CLIMATE CHANGE DRIVEN "ANTHROPOCENES": ARE THEY COMMON AMONG EXOCIVILIZATIONS?

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ABSTRACT

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1. INTRODUCTION

It has now become clear that human activity has altered the state of the coupled Earth systems (atmosphere, hydrosphere, cryosphere, lithosphere, biosphere). There are multiple measures of human impact on these systems including the transport of key compounds and materials (**?**); the colonization of surface area (**?**); human appropriation of the terrestrial productivity (**?**) and energy (**?**). Global Warming driven by CO_2 emissions represents the most dramatic example of the impact of civilization on the planet **?**.

Taken as a whole these changes in the state/behavior of Earth's coupled planetary systems have been described as a new planetary/geologic epoch termed the *Anthropocene* (**?**). The specifics of the long-term impact of the Anthropocene on human civilization is difficult to predict. These impacts are, however, accepted to have negative consequences with assessments ranging from a difficult adaptation to full-scale collapse (REF). Also unknown are the requirements needed to successfully manage our entry into the Anthropocene and then create a long-term sustainable version of civilization. One can even ask if such long-term sustainable versions of civilization are even possible. It is possible that the Anthropocene may represent a "tipping point" in the coupled dynamical system representing both planet and civilization such that once the point is crossed in state space, subsequent evolution proves detrimental to the civilization. (**?**)(**?**).

In Frank et al. (2018) the Earth's entry into the Anthropocene was examined from an astrobiological perspective. That study asked if the situation currently encountered on Earth was unique. In particular, given its global scale, might the transition represented by the Anthropocene be a generic feature of any planet evolving a species that intensively harvests resources for the development of a technological civilization? This question has direct consequences for both the study of astrobiology and sustainability of human civilization.

Relevant to astrobiology, it is now apparent that most stars harbor families of planets (**?**). Indeed, many of those planets will be in the star's habitable zones (**??**). Tremendous effort has gone into the study of biosignatures, i.e. imprints a biosphere leaves on detectable light from the planet. Recently it has been recognized that imprints from technology created by an intelligent civilization might be just as, or more easily detectable (REF) as "traditional" biosignatures. If Anthropocene's are a common consequence of a civilization developing on a given inhabited world then this co-evolutionary period between planet and civilization may effect the nature and even existence of technosignatures. In addition if Anthropocenes prove fatal for some civilizations then they can be considered as one form of a "Great Filter" and are therefore relevant to discussions of the Fermi Paradox (REF)

The possibility that Anthropocenes are common is equally of interest to the pressing concerns about our own immediate future. We are, essentially, without a playbook in dealing with the planetary transition we now face. Any understanding of generic features in the co-evolution of planetary systems and civilizations could be of use in charting out the possible futures for our own efforts to navigate our own version of the Anthropocene. Consideration from even purely modeling/theoretical perspectives of how techno-spheres co-evolve with the other geospheres (the biosphere in particular) may help us understand the range and efficacy of viable options.

The modeling framework presented in Frank et al. (2018) was meant as a first step in studying generic behaviors in the interaction between a resource-harvesting technological civilization (an *exo-civilization*) and the planetary environment in which it evolves. Using methods from dynamical systems theory, a suite of simple equations was introduced for modeling a population which consumes resources (for the purpose of running a technological civilization) and the feedback those resources drive on the state of the host planet. The feedbacks drive the planet away from the initial state that gave birth to the civilization. These simple models conceptualized the problem primarily in terms of feedbacks from the resource use onto the coupled planetary systems including "population growth advantages" gained via the harvesting of the resources. Three models of increasing complexity were explored: (1) Civilization-planetary interaction with a single resource; (2) Civilization-planetary interaction with two resources each of which has a different level of planetary system feedback; (3) Civilization-planetary interaction with two resources and nonlinear planetary feedback (i.e. runaways). All three models showed distinct classes of exo-civilization trajectories. The first of these were smooth entries into long-term, "sustainable" steady-states. The second class were population booms followed by various levels of "die-off". Finally were rapid "collapse" trajectories for which the population (n) approaches $n = 0$.

In this work we seek to take a step up in complexity and realism compared to (REF). In particular we represent the evolution of the planetary state via an explicit energy balance climate model (EBM) and take the global temperature to be representative of that state. We then consider the interaction between the civilization and the planetary coupled systems to take the form form of CO_2 production. This means we are explicitly considering civilization' whose energy generation comes through some form of combustion. As in the first paper we consider that the use of this energy allows the civilization to increase its population (via increases in the birth rate of the population). At the same time, the feedback of the energy use on the planetary state, now via CO_2 emissions, alters that state. In doing so planetary conditions can be driven beyond what is tolerable for the functioning of the civilization. This is reflected in an increase in the mortality (the death rate) of the population.

Of course, the evolution of coupled planetary systems - the geospheres - is highly complex. In principle it should be treated in 3-D using something like a Global Climate Model and includes many processes and actors such as oceans and multiple biospheric feedbacks. The computational expense of such an approach, however, would limit the range of models we could explore. Thus current study is meant to make a meaningful step forward in modeling technosphere/geosphere co-evolution by making a specific assumption about energy harvesting modalities and its feedback and use a simpler 1-D EBM to represent climate evolution.

