A model for the mean global surface temperature of an Earth-like planet derived from the geological history of Earth. Carlos Ortiz Quintana[1,2], Karen N. Delgado Vega[1], Vanelie Olivieri Encarnación[1,2] and Alanice Agosto Reyes[1,2], Abel Méndez[1], [1]Planetary Habitability Laboratory, University of Puerto Rico at Arecibo (abel.mendez@upr.edu), [2]University of Puerto Rico at Mayagüez (carlos.ortiz80@upr.edu).

Introduction: Proxy data from the geological record shows that the last 750 million years of Earth were characterized by drastic changes in the surface temperatures and atmospheric greenhouse gases (e.g., CO_2, CH_4) [1, 2, 3, 4, 5]. This variability might have been the result of a complex combination of extreme geological events driven by large igneous province (LIP) volcanism (e.g., Siberian Traps), global hyperthermal periods, and asteroid impacts (e.g., Chicxulub) that affected the atmospheric composition of the planet and, thus, the radiative forcing processes important in stabilizing the climate [6].

Surface temperatures are a fundamental parameter in establishing the conditions suited for habitability. Stable temperatures have been associated with the emergence of complex ecosystems due to physiological constraints in species [7, 8]. However, rapid changes in short geological timescales have been correlated with massive global extinctions such as the Permian-Triassic and the Triassic-Jurassic events [9,10]. For astrobiological purposes, surface temperatures are essential to establish the liquid water criteria of the Habitable Zone (HZ). Characterizing such properties is fundamental in constraining the current habitability models to understand the possibilities of life elsewhere [11].

Current models of Earth's surface temperatures in the last million years are mainly based on biogeochemical proxy reconstructions (e.g., $\delta^{18}O$, $\delta^{13}C$, TEX86, ice cores). Instead, models of surface temperatures of exoplanets have been based on stellar properties (e.g., stellar flux, stellar temperature) and a few planetary properties (e.g., greenhouse effect, equilibrium temperature, planetary albedo, obliquity) [12, 13, 14]. Most of these models are highly parametrized for Earth and can validate General Circulation Models (GCMs) of exoplanets. Here we derive the contribution of land and ocean fractions on the surface temperature of an Earth-like planet calibrated with Earth in the last 750 million years.

Model Description: The surface temperature of a planet is controlled by a complex interaction between surfaces reflectivity, atmospheric dynamics (i.e., greenhouse effects), and climate. We propose a simple model based on the Bond albedo and normalized greenhouse of the planet derived from land and ocean fractions to predict the surface temperature of rocky planets using Earth as an analog. We used the result in [14] to calculate the temperature as:

$$T_s = T_o \left[\frac{(1-A)L}{\beta\epsilon(1-g)r^2} \right]^{\frac{1}{4}}, \tag{1}$$

where β is the fraction of the surface of the planet that re-radiates the stellar flux, ϵ is the broadband thermal emissivity, A is the Bond albedo, g is the normalized greenhouse effect, L is the stellar luminosity, r is the distance between the star and the planet, and T_o is the equilibrium temperature of Earth for zero albedo (i.e., T_o = 278.5K). For Earth we can assume for simplicity that $\beta = 1$, $\epsilon \approx 1$, $r = 1$ AU, and $L = 1$ solar units. These assumptions make the surface temperature of Earth as

$$T_s = T_o \left[\frac{(1-A)}{(1-g)} \right]^{\frac{1}{4}}. \tag{2}$$

The general Bond albedo can be computed by knowing the fraction of each component of the planetary surface and its specific reflective properties (i.e., the specific albedo value). We are proposing a simplified multivariable model to predict this quantity, such that

$$A = a_l f_l + a_w f_w, \tag{3}$$

where f_l is the fraction of land, f_w is the fraction of ocean, and a_l and a_w are arbitrary constants related to the specific albedo property of each surface. As of this moment, we are only considering land and ocean fractions. Parameters such as the fraction of vegetation, icy surfaces, and distribution of clouds will be implemented in further studies.

