Astrobiology
Lecture 8

Planetary climates and habitable zones

University of Trieste, 2023
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Climate models and planetary habitability

- The determination of the physical conditions at the planetary surface requires the use of climate models
  - With climate models we can take into account a variety of processes that affect the surface planetary conditions

    E.g., greenhouse effect, ice-albedo feedback, water vapou-temperature feedback, and many others
- Climate models, originally developed for Earth studies, are becoming a key tool for modeling planetary habitability
  - The climate system is extremely complex, due to the presence of several feedbacks acting on different time scales
  - The state-of-the-art models, called "Global Circulation Models" (GCM), are extremely time consuming

Bibliographic material:

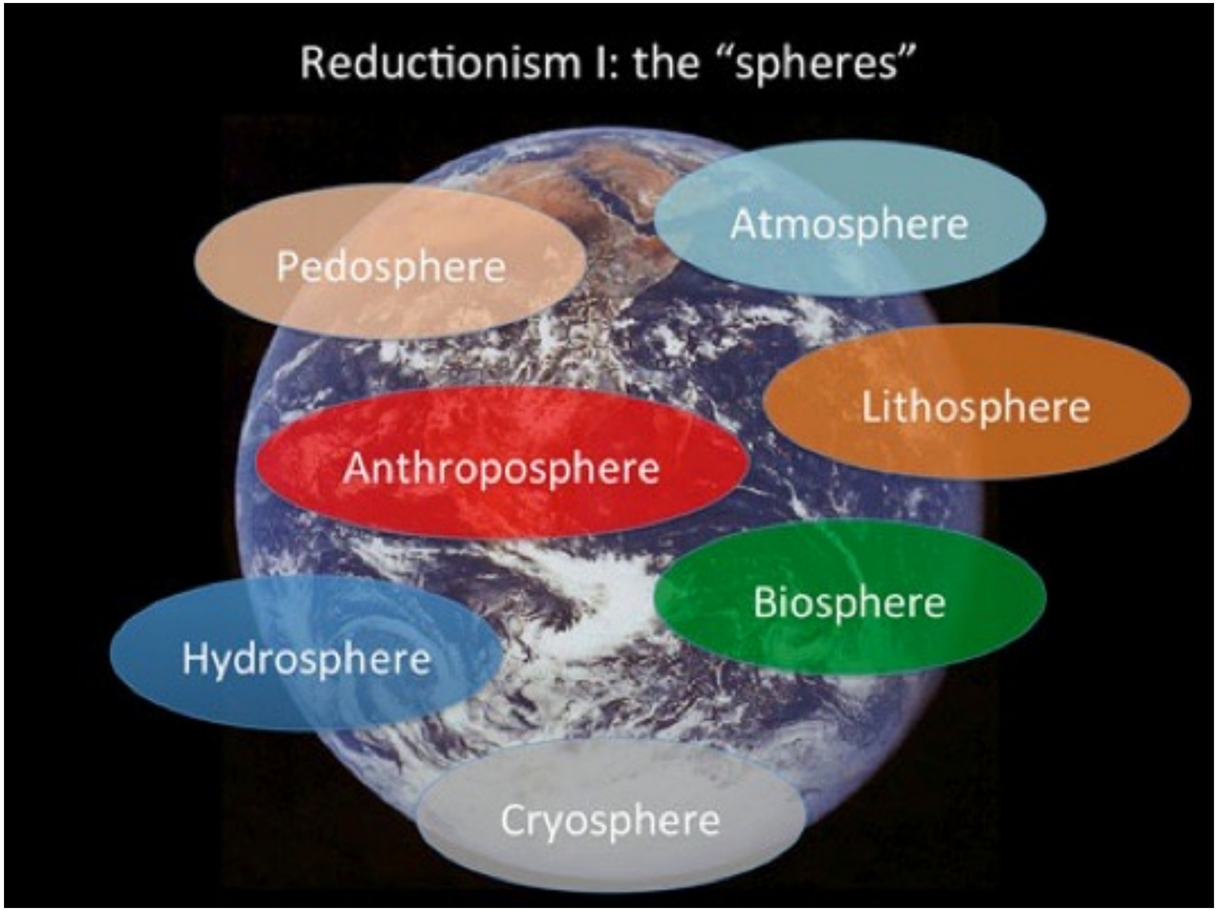
Pierrehumbert (2010) Principles of Planetary Climate

Complexity of the climate system: the problem of the time scales

Time scales of different components of the climate system

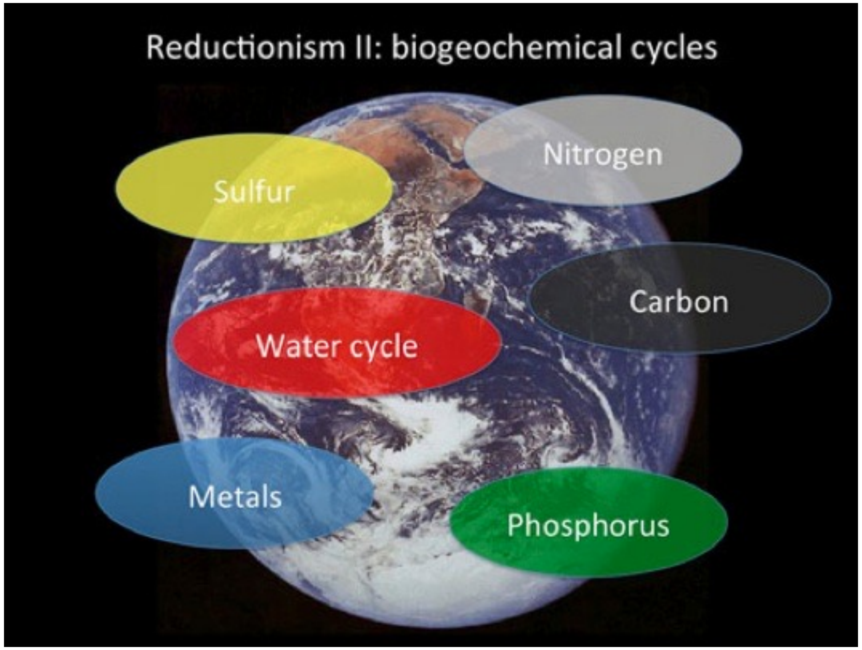
Atmosphere	
Overall response time to heating	months
Typical spin-down time of wind if nothing is forcing it	days
Frontal system lifetime (1000s of km)	days
Convective cloud lifetime (100 m to km horizontal; up to 10 km vertical)	hours
Time scale for typical upper-level wind ($20\,m\,s^{-1}$) to cross continent (a few 1000 km)	days
Ocean	
Response time of upper ocean (above thermocline) to heating	months to years
Response time of deep ocean to atmospheric changes	decades to millennia
Ocean eddy lifetime (10s to 100 km)	months
Ocean mixing in the surface layer	hours to days
Time for typical ocean current ($cm\,s^{-1}$) to cross ocean (1000s of km)	decades
Cryosphere	
Snow cover	months
Sea ice (extent and thickness variations)	months to years
Glaciers	decades to centuries
Ice caps	centuries to millennia
Land surface	
Response time to heating	hours
Response time of vegetation to oppose excess evaporation	hours
Soil moisture response time	days to months
Biosphere	
Ocean plankton response to nutrient changes	weeks
Recovery time from deforestation	years to decades
Lithosphere	
Isostatic rebound of continents (after being depressed by weight of glacier)	10 000s of years
Weathering, mountain building	1 000 000s of years

