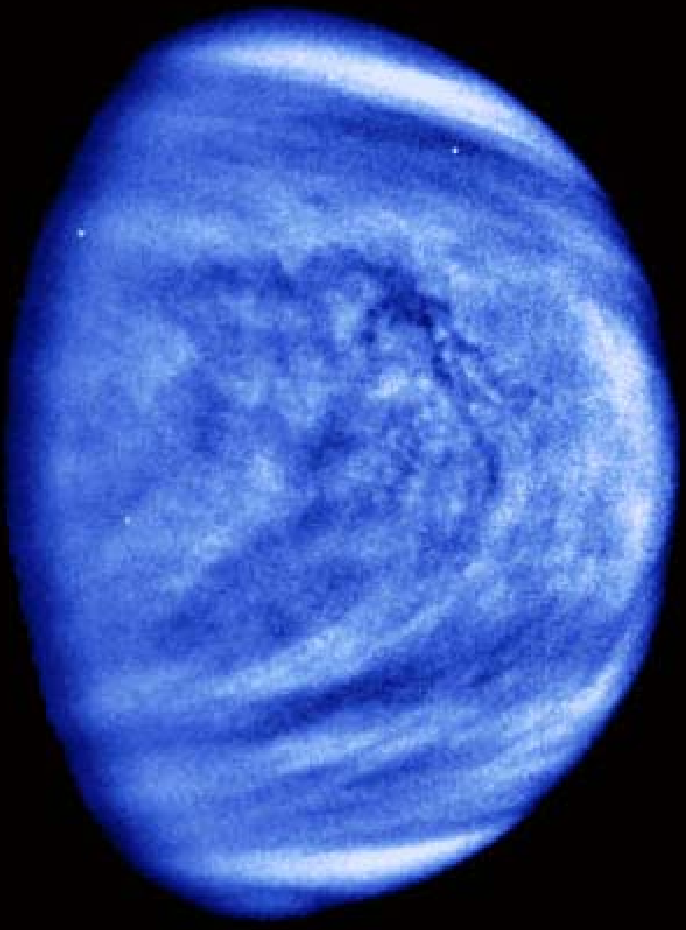
41st Saas-Fee Course
From Planets to Life
3-9 April 2011

Lecture 7—Limits on Climate Stability, Part 1

The runaway greenhouse/
Future evolution of the Earth

J. F. Kasting



Venus

- 93-bar, CO_2-rich atmosphere
- Practically no water (10^{-5} times Earth)
- D/H ratio = 150 times that on Earth

What went wrong with it?

Question:

What went wrong with Venus?

Possible answers:

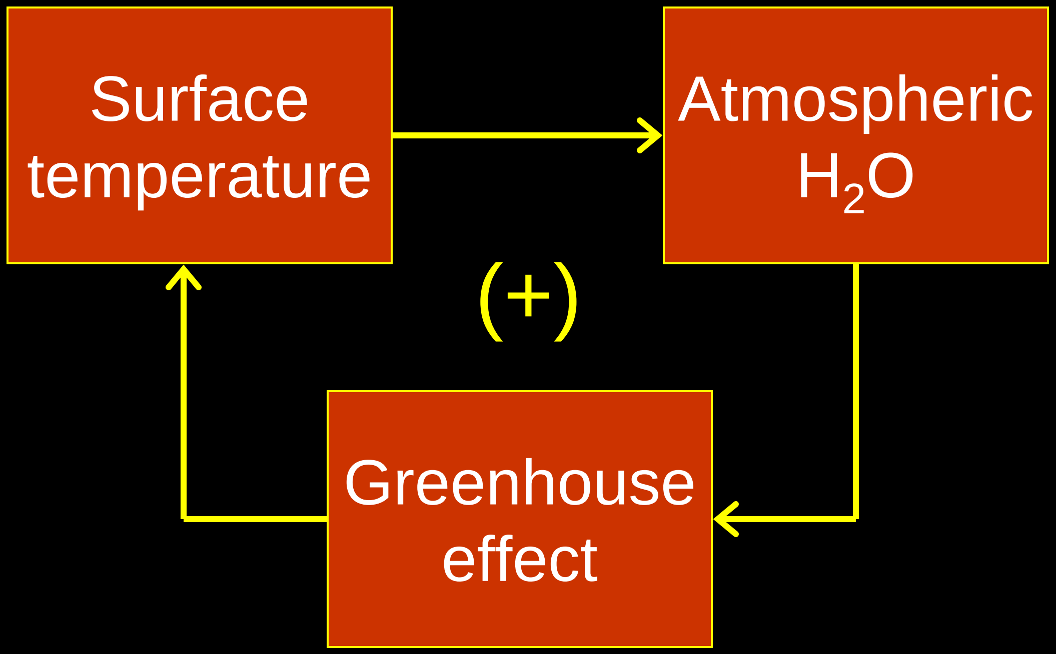
1) Venus never had any water to begin with
   --But this is unlikely if a significant fraction of Earth's water came from the asteroid belt region or beyond, as Jonathan has suggested

or

2) Venus' climate got out of control because of positive feedback loops in the climate system

Positive feedback loops (destabilizing)

