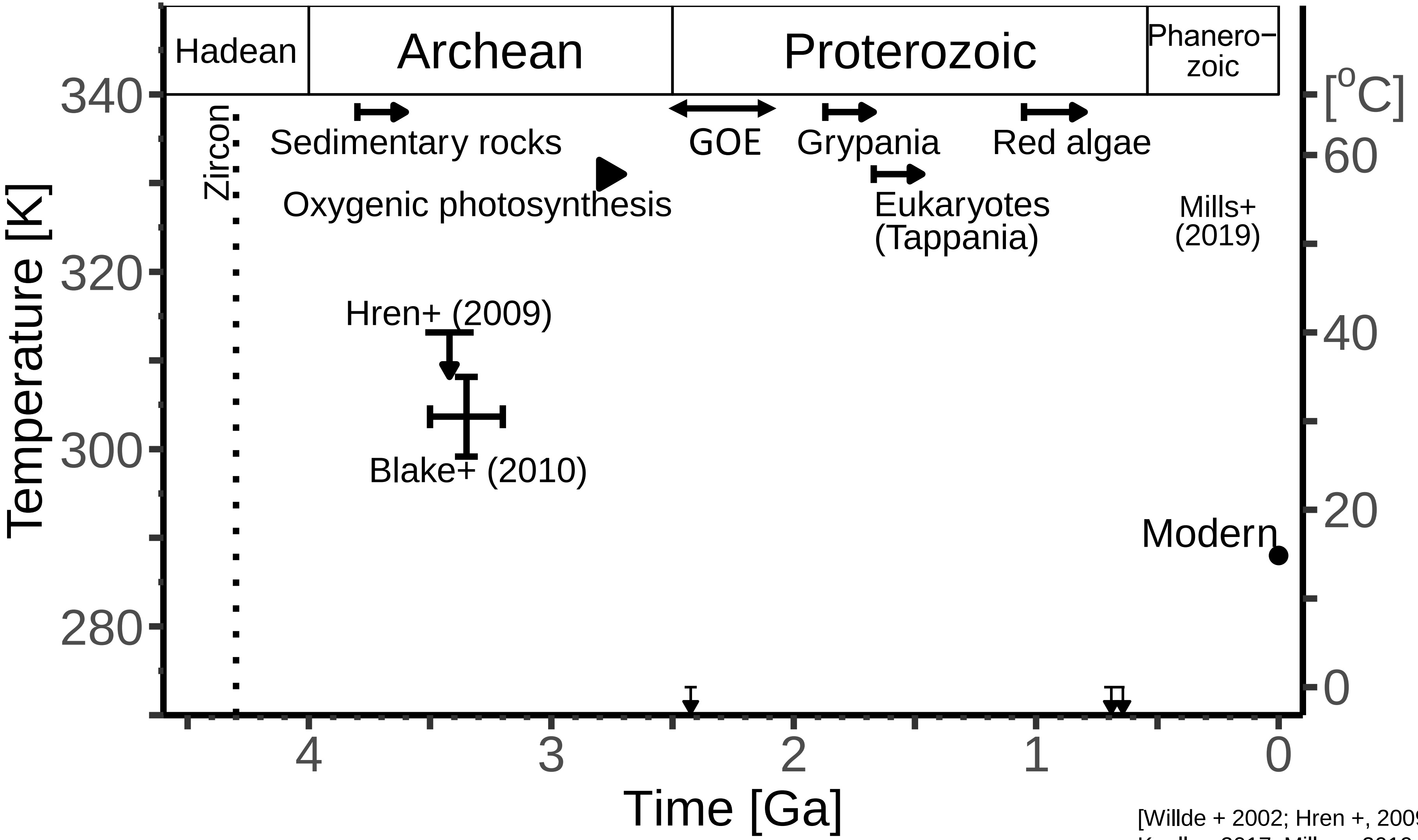
炭素循環に基づく
気候の安定性と長期進化

門屋 辰太郎
ELSI, 東工大

EARTH - LIFE SCIENCE INSTITUTE

Earth has kept warm climate.



[Willde + 2002; Hren +, 2009; Blake + 2010;
Knoll +, 2017; Mills +, 2019; Catling & Zahnle, 2020]

Temperature (~ possibility of liquid water),
Atmospheric and oceanic composition…

How does **the surface environment** evolve
to become and remain inhabitable
on the Earth and Earth-like planets.

A habitable planet ~ a planet with liquid water

[Kasting et al., 1993; Kopparapu et al., 2013]

S_0 = 1366 W/m^2

1.06 S_0 (~0.97 AU) ⟵ **Habitable zone** ⟶ 0.35 S_0 (~1.7 AU)

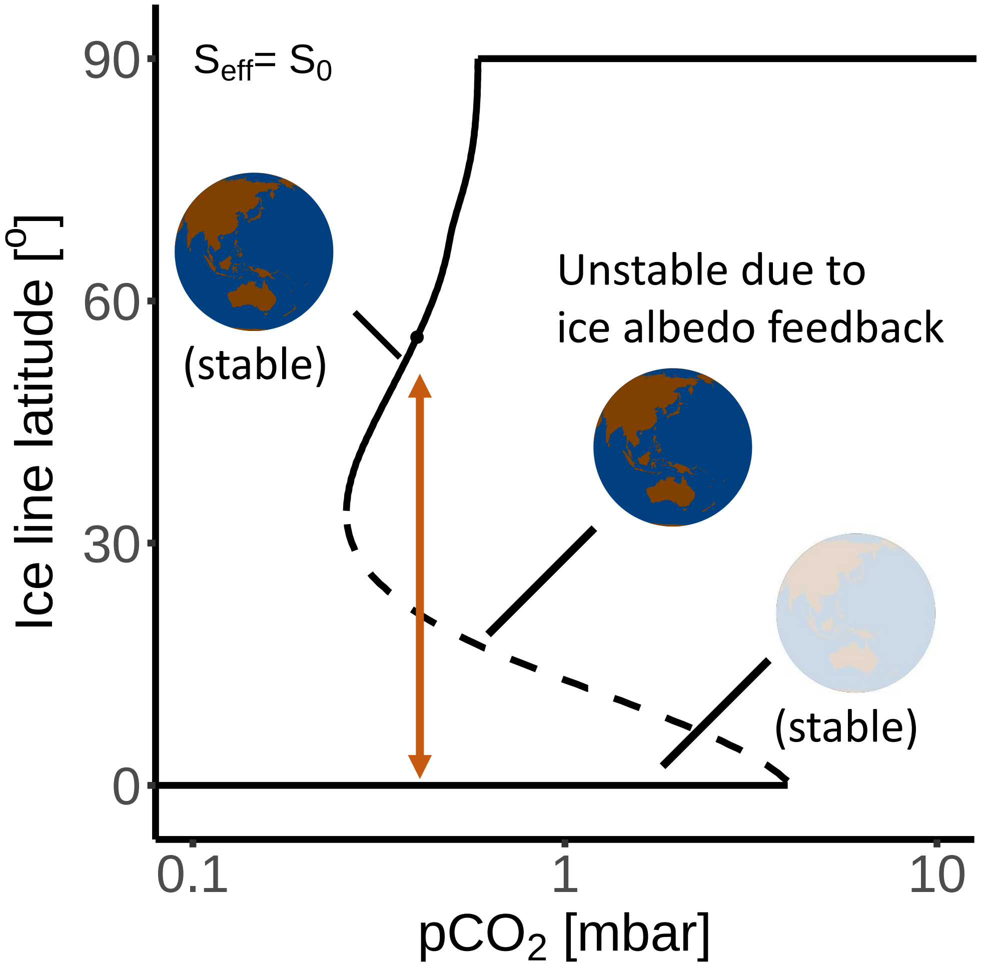
- Extremely hot
- w/o liquid H_2O

- Moderate (warm)
- w/ liquid H_2O (open ocean)

- Extremely (cold)
- Ice-covered ocean

Caution!
Without greenhouse gases like CO_2,
a planet within the HZ would be ice-covered.

Globally ice-covered state, as a stable climate state in HZ

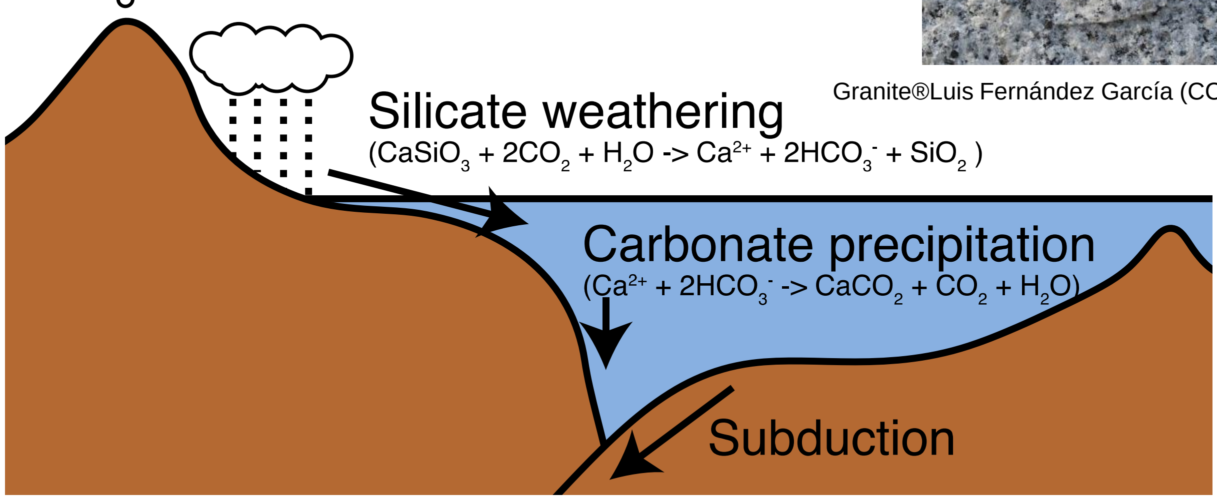


[e.g., North et al., 1981; Kirschvink, 1992; Tajika, 2003]

High albedo of ice-coverd surface

- makes a snowball state
  as stable as the warm state
  (i.e., partially or non-ice-covered state)
- requires a high atm. CO_2 level
  to escape from the snowball state

Carbon cycle as a thermostat for the surface environment



[e.g., Walker et al., 1981]

Silicate (e.g., granite)

Granite®Luis Fernández García (CC BY 2.5)

Quartz (SiO_2)

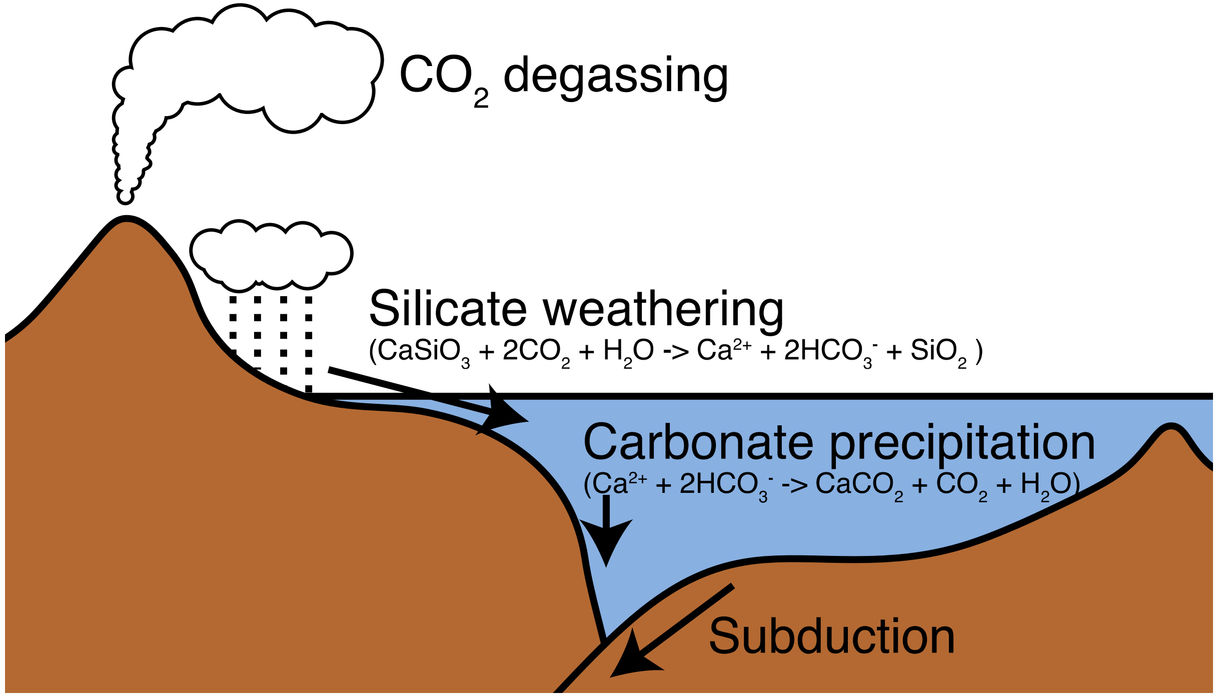
Quartz®Digier Descouens (CC BY 4.0)

Cray minerals (e.g., kaolinite)