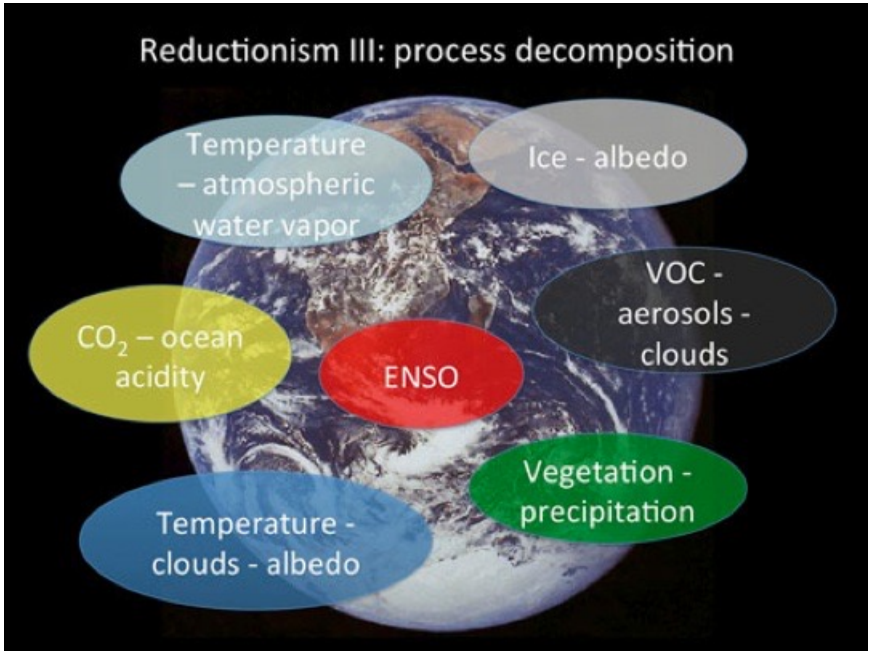
Tackling the complexity of the climate system: Reductionistic approaches



Provenzale (2013)

Tackling the complexity of the climate system: Reductionistic approaches

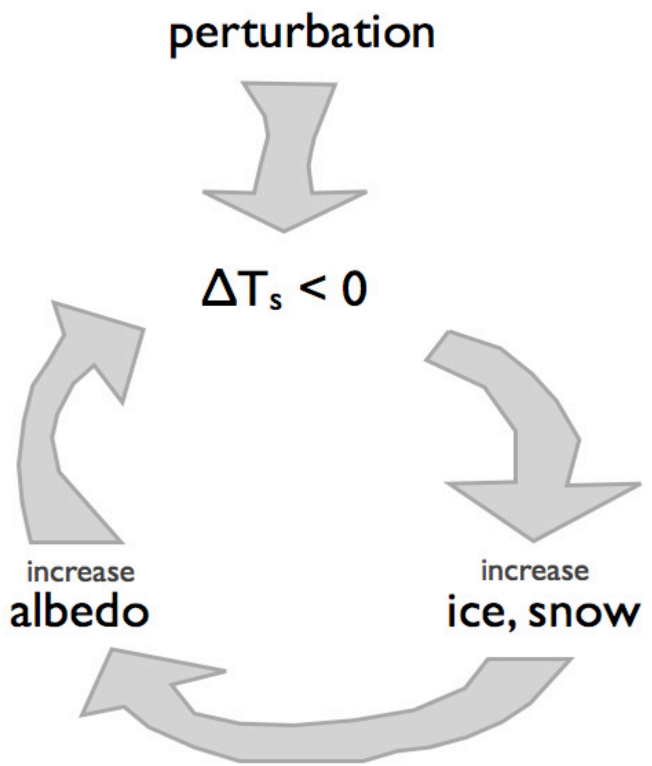




Provenzale (2013)