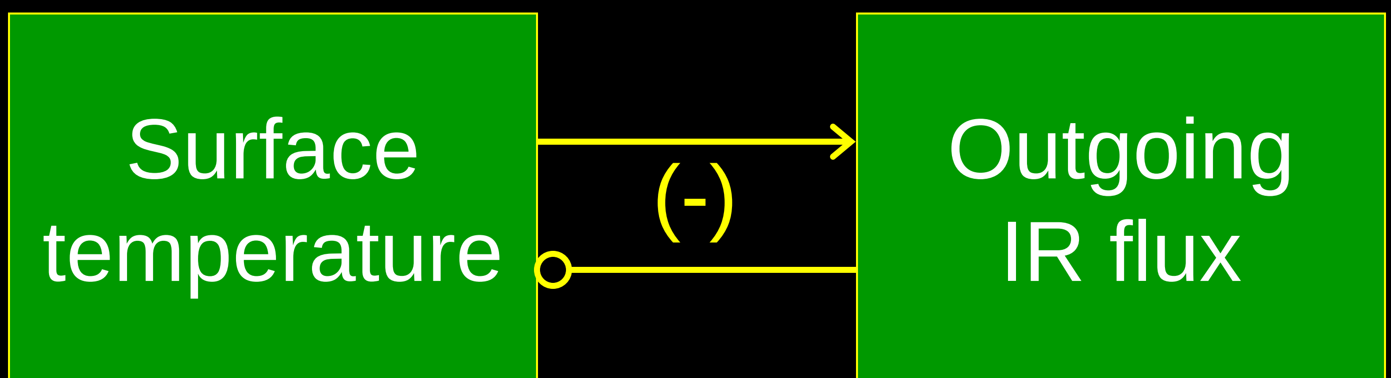
Water vapor feedback



- These next three slides are review, as you have seen them before…

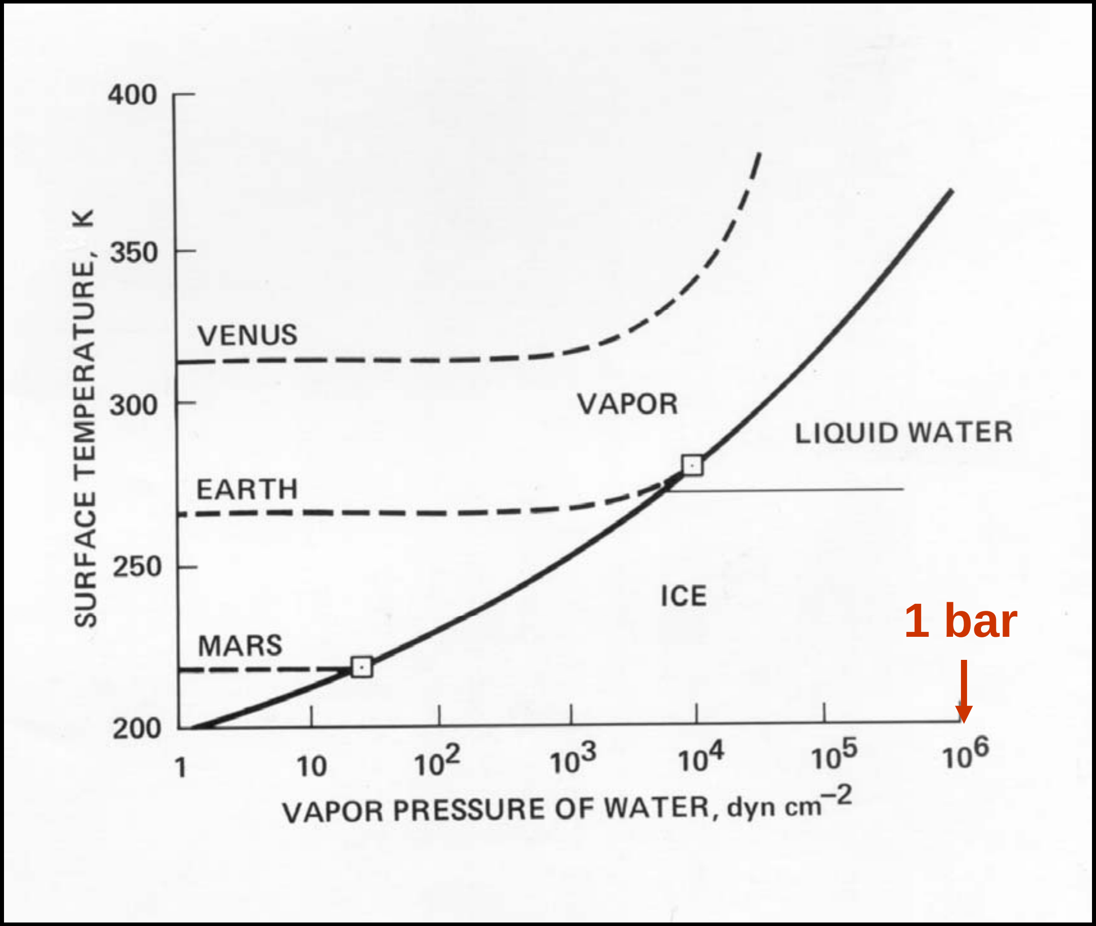
Negative feedback loops (stabilizing)

IR flux feedback



- This feedback can break down when the atmosphere heats up and becomes H_2O-rich

Classical "runaway greenhouse"



Goody and Walker, *Atmospheres* (1972)
After Rasool and deBergh, *Nature* (1970)

Assumptions:
- Start from an airless planet
- Outgas pure H_2O or a mixture of H_2O and CO_2
- Solar luminosity remains fixed at present value
- Calculate greenhouse effect with a gray atmosphere model

Problems with the classical runaway greenhouse model

- Gray atmosphere approximation
- No *convection*
- No variation in solar luminosity
- Planets acquire atmospheres during accretion by *impact degassing* of incoming planetesimals

