Runaway climate cooling of ocean planets in the habitable zone

A.Nakayama[1], T.Kodama[2], M.Ikoma[1], Y.Abe[1]
([1] University of Tokyo, [2] Bordeaux University)

Many exoplanets have been detected in the habitable zone where the liquid ocean is stable on the planetary surface. The habitable zone implicitly assumes the Earth-like planets and its carbon cycle which plays negative feedback, regulating the partial pressure of CO_2 and, thus, the surface temperature. However, planet formation theories predicted that many of terrestrial planets in the habitable zone are covered globally with thick oceans (termed ocean planets), instead of Earth-like water-poor planets. Thus, we must investigate the habitability on ocean planets in the conventional habitable zone. Ocean planets are inferred to have extremely hot climates in most cases by previous studies. This is because H_2O high-pressure ice on the seafloor prevents chemical weathering and, thus, removal of atmospheric CO_2. Those studies, however, ignored melting of the high-pressure ice and horizontal variation of the heat flux from the oceanic crust. In this study, we explore the possibility that high heat fluxes near the mid-ocean ridge lead to melting the high-pressure ice and, thus, to removing atmospheric CO_2. To do so, we develop integrated climate models of an Earth-size ocean planet with plate tectonics for different ocean masses, which include the effects of melting of the high-pressure ice, seafloor weathering, and the carbonate-silicate geochemical carbon cycle. We find that the heat fluxes near the mid-ocean ridge are high enough to melt the ice even for sufficiently large ocean masses, which enables seafloor weathering. In contrast to the prediction by the previous studies, climates of terrestrial planets with massive oceans lapse into extremely cold ones (i.e., snowball states) with CO_2-poor atmospheres. The reason why such extremely cold climates come out is that melting of HP ice fixes seafloor temperature at the melting temperature, thereby keeping a high weathering flux regardless of surface temperature. The critical ocean mass beyond which ocean planets no longer maintain temperate climates is estimated to several tens of the Earth's ocean mass. These results suggest that temperate climates ocean planets with Earth-like plate tectonics are uncommon beyond the solar system, given the diversity in ocean mass predicted by planet formation theories.

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Akifumi Nakayama[1]

Ph.D student in University of Tokyo

Collaborator

Takanori Kodama[2], Masahiro Ikoma[1], Yutaka Abe[1]

1:University of Tokyo, 2:Bordeaux University

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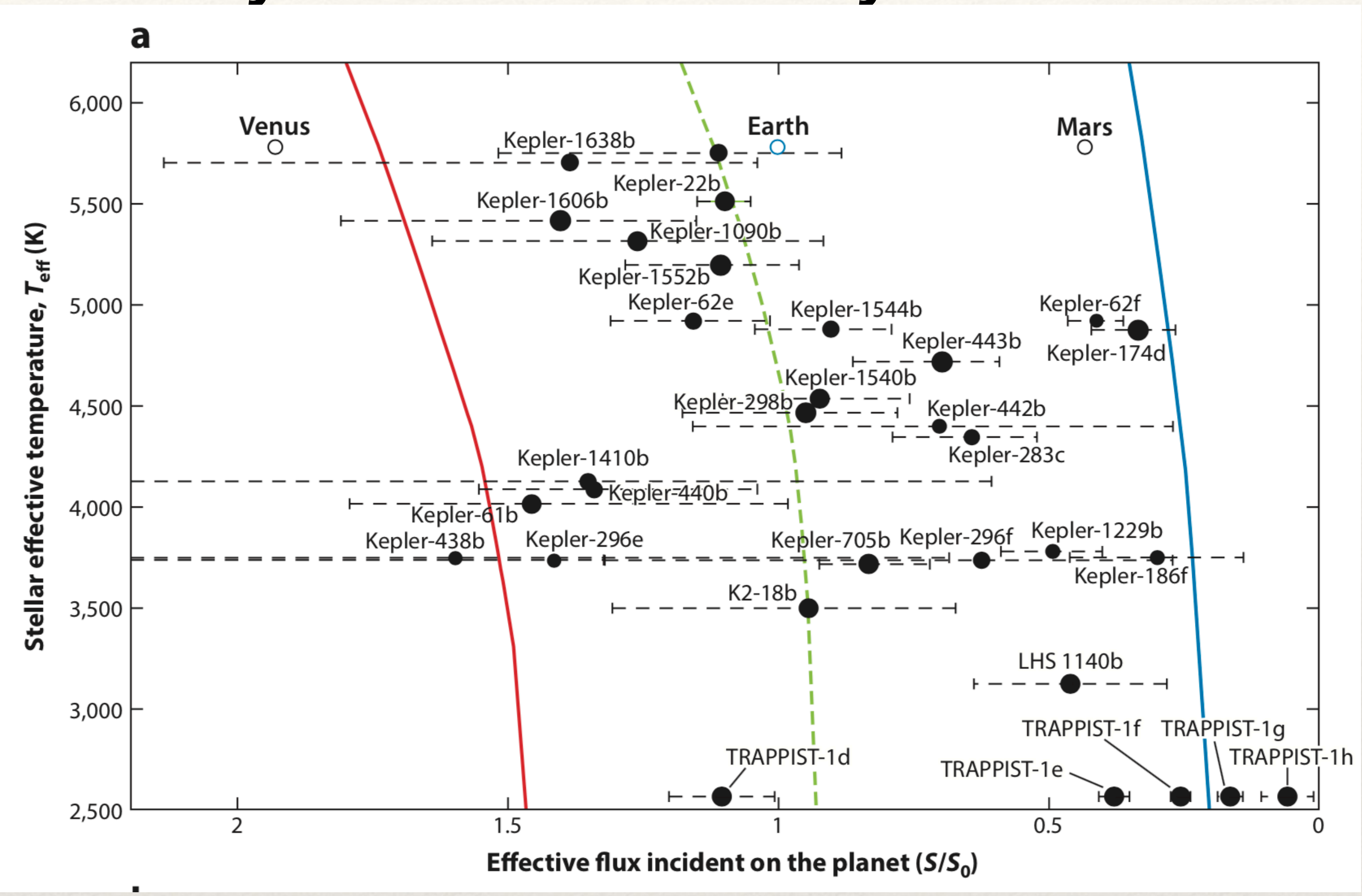
Potentially habitable planets are abundant !!

Solar system

Only Earth

Beyond the Solar system



Kaltenegger 2017

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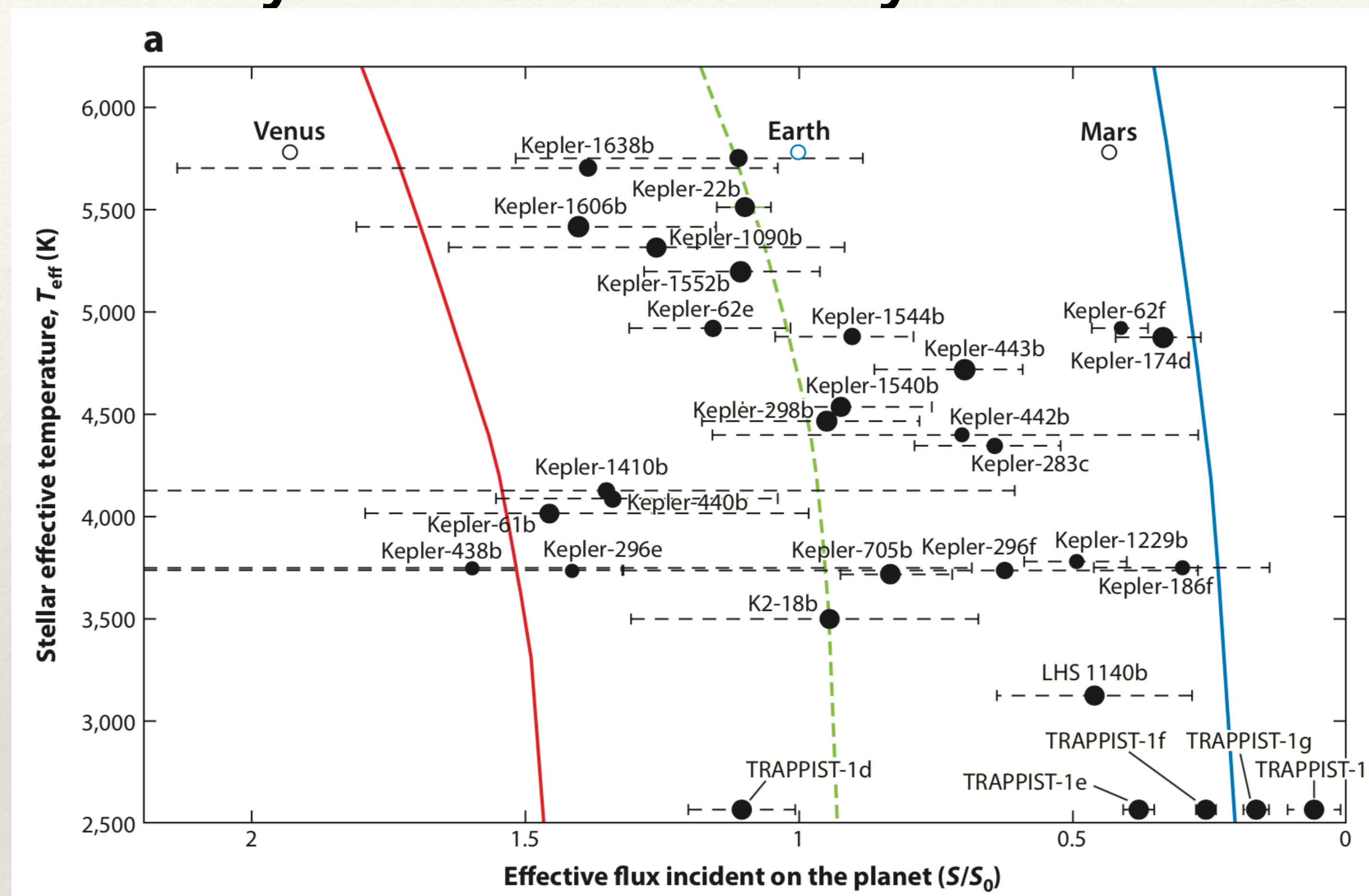