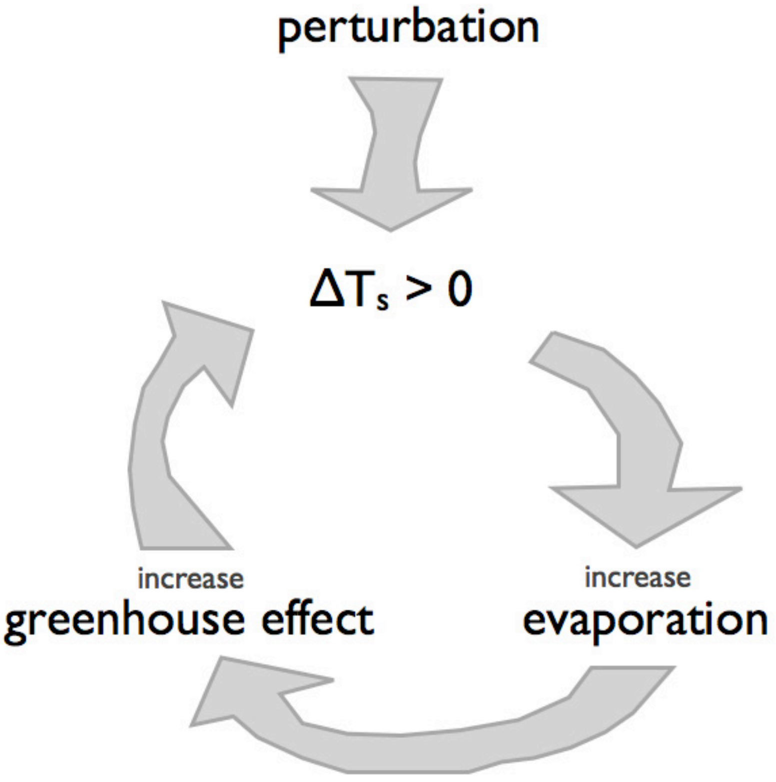
Feedbacks and climate instabilities

- The ice-albedo feedback
  - If water and ice are present on the planet, a decrease of temperature will increase the surface covered by ice
  - Ice has a very high albedo and an increase of the ice extension will cool the planet even more
  - In extreme conditions, this feedback may lead to a "snowball planet", i.e. a planet fully covered by ice



Feedback and climate instabilities

- The temperature-water vapour feedback
  - If water is present on the planet, the water vapour pressure rises with temperature
  - Water vapour is a strong greenhouse gas, and a rise of water vapour will rise the temperature even more
  - In normal conditions, this feedback is not catastrophic because the cooling rate scales as σT^4



Given the complexity of the climate system,
simplified climate models are often used for studying the habitability of planets other than the Earth

Zero-order planetary energy balance:
the starting point to build simplified climate models

$$I = S\,(1-A)$$

I: Outgoing Longwave Radiation

S: Insolation

A: albedo

Simplest climate models used in studies of habitability:

1) Radiative-convective models in a single atmospheric column

2) Energy Balance Climate models

Single atmospheric-column climate models

Used in early calculations of planetary habitability

Only the vertical component of the energy transport is considered

- Vertical transport approximated with radiative-convective models
  - Includes a treatment of the dependence of greenhouse effect on atmospheric composition
- Horizontal transport along the planetary surface is not considered

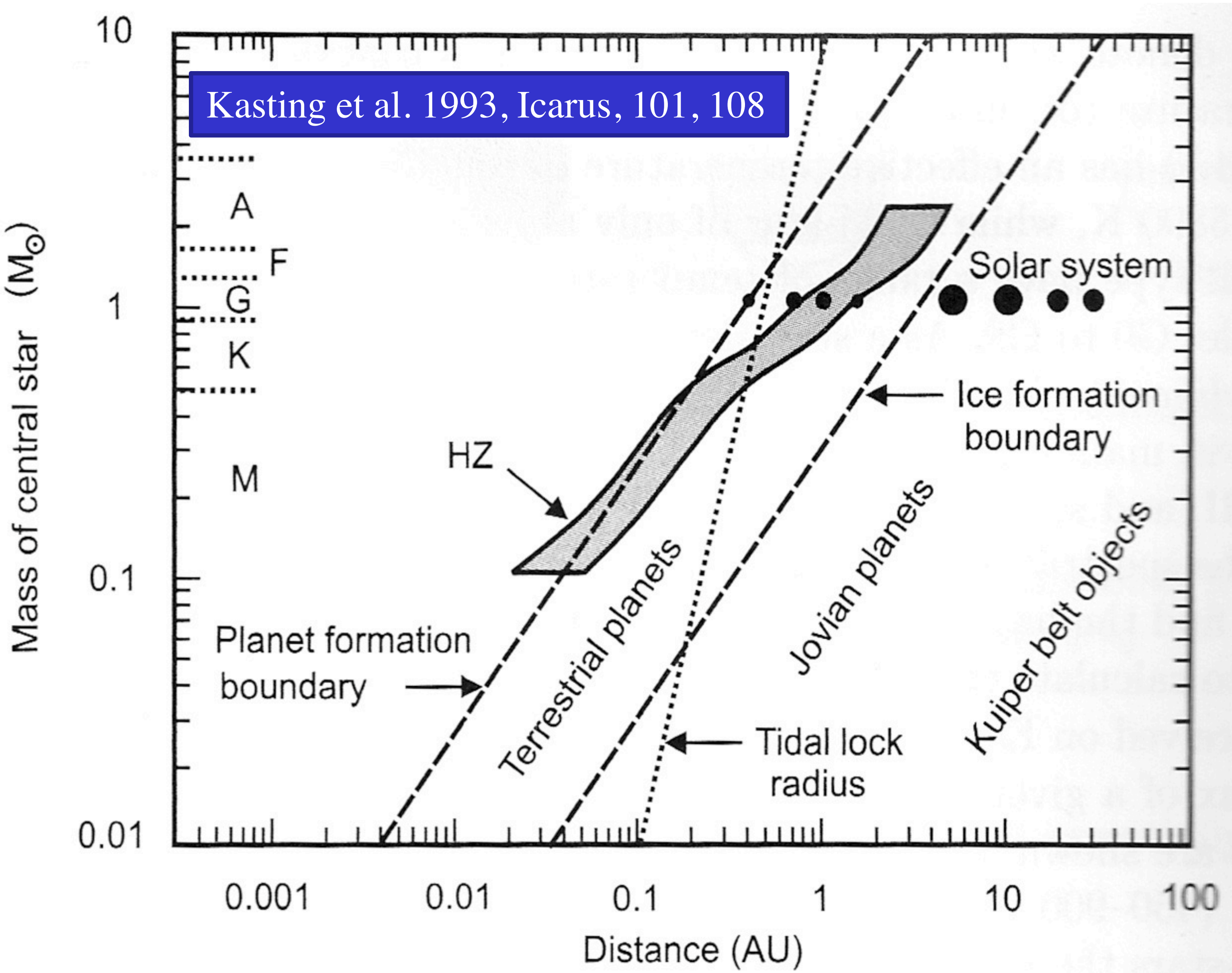
Average planetary properties are adopted for the albedo and insolation

