A Power Driven Model for Predicting Microbial Growth in Poorly Characterised Environments

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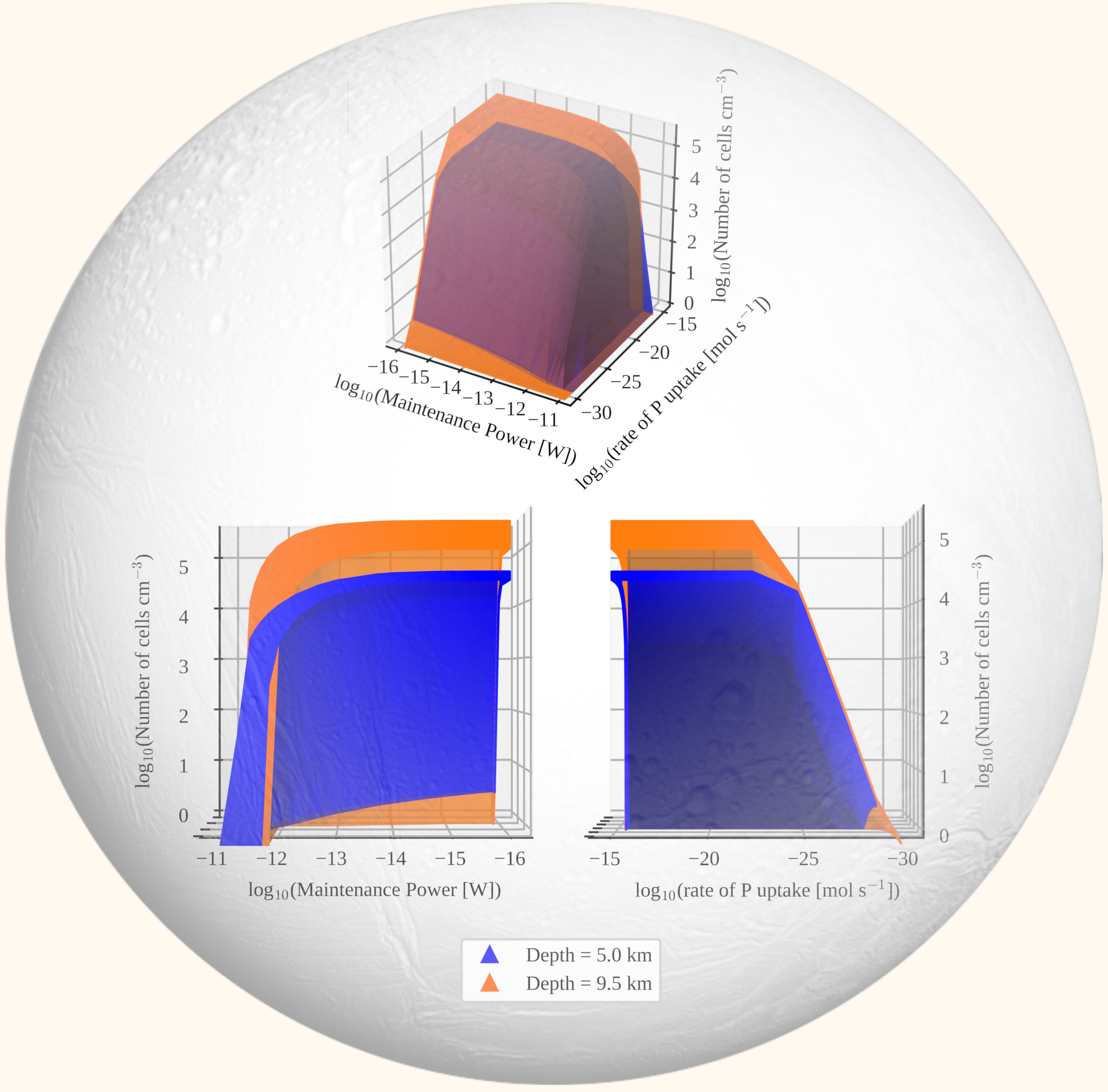
Introduction

Many estimations of energetic availability for life in extraterrestrial environments compute the amount of free energy offered by a given metabolic pathway and use that as a basis for potential habitability. However, the concept of energetic habitability goes far beyond that. We present a computational model which estimates the habitability of environments by not only asserting if there is energy available, but also whether there is enough to actually facilitate survival and growth against extremes and with limited nutrient availability. We use the model to predict the levels of biomass that Enceladus' subsurface ocean could sustain, and find that only a fraction of its expected parameters can provide conditions favourable to life as we know it [1].

