How to make Habitable Planets

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I want to know
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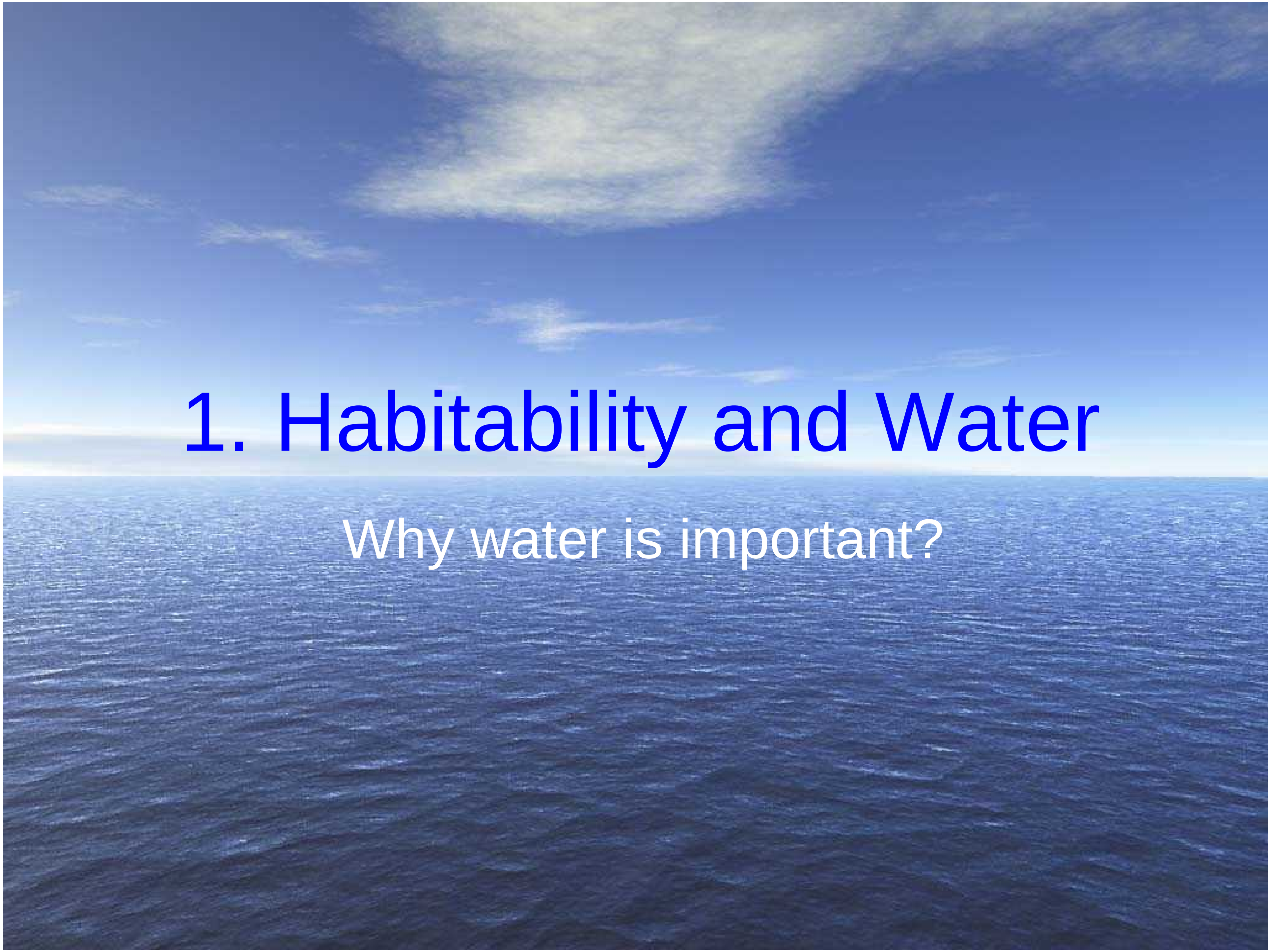
Contents


1. Habitability and Water
Why water is important?

Habitable Condition

Real necessary and sufficient conditions for life are not well constrained yet.
Terrestrial-life requires liquid water during at least some periods of their life.
Consider existence of liquid water as a conventional necessary condition.

Importance of Liquid

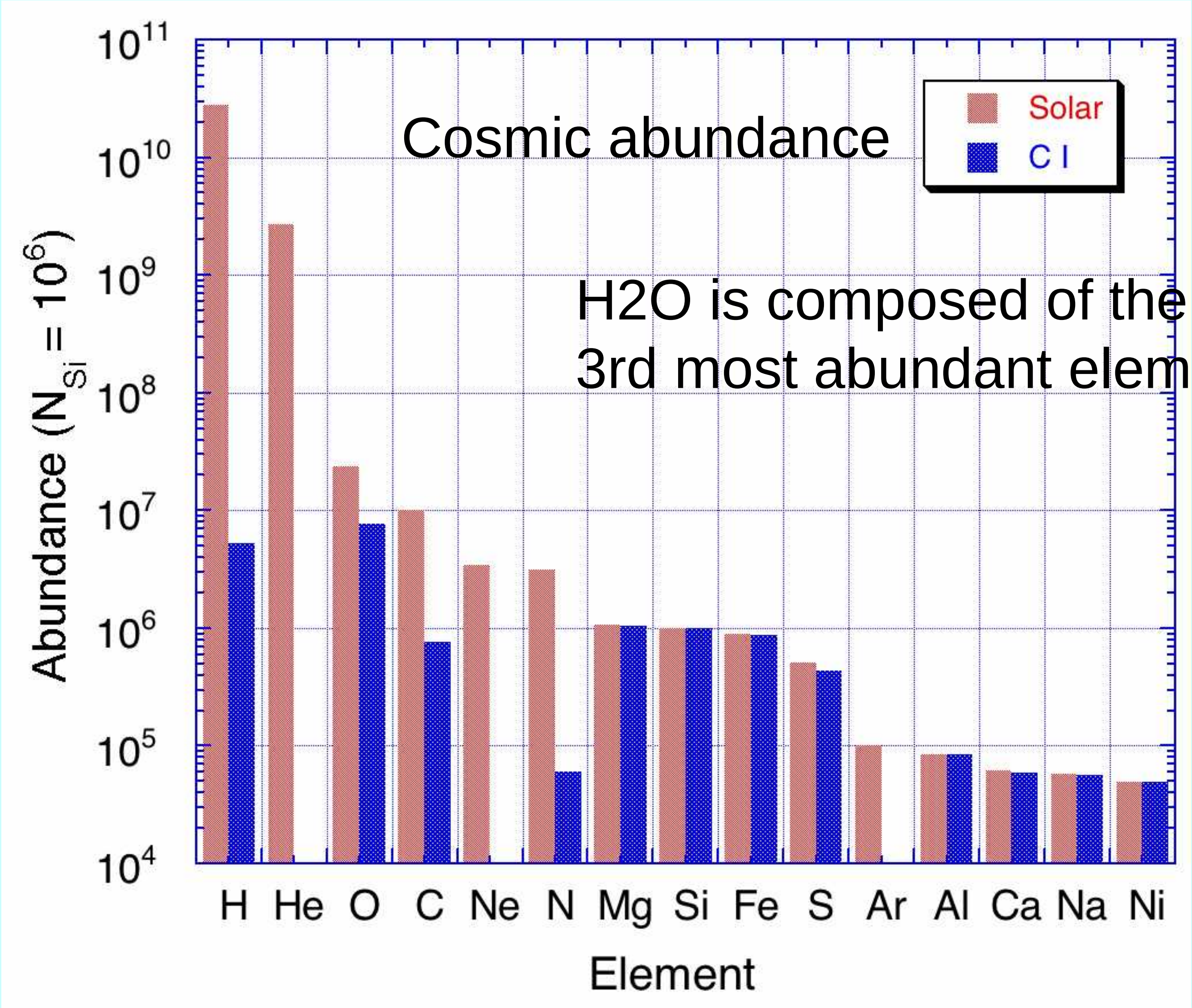
Life using chemical energy (~ like terrestrial life) requires flow of energy and material.

Gas: highly mobile, but low material density.
Solid: high density but very low mobility.
Liquid: high density and high mobility

Liquid is important media for life.

Habitable environments are likely environments with some liquid.

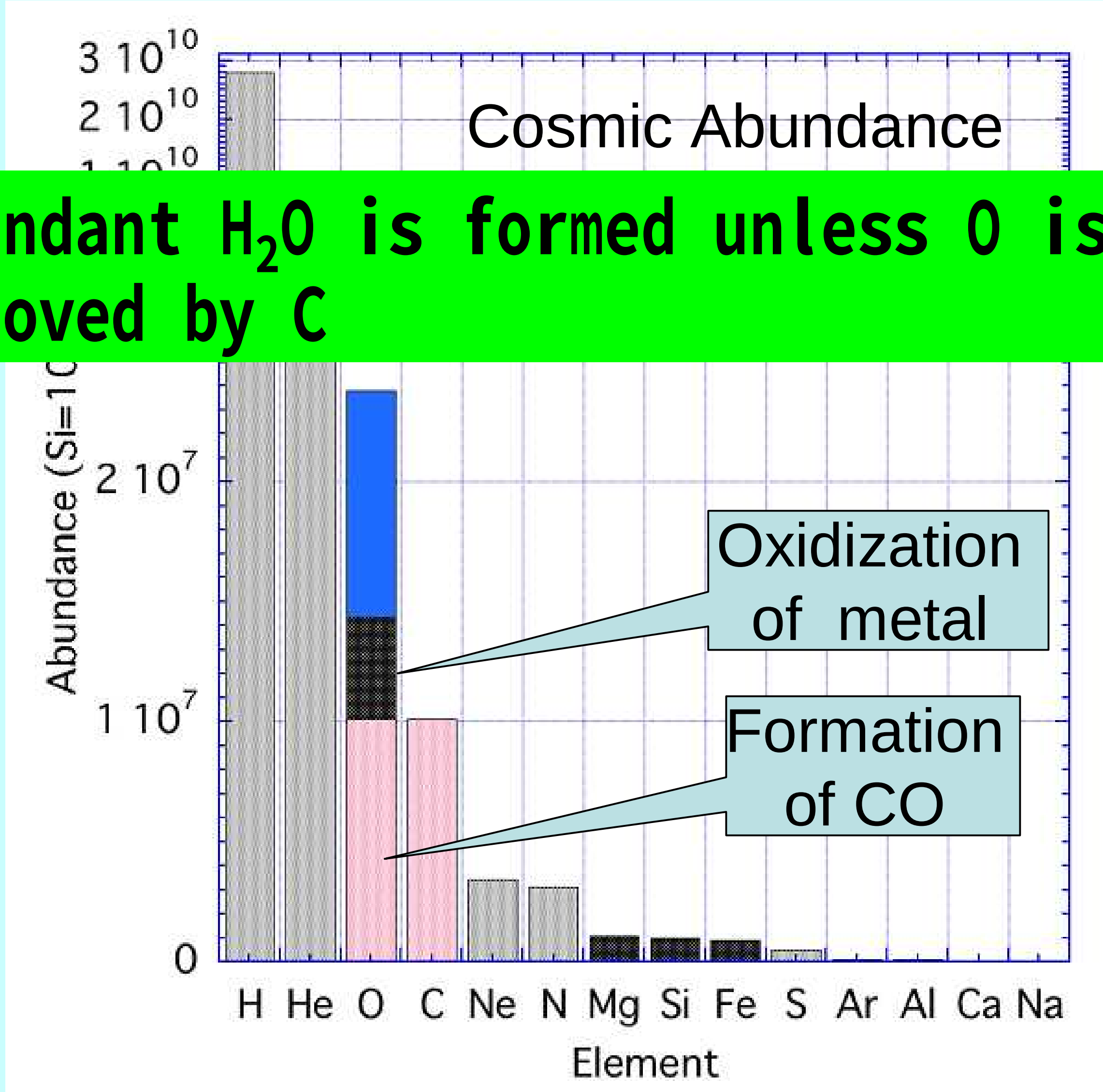
H2O



Cosmic abundance

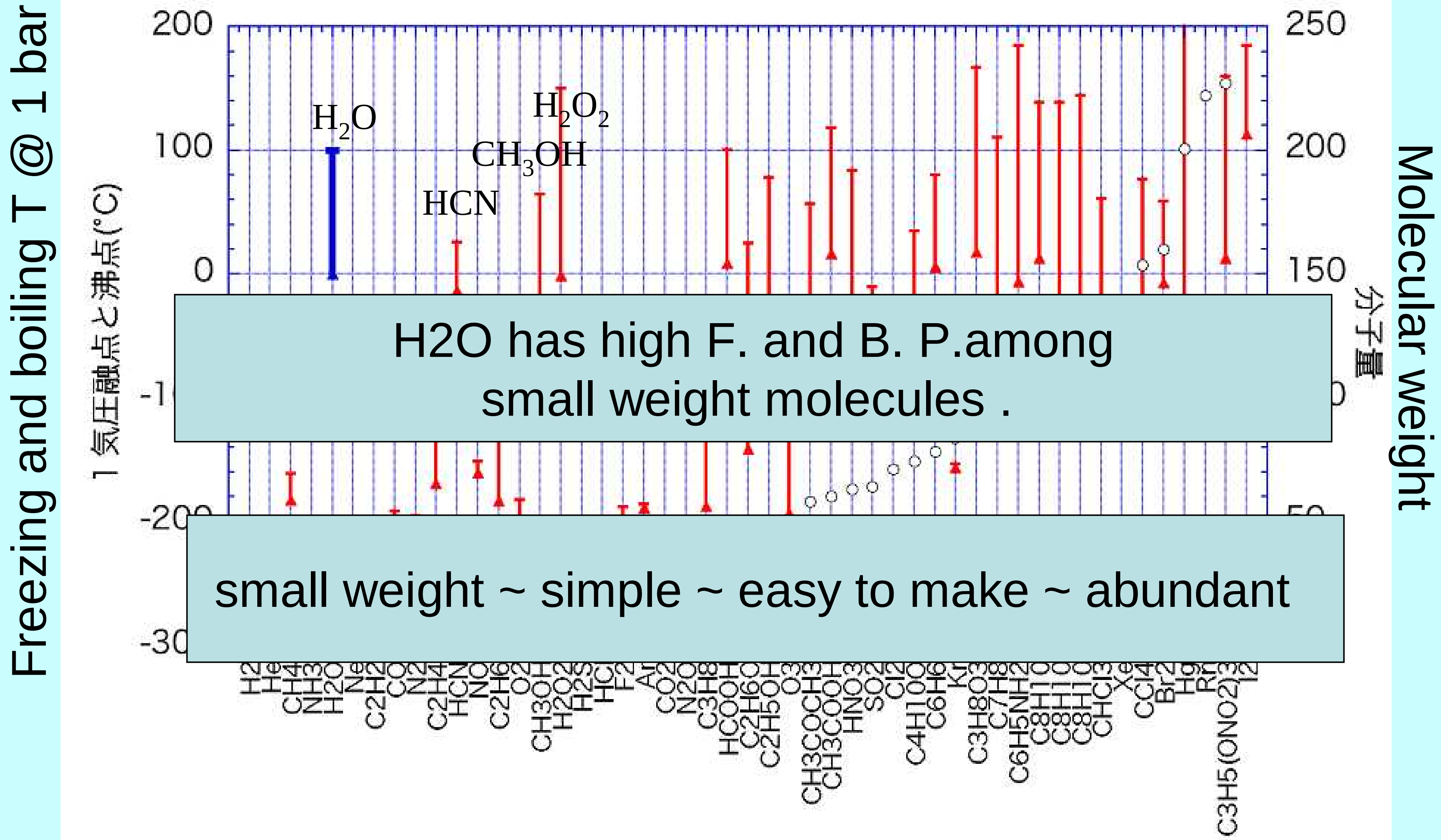
H2O is composed of the most and 3rd most abundant elements

H_2O as an abundant material



Abundant H_2O is formed unless O is removed by C

H_2O as a special liquid: high freezing and boiling T



H2O has high F. and B. P.among small weight molecules .

small weight ~ simple ~ easy to make ~ abundant

Habitability and Water

Water

Highly abundant in cosmos.

High freezing and boiling points

Water is in liquid phase at warm place near the central star

warm ~ easy for chemical reactions

Good solvant for ionized material

Probably, water is the 1st choice of life supporting liquid.

2. Water planets

One form of Habitable planets

Water Planets

Terrestrial planet with some amount of liquid water on its surface
実 solid planets with wet atmosphere

〜 Generalized Earth
〜 One group of habitable planets.

Conditions required for the formation of a Water planet

1. Supply of $H2O$ to the planet
   (or Supply of H and O)

   Planetary formation

2. $H2O$ degasses from the planetary interior

   Planetary formation and evolution

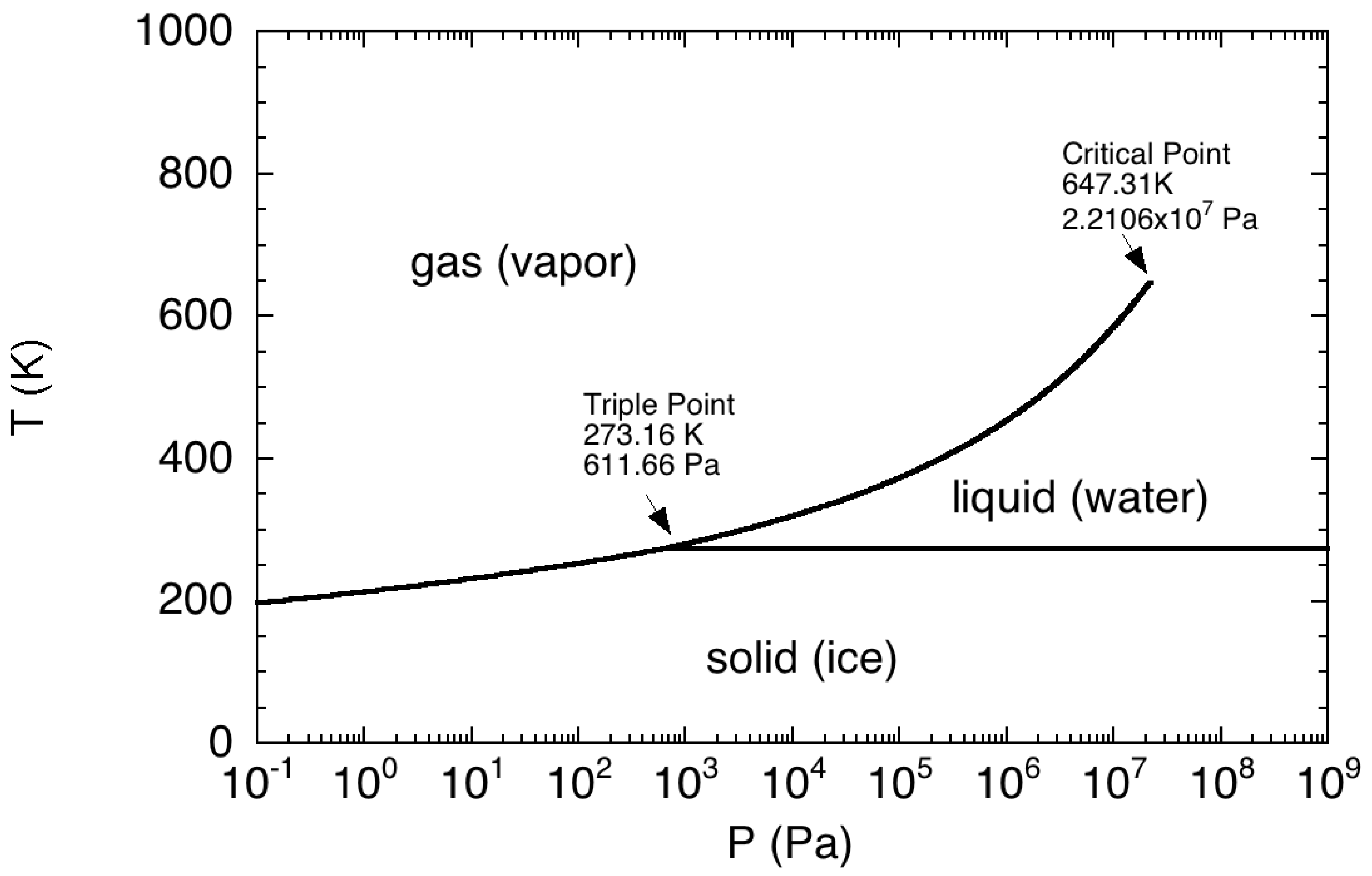
3. $H2O$is kept at the surface
   (not lost into the space)

   Planetary evolution and climate

4. Some $H2O$ is in the liquid phase

   Planetary climate

Stability field of liquid water



Temperature $>$0.1ºC $<$374.11 ºC

Pressure $>$Saturation vapor pressure

Water planet

In 0 dimensional = globally averaged consideration

Bounded by

complete vaporization ~ runaway greenhouse

global freezing

2.1 Runaway greenhouse

Water vapor is a strong greenhouse gas.
Large amount of water vapor in the atmosphere at high temperature.

High temperature yields strong greenhouse effect.

A typical positive feedback process.

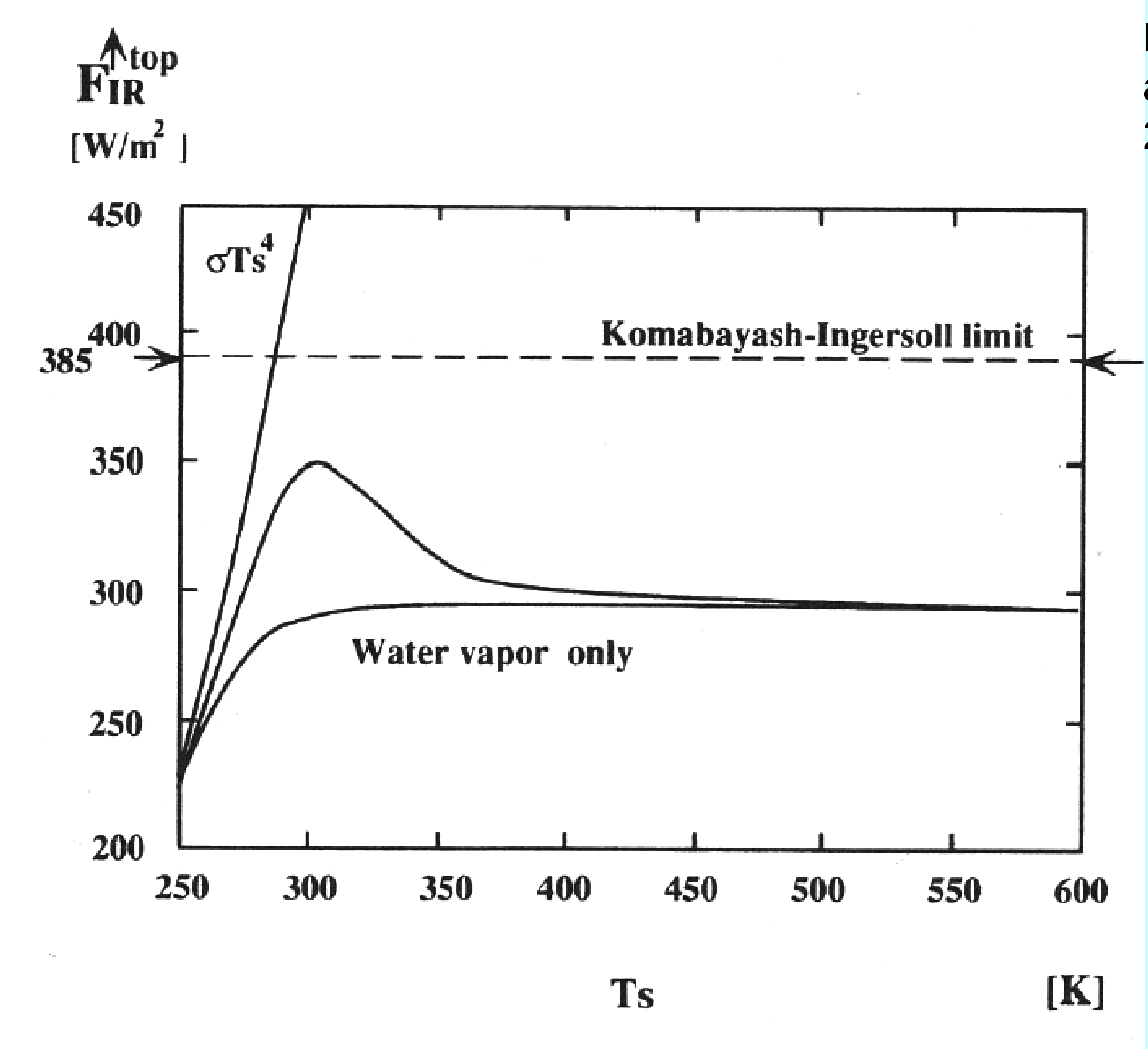
The critical flux for the runaway greenhouse

A moist atmosphere (saturated by water vapor) has an upper limit of the outgoing infrared flux that can be emitted:

If insolation exceeds this limit ,temperature increases until complete evaporation of liquid water from the surface.

