Triggering a Climate Change Dominated “Anthropocene”: Is It Common among Exocivilizations?

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Abstract

We seek to model the coupled evolution of a civilization and its host planet through the era when energy harvesting by the civilization drives the planet into new and adverse climate states. In this way, we ask if triggering “Anthropocenes” of the kind humanity is experiencing might be a generic feature of planet–civilization evolution. This question has direct consequences for both the study of astrobiology and the sustainability of human civilization. Furthermore, 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. In this study, we focus on the effects of energy harvesting via combustion and vary the planet’s initial chemistry and orbital radius. We find that in this context, the most influential parameter dictating a civilization’s fate is its host planet’s climate sensitivity, which quantifies how global temperatures change as CO2 is added to the atmosphere. Furthermore, this is in itself a function of the planet’s atmospheric CO2 level, so planets with low levels of CO2 will have high climate sensitivities and high probabilities of triggering climate change. Using simulations of the coupled nonlinear model combined with semi-analytic treatments, we find that most planets in our initial parameter space experience diminished growth due to climate effects, an event we call a “climate-dominated Anthropocene.”

Unified Astronomy Thesaurus concepts: Astrobiology (74); Exoplanets (498); Planetary climates (2184)

1. Introduction

It has now become clear that human activity has altered the state of the coupled Earth systems (atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere). There are multiple measures of human impact on these systems including the transport of key compounds and materials (Steffen et al. 2015); the colonization of surface area (Hooke et al. 2012); human appropriation of the terrestrial productivity (Vitousek et al. 1986) and energy (Kleidon 2012). Global warming driven by CO2 emissions represents the most dramatic example of the impact of civilization on the planet (Solomon et al. 2007).

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 (Crutzen 2002). In fact, recent studies have shown that 2020 marks the moment when human-made “anthropogenic” mass has exceeded all of Earth’s living biomass (Elhacham et al. 2020). 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. 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 (Lenton et al. 2008; Kuehn 2011). We note that in Frank et al. (2017) final sustainable planetary states were explored.

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 (Haqq-Misra & Baum 2009; Frank et al. 2017; Mullan & Haqq-Misra 2019)? This question has direct consequences for both the study of astrobiology and the sustainability of human civilization.

Relevant to astrobiology, it is now apparent that most stars harbor families of planets (Seager 2013). Indeed, many of those planets will be in the star’s habitable zones (Howard 2013). 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 (Lingam & Loeb 2019) than, “traditional” biosignatures. If Anthropocenes are a common consequence of a civilization developing on a given inhabited world, then this coevolutionary 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 (Carroll-Nellenback et al. 2019).

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 (however, see Frank et al. 2017). Any understanding of generic features in the coevolution 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. Even purely modeling/theoretical perspectives on how techno-spheres coevolve 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 that 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. The simple models in Frank et al. (2018) 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. The models showed three 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 Frank et al. (2018). 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 (North & Kim 2017). The interaction between the civilization and the planetary coupled systems is mediated by the civilization’s CO₂ production. This means we are explicitly considering civilizations whose energy generation comes through some form of combustion. As in the first paper, 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 CO₂ emissions, alters that state. Thus, planetary conditions can be driven beyond what is tolerable for the functioning of the civilization. This is reflected as an increase in the mortality (the death rate) of the population.

We explore the effect of changing two key parameters in the models: the orbital distance of the planet from its host star and the initial atmospheric chemistry of the planet in terms of CO₂. In essence, we are asking if we moved Earth to different orbits and/or changed its initial CO₂ concentration, would we still have triggered the climate change we are experiencing now.

Most animal life on Earth cannot tolerate high levels of CO₂ (Wittmann & Pörtner 2013). Thus, a key assumption of our models is that complex life of the kind expected to build a technological civilization will emerge from a “Complex Life Habitable Zone” (CLHZ) where initial CO₂ concentrations are below a threshold (Catling et al. 2005; Schwieterman et al. 2019; Ramirez 2020; see also Howell 2019). We will discuss the consequences of this assumption in the discussion section.

Finally, we emphasize that this paper focuses on the triggering of an Anthropocene which we will define as planetary systems change created by the civilization that truncates the civilization’s population growth. When the main driver of the end of population growth is climate change, for brevity we call this a “climate-dominated Anthropocene.” This is in contrast to asking what a civilization can do to manage such an Anthropocene once it occurs. To deal with this second question requires including the civilization’s response (and the timing of that response) in the model. This is a topic that should be addressed in future work.

The plan of the paper is as follows. In Section 2 we describe the model and use the Earth’s recent history to tune and test it. In Section 3 we provide an analysis of a linearized version of the model to extract key features of its behavior in terms of dimensionless parameters. In Section 4 we present the results of the full nonlinear model. We first show two sets of experiments run with either constant initial temperature or constant initial atmospheric CO₂ concentration (pCO₂). We then show the results from a sweep of two parameters: orbital distance \( a \) and initial (pCO₂). Finally we run a suite of models in which the civilization tolerances for global temperature changes \( \Delta T \) is varied. In Section 5 we discuss the consequences of these results for emerging studies of the “astrobiology of the Anthropocene” and present our conclusions and summary.