The main approach consists in creating multiple theoretical models with different realistic configurations of albedos. We assumed an initial albedo of 0.306 and a stable normalized greenhouse effect of 0.4. We then combined the theoretical data with experimental data from proxies to fit the model using a Markov chain Monte Carlo (MCMC) analysis. The analysis approximated the uncertainties of maximum likelihood parameters from the model.

Predictions and validation of the model: The MCMC implementation revealed best-fit parameters for the albedo model as

$$A = 0.504^{+0.231}_{-0.215} f_l + 0.220^{+0.073}_{-0.069} f_w$$

The uncertainties were based on the 16th, 50th, and 84th percentiles of the samples in the distributions. We were able to predict surface temperatures by applying the results from this model to equation 2. The general temperature model is shown in figure 1.

The analysis revealed that the model is correlated with the behavior of temperatures of our main Proxy

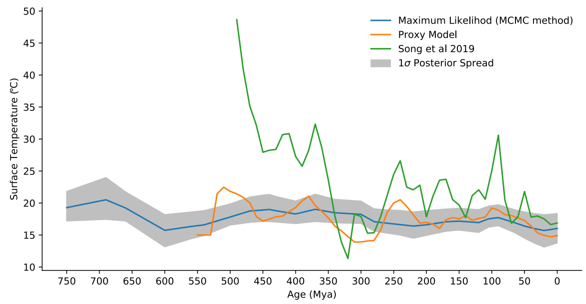

Figure 1. Surface temperatures with stable greenhouse effect as predicted by our model (blue line) and proxy models (orange and green lines).

Model [15] in the last 200 My and some periods between 300 Mya to 500 Mya. This also shows that the Proxy Model predicts a stable greenhouse effect in the last 200 My. For older periods, the atmosphere's composition might have experienced multiple changes that affected the surface temperatures, according to the model. In contrast, the temperatures predicted by Song *et al.* 2019 [16] are within the uncertainty of our model for only <50 Mya. This proxy also predicts drastic changes in surface temperatures that the Proxy Model or our model does not predict.

Applications to the greenhouse effect: The results can also predict the variability of the normalized greenhouse effect according to each proxy. As expected from the surface temperatures, the model predicts larger values of the greenhouse effect for Song *et al.* 2019 proxy. It also has larger variability in the greenhouse. On the other hand, the greenhouse effect from Proxy Model resulted in less variability and with values near the current greenhouse of 0.4. These values were relatively stable for the period between 0 Mya to 200 Mya. Assuming that our model is accurate, these results can be used to study the variability of the greenhouse effect on Earth and correlate it with the known atmospheric composition to correct proxy data.

Conclusion: We have described a model that could predict the mean global surface temperature of rocky planets based on their land-ocean fraction and atmospheric composition using data from Earth's geological history. As of this date, we have run an MCMC simulation to study the uncertainty of the parameters used to fit the data. The results showed large variability of surface temperatures due to changes in the land-ocean fraction and greenhouse effect. This means that our assumption of a stable greenhouse effect does not work for the entire geological timescale used in our study. Thus, we will fit the model for a variable greenhouse effect using the same MCMC method. This fitting might be a more accurate model for predicting surface temperatures.

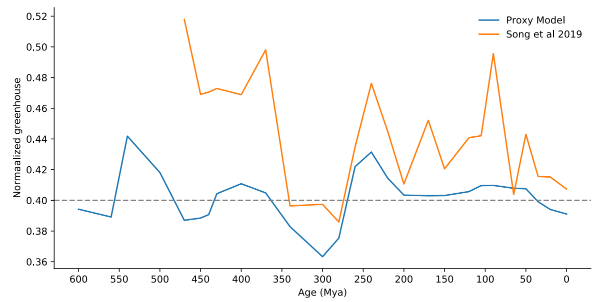

Figure 2. Variability of the normalized greenhouse effect for each proxy data based on the results from our model.

Nevertheless, the results look promising for some periods (e.g., the last 200 My) and might be improved by including a larger dataset of proxies. We will also include more surface properties in the model (i.e., vegetation, icy surfaces, clouds). These properties might provide insights into how the type of surface influences the temperatures of a planet. Our goal is to create a simple empirical model that predicts a rocky planet's mean global surface temperatures based on its surface and general atmospheric properties. Such a model could validate results from GCMs and characterize the habitability of exoplanets.

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