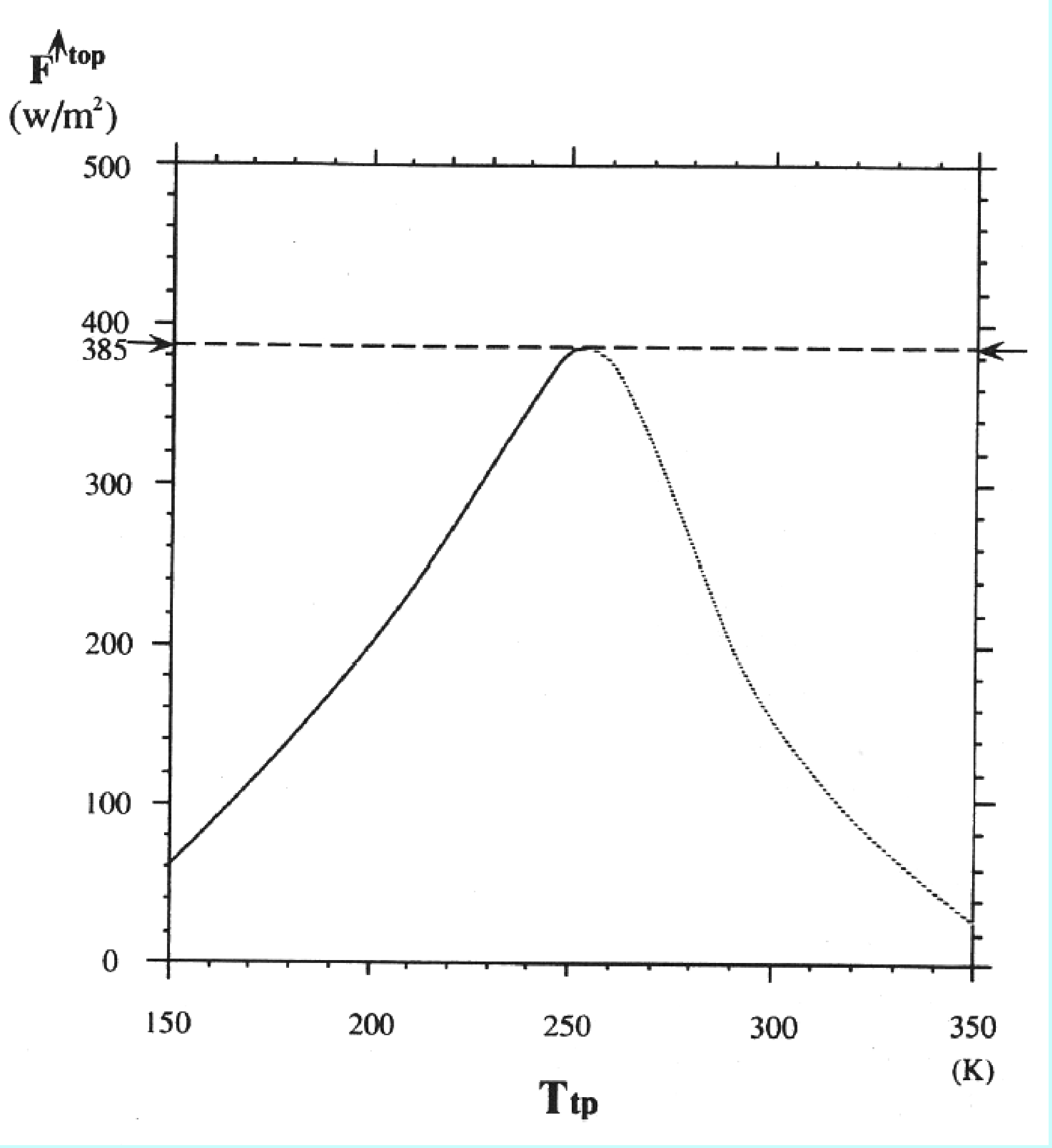
Komabayashi 1967,1968; Ingersoll 1969, Kasting et al. 1988; Abe & Matsui, 1988; Nakajima et al., 1992

Nakajima et al. 1992



Nakajima, S., Y.-Y. Hayashi and Y. Abe: J. Atmos. Sci., **49**, 2256–2266, 1992.

Komabayashi-Ingersoll Limit



Nakajima, et al., 1992 :

J. Atmos. Sci., 49, 2256.

Transfer of infrared radiation in a planetary atmosphere

Ignore the wavelength dependence of optical property: Gray approximation

$$\frac{2}{3}\frac{dF_{\uparrow}}{d\tau} = F_{\uparrow} - \pi B$$

$$\frac{2}{3}\frac{dF_{\downarrow}}{d\tau} = -F_{\downarrow} + \pi B$$

$$\tau \equiv \int_{z}^{\infty} \kappa(z')\rho(z')dz'$$ **Optical depth**

$$\pi B = \sigma T^{4}$$

Factor 2/3 arises from an assumption of zenith angle dependence of radiant flux.

Komabayashi-Ingersoll Limit

$$\frac{1}{2}F\left(\frac{3}{2}\tau_t+1\right)=\sigma T_t^{\ 4}$$

$$p^*(T)=p_0^*\exp\left(-\frac{l}{RT}\right)$$

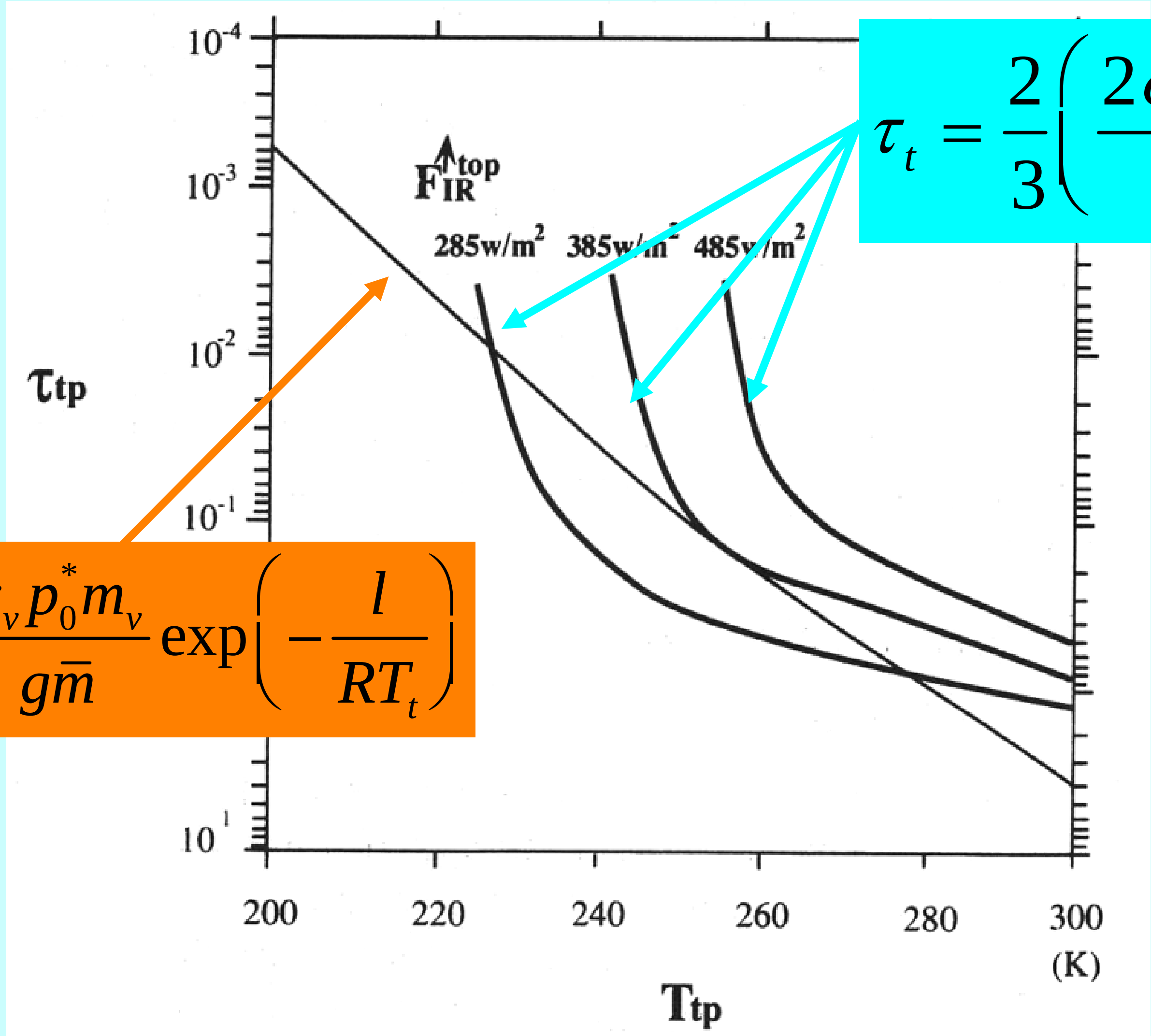
$$\tau_t=\kappa_v p^*(T)\frac{m_v}{g\bar{m}}$$

$$\Rightarrow$$

$$\tau_t=\frac{2}{3}\left(\frac{2\sigma T_t^{\ 4}}{F}-1\right)$$

$$\tau_t=\frac{\kappa_v p_0^* m_v}{g\bar{m}}\exp\left(-\frac{l}{RT_t}\right)$$

Komabayashi-Ingersoll Limit



$$\tau_t = \frac{2}{3}\left(\frac{2\sigma T_t^4}{F} - 1\right)$$

$$\tau_t = \frac{\kappa_v p_0^* m_v}{g\bar{m}} \exp\left(-\frac{l}{RT_t}\right)$$

Nakajima, et al., 1992 :

J. Atmos. Sci., 49, 2256.

Planetary Flux: outgoing infrared radiation

$$F_{p\lambda} = \frac{3}{2}\int_0^{\tau_{\lambda s}} \pi B_\lambda(t)\exp\left[-\frac{3}{2}t\right]dt + \pi B_{\lambda s}\exp\left[-\frac{3}{2}\tau_{\lambda s}\right] - F_{\lambda 0}$$

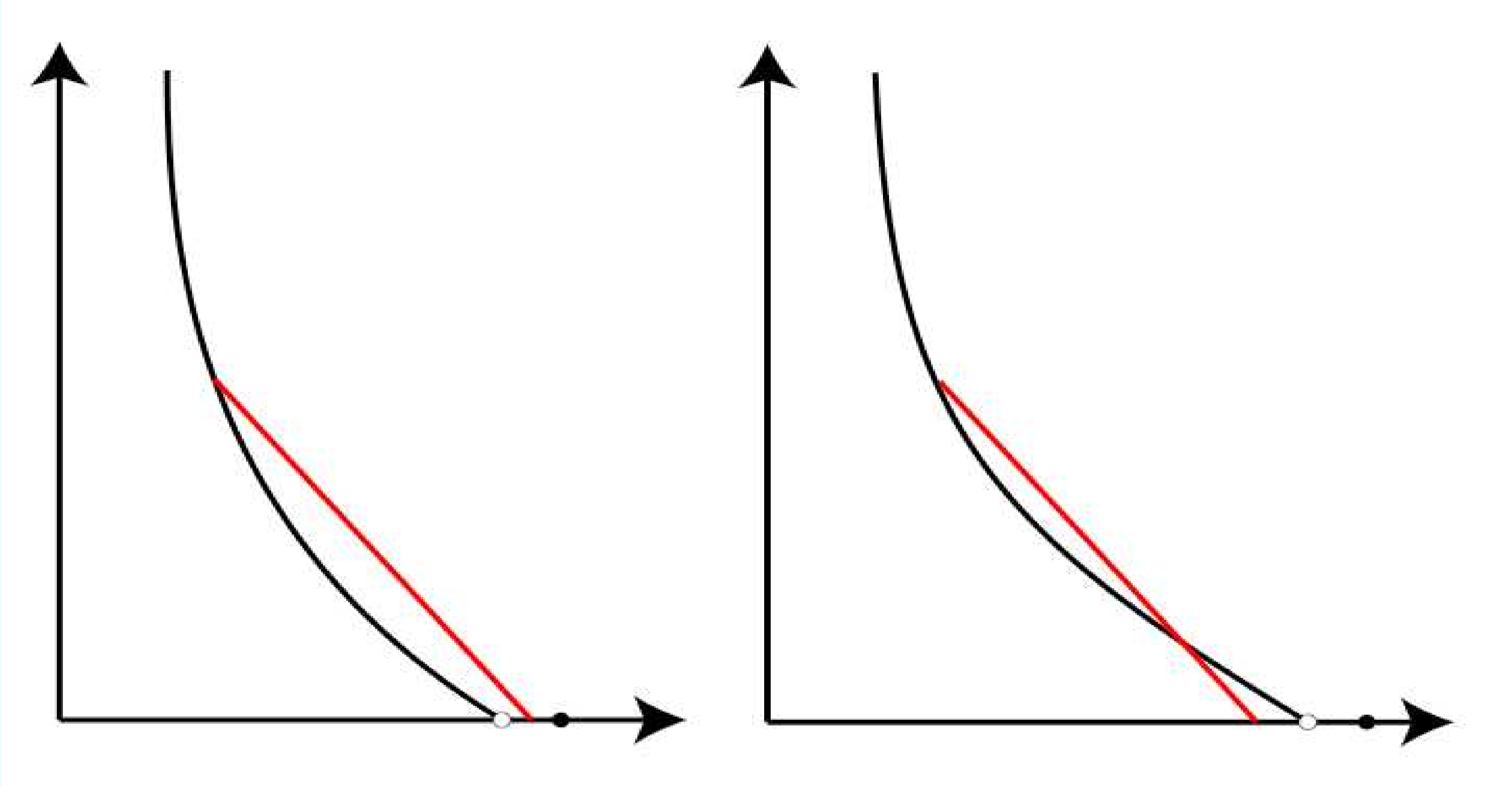
$F_{\lambda s} \rightarrow \pi B_{\lambda s}$ **When the surface is black body.**

Determined by the distribution of temperature and absorber

Integral of the Planck function weighed by optical depth.

Most sensitive to the temperature around τ_λ ; 1

Radiativ-convective equilibrium



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Dry Adiabat

$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{\alpha T}{\rho C_p} \qquad \rho = \frac{wp}{RT} \quad \alpha = \frac{1}{T}$$

$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{RT}{wpC_p} = \frac{RT}{pC_p'} = \frac{(C_p' - C_v')T}{pC_p'} = \frac{\gamma - 1}{\gamma}\frac{T}{p}$$

$$\left(\frac{T}{T_0}\right) = \left(\frac{p}{p_0}\right)^{\frac{\gamma - 1}{\gamma}}$$

Polytrope with exponent: $\gamma = \dfrac{C_p}{C_v}$

Moist adiabat

$$dS = \left(\frac{\partial S}{\partial p}\right)_{T,n_i} dp + \left(\frac{\partial S}{\partial T}\right)_{p,n_i} dT + \left(\frac{\partial S}{\partial n_v}\right)_{T,p,n_n} dn_v = 0$$

$$d\Delta G = \left(\frac{\partial \Delta G}{\partial p}\right)_{T,n_i} dp + \left(\frac{\partial \Delta G}{\partial T}\right)_{p,n_i} dT + \left(\frac{\partial \Delta G}{\partial n_v}\right)_{T,p,n_n} dn_v = 0$$

$$\Delta G = \mu_v\left(p,T,n_v,n_n\right) - \mu_c\left(p,T\right) = 0$$

Moist adiabat

$$\left[\frac{\left(\frac{\partial S}{\partial p}\right)_{T,n_i}}{\left(\frac{\partial S}{\partial n_v}\right)_{T,p,n_n}}-\frac{\left(\frac{\partial \Delta G}{\partial p}\right)_{T,n_i}}{\left(\frac{\partial \Delta G}{\partial n_v}\right)_{T,p,n_n}}\right]dp+\left[\frac{\left(\frac{\partial S}{\partial T}\right)_{p,n_i}}{\left(\frac{\partial S}{\partial n_v}\right)_{T,p,n_n}}-\frac{\left(\frac{\partial \Delta G}{\partial T}\right)_{p,n_i}}{\left(\frac{\partial \Delta G}{\partial n_v}\right)_{T,p,n_n}}\right]dT=0$$

$$\left(\frac{\partial T}{\partial p}\right)_s=-\frac{\left[\left(\frac{\partial \Delta G}{\partial n_v}\right)_{T,p,n_n}\left(\frac{\partial S}{\partial p}\right)_{T,n_i}-\left(\frac{\partial S}{\partial n_v}\right)_{T,p,n_n}\left(\frac{\partial \Delta G}{\partial p}\right)_{T,n_i}\right]}{\left[\left(\frac{\partial \Delta G}{\partial n_v}\right)_{T,p,n_n}\left(\frac{\partial S}{\partial T}\right)_{p,n_i}-\left(\frac{\partial S}{\partial n_v}\right)_{T,p,n_n}\left(\frac{\partial \Delta G}{\partial T}\right)_{p,n_i}\right]}$$

$n_c = 0$ moist pseudoadiabat

moist pseudoadiabat

$$\left(\frac{\partial T}{\partial p}\right)_{\substack{\text{moist}\\ \text{pseudoadiabat}}} = \frac{RT}{p\left(x_n c_{pn} + x_v^* c_{pv}\right)} \frac{1 + x_v^*\left(\dfrac{l}{RT} - 1\right)}{1 + x_v^*\left[\dfrac{l^2}{RT^2\left(x_n c_{pn} + x_v^* * c_{pv}\right)} - 1\right]}$$

$$\left(\frac{\partial T}{\partial p}\right)_{\substack{\text{moist}\\ \text{pseudoadiabat}}} \to \frac{RT}{pc_{pn}}$$

Dry adiabat @small water vapor fraction

$$\left(\frac{\partial T}{\partial p}\right)_{\substack{\text{moist}\\ \text{pseudoadiabat}}} \to \frac{RT}{p\left(x_n c_{pn} + x_v^* c_{pv}\right)} \frac{\dfrac{l}{RT}}{\dfrac{l^2}{RT^2\left(x_n c_{pn} + x_v^* * c_{pv}\right)}} = \frac{1}{p}\frac{l}{\dfrac{l^2}{RT^2}} = \frac{RT^2}{pl}$$

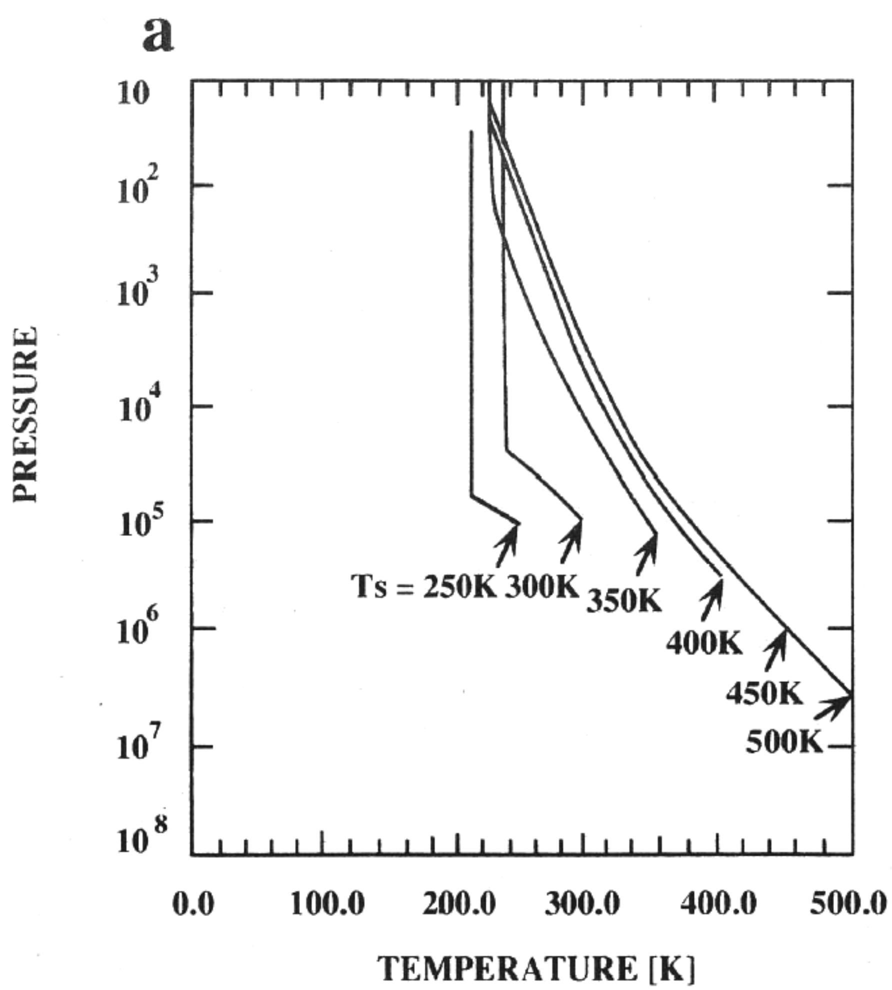
Saturated vapor pressure curve @large water vapor fraction