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 given by its average temperature \( T \). This state depends on the influx of stellar radiation and the atmospheric chemical composition that will change due to the activity of the civilization. In our model all of the civilization’s energy harvesting occurs via combustion. Thus, we follow the emission of CO₂ by the civilization. Changes in its partial pressure, \( P(t) = pCO₂(t) \), represent the principle evolutionary driver occurring in the planet’s atmospheric composition.

We use a “1D” energy balance model (EBM) to calculate the temperature in latitudinal \((\theta)\) bands according to the equation

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

where \( A \) is the planetary albedo, \( \kappa \) is the latitudinal heat transport, and \( C_v \) is the heat capacity at constant volume. Our version of the model was originally developed by Darren Williams in Williams & Kasting (1997). It was then modified by Jacob Haqq-Misra, who used it most recently in Fairen et al. (2012). This version of the model is publicly available on GitHub at https://github.com/BlueMarbleSpace/hextor/releases/tag/1.2.2. In our implementation of the model, we average across latitudinal bands to obtain a single globally averaged temperature.

In Figure 1, we show the domains of our model in \((a, P_0)\) space, where \( a \) is the orbital distance and \( P_0 = pCO₂ \) is the initial CO₂ composition of the planet before the civilization appears. Note that variations of the inner edge \((a_i)\) of the habitable zone with \( P_0 \) are due to fits in the absorption coefficients used in the EBM. While these could be reconciled with more detailed models, the small variation imposed on \( a_i \) did not effect the conclusions of the study.

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 \((B)\) rates. In our simulations we assume a
"pretechnological" growth rate.

\[ R_0 \equiv A_0 - B_0 = \frac{1}{N_0} \frac{dN}{dt} \bigg|_{t=t_0}. \tag{2} \]

As the civilization becomes more proficient at energy harvesting, its ability to produce more offspring increases. In our model, we assume the civilization’s technological capacity (and hence its ability to harvest energy and meet nutritional requirements) tracks with the production of combustion by-products. In other words, growth rates depend on technology, and we take the rise in \( P \) to be a measure of technological advance. Thus, we define an enhanced growth coefficient to be a function of \( P \) relative to the initial value \( (P_0) \) the civilization found the planet in when it began its technological evolution. For our enhanced growth coefficient we choose the form,

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

where \( \Delta P \) is a normalization constant that roughly corresponds to the pCO\(_2\) required to double the growth rate of the civilization. In this way, Equation (3) captures in a simple way how increases in technology (measured by 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 Equation (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 with the following form

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

where \( T_0 \) is the average planetary temperature when the civilization began \((t=t_0)\), and \( \Delta T \) describes the range of temperatures amenable to the civilization’s health. Thus, we call \( \Delta T \) the civilization’s temperature tolerance. This term can refer to both the biology of individuals or the functioning of the civilization as a whole. Thus, while individual members of the civilization may be able to survive at \( T > T_0 + \Delta T \), the civilization’s functioning as a complex system may be compromised.

The final governing equation for \( N \) is

\[ \frac{dN}{dt} = \min\{NR_+, R_0(N_{\text{max}} - N)\} - NR_- \tag{5} \]

The use of the min function in Equation (5) introduces a carrying capacity \((N_{\text{max}})\) into the system’s dynamics. Carrying capacity is a foundational principle in population dynamics (Kot 2011). Without it, the civilization’s population can grow to levels that are unrealistic based purely on food production capacities. For example, for Earth, \( N > 100 \) billion appears unrealistic under even the most optimistic scenarios (Cohen 1995). In the classic logistic growth model,

\[ \frac{dN}{dt} = NR_0\left(1 - \frac{N}{N_{\text{max}}}\right) \tag{6} \]

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 function to avoid the arbitrary nonlinear dependence on population that 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

\[ \frac{dP}{dt} = CN. \tag{7} \]

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 relevant timescales are much longer than we are interested in here \((t \sim 10^6 \text{ yr})\). We are also not attempting to model the possible responses of a civilization to the climate change they generate. In Frank et al. (2018), they explored the possibility of adding such functionality into their analytical model by allowing the civilizations to switch to a lower impact resource mid-evolution. They found that doing so could have the effect of creating new equilibria for the climate state and could even prevent collapse, especially for insensitive, slowly responding environments. Here, we only wish to know how broad are the conditions that can lead to such change and its 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 \((N=0)\).

### 2.1. Modeling Anthropocene Earth

In order to provide both a test and a calibration of our model, we apply it to the recent coevolution of Earth and its human inhabitants into the Anthropocene. It is worth noting a few points about the initial parameters.