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

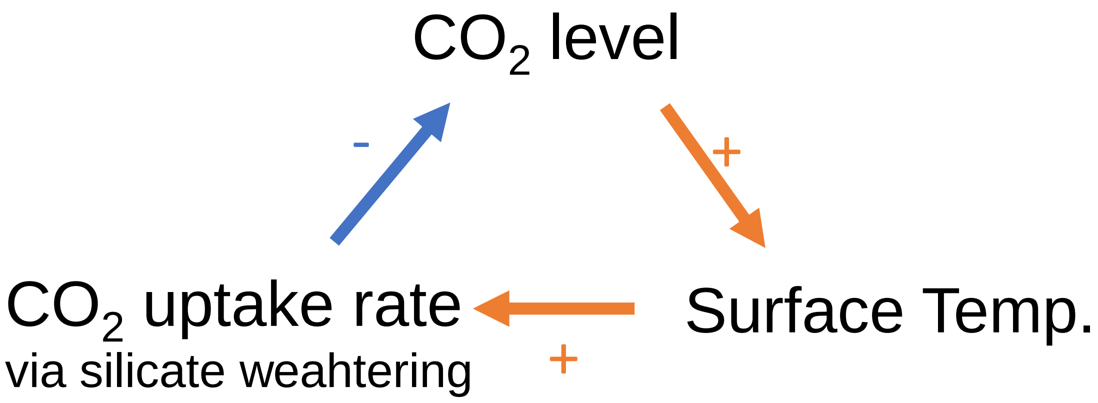
Carbonate (e.g., coral reef)

Carbon cycle as a thermostat for the surface environment

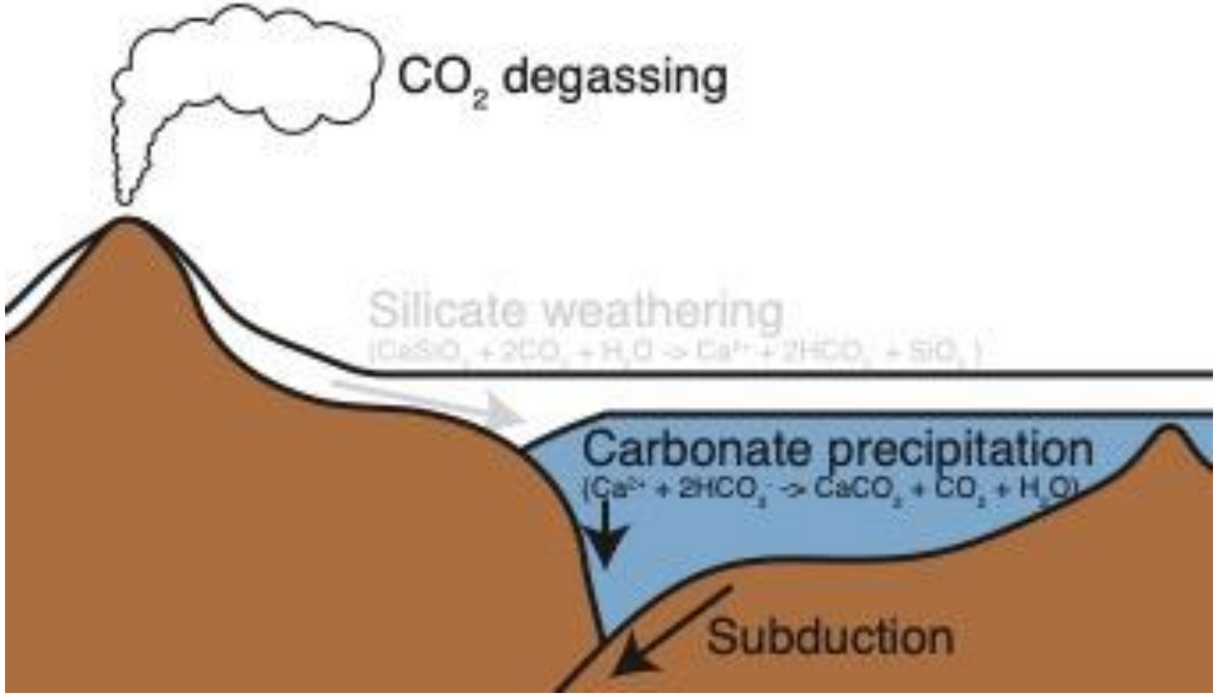


[e.g., Walker et al., 1981]

- **Negative feedback of the carbon cycle relaxes perturbations on the climate.**



Carbon cycle as a thermostat for the surface environment



[e.g., Walker et al., 1981]

A halt of weathering would increase atmospheric CO_2, leading to the melting of the global ice-sheet. [e.g., Kirschvink, 1992]

The carbon cycle would have contributed to maintain a warm climate state on the Earth throughout its history.

Question:

Does the carbon cycle always maintain a warm surface environment?

Model

[Kadoya & Tajika., 2014, 2015, 2016, 2019]

Input: Insolation (S) CO$_2$ degassing rate (F_D)

1D Energy Balance Climate Model

$$\frac{\partial T}{\partial t} = \left(1 - A_{(T,\ pCO_2)}\right) S_{(\phi)} - I_{(T,\ pCO_2)} + \frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left\{D\cos\phi\frac{\partial T}{\partial\phi}\right\}$$

S : Insolation, I : Planetary radiation,
A : Planetary albedo, D : Diffusion coefficient.

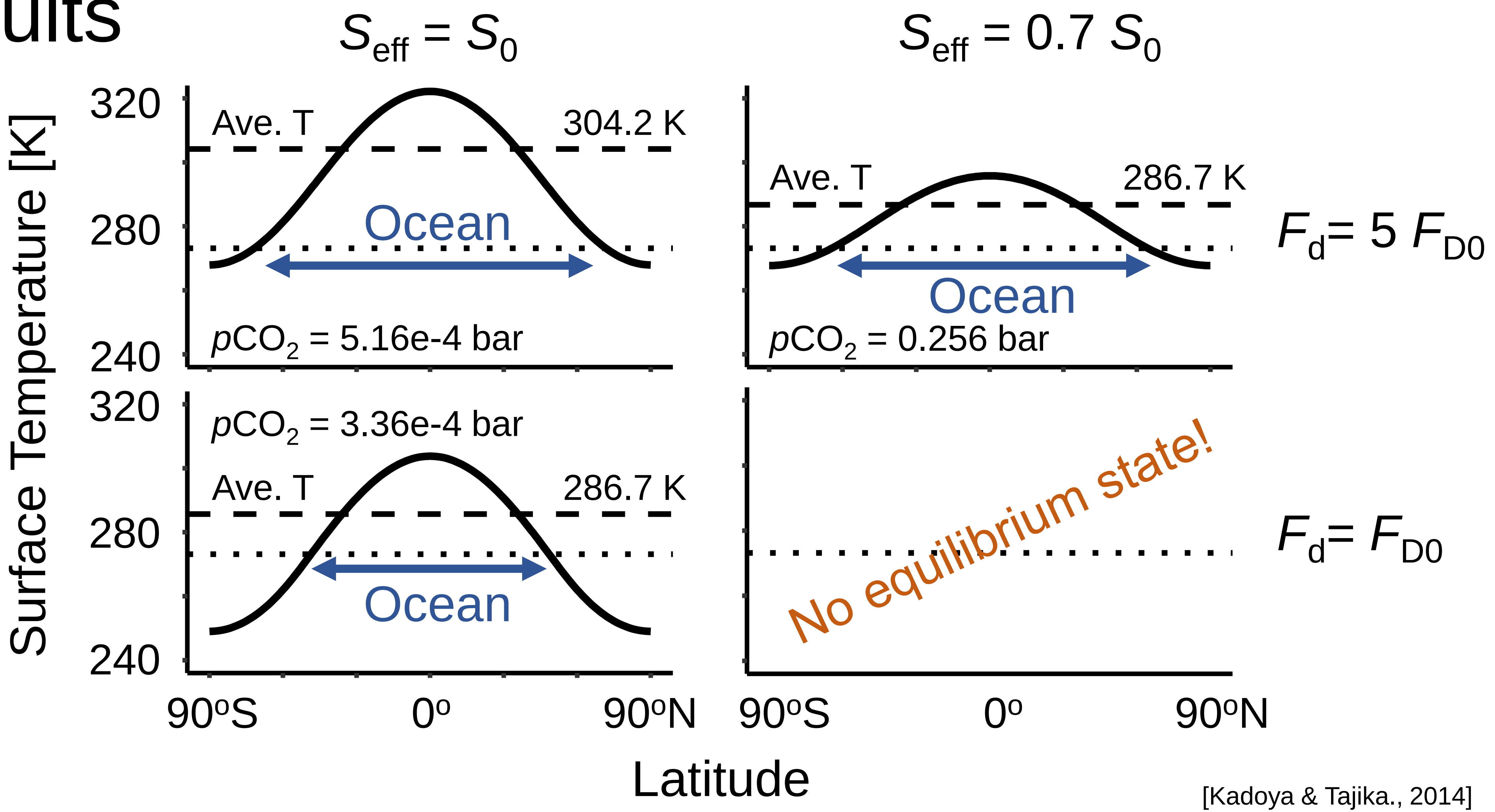
Carbon Cycle Model

$$\frac{\partial pCO_2}{\partial t} = F_D - W_{(T,\ pCO_2)}$$

F_D : CO$_2$ degassing via volcanic activity,
W : CO$_2$ consumption via silicate weathering.

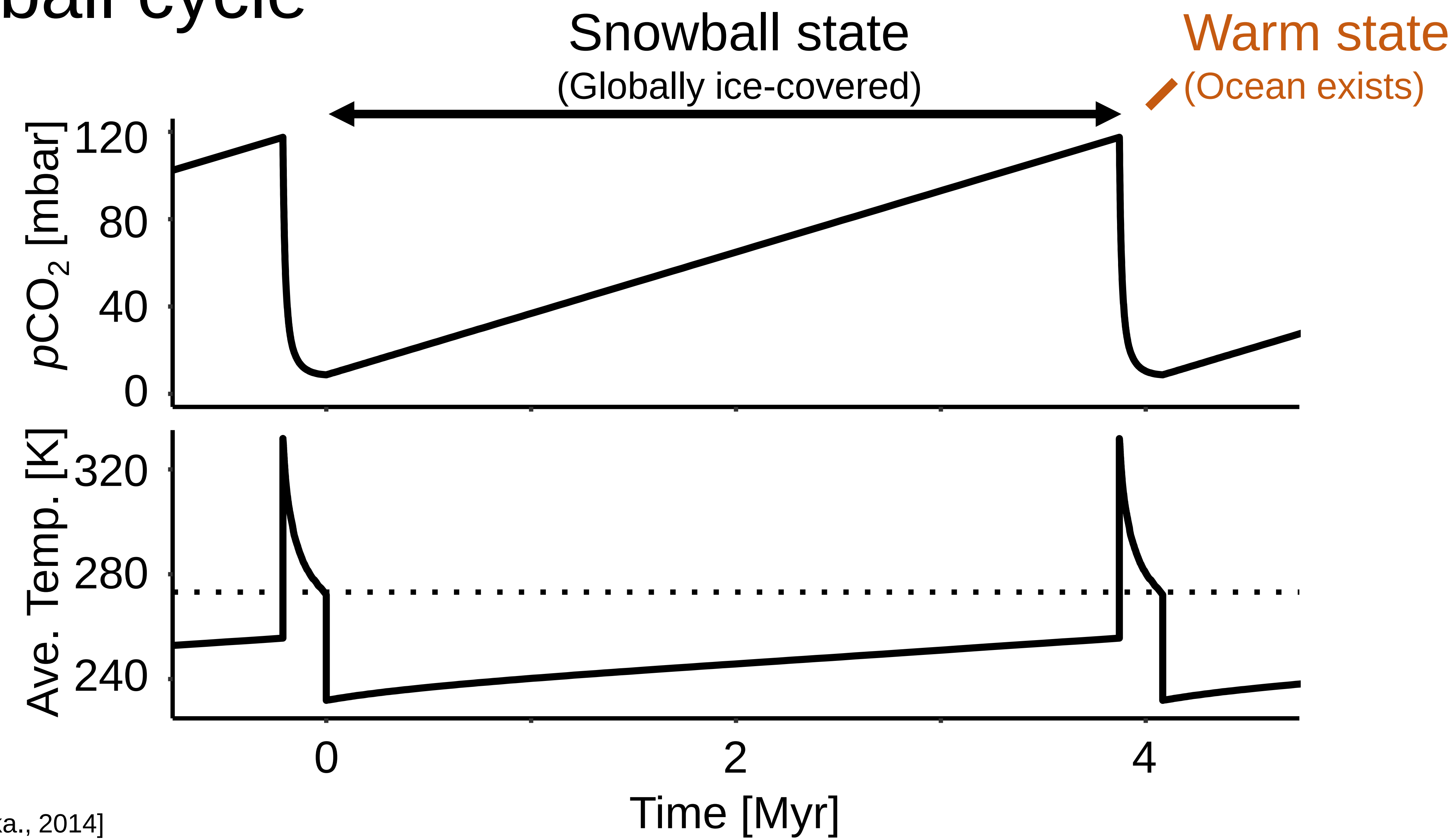
Output: Surface Temperature (T) Atm. CO$_2$ level (pCO_2)