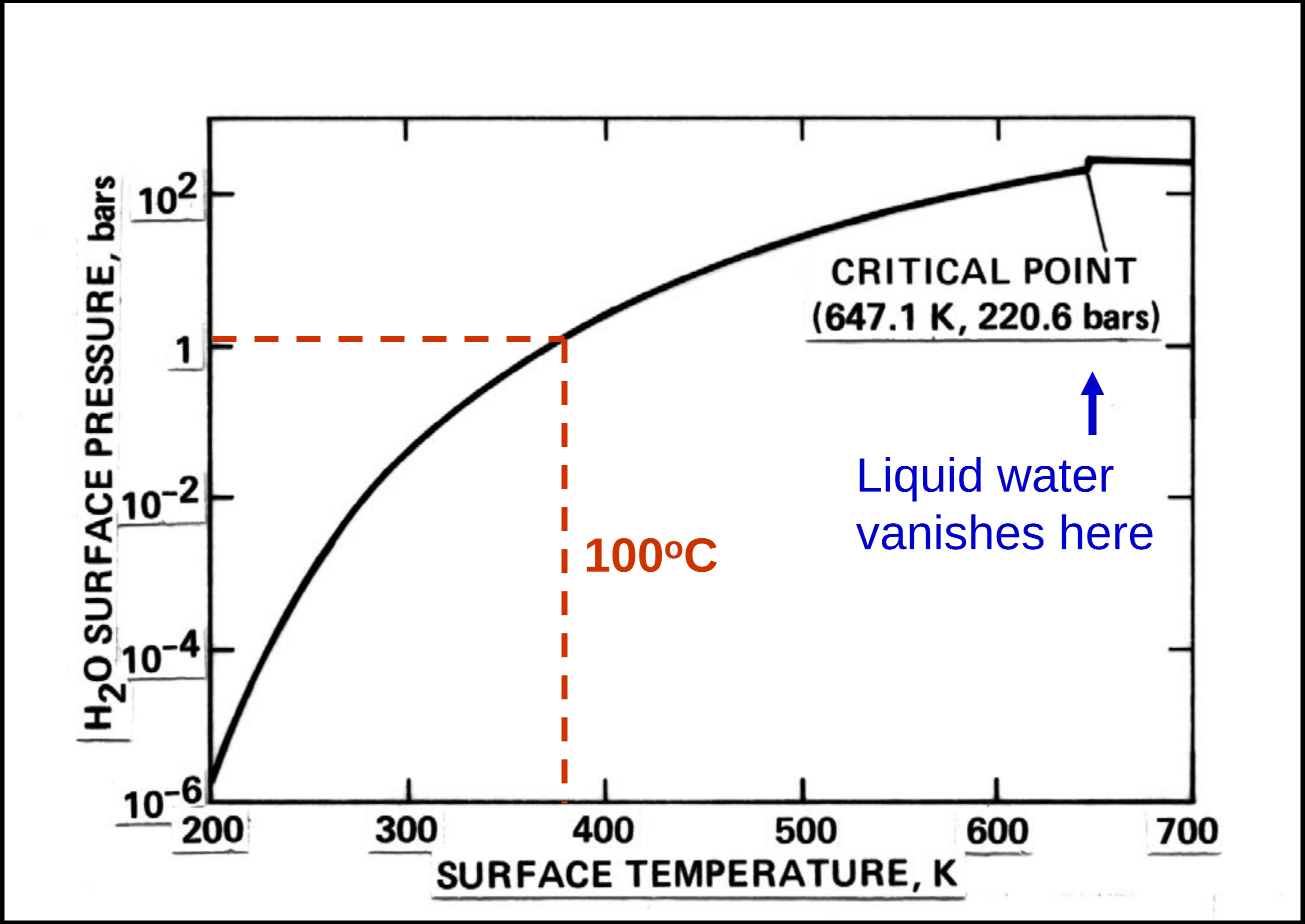
Alternative runaway greenhouse calculation

- Imagine a thought experiment in which you push the present Earth closer to the Sun

- Do this by gradually increasing the surface temperature in one's climate model $\Rightarrow$

J. F. Kasting, *Icarus*, 1988

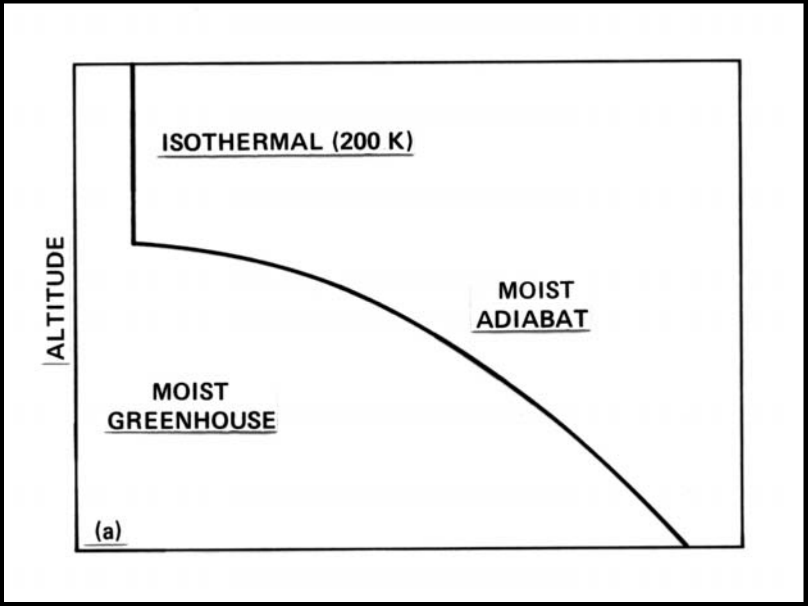
H_2O surface pressure vs. T_s

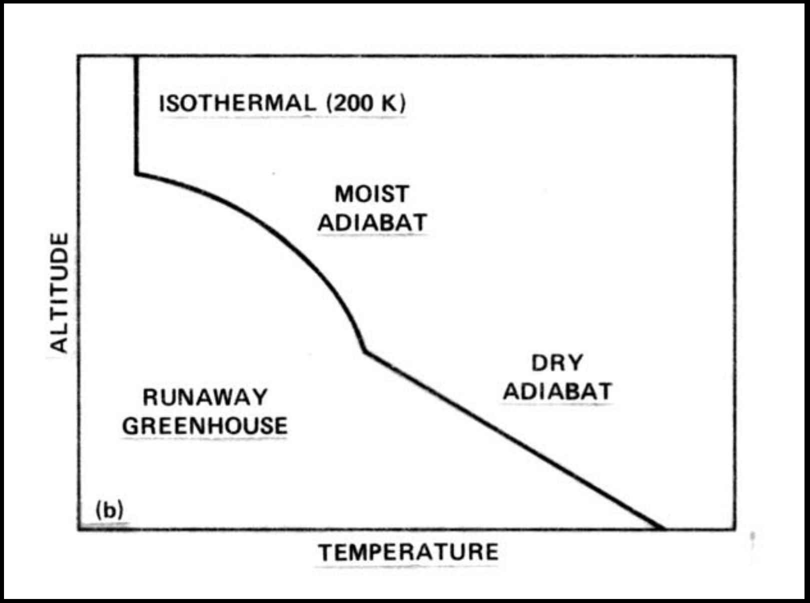


J. F. Kasting, *Icarus* (1988)

- Surface pressure approaches the saturation vapor pressure of water at high T_s
- Pressure exerted by a fully vapor-ized ocean is ~270 bars