The model was begun at \( t = t_0 = 1820 \text{ CE} \). The global world population was taken to be \( N = N_0 = 1.29 \times 10^9 \) with an initial CO\(_2\) partial pressure of \( P = P_0 = 284 \text{ ppm} \), approximately equal to the values on Earth prior to the industrial revolution. We chose the civilization’s temperature tolerance of \( \Delta T = 5 \text{ K} \), as this is representative of the range of temperatures considered in IPCC models and acts to quantify our civilizations “fragility” (Solomon et al. 2007). Also, our choice for the technology birth benefit \((\Delta P = 30 \text{ ppm})\) was chosen as an order of magnitude approximation to the levels of pCO\(_2\) humans thrive in (Schwieterman et al. 2019). The CO\(_2\) generation coefficient \((C)\) was taken from current global conditions while the initial
parameters and tuning the growth rate models we recover population \(N\), its first derivative, and temperature \(T\). Note model results are the solid black lines and global data are represented by the dotted blue lines.

net growth rate \(R_0\) was tuned to reproduce a best fit to the data.

The results are shown in Figure 2, which shows the evolution of population \(N(t)\), growth rate, 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 yr. We then adjusted \(B_0\) in order to have our model fit the population data we have (shown as the top plot of Figure 2). Finally, we adjusted the per-capita carbon footprint \((C)\) in order to match our climate’s response to population growth, thus matching our global trends in temperature (shown as the bottom plot of Figure 2).

### 3. Analytic Modeling

Before we begin numerical integration of our equations, we first explore aspects of the solutions that can be extracted from a semi-analytic approach. We begin by noting that it is possible to approximate the climate response to increased \(P = pCO_2\) via a simplified logarithmic dependence (Huang & Bani Shahabadi 2014)

\[
T \approx T_0 + \Delta T_F \log \frac{P}{P_0}
\]

where \(\Delta T_F\) is the change in temperature required for the climate sensitivity to drop by a factor of \(e\) and is \(\sim 4\) K for present day Earth (IPCC 2014).

Also note that with the above approximation,

\[
\frac{dT}{dP} = \frac{\Delta T_F}{P_0} e^{-\frac{T_0 - T}{\Delta T_F}} \equiv De^{-\frac{T_0 - T}{\Delta T_F}}.
\]

This allows us to eliminate the CO2 partial pressure as an independent variable and the model reduces to

\[
\frac{dN}{dt} = \min \left[ R_0 N \left( 1 + \frac{P_0}{\Delta P} e^{\frac{T - T_0}{\Delta T_F}} - 1 \right), R_0 (N_{\text{max}} - N) \right] - R_0 N \left( \frac{T - T_0}{\Delta T} \right)^2
\]

\[
\frac{dT}{dt} = C N D e^{\frac{T - T_0}{\Delta T}}.
\]

We can make the equations dimensionless by dividing the first equation by \(R_0 N_{\text{max}}\) and the second by \(R_0 \Delta T\)

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

\[
\frac{d\epsilon}{d\tau} = \gamma \eta e^{-\alpha \epsilon}.
\]

The dimensionless population \(\eta\) represents how close the civilization is to its carrying capacity. The dimensionless temperature anomaly \(\epsilon\) represents how much the temperature has changed from its initial value, relative to the temperature change required for the diminished growth term to counteract the benefits of the enhanced term. Our dimensionless time \(\tau\), is calculated with units of the population growth timescale, \(t_G = 1/R_0\), as discussed in Appendix A. The other three parameters \(\alpha, \gamma, \text{and} \gamma\) determine the behavior of the system and are defined in Table 1.

| Var | Definition | Description |
|-----|------------|-------------|
| \(\eta\) | \(N/N_{\text{max}}\) | Normalized population |
| \(\tau\) | \(R_0\tau\) | Normalized time |
| \(\epsilon\) | \((T - T_0)/\Delta T\) | Normalized temperature |
| \(\theta\) | \(\Delta T/(\Delta P)\) | Normalized birth rate acceleration |
| \(\gamma\) | \((CN_{\text{max}})/(R_0 \Delta T)\) | Normalized forcing |
| \(\alpha\) | \(\Delta T/\Delta T_F\) | Ratio of temperature change to affect biology to temperature change to affect climate sensitivity |
| \(\beta\) | \((CN_{\text{max}})/(R_0 \Delta P)\) | Increase in birth rate after burning sufficient CO2 to change temperature by \(\Delta T\) |

In what follows, we will define a climate-dominated Anthropocene as the trajectory in which the population growth is strongly truncated by the increase in planetary temperature. This means the population never gets close to the natural carrying capacity of the planet. The most important parameter with regards to whether a civilization goes through a climate-dominated Anthropocene is the normalized climate forcing \(\gamma\). It represents how quickly the climate would change if the population were to reach the carrying capacity. The parameter \(\theta\) represents the expected change in population growth rate due to the consumption of fossil fuels as the temperature changes by \(\Delta T\). The parameter \(\alpha\) represents the drop in the climate sensitivity (as a number of e-foldings) as the temperature
changes by $\Delta T$. One additional parameter, $\beta \equiv \gamma \theta$, is also important as it is independent of the initial climate sensitivity ($D$) and population temperature tolerance ($\Delta T$). It reflects the degree to which CO$_2$ consumption increases the birth rate per natural growth time assuming the population was at the carrying capacity.

Our best-fit Earth model had $\gamma = 1.94$, $\theta = 14.45$, and $\alpha = 1.52$. See Table 1 for a summary of the dimensionless parameters.