Results



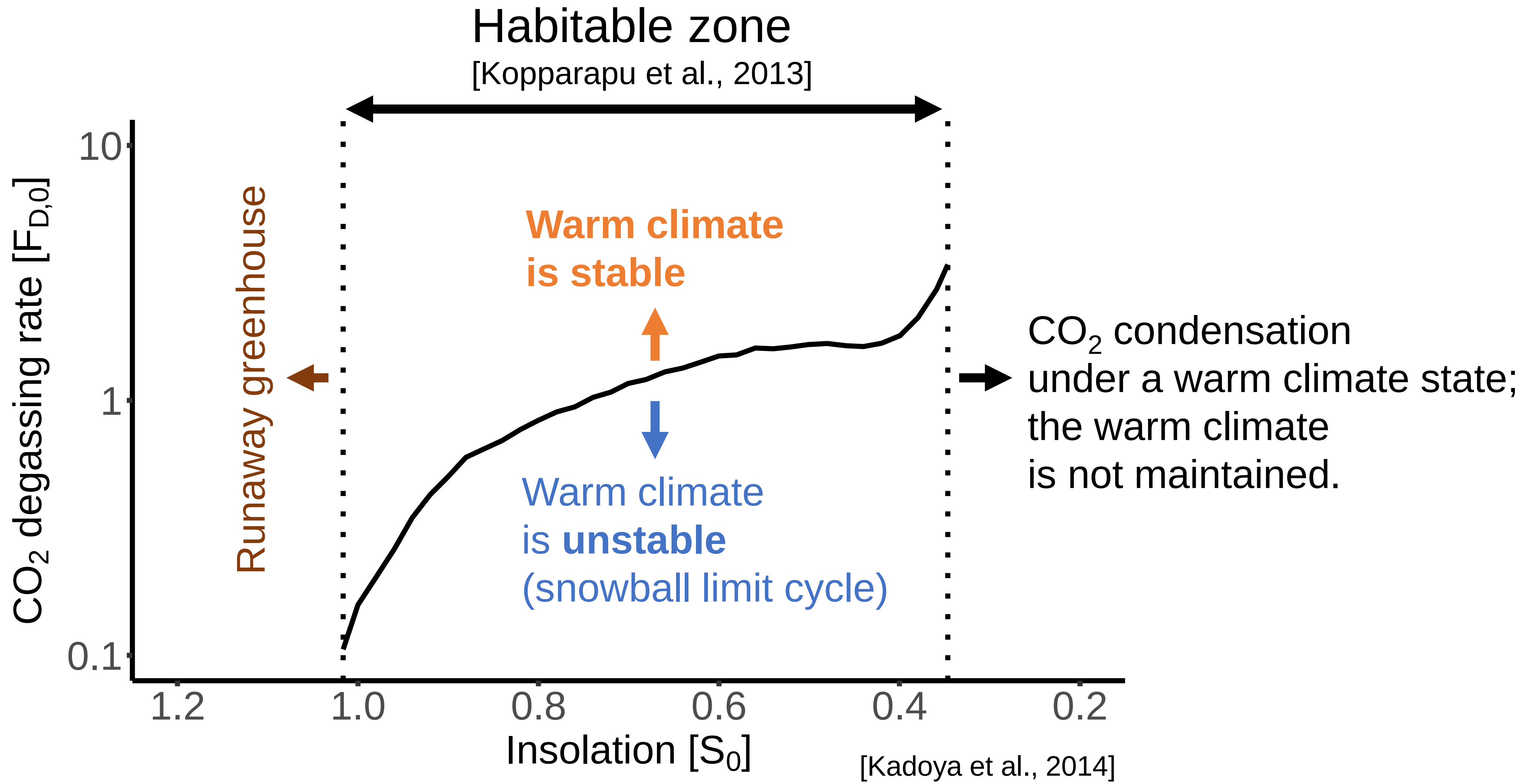
[Kadoya & Tajika., 2014]

Snowball cycle

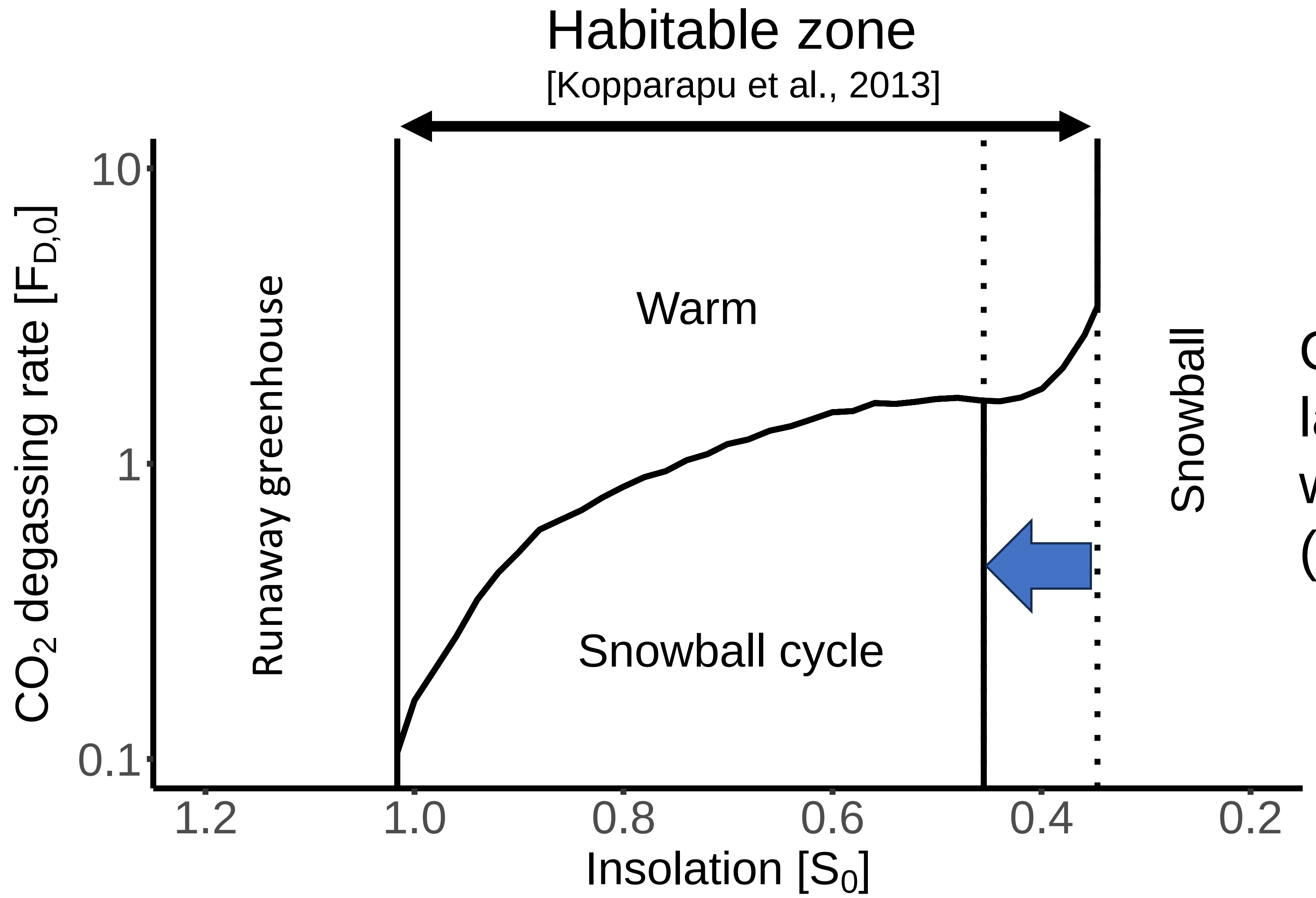


[Kadoya & Tajika., 2014]

Habitable zone and carbon cycle does not always result in a warm climate

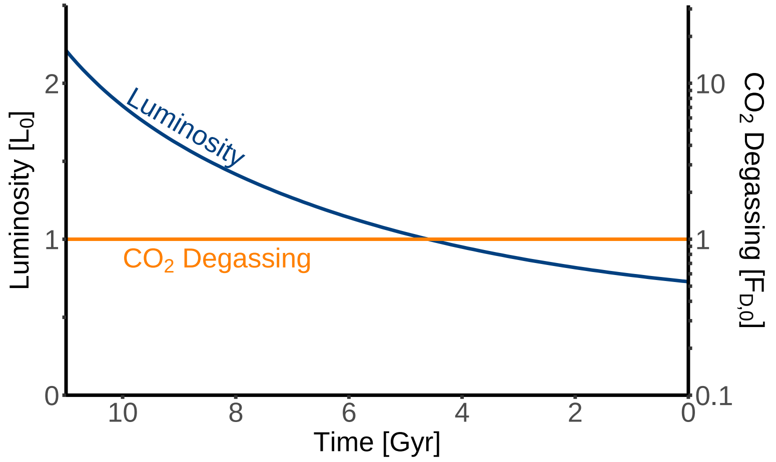


Outer limit of the HZ for a planet with weak volcanism



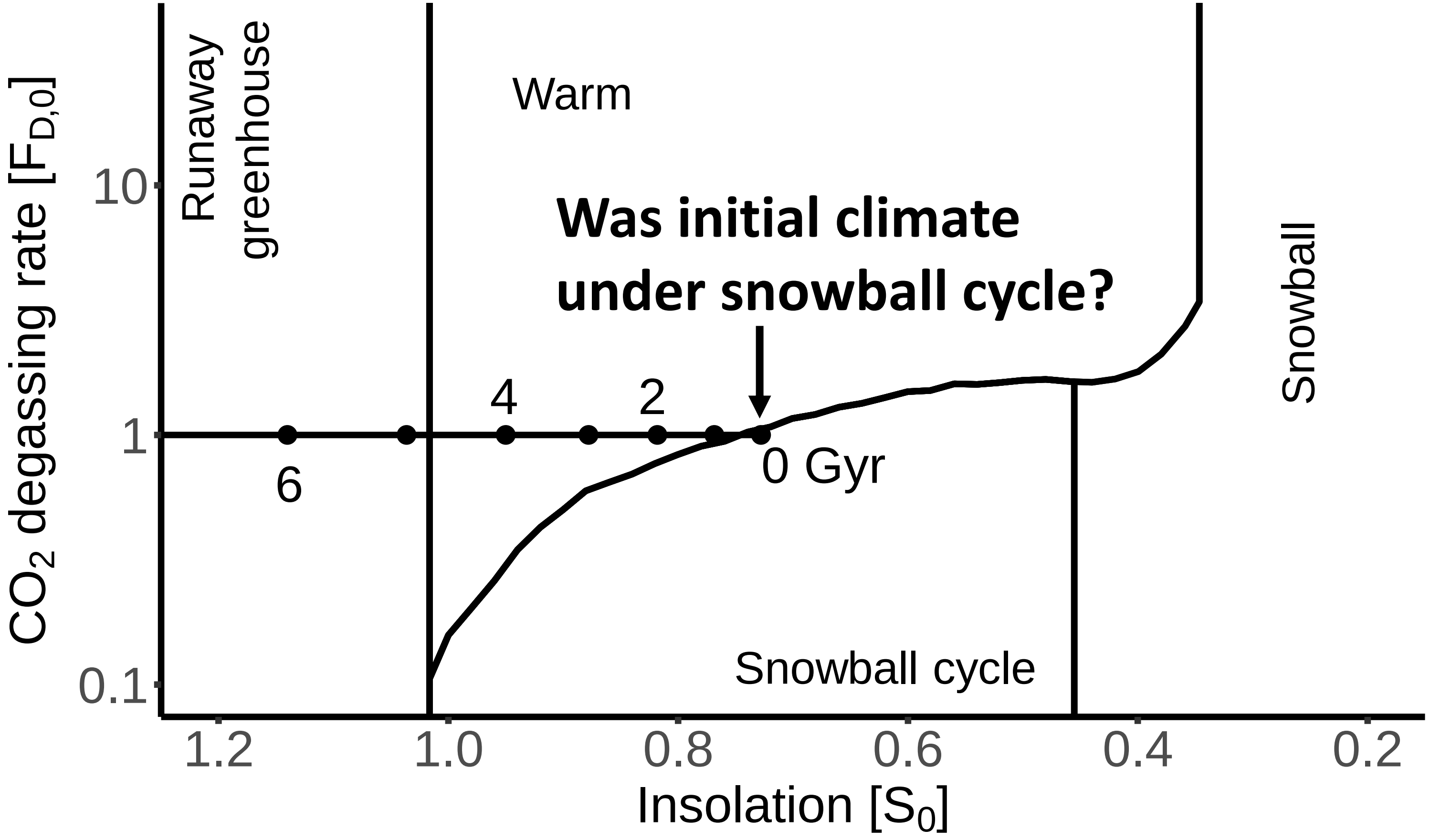
Outer limit of the HZ is larger for a planet with weak CO_2 degassing (i.e., volc. activity).

Evolution of the Earth's climate: Constant Degassing case

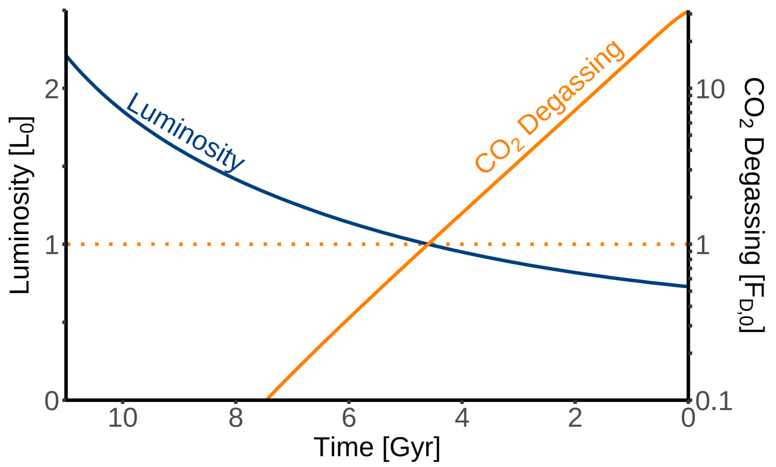


Luminosity increases.