Energy and Life

Almost any interaction can be interpreted as an energetic exchange, hence the success and propagation for life can be described in terms of a series of energetic and physiochemical processes. This notion can be used in astrobiology in a so-called energetic approach to habitability [2]. A simple organism has two main uses for its energy: Maintenance and growth [3].

In qualitative terms, the model follows the flowchart opposite. Only a certain amount of energy from some environment can be recovered and stored. A portion of this is then periodically removed to quench some 'maintenance power', and the rest can go into growth. However, this can only occur if there is sufficient nutrient uptake from the habitat to build the relevant structures (e.g. proteins) [1, 2].

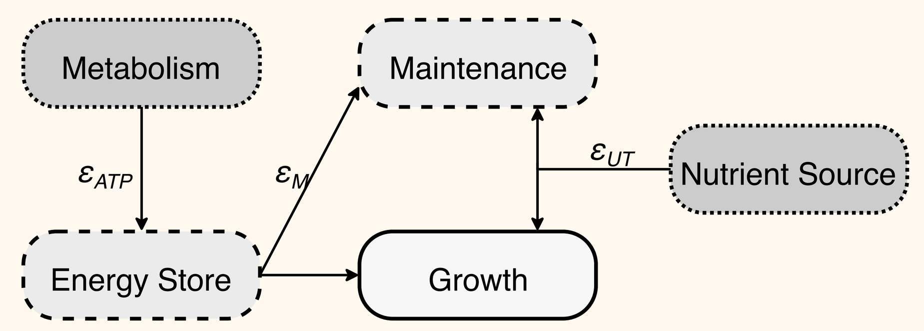


Above: *Maps of the final predicted biomass for a pH 8.5 Enceladean subsurface ocean, at two depths (corresponding to 273 K and 383 K for blue and orange, respectively), varying the rate of Phosphorus uptake, maintenance power, and ATP yield (denoted by thickness). For clarity, plots omit data points where both P molarity < 5 x 10^{-14} M and P uptake rate constant > 10^{-14} s^{-1}, as these introduce 'wells' in the plot, where P is running out as it can be consumed faster. These wells remain small in relation to the uncertainty regarding ATP uptake. Background photo of Enceladus from Cassini (cred. NASA).*