The plan of the paper is as follows. In section 2 of the paper we describe the model and its assumptions. In section 3 we describe the method used to deploy these equations to technosphere/geosphere co-evolution and use Earth's recent history validate our approach. In section 4 we present the results of a selected set of runs to understand the dynamics found in the models. In section 5 we discuss the full suite of results describing broad patterns found in the co-evolution models. Finally in section 6 we discussion the implications of our results for both astrobiology and anthropocene studies.

2. THE MODEL

We take a dynamical systems approach to the coupled evolution of the planet and civilization. The planet is described in terms of its atmospheric state which is given by its average temperature T. This state depends on the both the influx of stellar radiation and the atmospheric chemical composition which will change due to the activity of the civilization. In our model all the civilization's energy harvesting occurs via combustion. Thus we follow the emission of CO_2 by the civilization and changes in its partial pressure, $P = P(CO_2)(t)$, represents the principle change occurring in the planet's atmospheric composition.

We use a "1-D" energy balance model to calculate the temperature in latitudinal (θ) bands.

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

where A is the planetary albedo, κ is the latitudinal heat transport and C_v is the heat capacity at constant volume. The details of the model can be found in (REF). We extract a single globally averaged temperature from 1.

In figure 1 we show the domains of our model in $(a, P(CO_2)_o)$ space. Note the at the variations of the inner edge of the habitable zone with $P(CO_2)_o$ are due to fits in the absorption coefficients used in the EMB. While the could be reconciled with more detailed models the small variation imposed on $a_{hab,inner}$ did not effect the conclusions of the study.

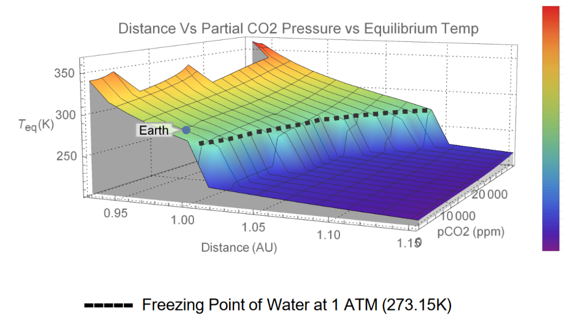

Figure 1. : Surface plot of our solar systems Habital Zone, calculated with the EBM given by equation (1)

The dynamics of the civilization's population, N, is governed by the per-capita net growth rate R, which we let vary with time ($R = R(t)$) and define as the balance between the per-capita birth (A) and death rates (B). In our simulations we assume a "pre-technological" growth rate.

$$R_0 \equiv A_0 - B_0 = \frac{1}{N}\frac{dN}{dt}\bigg|_{t=0} \tag{2}$$

As the civilization becomes more proficient at energy harvesting it's ability to produce more offspring increases. In our model we associate the civilizations technological capacity (and hence its ability to harvest energy) with the production of combustion byproducts. Thus we define an enhanced growth coefficient to be a function of P relative to the initial value the civilization found the planet in when it began its technological evolution (i,e $P = P_0$). Thus our enhanced growth coefficient takes the form.

$$R_+ = R_0\left(1 + \frac{P - P_0}{\Delta P}\right) \tag{3}$$

Where ΔP is a normalization constant that roughly corresponds to the amount of pCO_2 that needs to be generated by a civilization in order to double the growth rate of the civilization. As can be seen from equation 3, increases in technology, as measured by the combustion products released into the atmosphere, increase the birth rate of the civilization.

As technology produces higher P and more births there will, eventually, be a corresponding feedback on the planet, dictated by (1), and hence on the population. We model this feedback via a term we denote the diminished growth rate, which we take to be temperature dependent.

$$R_- = R_0\left(\frac{T - T_0}{\Delta T}\right)^2 \tag{4}$$

Where T_0 is the average planetary Temperature when the civilization began and ΔT describes the range of temperatures amenable to the civilization's health. As we will discuss below, this term can focus on either the biology of individuals or the functioning of the civilization as a whole.

The final governing equation for N is,

$$\frac{dN}{dt} = min\left[NR_+,\ R_0(N_{max} - N)\right] - NR_- \quad (5)$$

The use of the min function in equation in the equation above serves to introduce a carrying capacity (N_{max}) into the systems dynamics. Carrying capacity is a foundational principle in population dynamics and without it the civilization's population can grow to levels that are unrealistic based purely on food production capacities ($N > 100$ billion) In the classic logistic growth model

$$\frac{dN}{dt} = NR\left(1 - \frac{N}{N_{max}}\right) \quad (6)$$

the carrying capacity appears in the second term which functions as the death rate. In our model we chose to impose the carrying capacity through the min functions to avoid the arbitrary non-linear dependence on population which occurs in the logistic equation. We will discuss the behavior this produces in the results section.

Finally we model the production of CO_2 via the simple equation

$$\frac{dP}{dt} = CN \quad (7)$$

We ran a suite of over 1000 models using different values of the input parameters: $N_{max},\ R_0,\ \Delta T,\ \Delta P$ and C.

2.1. *Modeling Anthropocene Earth*

In order to provide both a test and a calibration of our model we apply to the recent evolution of the Earth and its human population into the Anthropocene. The values of the input parameters are shown in table 1.