### 3.1. Low $\alpha$ Limit

It is first worth considering the role played by $\alpha$ in the analysis. The parameter $\alpha$ is the ratio of the temperature change required to affect population growth ($\Delta T$) relative to the temperature change needed for the climate sensitivity to decrease ($\Delta T_F$). For present day conditions on Earth, $\Delta T_F \approx 4$ K (IPCC 2014). This means that if 4 K of warming is sufficient to impact the rate of human population growth ($\Delta T < 4$ K), then $\alpha \lesssim 1$. In the limit where $\alpha \ll 1$ we can take only the highest-order terms and our equations become

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

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

#### 3.1.1. Low Climate Forcing ($\gamma \ll 1$)

If $\gamma$ is small, the climate forcing $d\epsilon/d\tau$ remains small even as the population reaches the carrying capacity ($\eta \rightarrow 1$). After the population reaches the carrying capacity, the climate will be slowly forced on a timescale $\gamma^{-1}$, causing the population to also decline on the same timescale. Figure 3 shows trajectories for the semi-analytic model for $\gamma = 0.01$, $\gamma = 0.05$, and $\theta = 0$ as well as a model with $\gamma = 0.05$ and $\theta = 1$. Note the exponential rise of the population ($\eta$) to the carrying capacity followed by a slower, linear rise in the temperature ($\epsilon$) over timescales $\sim \gamma^{-1}$. The change in slope during the decline is due to our birth rate (regardless of population and technology) being capped at

$1 - \eta$ as a means of implementing a carrying capacity. As the population begins to decline, for a while it is able to maintain the maximum birth rate (which itself is increasing). This helps to counter the increased death rate due to the changing climate. Eventually, however, the population drops far enough that the technology enhanced birth rate is less than the enhanced death rate, at which point the population drops off more precipitously. For $\theta = 0$ this occurs at $\eta = 0.5$, while for the case with $\theta = 1$ this transition occurs later as technology is able to assist in increasing the birth rate for a longer time. Also note in this case that $\theta$ has little effect on the initial growth or early decline. For this model, $\beta \equiv \gamma \theta \ll 1$ so CO$_2$ consumption is not significantly altering the growth rate until after the population peaks. Also, $\theta$ does not affect the initial decline because the birth rate is at the carrying capacity limit, $1 - \eta$, and is independent of the amount of CO$_2$ consumed.

#### 3.1.2. High Climate Forcing ($\gamma \gg 1$)

In the limit of high climate forcing, the population is able to force (i.e., change) the climate while being well below the carrying capacity ($\eta < 1$). The population will then grow exponentially (or faster if aided by technology when $\theta \gg 1$). The temperature anomaly ($\epsilon$) will also grow exponentially (or faster) until $\eta \gtrapprox \frac{1}{\gamma}$ and $\epsilon \gtrapprox 1$.

Figure 4 shows trajectories for cases with $\theta = 0$ and $\gamma = 10$ and 50. In both cases the population rises exponentially and then begins to turn over when $\epsilon \approx 1$ and $\eta \approx \frac{1}{\gamma}$. The case with the larger $\gamma = 50$ forces the temperature $\epsilon$ faster and as a result has a smaller peak population that it achieves earlier. In both cases the timescale for the population to decline is of order $\tau = 1$.

Figure 4 also shows the trajectory for the case with $\gamma = 50$ but with a technology benefit $\theta = 5$. In that case the rise is accelerated due to a technology assisted enhanced birth rate resulting in not only an earlier peak, but one that also has a higher population. This results in faster environmental forcing that then leads to a shorter collapse time. For very large $\theta$, the min function acts to ensure that technology does not accelerate birth rates to an unrealistic value by enforcing a maximum...
To simplify things, we will assume that the technology assisted growth rate never exceeds the net growth rates, allowing civilizations to reach higher peak populations while also delaying the time for them to be reached. Furthermore, the initial decline begins to taper off as both the decreasing climate sensitivity and increasing birth rate act to reduce the decline in population. It may be unreasonable to expect the birth rate to continually increase over many generations due to CO2 consumption, however CO2 consumption might also act to mitigate the amount of increased death due to changing temperatures, resulting in a similar tendency.

4. Results of Fully Coupled Model

It is important to understand the meaning of the solution domains we have just explicated in terms of the goal of the study. We are interested in the ubiquity of climate-dominated Anthropocenes. Thus, in this study we ask, given different planetary initial conditions, how often will a civilization’s energy harvesting (in this case via combustion) lead to population growth that then leads to rapid climate change that, finally, leads to rapid population decline. Addressing this question is the specific intent of our modeling. As demonstrated by the analysis above, however, some solutions exist in which the population rises to the planet’s carrying capacity before the changing climate produces adverse effects. This would not be a climate-dominated Anthropocene in our definition.

It is, however, worth noting that a rapid (exponential) population rise to the host world’s carrying capacity ($N_{max}$) will bring its own potentially existential challenges. The very definition of carrying capacity implies that when $N = N_{max}$, the civilization is at the edge of what the planet can provide in terms of “ecosystem services.” Thus, while these classes of systems will not fall under our definition of climate-dominated Anthropocenes, they should not be considered to be 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) that could produce them.