Vertical temperature structure





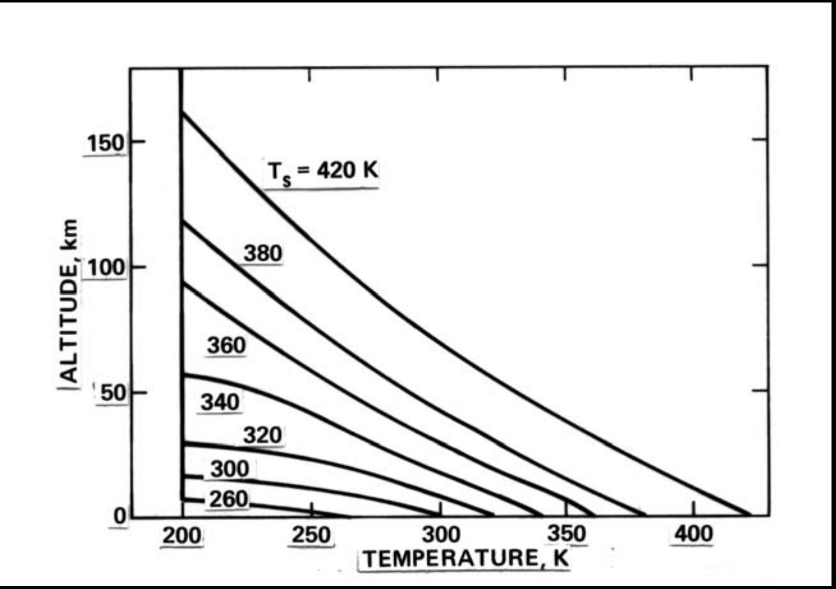
Ocean present

No ocean

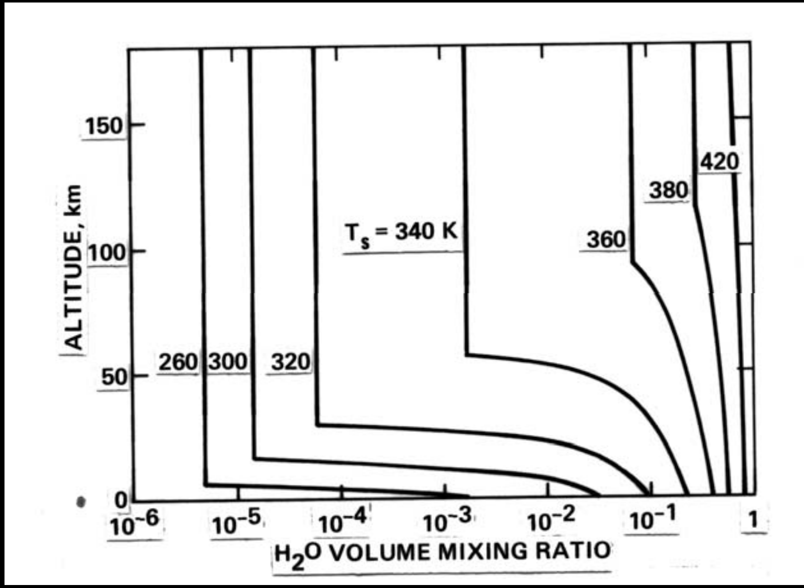
- Lower atmosphere temperature structure should be approximately adiabatic
- Get moist or dry adiabat near the surface, depending on whether liquid water is present

J. F. Kasting, *Icarus* (1988)

Calculated T and H_2O profiles



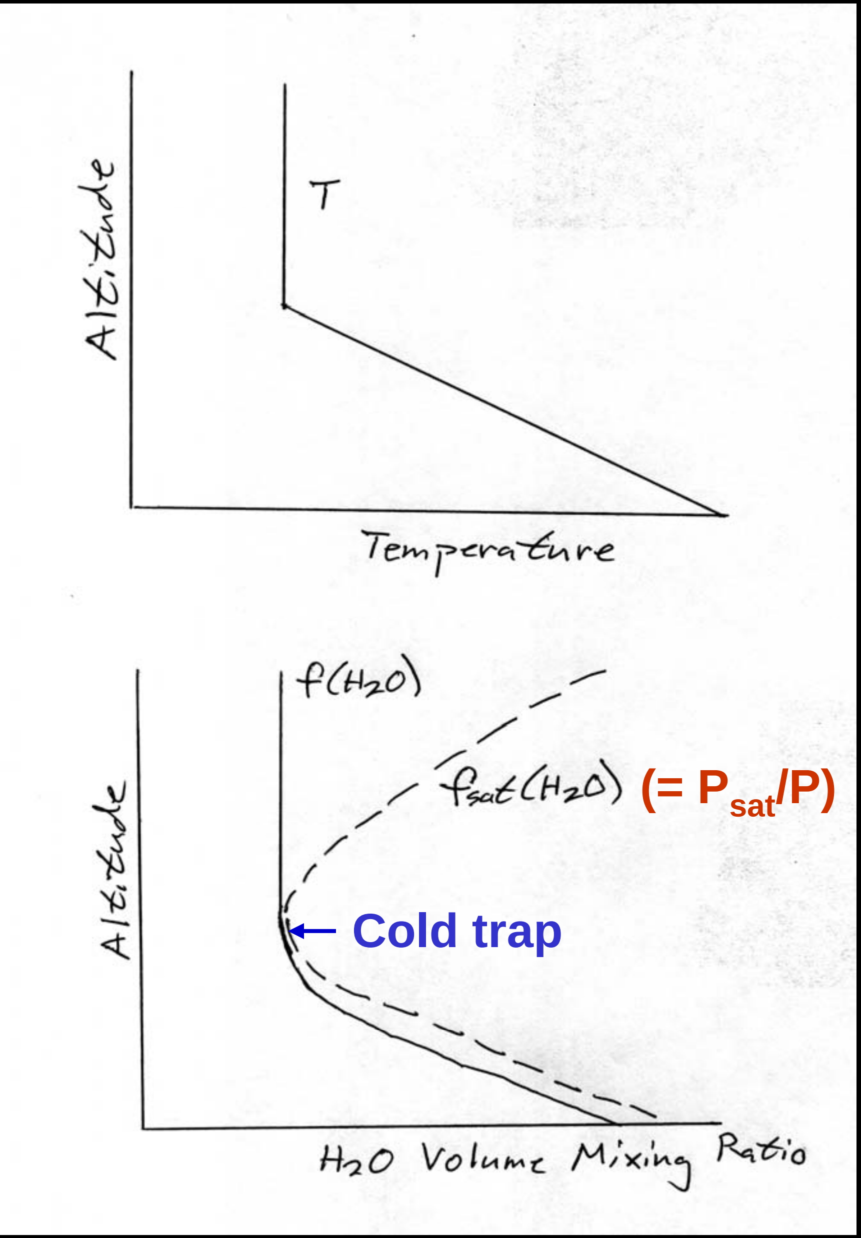
Temperature



Water vapor

- The troposphere expands as the surface temperature rises
- Water vapor becomes a major constituent of the stratosphere at surface temperatures above ~340 K (Ingersoll, *JAS*, 1969)
- Hydrogen can then escape rapidly to space because the *diffusion limit* is overcome