It is worth noting a few points about the initial parameters. We chose a population temperature sensitivity of $\Delta T = 5K$ as this is representative of the range of temperatures amenable to human evolution; it also acts to quantify our civilizations "fragility". Also our choice for the technology birth benefit ($\Delta P = 30ppm$) was chosen because it is an order of magnitude approximation to the levels of pCO_2 humans thrive in. The CO_2 generation coefficient C was taken from current global conditions while the initial birth and death rates A_o and B_o where tuned to reproduce a best fit to the data.

The model was begun at $t = 1820$ CE. The initial world population was taken to be $N = N_o = 1.29 \times 10^9$ with an initial CO_2 partial pressure of $P = P_o = 284$ ppm

The results are shown in Figure 2, which gives the evolution of population $N(t)$, and global mean temperature $T(t)$. As can be seen, the model does an excellent job of tracking both the rise in temperature and population during the last two centuries. B_0 is the parameter we used to tune the population part of our model. A_0 was fixed by our assumption that the average time between births was approximately 25 years. We then adjusted B_0 in order to have our model fit the population data we have (shown as the top plot of figure 1). Finally, we adjusted the per-capita carbon footprint C in order to match our climates response to population growth, thus matching our global trends in temperature (shown as the bottom plot of figure 1).

Table 1: Input Parameters for Planet-Civilization Model

Parameter	Description	Earth Value
N_{max}	Carrying Capacity	20 billion
$R_0 = A_0 - B_0$	Initial Birth Coeff.	0.005 yr^{-1}
ΔT	Population Temp Sensitivity	$5K$
ΔP	Technology Birth Benefit	30 ppm
C	per capita CO_2 generation	$2.75 \times 10^{-4} \frac{ppm}{10^6 ppl*yr}$

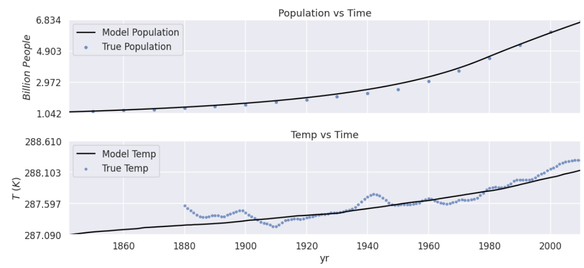

Figure 2. : Model Output (solid black line) vs Real Global Data (dotted line)

3. ANALYTIC MODELING

Before we begin numerical integration of our equations, we first explore aspects of the solutions that can be extracted from purely analytic considerations. In doing so we see that the problem contains three intrinsic timescales. For the population growth we have,

$$t_g \equiv \frac{1}{R_0} \quad (8)$$

This is the timescale for the increase in population without the addition of technology. This will prove important for thinking about how civilizations can respond to the climate change they drive.

In order to quantify the climate response timescale, we first need a way to quantify how changes in pCO_2 affect the climate. In principle, this can be done with the 1D climate model, but would result in an unnecesarily complicated, multi-term expression. To first order, we can approximate the temperatures response to pCO_2 by expanding temperature in a Taylor series around pCO_2.

$$T \approx T_0 + \left.\frac{dT}{dP}\right|_0 (P - P_0)$$

We can use this first-order approximation to define the civilizations climate sensitivity, which we denote D.

$$D(T) \equiv \frac{dT}{dP} \approx \frac{T - T_0}{P - P_0} \quad (9)$$

Using D, we can express the timescale for the climate to respond to population growth as,

$$t_c \equiv \frac{\Delta T}{CN_{max}D} \quad (10)$$

Note that the population climate sensitivity ΔT appears in t_c because it determines the timescale for the climate to be driven out of the civilization's "safe operating zone". Finally, we can define a technological timescale which describes the timescale for a civilizations technological advancements.

$$t_t \equiv \frac{\Delta P}{CN_{max}} \tag{11}$$

We can use the timescales given by equation 8 and 10 in order to define a dimensionless parameter γ which bifuracates our model into two classes of solutions:

$$\gamma \equiv \frac{t_g}{t_c} = \frac{DCN_{max}}{R_0 \Delta T} \tag{12}$$

Since γ is the ratio of the timescale for population growth relative to the timescale for the climate to be driven from its initial state, it serves as a measure of when an "anthropocene" can be expected. For our purposes we define an anthropocene to be changes in climate occuring on timescales that are short with respect to the population own changes. The logic here is that an industrial scale civilization is likely to involve considerable investments (i.e. sunk costs) in a particular energy-harvesting technological infrastructure. If climate changes occur in less than a two to three generations, the civilization will face the challenged in making rapid shifts in their energy harvesting infrastructure.

Thus our solutions then take two possible forms. If $\gamma << 1$ the climate will change on timescales much longer than a generation. Under these conditions the civilization will have ample tome to adjust or respond to the shifting climate conditions. Thus $\gamma << 1$ corresponds to a civilization having a low risk for an Anthropocene. If however $\gamma >> 1$ the climate will change on timescales much shorter than the single generation. As discussed above, given that civilizations will, by definition, be complex systems composed of both physical infrastructure of societal institutions, such rapid change in the climate may provide significant challenges for maintenance of the civilization. Thus $\gamma >> 1$ corresponds to a civilization having a high risk for an Anthropocene.