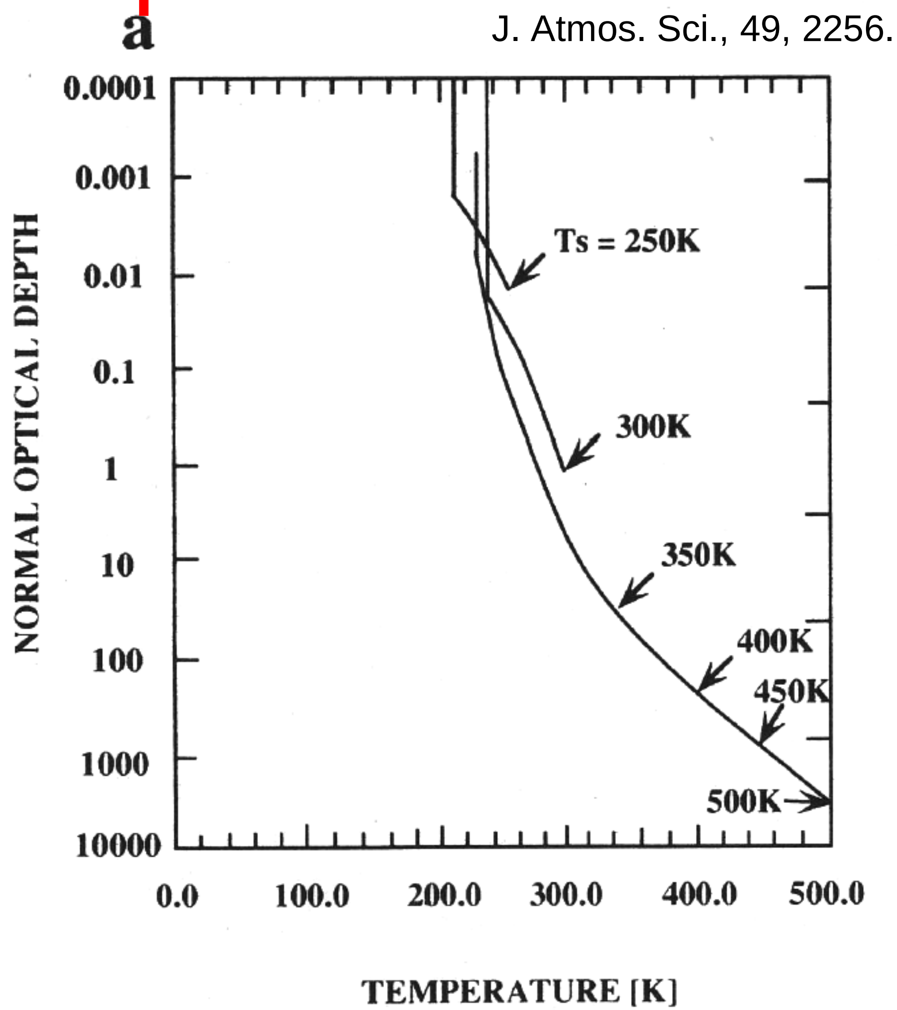
$$\frac{dp^*}{dT} = \frac{l}{RT^2}p^*$$

Assymptotic limit controlled by moist troposphere

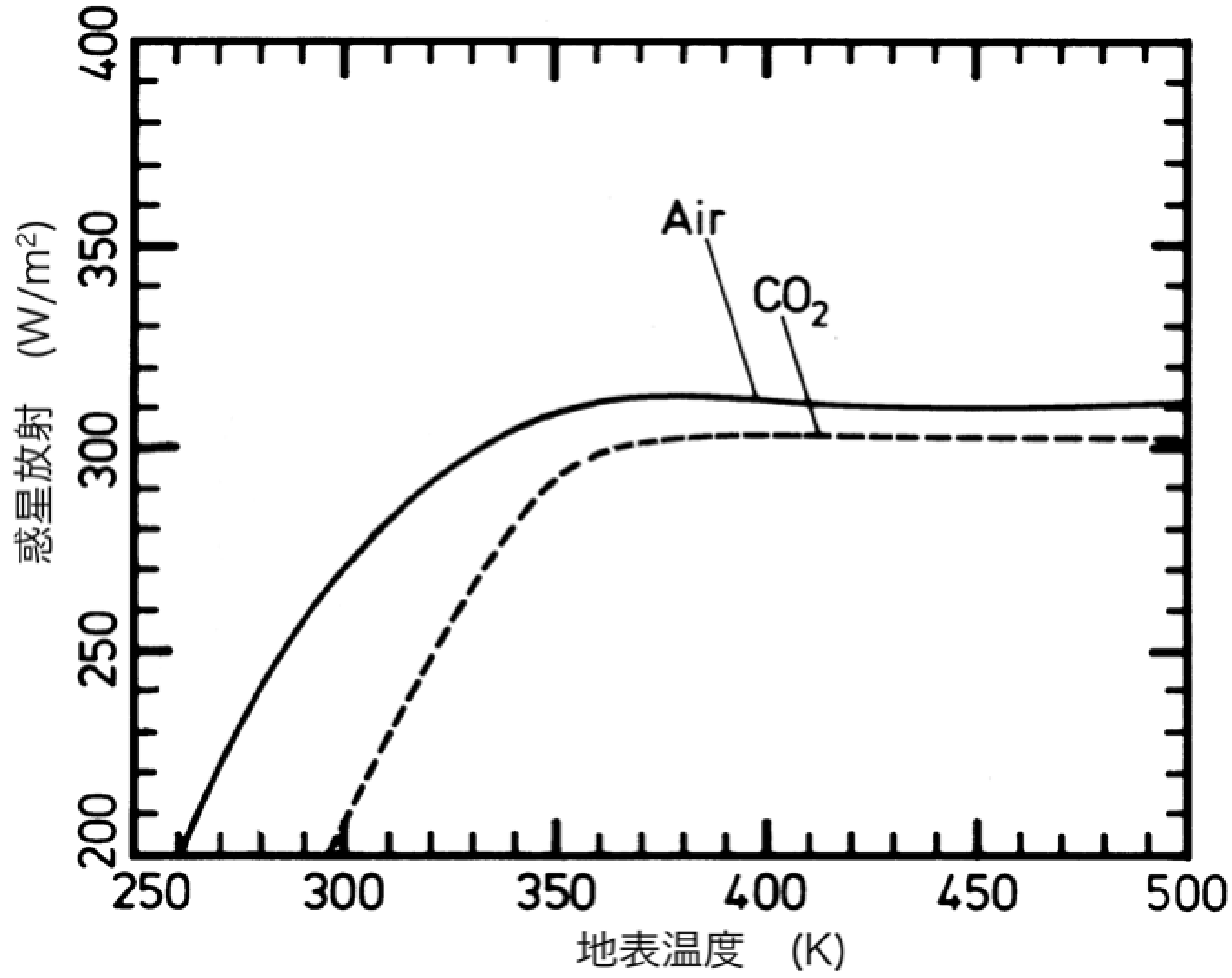
Nakajima, et al., 1992 :

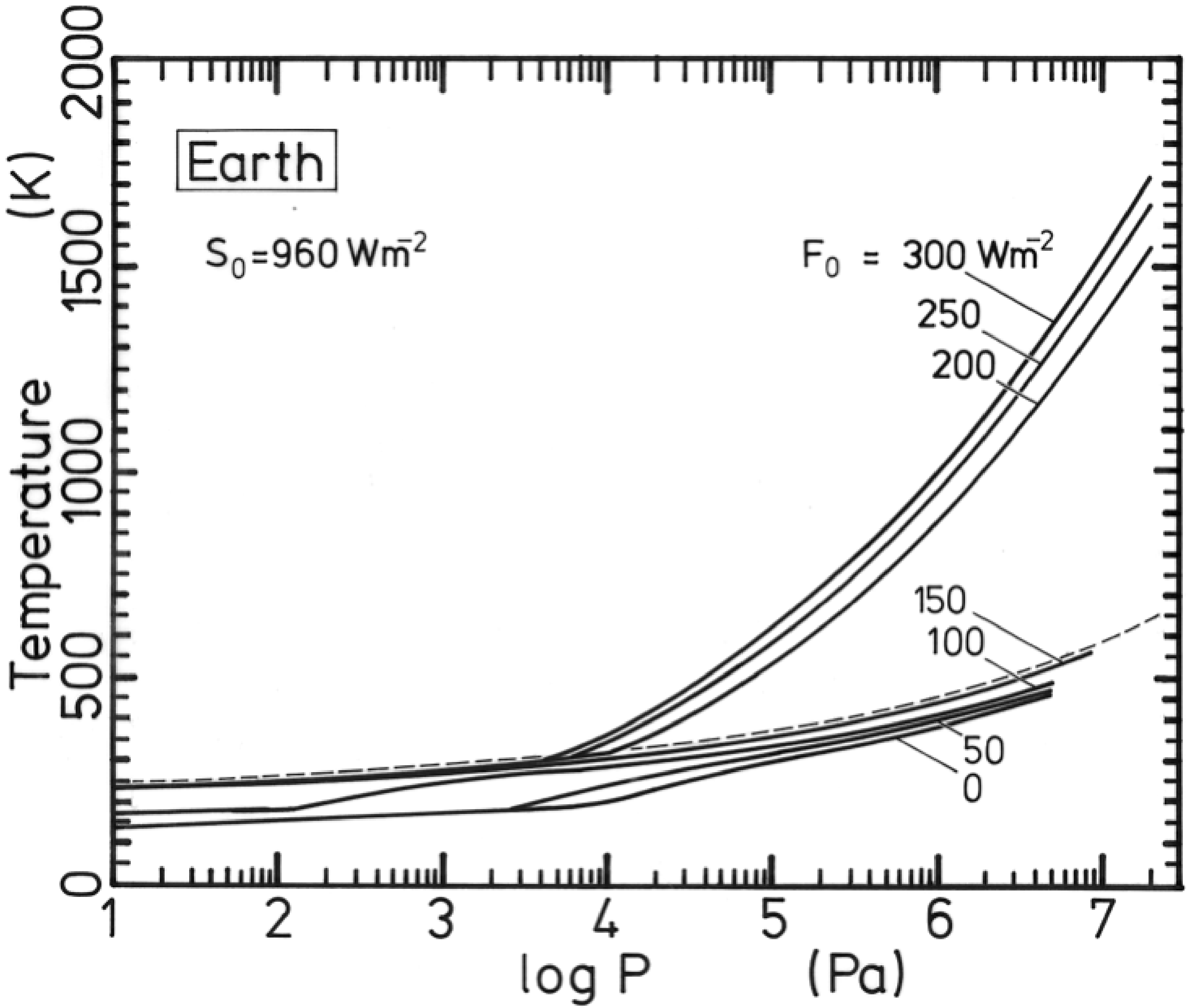
J. Atmos. Sci., 49, 2256.



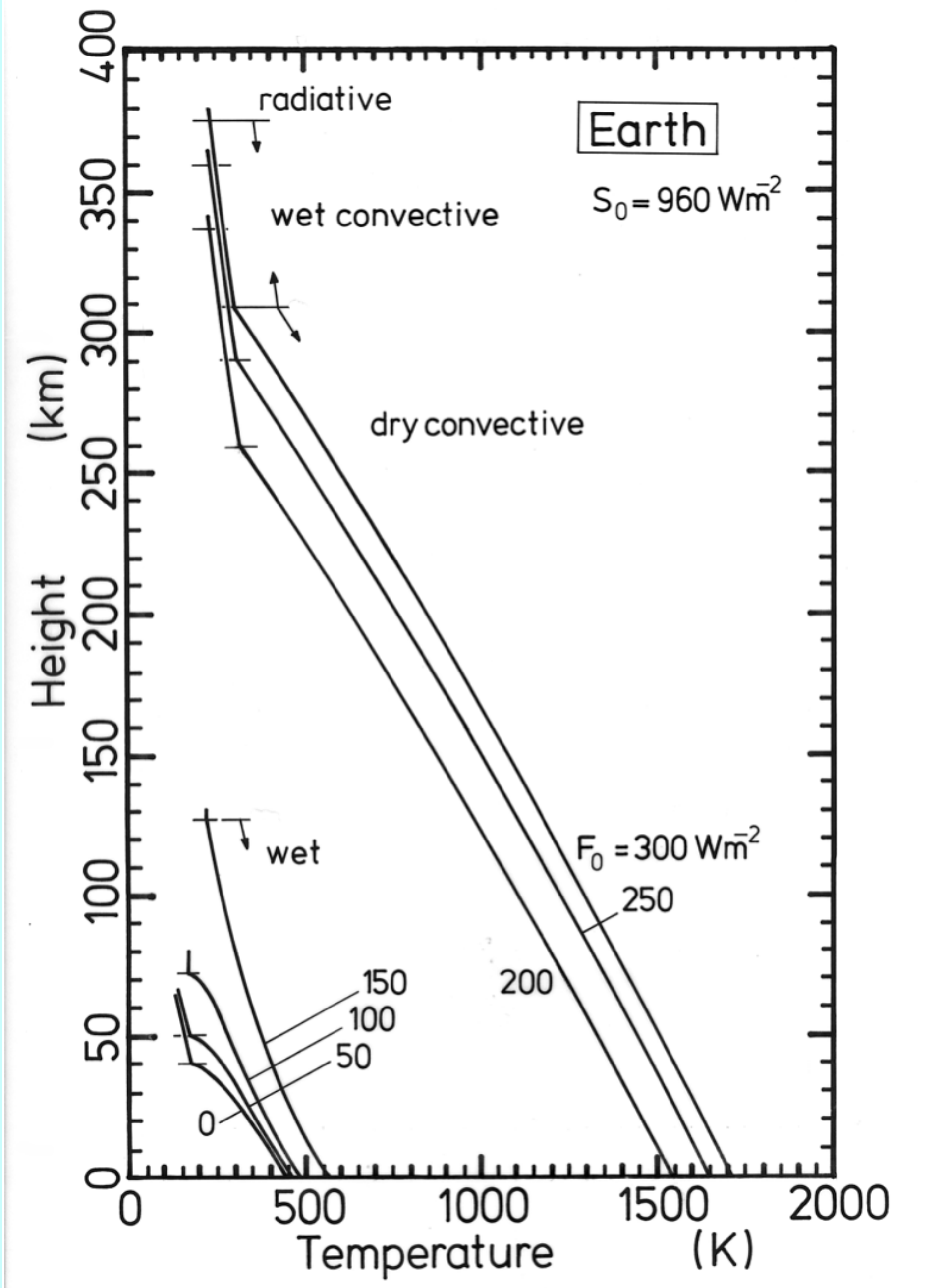


Runaway greenhouse

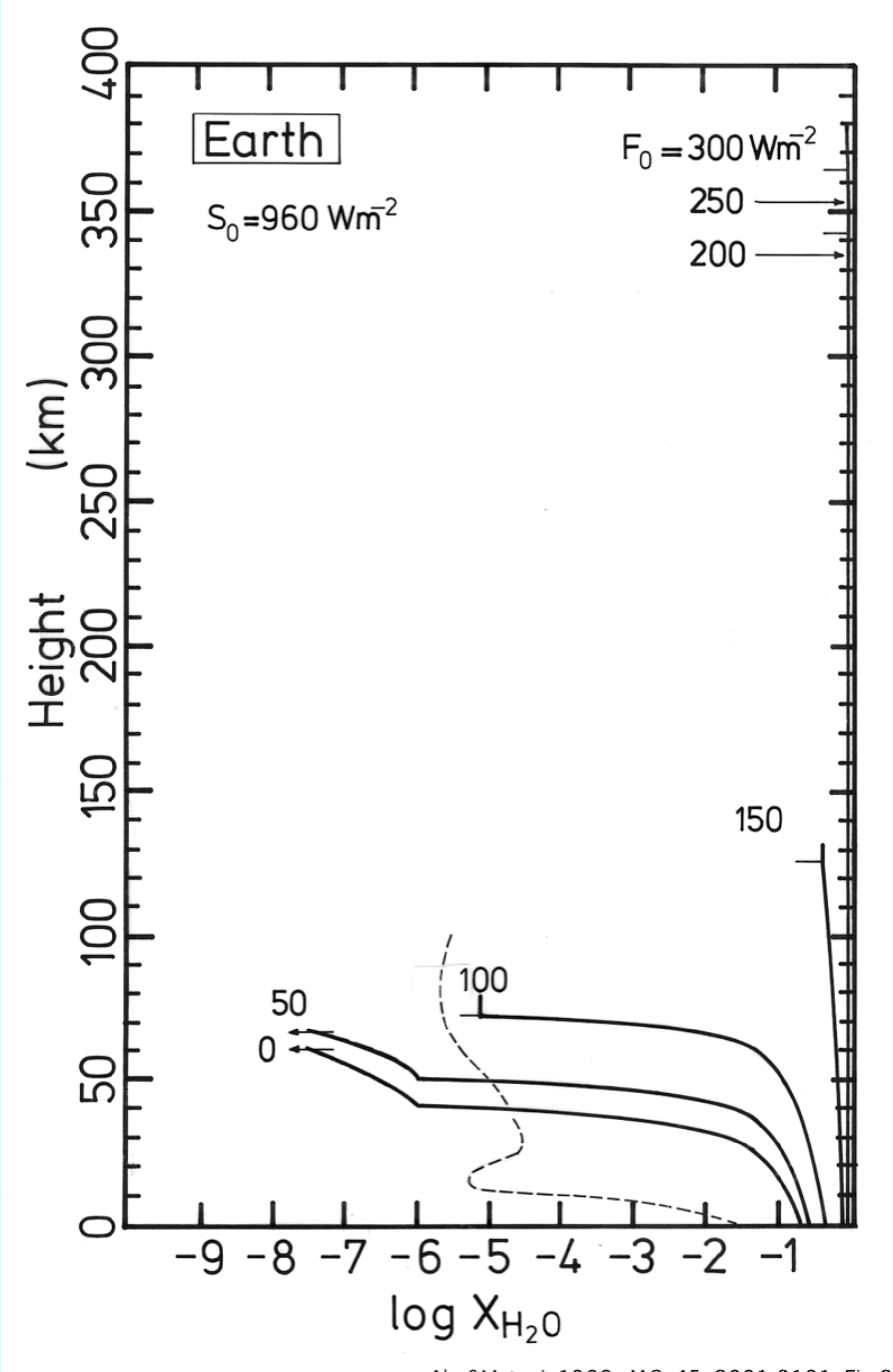




Abe&Matsui, 1988: JAS,45,3081-3101. Fig.1



Abe&Matsui. 1988: JAS. 45. 3081-3101.Fig.2.



Abe&Matsui, 1988: JAS, 45, 3081-3101, Fig.3.

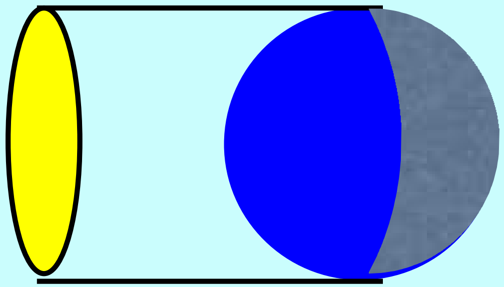
2.2 freezing limit

A simple global energy balance model with ice albedo feedback.

$$\pi r^2 S(1-A) = 4\pi r^2 F$$

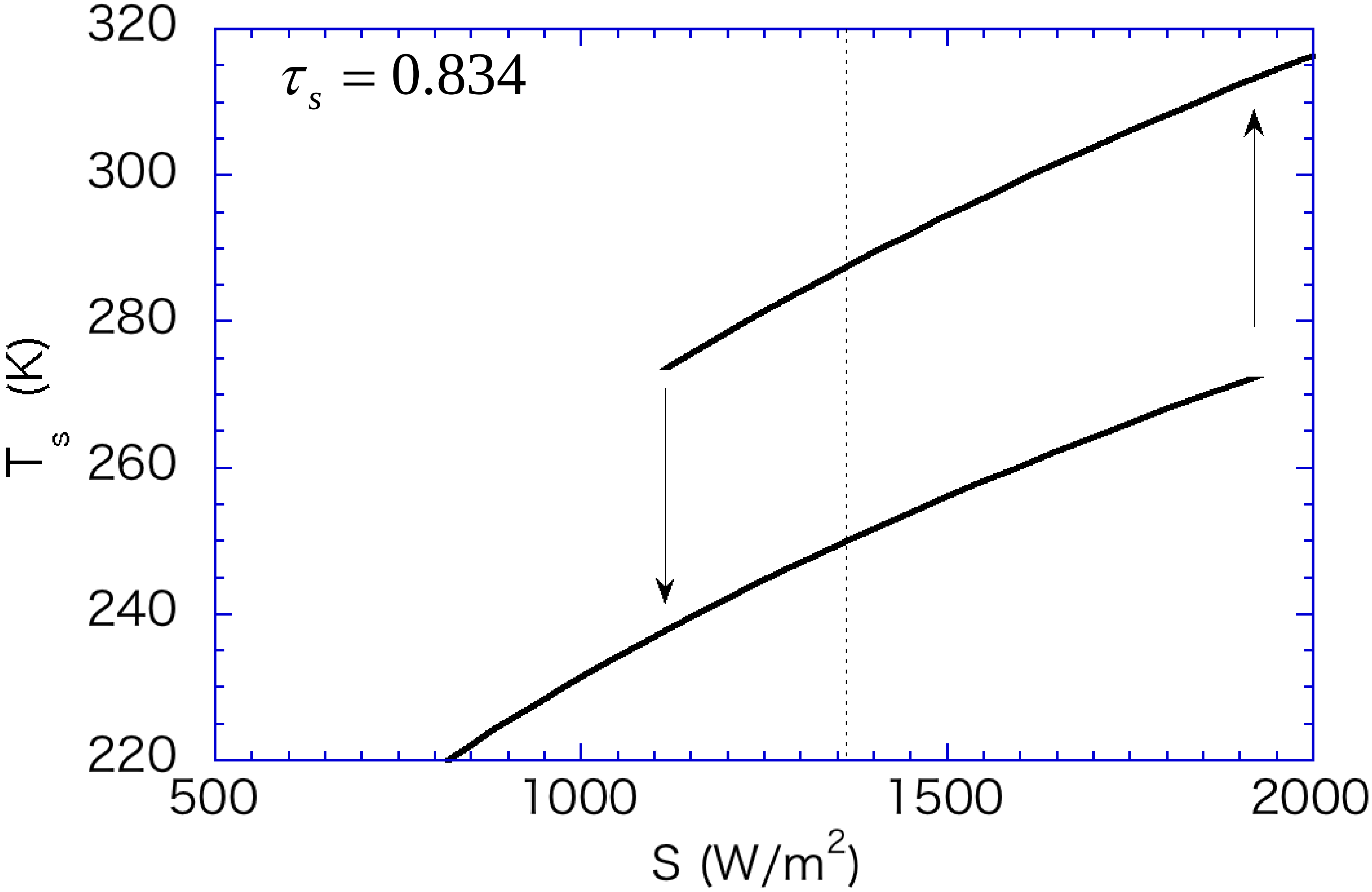
$$F = \frac{2\sigma T_s^{\,4}}{\frac{3}{2}\tau_s + 2}$$