  - Includes a treatment of the dependence of the albedo on the spectral distribution of the stellar flux
- Clouds are not considered

The classic habitable zone

- Early calculations of planetary habitability were performed before exoplanets were discovered
  - J. Kasting and collaborators (Penn State University)
- Simplified climate models
  - Radiative-convective transport in a single atmospheric column
- Calculated for stars of different spectral types
  - The energy distribution of the stellar spectrum affects the albedo
- Definition of the circumstellar habitable zone
  - Interval of distances from the central star where a planet can have surface conditions suitable for the long-term presence of liquid water
  - Two different criteria are adopted to define the inner and outer edge of the habitable zone

The classic habitable zone



The inner edge of the habitable zone

- The runaway greenhouse mechanism
  - If the temperature-water vapour feedback is extreme, the vapour may reach the outer layers of the atmosphere
  - In the outer layers the water molecules can be dissociated by high energy stellar photons
  - The hydrogen produced by photodissociation can be lost to space
  - This chain of events is called the runaway greenhouse mechanism
  - In the long term, this mechanism may lead to the disappearence of liquid water on the planet
  - The "runaway greenhouse" mechanism is used to define the inner edge of the habitable zone

The outer edge of the habitable zone

- An increase of greenhouse gases in the planetary atmosphere makes the planet habitable at lower levels of stellar flux, i.e. at larger distances from the central star

- To keep the planet habitable in the outer regions of the habitable zone it is assumed that the planetary atmosphere is dominated by CO_2
  - as in the case of Mars

- The amount of CO_2 that is able to warm the planet at low levels of insolation is limited by the rise of the albedo due to CO_2 (clouds and atmosphere), which counteracts the heating due to greenhouse effect

- The outer edge is defined via the "maximum greenhouse" criterion, i.e. the maximum amount of CO_2 before cooling of the clouds take place

Mechanisms of climate stabilization

In the definition of the classic habitable zone it is assumed that the planet has the capability of adjusting its level of CO_2 through a <u>mechanism of climate stabilization</u>

The fact that Earth's climate has been relatively stable in the course of geological time scales suggests the existence of a mechanism of climate stabilization

This mechanism must have been able to stabilize the Earth's climate despite changes that have occurred in terms of solar radiation, atmospheric composition and other factors

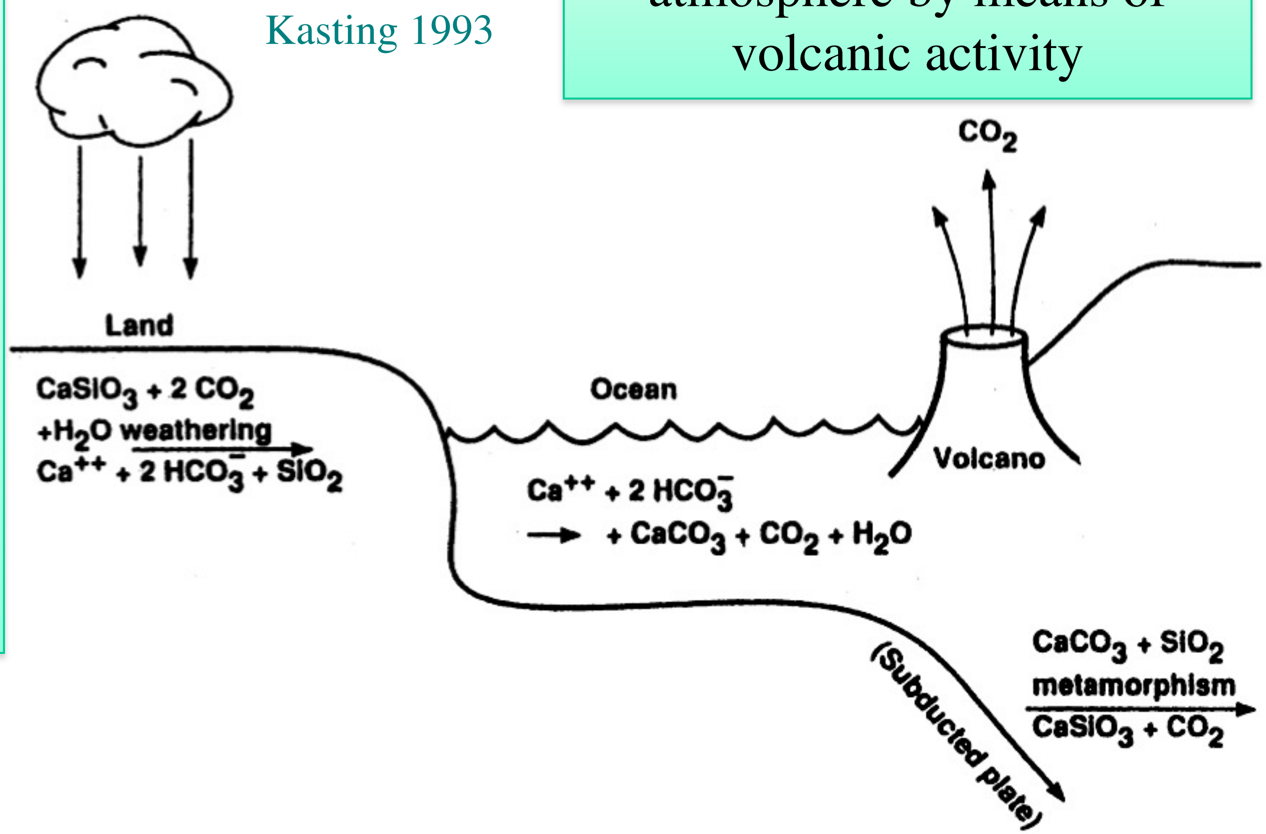
The mechanism invoked for the Earth is based on a CO_2 inorganic cycle

The CO_2 cycle of climate stabilization

1. - Weathering processes remove CO_2 from the atmosphere

2. - The chemical products are gradually deposited to the bottom of the oceans and eventually subducted, due to tectonic activity