Note we can use this conceptual framework to also define an "anthropogenic population" (N_A). This is the value of N that yields $\gamma = 1$,

$$N_A \equiv \frac{N_{max}}{\gamma} = \frac{R_0 \Delta T}{DC} \tag{13}$$

N_A can be considered the number of individuals required to force the climate out of equilibrium in a generation. Furthermore, since we have defined civilizations with high $\gamma >>$ to be at high risk for an anthropocene, we can equivalently say that if a civilzation has $N_A << N_{max}$, they are also at high risk.

It is however not just the entry into an anthropocene that matters. Even more important is how rapidly the civilization begins to feel the effects of the climate change they drive. Thus if we wish to define an anthropocene as a destructive phase of evolution for the civilization (a "bad anthropocene") we must consider the relative speed at which the population is adversely effected by climate change. With our technological timescale, we can define another dimensionless quantity

$$\theta \equiv \frac{t_t}{t_c} = \frac{\Delta T}{D \Delta P} \tag{14}$$

Since θ is the ratio of the timescale for climate to be driven from its initial state to the timescale for technology to help prop up the population, it serves to quantify how much technology helps your civilization as you are impacting your environment. We can further use our two dimensionless quantities θ and γ in order to define our final dimensionless quantity

$$\beta \equiv \theta\gamma = \frac{t_g}{t_t} = \frac{CN_{max}}{R_0 \Delta P} \tag{15}$$

Since this quantity is the timescale for population growth relative to the timescale for technological advancements, it serves to quantify how much technology props up your population, independent of the climates response. We can use this parameter to help us define technological civilzations. We say that a civilization is considered technological if $\beta > 1$.

Thus, with our three dimensionless quantities and three timescales, we now have six total classes for our models. Since our study is aimed towards technological civilizations, our requirement that $\beta > 1$ eliminates half of the classes. If $\gamma > 1$, then θ can be greater or less then one, while if $\gamma < 1$, then θ must be above one in order to make $\beta > 1$. These three classes will be discussed in more detail in the following section.

3.1. *Dimensionless Model*

Let us now consolidate our equations in order to derive their non-dimensional form. We will then linearize this system and explored it analytically. Our inputs are: natural birth rate A_0; natural death rate B_0; per capita emission rate C; birth rate temperature sensitivity ΔT; CO2 emission birth rate advantage range ΔP; and carrying capacity N_{max}; Our model system variables are: the population N, CO2 concentration P, and temperature T.

$$\begin{aligned}
\frac{dN}{dt} &= \min\left[A_0 N\left(1 + \frac{P - P_0}{\Delta P}\right),\ B_0 N_{\mathrm{max}}\right] \\
&\quad - B_0 N\left[1 + \left(\frac{T - T_0}{\Delta T}\right)^2\right] \\
\frac{dP}{dt} &= CN \\
\frac{dT}{dt} &= \frac{\psi(1 - A) - I + \nabla \cdot (\kappa \nabla T(\theta))}{C_v}
\end{aligned}$$

In order to linearize the climate response, we refer to our first-order approximation (9), which is calculated using our energy balance model as a function of orbital distance (a) and global temperature (T).

$$D(T, a) = \frac{dT}{dP} \approx \frac{T - T_0}{P - P_0} \tag{16}$$

Using this variable, we can simplify equation (1) while also incorporating the effects of equation (5)

$$\frac{dT}{dt} = \left(\frac{dT}{dP}\right)\left(\frac{dP}{dt}\right) = DCN$$

Table 2: Dimensionless Model Quantities

Var	Definition	Description
η	$N/N_{\max}$	Normalized population
τ	$R_0 t$	Normalized time
ϵ	$(T-T_0)/\Delta T$	Normalized temperature
θ	$\Delta T/(D\Delta P)$	Normalized Birth rate acceleration
γ	$(DCN_{\max})/(R_0\Delta T)$	Normalized forcing

Furthermore, we can use our expression for the approximate climate response to express changes in pCO_2 as a function of changes in temperature...

$$P - P_0 \approx \frac{T-T_0}{D}$$

This allows us to reduce our system of equations to,

$$\frac{dN}{dt} = \min\left[R_0 N\left(1+\frac{T-T_0}{D\Delta P}\right), R_0(N_{\max}-N)\right] - R_0 N\left(\frac{T-T_0}{\Delta T}\right)^2$$
$$\frac{dT}{dt} = DCN$$

By dividing both equations by R_0, the first equation by $N_{\max}$ and the second equation by ΔT we arrive at our non-dimensional form

$$\frac{d\eta}{d\tau} = \min\left[\eta\left(1+\theta\epsilon\right), 1-\eta\right] - \eta\epsilon^2$$
$$\frac{d\epsilon}{d\tau} = \gamma\eta$$

The meaning of the various parameters are given in table 2.

Note that we do not include any means of reducing the CO_2 in the atmosphere. While this can occur through natural means via weather and carbonate cycles, the relevent timescale are much longer than we are interested in here ($\tau \sim 10^6$ y). We are also not attempting to model the possible responses of a civilization to the climate change they generate. Here we only wish to know how broad are the conditions that can lead to such change and detrimental impacts. In terms of our equations this means there is no equilibrium for the temperature except for the trivial one of the absence of a technological civilization ($\eta = 0$). Also, because of the min function, the population will peak in one of two scenarios we describe in the section.

