GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

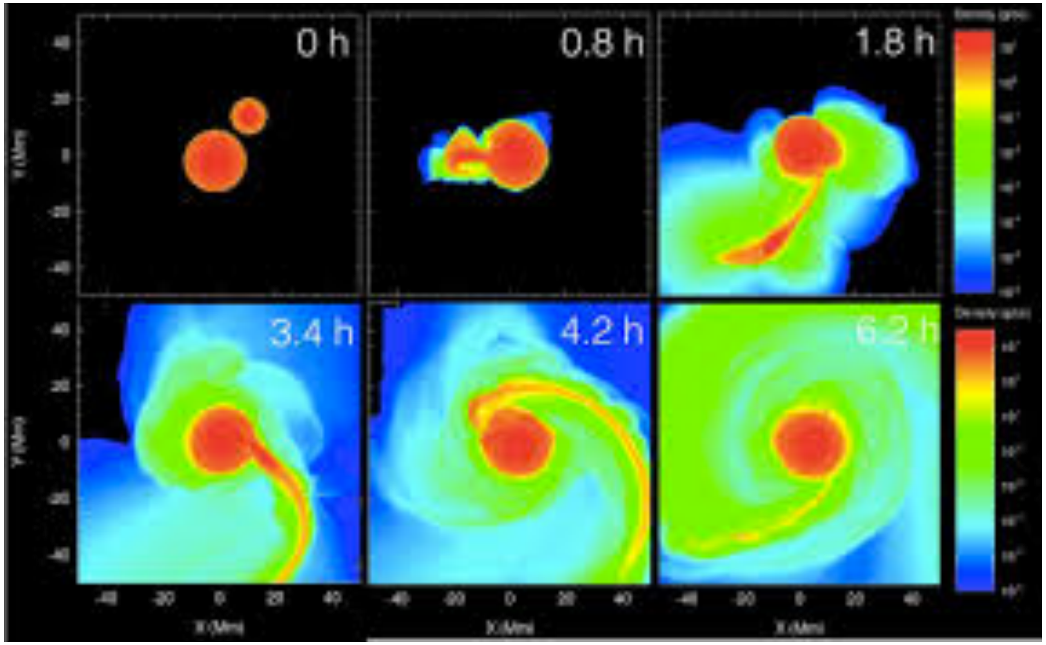
Lecture 9

Thursday 26 April 2018

Today

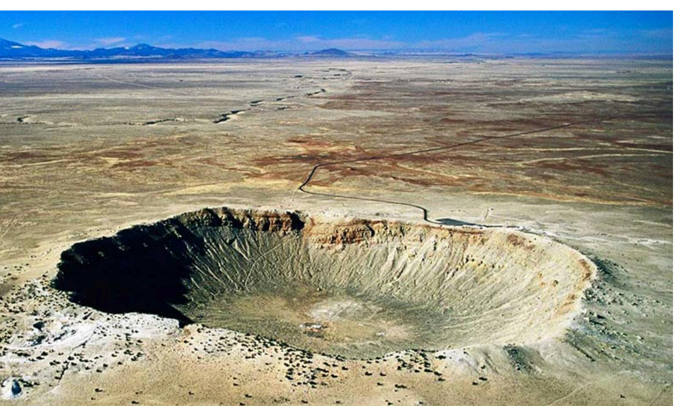
- Reminder: Graduate students + undergraduates who choose the term paper option: Send term paper topics to kite@uchicago.edu before end Fri 27 for approval. Term papers due in at the start of the final (10:30a-12:30p , Thu 7 June , HGS 180)
- **Seeking volunteers for Yang et al. 2013 'Stabilizing cloud feedback dramatically expands the habitable zone of tidally locked planets' (to be presented on Tue 8 May)**
- Homework 3 is due in class Tue 1 May
- Office hours after class today
- Wrap-up of impact erosion
- **Runaway greenhouse**

Wrap-up: impact erosion

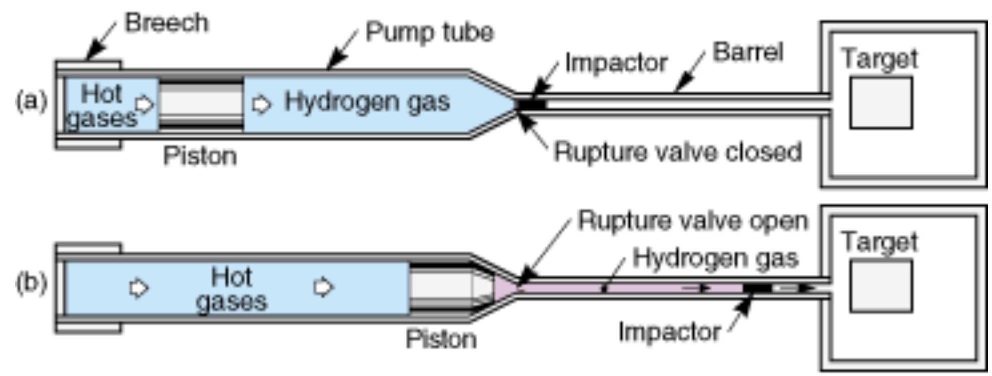


Hydrocode

Nuclear tests



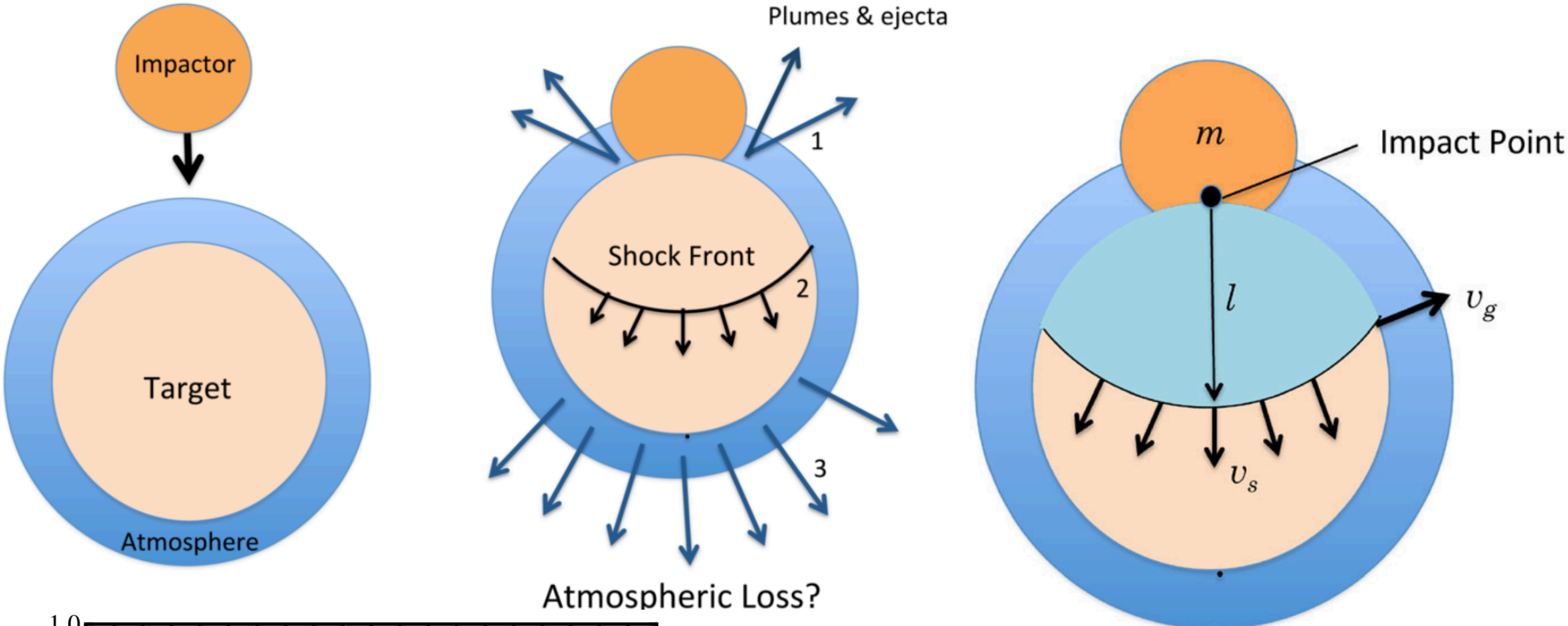
Terrestrial impact craters

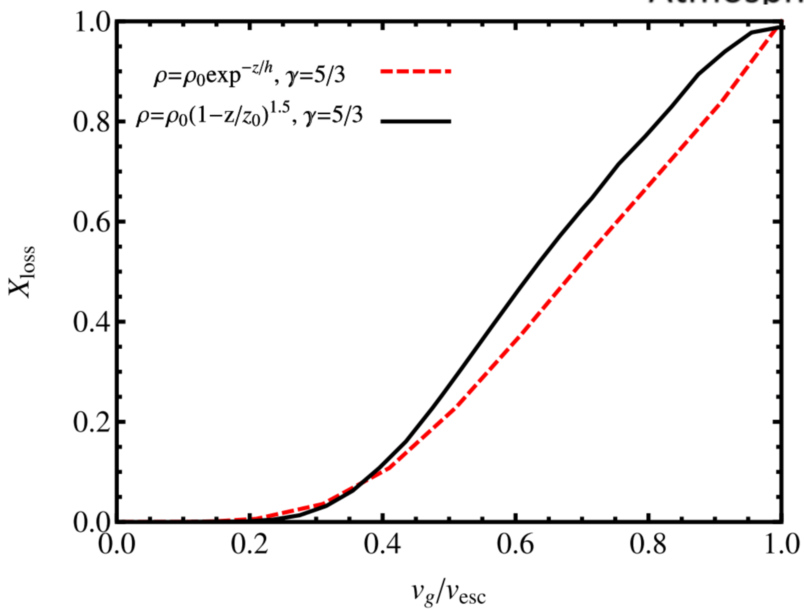


(a) In the first stage of the gas gun (blue shading), hot-burning gases from gunpowder drive a piston, which in turn compresses hydrogen gas. (b) In the second stage (pink shading), the high-pressure gas eventually ruptures a second-stage valve, accelerating the impactor down the barrel toward its target.

Two-stage gas gun

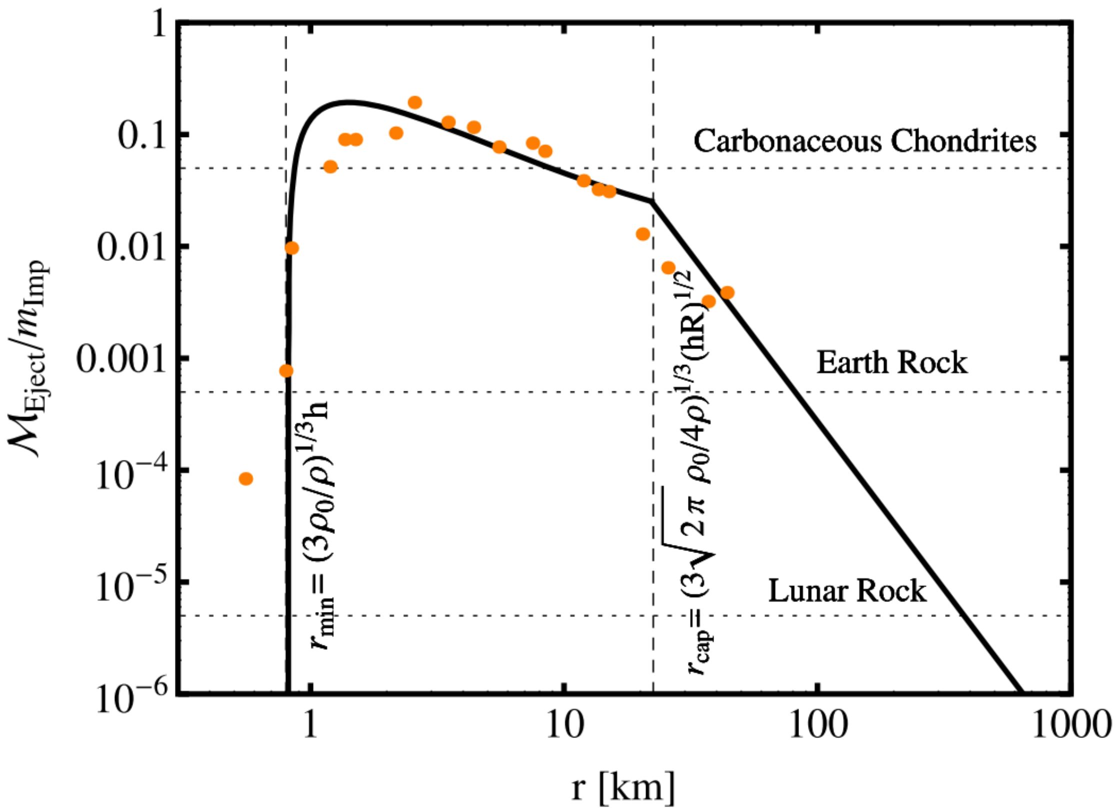
The atmosphere-loss escape efficiency of giant impacts is set by the ground-motion speed





Schlichting & Mukhopadhay 2018

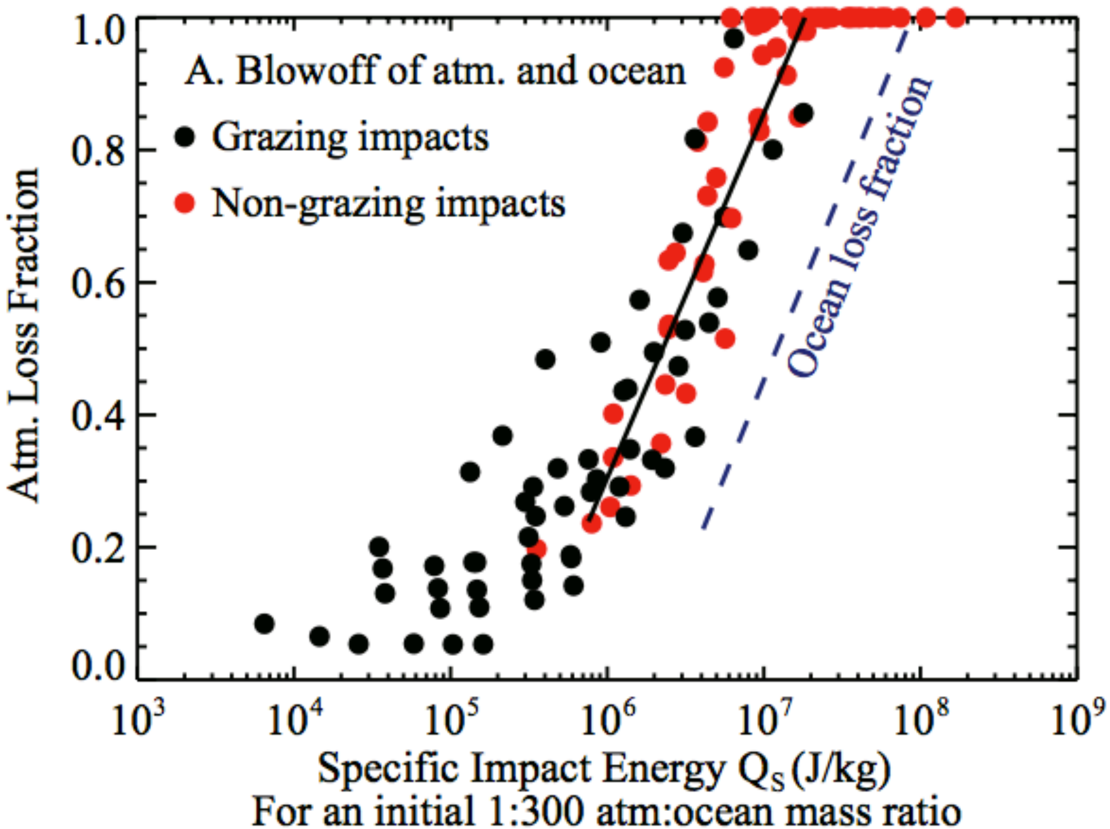
Impacts by small asteroids/comets efficiently eject ~1 bar atmospheres