3. - CO_2 from the Earth's mantle is emitted to the atmosphere by means of volcanic activity



The CO_2 cycle of climate stabilization

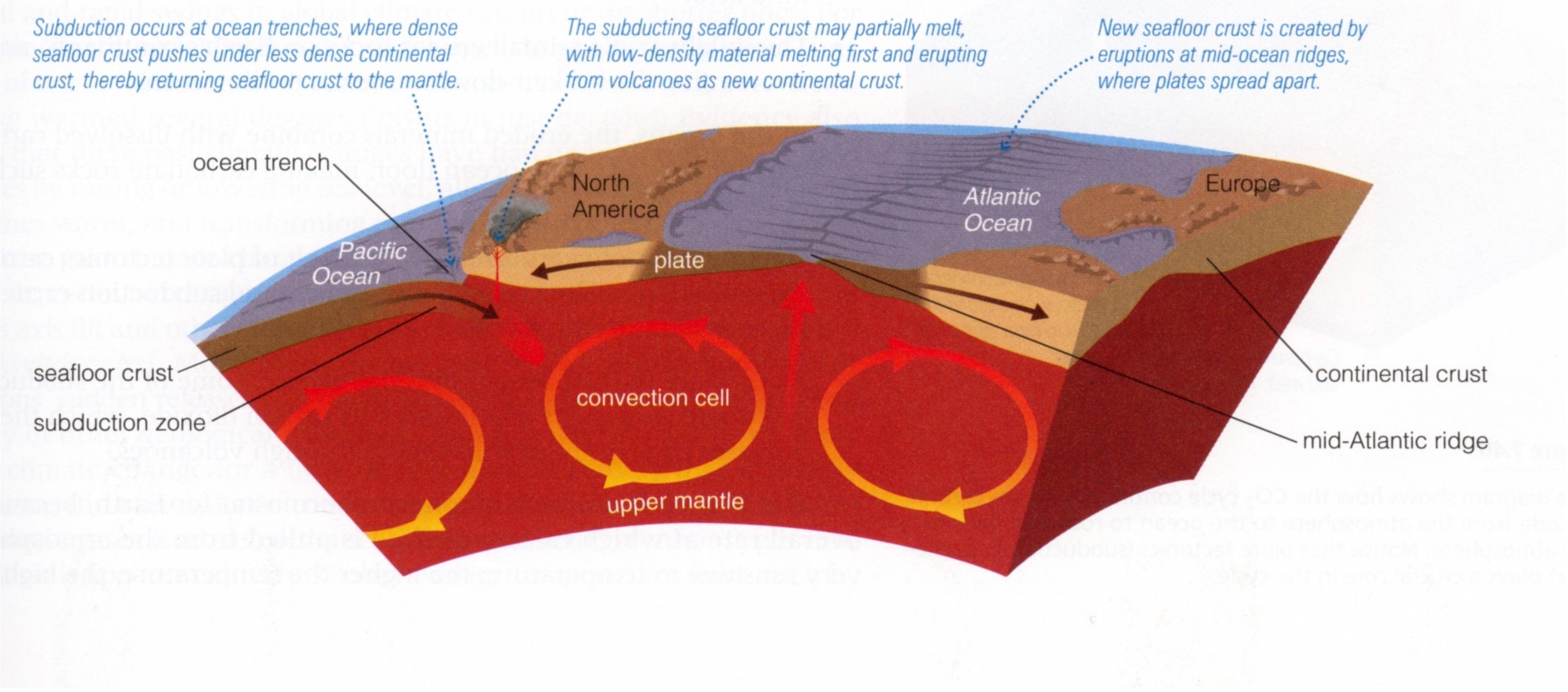
The weathering efficiency increases with atmospheric temperature

The rate of CO_2 emission is independent of the atmospheric temperature

As a result, there is a negative feedback temperature-CO_2 that stabilizes the climate

- The time scale of the cycle is estimated to be ~ 5×10^5 years

- The sustainance of the CO_2 stabilization cycle requires geophysical activity (tectonics and volcanism)
  - In the present-day Solar System, only the Earth has these types of geophysical activities
  - The CO_2 cycle of climate stabilization is invoked in the definition of the classic habitable zone
  - How common this mechanism can be in terrestrial-type exoplanets is currently the subject of studies of exoplanetary interiors

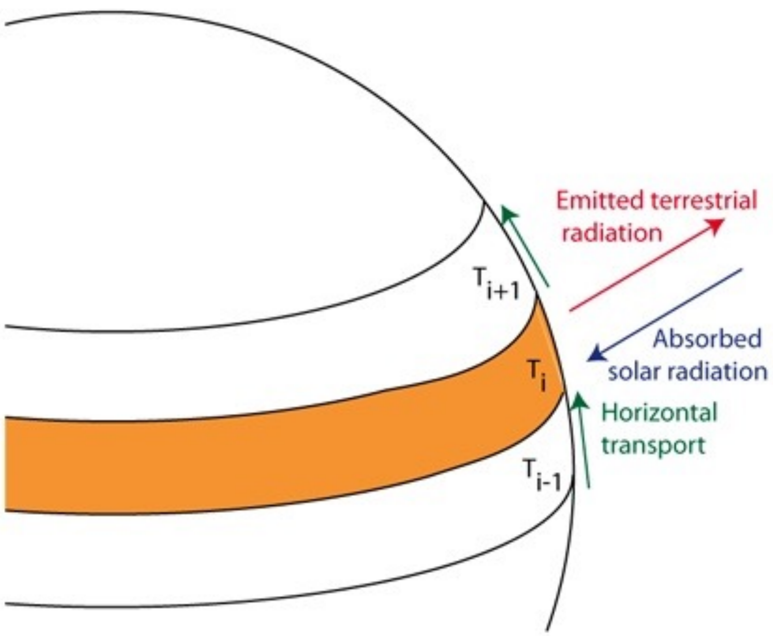


Habitability under the planet surface

- The definition of habitable zone relies on the concept of surface habitability
  - Habitability under the planet surface can be present in planetary or minor bodies outside the circumstellar habitable zone, in particular beyond the outer edge
- Temperature and pressure gradients may yield conditions of habitability in the interior of planets or satellites
  - Internals sources of heat yield a temperature gradient from the surface to the planetary interior
  - The pressure gradient towards the planetary interior might shift the local pressure above the triple point of water