3.2. *High carrying capacity ($\gamma >> 1$)*

If $\gamma >> 1$, the carrying capacity is large enough that anthropogenic forcing of the climate can push temperatures far from their initial equilibrium. This can increase the death rate to the point where population growth halts. In this limit, the population growth rate $\eta\,(1+\theta\epsilon)$ never exceeds the maximum growth rate β, and we can solve for how far the climate is pushed out of equilibrium when the population peaks.

$$\frac{d\eta}{d\tau} = \eta\left[1+\theta\epsilon-\epsilon^2\right] = 0$$
$$\rightarrow \epsilon_c = \frac{\theta}{2} + \sqrt{1+\left(\frac{\theta}{2}\right)^2}$$

We can also find the time scale for the population to decline after it reaches its peak. This is particularly important because if the decline is fast compared with the generational timescale we possible, once again, that the civilization will be unable to maintain the complex system required for its function.

$$\left.\frac{d^2\eta}{d\tau^2}\right|_{\epsilon_c} = \eta\left.\frac{d\epsilon}{d\tau}\right|_{\epsilon_c}\left[\theta - 2\epsilon_c\right]$$

In the case of high γ, we expect the population to begin to decline before reaching its carrying capacity, as the environment continues to increase at an exponential rate. Thus, in the case of high gamma, at the time when the population begins to turn over, the rate of the increasing temperature is approximately equal to its value..

$$\left.\frac{d\epsilon}{d\tau}\right|_{\epsilon_c} \approx \epsilon_c$$

Thus we can define a collapse time τ_{coll} based on the second acceleration of the population decline.

$$\tau_{col} = -\sqrt{\frac{\eta}{\frac{d^2\eta}{d\tau^2}}} = \left[2\epsilon_c^2 - \theta\epsilon_c\right]^{-1/2}$$

This timescale can be further broken down into cases of high θ and those of low θ. For high θ ($\theta >> 1$),$\epsilon_c \rightarrow \theta$, thus

$$\tau_{col} \rightarrow \frac{1}{\theta}$$

Similarly, for low θ ($\theta << 1$), $\epsilon_c \rightarrow 1$, thus

$$\tau_{coll} \rightarrow \frac{1}{\sqrt{2}}$$

Putting those two cases together gives is an expression for the collapse timescale for high gamma.

$$\tau_{col} = \frac{1}{max(\sqrt{2},\ \theta)} \quad (\gamma >> 1) \tag{17}$$

3.3. *Low Carrying Capacity ($\gamma << 1$)*

On the other hand, if the forcing γ is small,the population can reach the carrying capacity without impacting the climate. In this regeme we expect $\eta \rightarrow 1$ while $\epsilon \sim 0$. Under these conditions case we can calculate how long it takes to push the climate into its critical "anthropocene" regeme, $\epsilon = 1$, using

$$\frac{d\epsilon}{d\tau} = \gamma\eta$$

At the carrying capacity, $\eta = 1$ the time scale for $\epsilon \to 1$ then becomes $\tau_{\rm coll} = \frac{1}{\gamma}$. An alternative way to look at this is that the timescale for population to collapse is dictated by the timescale for the climate to response to population growth, which we denoted in the previous section as t_c. Thus, $\tau_{coll} \approx R_0 t_c = \frac{1}{\gamma}$.

Combining all conditions results in

$$\tau_{\rm coll} = \max\left[\frac{1}{\gamma},\ \frac{1}{max(1,\theta)}\right] \tag{18}$$

It is important to understand the meaning of these solutions in terms of the goal of the study. We are interested in ubiquity of anthropocenes driven by climate change. This means that given different planetary initial conditions, how common will be energy harvesting (by combustion) lead to population growth which leads to rapid climate change which then leads to rapid population declines. This is the specific intent of our modeling. As demonstrated by the analysis there will be solutions in which the population rise, driven by energy harvesting, brings the civilization to the planets carrying capacity () the changing climate drives adverse effects. But a rapid (exponential) population rise to the host world's carrying capacity will bring its own potentially existential challenges. The very definition of carrying capacity implies that at N_{max} the civilization is at the edge of what the planet can provide in terms of "ecosystem services" for the civilization's proper function. Thus, while these class of systems will not fall under our definition of climate driven anthropocene's they should not be considered to cases that have escaped the possibility of rapid population declines or even collapse. It is simply that our models do not include the processes (i.e. biospheric feedbacks) which could produce them.