[e.g., Gough, 1981]

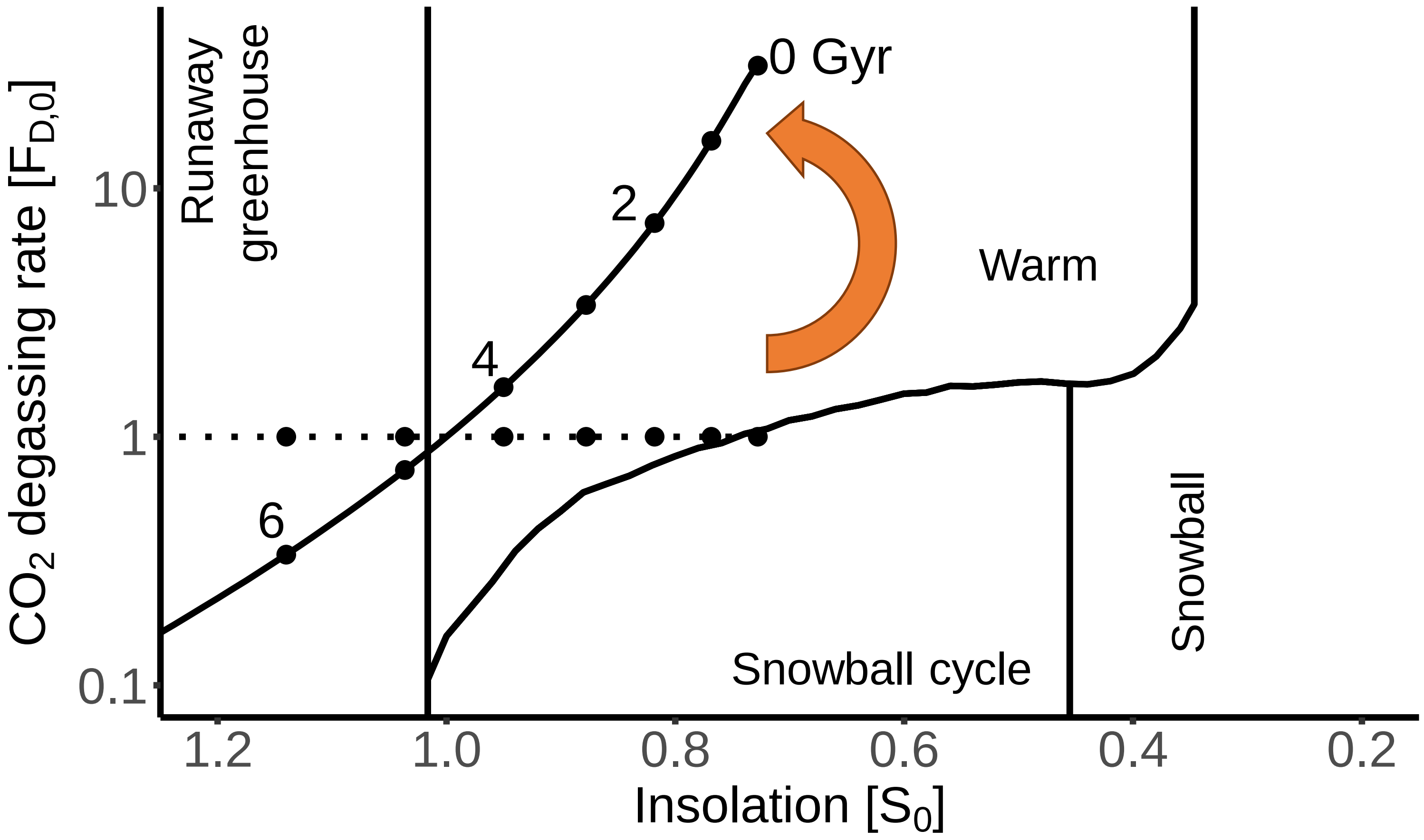


Evolution of the Earth's climate: Degassing evolution

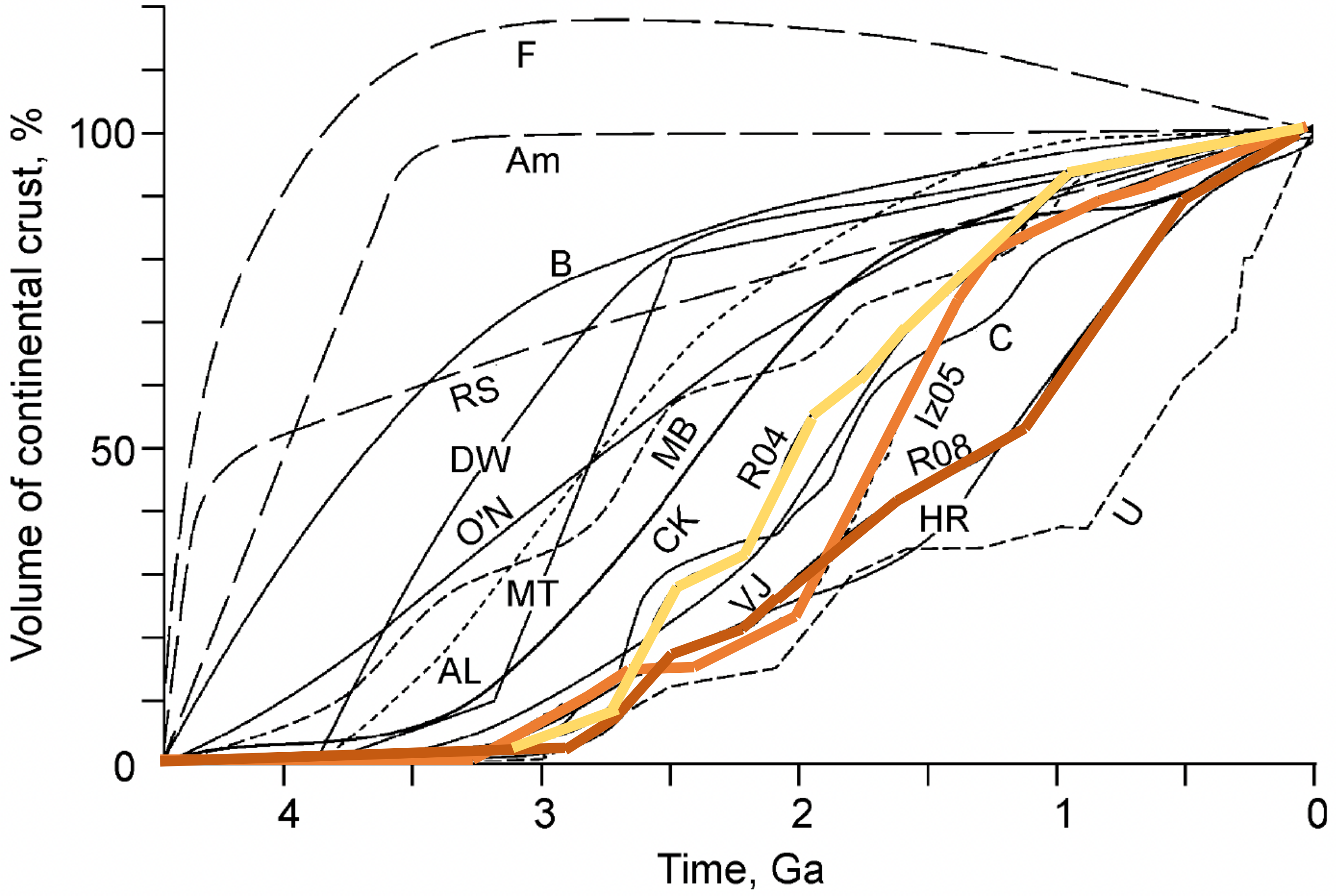


Volcanic activity would decrease. [e.g., Tajika & Matsui, 1992]

Planetary cooling, reducing volcanic activity, could cause a warm climate initially.



Evolution of the Earth's climate: Continental evolution

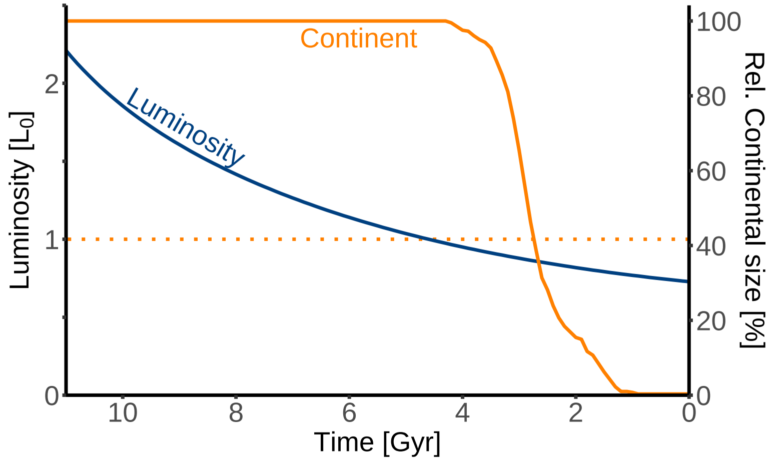


Small continent

Small CO_2 uptake via continental weathering

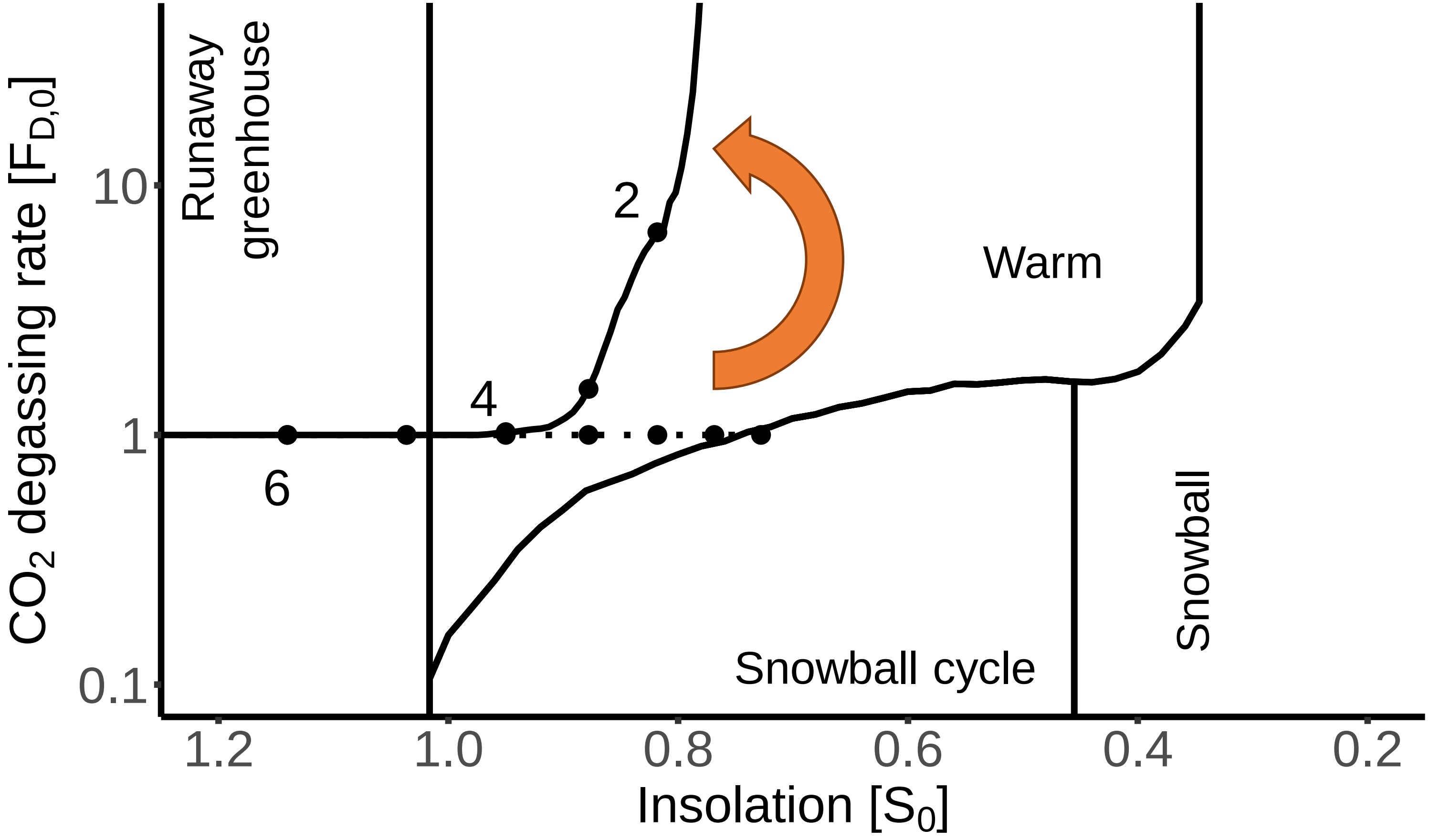
[Komiya, 2011]

Evolution of the Earth's climate: Continental evolution



Volcanic activity would decrease. [e.g., Iizuka et al., 2005]

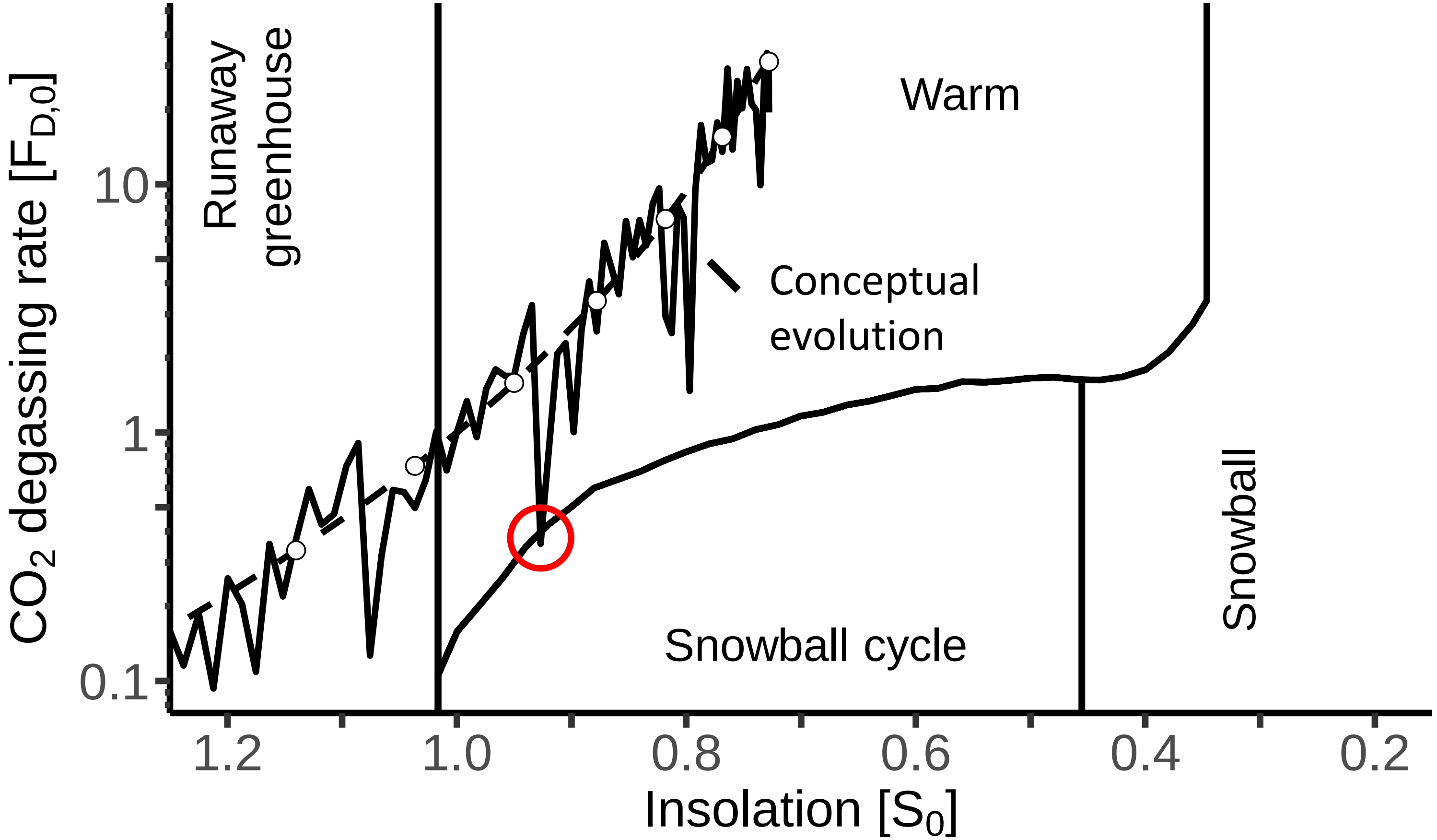
Continental growth could cause a warm climate initially.