J. F. Kasting, *Icarus* (1988)



Tropopause cold trap

- Temperature decreases rapidly with height in the troposphere, then levels out (or increases) in the stratosphere
- The H_2O vapor pressure decreases with height in the troposphere, then remains constant (or increases) in the stratosphere
- H_2O saturation mixing ratio, $f_{sat} = P_{sat}/P$, must therefore go through a minimum at some height. We call that height the tropopause *cold trap*

Alternative runaway greenhouse calculation

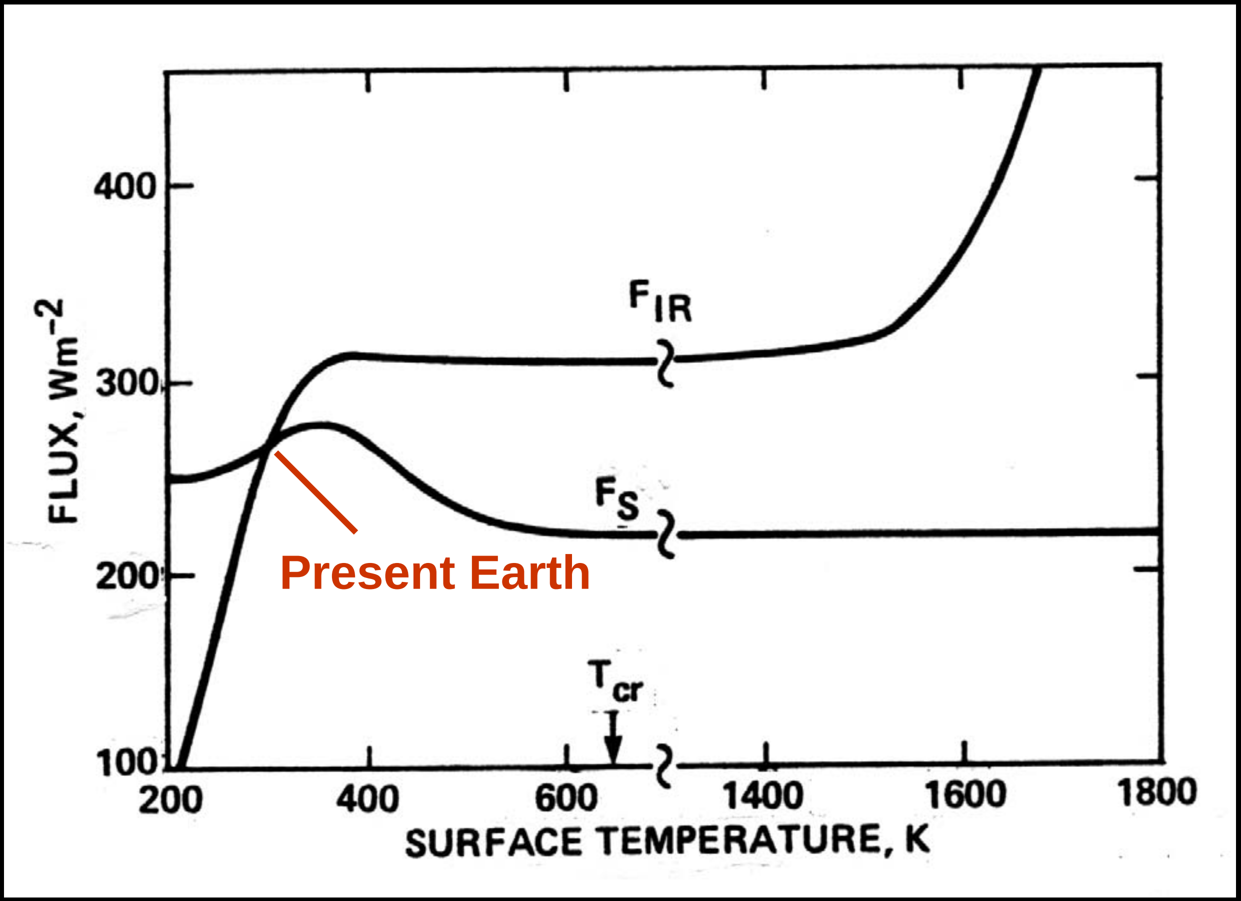
- Now, calculate radiative fluxes. Define

  F_{IR} = net outgoing IR flux
  F_S = net absorbed solar flux *for the present solar luminosity*

- Then

  $S_{EFF} = F_{IR}/F_s$ = solar flux (relative to today) needed to sustain that temperature