4. NUMERICAL EXPERIMENT SETUP

The model described in section 2 is used to carry forward a large suite of numerical experiments. Our principle goal in designing these was to investigate how the trajectory of the coupled planet-civilization system depends on initial conditions on the planet to. To carry out our models we make a two key of assumptions. (1) The biology of the organisms building the civilization require liquid water and so the host planet must be within the star's habitable zone. (2) The organisms have temperature, (ΔT) and $P(CO_2)$, ΔP, limits beyond which they can not survive. We will begin our study by using limits similar to Earth and humans life for illustrative purposes but will always consider these to be free parameters. We focus on two initial planetary parameters: the orbital distance a of the planet from the host star, and the initial chemical composition of the atmosphere in terms of CO_2. The effect of these parameters on the models are not independent as both effect the width of the habitable zone for the planet because the width of the habitable zone depends on each. We have thus run two sets of experiments the first of which we call constant composition models. These keep initial $P(CO_2)$ constant and allow the initial (equilibrium) planetary temperature T_o to vary as we change the orbital distance a. Starting at earth, with $T_o = 287.09K$, we continued by running two models with temperatures greater than earths, and two less, all evenly spaced by $6K$. This

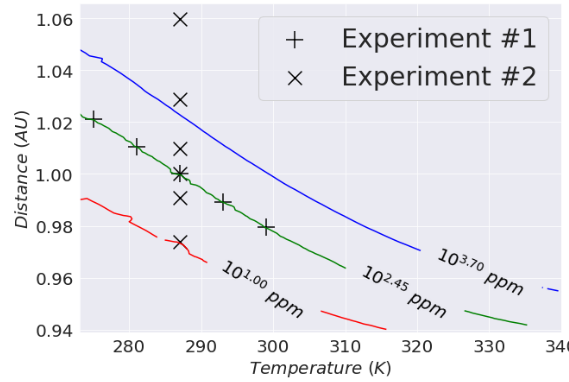

Figure 3. : Visualization of our numerical experiments. The contour lines are of $P(CO_2)$.

spacing was chosen in order to have all models safely within our habitable zone, defined here as the range of distances that result in temperatures above freezing and below boiling $(273.15 < T_o < 373.15)$. In the second set of experiments, we varied the initial $P(CO_2)$ while keeping $T_o = 287K$. We ran two with lower values of initial $P(CO_2)$, and three above, all spaced by $logP(CO_2) = 0.7$. The reason we ran three above was in order to illustrate what a model within our danger zone looks like. In these experiments the danger zone is areas of parameter space with values of $P(CO_2)$ less then 10 ppm or higher than $5,000$ ppm. The lower limit was chosen as it represents the lowest value allowed by our simulation, while the upper limit was chosen as it is considered to be the value of $P(CO_2)$ toxic to intelligent civilizations. The locations of the experiments are shown in figure 3.

The resulting evolution of population for all of our experiments are shown in figure 4. To further investigate these trajectories, we choose five for which we will show the evolution of temperature and $P(CO_2)$ as well. For experiment #1, we choose the models corresponding to the highest and lowest distances. Similarly, for experiment #2, we choose models corresponding to the two highest and single lowest distances. The reason we choose three distances from experiment #2 was in order to have one of the trajectories demonstrate what evolution in the danger zone is like.

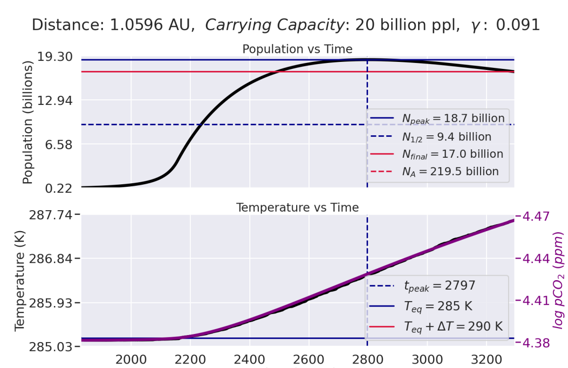

Figure 6. : This model results in the civilization reaching their carrying capacity, thus overpopulating their planet. The initial pCO_2 is $10^{4.38} \approx 24,000$ ppm, which puts it in the "danger zone" for habitability.