The peak would move to larger *r* if the initial atmospheric pressure were greater

Fig. 9 Ratio of atmospheric mass ejected to impactor mass, $\mathcal{M}_{Eject}/m_{Imp}$. Numerical values are scaled to the current Earth's atmosphere and shown for $v_{imp}\eta/v_{esc} \sim 1$. Small impactors with $r_* = \sqrt{3}r_{min}$ are the most efficient impactors per unit mass in ejecting the atmosphere and the ejection efficiency decreases rapidly for larger planetesimals. Whether or not planetesimal impacts will lead to a net loss of planetary atmospheres depends on the impactor sizes distribution, their volatile budget and the amount of outgassing their impacts can initiate. The *three dotted horizontal lines* correspond to volatile contents of 5 wt.% (representative of some of the most water rich carbonaceous chondrites), 0.05 wt.% (representative of the average water content in the bulk Earth excluding the hydrosphere) and 0.0005 wt.% corresponding to an estimate of the minimum water content of the bulk moon (McCubbin et al. 2010). For comparison, data from oblique impact simulations for escape velocities of 11.2 km/s and impact velocities of 30 km/s from Shuvalov (2009) are shown by the orange points. Figure after Schlichting et al. (2015)

Ocean removal by giant impacts?
(Ocean vaporization is not sufficient for ocean removal)



Stewart et al. LPSC 2014

Simulations suggest that the Moon-forming impact was marginally able to remove any pre-existing Earth ocean

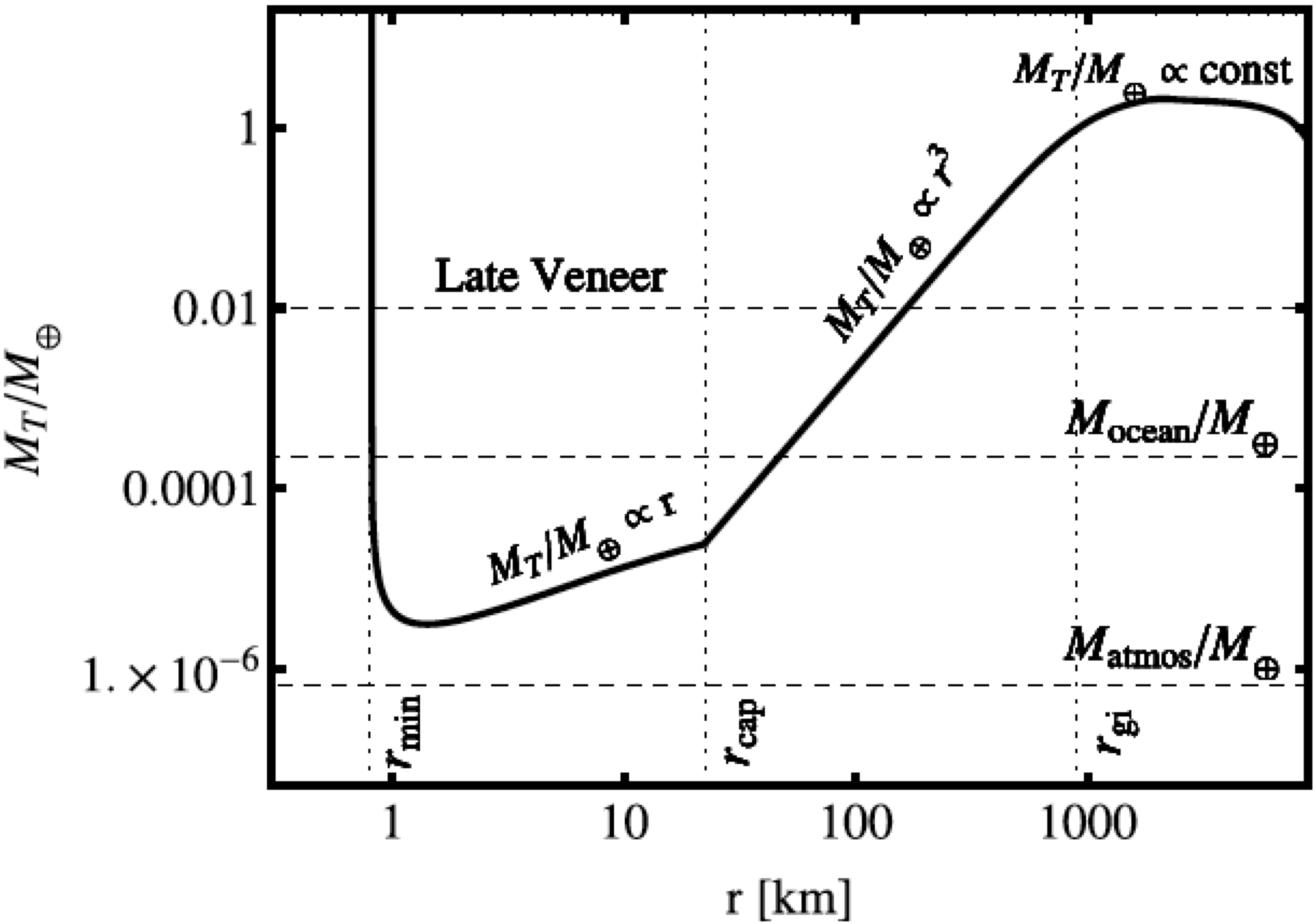
$Q_s \sim v_e^2$ for oligarchic impact

$$v_e = \sqrt{\frac{2GM}{r}}$$

escape velocity

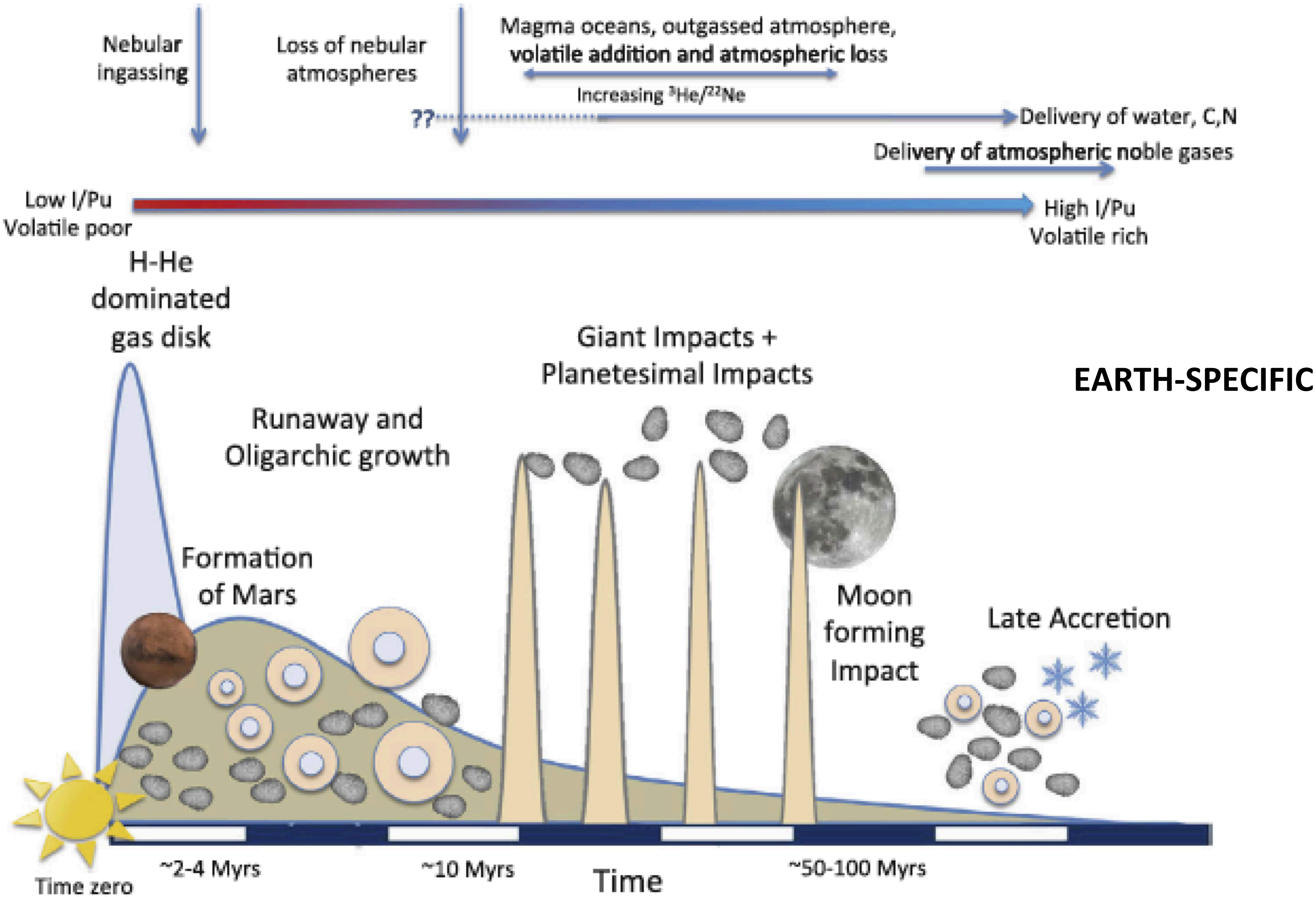
There have also been major recent developments in our understanding of Moon formation, the Moon's orbital evolution, and Moon-induced tidal heating, but orbital/tidal effects are not part of this course.

Total impactor mass needed to eject the atmosphere as a function of impactor radius