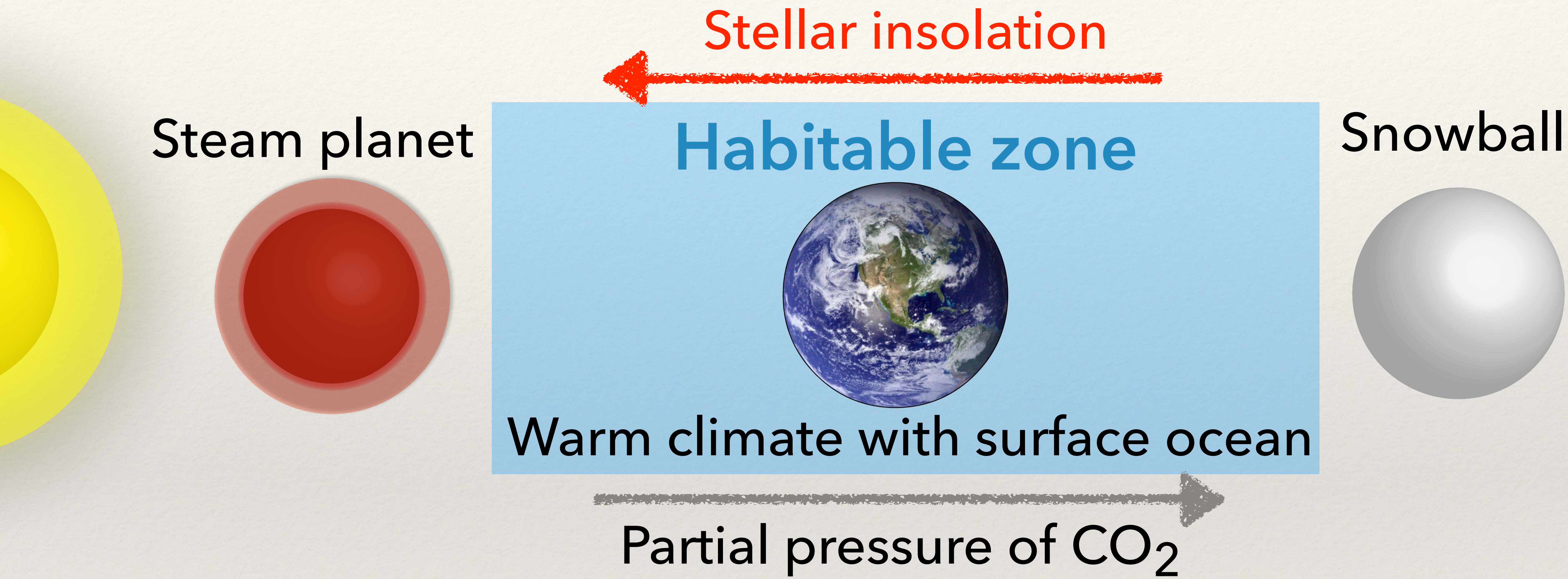
Kaltenegger 2017

Are they really Earth-like habitable planets ?

Diversity of ocean mass
Water-rich planets
are predicted

e.g., O'Brian+ 2018

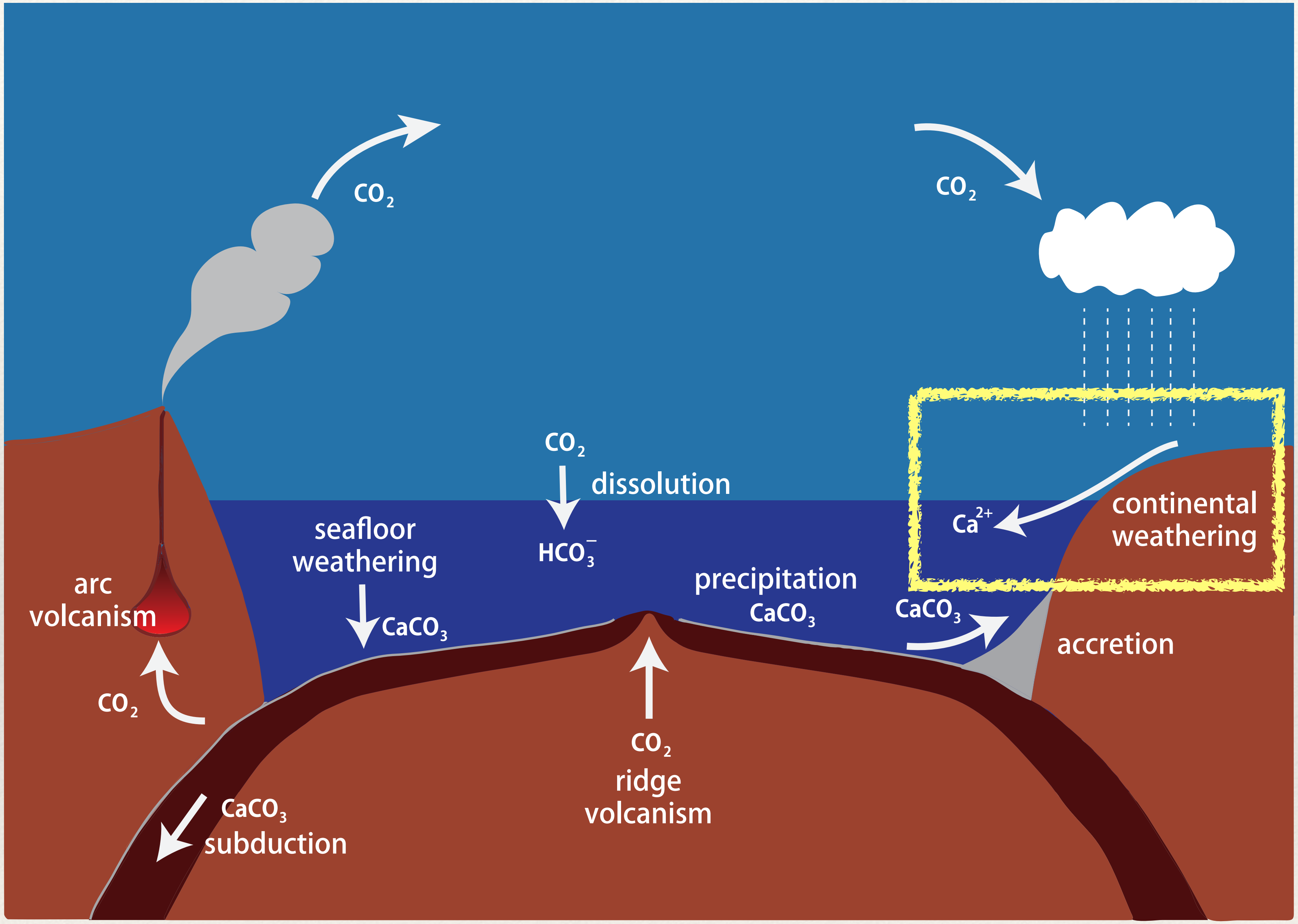
The habitable zone is useful concept



Kasting+ 1993; Kopparapu+ 2013

However,
habitable zone assumes Earth-like carbon cycle

Carbon cycle on the Earth (Earth-like planets)



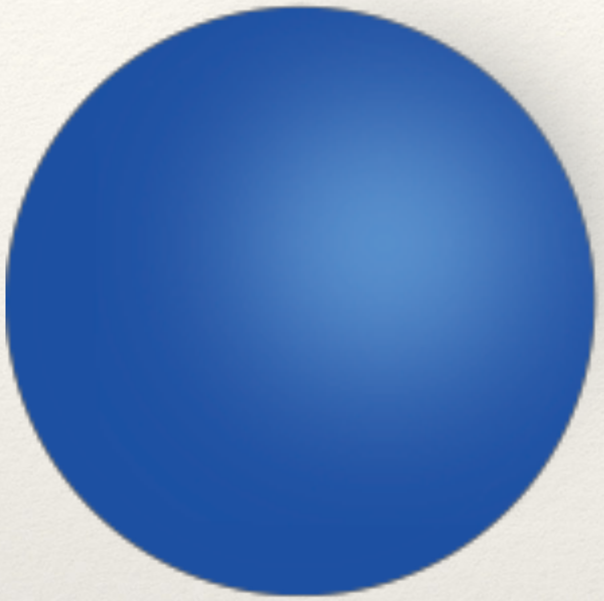
Continental weathering rate depend on the surface temperature

