Climate models and planetary habitability

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Climate calculations and planetary habitability

- The calculation of the physical conditions at the planetary surface requires the use of climate models
  - With climate models we can take into account the greenhouse effect and a variety of other processes that affect the physical conditions at the planet surface
- Climate models, originally developed for Earth studies, are becoming a key tool for modeling planetary habitability
  - The state-of-the-art models, called “Global Circulation Models” (GCM), are extremely time consuming
  - Simplified climate models are often used for studies of planetary habitability

Bibliographic material:
Pierrehumbert (2010) Principles of Planetary Climate
Neelin (2011) Climate Change and Climate Modeling

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

Time scales of different components of the climate system

Reductionistic approaches to tackle the complexity of the climate system

Provenzale (2013)
Reductionistic approaches
to tackle the complexity of the climate system

Provenzale (2013)

Climate instabilities
can drive the planet temperature out of the range of habitability

• 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

• 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 $\sigma T^4$
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
  - Different spectral energy distribution affects the albedo
- Calculations used to define the circumstellar habitable zone
  - Interval of distances from the central star where a habitable planet can be found
  - Different types of criteria are adopted to define the inner and outer edge of the habitable zone
  - Climate instabilities play an important role in the definition of the 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 disappearance 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
- The outer edge of the habitable zone is defined assuming 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 onset of CO$_2$ clouds with high albedo, which would counteract the heating due to greenhouse effect
Mechanisms of climate stabilization

In the definition of the classic habitable zone it is assumed that the planet has the capability of adjusting the level of CO$_2$ through a mechanism of climate stabilization.

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

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 $\sim 5 \times 10^5$ years.

- The existence of tectonics and volcanism is necessary for the existence of the CO$_2$ stabilization cycle.
  - 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.
  - Not clear how common this mechanism can be in terrestrial-type exoplanets.
Habitability under the planet surface

- The definition of habitable zone relies on the concept of surface habitability
  - Habitability under the planet surface could be present in planetary 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 in the planet interior
  - The pressure gradient towards the planetary interior may improve the conditions of habitability

Surface habitability with Energy Balance Models (EBMs)

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

Energy balance climate model

- Planet surface temperature
- Temperature-dependent habitability criterion
- Planet surface habitability

Energy balance models (EBM) of planetary climate

\[ I_i + C_i \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left[ D_i (1 - x^2) \frac{\partial T}{\partial x} \right] = S_i (1 - A_i) \]
Examples of application of the ESTM
Seasonal and latitudinal surface temperature of the Earth

Variation of stellar insolation

Variation of surface pressure

Examples of application of the ESTM
Seasonal and latitudinal surface temperature of an Earth-like planet

Variation of rotation period

Quantifying the habitability with the liquid water criterion

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

\[ T(\phi, t) \]

Habitability function:

\[ H(\phi, t) = \begin{cases} 1 & \text{if } T_{\text{min}}(\phi) \leq T(\phi, t) \leq T_{\text{max}}(\phi) \\ 0 & \text{otherwise} \end{cases} \]

Liquid water criterion:

\[ h = \frac{\int_{-\pi/2}^{\pi/2} \int_{0}^{1} \delta(\phi, t) \cos \phi \, dt \, d\phi}{2P} \]

Mean global annual habitability:
Pressure dependence of the habitable zone
Obtained running a large number of climate simulations
Vladilo et al. (2013)

At low pressure, the mean planet temperature is not a good diagnostic of habitability

Pressure dependence of the habitable zone
Obtained running a large number of climate simulations
Vladilo et al. (2013)

The atmospheric mass habitable zone
for complex life and atmospheric biomarkers
Obtained using the temperature limits 0°C ≤ T ≤ 50°C
Silva et al. (2016)