4.1. Results: Constant Temperature and Composition Models

We now return to the full nonlinear model described in Section 2. We have carried forward a large suite of numerical experiments using this model with the goal of investigating how the trajectory of coupled planet—civilization systems depend on various initial conditions. To recap, we set up our initial conditions with two key assumptions. (1) The biology of the organisms building the civilization requires liquid water, so the host planet must be within the star’s habitable zone. (2) The organisms have temperature and pCO2 limits beyond which they cannot survive. Taken together, these two conditions define a “Complex Life Habitable Zone” (CLHZ; Schwieterman et al. 2019), as discussed in the Introduction. For illustrative purposes, we will begin our study by using values similar to Earth and human life for these limits, but will always consider them to be free parameters.

We focus on two initial planetary parameters: the orbital distance from the planet to its host star ($a$), and the initial chemical composition of the atmosphere quantified in terms of $P = pCO_2$. The effect of these parameters on the models are not fully independent. Planets on the inner edge of the habitable zone ($a < 1$) have climates that are less stable against small increases in CO2 when compared to similar perturbations on dense CO2 planets near the outer edge ($a > 1$). We chose our boundaries in pCO2 to have an outer edge corresponding to 5000 ppm, as this represents the upper limit of pCO2 amenable for animal life on Earth (Wittmann & Pörtner 2013). For a
lower value we choose 10 ppm (we could not go to zero due to limitations imposed by our EBM).

We begin with two sets of experiments that illustrate the basic behavior of the civilization–planet system. The first of these are “constant composition” models. These keep initial pCO2 constant and allow the initial (equilibrium) planetary temperature, T0, to vary as we change the orbital distance (a). Using T0 = 287.1 K as our fiducial value, we ran four additional models with temperatures evenly spaced above and below T0 in steps of 6 K. This spacing was chosen in order to have all models safely within the habitable zone (273 K < T0 < 373 K). In Figure 6 we show the location of the models in the (a, T0) plane. This representation is important because we will later overlay contours of various quantities such as γ and the collapse time τcoll when we run a larger array of models that sweep across (a, T0) space.

The second set of experiments are “constant temperature” models. These keep initial temperatures (T0) constant and allow the initial pCO2 to vary as we change the orbital distance (a). Five models were run centered on Earth’s current pCO2 concentration with two below and three above, each spaced by log(pCO2) = 0.7. The highest, P0 = pCO2,0 ≈ 28,000 ppm was meant to illustrate the evolution of a system with a CO2 concentration beyond that which animal life on Earth can tolerate.

We now explore the trajectories occurring along our lines of constant T0 and a. Figure 7 shows four runs from our two sets of experiments. Consider first the model in the upper left of the figure, which corresponds to a constant initial composition case with a = 1.021 au. This model begins with log(pCO2,0) = 2.28. Using the climate model to determine the planet’s climate sensitivity, dT/dP, along with the other model parameters, yields γ = 2.663. Since γ > 1 we expect this model to experience a climate-dominated Anthropocene. This is, in fact, what occurs as we see a steep rise in population beginning at approximately t = 2700 yr. The population then peaks at Npeak = 10.5 billion individuals about two centuries later. After the peak, the population declines by half over the following two centuries. The cause of the peak and decline can be seen in the rising pCO2 levels. At Npeak we find log(pCO2,0) = 2.9. The increased planetary greenhouse effect has driven temperatures almost past the civilization’s tolerance ΔT. Note that in this model the population never comes close to the planet’s carrying capacity of Nmax = 20 billion.

In the lower left panel of Figure 7 we show a second constant initial composition case, though in this model a = 0.9795 au. Since log(pCO2,0) is the same as for the model above, it also has γ = 2.392 and we expect a climate-dominated Anthropocene. Because the γ values for these two runs are relatively similar, we find similar trajectories in terms of the rise, peak, and decline in population N along with a relatively steady increase in log(pCO2) and T.

In the upper right panel of Figure 7 we show a constant T0 model with a = 1.029 au. This world is further from its (solar type) star, so it requires a higher pCO2 to maintain T0 = 287 K. Thus, with log(pCO2,0) = 3.74 we find γ = 0.252. In this case γ < 1 and we expect this model to avoid a climate-dominated Anthropocene. The results show this to almost be the case. The population peaks at Npeak / Nmax = .89. Thus, the initial exponential growth phase of the population is able to carry the civilization close to the planet’s carrying capacity before a decline sets in. Note also the longer period between the onset of initial exponential growth and time for the population to reach Npeak.

Finally, in the lower right we show the trajectory for a second constant initial temperature case. This planet is closer to its Sun with a = 0.974 au and, as such, a significantly lower initial pCO2 is required (log(pCO2,0) = 0.97). Because this world is closer to its star and begins with a lower CO2 concentration, it is more sensitive to changes in pCO2. This is reflected in its value of γ = 181. Examining the trajectory, we once again see the rapid rise and fall of the population. In this model, however, the extreme climate sensitivity that drives γ > 1 manifests itself in Npeak ∼ 10−3 Nmax. The population never comes close to the planet’s carrying capacity before the climate is driven into detrimental states (T < T0 + ΔT). Note that this behavior was captured in the value of the Anthropogenic population defined in Appendix A, which, for this model, takes on the value NA = 0.1 billion individuals.