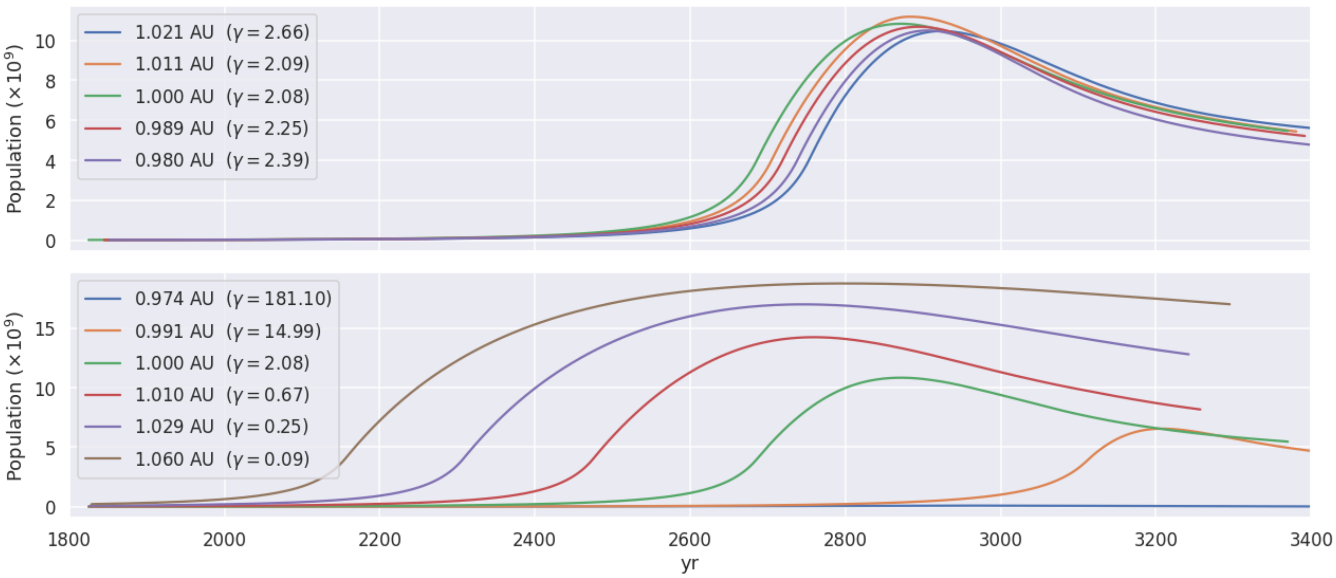

Figure 4. : Top is experiment #1, bottom is #2.

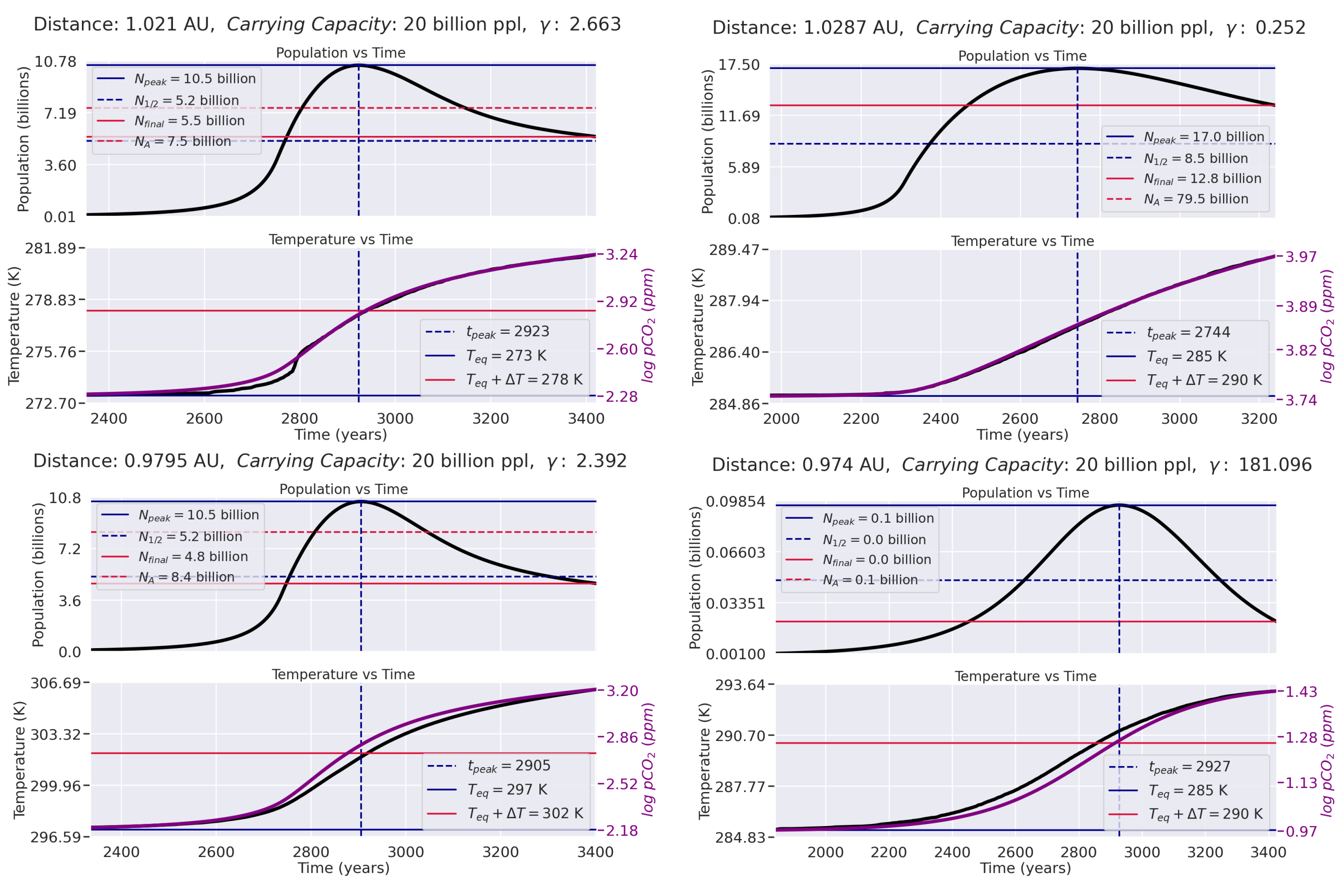

Figure 5. : Selected trajectories. The left column shows the highest and lowest distance from experiment #1 (top and bottom respectively). Similarly, the right column shows the same for experiment #2.