$$A = \begin{cases} 0.3 & (T_s \geq 273) \\ 0.6 & (T_s < 273) \end{cases}$$

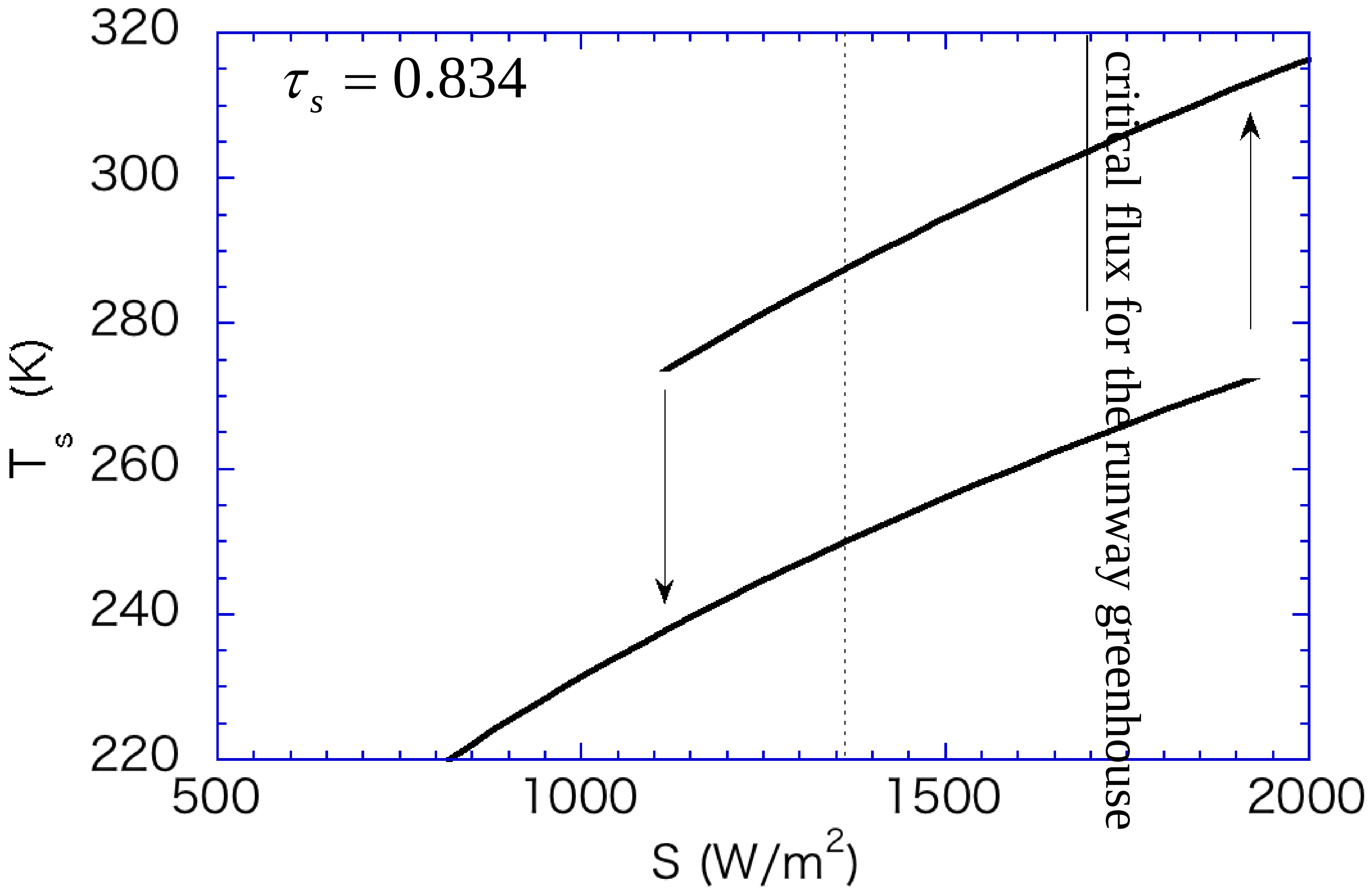


πr^2 $4\pi r^2$

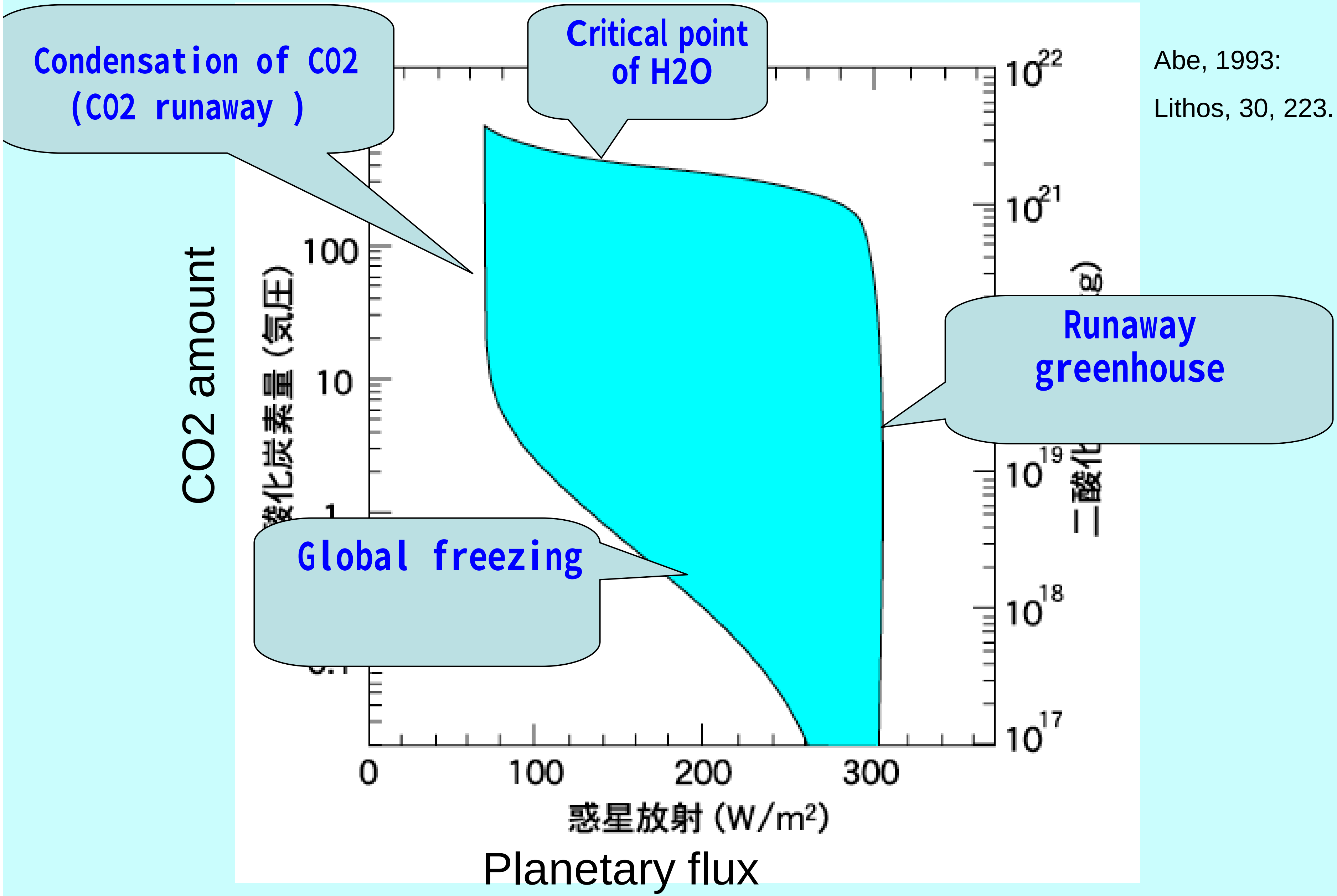
Multiple equilibrium state



Multiple equilibrium state



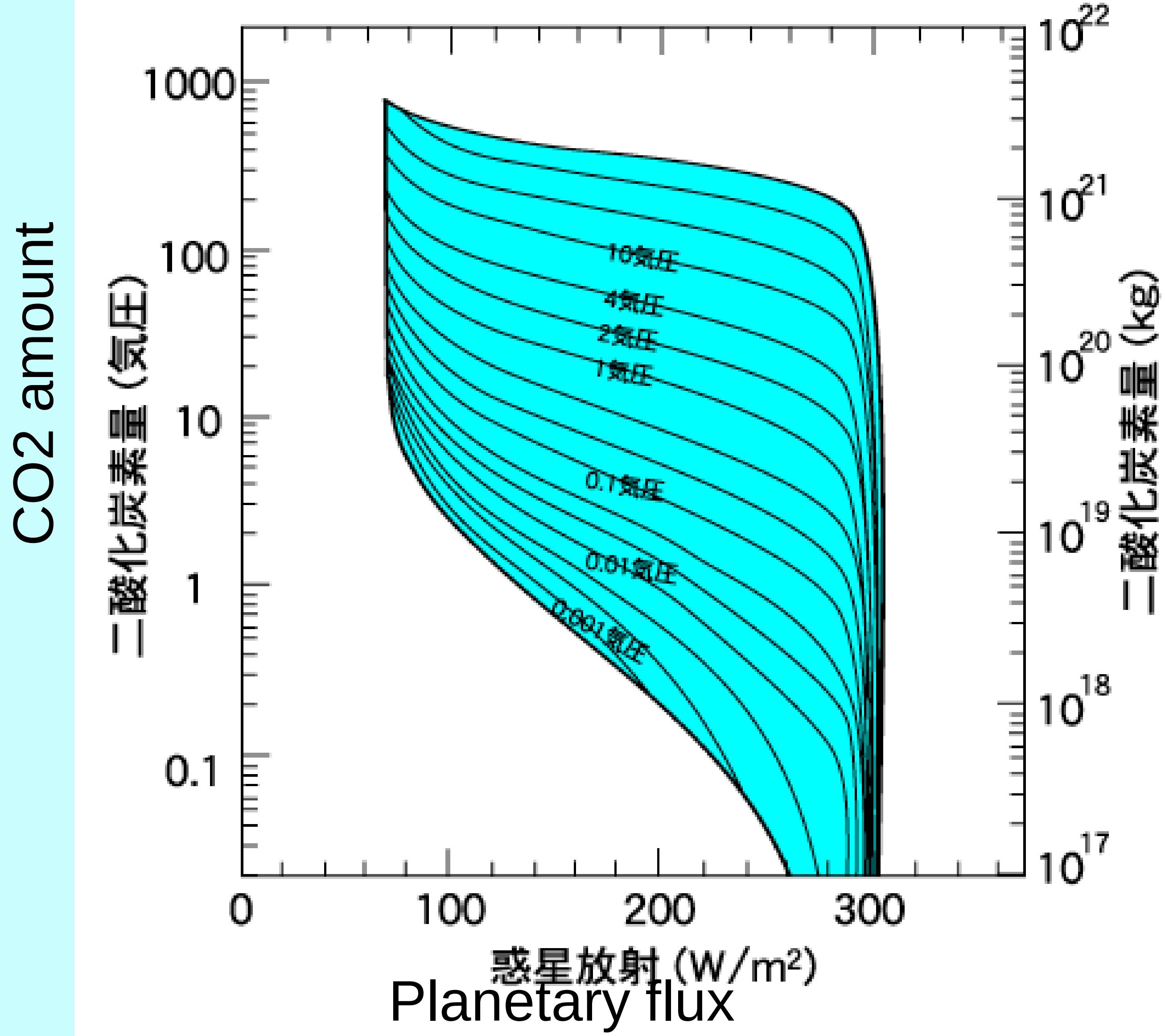
2.3 stability of liquid water



Abe, 1993:

Lithos, 30, 223.

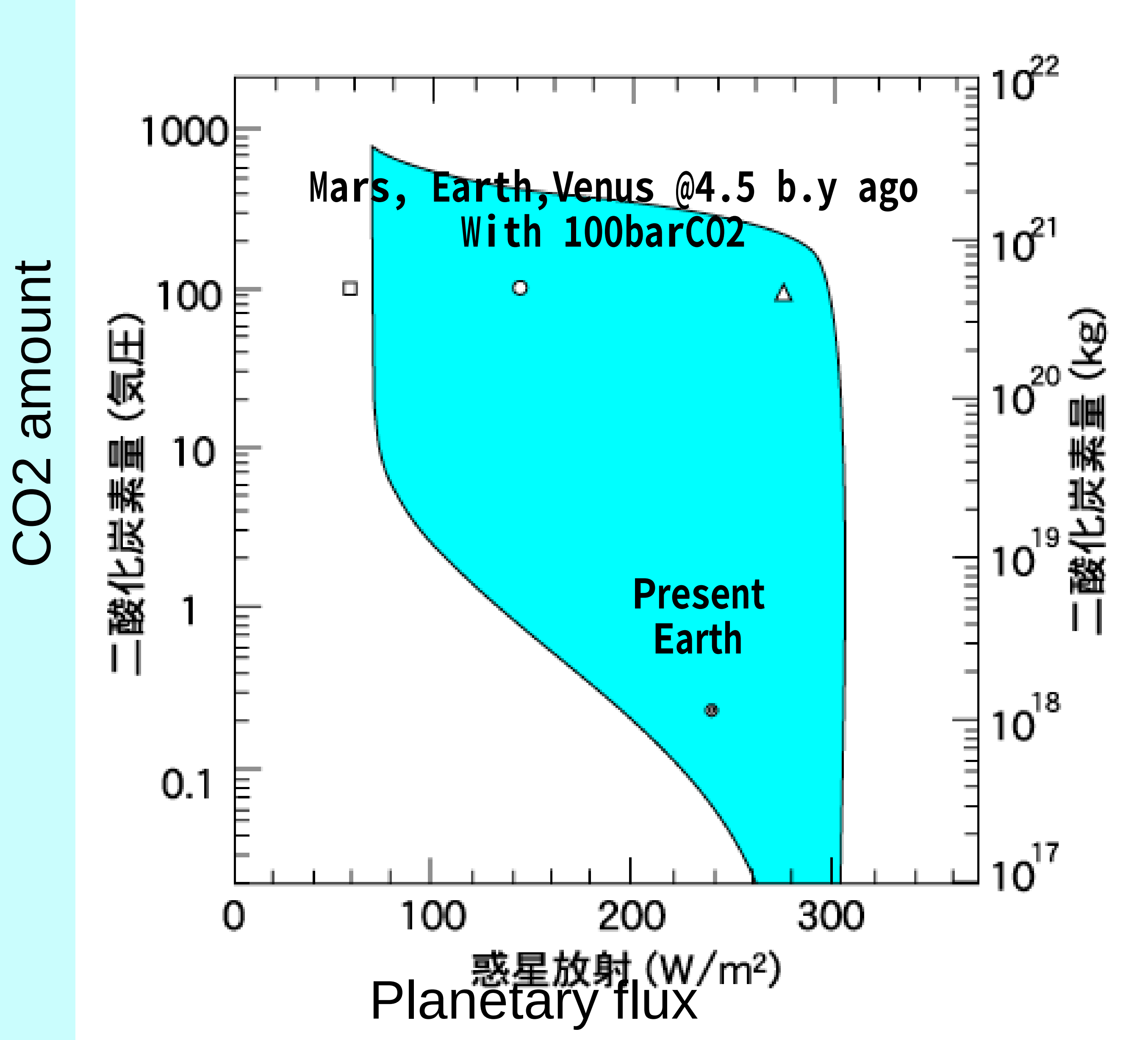
Amount of H2O necessary for formation of liquid water



Abe, 1993:

Lithos, 30, 223.

Earth-sized planet @Mars, Venus, Earth orbit



Abe, 1993:

Lithos, 30, 223.

3. Water planet in geological time scale

Continuously Habitable Condition

Cause of change

1. Loss of H2O
   H2O is dissociated in the upper atmosphere.
   lost into space as H.
2. Evolution of the central star
   increase of the insolation about 30% in 4.5b.y.
3. Carbonate formation
   CO2 dissolves into liquid water
   fixed as carbonate

3.1. Loss of H_2O

H loss from the present Earth is rather rapid.

UV dissociation of H_2O into H is also rapid.

Limited by supply of H_2O to the upper atmosphere.

Water content in the upper atmosphere

Water vapor condenses in the troposphere.

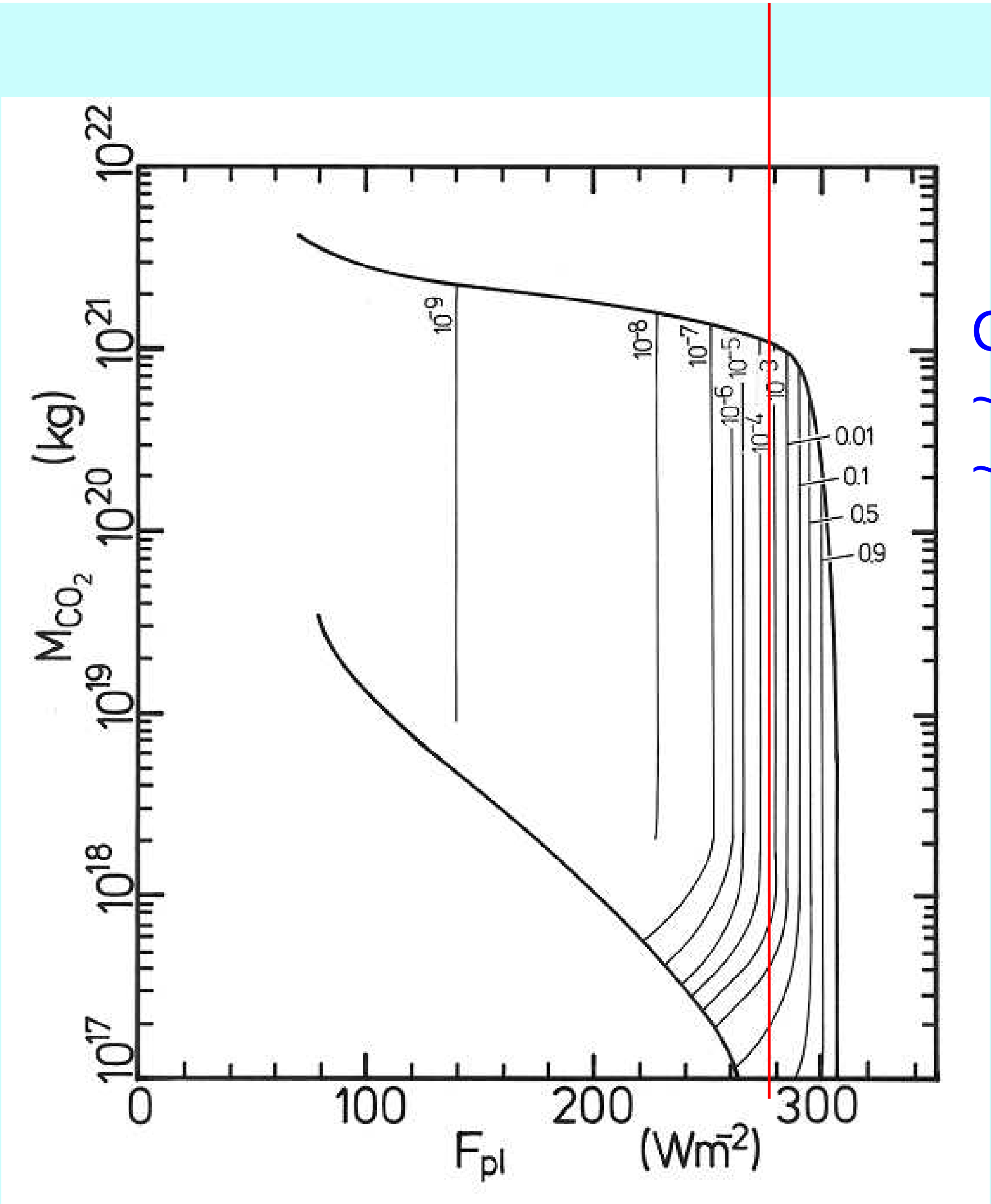
Water content in the upper atmosphere limited by the P-T condition at the tropopause. Cold Trap

While water vapor mixing ratio $< 10^{-3}$

1 ocean mass water survives > 4.5 b. y.

(Diffusion Limit)

CO2 amount

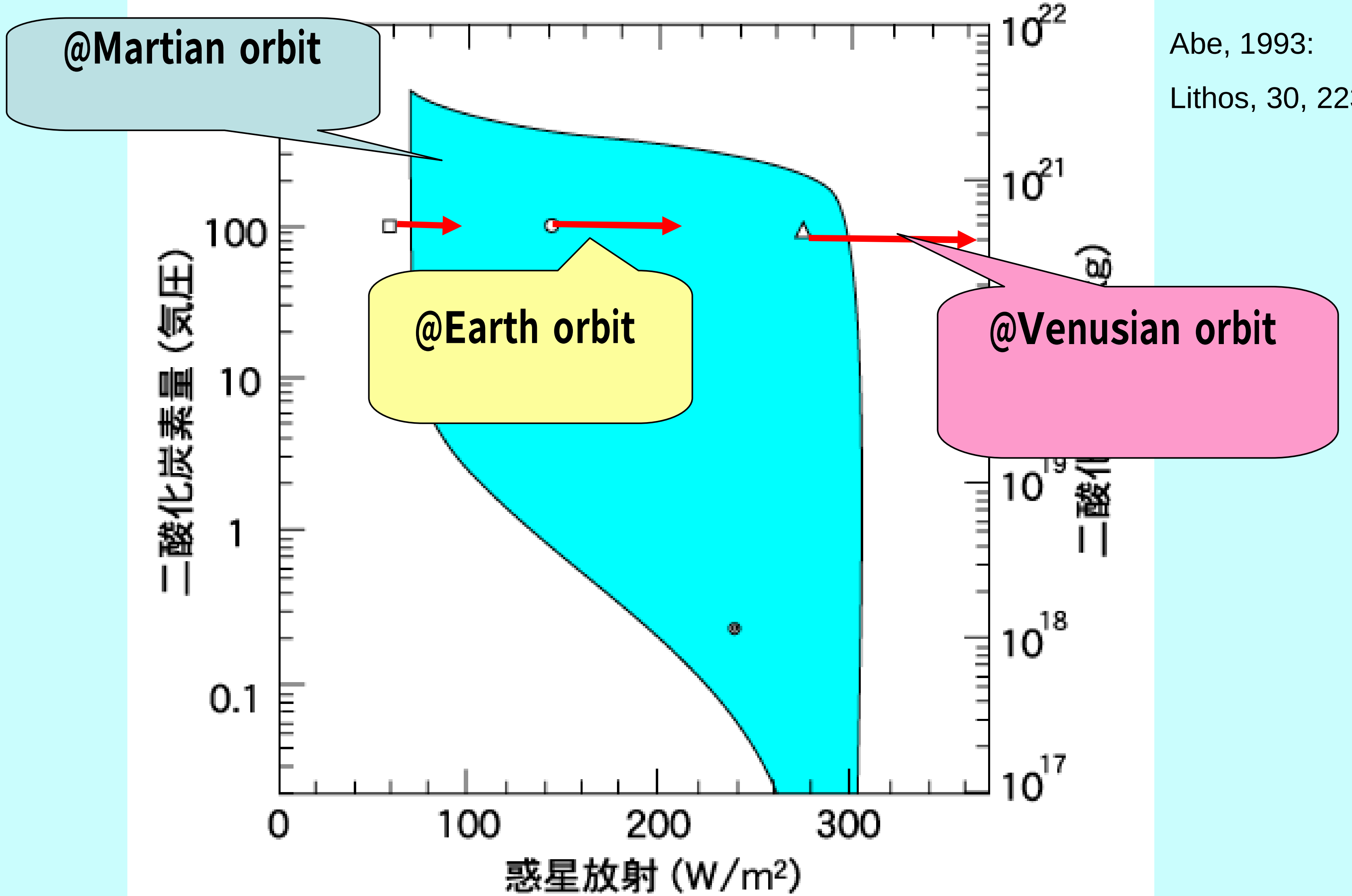


Planetary flux

Critical flux
~280 W/m2
~115%

2. Evolution of the central star

Increase of insolation: Planets move right on this diagram.



Abe, 1993:

Lithos, 30, 223.