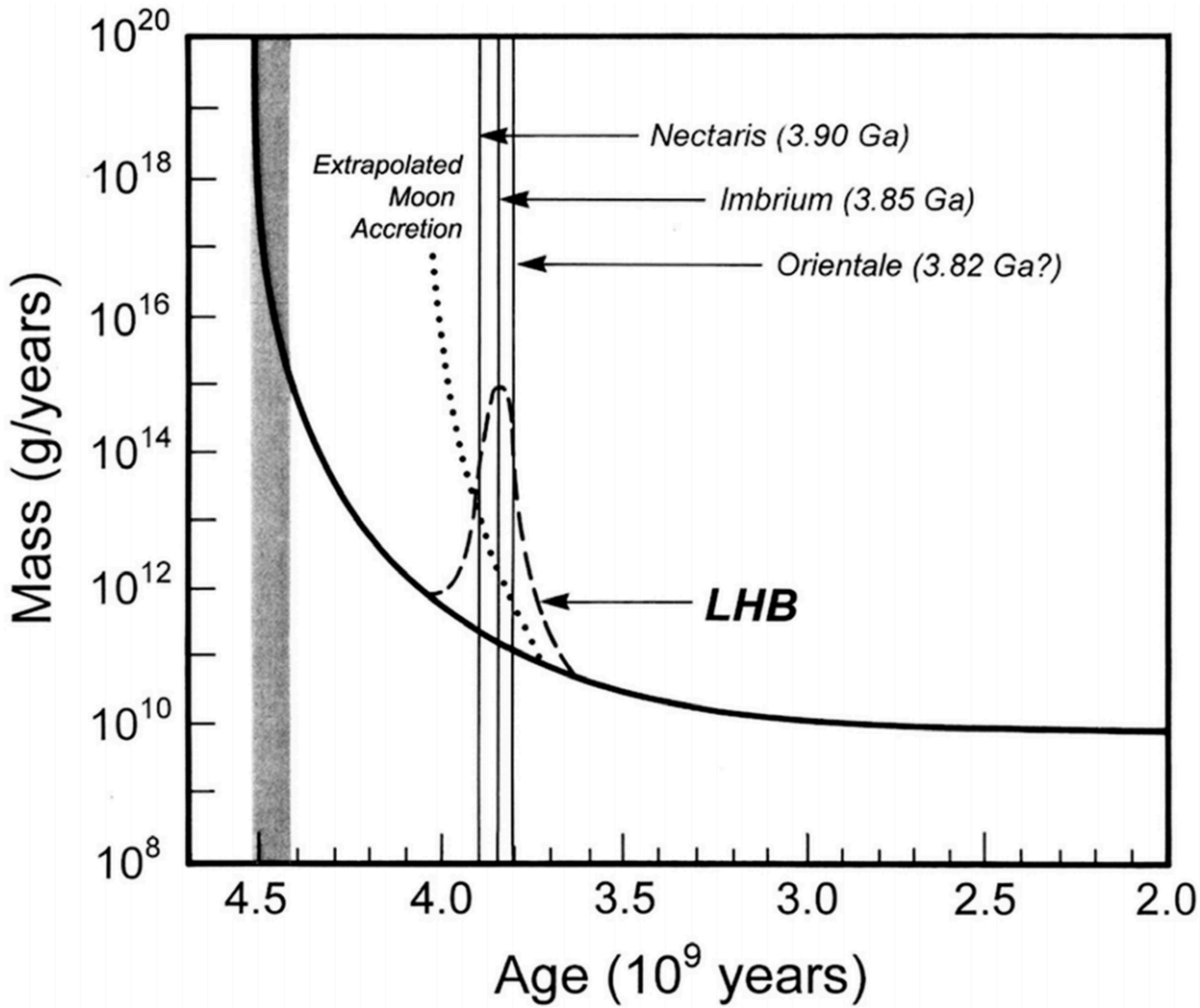
Schlichting & Mukhopadhay 2018

History of Earth's volatile delivery and removal



Schlichting & Mukhopadhay 2018

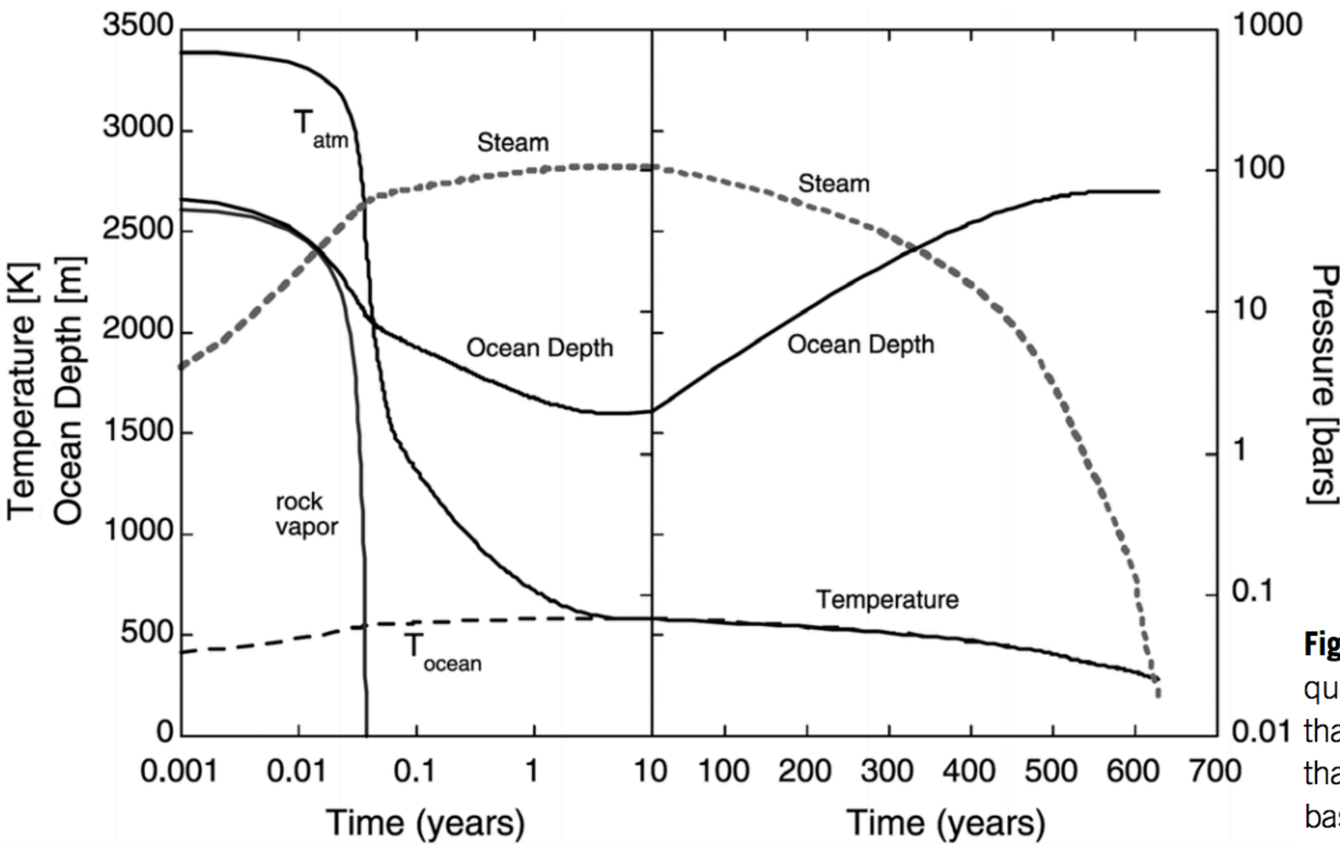
An uptick in bombardment ~3.9 Ga?



Catling & Kasting ch. 6 (Fig. 6.18)

Effect of basin-forming impacts on habitability: impact frustration of life establishing itself on Earth?

Based on Lunar cratering record, 10-100 Hellas-sized events would have occurred on the Earth (which has since been resurfaced by plate tectonics)



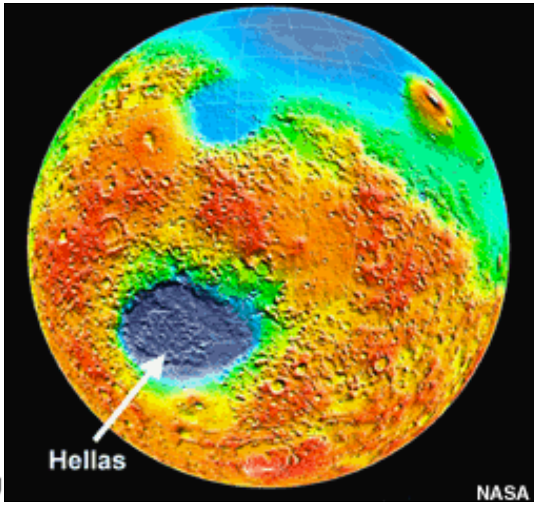


Figure 6.19 The environmental consequences on the early Earth of an impactor that released 10^{27} J, comparable to that that caused the 2100 km-wide Hellas basin on Mars. Ocean depth, ocean temperature, and atmospheric temperature are shown as a function of time, along with the pressure of rock vapor and steam. (From Nisbet *et al.* (2007a). Reproduced with permission of Springer. Copyright 2007, Springer Science + Business Media, Inc.)

(Ocean vaporization is not sufficient for ocean removal)

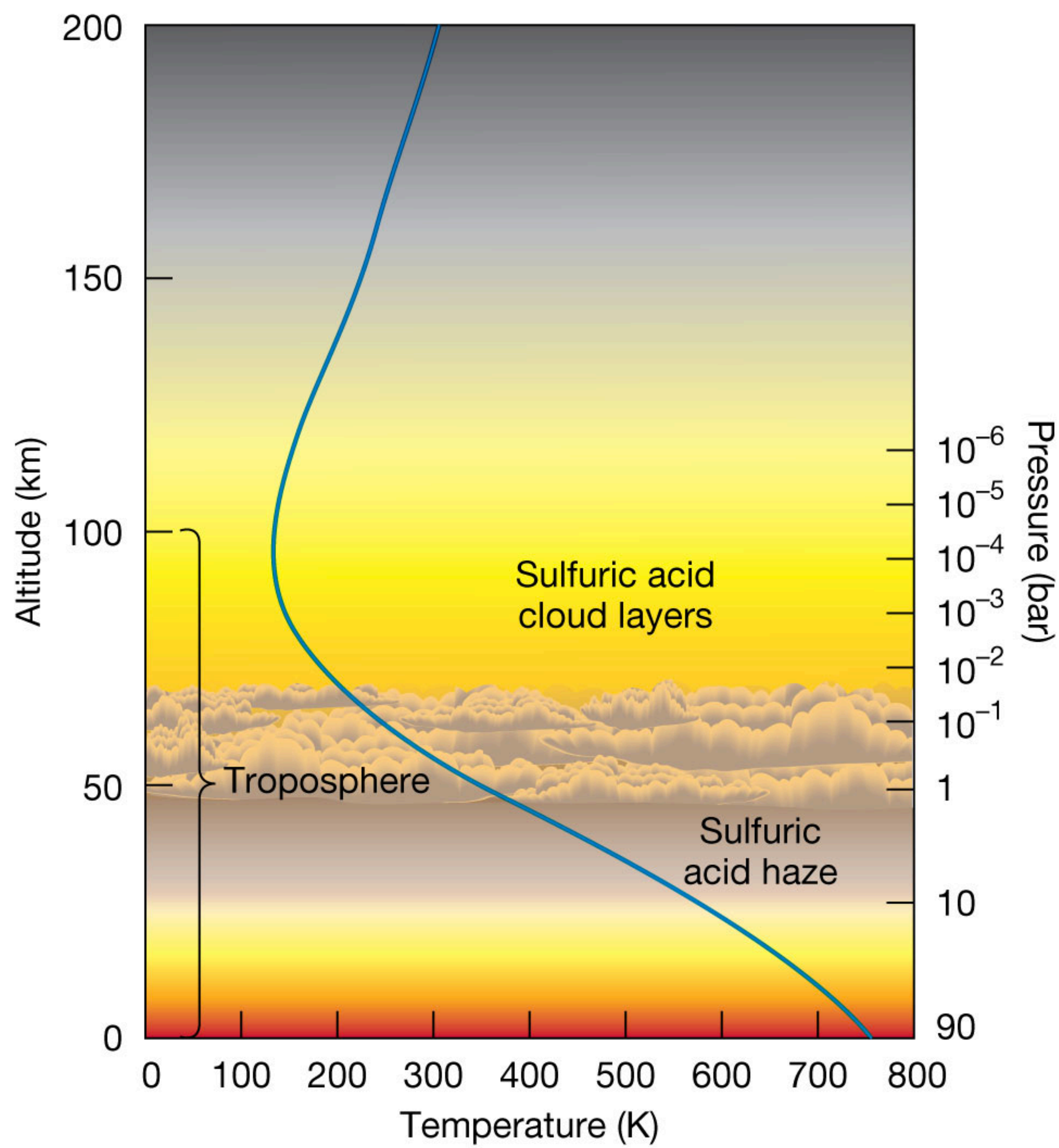
e.g. Maher & Stevenson 1987

Microbial life might persist km deep within the crust

Runaway greenhouse – key points

- The (H_2O-)runaway greenhouse is a geologically rapid increase in planet surface temperature from <400K to >1000K caused by a positive feedback between the saturation vapor pressure of water vapor and the
- Be able to explain the mechanism of the runaway greenhouse
- It is almost certain that release of CO_2 by humans cannot cause a runaway greenhouse
- The exact threshold for the runaway greenhouse depends on cloud cover, land fraction, and planet rotation rate

Venus is dry today



The inner edge of the habitable zone is defined by the runaway greenhouse limit

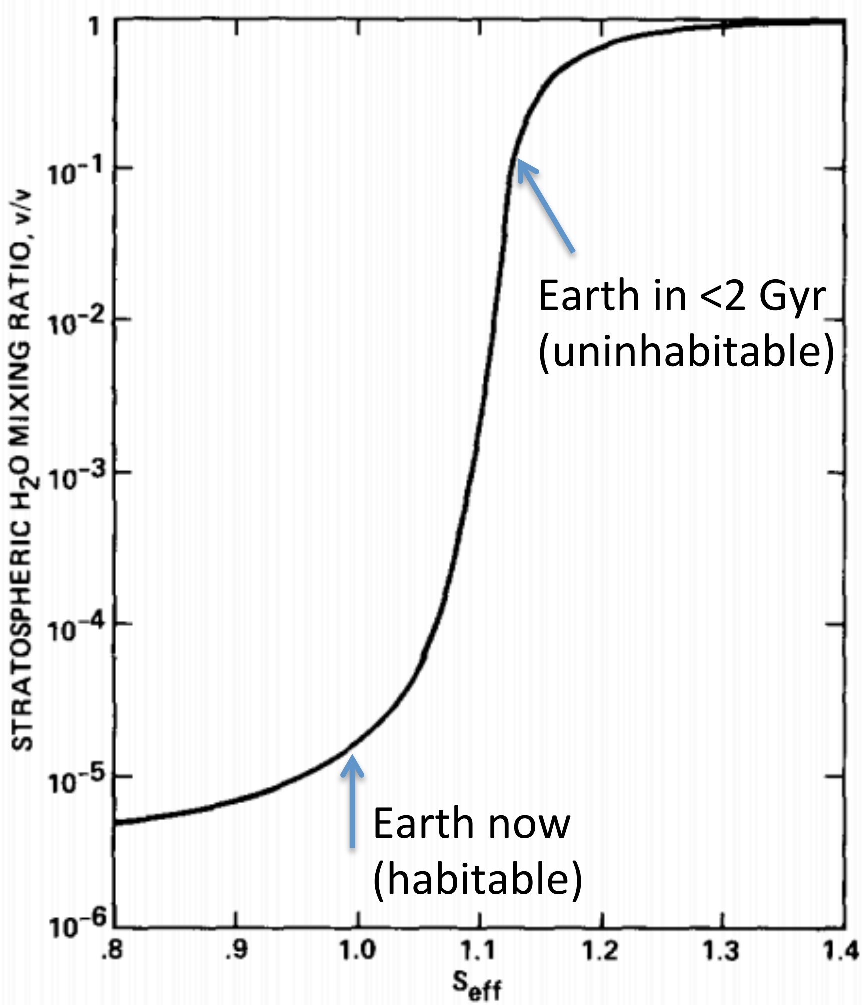


FIG. 14. H_2O volume mixing ratio in the stratosphere versus effective solar constant S_{eff}.