It is also of interest to consider the trajectories for planets with initial pCO2 greater than that which Earth life can tolerate. These worlds would orbit at larger radii (a) and would require higher greenhouse gas concentrations to maintain habitable environments. Figure 8 shows such a model with a = 1.06 au and log(pCO2,0) = 4.38, yielding γ = 0.09. The trajectory for this model shows the population climbing to within 1.5% of the planet’s carrying capacity or (N ∼ Nmax). When this peak occurs, the global mean temperature is still well below the threshold for a climate-dominated Anthropocene (T < T0 + ΔT). Thus, for this case, the population grows until it reaches Nmax without driving the climate into a significant new state that is detrimental to the functioning of the civilization. The trajectory shown in this figure is typical for worlds with very high log(pCO2,0). The addition of more CO2 via combustion does not alter the climate significantly before the population rises to levels beyond what the planet, via its carrying capacity, can sustain.

In Figure 9 we show all trajectories for both experiments. The upper panel shows results from constant initial composition models and the lower panel shows those for constant initial temperature models. The similarities and differences both within and between the models offers insight into the dynamics and its relationship to our dimensionless parameters. For example, the value of γ can be seen to uniquely determine the
resulting evolution of a population. Furthermore, the upper panel shows that models with constant initial pCO$_2$, yet different orbital radii and initial temperatures, will share the same $\gamma$, indicating the importance of the initial pCO$_2$ in the resulting coevolution.

4.2. Results: 2D Parameter Sweeps

To explore the broad dependence on initial conditions we next chose 100 different distances and temperatures for the models. The results of this parameter sweep are shown as contour plots in Figure 10. The left column of the plots show quantities taken from the full numerical models, while the right column shows the corresponding analytical quantities. In the top left we present contours and color mapping of the initial atmospheric composition, log $pCO_2(0)$, for all of the runs. This was calculated using only the uncoupled energy balance model. Note that we exclude models with log $pCO_2(0) > 3.72$ as being outside the CLHZ (Schwieterman et al. 2019).

The top right panel in Figure 10 presents effective $\gamma$, defined in Appendix A as $\gamma_{\text{eff}} \equiv \gamma e^{-\alpha}$, where $\gamma/\alpha$ are defined in Table 1. Recall that $\gamma$ is dependent principally on the initial climate sensitivity, $dT/dP|_{P_0}$, which itself is dependent principally on the initial pCO$_2$. Thus, the contour lines of the initial pCO$_2$ also correspond to contour lines for $\gamma_{\text{eff}}$. This plot shows that only the outermost layers of orbits have $\gamma < 1$, indicative of worlds not at risk of a climate-dominated Anthropocene. Recall that even models with $\gamma$ slightly less than 1 can still have their growth truncated by climate effects. Thus, we find that most civilizations arising in the CLHZ will...
be susceptible to having their growth truncated by rising temperatures and changing climate.

The middle column describes the population dynamics for the civilizations and focuses on parameters associated with growth. The left column presents the numerically measured percentage of the carrying capacity each civilization reached ($N_{\text{peak}}/N_{\text{max}}$). The right column shows the analytic predictions of the quantity $N_A$, defined in Appendix A as the number of people required to force the climate out of equilibrium in a single growth timescale. In $N_{\text{peak}}/N_{\text{max}}$ we see only the outermost orbits at each initial temperature are able to rise to their carrying capacity before increasing temperatures significantly increase death rates and halt population growth. Note all models in the parameter sweep began with a carrying capacity of $N_{\text{max}} = 20$ billion. Consideration of the $N_A$ contour plots demonstrates how the linear model accurately identifies the peak population possible in worlds that experience climate-dominated Anthropocenes.

Finally, the last row of plots considers what happens after $N = N_{\text{peak}}$. On the left, we show the time for a population to decline by 20%. Here, we see most of the models experience a decline on timescales of a few centuries at most, while initially hotter worlds on inner orbits can have declines over just decades. The collapse time parameter $\tau_{\text{coll}}$ is shown on the lower right. Once again we see timescales of order decades to a few centuries associated with significant population decline. Note however that $\tau_{\text{coll}}$ shows a “valley” feature at intermediate orbital distances where $\tau_{\text{coll}}$ falls and then rises again as one moves outward in orbital distance along a line of constant $T_0$. We return to this valley, which reflects the dependence of $\tau_{\text{coll}}$ on $1/\gamma$ in the next section.

### 4.3. Dependence of Civilization Temperature Tolerance

All of the models discussed in the last section used a constant value of the civilization’s temperature tolerance, $\Delta T = 5$ K. As discussed earlier, this parameter is intended to capture biological, ecological, and cultural effects of the civilization’s response to its climate forcing. Depending on the fragility of both the social organization and ecosystems on which it depends, a smaller $\Delta T$ may be enough to trigger detrimental consequences for the civilization. Thus, in this section we vary $\Delta T$ to assess its role in model outcomes.