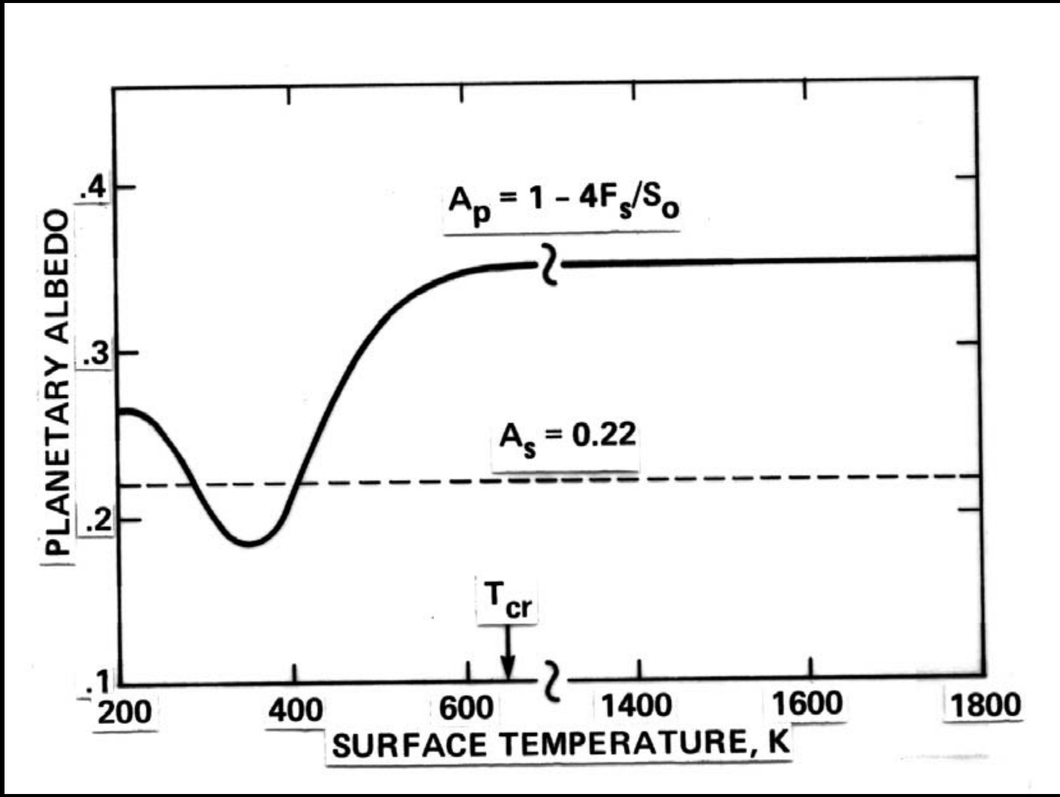
Runaway greenhouse: F_{IR} and F_S



J. F. Kasting, *Icarus* (1988)

- Outgoing IR flux levels out above ~360 K (90^{o}C) because the atmosphere is now opaque at those wavelengths
- (You have seen this figure earlier, also)

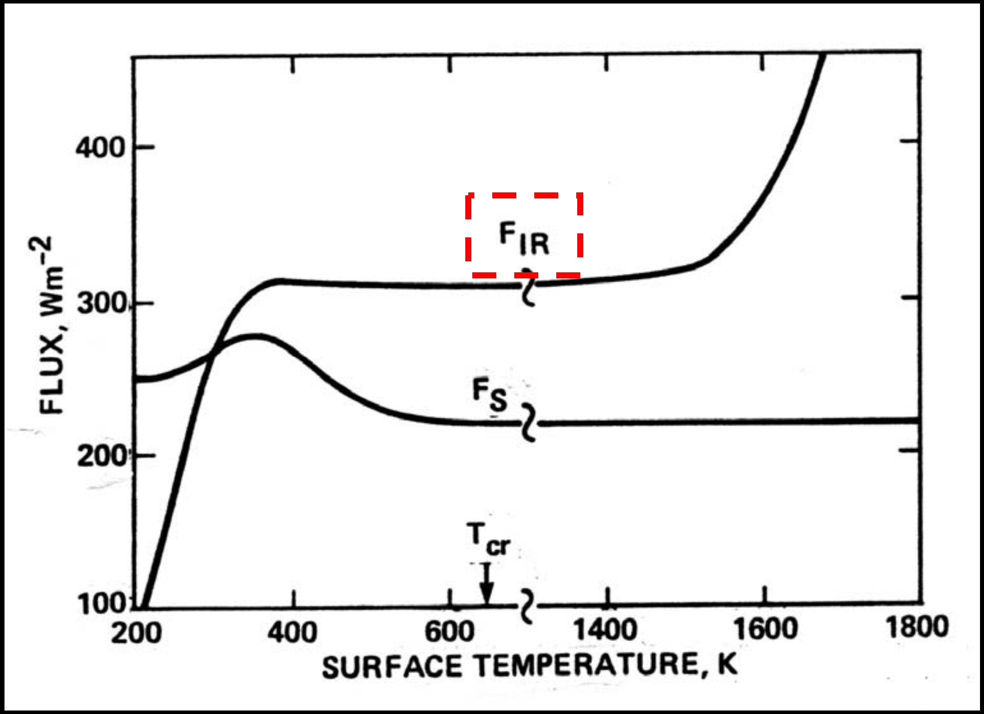
Planetary albedo vs. surface temperature



- The albedo *decreases* with increasing T_s initially because of increased absorption of solar near-IR radiation by H_2O
- At higher T_s, the albedo *increases* because of increased Rayleigh scattering by H_2O

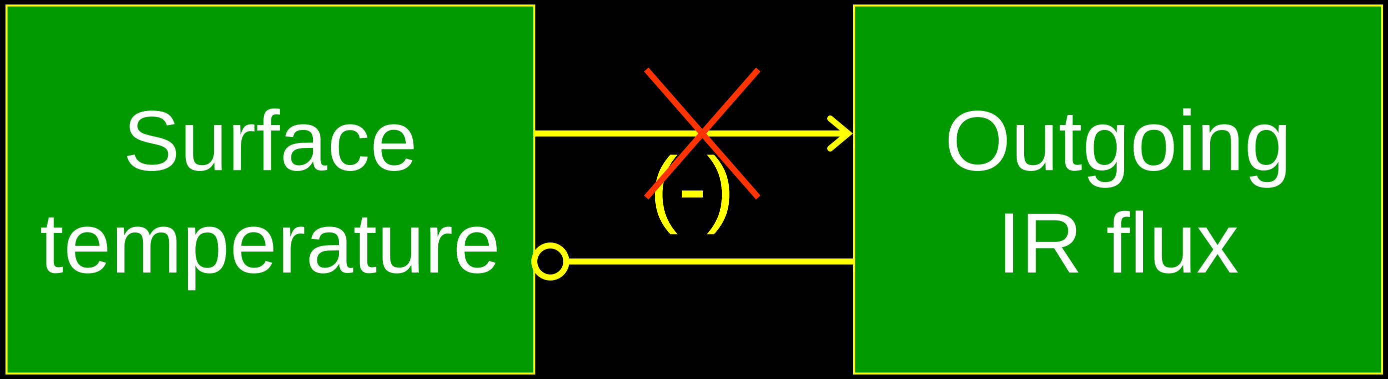
Back to the infrared…

- The key to understanding the runaway greenhouse is to think about the behavior of the outgoing IR flux, F_{IR}