Energy balance models (EBM) of planetary climate

Simplified models aimed at predicting the seasonal and latitudinal distribution of the surface temperature



$$I_i + C_i \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[D_i\left(1-x^2\right)\frac{\partial T}{\partial x}\right] = S_i\left(1-A_i\right)$$

$x = \sin\phi$ (ϕ is the latitude)

Climate models for exoplanets developed at INAF-OATs (I)

Earth-like Surface Temperature model (ESTM)

EBM with improved treatment of the latitudinal transport

The Astrophysical Journal, 767:65 (23pp), 2013 April 10 doi:10.1088/00

THE HABITABLE ZONE OF EARTH-LIKE PLANETS WITH DIFFERENT LEVELS OF ATMOSPHERIC PRESSURE

Giovanni Vladilo[1,2], Giuseppe Murante[1], Laura Silva[1], Antonello Provenzale[3], Gaia Ferri[2], and Gregorio Ragazzini[2]

The Astrophysical Journal, 804:50 (20pp), 2015 May 1 doi:10.1088/0004-637X/804/1/50

MODELING THE SURFACE TEMPERATURE OF EARTH-LIKE PLANETS

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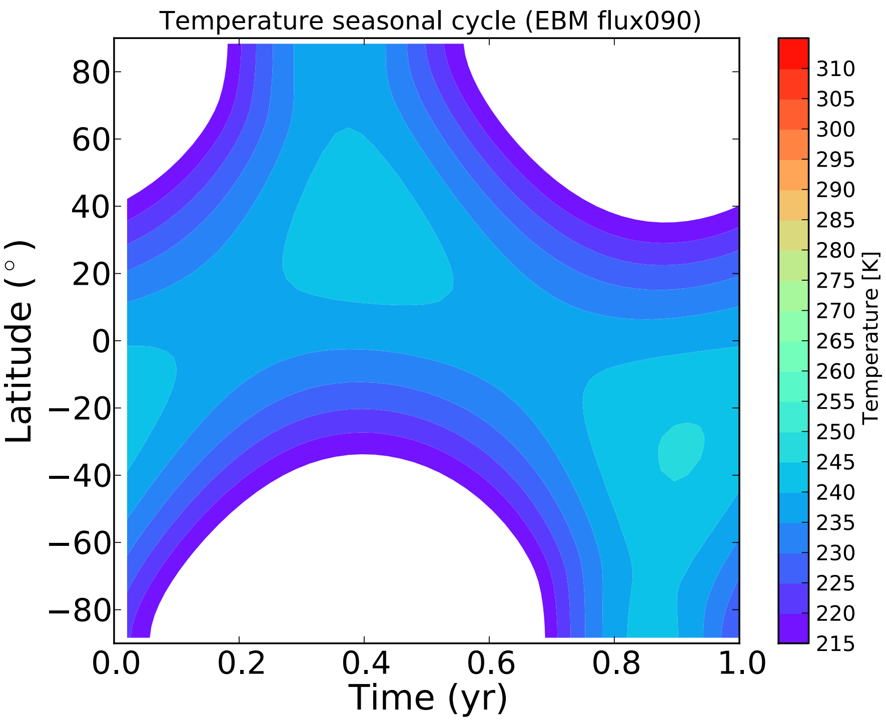
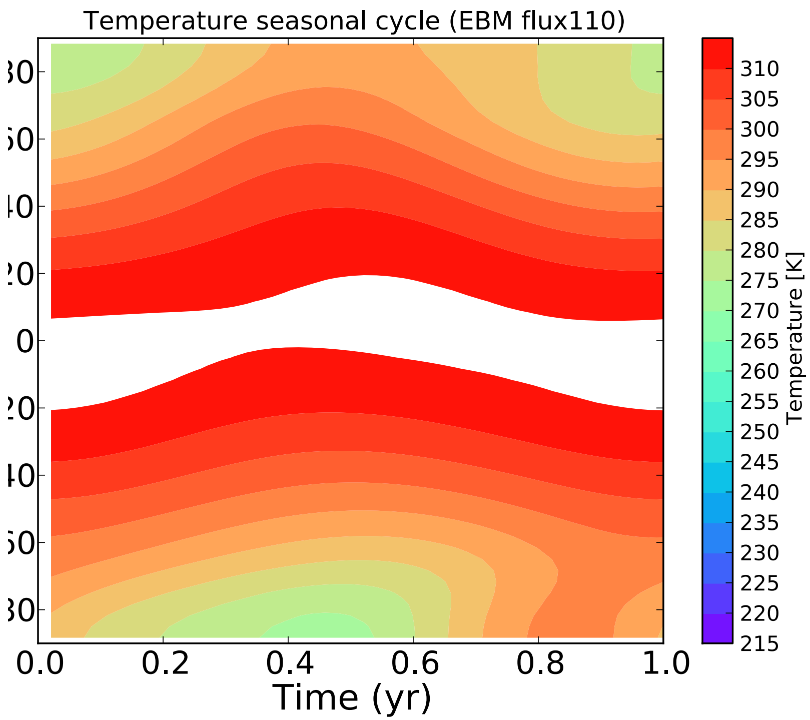
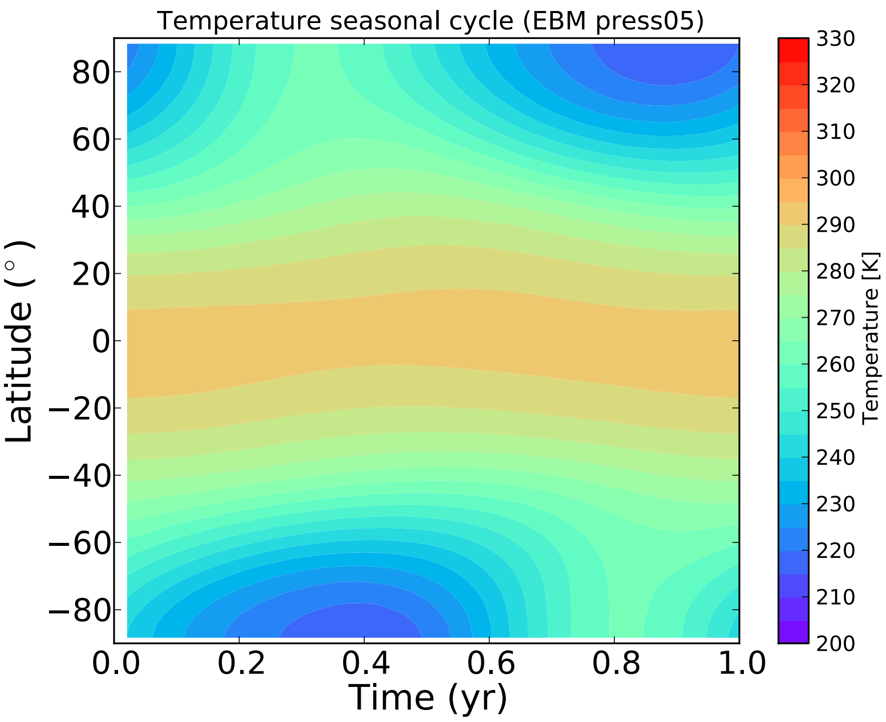
Examples of application of the ESTM
Seasonal and latitudinal surface temperature of the Earth