3.3 Carbonate formation

$$CaO + 2CO_2 + H_2O \text{ Å®} Ca^{2+} + 2HCO_3^-$$

Chemical erosion

$$HCO_3^- + H^+ \leftrightarrow H_2CO_3$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$$

Dissolution

$$H_2CO_3 \leftrightarrow CO_2 + H_2O$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$$

Precipitation as carbonate

$$CaO + CO_2 \rightarrow CaCO_3$$

Carbonate formation

$$CaO + 2CO_2 + H_2O \text{ Å®} Ca^{2+} + 2HCO_3^-$$

Slow

$$HCO_3^- + H^+ \leftrightarrow H_2CO_3$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$$

$$H_2CO_3 \leftrightarrow CO_2 + H_2O$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$$

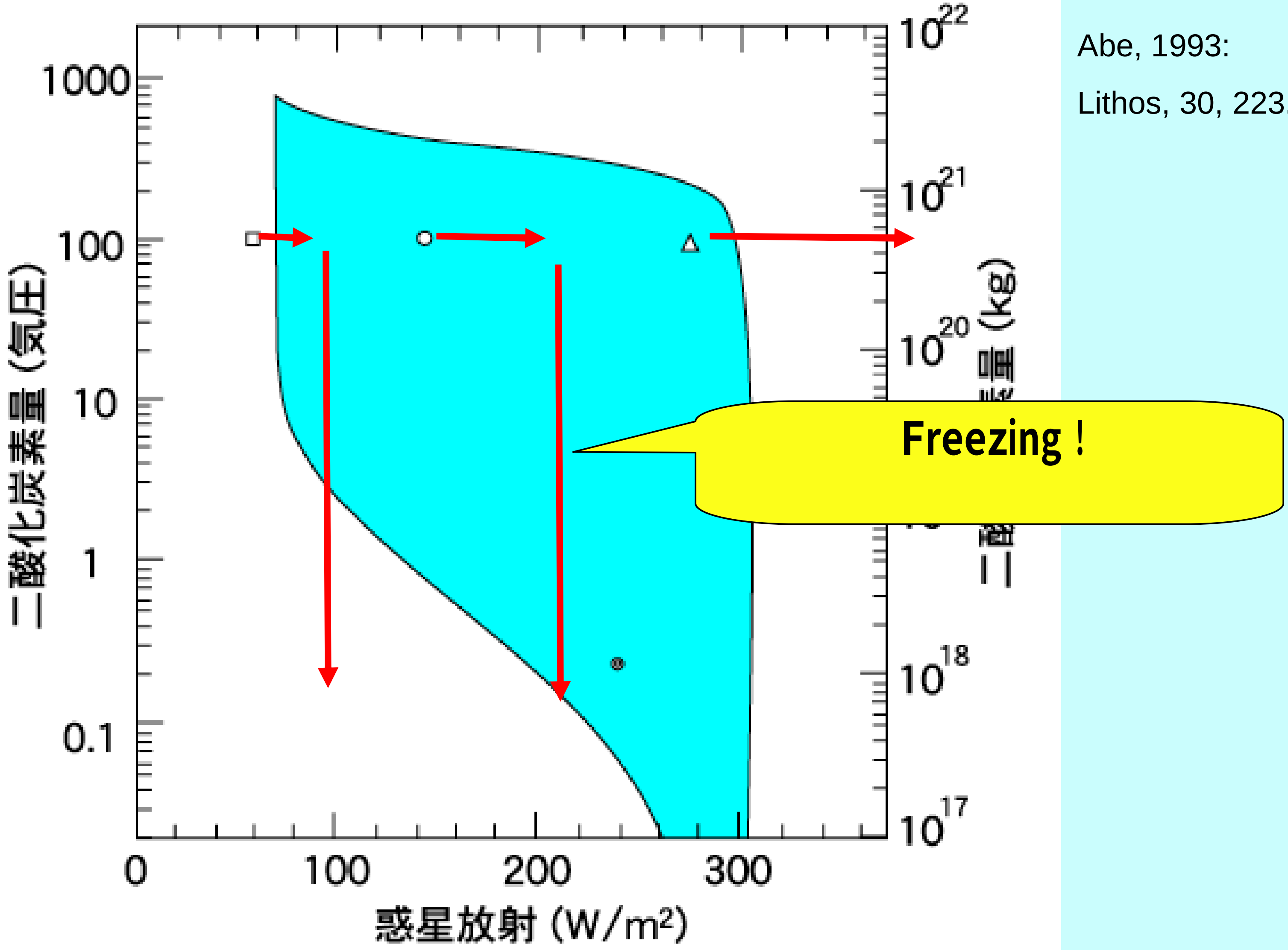
Rapid

Ca^{2+} supply by chemical erosion is the most important rate controlling process

$$\tau_{carb} \sim 10^{5-6}\,\mathrm{y}$$

Effect of carbonate formation

Decrease of CO2: Planets move downward on this diagram.

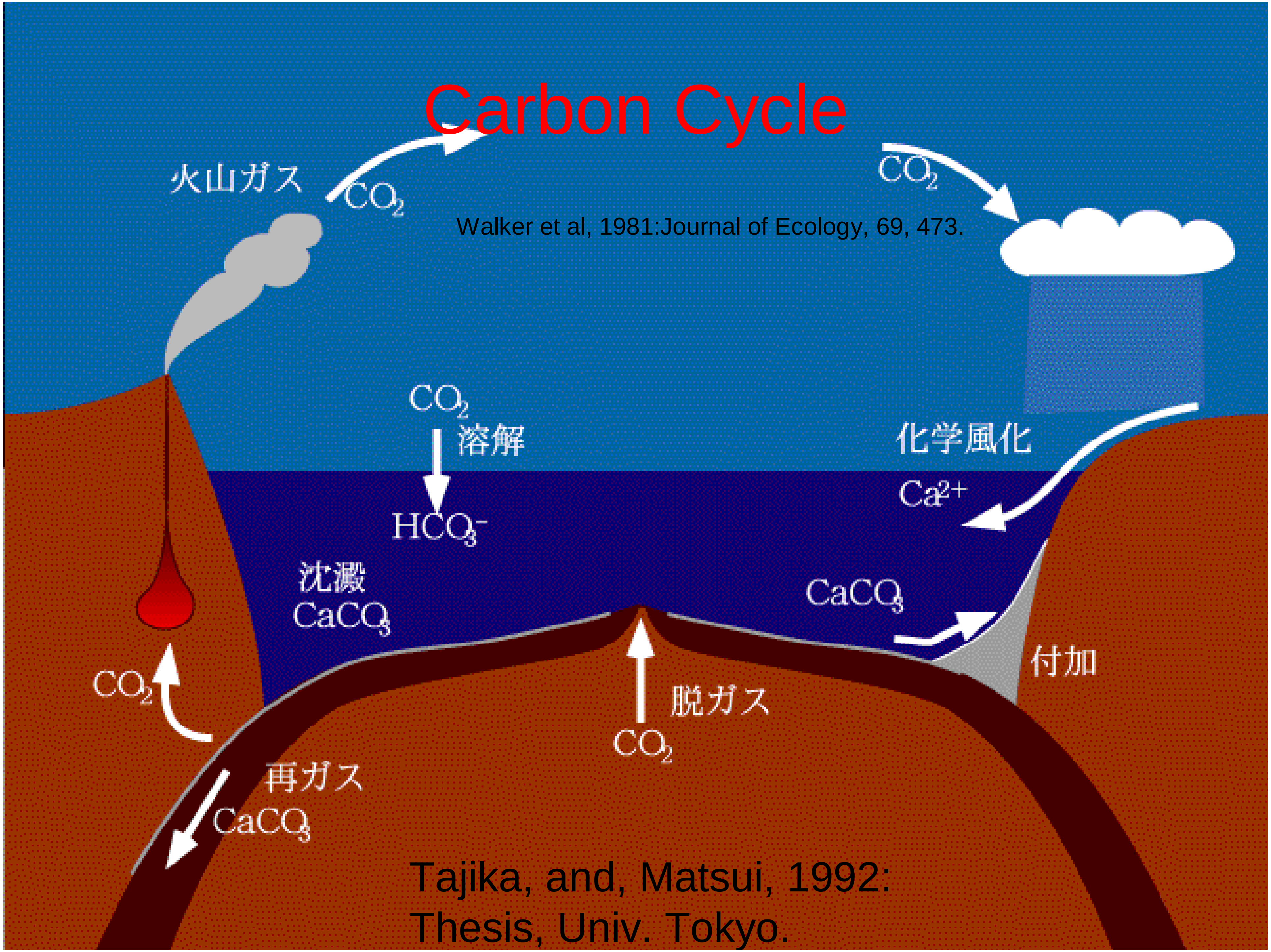


Abe, 1993:

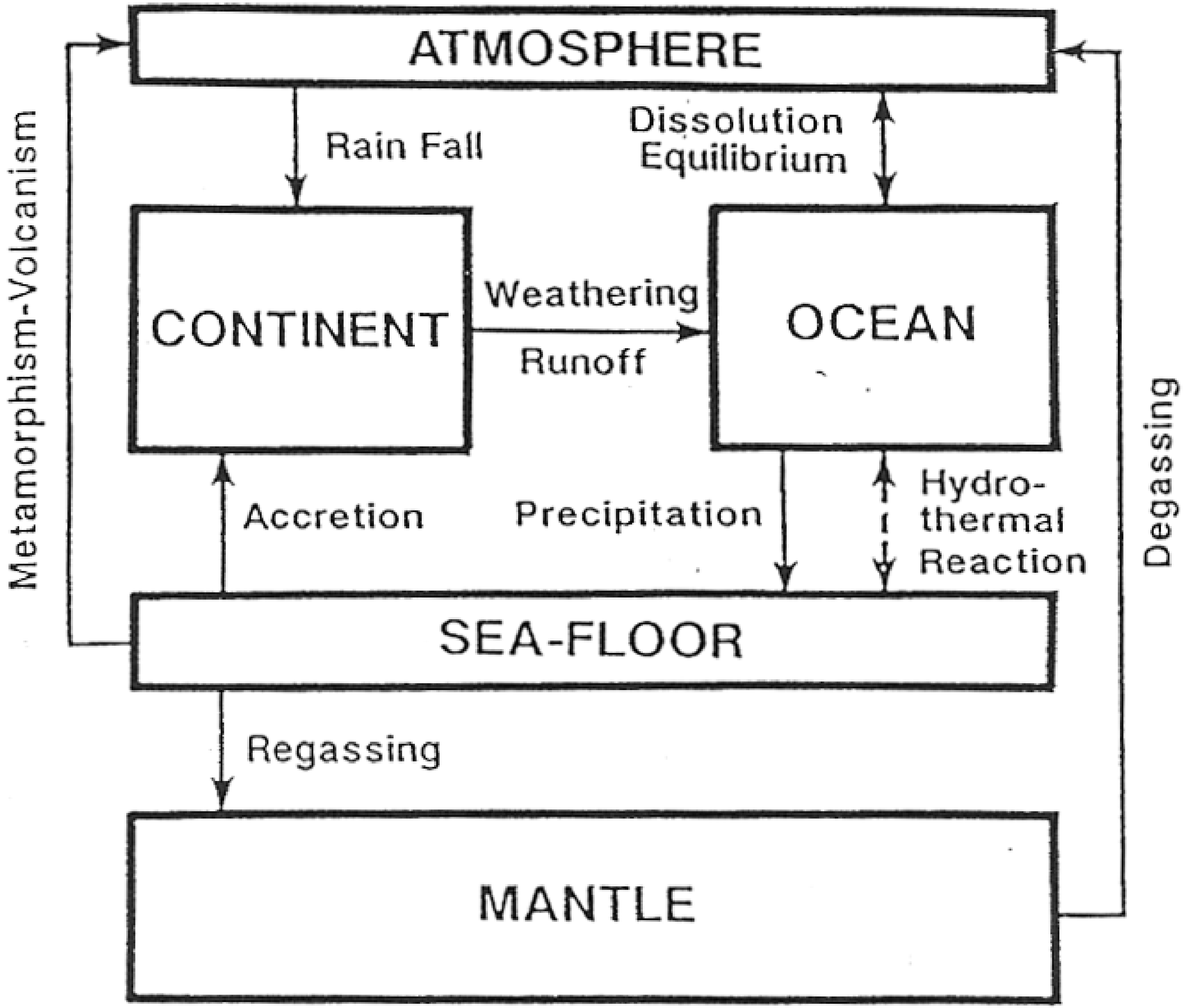
Lithos, 30, 223.

Carbon Cycle

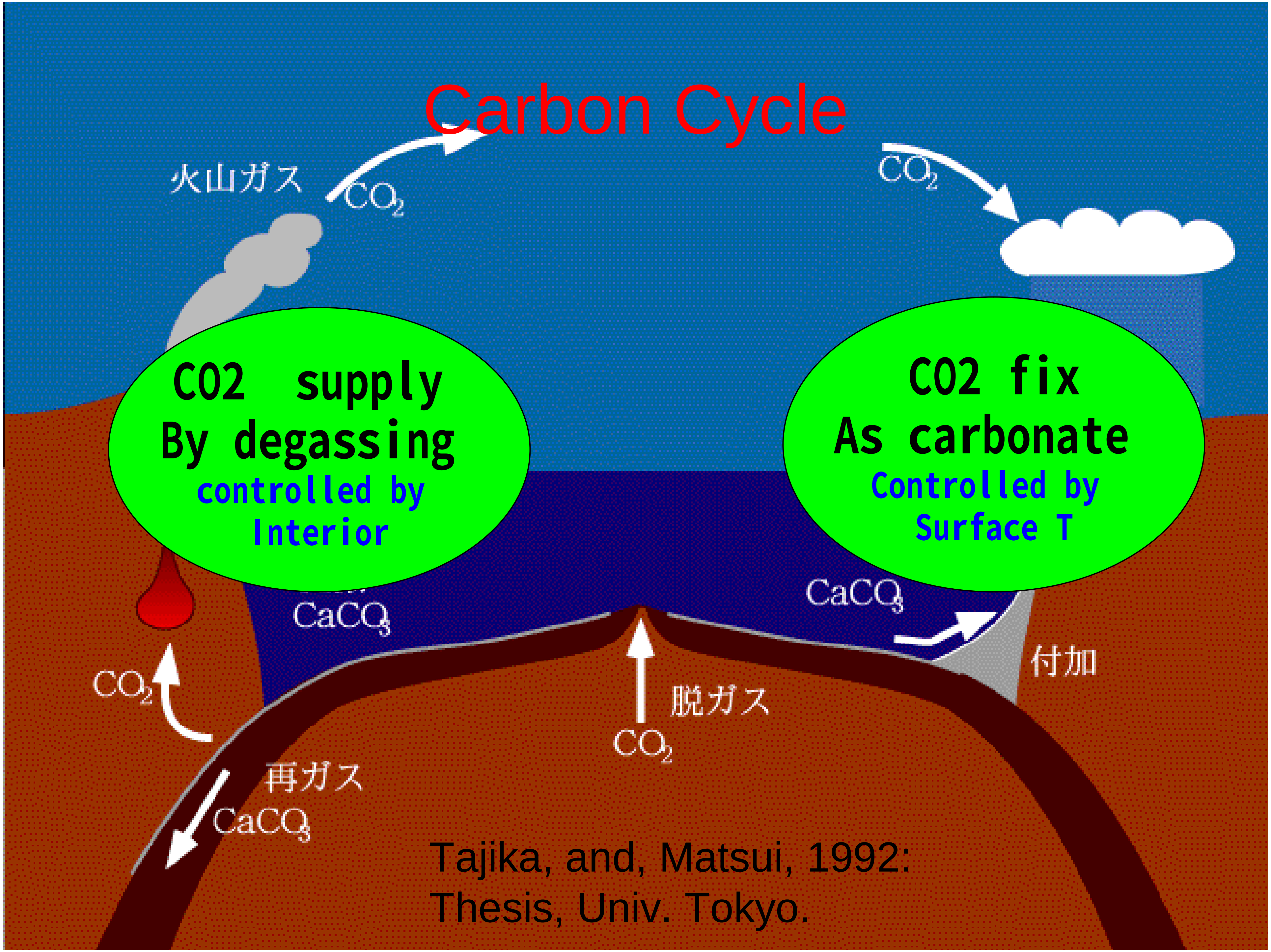
Walker et al, 1981:Journal of Ecology, 69, 473.



Tajika, and, Matsui, 1992:
Thesis, Univ. Tokyo.



Tajika&Matsui 1990, Tajika, 1992


Carbon Cycle
火山ガス
CO_2
CO_2
CO2 supply
By degassing
controlled by
Interior
CO2 fix
As carbonate
Controlled by
Surface T
$CaCO_3$
$CaCO_3$
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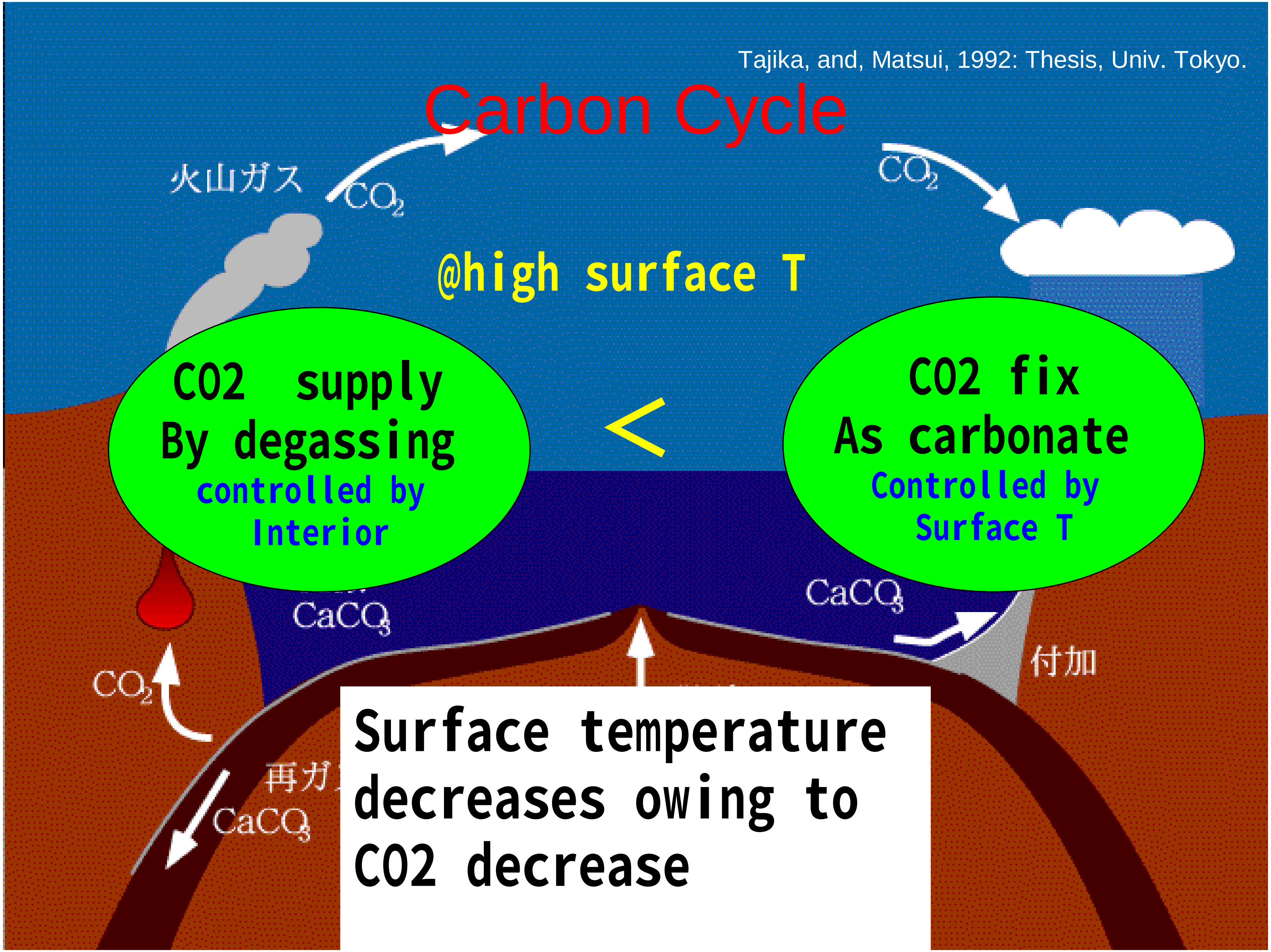
$CaCO_3$
Tajika, and, Matsui, 1992:
Thesis, Univ. Tokyo.