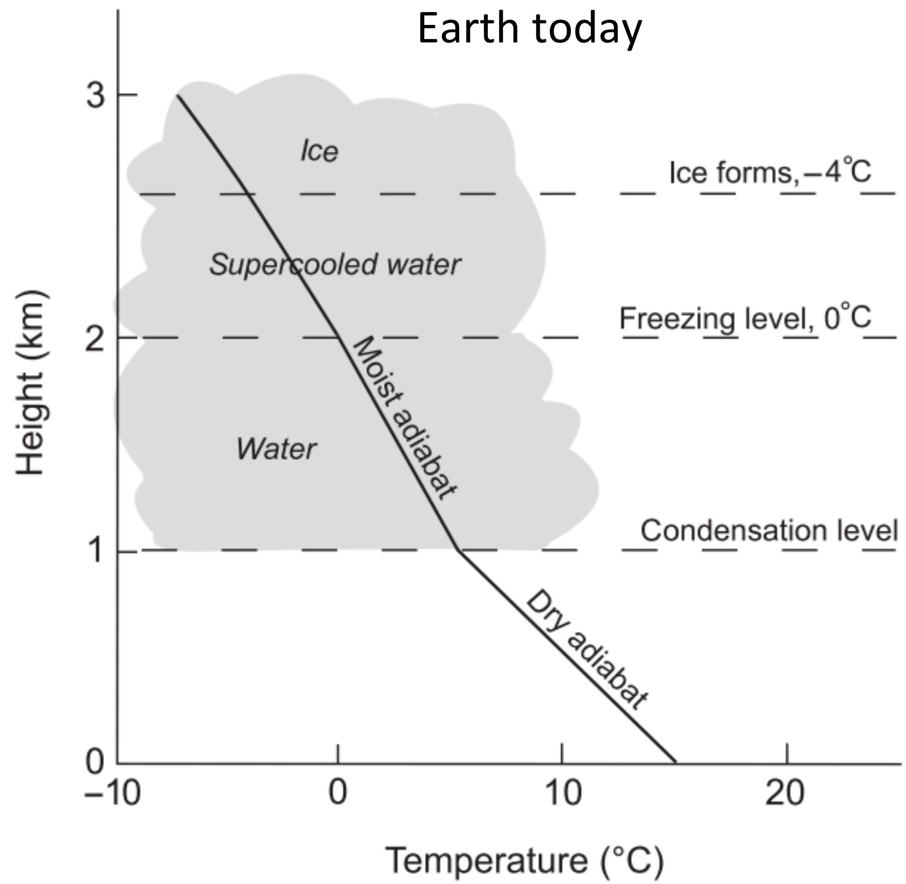
Clasius-Clapeyron relation: exponential increase in water vapor partial pressure with increasing T

$$\frac{de_s}{dT} = \frac{l_c e_s}{R_c T^2}, \qquad \text{or} \qquad \frac{\mathrm{d}(\ln e_s)}{dT} = \frac{l_c}{R_c T^2}$$

$$e_s(T) = e_s(T_0)\exp\left(\int_{T_0}^{T} \frac{l_c}{R_c}\frac{dT}{T^2}\right) \approx e_s(T_0)\exp\left[\frac{l_c}{R_c}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \tag{1.49}$$

section 1.1.3.5 of Catling & Kasting, ch. 1

Definitions: adiabat and moist adiabat



Definitions: adiabat and moist adiabat

Condensible "c" (e.g. water) and noncondensible "a" (e.g. O_2/N_2)
Assume instant precipitation of condensate

$$(m_a + m_c)\delta Q = m_a c_{pa} dT - \frac{m_a}{\rho_a} dp_a + m_c c_{pc} dT - \frac{m_c}{\rho_c} dp_c + L dm_c$$

zero by definition of adiabat

Assuming saturation (relative humidity = 1),

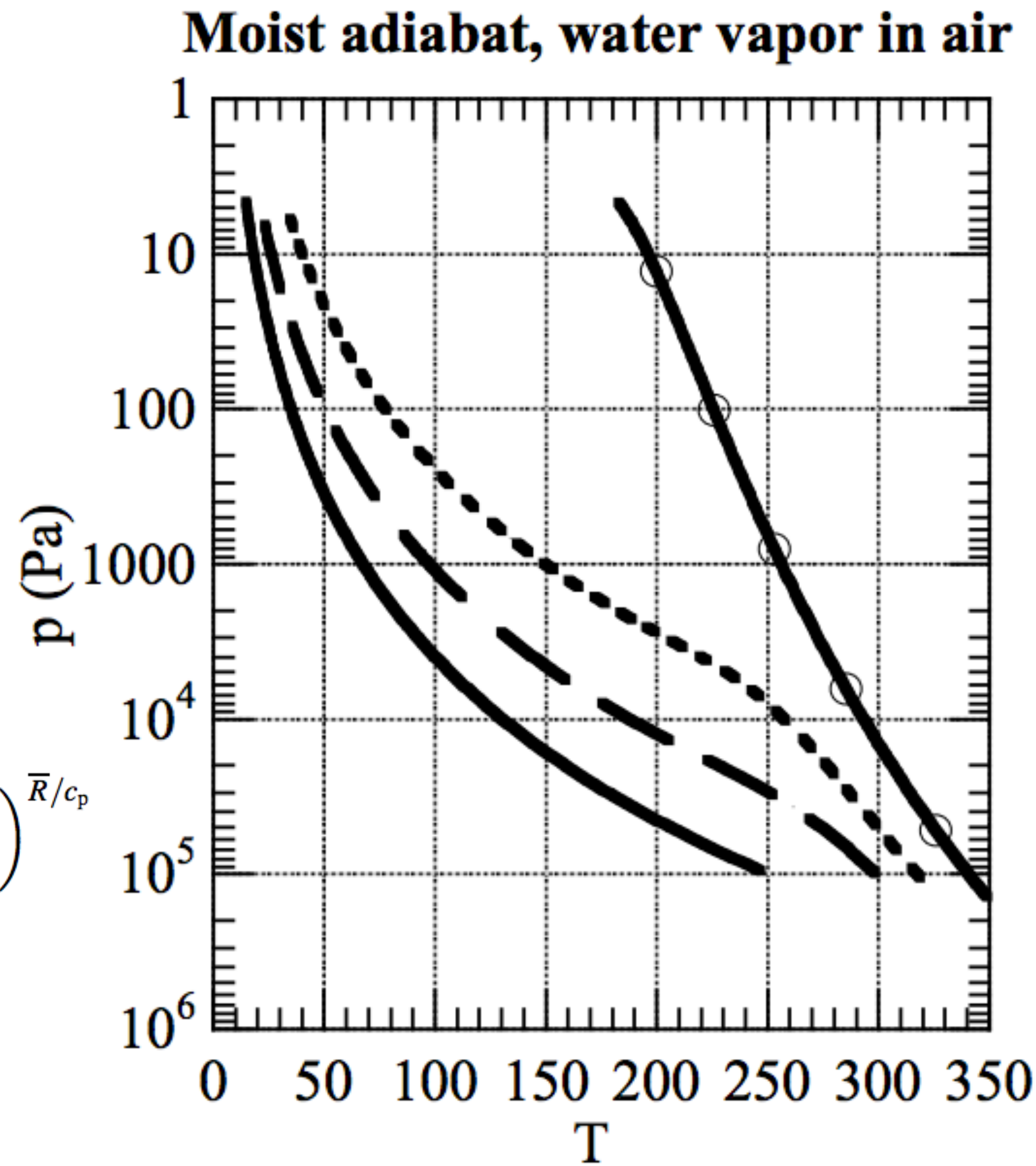
$$\frac{d\ln T}{d\ln p_a} = \frac{R_a}{c_{pa}} \frac{1 + \frac{L}{R_a T} r_{sat}}{1 + (\frac{c_{pc}}{c_{pa}} + (\frac{L}{R_c T} - 1)\frac{L}{c_{pa} T}) r_{sat}}$$

Mixing ratio at saturation

In the limit $r_{sat} = 0$ (dry atmosphere), this equation gives the dry adiabat

In the limit where water vapor is the dominant constituent of the atmosphere, this tends to the saturation vapor pressure curve.

As temperature increases, the moist adiabat increasingly diverges from the dry adiabat



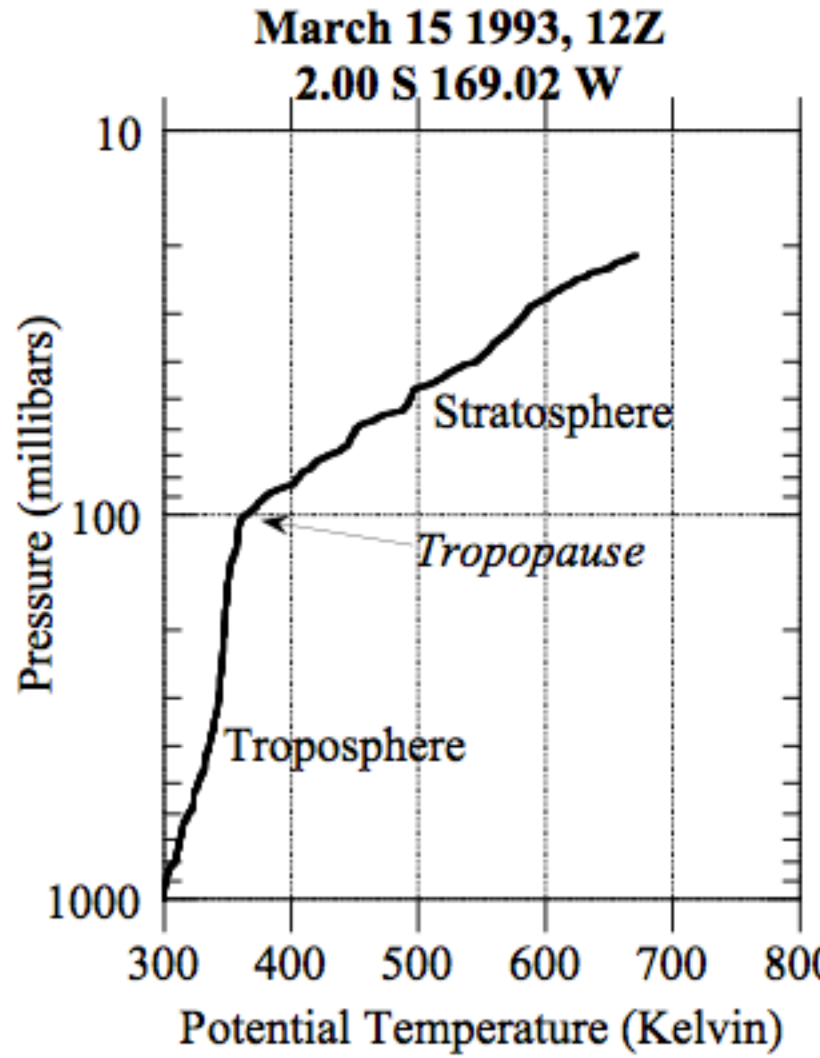
dry adiabat:

$$T = T_{\mathrm{ref}} \left(\frac{p}{p_{\mathrm{ref}}} \right)^{\overline{R}/c_p}$$

RELATIVE HUMIDITY=1
EARTH AIR, 1 BAR (DRY)
Pierrehumbert 2010

Stratospheric cold-trap

potential temperature: $\vartheta = T\left(\frac{p_{\mathrm{ref}}}{p}\right)^{\kappa}$



The runaway greenhouse leads to the end of habitability

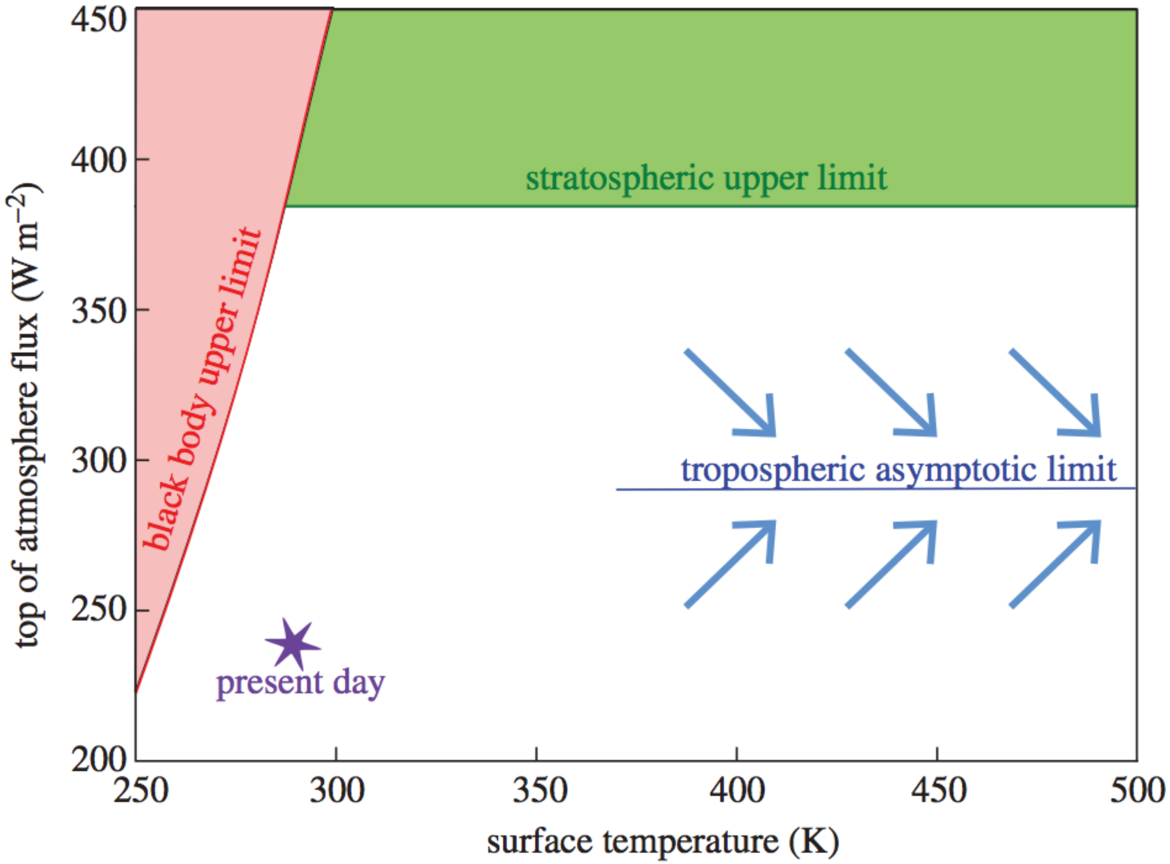
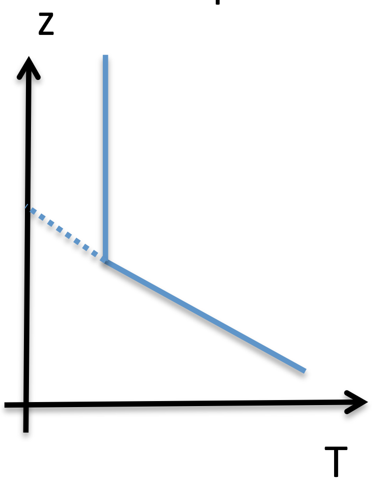


Figure 1. Radiation limits (solid lines) as a function of surface temperature, after Nakajima *et al.* [13]. Inaccessible regions are shaded. All of the white area can, in theory be occupied depending on the amount of non-condensible greenhouse gas (e.g. carbon dioxide) present, but at higher temperatures, outgoing flux will tend towards the tropospheric limit, as indicated by the arrows. Present day mean surface temperature is 289 K with an outgoing thermal flux of 239 W m^{-2}. Note that the change in temperature with flux is equivalent to the climate sensitivity, so the horizontal lines of the radiation limits imply infinite climate sensitivity, hence a runaway greenhouse.