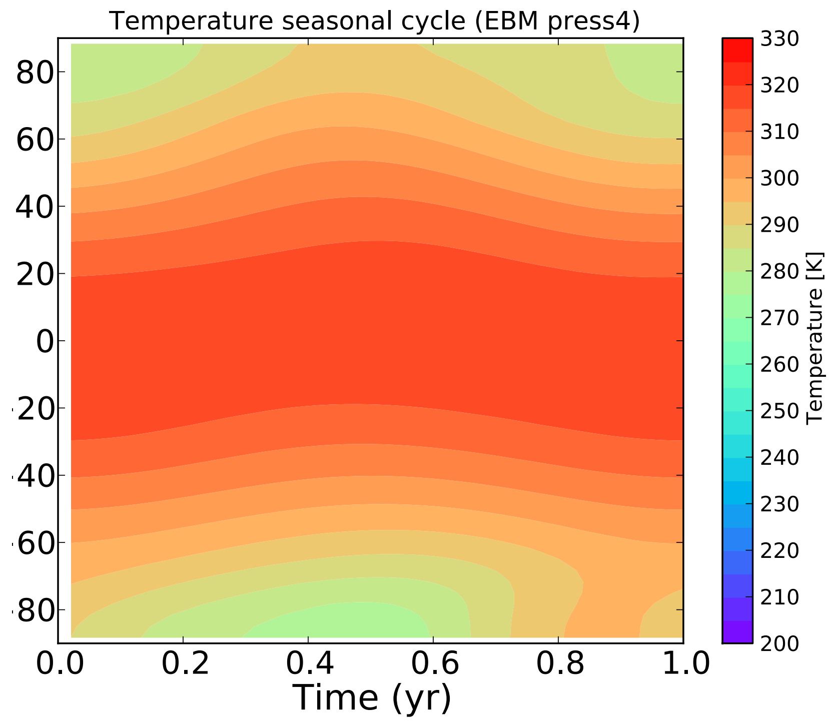
Impact of stellar insolation on the surface temperature distribution