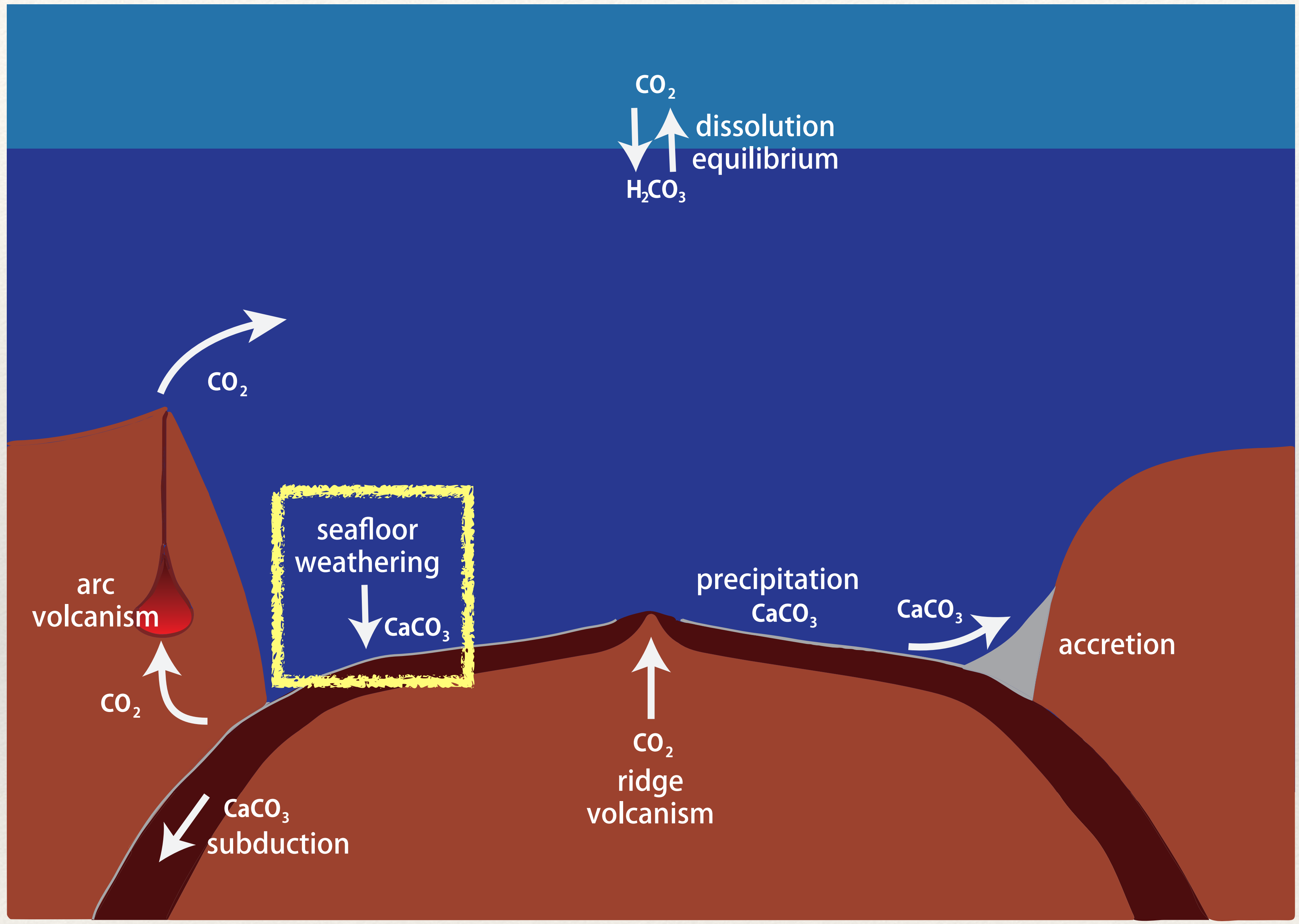
➡ Carbon cycle stabilizes the surface temperature

(Walker+ 1981)

Introduction / key process: Carbon cycle

Carbon cycle on Ocean Planets





Continental weathering does not work on ocean planet

➡ Can seafloor weathering stabilize the surface temperature ?

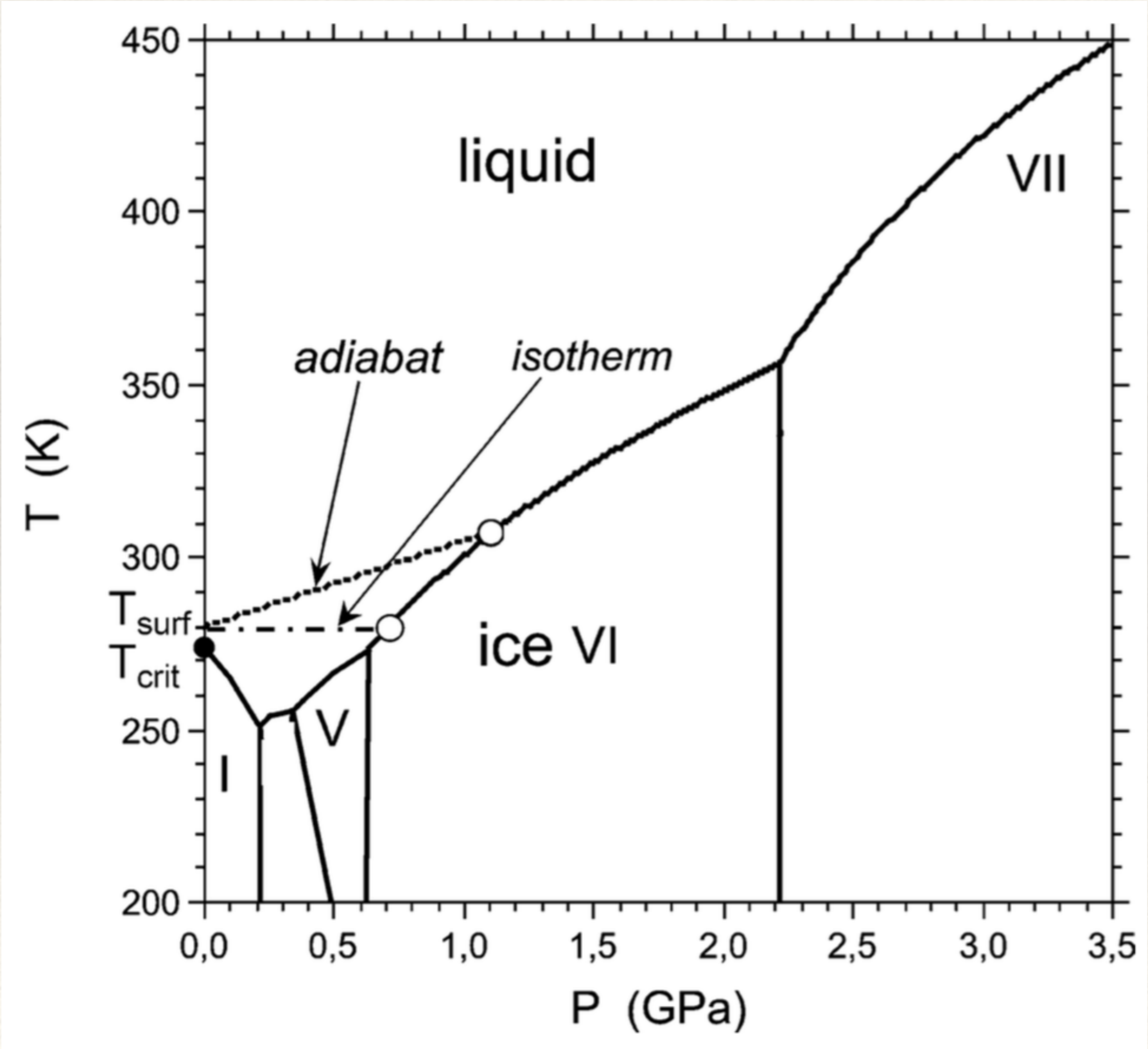
(e.g., Abbot+ 2012)

High-pressure (HP) ice prevents carbon cycle

For planets with large ocean,

internal structure model predicted the **HP ice** on the seafloor

(Leger+ 2004)



Leger+ 2004

It will prevent water-rock reaction

➡ no weathering processes

(e.g., Alibert 2014)

