The Mean Global Surface Temperature of Earth-like Planets. Carlos Ortiz Quintana[1,2], Karen N. Delgado Vega[1], Vanelie Olivieri Encarnación[1,2], Alanice Agosto Reyes[1,2], Eduardo J. Cruz Vega[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: Earth is the standard and the only example of an Earth-like planet in the Solar System. However, the evolution of Earth through time can be studied as different examples of exoplanets similar to Earth. For instance, surface temperature proxies from the geological record show a large variability of the mean global surface temperatures of Earth during the Phanerozoic [1,2,3].

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 [4,5]. Consequently, rapid changes in short geological timescales have been correlated with massive global extinctions (e.g., Permian-Triassic, Triassic-Jurassic events) [6,7]. 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 [8].

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) [9,10,11]. Here we derive the contribution of different surface 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 [11] to calculate the temperature as:

$$T_s = T_o \left[\frac{(1 - A_b)L}{\beta\epsilon(1 - G_n)r^2} \right]^{\frac{1}{4}}$$

where β is the fraction of the surface of the planet that re-radiates the stellar flux, ϵ is the broadband thermal emissivity, A_b is the Bond albedo, G_n 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.

We can further redefine the model as

$$= \kappa T_o S^{\frac{1}{4}}$$

where S is the stellar flux and κ is a new quantity called the thermality. κ is a constant that directly relates the stellar flux to the surface temperatures due to both the albedo and greenhouse. We have defined the thermality as

$$\kappa = \left[\frac{(1 - A_b)}{\beta\epsilon(1 - G_n)} \right]^{\frac{1}{4}}$$

We propose a model for the Bond albedo of a planet as a linear combination of the contribution of each surface given by

$$A_b = (A_v f_v + A_i f_i + A_d f_d) f_l + A_w f_w + A_c f_c$$

where A_v, A_i, A_d, A_w, A_c represent the net albedos of vegetation, ice, desert, ocean, and clouds respectively.

The main approach consists in fitting the model to reconstructed geological maps of the Phanerozoic, albedo satellite data from NASA CERES and proxy data of surface temperatures. We assumed an initial albedo of 0.306 and a stable normalized greenhouse effect of 0.4 to validate the model to current conditions. We then combined the theoretical data with experimental data from proxies to fit the model using a Markov chain Monte Carlo (MCMC) sampler.

Surface Temperatures and Albedo Predictor: The MCMC implementation resulted in bet-fit parameters for the albedo model as

$$A_b = (0.261 f_v + 0.896 f_i + 0.331 f_d) f_l + 0.06 f_w + 0.6 f_c$$

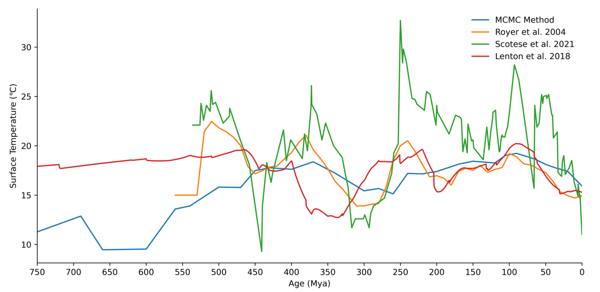

Figure 1. Variability of surface temperatures for the Phanerozoic according to our model and [1], [2] and [3].

The values for A_v, A_i, A_d were found by comparing known distributions of surface fractions to the CERES albedo maps, while the values for A_w, A_c were assumed based on approximations. It is important to note that we do not include the uncertainties because we are still in the process of running different MCMC chains to better constrain the parameters.

Figure 1 shows the predicted surface temperatures of our model compared to three different proxy data. We observe similar temperatures within the last 200 My between our model, [1] and [2], and in some periods between 400 to 450 Mya. This suggests that [1] and [2] predict a stable greenhouse effect in the last 200 My. Whereas there is no correlation between our model and [3]. Assuming a stable greenhouse effect of 0.4, the model predicts a lower contribution to the surface temperature for the early Phanerozoic. With the emergence of vegetation and the evolution of the distribution of continental masses on the late Phanerozoic the contribution to increasing the surface temperature became more significant. The differences between proxies and our model could be due to multiple changes in the atmosphere's composition, implying that we need to compensate for changes in the greenhouse effect to improve the model.

Application to Greenhouse and Thermality: We computed the evolution of the greenhouse effect and the thermality for the Phanerozoic using the albedo correction. Figure 2 suggests that an Earth-like planet with similar conditions should have a normalized greenhouse effect range between 0.36 to 0.48 to reproduce similar temperatures as the Phanerozoic. Similarly, figure 3 suggests a range for the thermality of the Phanerozoic between 1.04 to 1.09, implying that for Earth-like planets under Phanerozoic-like conditions this quantity should be a constant of about 1. For instance, this result shows evidence of a simplified way of calculating the surface temperature of an Earth-like planet based on the redefined model presented earlier.

Conclusions: We propose a model to predict the mean global surface temperature of an Earth-like planet validated with Earth's geological history. We suggest that a planet with a similar stellar flux and

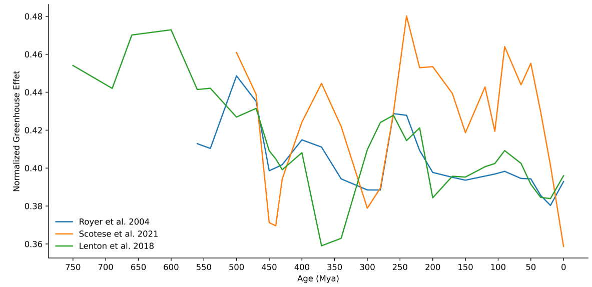

Figure 2. Predictions of the greenhouse effect for the Phanerozoic based on corrections with our albedo model.

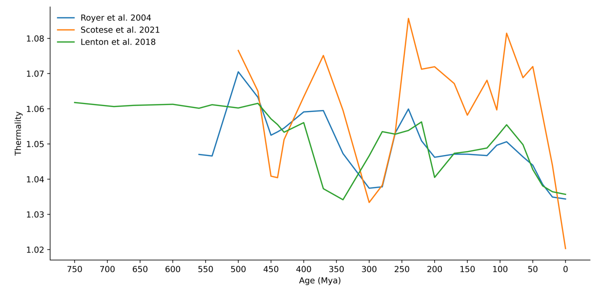

Figure 3. Predictions of the thermality for the Phanerozoic based on corrections with our albedo model.

atmospheric composition as Earth should have a normalized greenhouse between 0.3 to 0.5 and a constant thermality of around 1 to support surface temperatures between 0°C and 50°C. Our model presents a new analytical approach to assess the mean global surface temperature of Earth-like planets based on their albedo and greenhouse. This model could be used to validate and compare results from General Circulation Models (GCMs) and characterize the habitability of exoplanets.

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