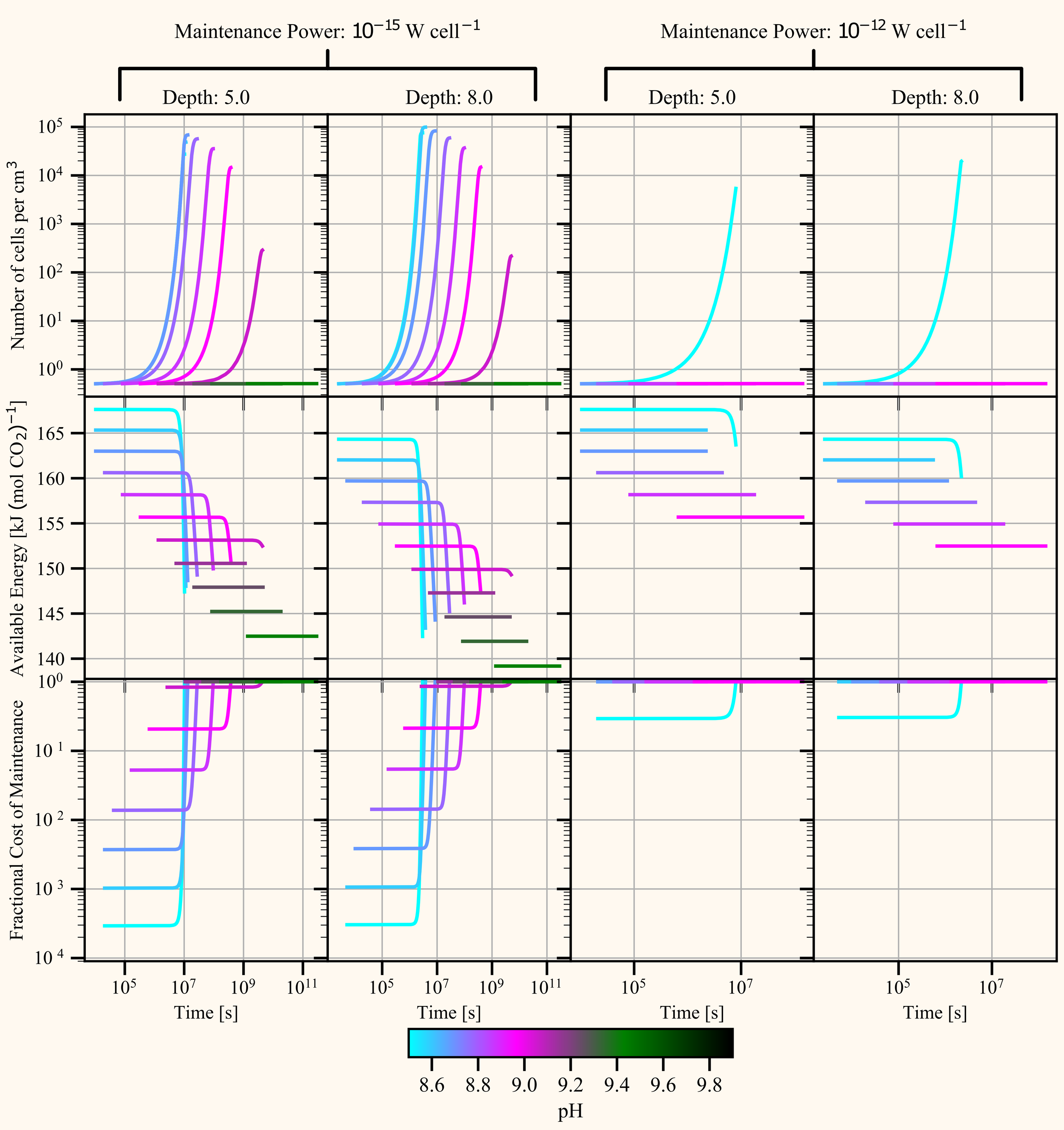
Energetic Availability at Enceladus

To demonstrate the concept, several small simulations of methanogens in an Enceladus' ocean 'sample' have been performed using the limited data available in the literature for this environment. Cassini measurements point to the existence of CH_4, CO_2, and H_2 in the subsurface ocean [e.g. 4] – the ingredients of the methanogenesis metabolism. However, predicting the actual oceanic composition of these species has proven difficult, limiting estimates to many orders of magnitude with strong dependencies on pH [4], which is poorly constrained itself, as somewhere between 8.5–13.5 [5, 6].

Using standard thermochemical modelling, the amount of free energy per mole of CO_2 has been calculated at the oceanic compositions related to the pHs, and is shown below, right. As increasing the pH may limit the availability of CO_2 [4], the total amount of energy retrievable by methanogenesis decreases. This helps to throttle the power supply which severely limits growth above as little as pH 9 (see below, left).