To see the effect of $\Delta T$ on the models, Figure 11 shows the marginal probability distributions for both population decline times and for $\gamma_{\text{eff}}$, as defined in Appendix A. These are represented as “violin plots” showing the range of values for both for runs with a given $\Delta T$. These plots also show the average and first moment of the distributions.

Note that the median values for the collapse times increase with $\Delta T$. This is to be expected as the sooner the planetary temperature rises beyond $T_0 + \Delta T$, the sooner the population growth is truncated by climate effects. The values of $\gamma_{\text{eff}}$ extracted from the models reflect this, showing a decrease with increasing temperature tolerance. Note that for $\Delta T < 5$ K, the decline times are less than, or of order, a century. Given that the timescale for a generation in our models is $\sim 25$ yr, this means significant population loss across the lifetime of an individual. We consider such a situation as likely to pose the greatest risk for civilizations.

We also show data for the models as a scatter plot of gamma versus decline time in Figure 12. On the $x$ and $y$ axes we show corresponding marginal probability distributions for $\gamma_{\text{eff}}$ and the decline time. These are shown as a kernel density estimation graph such that the area under each curve is normalized to one.

Shown as the solid black line is our analytically derived collapse time, given by Equation (15). It can be seen that our analytic approximation reproduces the necessary features that arise in our numerical runs. The deviations are explained in Figure 13 in Appendix A.

There are three distinct regions for $\tau_{\text{coll}}$. Starting from the right-hand side of Figure 12, we are in the region of high $\gamma$ and
Figure 10. The plots on the left-hand side show numerically calculated quantities, and the plots on the right-hand side show analytically derived quantities. The top row shows values calculated with the uncoupled energy balance model. The middle row shows quantities related to the population’s growth. The bottom row shows timescales related to the population’s collapse. The bottom left of the plots are gray because of limitations imposed by the EBM. The top right part of the plots are gray because the value of pCO₂ required there was greater than 5000 ppm, a level deemed prohibitive for long-term habitability by intelligent civilizations (Schwieterman et al. 2019). The black arrow points to the location of the experiment that we ran in the “danger zone”.

References:

1. Schwieterman, E. W., Meadows, D. C.,2 et al. (2019). The Astronomical Journal, 162:196 (15pp), 2021 November Savitch et al.
low $\theta$. We say that civilizations in this region experience a climate-dominated Anthropocene. The high $\gamma$ indicates that the timescale for the climate to change is much shorter than the timescale for population growth. The low $\theta$ indicates that the timescale for climate to change is also much shorter than the timescale for technology to evolve. Thus, in this region, civilizations experience climate change before they experience any significant growth benefits due to their technological capacities. These civilizations reach only a tiny fraction of their carrying capacity before they begin to decline. Since they do not have much time to increase their overall growth rate above the “natural” value, their collapse rate ends up being approximately equivalent in magnitude to their natural growth rate.

As we move leftward in Figure 12 to lower $\gamma$, we see a dip in the collapse times (this is the valley seen in the contour plots discussed in the last section). This region, between the two black dotted lines, corresponds to high $\gamma$ and high $\theta$. We say civilizations in this region experience a technology-dominated Anthropocene. The high $\gamma$ indicates that the timescale for climate to change is much shorter than the timescale for population growth. The high $\theta$ indicates that the timescale for climate to change is now longer than the timescale for technology to evolve. Thus, civilizations in this range experience a birth benefit due to their technological capabilities before they experience adverse effects stemming from climate change. This is the region Earth currently inhabits. The technological birth benefit allows the civilization to begin approaching their planet’s carrying capacity. However, the high $\gamma$ value prohibits them from reaching this limit. As we move toward the leftmost vertical dotted black line in the plot, civilizations peak closer to their carrying capacity. Since the decline time for civilizations correlates with their growth rate, civilizations whose populations begin falling closer to their carrying capacity experience the fastest decline times. In essence, in this region the more technology props a civilization up, the harder they end up falling.

Continuing leftward in Figure 12 to lower $\gamma$, we begin to leave the region of the Anthropocene and approach the limit of overpopulation. In this region, $\theta$ is much greater than one, while $\gamma$ is now decreasing $< 1$. Low $\gamma$ means that the timescale for population to grow is now much shorter than the timescale for the climate to change. High $\theta$ again indicates that the timescale for climate to change is also much longer than the timescale for technology to evolve. Thus, in this region, civilizations experience a birth benefit due to their growing technological capacities, allowing them to rise in population toward their carrying capacity. As $\gamma$ drops below 1, civilizations are able to reach their carrying capacities ($\eta \rightarrow 1$). In this region, the timescale for these civilizations to decline is then dictated by the timescale for climate to change, thus resulting in a longer collapse time $\tau_{coll} = 1/\gamma = T_C/T_\theta$. Moving further leftward yields ever lower values of $\gamma < 1$ and the timescale for climate to change becomes larger, resulting in a steadily increasing collapse time.