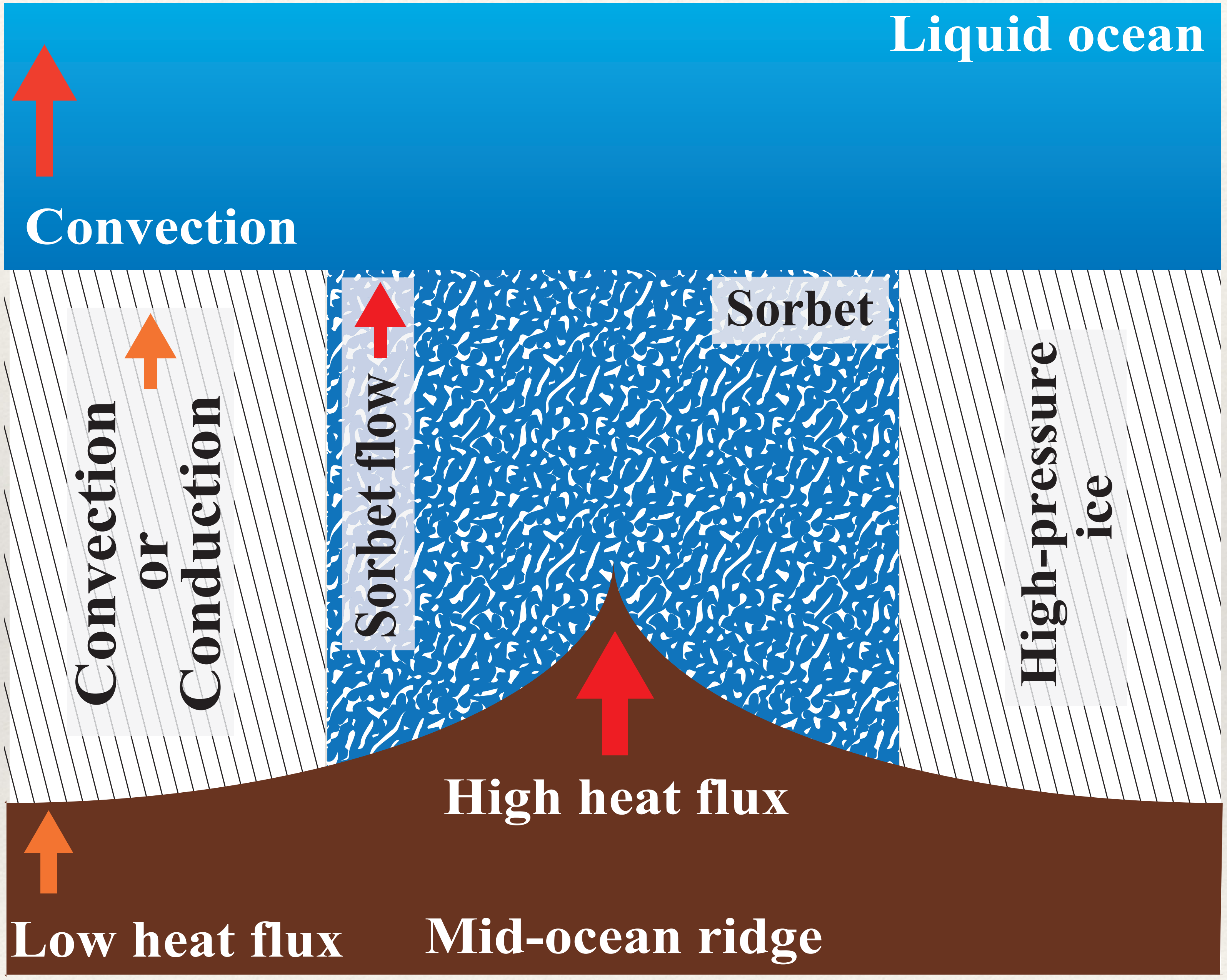
Climate on ocean planet is controlled by partitioning CO_2 between atmosphere-ocean

➡ Extremely **hot climate**

(Kitzmann+ 2015)

HP ice will be molten

Plate tectonics produces the variation of heat flux from crust

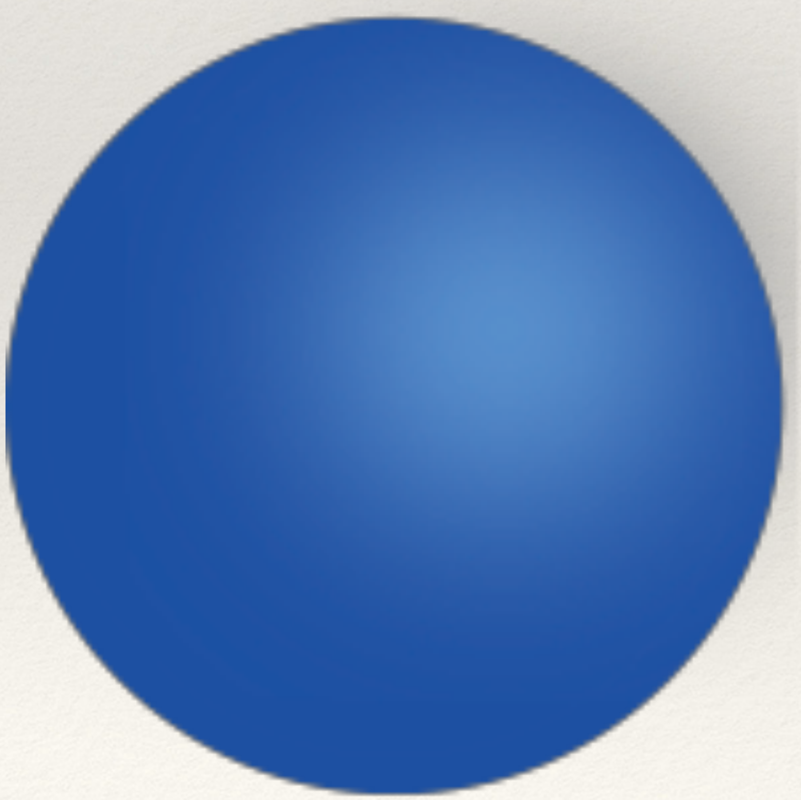


Above mid-ocean ridge,

HP ice will be **molten** and **seafloor weathering can work**

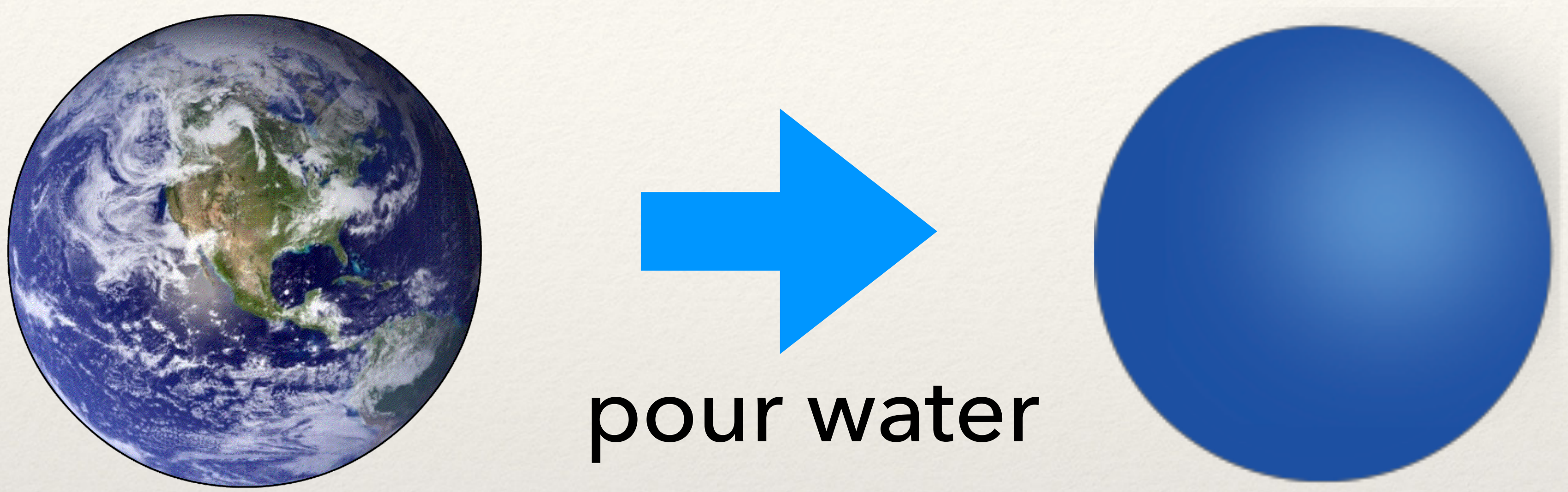
Introduction / Purpose of this study

In this study,
we investigate how the presence of HP ice affects seafloor weathering and climate



Planetary climate on ocean planets of Earth-sized in HZ

We consider almost Earth-like planets with plate tectonics excepted for ocean mass



