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Swansong Biospheres: The biosignatures of inhabited earth-like planets nearing the end of their habitable lifetimes

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Abstract. The biosignatures of life on Earth are not fixed, but change with time as environmental conditions change and life living within those environments adapts to the new conditions. A latitude-based climate model, incorporating orbital parameter variations, was used to simulate conditions on the far-future Earth as the Sun enters the late main sequence. Over time, conditions increasingly favour a unicellular microbial biosphere, which can persist for a maximum of 2.8 Gyr from present. The biosignature changes associated with the likely biosphere changes are evaluated using a biosphere-atmosphere gas exchange model and their detectability is discussed. As future Earth-like exoplanet discoveries could be habitable planets nearing the end of their habitable lifetimes, this helps inform the search for the signatures of life beyond Earth

Keywords. Astrobiology, Sun: evolution, Earth.

1. Introduction

The increasing luminosity of the Sun as it ages will cause surface temperatures on Earth to increase, eventually leading to runaway ocean evaporation, making conditions more favourable for a unicellular microbial biosphere, similar to (but smaller than) that present for the first 2.5 Gyr of Earth's habitable lifetime (O'Malley-James *et al.* 2013a).

2. Temperature Model

The primary driver for habitability change is the solar luminosity increase over time, which can be modelled using the methods of Gough (1981), which, when combined with future orbital parameter changes, then determines surface insolation. This, coupled with greenhouse gas changes is used to calculate the flux of energy in and out ($F_{in/out}$) of the Earth climate system,

$$\frac{dT}{dt} = \frac{F_{in} - F_{out}}{C_p} \tag{2.1}$$

at different latitudes (where C_p is the heat capacity at constant pressure), giving a mean surface temperature profile for the planet. The temperature change with altitude can also be derived from this by calculating the adiabatic lapse rate.

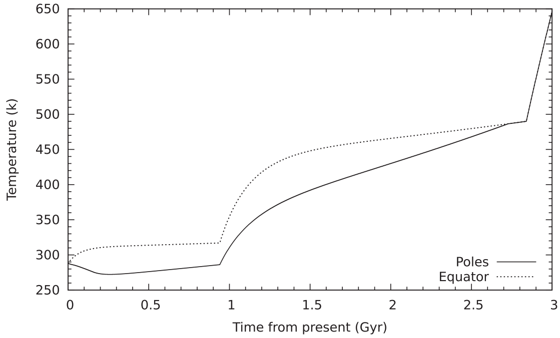

Figure 1. Change in global mean temperature over time with increasing solar luminosity. (O'Malley-James *et al.* 2013a).

3. Stages of biosphere death

Increased temperatures cause an increase in atmospheric water vapour, raising silicate weathering rates, which draws down more atmospheric CO_2. Decreasing CO_2 levels result in the gradual decline of plant species and the animal species they depend on (Calderia & Kasting, 1992; O'Malley-James *et al.* 2013a;b). This leaves behind a microbial biosphere.

Rapid ocean evaporation begins 1 Gyr from present. As water vapour is a greenhouse gas, there is a rapid increase in surface temperatures, reducing the extent of the biosphere by restricting life to remaining areas of liquid water. Such refuges include high altitude pools (for 2.2 Gyr from present), cold trap caves (for 2.8 Gyr from present) and the subsurface (O'Malley-James *et al.* 2013a).

The atmosphere-biosphere model is driven by the surface temperature model. For rapid extinction rates, the die-off of plants and animals may be indicated by elevated atmospheric CH_4 levels, isoprene and ethane (O'Malley-James *et al.* 2013b). Unlike the more productive microbial biospheres of the early Earth, the only potentially detectable biosignature of a far-future microbial biosphere is CH_4, although this may not reach remotely detectable levels in the atmosphere, essentially making a dying biosphere undetectable.

4. Summary and Conclusions

As Earth nears the end of its habitable lifetime it will only be capable of supporting microbial life adapted to multiple extreme conditions. This makes Earth a world predominantly inhabited by microorganisms for approximately two-thirds of its habitable lifetime, which, assuming a similar evolutionary history on Earth-like exoplanets, makes microbial biosignatures important in the search for life beyond the solar system.

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