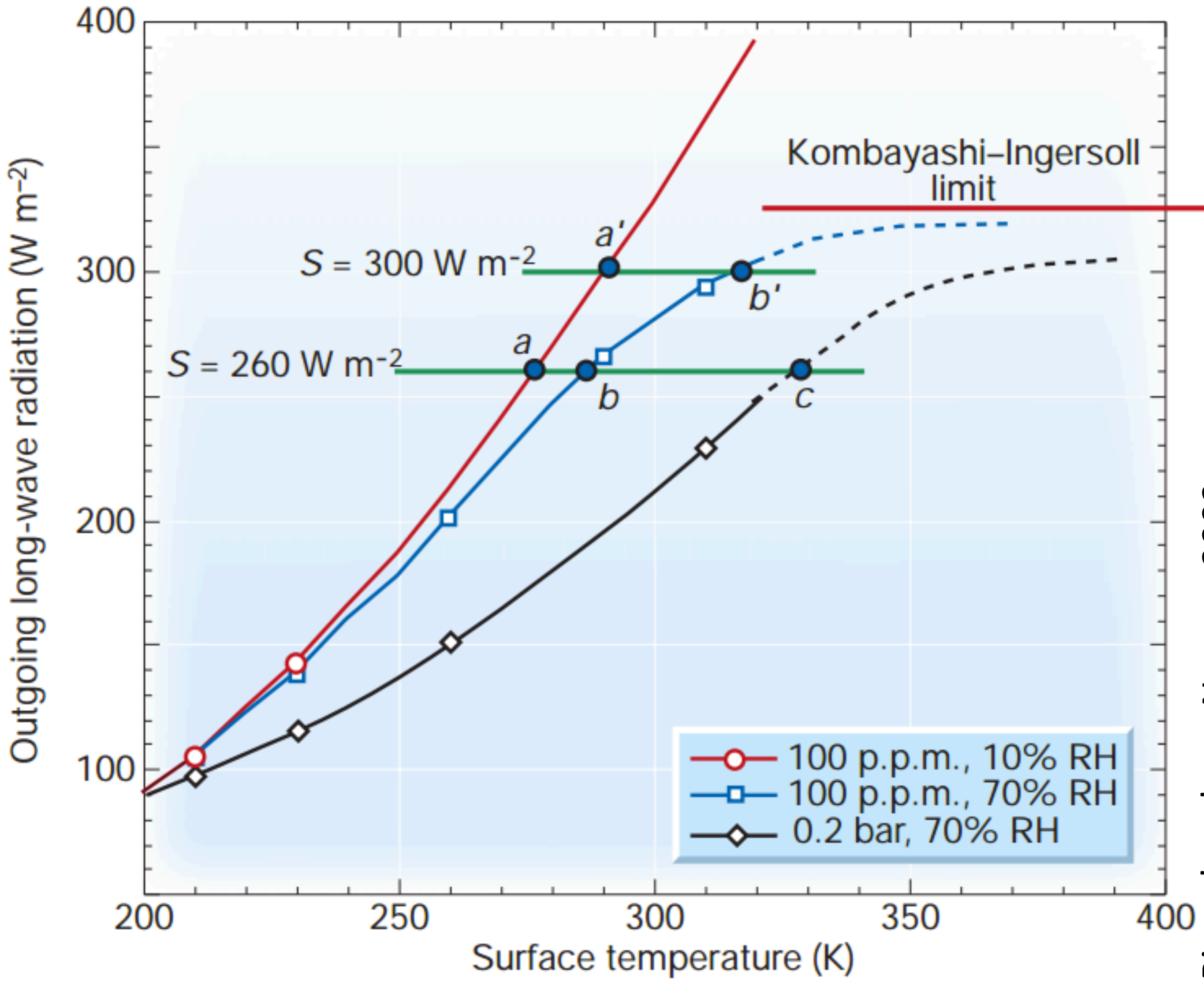
Goldblatt & Watson 2012, following Nakajima 1992

Condensable greenhouse gases lead to climate instability (Kombayashi-Ingersoll limit)

Assumptions:

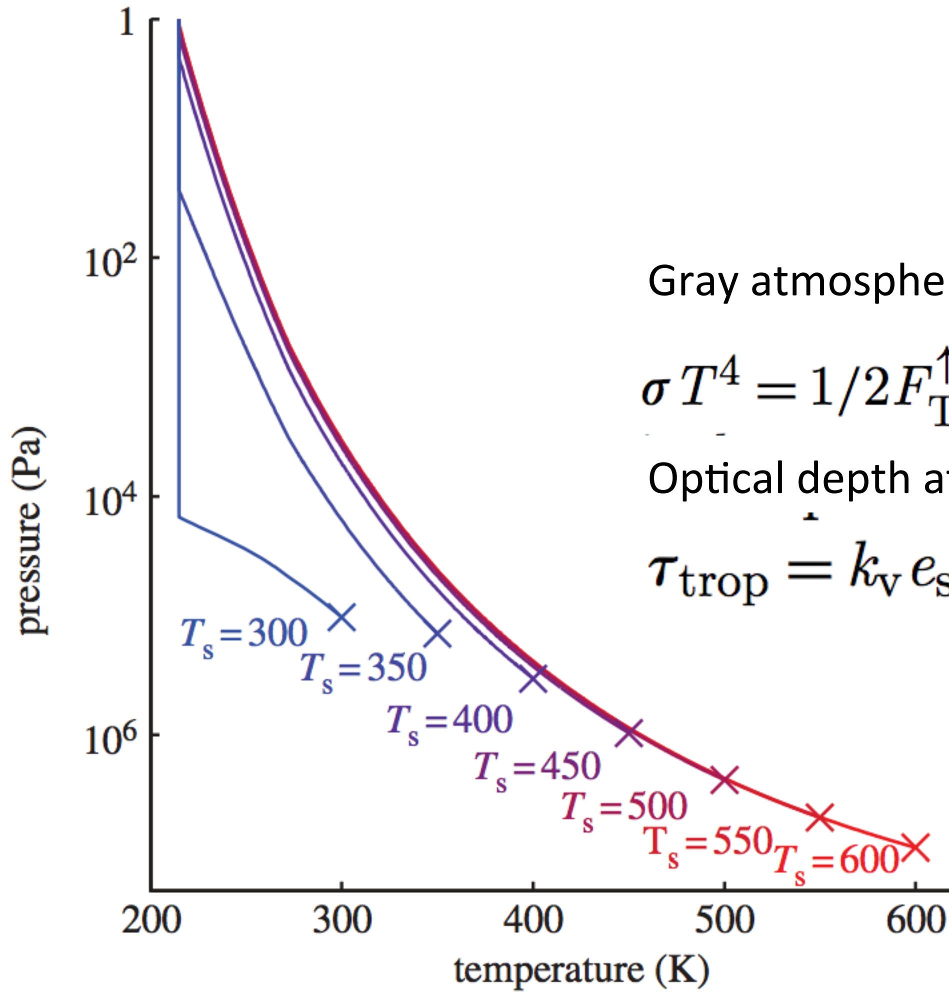


Constant RH (RH = relative humidity)



Pierrehumbert, Nature, 2002

Consequences:
(all are important)
H_2O dissociation
VNIR window
Surface magma
All water lost to space
Carbonates decompose



Gray atmosphere:

$$\sigma T^4 = 1/2 F^{\uparrow}_{\mathrm{TOA}} (3/2\tau + 1)$$

Optical depth at tropopause:

$$\tau_{\mathrm{trop}} = k_{\mathrm{v}}\, e_{\mathrm{s}}(T_{\mathrm{trop}})\, 1/g\, M_{\mathrm{v}} / \bar{M}$$

(1/g) in brackets

Figure 4. Temperature structure of the atmosphere with increasing surface temperature. A background pressure of 10^5 Pa is assumed, equal to that of Earth's atmosphere.

Goldblatt & Watson 2012

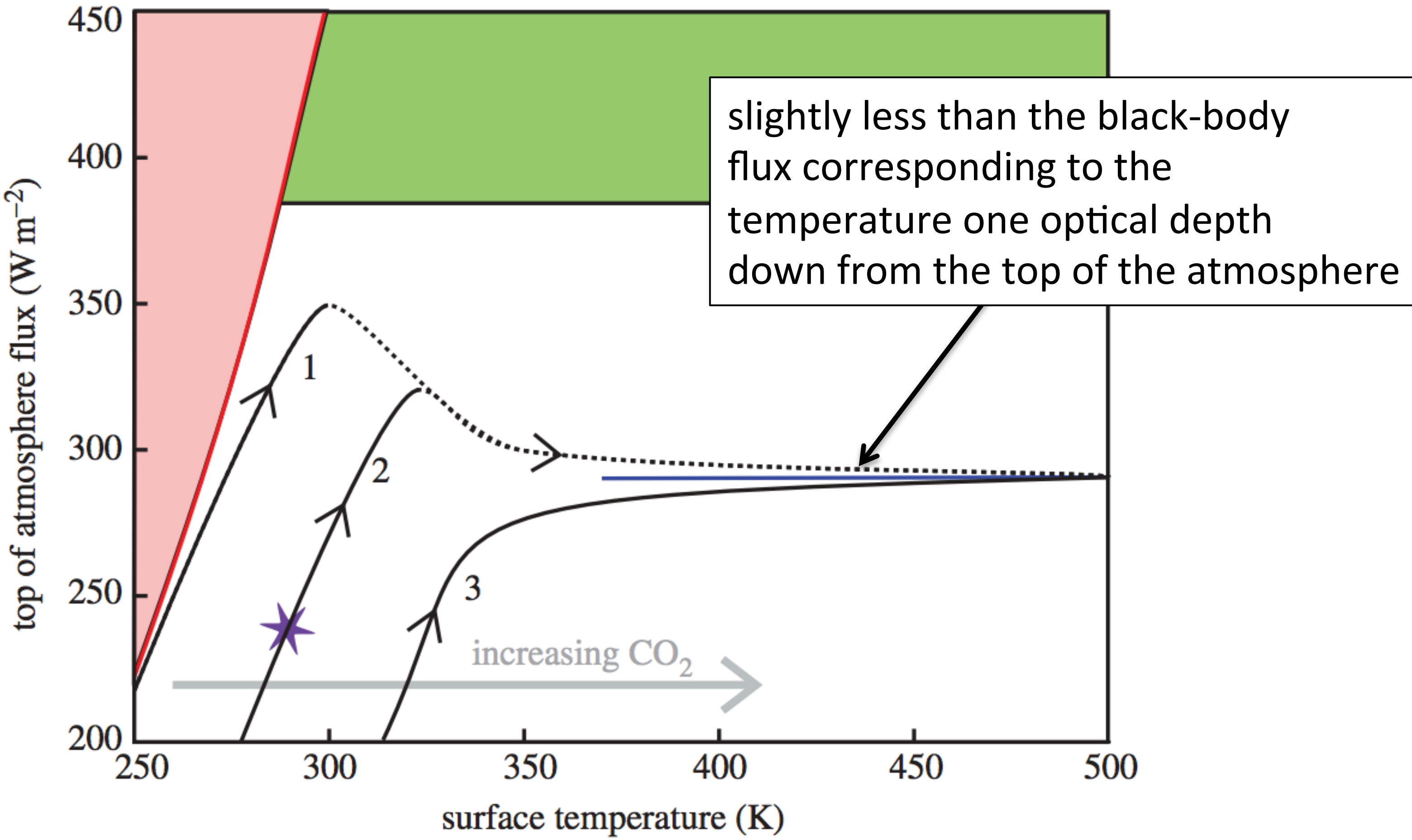
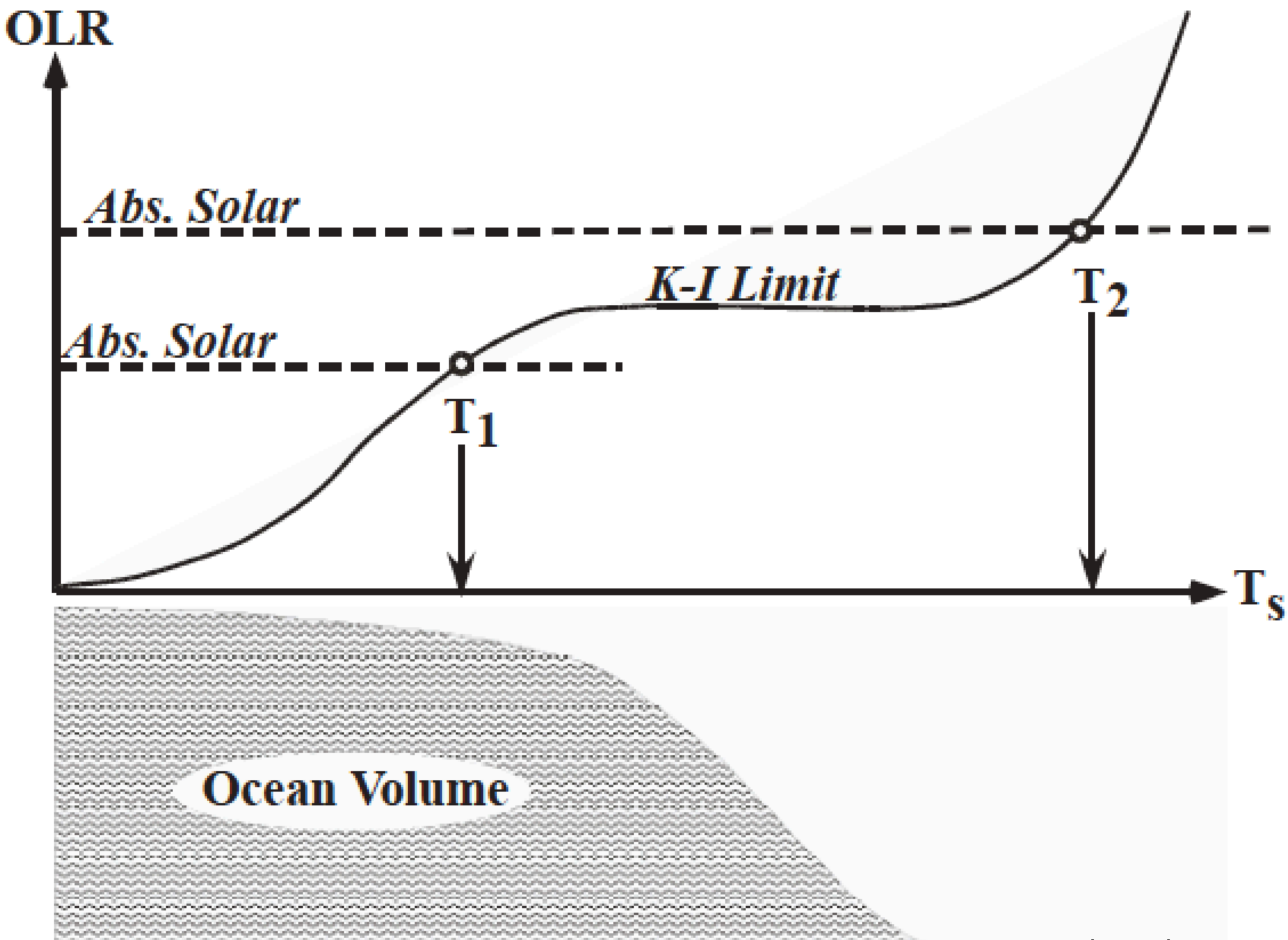


Figure 5. Increase in outgoing thermal flux as a function of surface temperature, after Nakajima *et al.* [13]. Black lines marked from 1 to 3 show how the top of atmosphere flux changes with increasing surface temperature for successively higher concentrations of a non-condensible greenhouse gas (e.g. carbon dioxide). Line 2 corresponds to Earth's present amount of non-condensible greenhouse gases and lines 1 and 3 are illustrative of lower and higher concentrations, respectively. All lines are for an amount of background, non-condensible and non-radiatively active gas similar to Earth's (see fig. 6 of Nakajima *et al.* [13] for other background gas inventories). Radiation limits are shown in colour (see figure 1 for labels). Fig. 9 of Kasting [12], derived from a spectrally resolved model, has similar features.