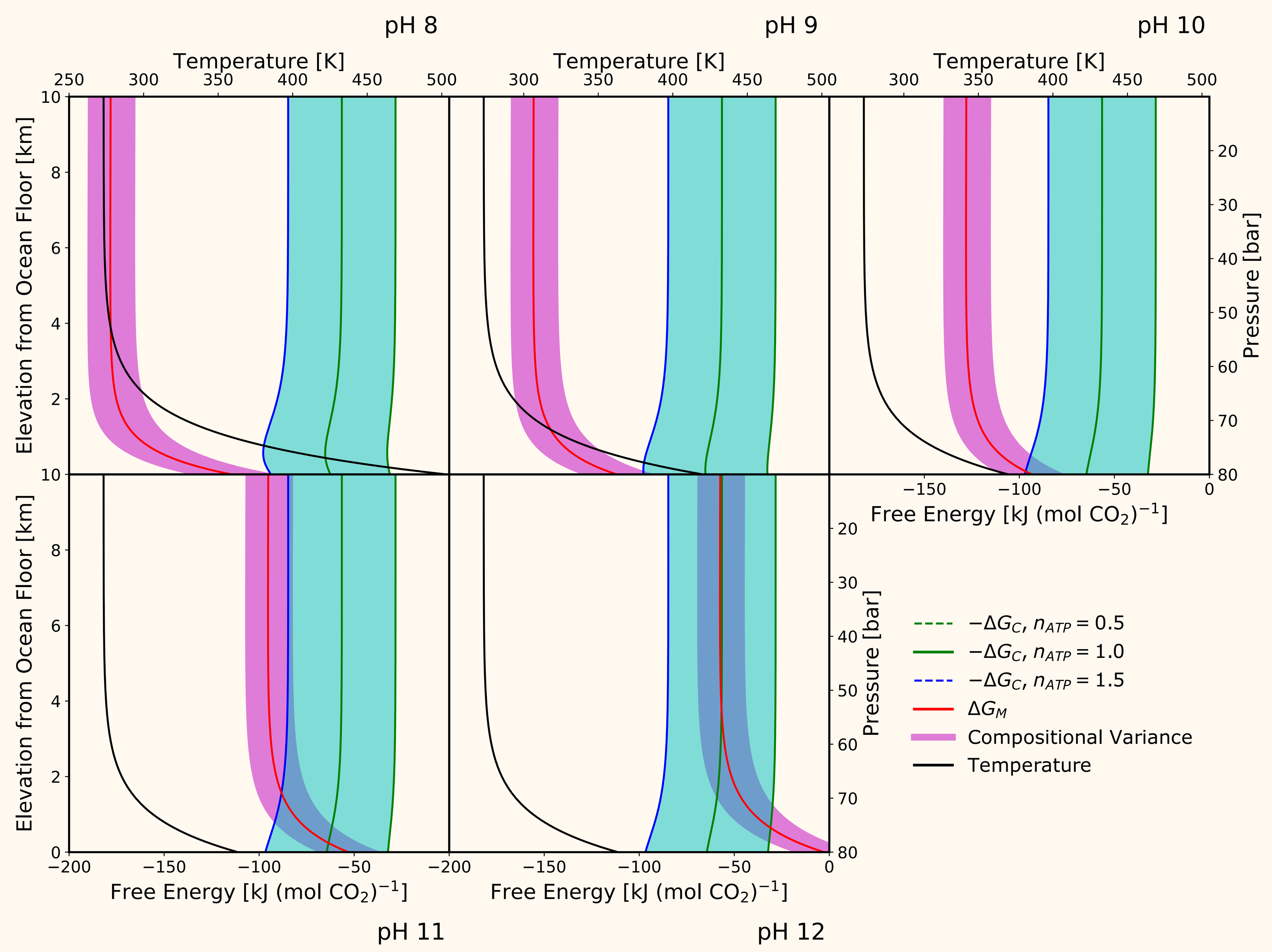


Above: *Flowchart to show our energetic/nutrient based approach to modelling habitability and microbial growth. ε_{ATP}, ε_M and ε_{UT} are efficiencies of ATP storage, maintenance, and CHNOPS uptake, respectively.*



Left: *The final predicted volume of biomass, trends in available energy via methanogenesis and the fractional cost of maintenance at varying pH, locations in the ocean (affecting temperature and pressure), and maintenance costs per cell (where 10^{-15} is a low thermodynamic estimate [7] and 10^{-12} more typical of laboratory cultures). Assumed a closed 1L vessel with no mixing.*

Right: *Energetic availability in the Enceladean ocean at various pHs, where the violet bar shows the energy available through methanogenesis and the cyan how much a methanogen could conserve.*



Potential for Microbial Growth

Enceladus may not be as energetically favourable a candidate for methanogens as previously thought. In the most thermodynamically favourable scenario, pH 8.5, a maximum possible cell density of approx 10^4-10^5 cells cm^{-3} and minimum of 0 (e.g. no growth at all) was predicted. Assuming this scenario, and a global temperature of about 273 K, the total biomass in the ocean could reach approx. 10^{10} kg. This represents a very slim slice of the potential environment, however, and in the majority of cases there is simply not enough energy for the simulated methanogens to grow against realistic maintenance costs. Predictions drop off sharply with pH, as seen in the plots above, meaning future analyses should focus on characterising the pH with higher accuracy.

Summary of Results

A simple conceptual model for predicting energy flow and biomass in terrestrial and extraterrestrial environments has been presented, along with an example toy model of Enceladean subsurface ocean simulated conditions. At pH 8.5 the final estimated biomass of the methanogens begins to be significantly throttled by the maintenance contribution when it exceeds 10^{-14} W $cell^{-1}$ in the wider ocean and 10^{-13} W $cell^{-1}$ in the hydrothermal vents. In any case, when considering maintenance powers, the available energy in the subsurface ocean may not be as plentiful as once thought; even the level of maintenance energy usually required for bacteria in the laboratory may provide a significant throttle to growth (full pH independent results in [1]).

Remarks

These results do not aim to be pessimistic, but reflect how astrobiologists should be cautiously pragmatic in our approach to calculating the theoretical habitability of bodies which are not yet well characterised. Unless better constrained, at the current level of understanding there is no definitive answer to whether Enceladus' subsurface ocean could be habitable by taking an energetic approach, simply a small subset of its expected parameters which may be favourable for life. We identify pH as one of the most important parameters which needs to be better understood in order to more accurately constrain Enceladus' habitability.

References

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