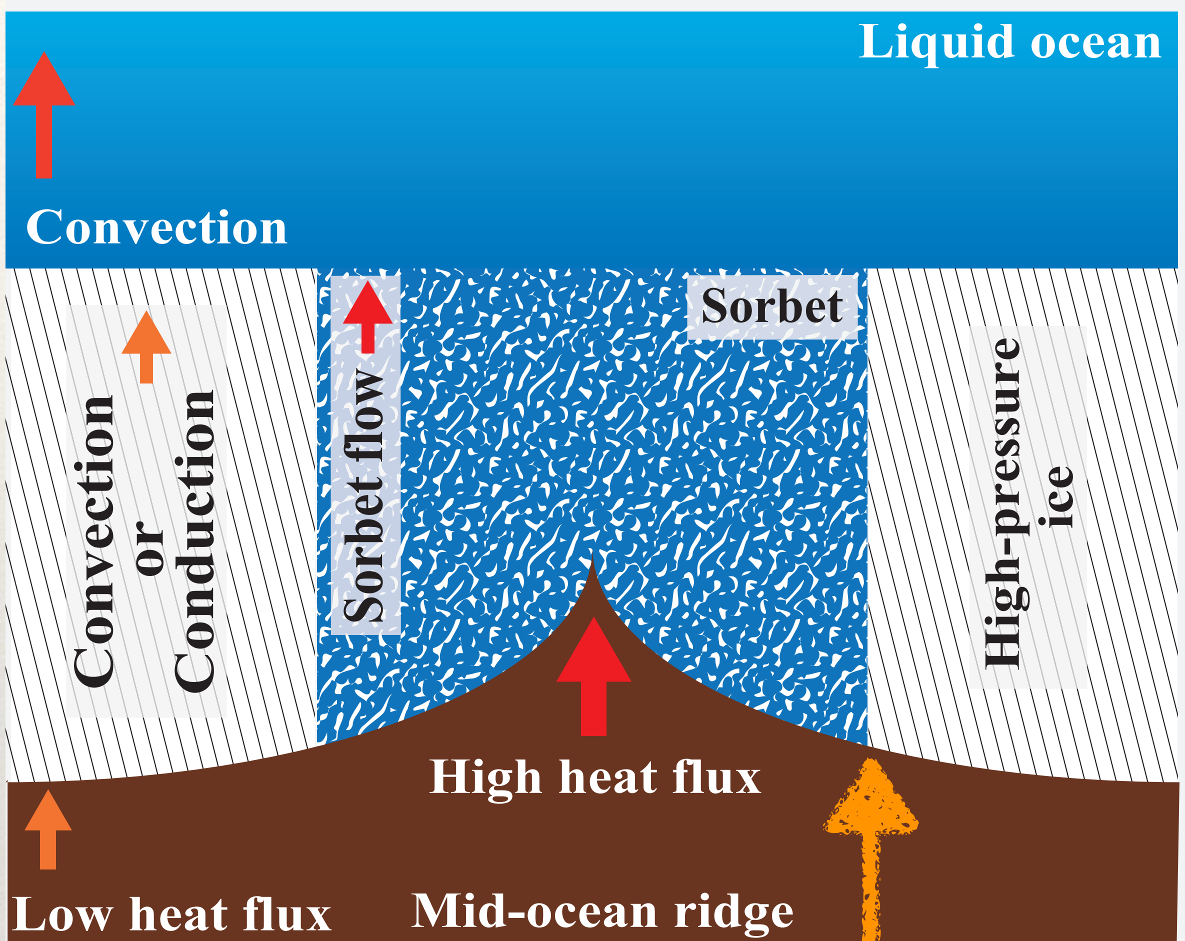
Earth — Ocean planets

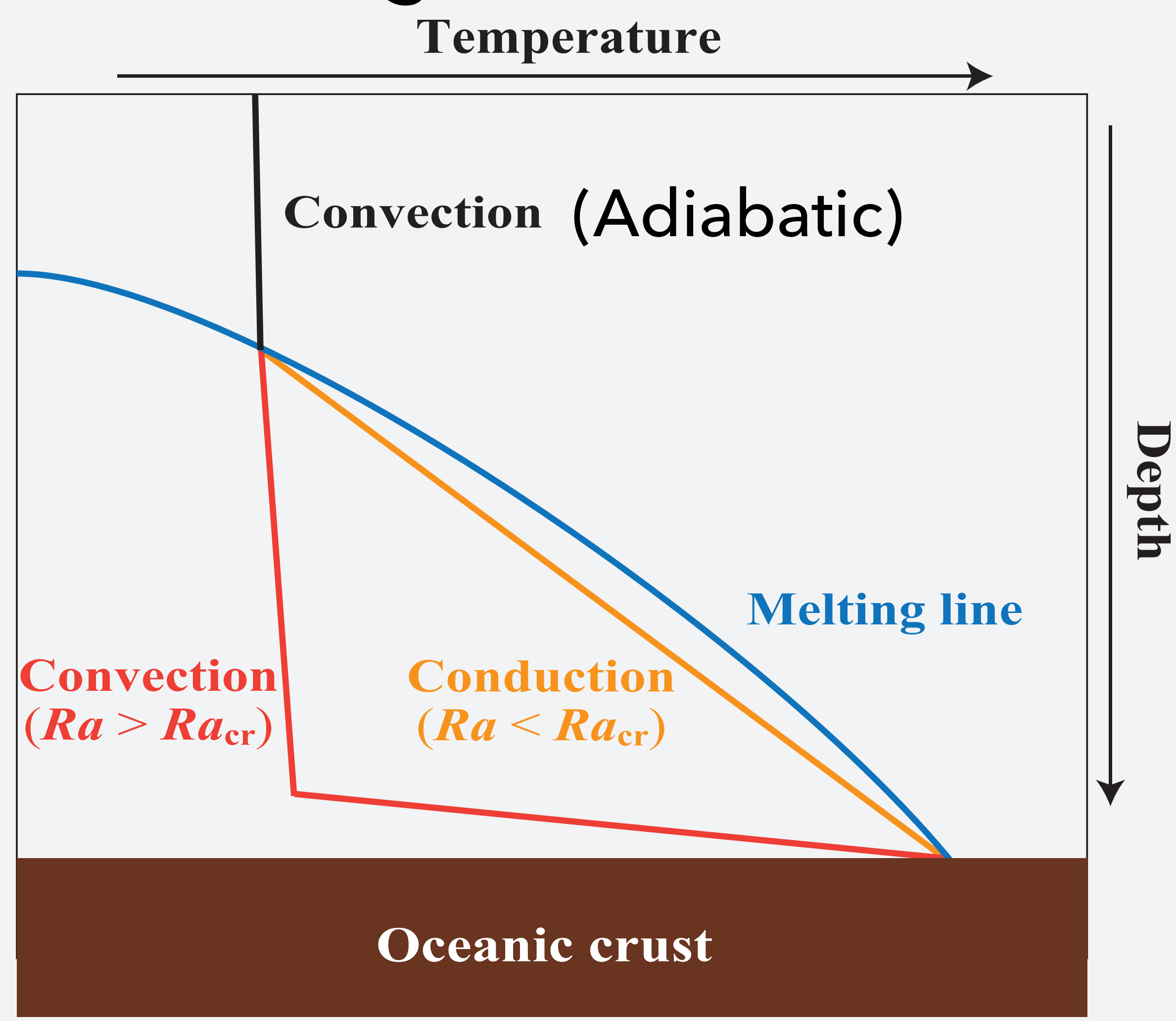
Outline of climate model

- ✓ Internal structure ➡ Thickness of HP ice
- ✓ Seafloor environment ➡ Effective weathering area
- ✓ Carbon cycle ➡ Surface temperature

Climate model / Seafloor environment model

Calculate the area where seafloor weathering can work (foc)





Find this boundary

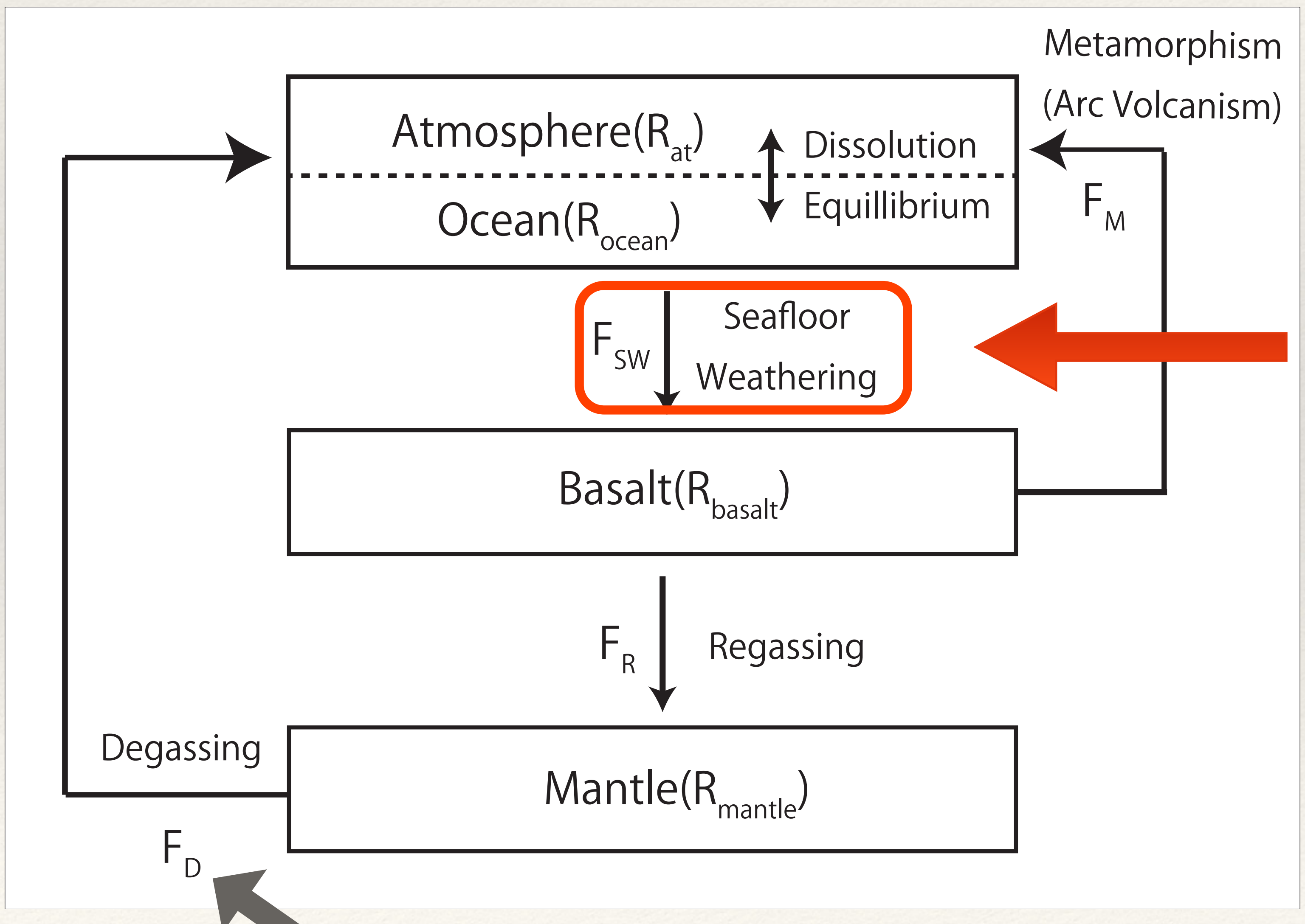
Thermal structure of the HP ice

1. Calculate critical heat flow below which HP ice remains solid
2. Find the position of oceanic crust satisfied critical heat flow using semi-infinite half space cooling (Turcotte & Shubert 2002)

Box model based on Earth's carbon cycle

(Tajika & Matsui 1992; Sleep & Zahnle 2001)

- Add seafloor weathering and HP ice effect
- Neglect continental weathering and reservoir
- Seafloor temperature adiabatically derived from surface temp.