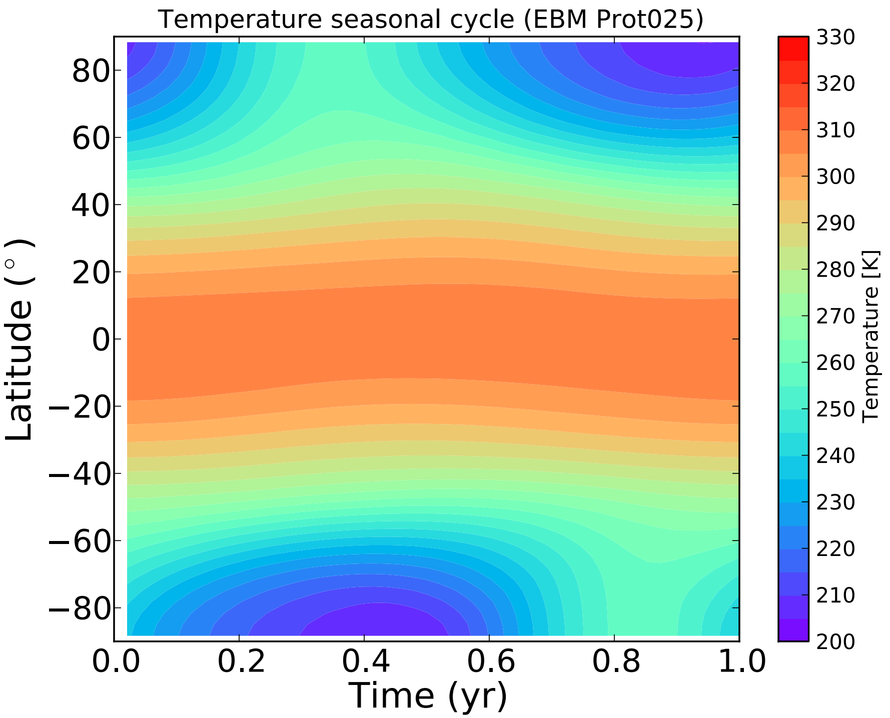


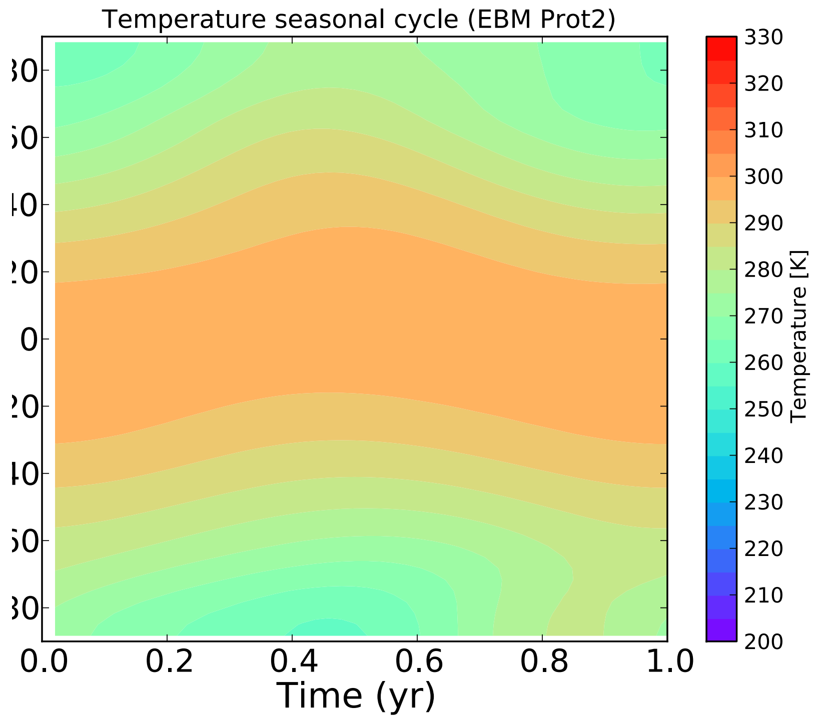
Impact of atmospheric pressure on the surface temperature distribution





Impact of rotation period on the surface temperature distribution





Energy balance climate model

⬇

Planet surface temperature distribution

⬇

Temperature-dependent habitability criterion

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Planet surface habitability

The climate simulation yields
the surface temperature
as a function of latitude and time

$$T(\phi, t)$$

Habitability function

$$H(\phi, t) = \begin{cases} 1 & \text{if } T_{\text{melt}}(p) \leq T(\phi, t) \leq T_{\text{boil}}(p) \\ 0 & \text{otherwise} \end{cases}$$

Liquid water criterion

Mean global annual habitability

$$h = \frac{\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\phi \int_0^P dt \, [H(\phi, t) \cos\phi]}{2P}$$

The habitable zone in the plane
Insolation – Atmospheric columnar mass

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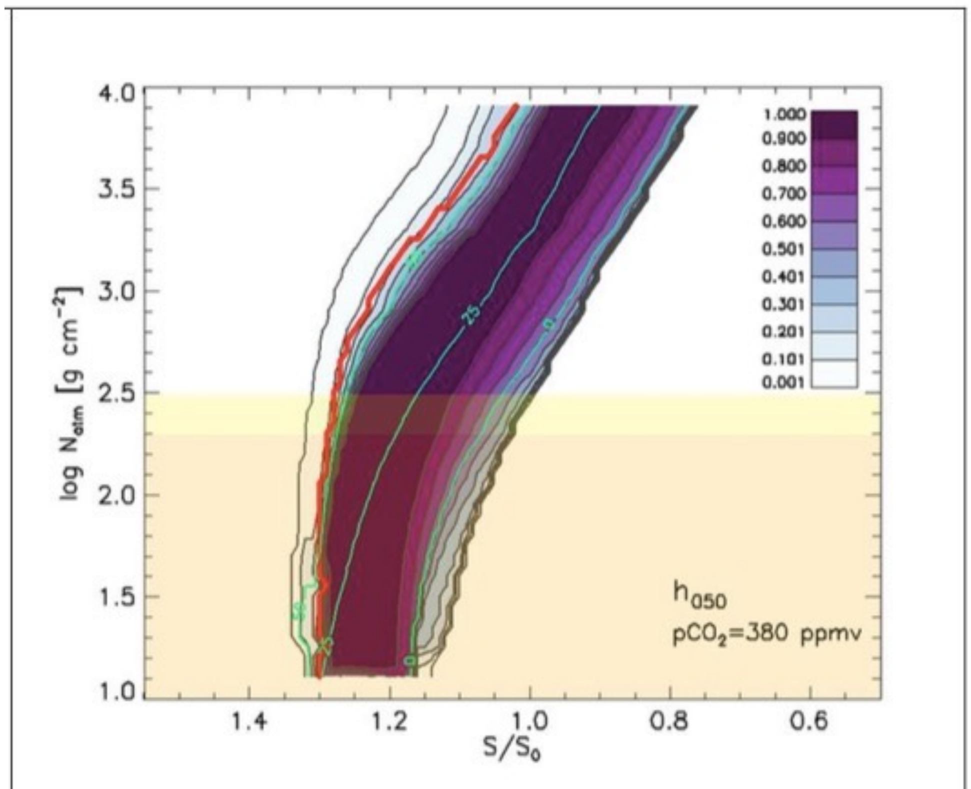
From climate models to planetary habitability: temperature constraints for complex life

Laura Silva[1], Giovanni Vladilo[1], Patricia M. Schulte[2], Giuseppe Murante[1] and Antonello Provenzale[3]



Example obtained using the temperature limits 0°C ≲ T ≲ 50°C

Climate models for exoplanets developed at INAF-OATs (II)

The Astrophysical Journal, 925:105 (18pp), 2022 February 1
https://doi.org/10.3847/1538-4357/ac32ca

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EOS: Atmospheric Radiative Transfer in Habitable Worlds with HELIOS

Paolo Simonetti[1,2], Giovanni Vladilo[2], Laura Silva[2,3], Michele Maris[2], Stavro L. Ivanovski[2], Lorenzo Biasiotti[2], Matej Malik[4], and Jost von Hardenberg[5]

MNRAS **514,** 5105–5125 (2022)
https://doi.org/10.1093/mnras/stac1642
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EOS-ESTM: a flexible climate model for habitable exoplanets

L. Biasiotti,[1,2★] P. Simonetti,[1,2] G. Vladilo,[1] L. Silva,[1,3] G. Murante,[1] S. Ivanovski,[1] M. Maris,[1] S. Monai,[1] E. Bisesi,[1] J. von Hardenberg[4] and A. Provenzale[5]