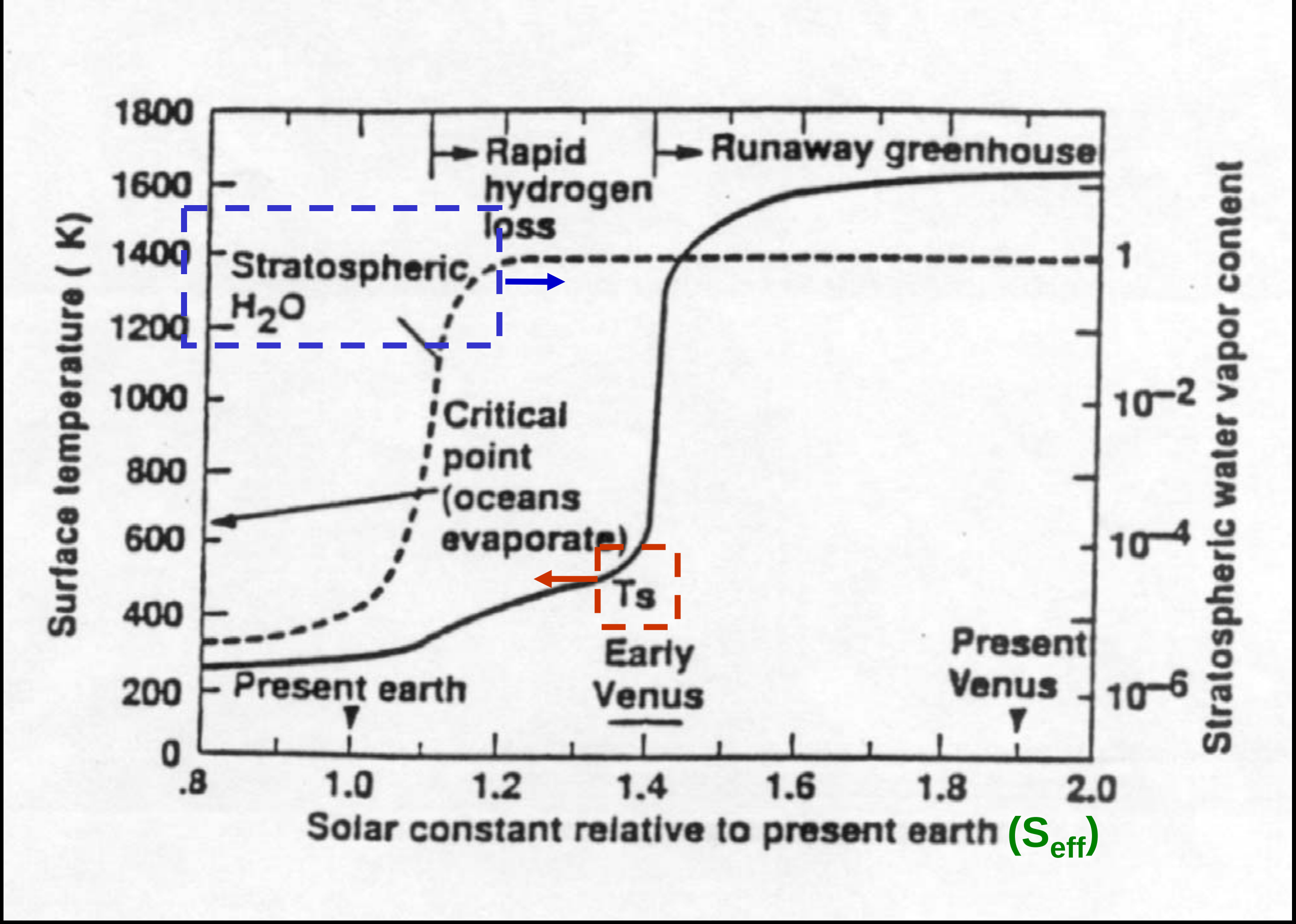


Negative feedback loops (stabilizing)

IR flux feedback



- Above 360 K, the negative feedback loop is broken, so the surface temperature is free to run away



J. F. Kasting, *Icarus* (1988)

- Recall that $S_{eff} = F_{IR}/F_S$
- The stratosphere becomes wet (and the oceans are thus lost) at S_{eff} = 1.1. The corresponding orbital distance is 0.95 AU
- Venus is at 0.72 AU

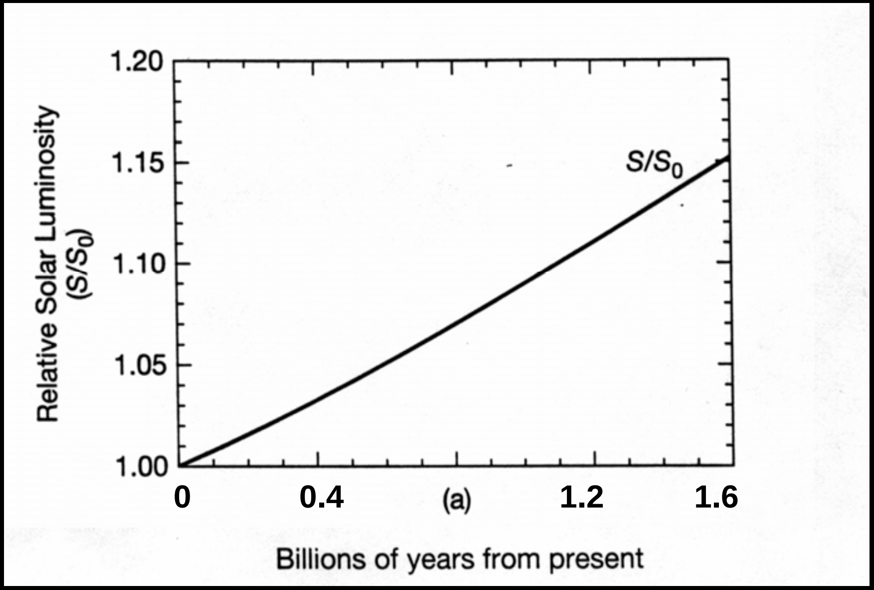
Evolution of Venus' atmosphere (summary)