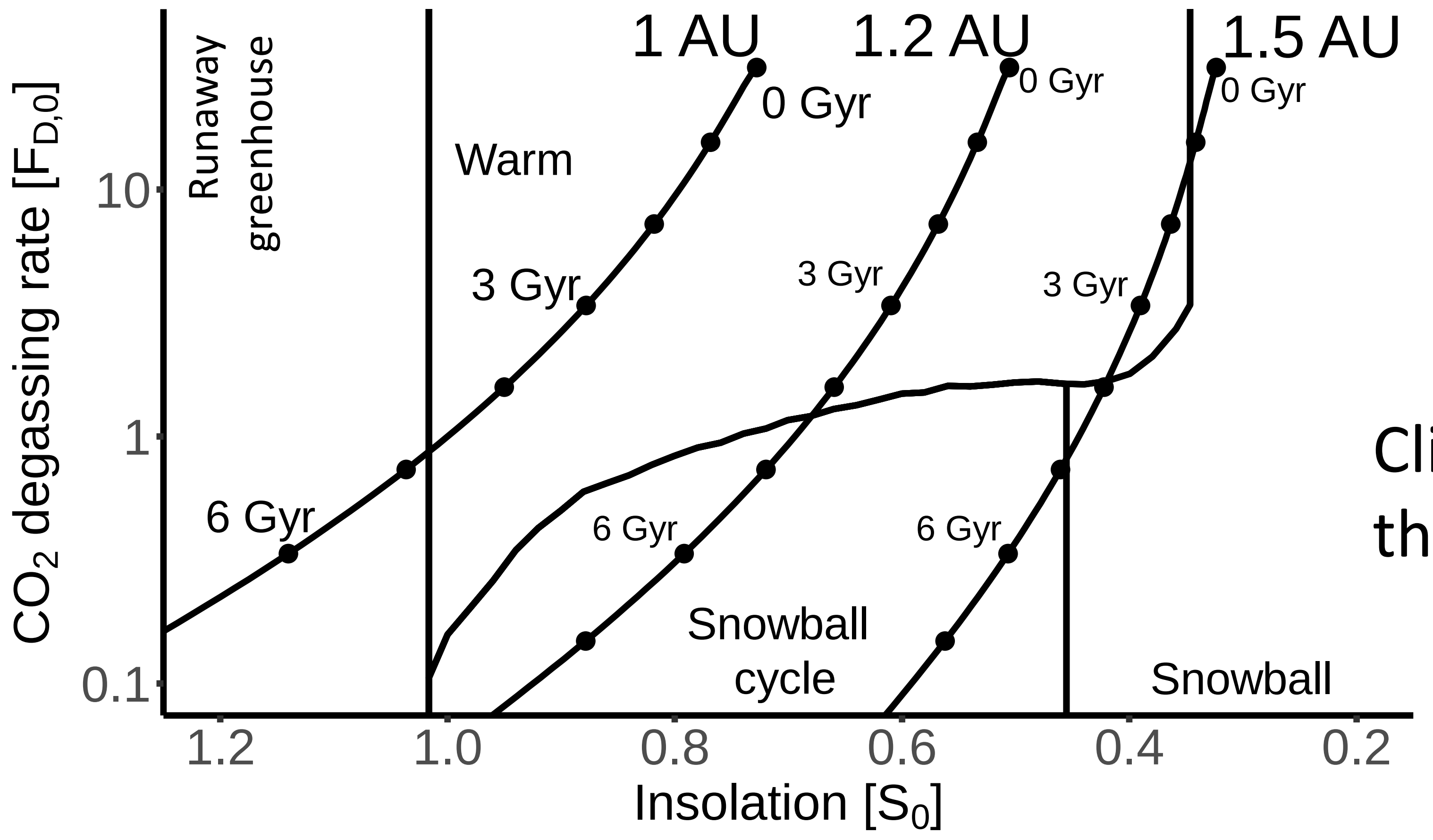
Fluctuation could result in a snowball event

Continental break-up which would provide a fresh and easily-weatherable basalt, could result in Neoproterozoic snowball Earth events.

[Donnadieu +, 2004]

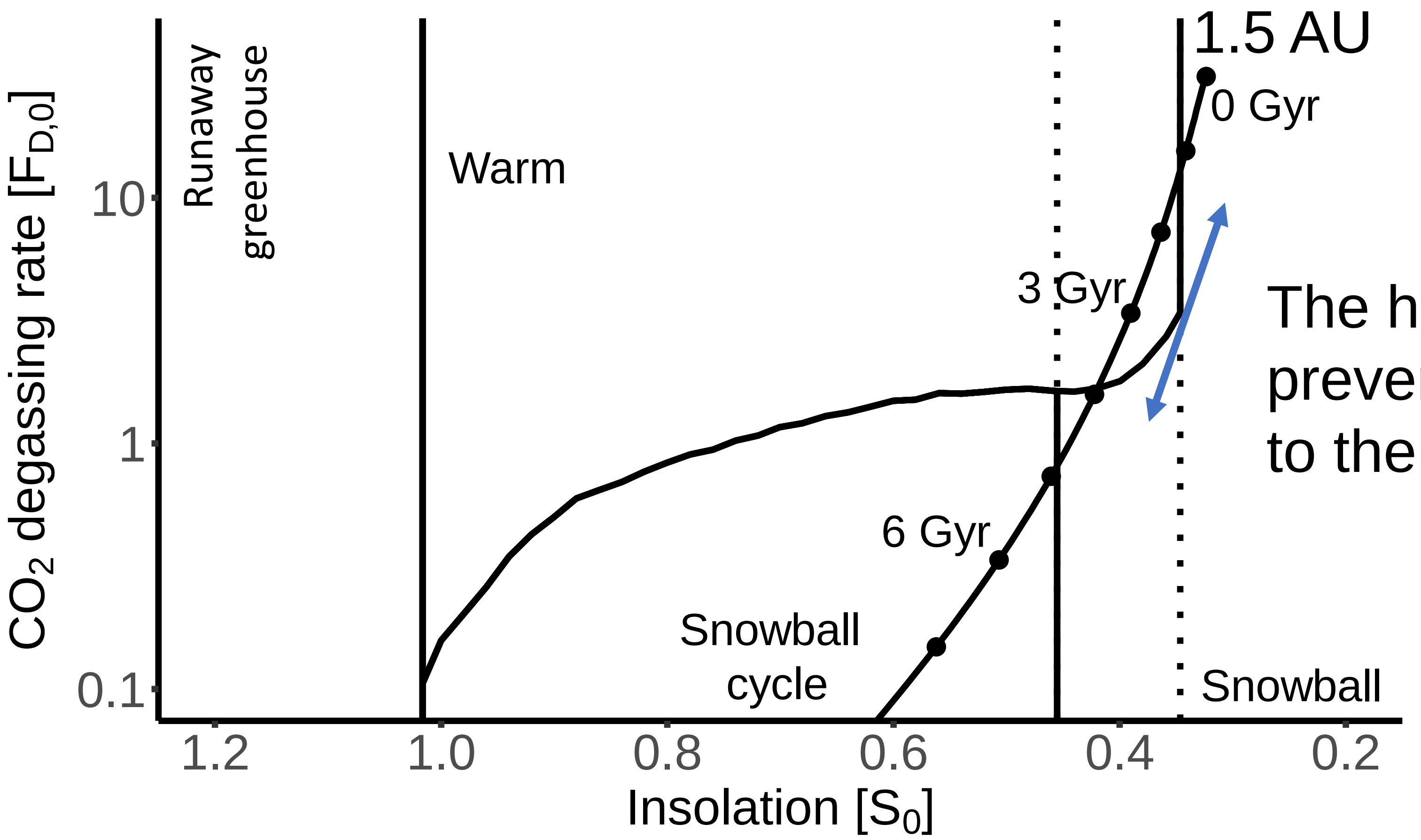


Climate for different orbital radius



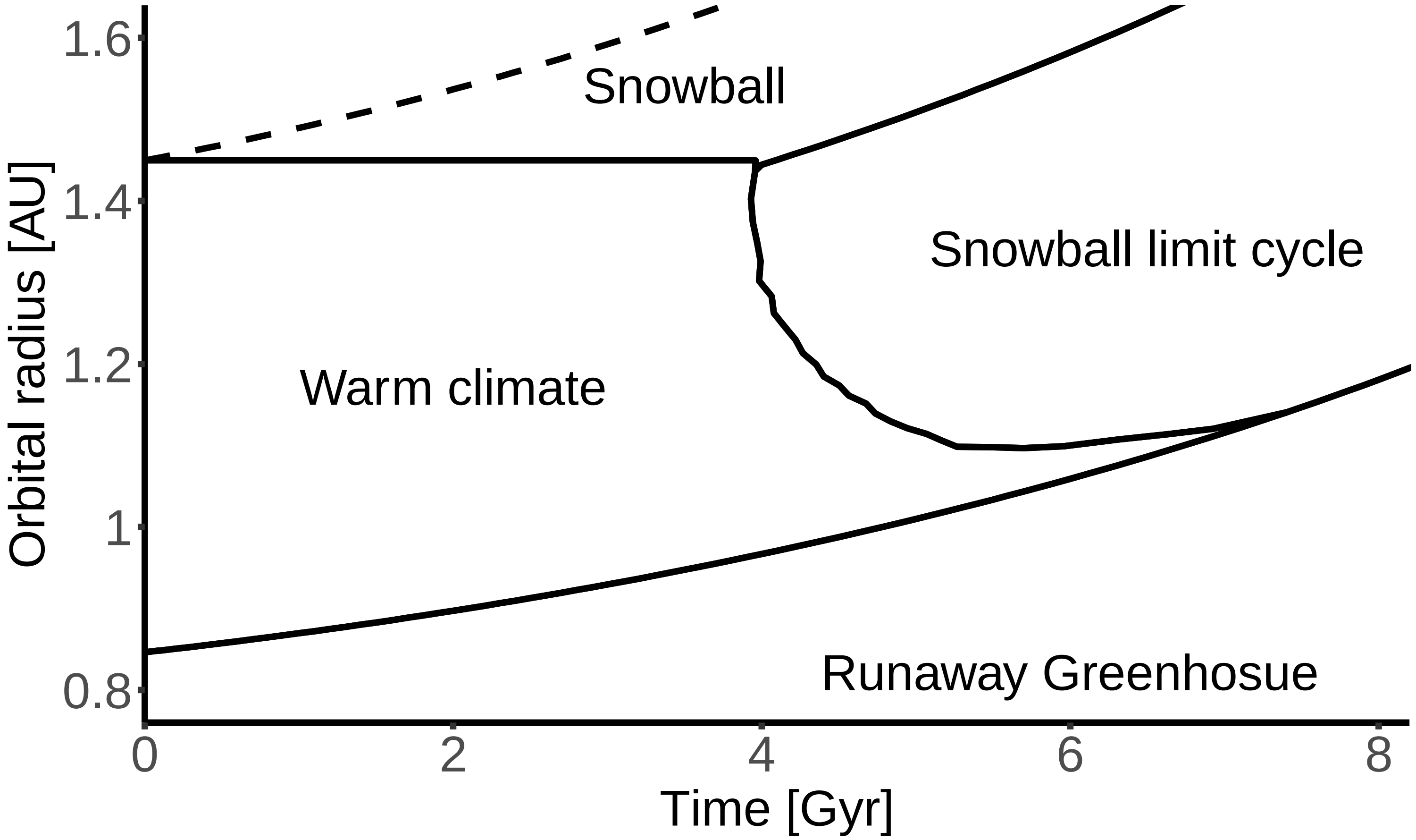
Climate evolution depends on the orbital radius of a planet

Climate for different orbital radius



The high albedo of ice would prevent a planet from shifting to the warm climate

Evolution of the climate on Earth-like planet



Possibility
of a warm surface environment
would decrease with age.