5. RESULTS

To explore the broad dependence on initial conditions we chose 10 different distances and temperatures. Using the uncoupled Energy Balance Model we found the value of $pCO2$ that would make that distance take a given habitable zone temperature, shown as the top left plot in the grid of plots shown in figure 8. We then used this initial pCO_2 as the input for the coupled model in order to see how a civilization at that distance and temperature would evolve. The results are shown below as a grid of contour plots. The bottom left of the plots are grey because of limitations imposed by the EBM. The top right part of the plots are grey because the value of pCO_2 required there was greater than $5,000$ ppm, a level we have deemed uninhabitable for intelligent civilizations.

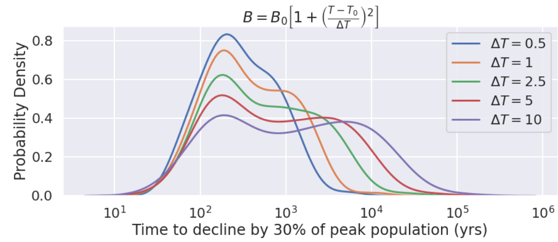

Figure 7. : KDE Plots for various values of dT

We continued to further explore the model by repeating this process for multiple values of ΔT. The resulting distribution of times for civilizations to decline by 30% from their peak population is shown below, normalized so the area under each curve is one. We see that for smaller population temperature sensitivity a significant fractions of our models lead to climate anthropocenes.

6. DISCUSSION

REFERENCES

Frank A., Carroll-Nellenback J., Alberti M., Kleidon A., 2018, Astrobiology, 18, 503

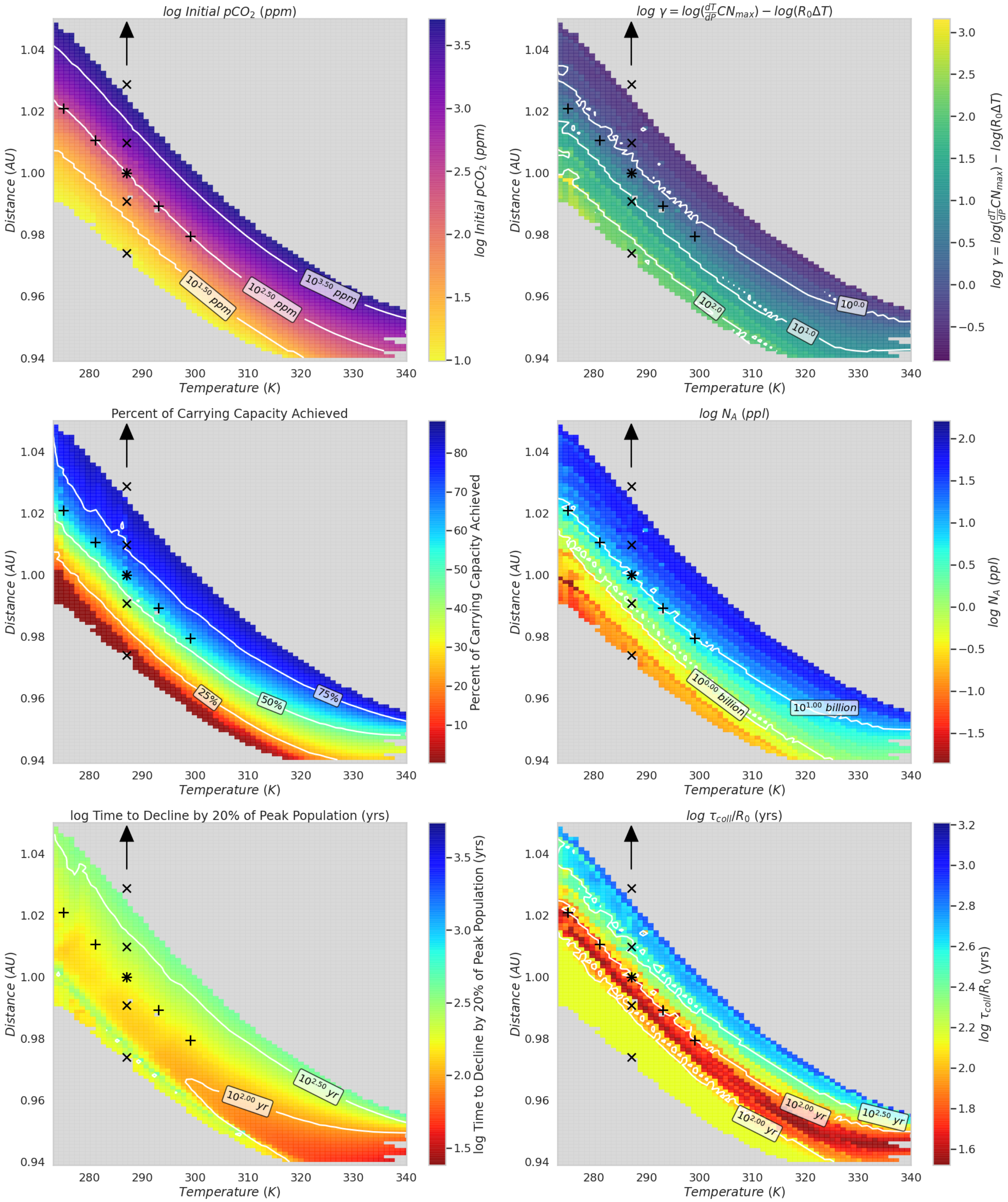

Figure 8. : The full parameter sweep is here.