Seafloor Temperature dependence

[Brady & Gislason 1997]

$$= F^*_{\mathrm{SW}} f_{\mathrm{oc}} \exp\left[\left(\frac{E_{\mathrm{a}}}{R_{\mathrm{gas}}}\right)\left(\frac{1}{T^*_{\mathrm{floor}}} - \frac{1}{T_{\mathrm{floor}}}\right)\right]$$

f_{oc}: effective weathering area

Surface temperature as a function of PCO_2 calculated by

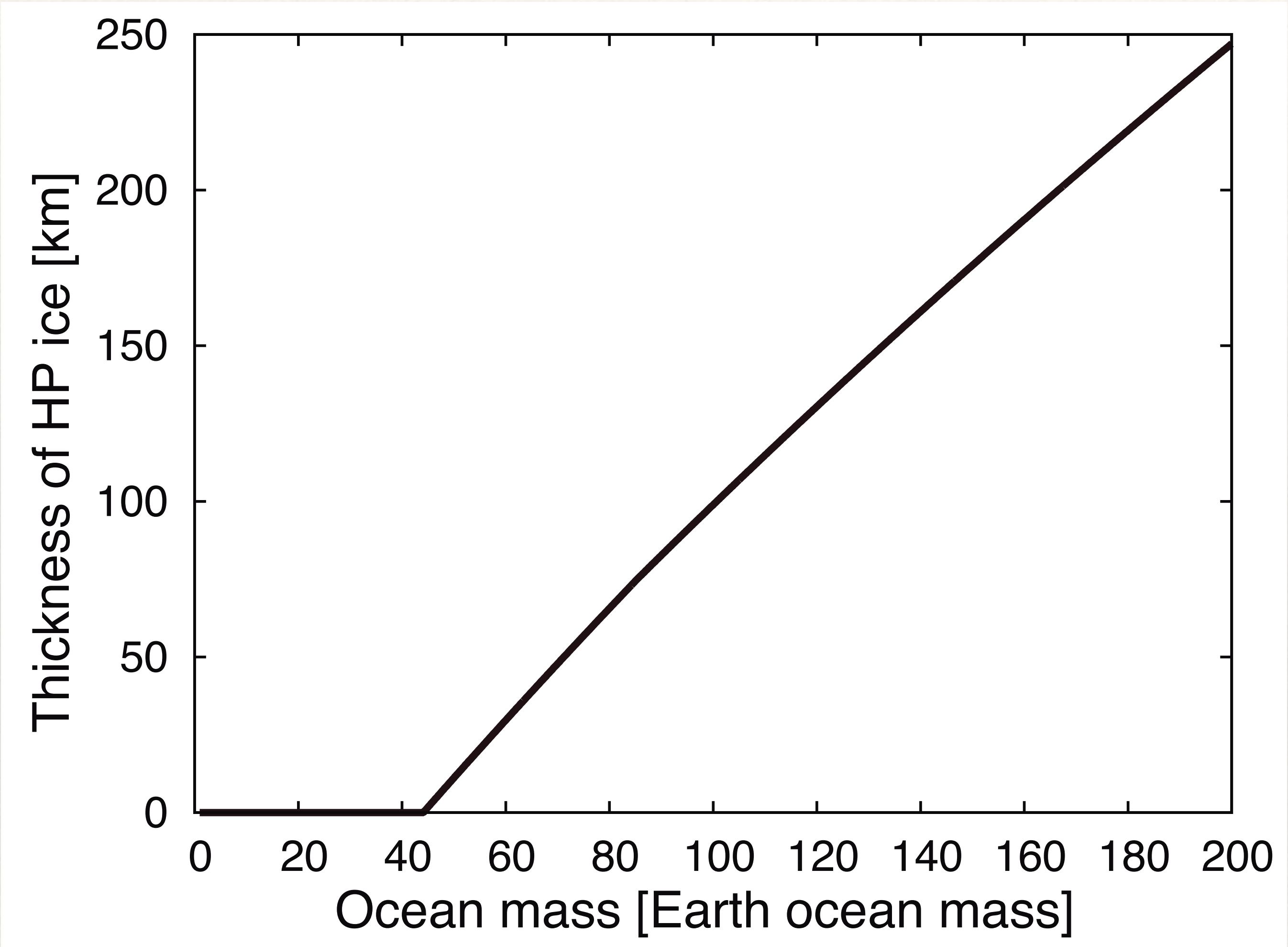
1-D radiative-convective model *Atmos* [Kasting+1993; Kopparapu 2013]

F_D: proportional to ocean mass or free parameter

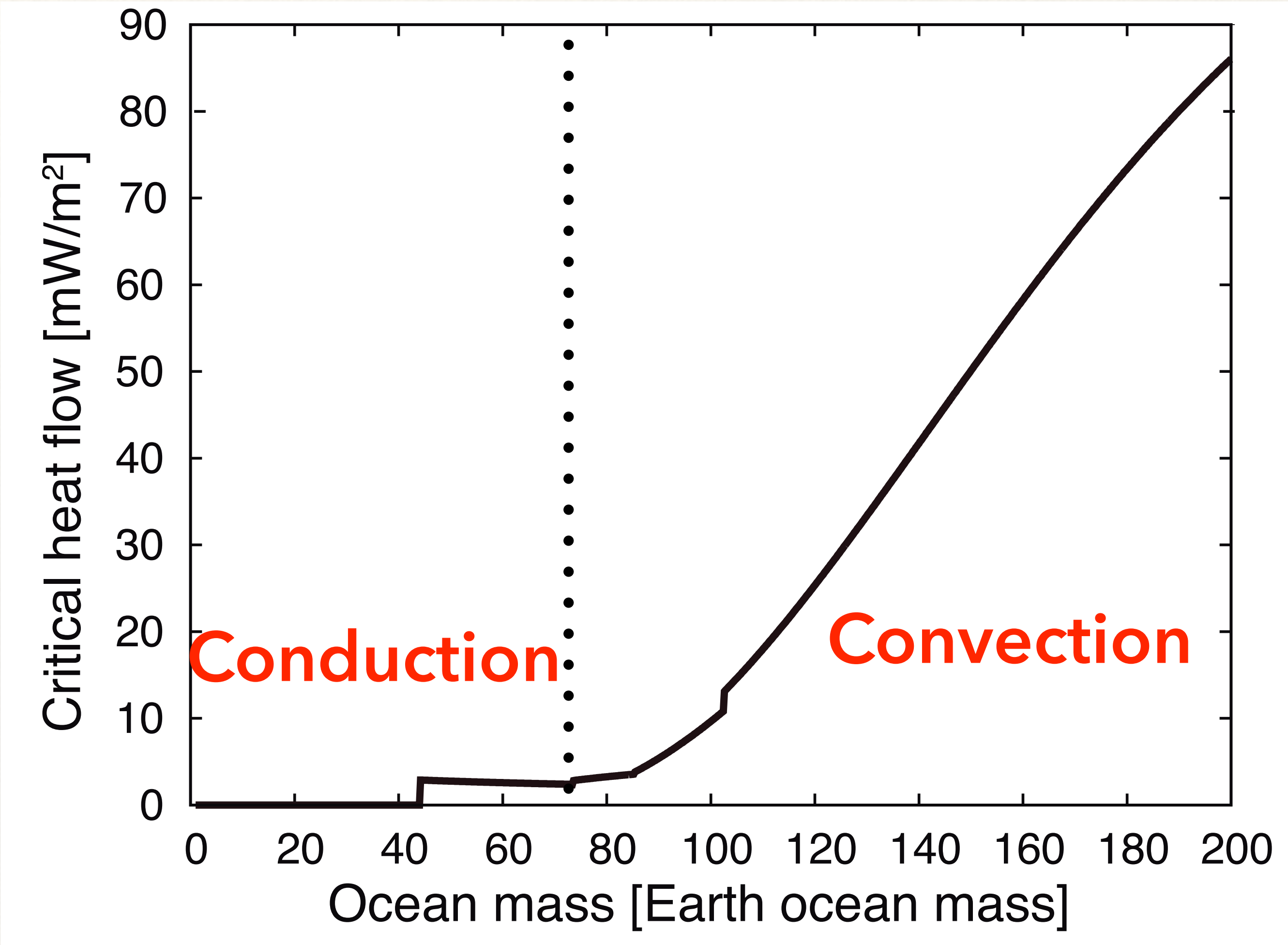
Results / Critical heat flow & thickness of HP ice