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Carbon Cycle
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Interior
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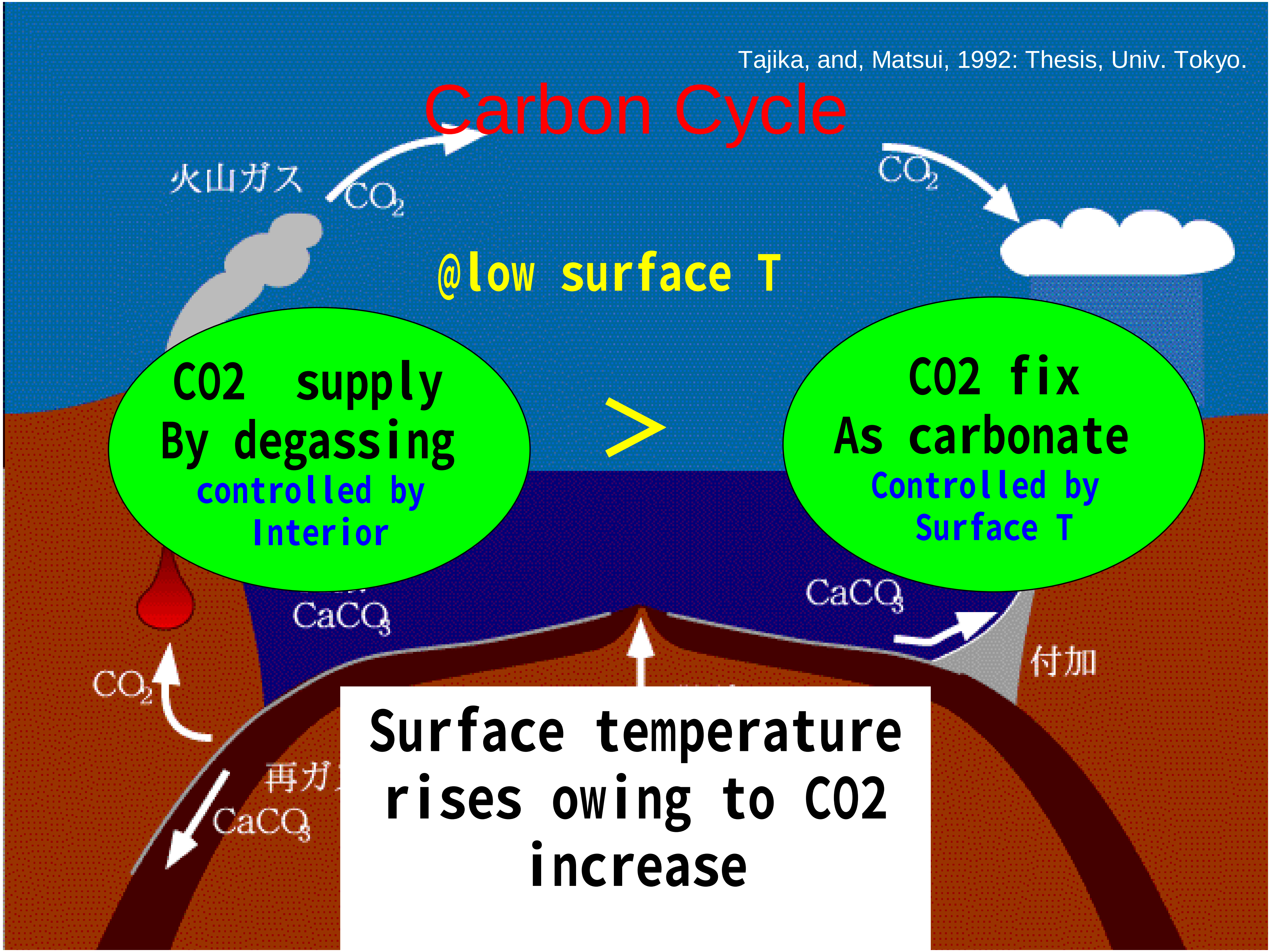
$CaCO_3$
付加
CO_2
$CaCO_3$
Surface temperature
decreases owing to
CO2 decrease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Carbon Cycle
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Interior
>
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Controlled by
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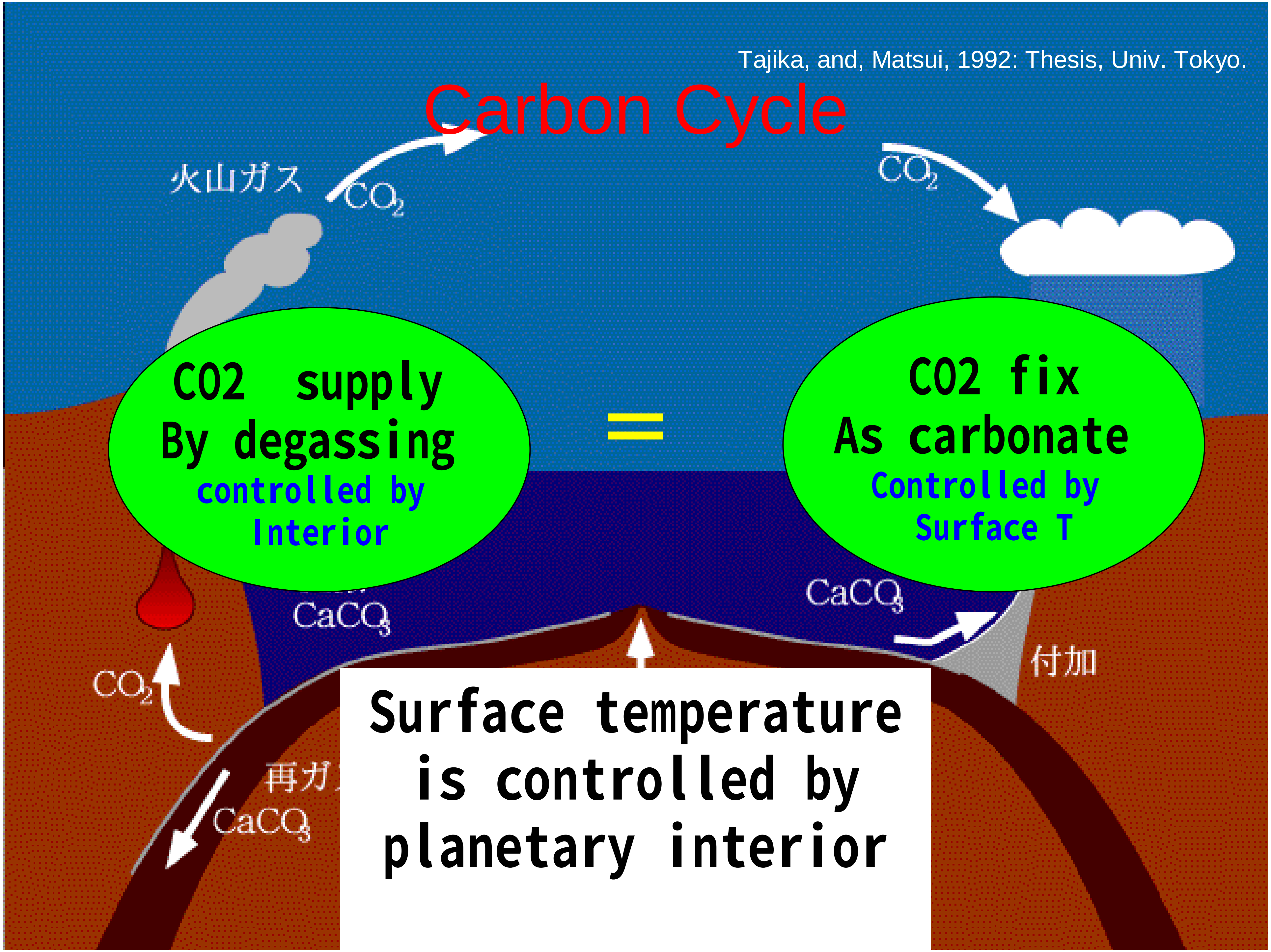
CaCO3
付加
CO2
CaCO3
Surface temperature
rises owing to CO2
increase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Carbon Cycle
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付加
CO2
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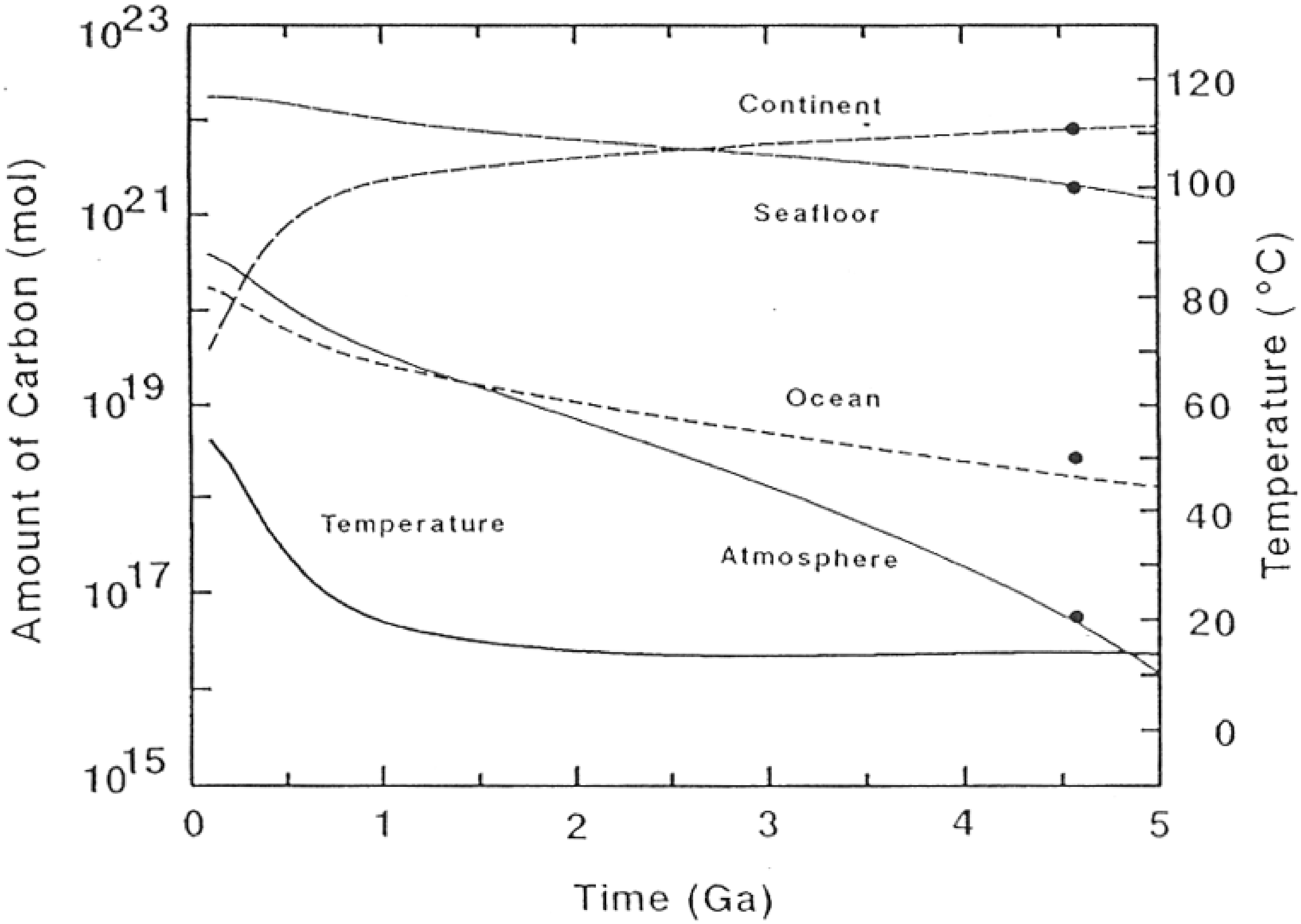
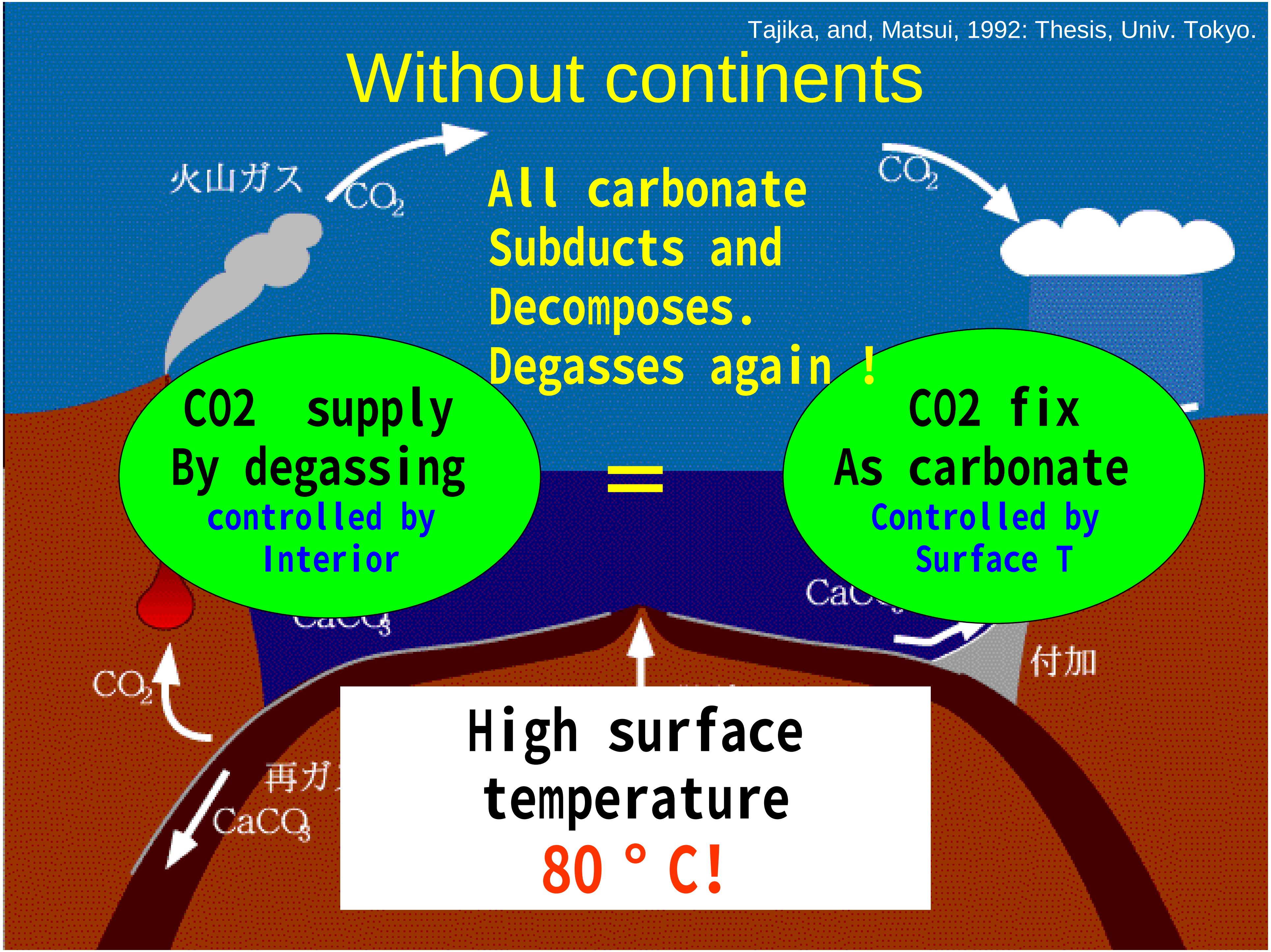
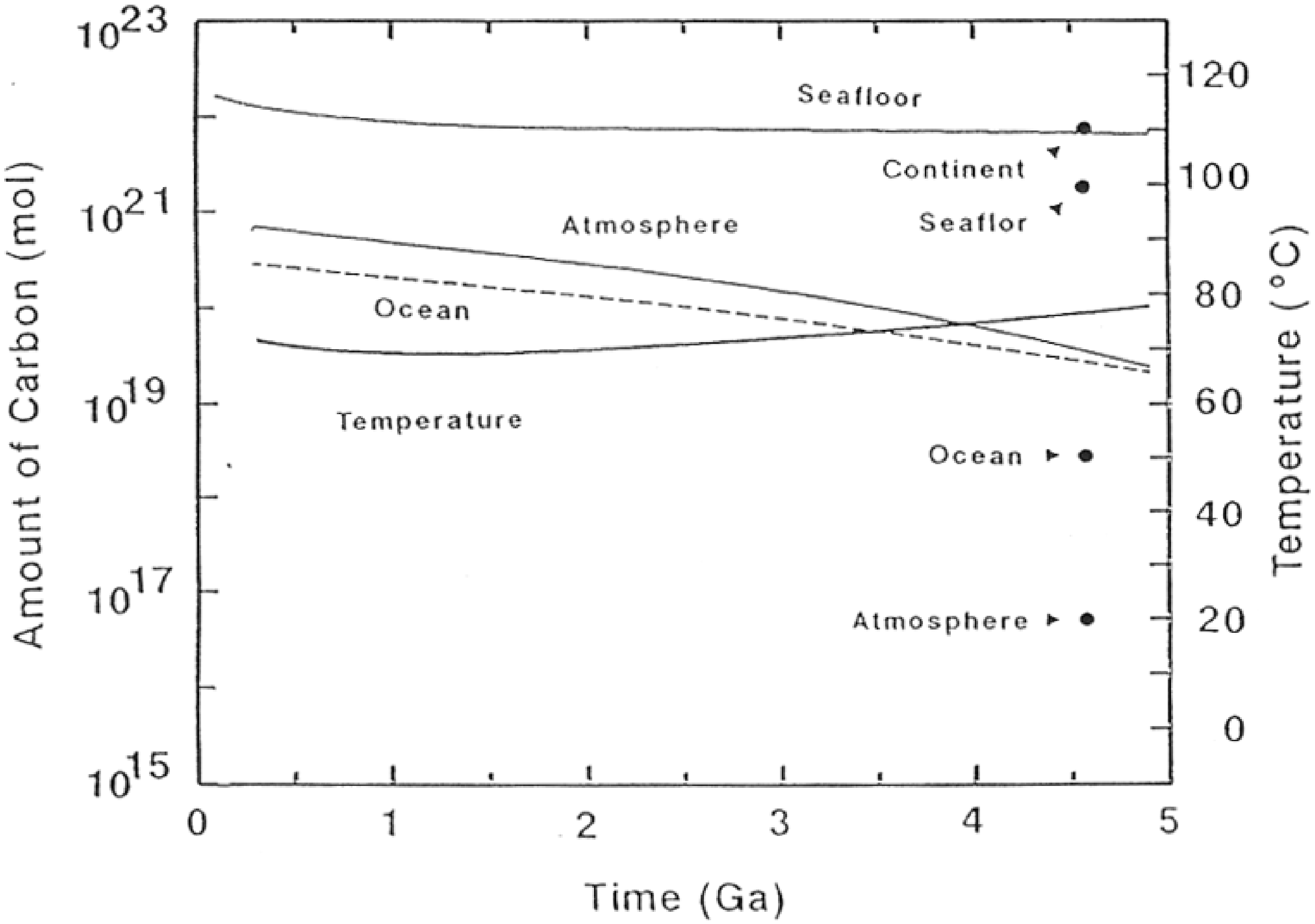
Surface temperature
is controlled by
planetary interior



Tajika&Matsui, 1990; Tajika, 1992


Tajika, and, Matsui, 1992: Thesis, Univ. Tokyo.
Without continents
All carbonate
Subducts and
Decomposes.
Degasses again !
火山ガス
CO2
CO2
CO2 supply
By degassing
controlled by
Interior
=
CO2 fix
As carbonate
Controlled by
Surface T
付加
CO2
CaCO3
High surface
temperature
80°C!

Without Continents



Tajika&Matsui, 1990; Tajika1992

Importance of planetary interior

Degassing from planetary interior is crucial .

Continents play important role in determining the environment .

Continuously Habitable Zone

Zone **の内側限界**：H2O**の散逸**
暴走限界
Zone **の外側限界**：CO2**の凝縮**
テクトニックな活動が活発で大きな脱ガスが維持される場合
現在の太陽系：0.95**ー**1.37AU
46**億年間**：0.95-1.15AU
(Kasting et al: Habitable zones around main sequence stars, Icarus, 101,108-128, 1993.)

4. Various Water Planets

Habitable Zone Limits for Dry Planets
Y. Abe, A. Abe-Ouchi, N. H. Sleep, and K. J. Zahnle
Submitted to J. Astrobiology

Problem of global average

Discussion using global average implicitly assumes an ocean-covered ‘aqua’ planet that has a large amount ofliquid water like the present Earth.

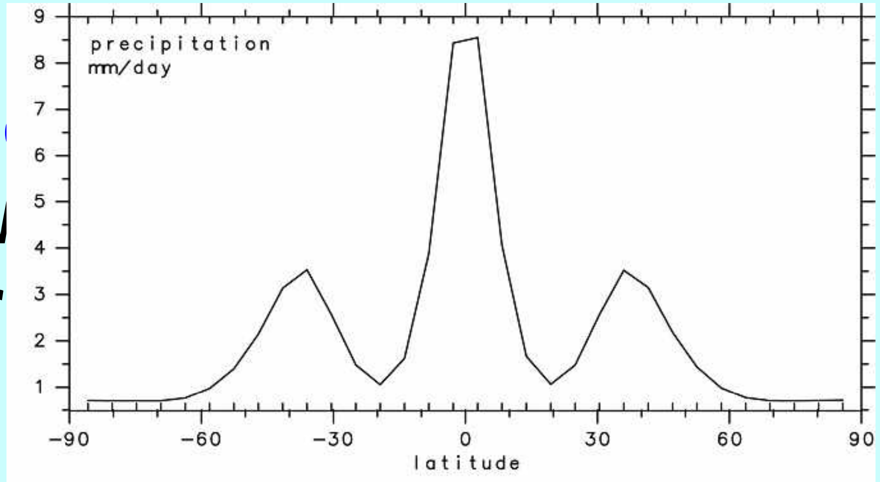
However, there is a possibility of a habitable ‘land’ planet that is covered by vast dry desert but has locally abundant water.
Ancient Mars might be in such a state.

Liquid water: limited by itself

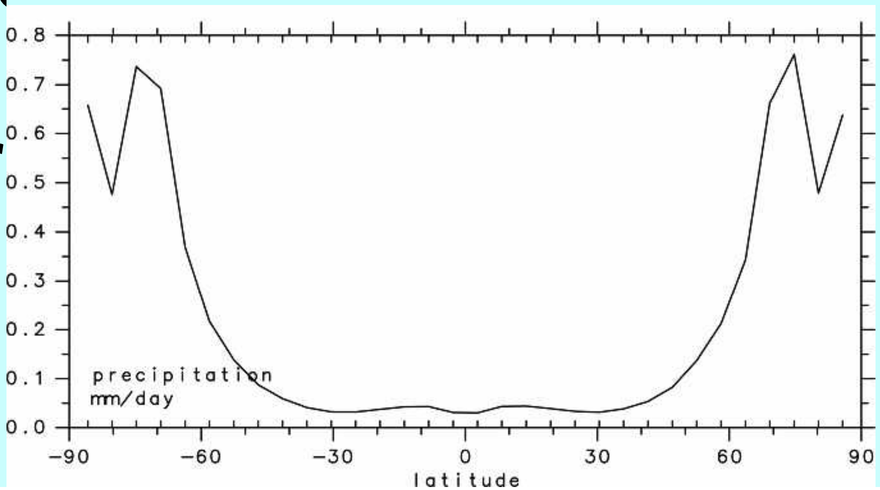
The conditions for the existence of liquid water can be different for a less water land planet from that of an aqua planet, because both
the ice-albedo feedback, which causes the complete freezing,
and the runaway greenhouse, which causes the complete evaporation,
are caused by the phase change of water.

Ocean planet and Land planet

Aqua Planet (ocean plan
A planet with a globally w
Precipitation and evapor



Land Planet:
A planet on which the su
is dominated by the atmo
et al., 2005).
Precipitation and evapor



榧根, 1980:
自然地理学講座(3) **水文学**, **大明堂**, 272pp.

Ocean planet and Land planet

Aqua Planet (ocean pla
A planet with a globally
Precipitation and evap
Earth like
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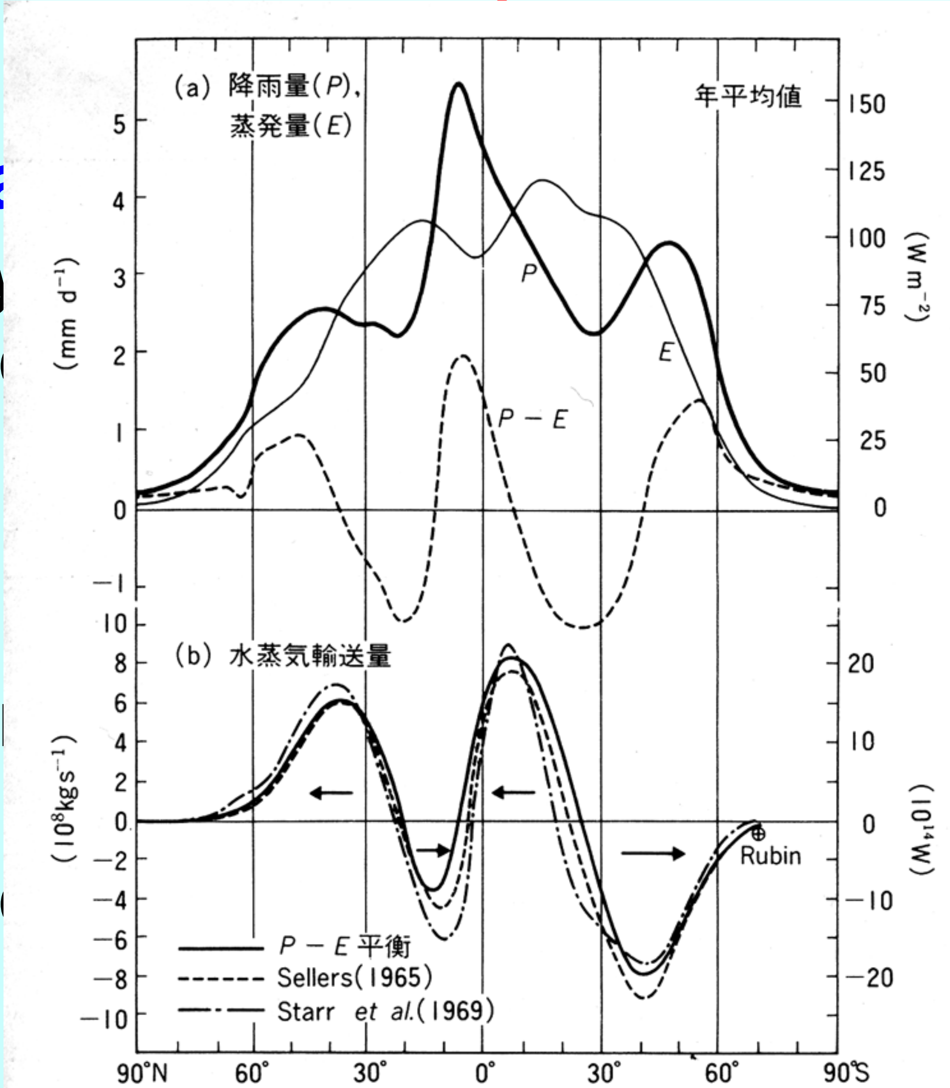


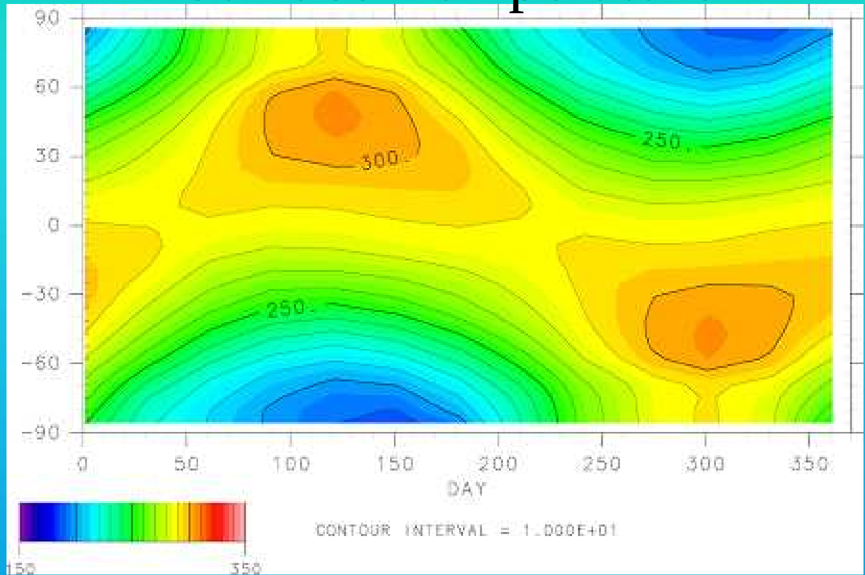
図 3. 20 (a)年平均でみた降雨量 (*P*) と蒸発量 (*E*) と *P*—*E* の南北分布. (b)水蒸気の南北輸送量, 実線は(a)図の *P*—*E* の分布を維持するのに必要な輸送量を求めたもの, 破線は Sellers (1965) による同様な見積り, 一点鎖線は Starr *et al.* (1969) による輸送量の計算値 (Newton, 1972).