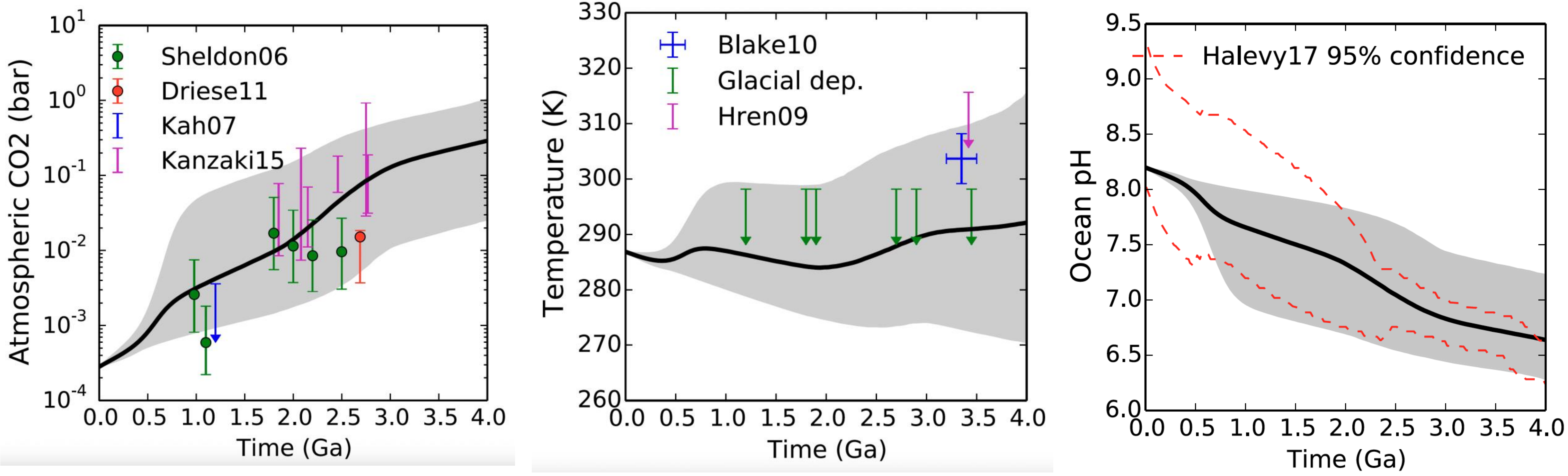
An old planet within the HZ
would likely be obserbed as
a snowball planet

Question:

How have the Earth evolved with the carbon cycle?

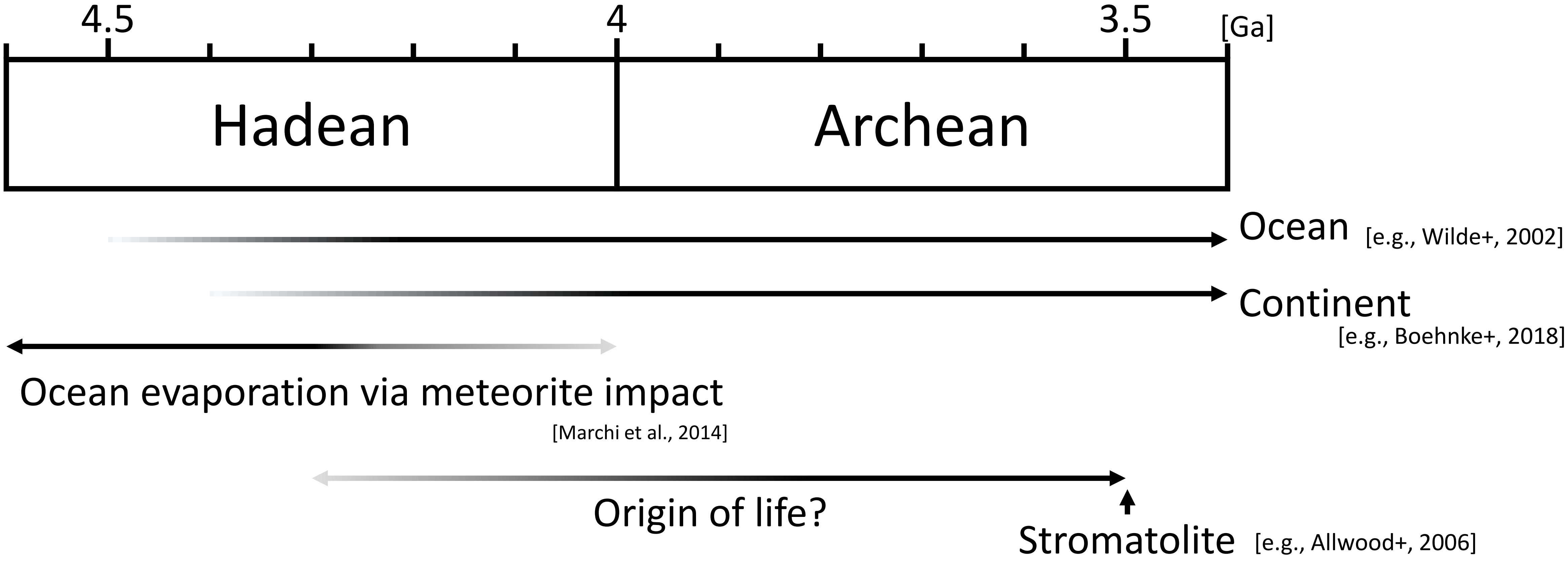
Estimate of pCO_2,Temp., & pH evolution on the Earth

[Krissansen-Totton +, 2018]



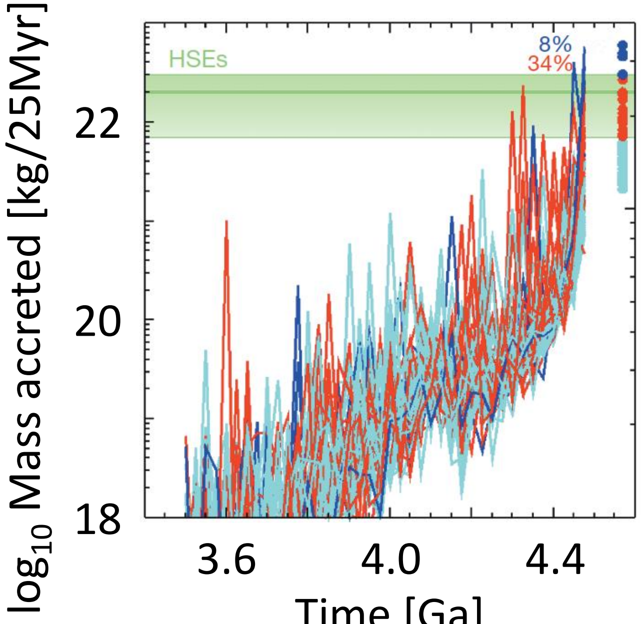
How would the surface environment during the Hadean eon be?

History of the early Earth's surface

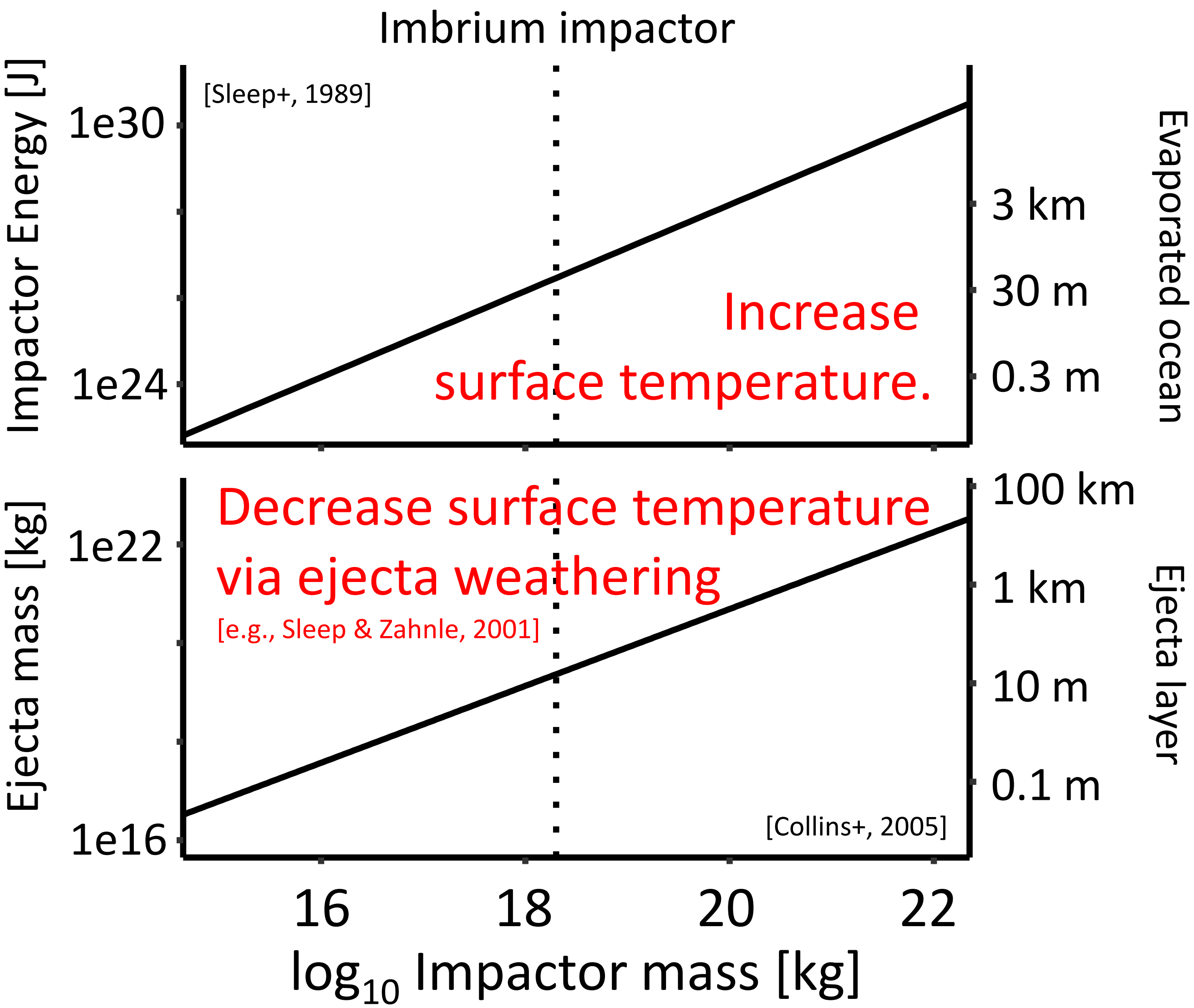


On the Hadean Earth, a life might arise.

Effect of impact

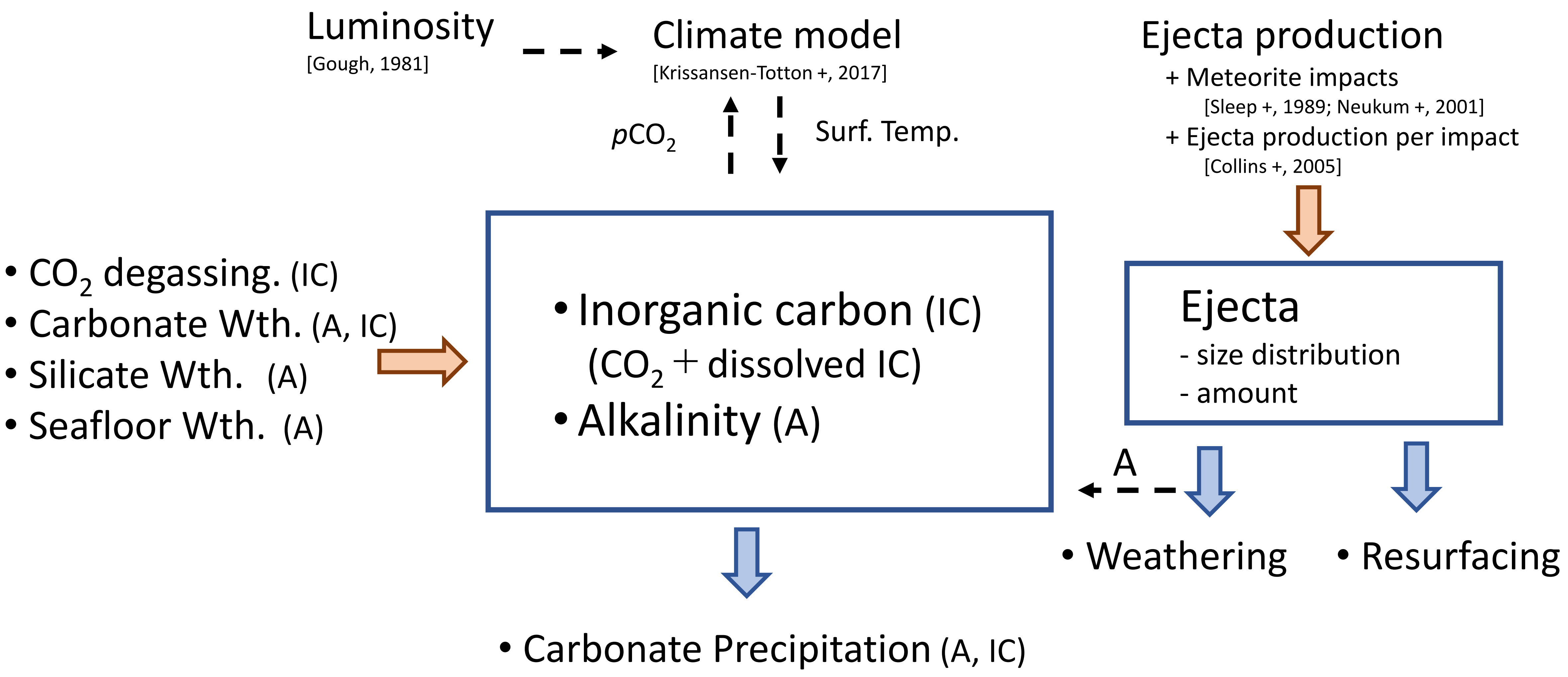


[Marchi+, 2014]