Goldblatt & Watson 2012

The runaway greenhouse leads to the loss of surface liquid water
(However, a supercritical H2O-rich C-poor phase may persist)



Pierrehumbert 2010 figure 4.4

Two key windows in the water vapor absorption spectrum: 8-12 microns and <~4 microns

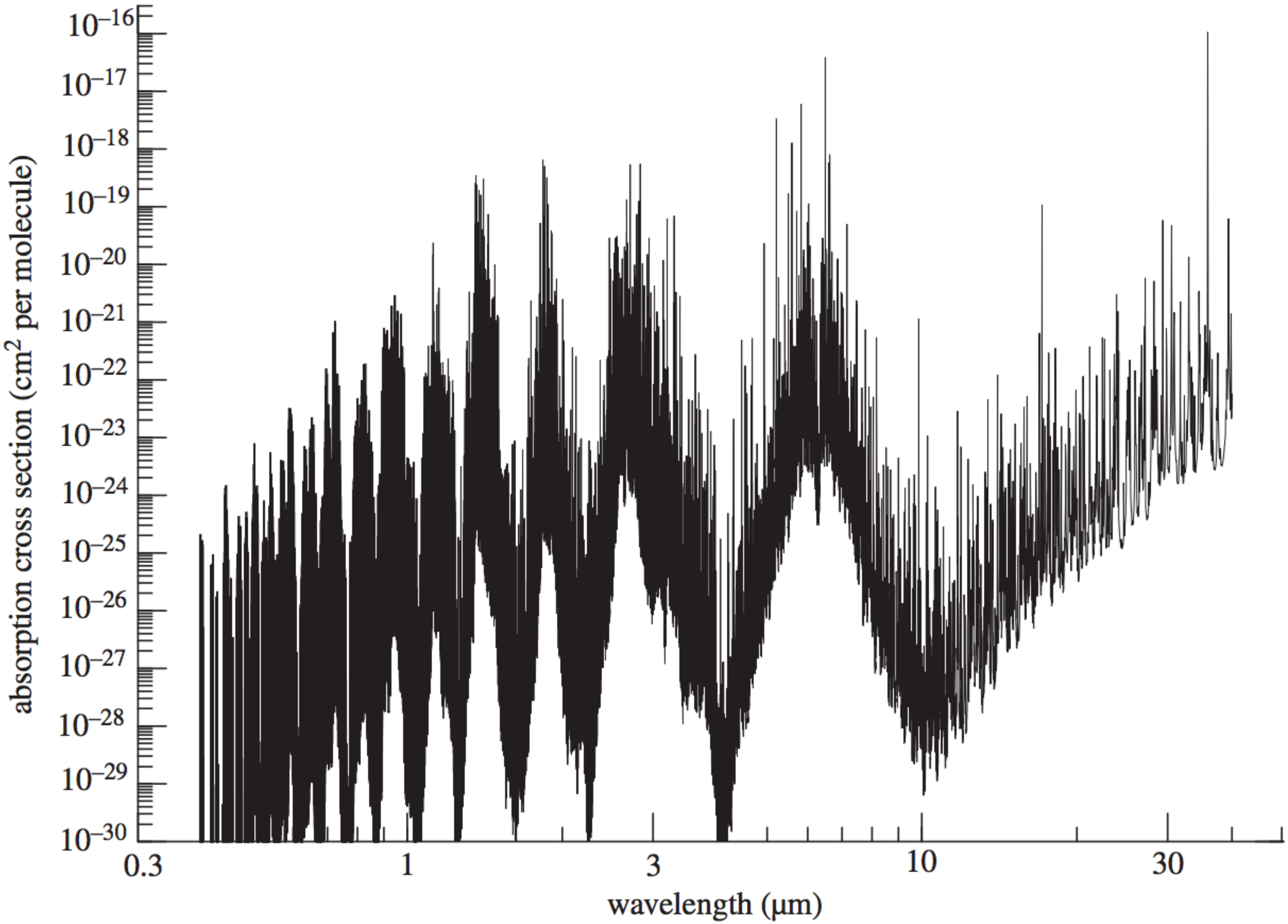
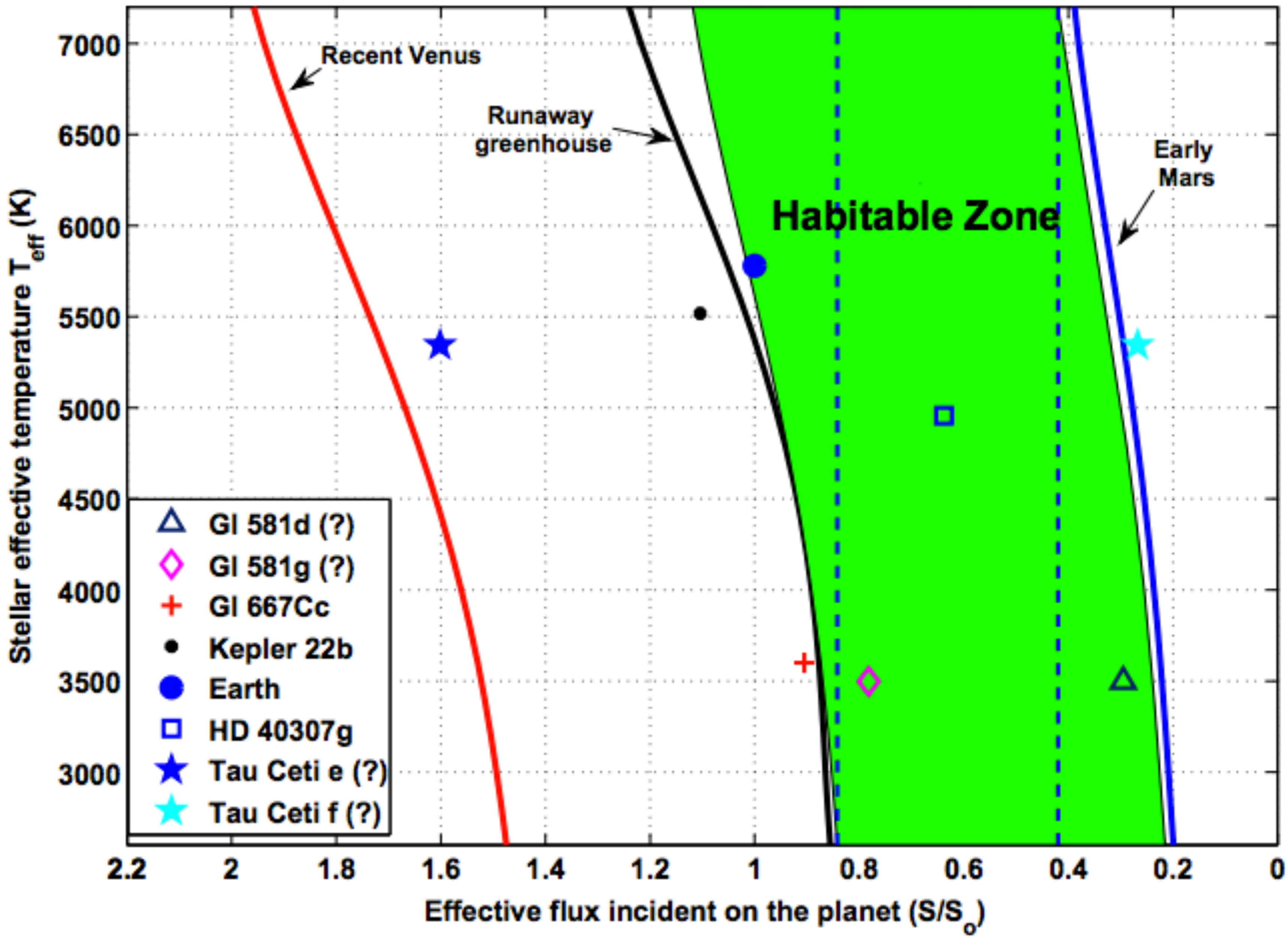


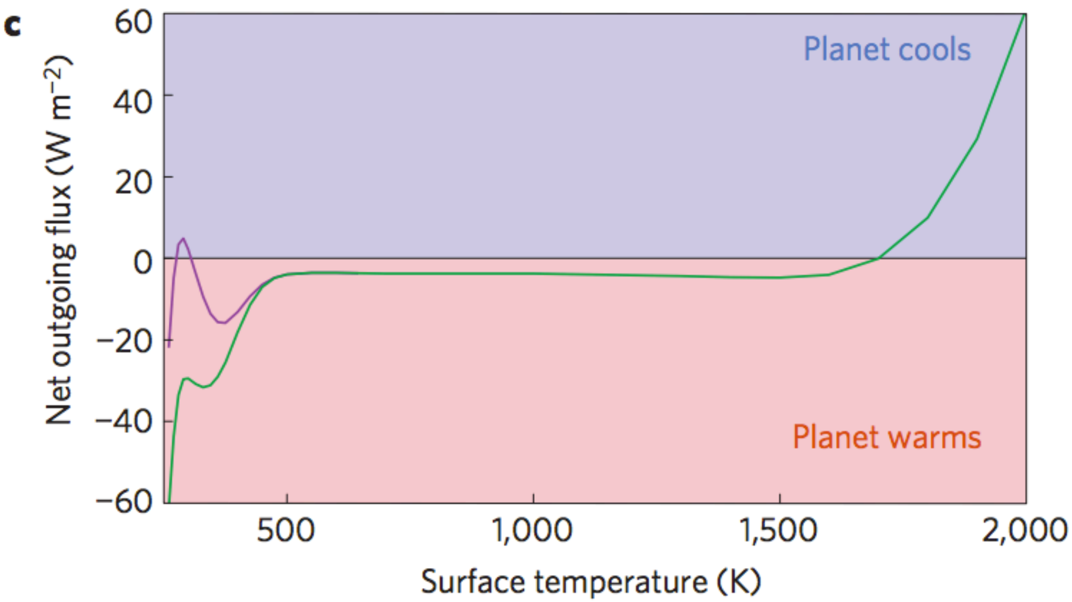
Figure 6. Absorption spectrum of water vapour (0.3–40 μm) shown at 220 Pa and 260 K. Note the ‘window’ regions where the absorption coefficient is low and the general decline of absorption coefficient at a shorter wavelength.



Recent Venus
Runaway greenhouse
Early Mars
Habitable Zone
Stellar effective temperature T_{eff} (K)
Effective flux incident on the planet (S/S$_o$)
7000
6500
6000
5500
5000
4500
4000
3500
3000
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Gl 581d (?)
Gl 581g (?)
Gl 667Cc
Kepler 22b
Earth
HD 40307g
Tau Ceti e (?)
Tau Ceti f (?)

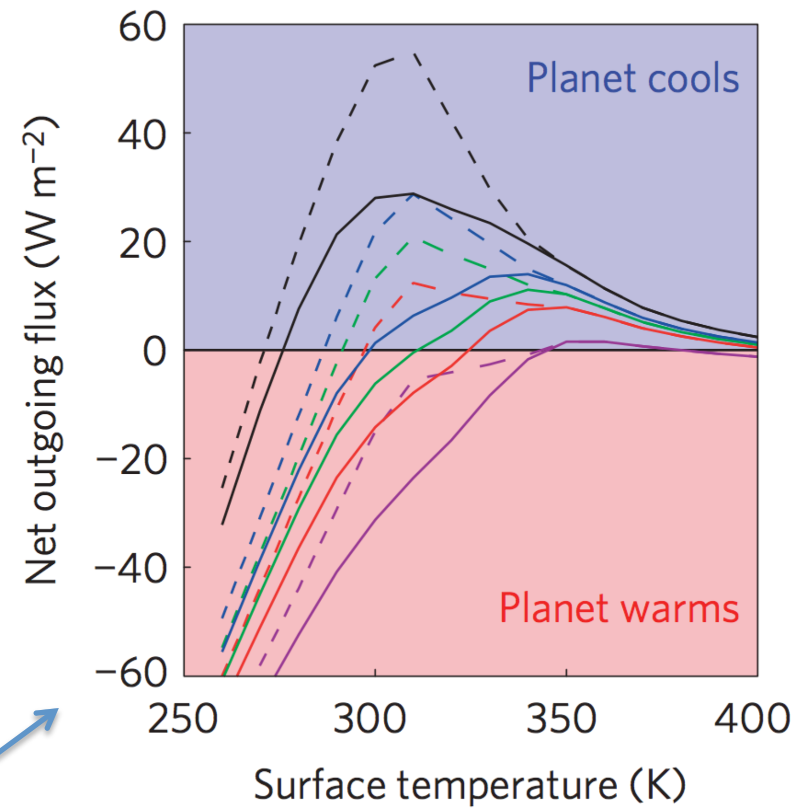
Anthropogenic greenhouse gases (probably) cannot trigger the runaway greenhouse.