- Negative cloud feedback may well have pushed early Venus into the liquid water regime
- Venus lost its water anyway because the stratosphere became wet, leading to rapid photolysis and escape of H
- Surprisingly, the presence of liquid water on the surface makes it easier to get rid of the last part of the water by reducing the CO_2 partial pressure and thereby helping to overcome the diffusion limit on H escape
- Once the water was gone, volcanic CO_2 (and SO_2) built up in Venus' atmosphere, leading to its present, hellish state

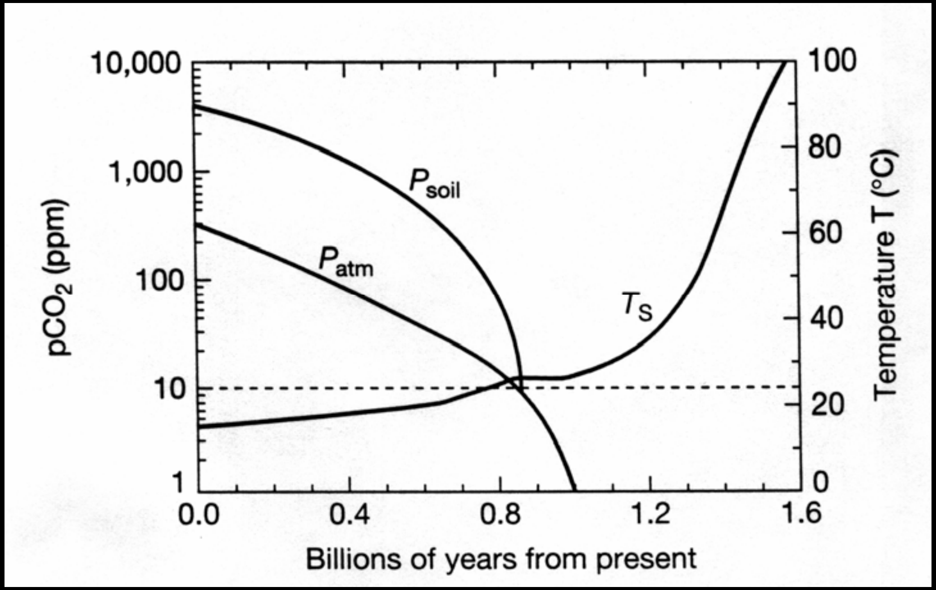
Future climate evolution on Earth

- The Sun continues to get *brighter* at a rate of ~ 1 percent every hundred million years
- This should increase surface temperatures, which in turn should cause faster silicate weathering and a corresponding *decrease* in atmospheric CO_2 $\Rightarrow$

Future Climate Evolution



Solar luminosity



Surface temperature/ atmospheric CO_2

Kump et al., *The Earth System* (2002), Fig. 19-1
After Caldeira and Kasting, *Nature* (1992)

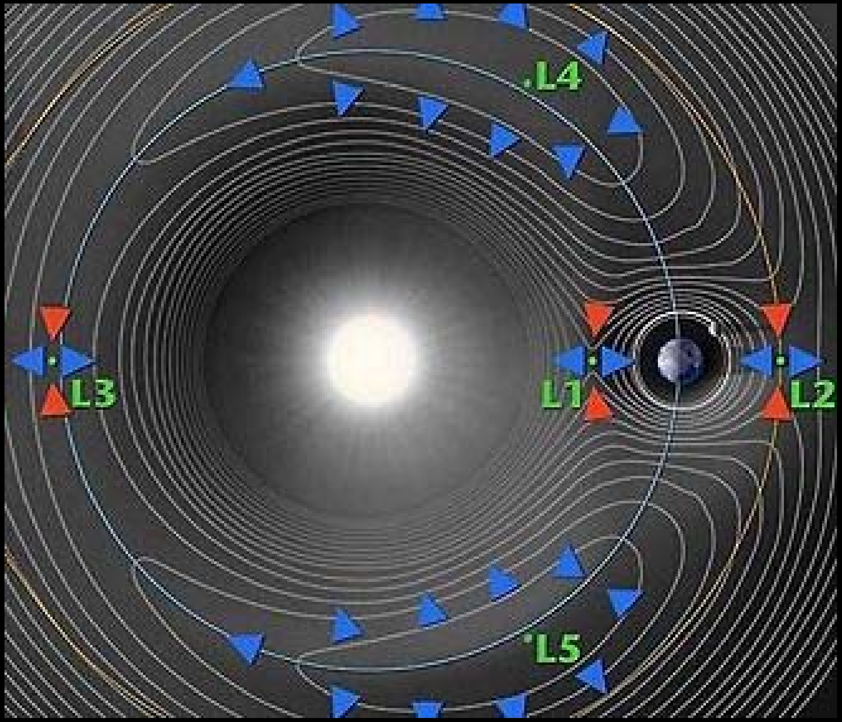
Long-term implications for habitability of Earth

- 500 m.y: CO_2 falls below 150 ppmv ⇒ C_3 plants should become extinct
- 900 m.y.: CO_2 falls below 10 ppmv ⇒ C_4 plants become extinct
- 1.2 b.y.: The rapid rise in surface temperature causes the stratosphere to become wet ⇒ Earth's oceans should be lost over the next few hundred million years, and all life will go extinct

Is there any way to counteract these effects?

Yes! We may be able to build a solar shield and block out part of the light from the Sun $\Rightarrow$

Lagrange points of the Earth-Sun system



“How to Find a Habitable Planet”,
Fig. 7.2

- Points L4 and L5 are *stable* equilibria
- Points L1, L2, and L3 are *unstable* equilibria but you can orbit around them at low cost

Sunshield at L_1

- The idea (from Roger Angel, PNAS, 2006*) would be to build a big lens at L_1 and use it to deflect some of the incoming sunlight
  - Probably a collection of $\sim 10^{12}$ smaller lenses, in reality
- This might also be a way to counteract global warming
- One CO_2 doubling is roughly equivalent to a 2% increase in solar luminosity
- Hence, to cancel out 1 doubling, we'd need to block out about 2% of the Sun's light $\Rightarrow$ need a lens about 1000 km in diameter
  - Effective scattering area is twice the surface area because of diffraction

*Original idea from J.T. Early, *J. Br. Interplanet. Soc*. **42**, 567 (1989)

- Question: How do you build a really huge object in space?
- Answer: You mine the materials on the Moon, then launch them into space using a mass driver (an electromagnetic rail gun)
- Which should we do: Try to keep CO_2 concentrations low, or simply offset their effect in this way?