# REU Research Report

## The Anthropocene Generalized: Coupled Evolution of Planets and Civilizations

Ethan Savitch

August, 2019

The main goal of this project has been to build off of the prior work done in Frank et al (2018)[1], where they generalized the predator-prey equations to model the coupled evolution of exo-civilizations and their planetary feedback, as a demonstration of method. The main addition to that work in this project has been the introduction of a physical climate model into his equations for temperature rise. We used an energy balance climate model from Haqq-Misra, 2014.[2]

Energy balance models (EBM's) approximate planetary temperature by balancing the incoming solar radiation with the outgoing long-wave, terrestrial radiation. Our specific version of the model takes in a variety of planetary inputs, such as $pCO_2$ levels, semi-major axis, planetary albedo, orbital eccentricity, orbital rates, etc. Another input for the program was the number of latitude belts to include. The program then discretizes global temperatures into these bands in order to model our latitudinal heat transport as diffusion. A full description of the model and it's parameters can be found in Williams and Kastings, 1997.[3]

$$C_v \frac{dT}{dt} = \psi(1-A) - I + \nabla \cdot (\kappa \nabla T) \tag{1}$$

This EBM also includes a carbonate-silicon cycle, with a weathering parameter that is used to quantify the recovery timescale of a civilization. For this version of the model, we turned this function off, instead introducing a simpler weathering constant ($\omega$) to our differential equation of $pCO_2$ (P), allowing us to specify the timescale of reduction of $pCO_2$ by natural weathering processes.

$$\frac{dP}{dt} = \epsilon N - \omega \tag{2}$$

For our differential equation describing rise in pCO2 levels, we introduced an annual, per-capita increase in $pCO_2$ with the variable $\epsilon$, allowing us to have an input describing carbon footprint. We proceeded to subtract a term ($\omega$) representing a planet's annual reduction of $pCO_2$ due to natural weathering processes. Such processes as the carbonate-silicon process become important as the timescale of this process becomes the timescale of the planetary recovery.

$$\frac{dN}{dt} = rN \tag{3}$$

The final contribution to the work in this project so far has been the addition of a temperature dependence on the relative growth rate (r), to effectively act as a carrying capacity would in a logistic equation. The increase in population results in an increase of $pCO_2$, which increases global temperatures, which reduces relative growth rates, and so on.

$$r \Longrightarrow r(T) = r_{birth}(T) - r_{death}(T) = B_0 e^{-(\frac{T-T_{max}}{\Delta t})^2} - D_0 e^{(\frac{T-T_{max}}{\Delta t})^2} \tag{4}$$

We made the functional dependence equal to the difference between two Gaussian functions for three reasons.

1. To be able to specify as an input to our program a constant temperature range ($\Delta$T) in which growth rates are positive, which we can use to quantify a civilizations fragility
2. To allow us to have temperatures that are outside this range result in negative growth rates
3. To ensure that this range remains unchanged even if the peak rises (constant dispersion)
   - will allow us to progress this model by adding an input, E, which can quantify the evolution of a civilizations technological capacities
   - will act to raise the peak of r, while also increasing the per-capita CO2 contributions ($\epsilon$)

[1] The Anthropocene Generalized: Evolution of Exo-Civilizations and Their Planetary Feedback, A. Frank, Jonathan Carroll-Nellenback, M. Alberti, and A. Kleidon, Astrobiology 2018 18:5, 503-518

[2] Haqq-Misra, J. (2014), Damping of glacial-interglacial cycles from anthropogenic forcing, J. Adv. Model. Earth Syst.

[3] Williams, D. M., & Kasting, J. F. 1997, Icarus, 129, 254