Goldblatt et al. Nature Geoscience 2014



Scenario	CO_2 (ppmv)
Baseline	0
Pre-industrial	287
RCP 8.5, year 2100	936
Extreme anthropogenic	3,000
Arbitrarily high	30,000

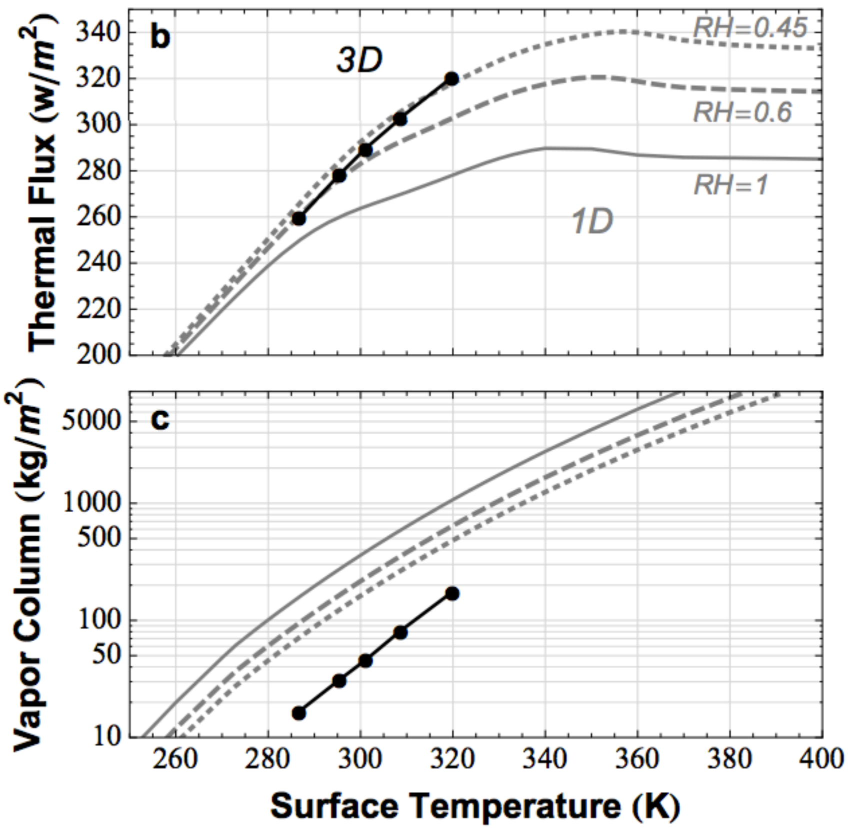
Black
Green
Blue
Red
purple



Dashed lines: RH < 1
Solid lines: RH = 1

Modern albedo

Earth today is close to the runaway greenhouse limit. The runaway greenhouse can be triggered by an increase in solar luminosity



Leconte et al. 2013 Nature

Time for loss (10^9 yr)

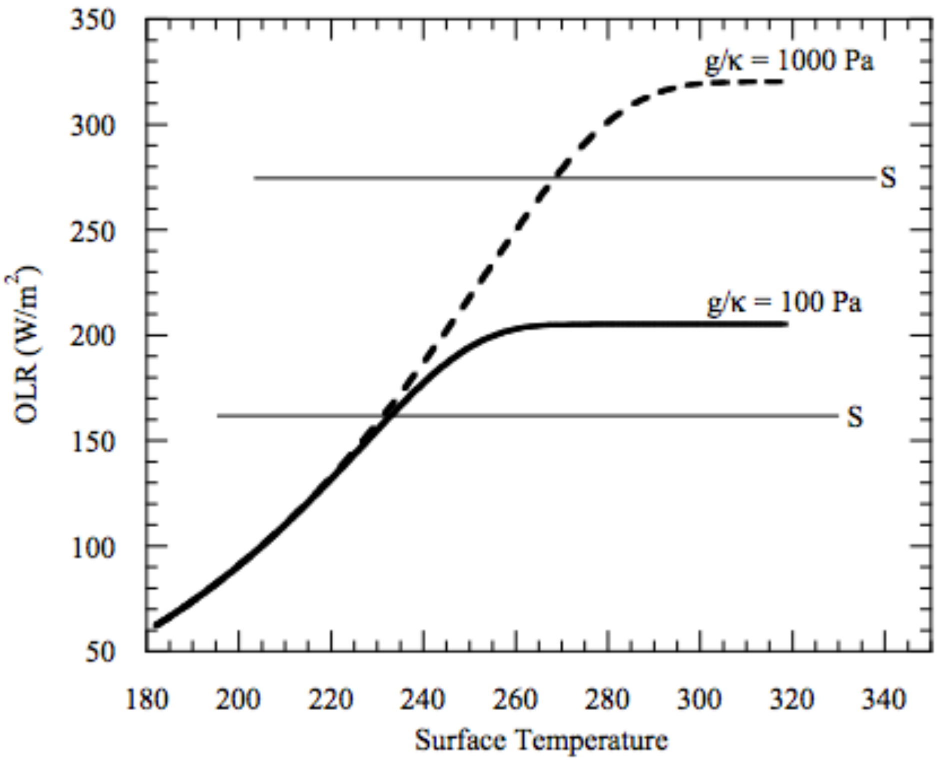
water lost (bars)

$$\Delta t(\text{by}) = 2.4 \times 10^9\ \Delta p(H_2O)/\Phi_{esc}(H)$$

H loss flux (atoms cm^{-2} s^{-1})

High gravity moves the runaway greenhouse limit closer to the star
e.g. metal-rich planet, larger-radius super-Earth

Temperature → vapor pressure
Vapor pressure x humidity / gravity → column mass of greenhouse gas
Column mass → greenhouse effect.

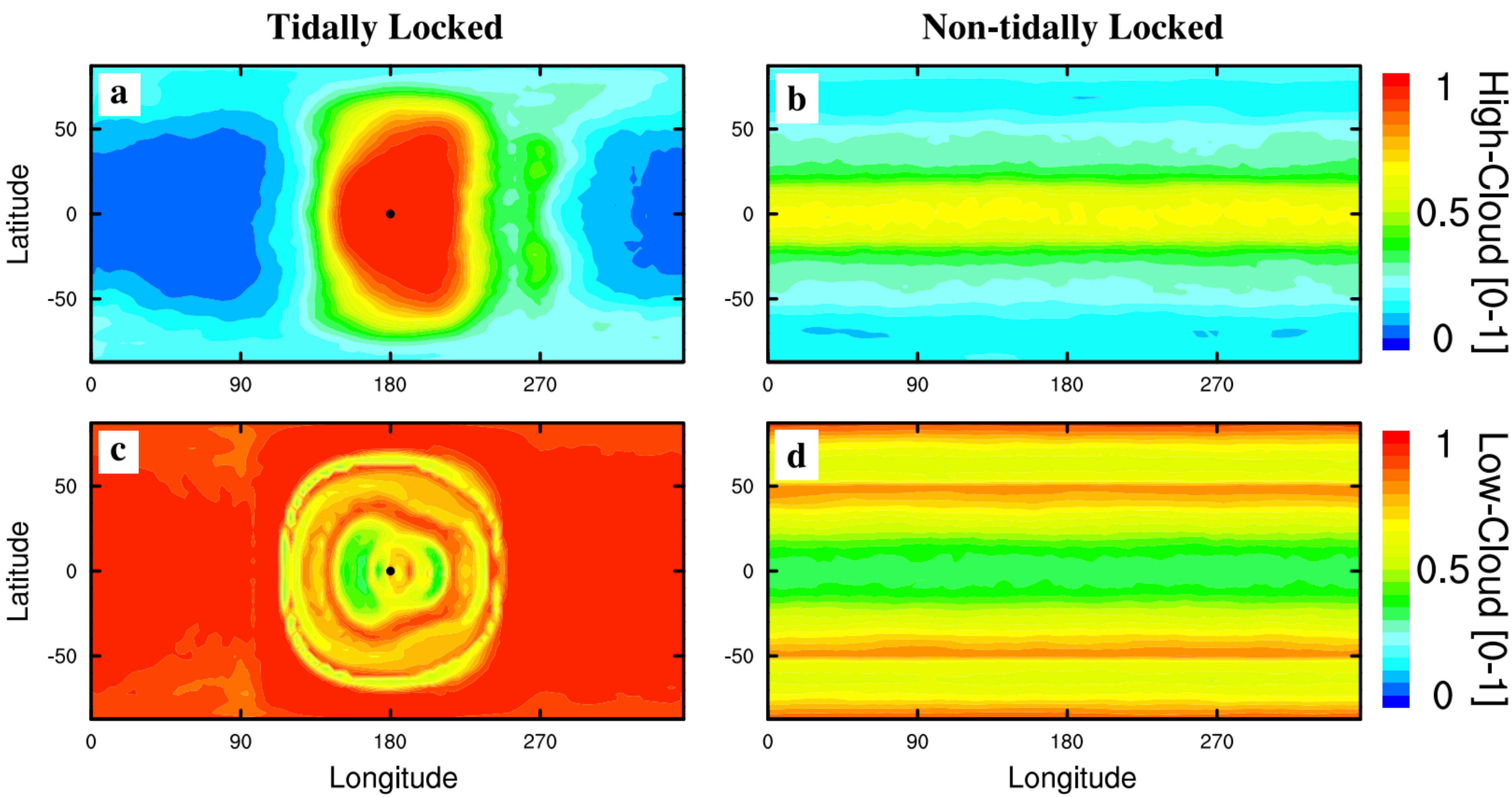


	Inner Habitable Zone	
Model	Moist greenhouse	Runaway greenhouse
Mars-sized planet*	1.035 AU	1.033 AU
Earth	0.99 AU	0.97 AU
Super-Earth**	0.94 AU	0.92 AU
$pCO_2 = 5.2 \times 10^{-3}$ bar†	**1.00 AU**	**0.97 AU**
$pCO_2 = 5.2 \times 10^{-2}$ bar	1.02 AU	0.97 AU
$pCO_2 = 5.2 \times 10^{-1}$ bar	1.02 AU	0.97 AU
$pCO_2 = 5.2$ bar	0.99 AU	0.97 AU

* Surface gravity = 3.73 $m.s^{-2}$
** Surface gravity = 25 $m.s^{-2}$

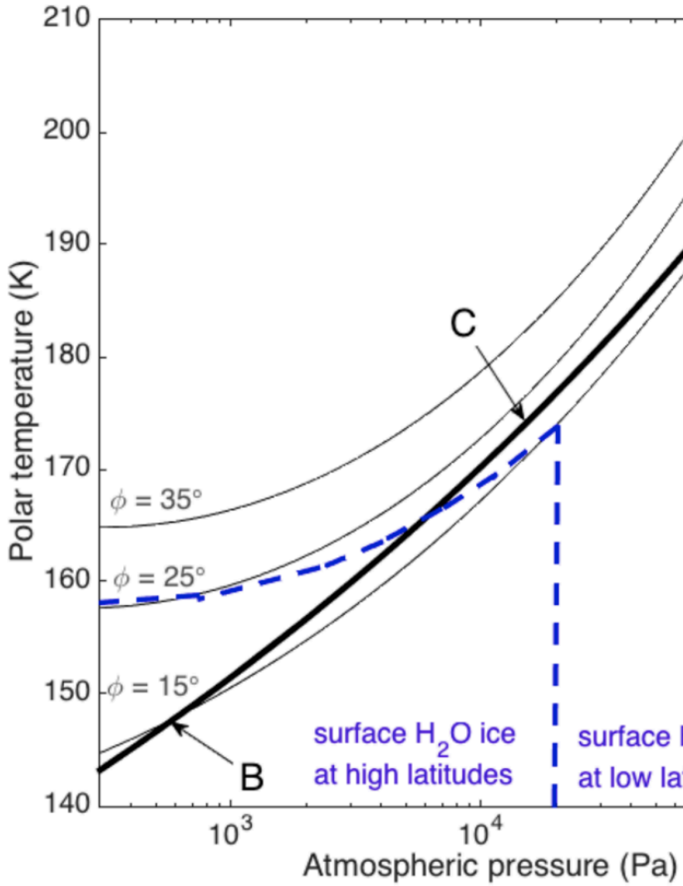
Max OLR ~= slightly less than the blackbody flux corresponding to the temperature one optical depth down from the top of the atmosphere

High-albedo clouds can shift the runaway GH boundary closer to the star. High-albedo clouds are at the substellar point when the planet is slowly rotating (e.g., tidally locked and in the habitable zone).



Yang et al. 2013

Runaways due to the GH-effect of a condensable apply to non-H2O condensates as well – e.g., CO2 on Mars



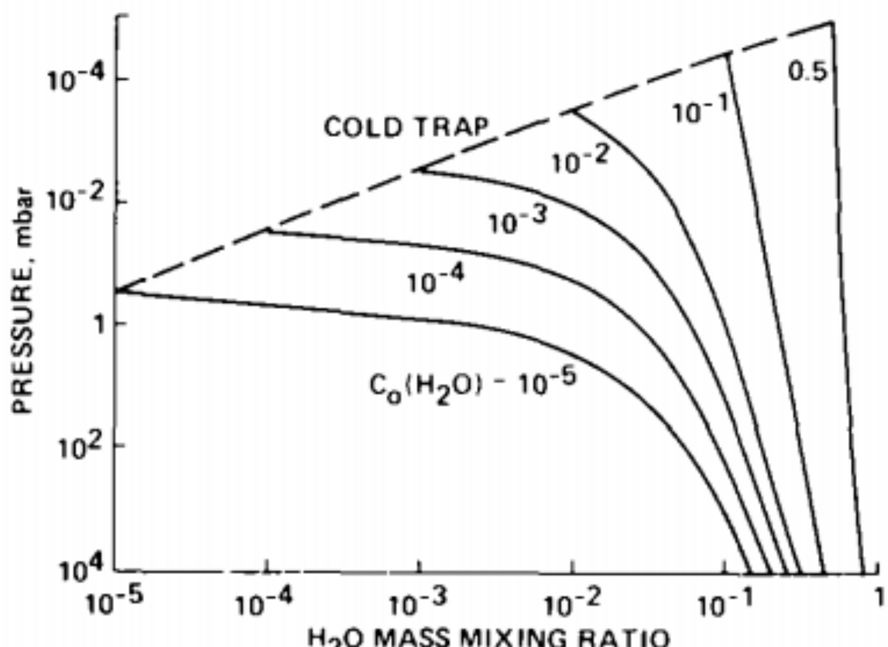
Kite et al. arXiv:1709.08302

Fig. 3. Phase portrait for atmospheric collapse on Mars, showing how atmospheric collapse drives H_2O-ice distribution (this calculation uses the GCM of ref. 17). Thin black lines show annual-mean polar temperature as a function of atmospheric pressure assuming Faint Young Sun luminosity. Thick black line is the condensation curve for CO_2; atmospheres below this line are collapsing onto polar CO_2 ice caps (e.g., **A→B**). Blue dashes outline the approximate pressures and obliquities below which H_2O ice is stable only at Mars' poles [e.g. 17, 29, 54]. Collapse leads to relocation of surface H_2O ice from highlands to poles. In this GCM, for an initial CO_2 inventory of 8×10^{18} kg (= 2 bar), the atmosphere is stable until $\varphi \leq 15$ deg (at **A**). Rapid collapse (~10^3 yr) moves the system to point **B**. Increasing obliquity (over 10^5-10^7 yr) moves the (ice cap)/atmosphere system along the condensation curve to **C**, (the highest φ consistent with permanent CO_2 ice caps). Further φ rise leads to sublimation of the CO_2 ice cap (~10^3 yr) and the system returns to **A**.