Ocean planet and Land planet

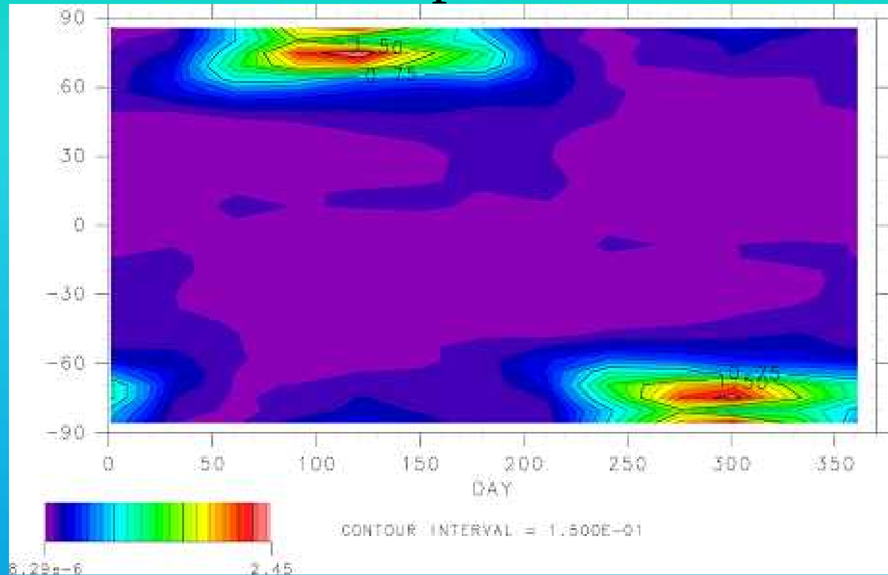
Aqua Planet (ocean planet):
A planet with a globally wet surface.
Precipitation and evaporation are not in balance
Earth like
Land Planet:
A planet on which the surface water distribution is dominated by the atmospheric circulation (Abe et al., 2005).
Precipitation and evaporation are in balance
Scattered lake, large desert
Dune planet (Herbert, F. (1965) *Dune*,)
Titan, ancient Mars?

Example of A Land Planet

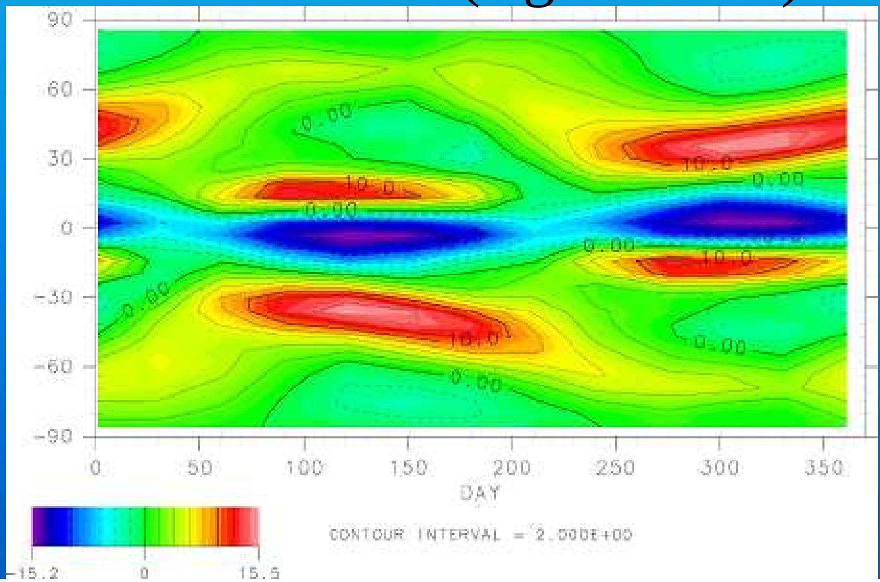
Surface Temperature



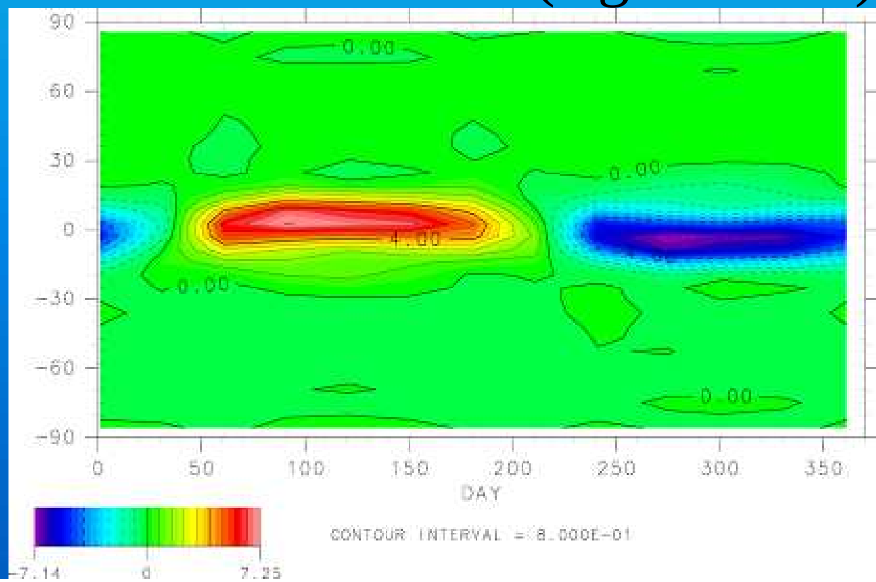
Precipitation



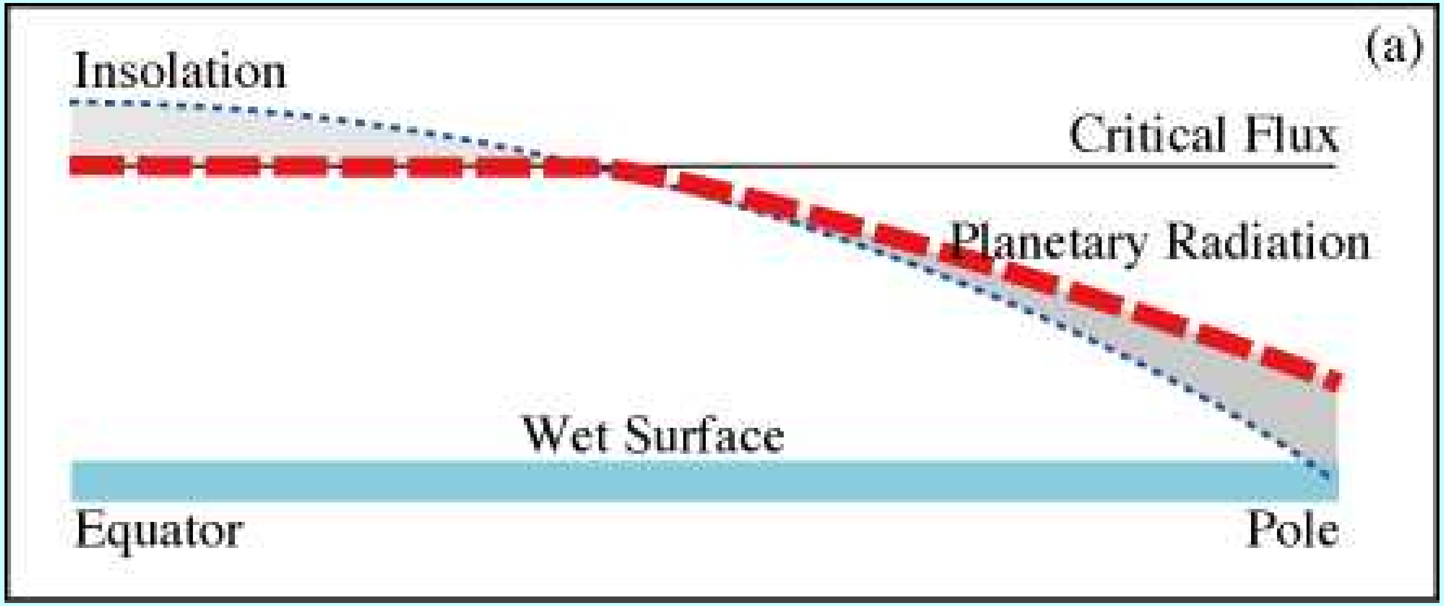
Zonal Wind (sigma=0.81)



Meridional Wind (sigma=0.81)



Runaway greenhouse of an ocean planet

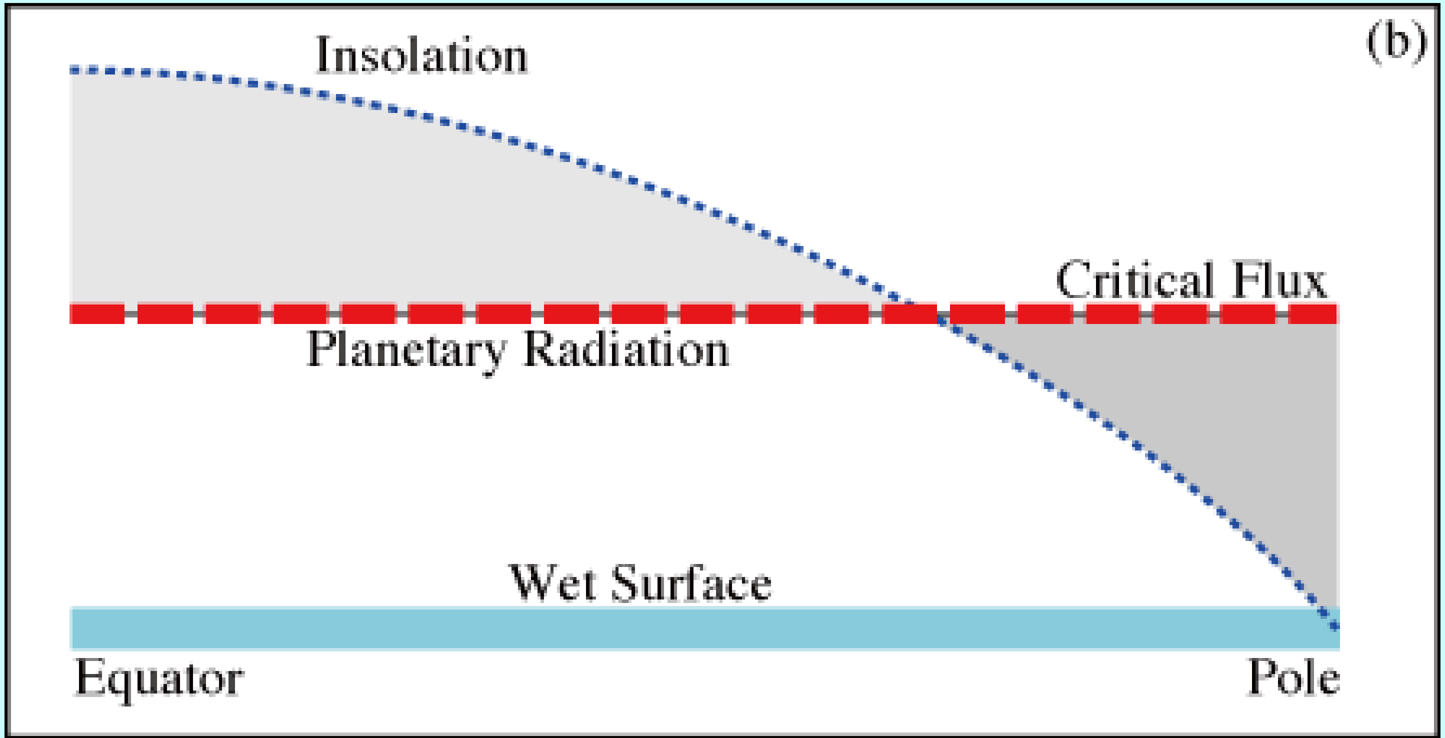


Global average insolation below the critical flux

Even if the insolation at the low latitude is above the critical ,
High latitude emits the excess

Present Earth is in this state

Runaway greenhouse of an ocean planet

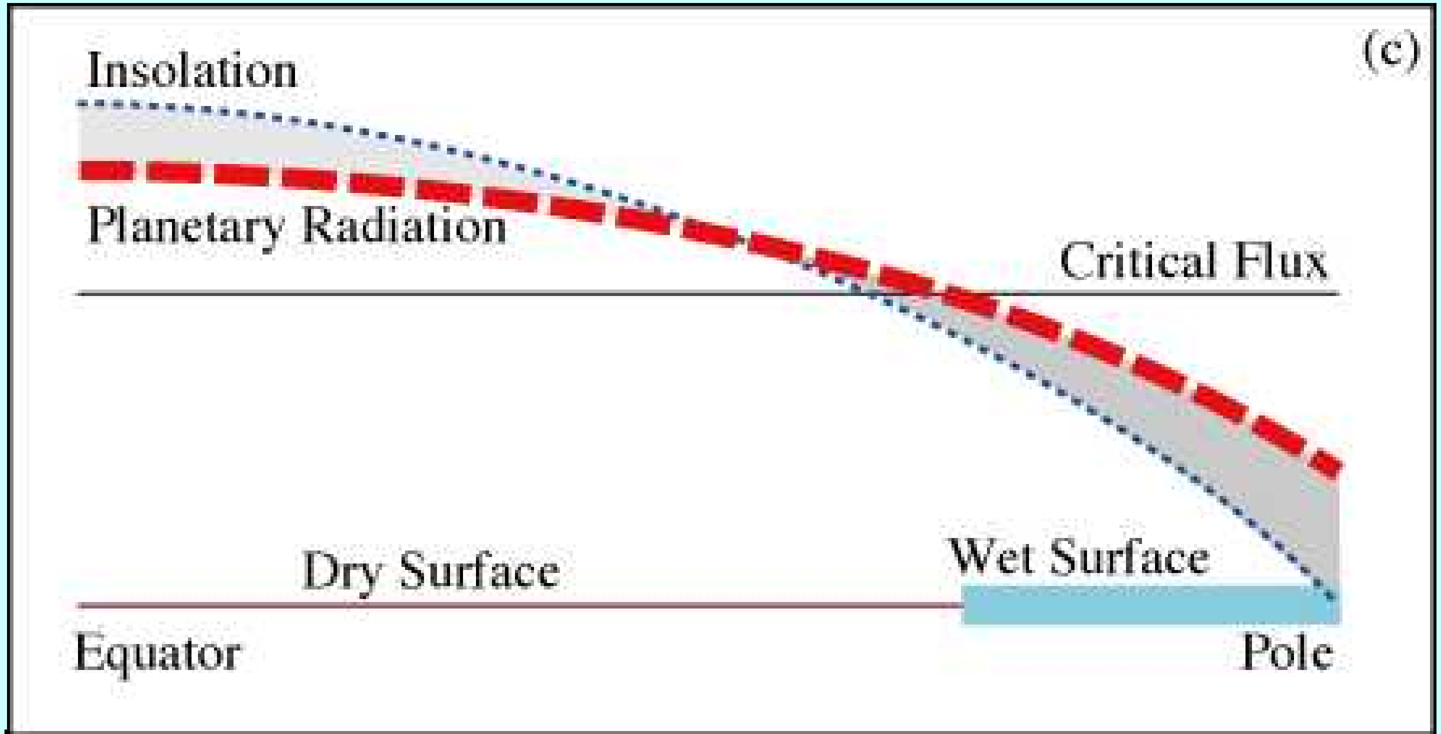


Global average insolation above the critical flux

Planetary radiation cannot exceed the critical
Energy balance cannot be achieved

Runaway

Runaway greenhouse of a land planet

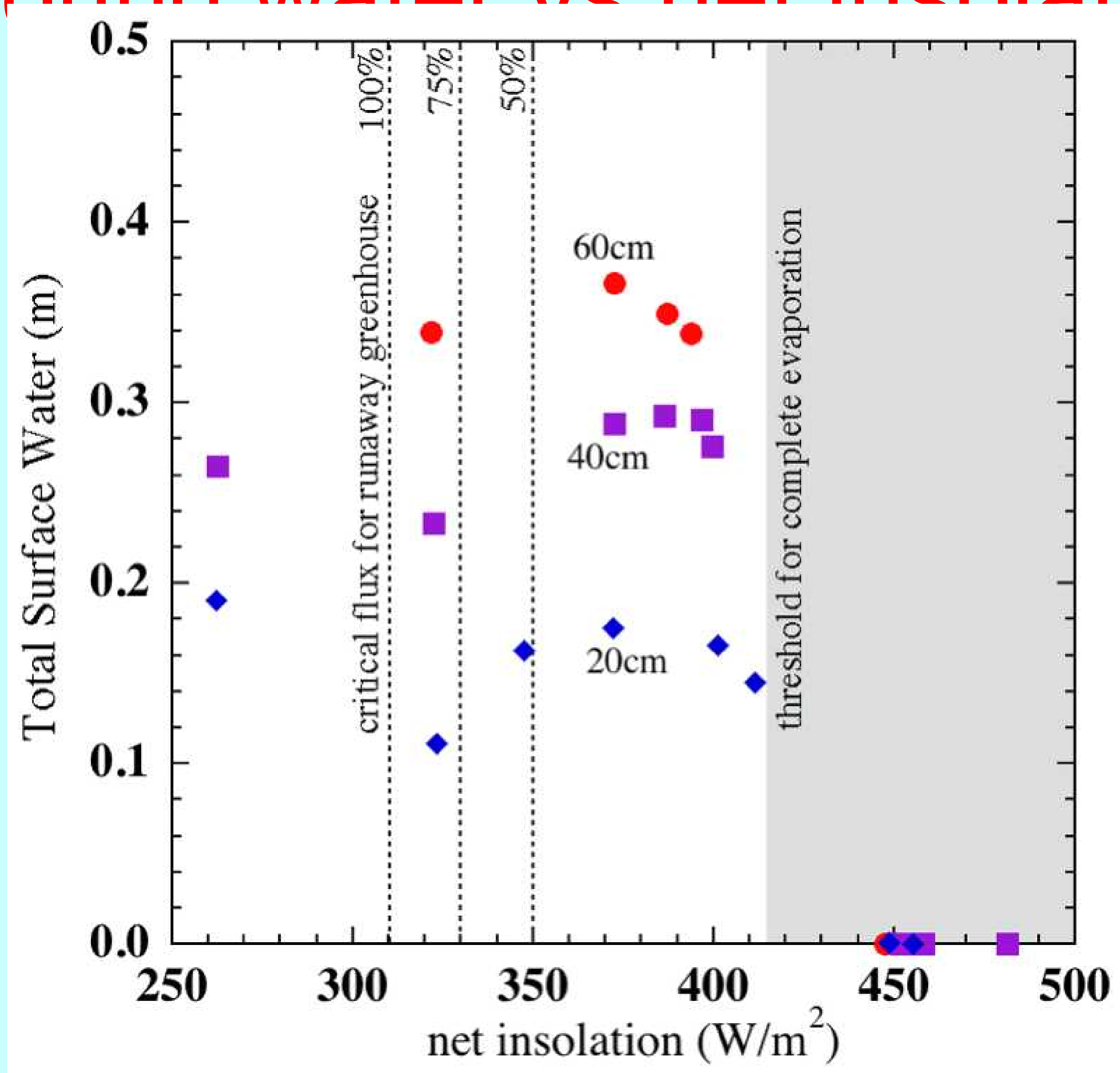


Global average insolation above the critical flux

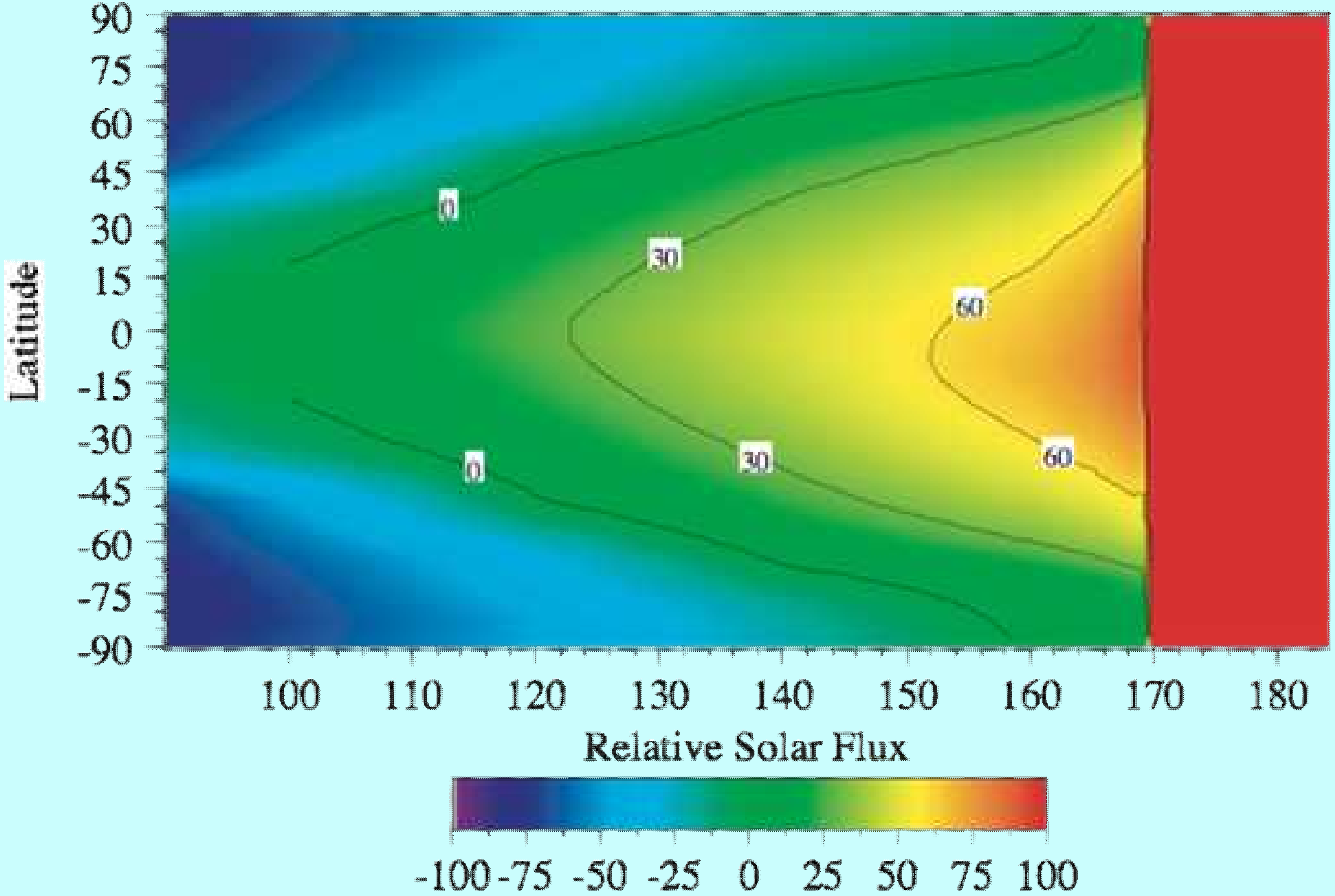
Dry low latitude can emit above the critical ,
High latitude is below the critical