Surface temperature : 300K

Thickness of HP ice



Critical heat flow



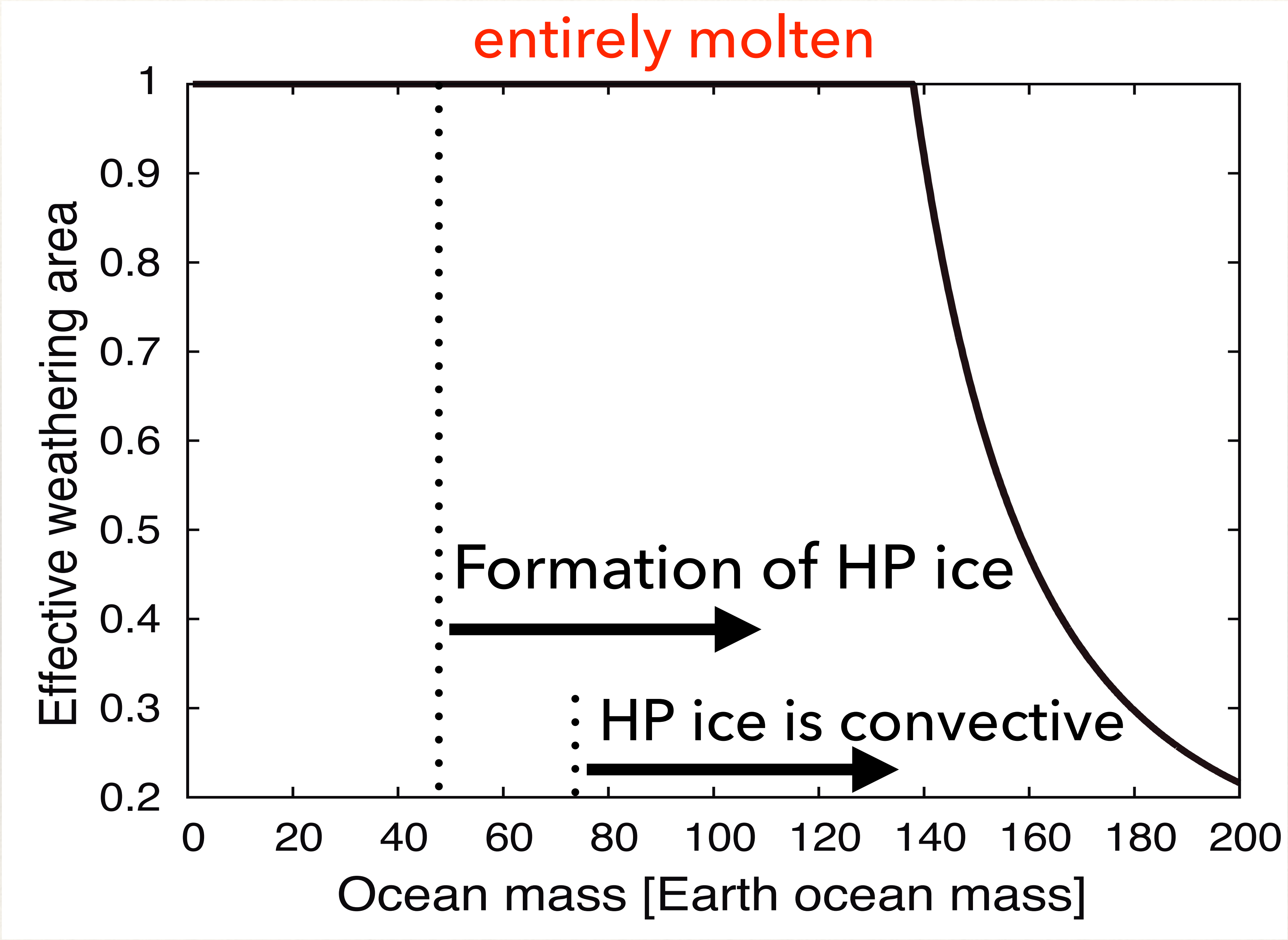
Without sufficiently thick HP ice,

critical heat flow is smaller than mean mantle heat flow (~80mW/m^2)

Results / Effective weathering area

Surface temperature : 300K
Mean mantle heat flow : 80 mW/m^2

Thickness of HP ice ~150 km
@140 Earth ocean mass

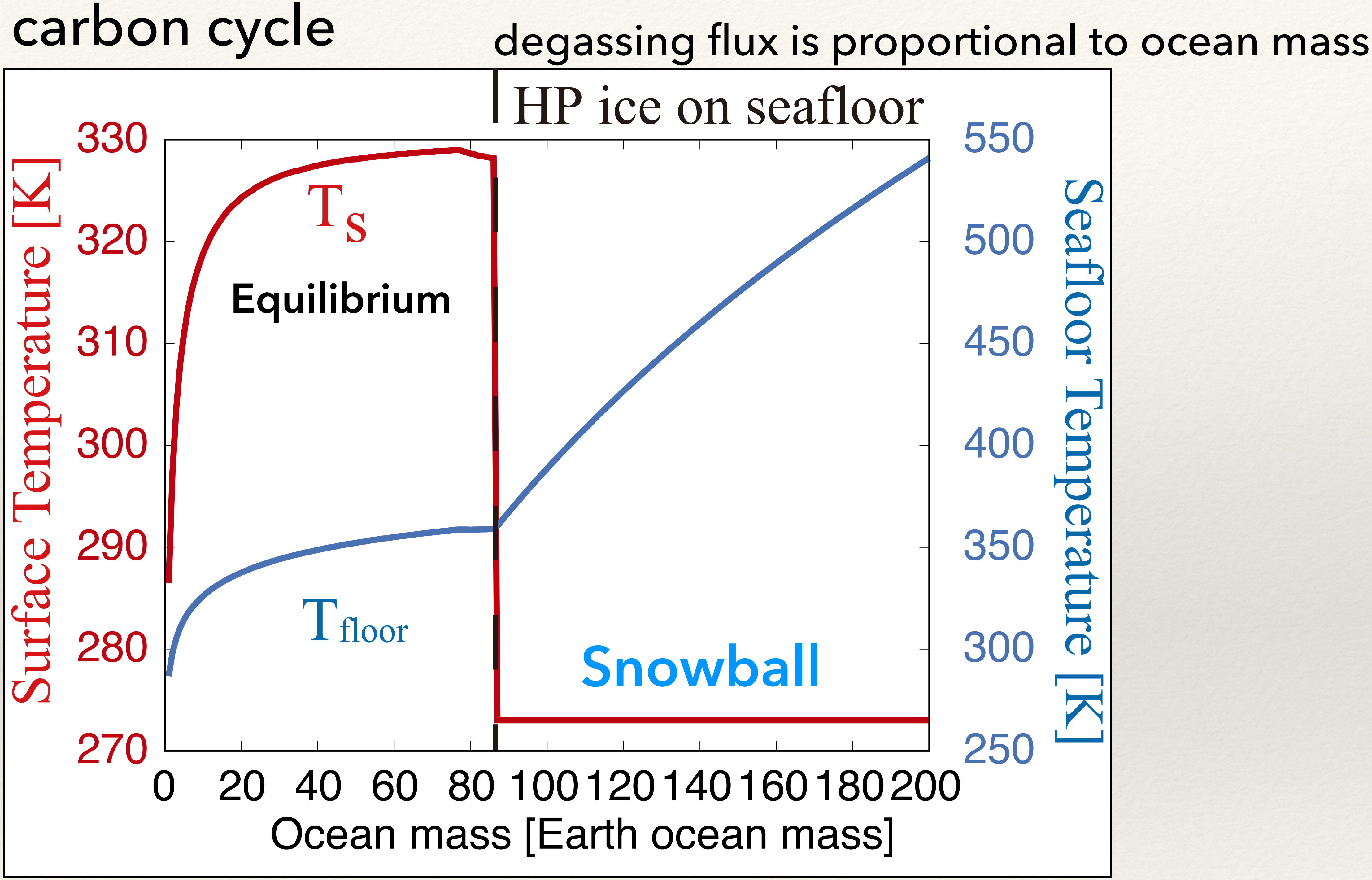


Thin HP ice is entirely molten

Even if thick HP ice (>150km), >10% of HP ice is molten

Results / Runaway cooling due to melting the HP ice

Results of carbon cycle



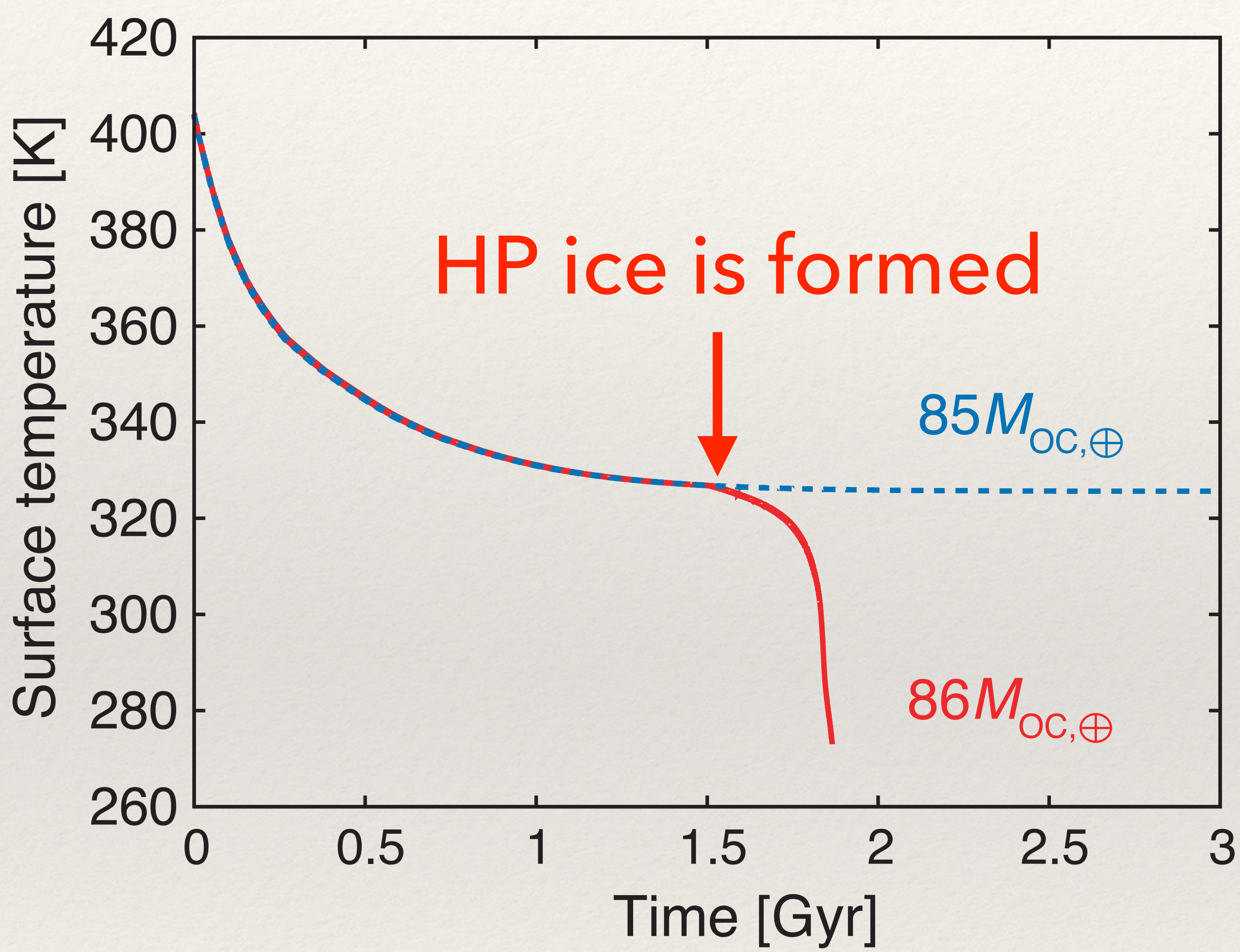
Once HP ice is formed, weathering flux remains fixed