Model

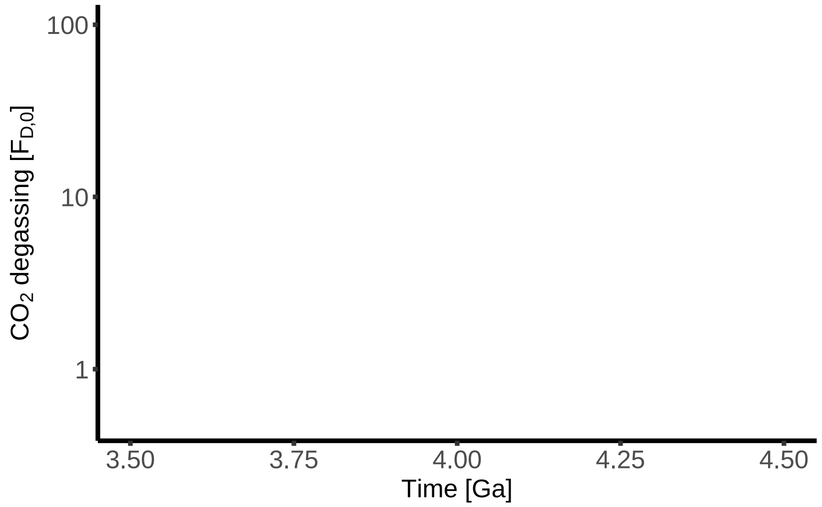
[Kadoya +, 2019, G-cubed]

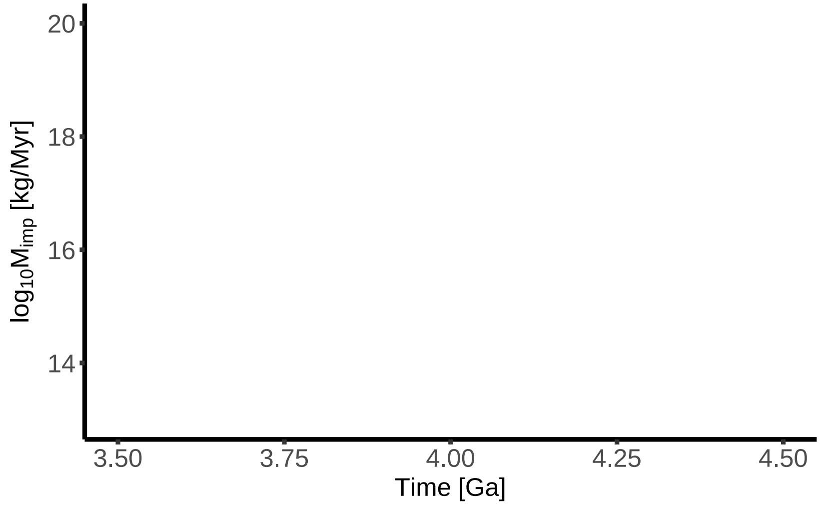


[Kadoya +, 2019, G-cubed]

Table S1. Parameter ranges for parameters randomly sampled. 1

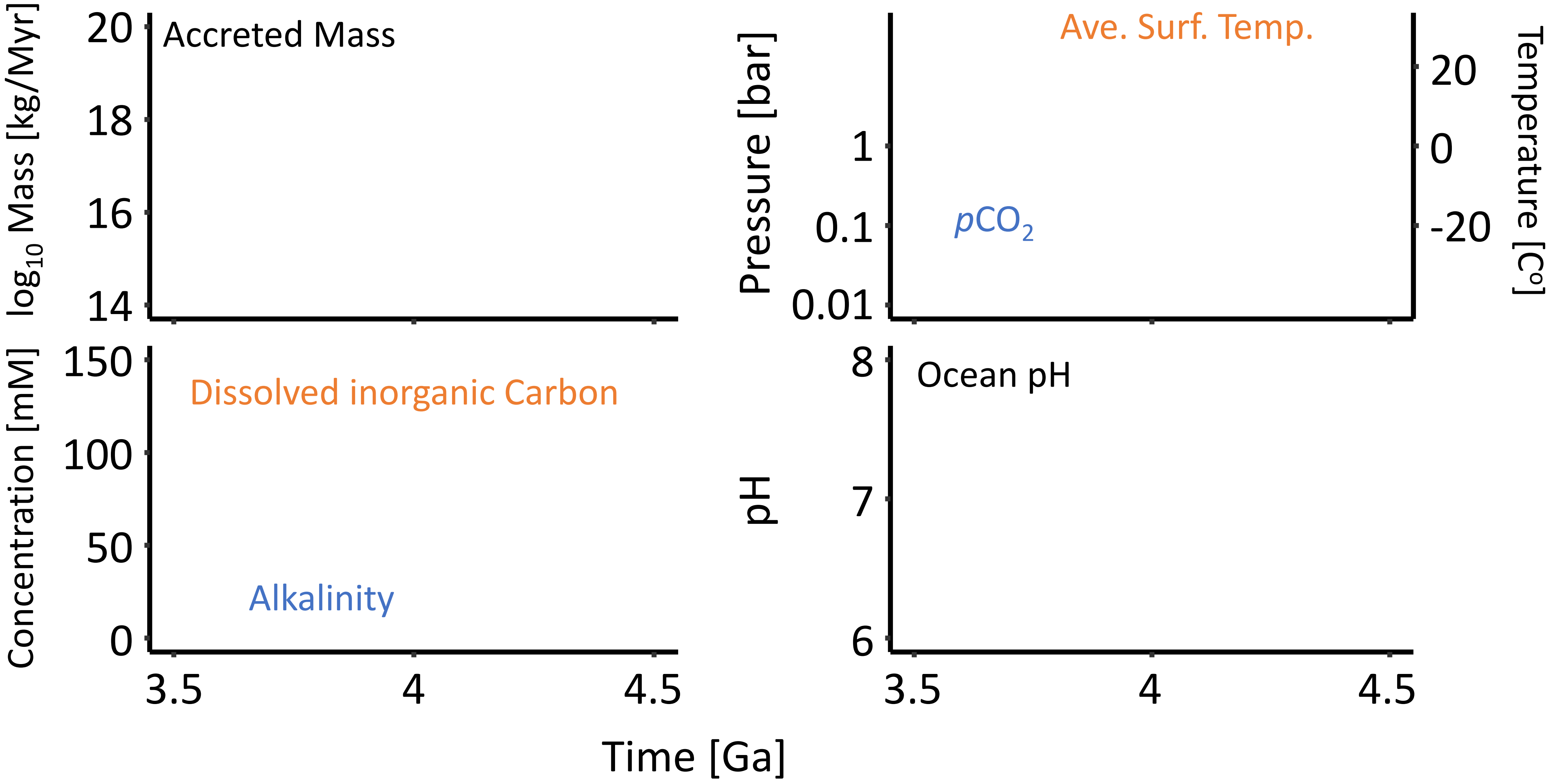
Mixing		(See Equation S5)
t_{mix}	0.02 - 1	Mixing timescale; [Myr]
Thermal evolution		(See Equation S7 & S8)
n	0 - 0.8	Exponent for heat flow
n_{sp}	0 - 2	Exponent for seafloor spreading rate
Degassing rate		(See Equation S6)
$F_{out,0}$	6 - 10	Modern rate; [TmolC/yr]
n_{out}	1 - 2	Exponent for degassing rate
Continental weatherings		(See Equation S9 & S10)
B_{precam}	0.1 - 0.999	Precambrian relative weatherability
T_w	10 - 40	e-folding temperature dependency; [K]
β_{sil}, β_{carb}	0.1 - 0.5	CO_2 dependence
$F_{carb,0}$	7 - 14	Modern rate; [TmolC/yr]
Continental growth		
L_{arch}	0.1 - 0.75	Relative Archean land fraction Note: for the No-land case, 0
Seafloor weathering		(See Equation S11)
E_{diss}	60 - 100	Temperature dependence; [kJ/mol]
$F_{diss,0}$	0.225 - 0.675	Modern rate; [TmolC/yr]
β_{diss}	0 - 0.5	pH dependence
Carbonate precipitation		(See Equation S16 & S17)
β_{pre}	1 - 2.5	Exponent for carbonate precipitation
Pore-space temperature		
a_{dt}	0.8 - 1.4	Surface-deep temperature gradient
$\eta_{sed,0}$	0.2 - 1	Relative thickness of sediment





An example

[Kadoya +, 2019, G-cubed]

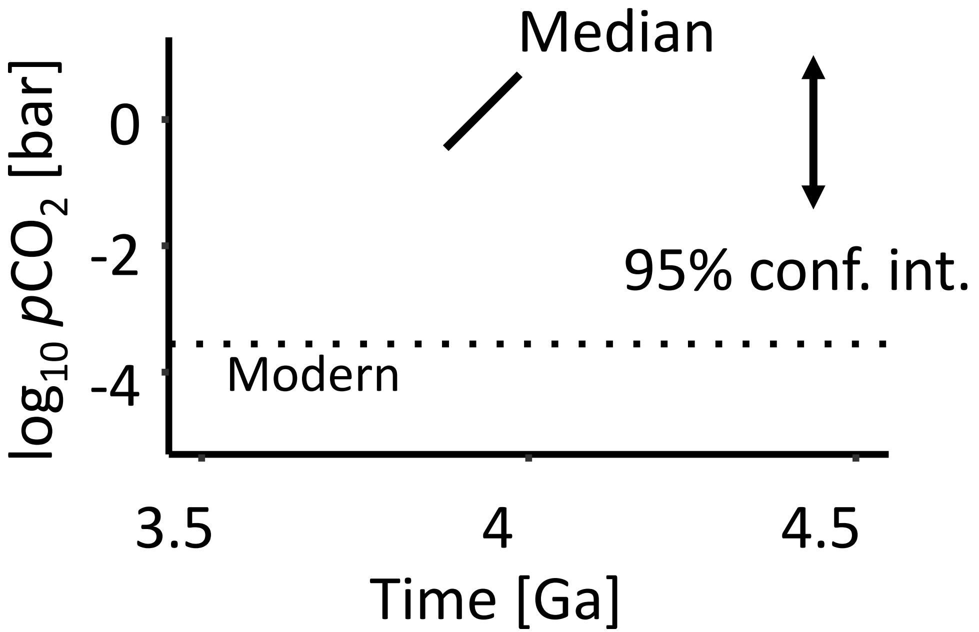


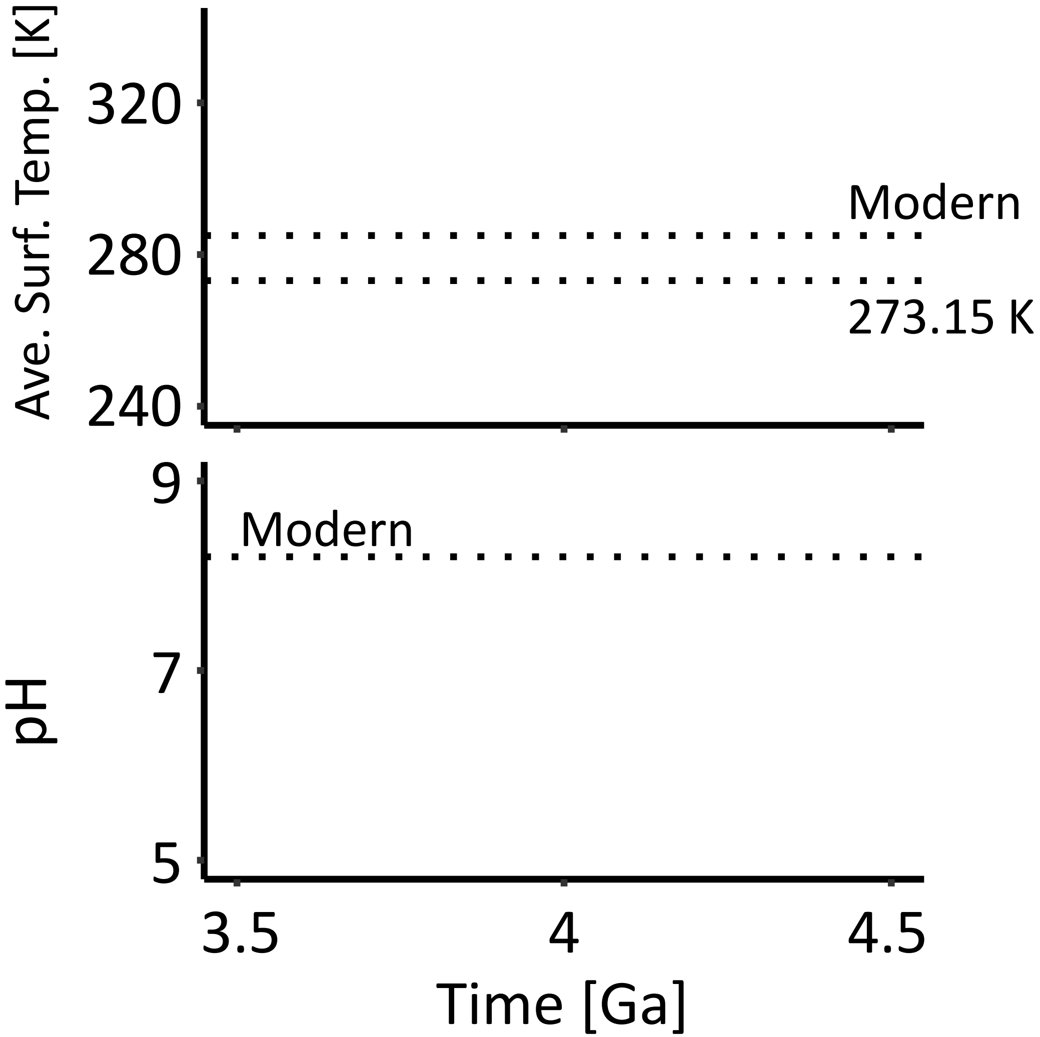
Case: without Ejecta weathering

[Kadoya +, 2019, G-cubed]