Water can exist at high latitude

GCM result : Ground water vs net insolation



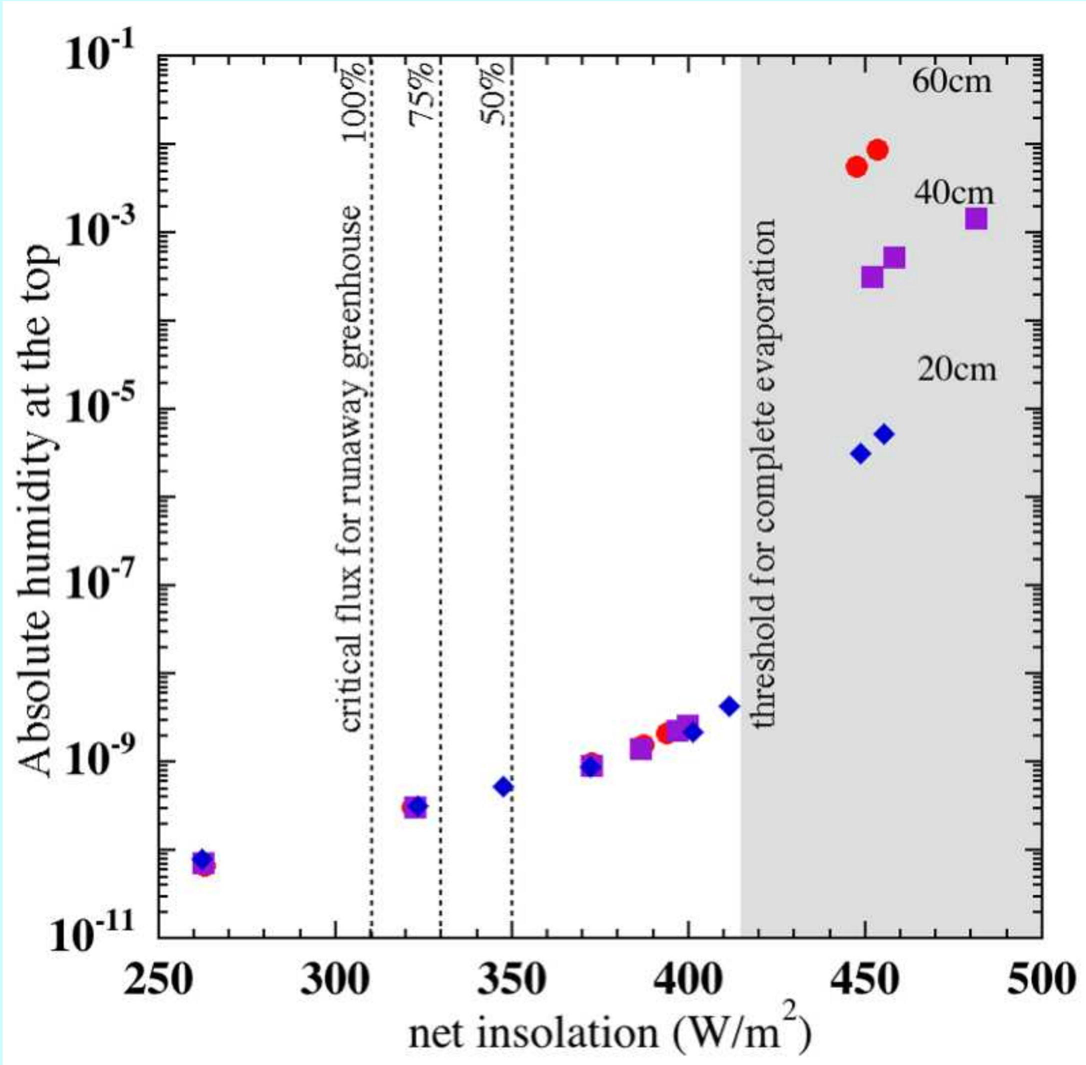
Surface temperature vs relative insolation



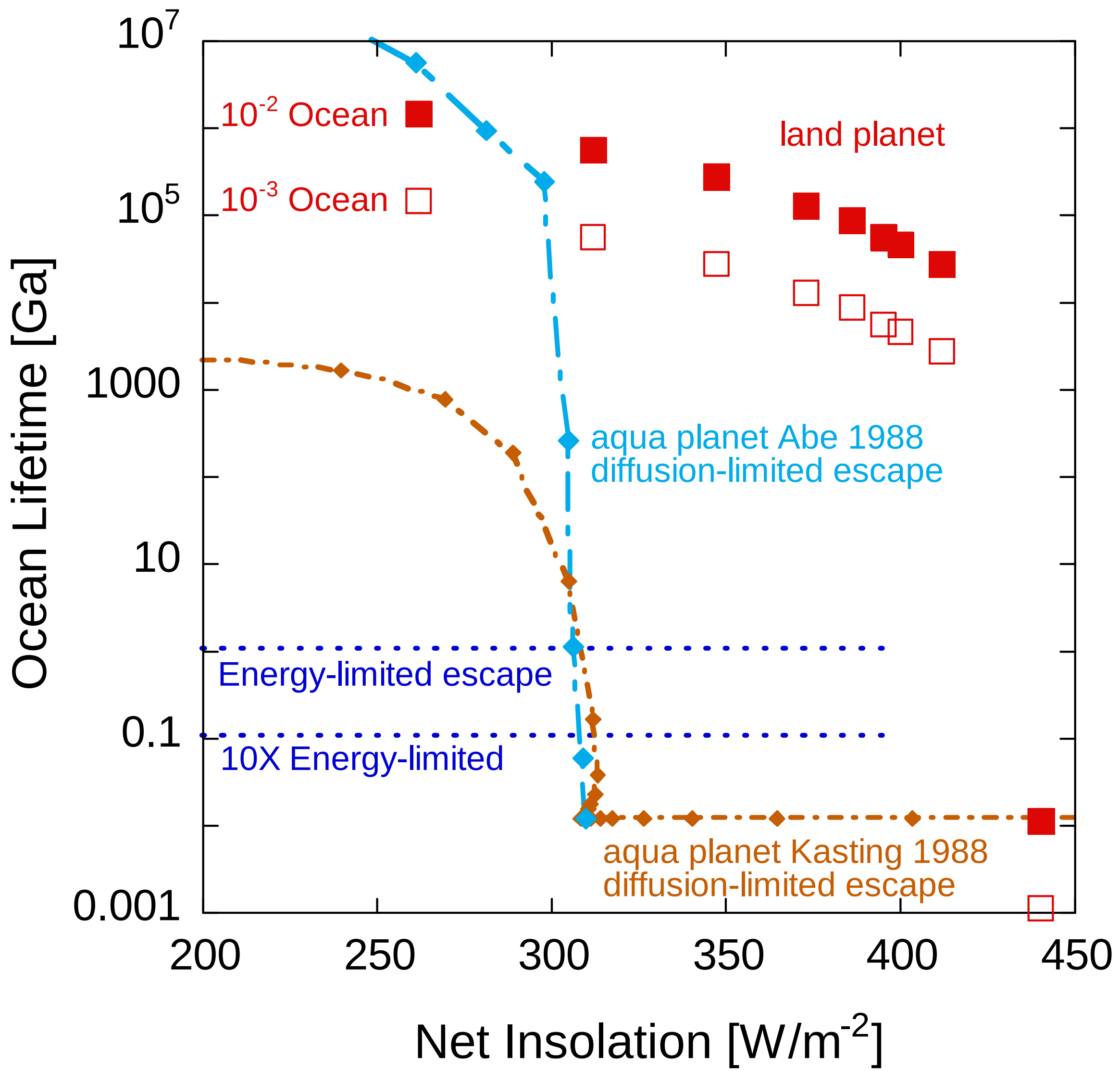
Water content in the upper atmosphere

成層圏上部の水蒸気量は極端に小さい：非常にわずかな水の量（平均1mm）でも長期間安定に存在できる

The water content in the upper atmosphere is extremely small.

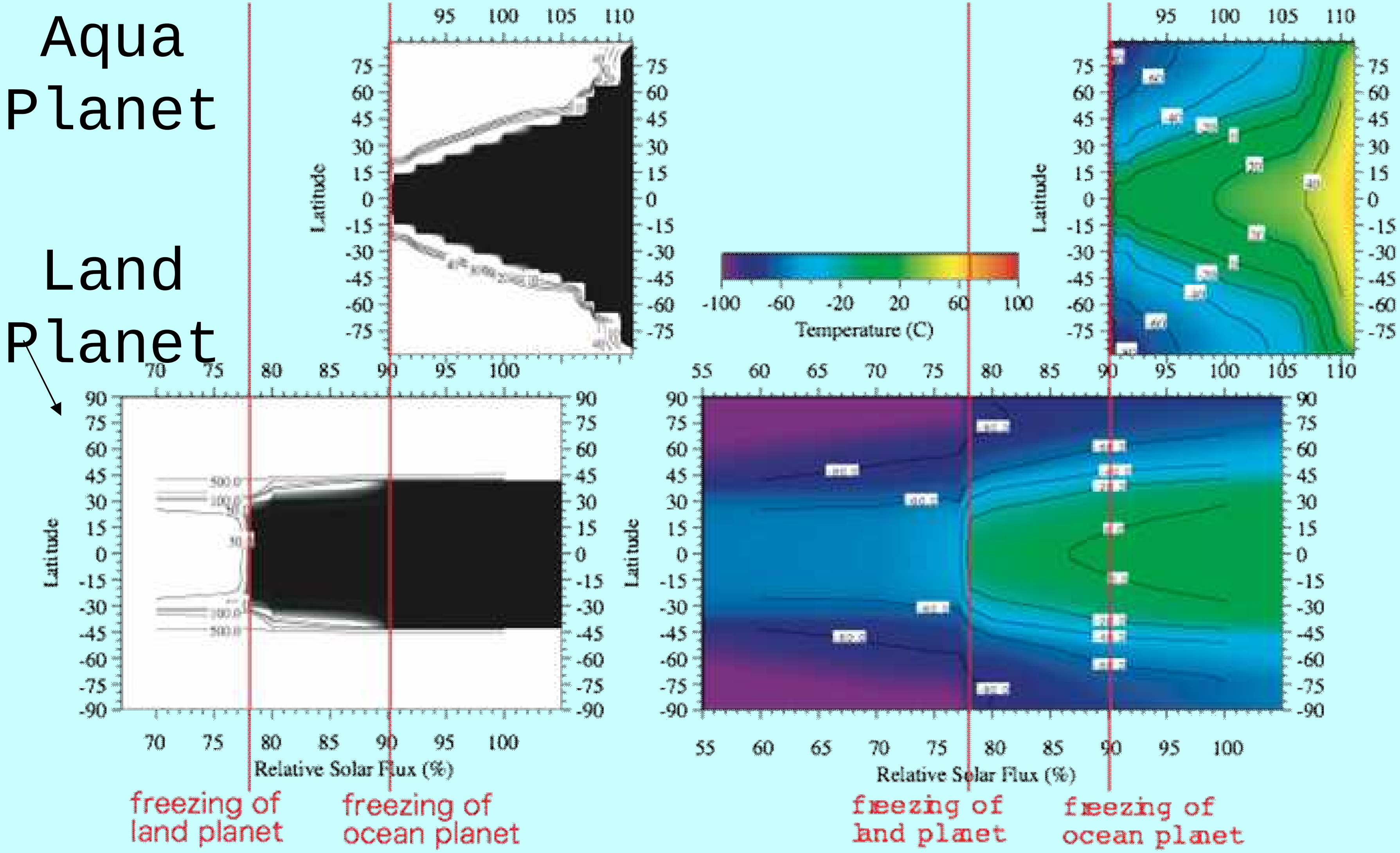


The lifetime of water on the surface



The lifetime of water on the surface of the land planet is longer than that of the aqua planet.

Freezing limit

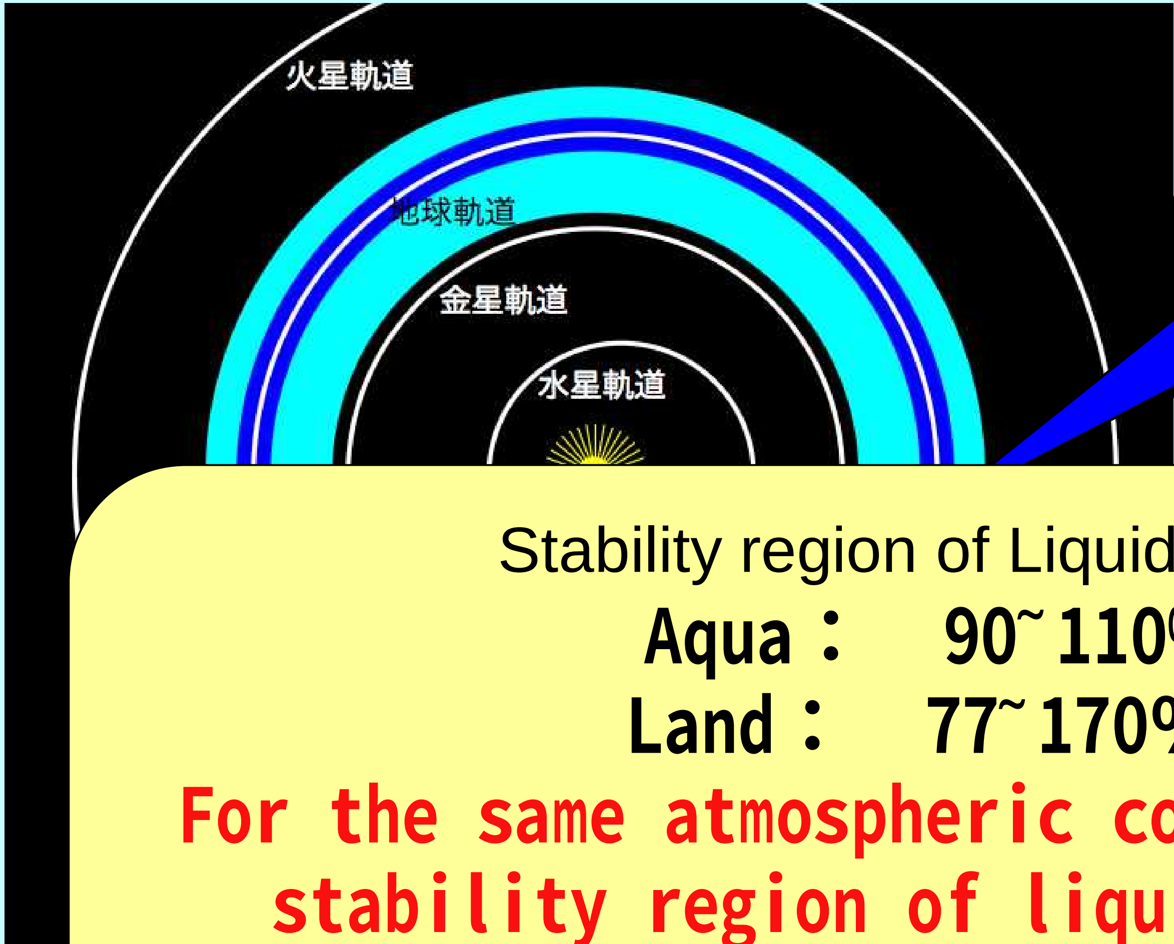


The freezing limit (of solar flux) is smaller on land planet than on aqua planet.

阿部, 1993:

惑星の科学, **朝倉書店**, pp. 227.

Land Planet vs Aqua Planet



Stability region of Liquid water

Aqua Planet

Stability region of Liquid water

Aqua：	**90~110%**	**Land Planet**
Land：	**77~170%**	

For the same atmospheric conditions, the stability region of liquid water is narrower for Aqua planet than Land planet ~ by factor 3 !!

Various Water Planets

(1) Aqua Planet

1-1 Ocean (only) Planet:

Without continents, surface can be very hot

1-2 Ocean-Land Planet:

Earth-like

(2)Land Planet:

Dune Planet, ancient Mars?

The abundance of water is important!

Ocean-Land Planets: x0.1 ~ x10 earth ocean mass water


5. Supply of water

Water amount and Water Planet

H_2Oitself is very abundant

water is more abundant than rock

If we collect all water,

--> the planet should be like Uranus or Neptune.

Water planets

Only small amount of water is captured

Earth Ocean:only 0.027**%** of the Earth mass

10 x ocean mass ---> Ocean (only) planet

0.1 x ocean mass ---> Land Planet

Supply of water to planetary material

Supply of water to planets

---contained in the solid material

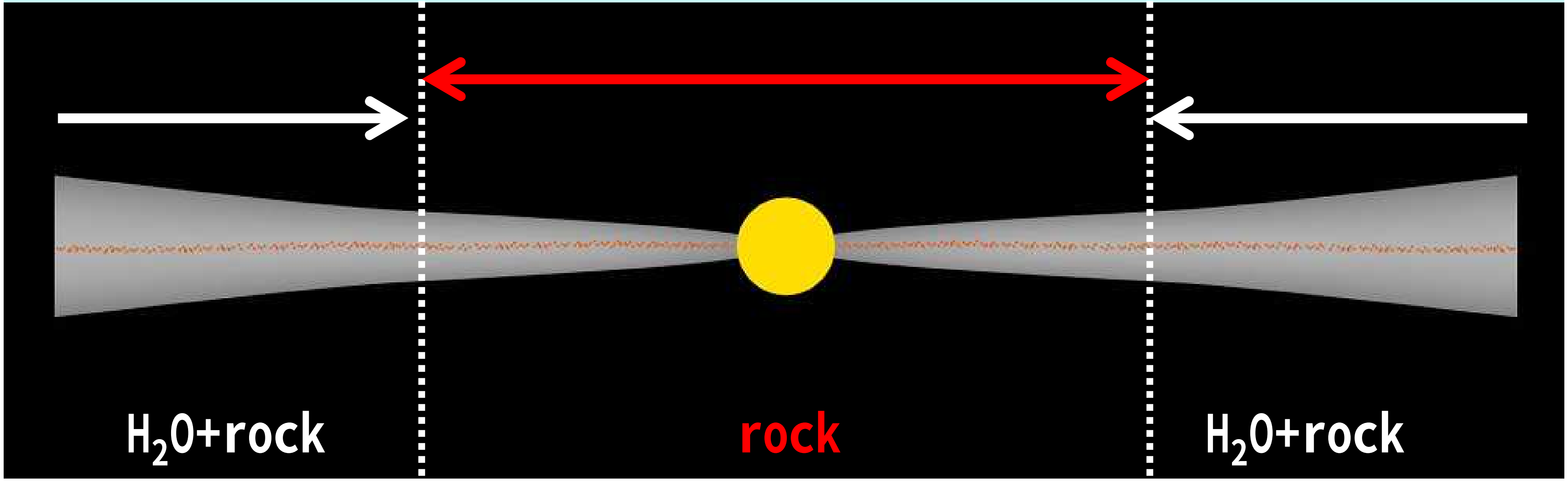
Solar nebula: low pressure, H_2O cannot be liquid

----> H_2O is taken in as ice at first

(Maybe reacted with rock later ---> Hydrous mineral)

This occurs beyond 2.7AU.

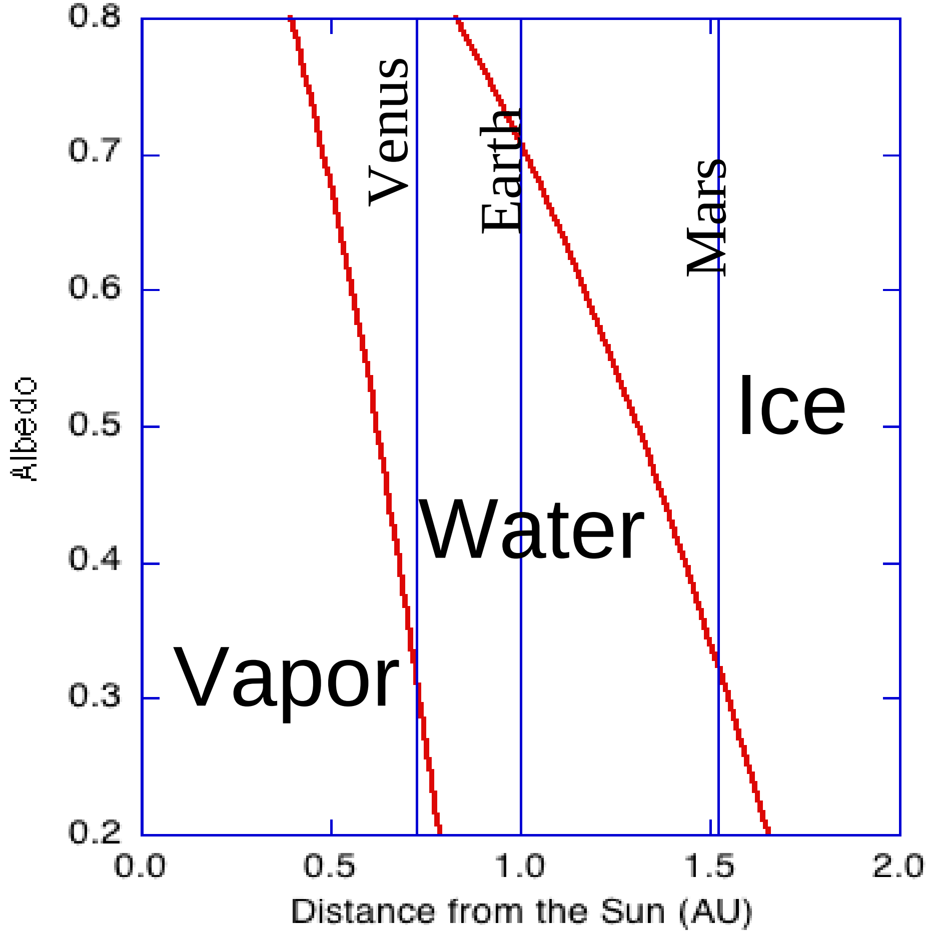
'Snow line' ~ 2.7AU



Stability of liquid water on planets

The region where H_2O is taken in the solid planet material (>2,7AU)
Is beyond the region where liquid water is stable on planets.
---> Transport mechanism determines water abundance on planets.
However, the mechanism is not clarified yet.

阿部, 2009, 日本惑星科学会誌「遊星人」.



Candidates of Water source

Not well constrained

1. Nebula Gas
2. Comets
3. Material of Asteroid belt
4. Planetesimal of earth orbit

In our solar system, 3 or 4 is likely.
However, in extra solar systems, any source will be possible. ---> Variety of water planets.

How to make a habitable planet

Unresolved

---> Major issues:
-Habitable planets other than water planets
-Variety of water planets
-Cause of Variety

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