Also: N2 runaway on Early Titan?

The runaway & moist greenhouses: under the hood

Raising temperature raises the H_2O mixing ratio at the cold trap (assumed isothermal)



Kasting 1988

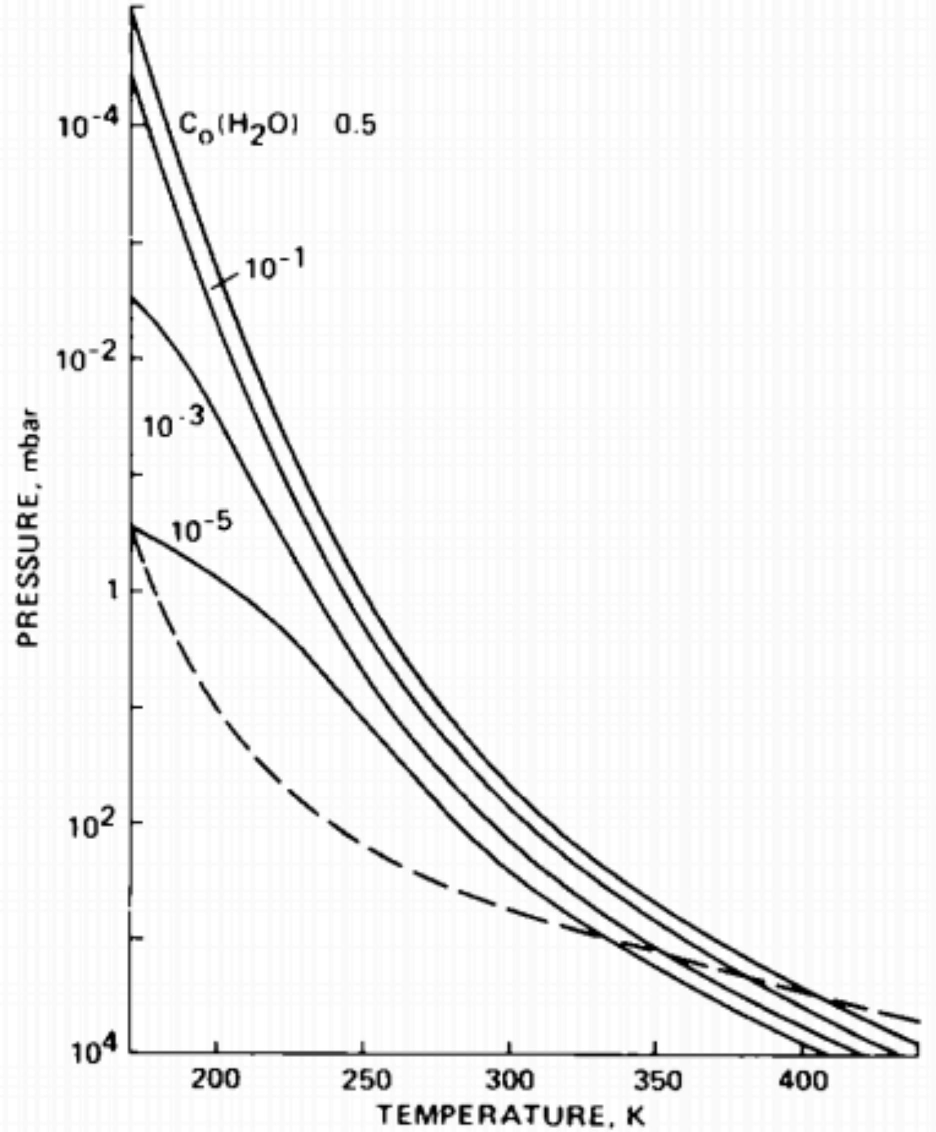


FIG. 15. Calculated pseudoadiabatic temperature profiles for various values of the H_2O mass mixing ratio at the cold trap. The dashed curve represents the dayside temperature profile below 90 km in the present Venus atmosphere.

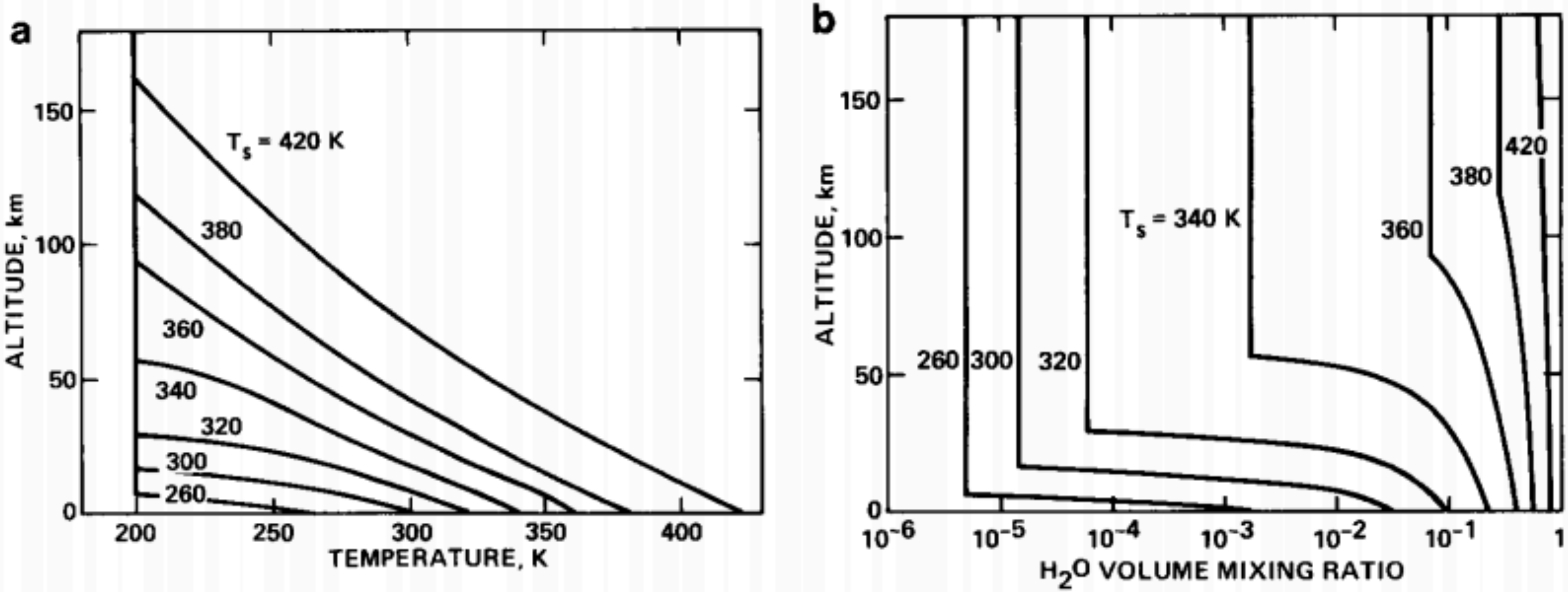


FIG. 5. Temperature (a) and H_2O volume mixing ratio (b) versus altitude for selected moist greenhouse atmospheres. The lower portions of the curves represent moist pseudoadiabats.

Kasting 1988

How was the last 10th of Venus' ocean removed?

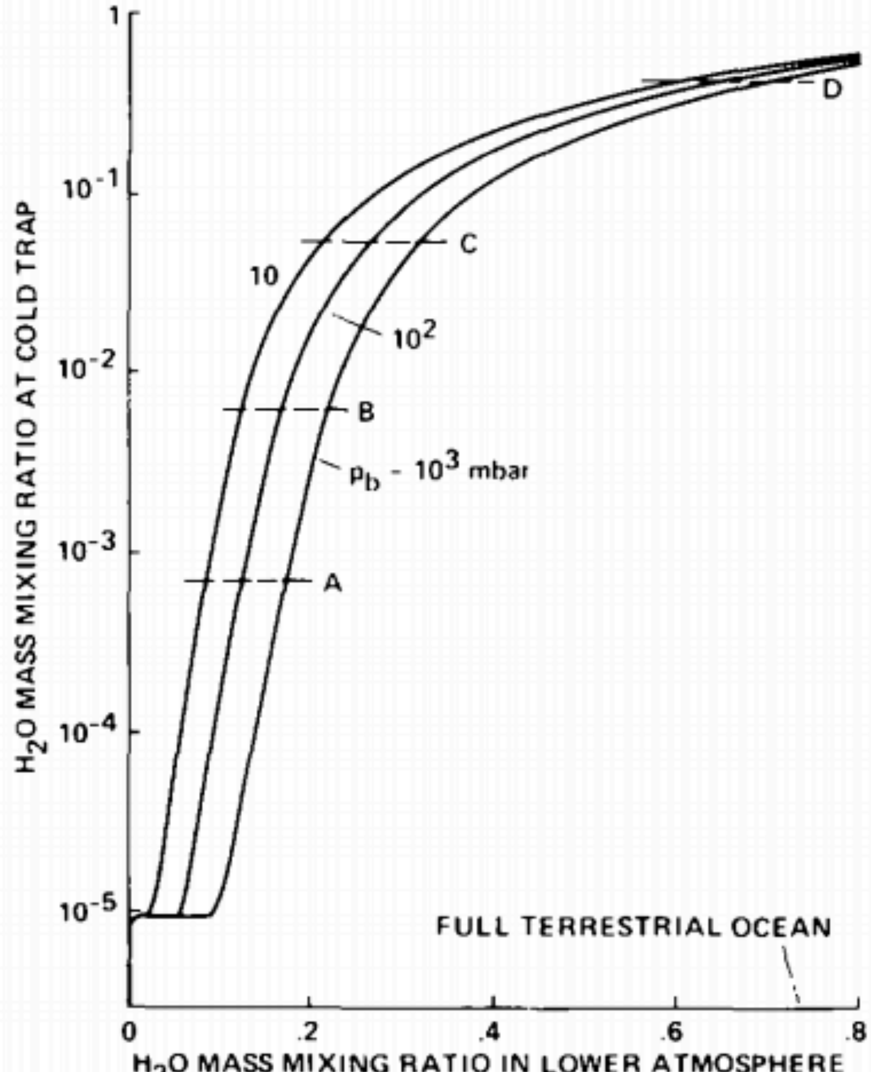


FIG. 17. Relationship between the H_2O mass mixing ratio at the cold trap and in the lower atmosphere for three different values of the pressure p_b at the bottom of the moist convective layer. The horizontal dashed lines labeled A to D correspond to the cases described in the text.

Kasting 1988

Runaway greenhouse – key points

- The (H2O-)runaway greenhouse is a geologically rapid increase in planet surface temperature from <400K to >1000K caused by a positive feedback between the saturation vapor pressure of water vapor and the
- Be able to explain the mechanism of the runaway greenhouse
- It is almost certain that release of CO2 by humans cannot cause a runaway greenhouse
- The exact threshold for the runaway greenhouse depends on cloud cover, land fraction, and planet rotation rate

Backup/additional slides

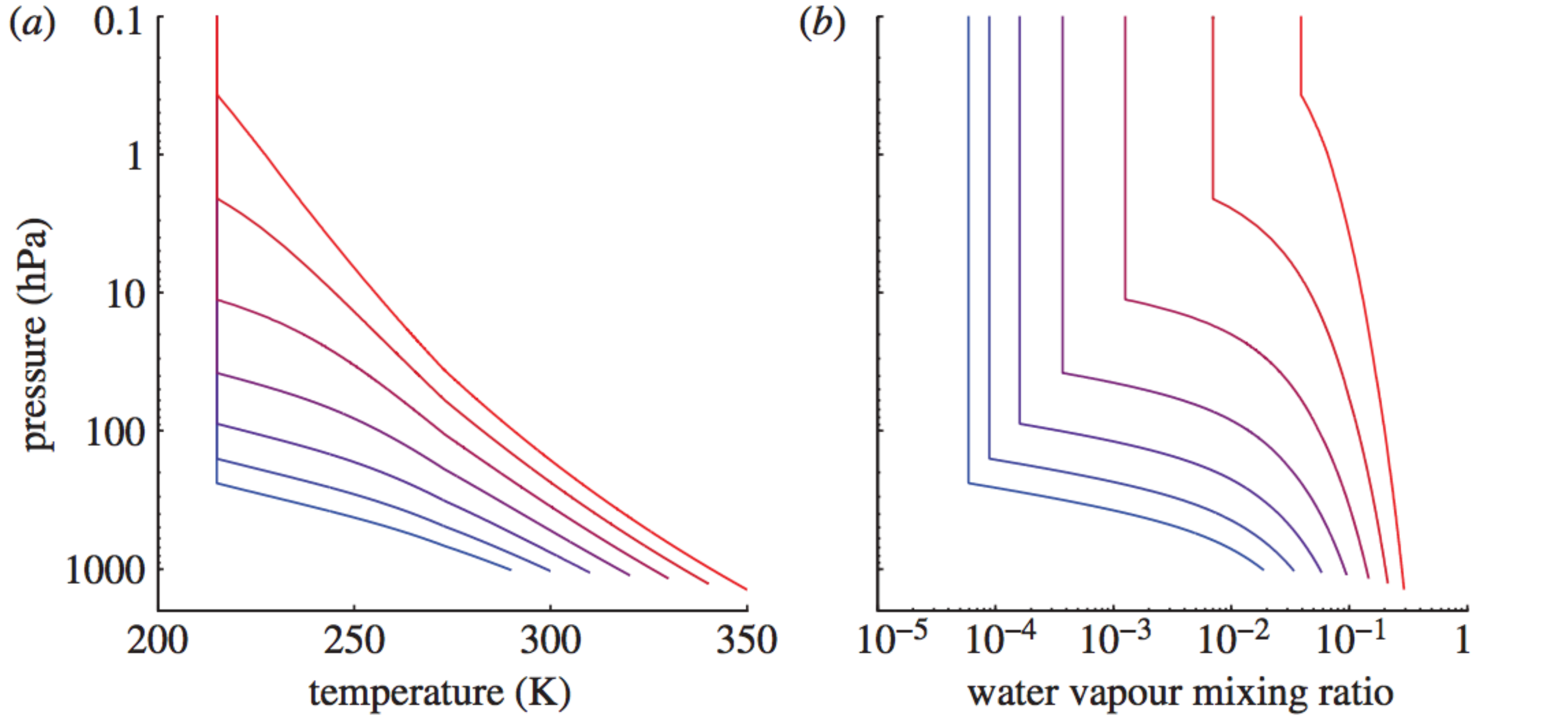


Figure 3. (*a*) Change in temperature structure and (*b*) moisture structure for warming atmospheres. A background pressure of 10^5 Pa is assumed, equal to that of Earth's atmosphere.

Goldblatt & Watson 2012