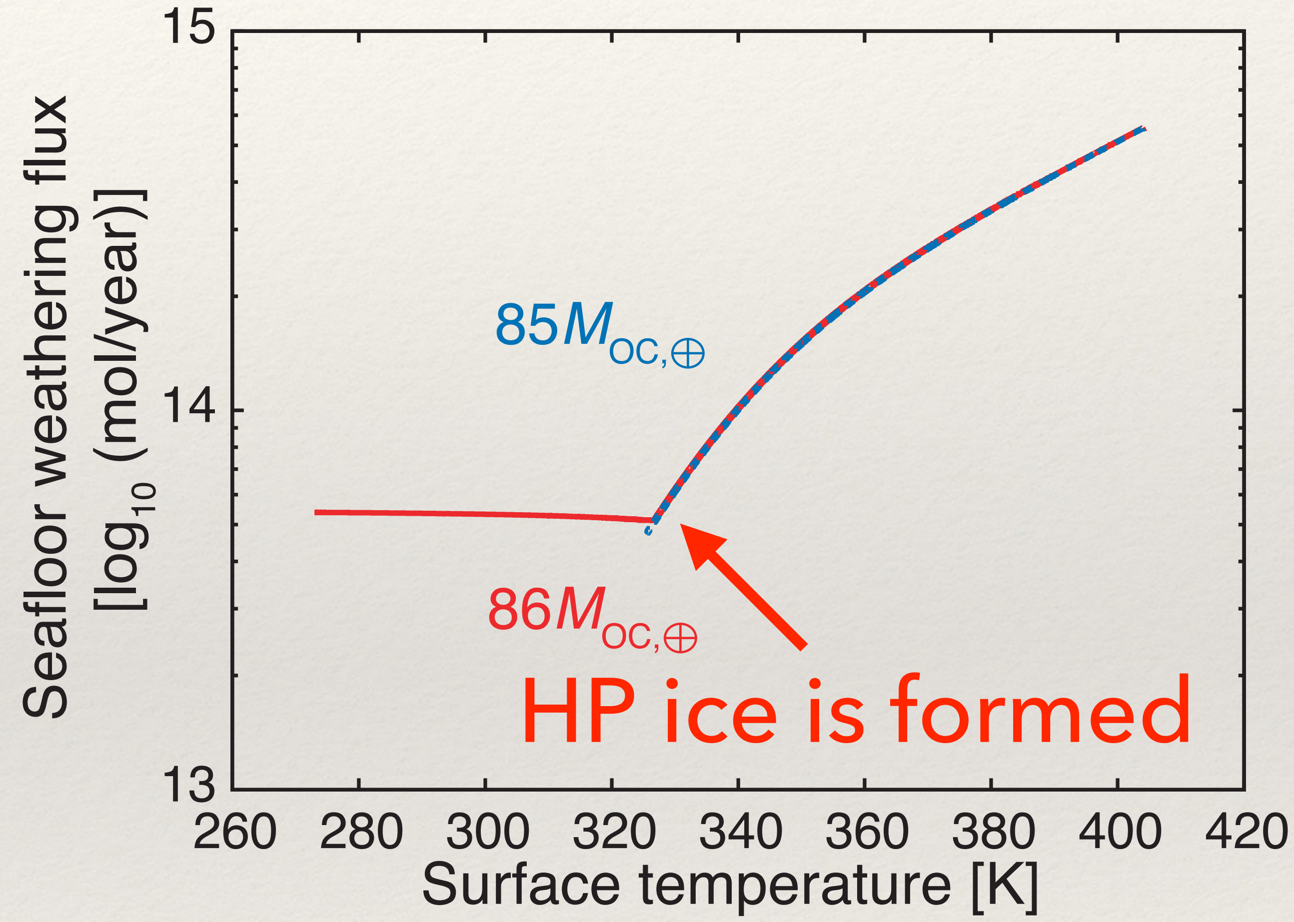
➡ **Runaway cooling results in cold climate (snowball)**

Results / Runaway cooling due to melting the HP ice

Time evolution of carbon cycle

Seafloor temperature is bounded at melting point regardless of surface temperature





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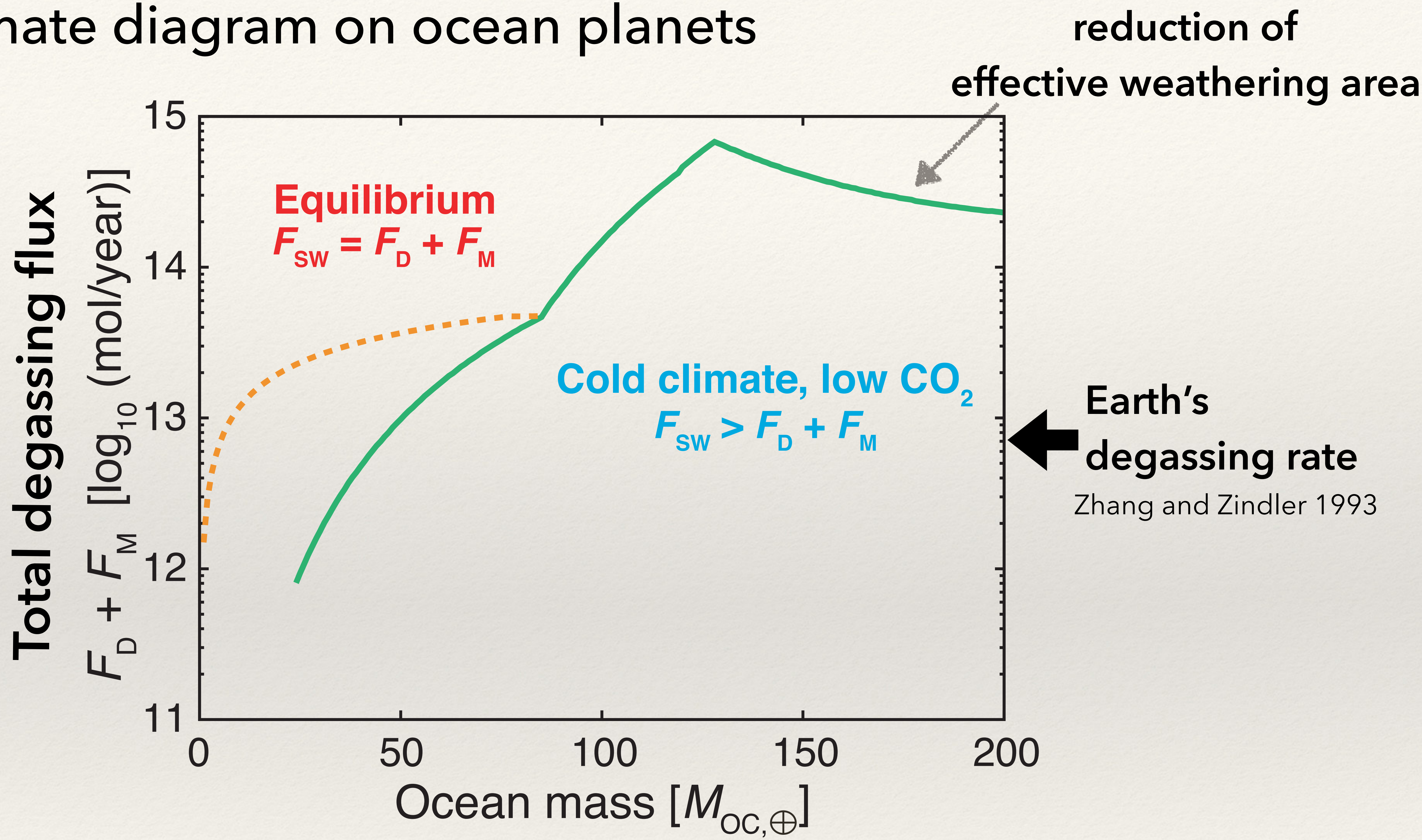
Climate diagram on ocean planets



There is **critical ocean mass**

beyond which no longer maintain clement climate

(without another greenhouse gas)

Summary

- We have performed carbon cycle simulation on water-rich ocean planet in the habitable zone
- We have found runaway cooling due to CO_2 consumption triggered by formation and melting of high-pressure ice.