Randomly sampling
uncertain parameters
(e.g., CO_2 degassing evolution)

Statistically obtain the evolutions





Case: with Ejecta weathering

[Kadoya +, 2019, G-cubed]

Randomly sampling
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⬇

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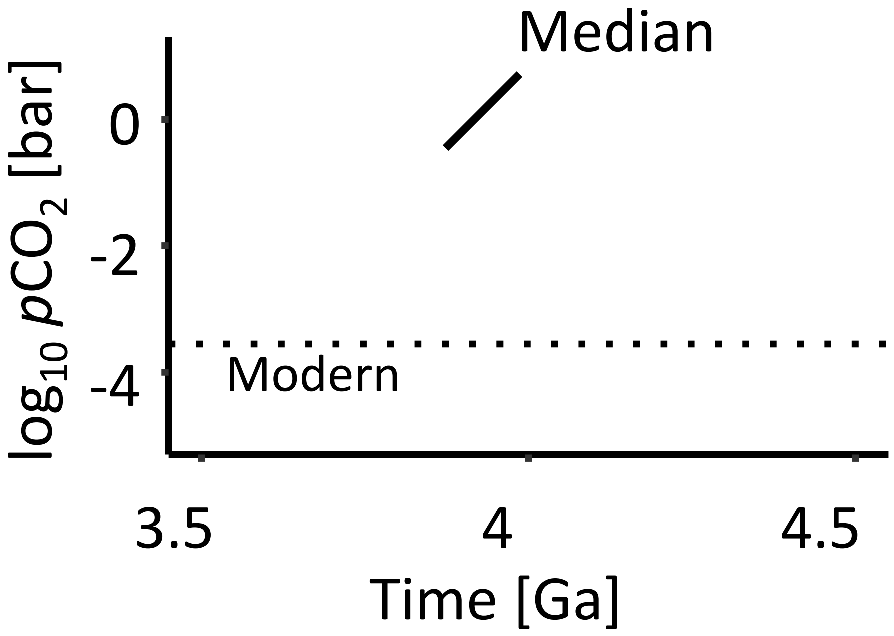

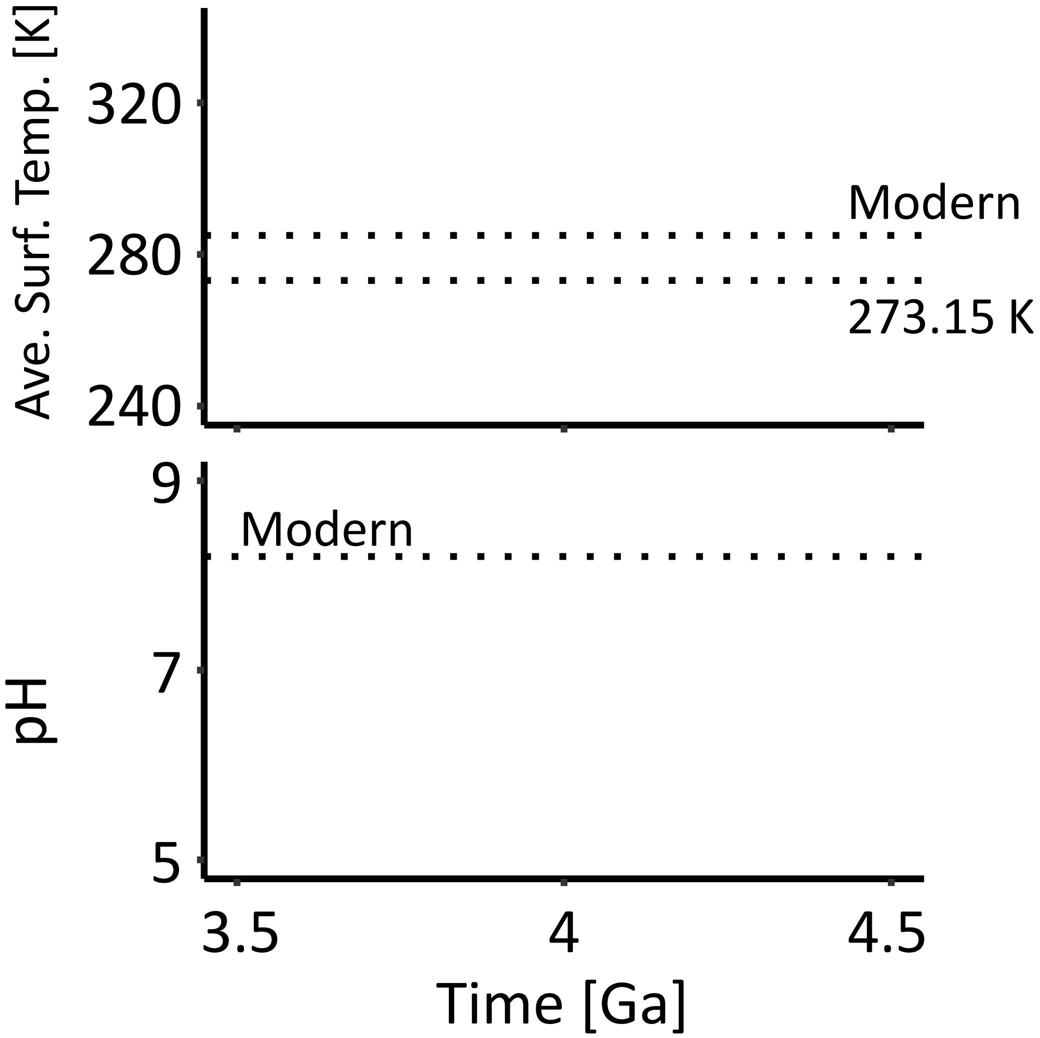

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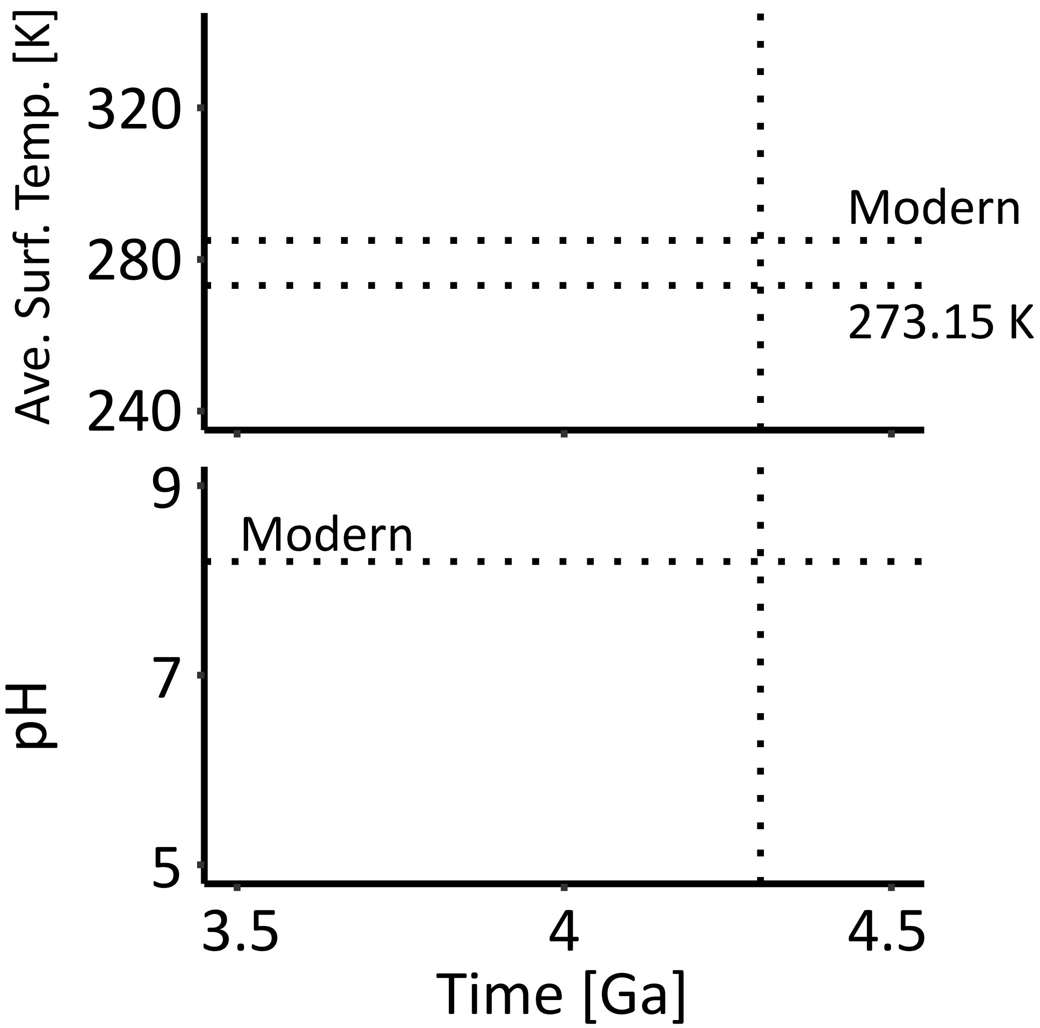

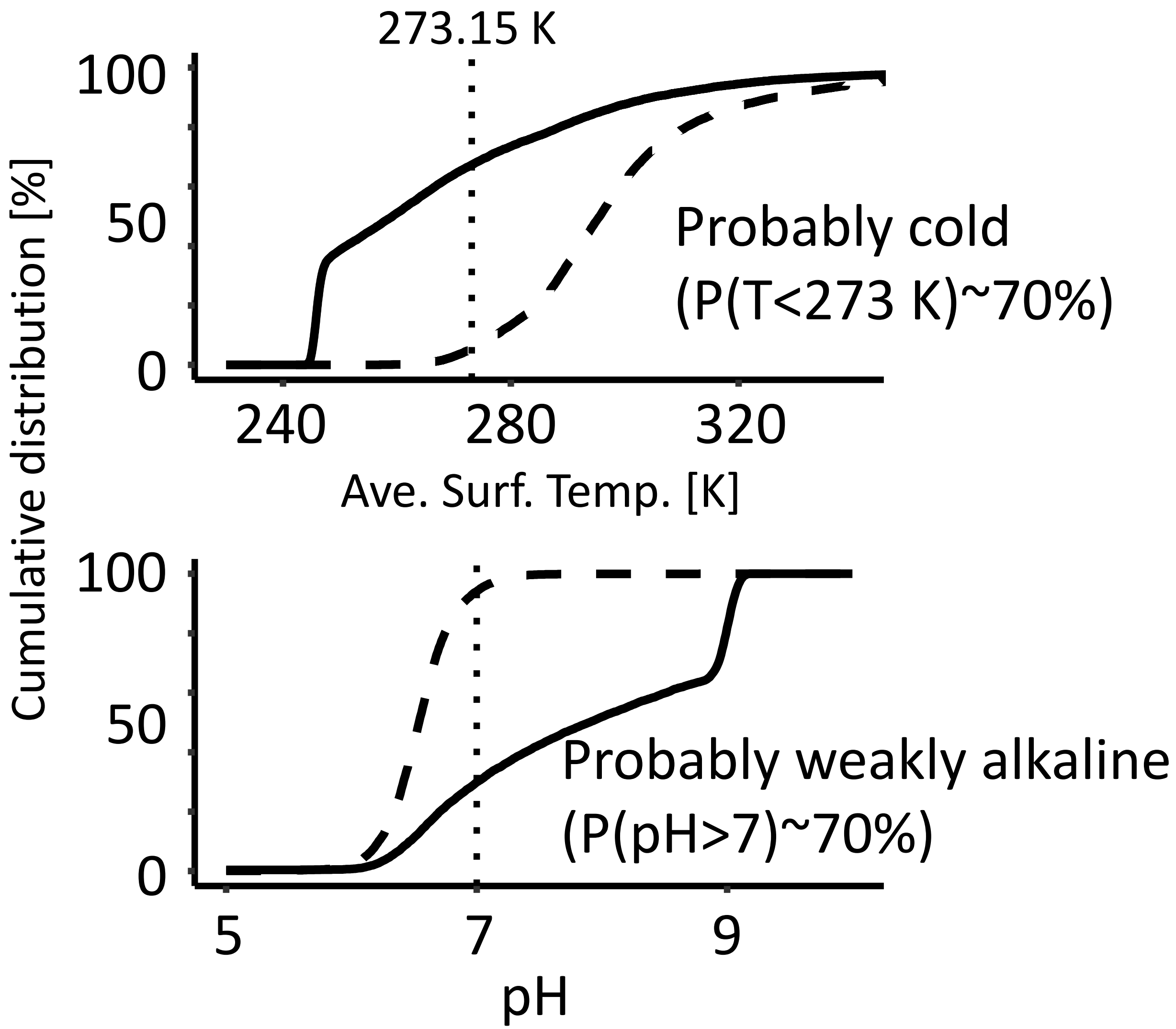

Advantage for the Origin of Life

[Kadoya +, 2019, G-cubed]

Hadean Ocean would probably be

- Cold

&

- weakly alkaline.

Prebiotic synthesis of RNAs
would favor the cold environment
[Bada & Lazcano, 2002l Mat+, 2008]
Eutectic freezing could concentrate
prebiotic ingredients, potentially
enhancing polymerization
[Bada & Lazcano, 2002l Mat+, 2008]

Alkaline conditions have an advantage
in preserving amino acids
[Cleves+, 2008]
Quasi-neutral to basic lakes could
concentrate cyanide (HCN) and phosphate,
which could play a central role
in the production of biomolecules
[e.g., Toner & Catling, 2019]

Summary

Thermal evolution of planetary interior

Supercontinent cycle

Stellar evolution

Meteorite bomberdment, and etc.

The carbon cycle

would contribute (have contributed) to
the warm (i.e., habitable) surface environment
on the Earth and Earth-like planets