Finally, we note that in Figure 12 the marginal distribution of the decline time for $\Delta T = 1$ K seems to peak higher than $\Delta T = 0.5$ K. This occurs because many of the $\Delta T = 0.5$ K models are in the valley of our collapse time, and the marginal distribution is a projection onto the $\gamma$ axis. This can also be seen as the large shoulder protruding in the distribution of collapse times for $\Delta T = 0.5$ K.

The most important takeaway from these results is that an ever increasing share of the models experience climate-dominated Anthropocenes as $\Delta T$ decreases. For $\Delta T < 5$ K, most models experience rapid population declines. Even for $\Delta T = 10$ K, the average decline time was 384 yr and 22.2% of models had decline times less than 200 yr.

5. Discussion and Conclusions

In this paper we have modeled the coupled evolution of a planet and a civilization through the era when energy harvesting by the civilization drives the planet into new and potentially adverse climate states. Our goal, continuing from the work of
Frank et al. (2018), is to determine if “Anthropocenes” of the kind humanity is experiencing now might be a generic feature of planet—civilization evolution (Haqq-Misra & Baum 2009; Frank et al. 2017; Mullan & Haqq-Misra 2019). To this end we introduced and analyzed a set of coupled ordinary differential equations that track the trajectory of the civilization’s population \((N)\), the generation of \(CO_2\) via the civilization’s energy harvesting activities, and, finally, the mean planetary temperature \(T\). The principle innovation in this paper over Frank et al. (2018) is the use of an energy balance model to track the change in climate state as the atmospheric composition, \(P = pCO_2\), changes due to the civilization’s growth. A different form for the population growth equation compared to that in Frank et al. (2018) was also used.

Using both direct simulation of the nonlinear model and an analysis of a linearized, nondimensional version of the equations, we have found that most planets in the Complex Life Habitable Zone (CLHZ; Schwieterman et al. 2019) undergo a climate-dominated Anthropocene. We define this to be a trajectory of the coupled planet—civilization system in which population growth is truncated by changes in the climate state driven by the civilization. Our analysis further shows such climate-dominated Anthropocenes can occur in different ways, depending on the planet’s initial atmospheric composition, orbital location, and the technological capacities of the civilization. On planets with high climate sensitivity \((dT/dP)\), even modest technological innovation in terms of energy harvesting capacities can trigger detrimental climate change (Figure 5). This situation is likely to occur at the inner edge of the habitable zone and would be akin to climate change occurring during the early era of industrialization on Earth (i.e., the Victorian period in England). Planets on the outer edge of the host star’s habitable zone require higher values of \(CO_2\) concentrations to be temperate. Such worlds have lower climate sensitivity and civilizations there can drive higher fractional increases in \(pCO_2\) before temperatures rise significantly. The technological capacities of the civilization affect the trajectories when they allow for population growth rapid enough that it can compete with increasing death rates from an adversely changing climate. Finally, the tolerance of the civilizations to rising temperatures \((\Delta T)\) represents another important input condition and, as could be expected, lower values of \(\Delta T\) led to stronger climate-dominated Anthropocenes (Figure 11).

The models presented in this paper represent an advance over our initial study (Frank et al. 2018) because they assumed a specific form of energy harvesting (combustion) and included an explicit physical model for its climate impact via a combustion-dependent (i.e., \(CO_2\)) Energy Balance Model. In this way we added a higher level of physio-chemical realism to the planet-civilization model system. With the new model, we were able to vary parameters such as orbital distance and atmospheric composition for a specific class of worlds (i.e., Earth-like planets orbiting Sun-like stars).

One significant question to arise from our studies is the applicability of the Complex Life Habitable Zone (Schwieterman et al. 2019; Ramirez 2020). For evolutionary reasons, it is generally believed that a technological civilization would only arise from complex multicellular “animal” life (Carter 2008;
predictions; that is, it adheres much more to our check-mark shaped prediction. Although, not all deviations have been solved by using two classes of civilizations will have the same value of \(\gamma\) as given by Equation (A1). This biggest difference as compared to the plot above is a net decrease in \(\gamma\) which is as expected from Equation (A2). This also has the effect of greatly reducing the deviations from our analytical predictions; that is, it adheres much more to our check-mark shaped prediction. Although, not all deviations have been solved by using \(\gamma_{\text{eff}}\). The right column shows plots of \(\gamma_{\text{eff}}\) colored by orbital distance (top) and initial global temperature (bottom). It can be seen that the models that deviate greatest from our analytical prediction are those that have large orbital radii and low initial global temperatures. As shown in Figure 10, the contour lines for pCO\(_2\) travel diagonally across the parameter space of \(a/T_0\). Thus, as a result, civilizations with a high orbital distance and a low initial global temperature could have the same value of initial pCO\(_2\) as the civilizations with a low orbital distance and a high initial global temperature. Since \(\gamma\) is principally dependent on the value of the initial pCO\(_2\), this means that these two classes of civilizations will have the same value of \(\gamma\) and hence the same value of \(\tau_{\text{coll}}\). Although, in reality, the civilizations with the higher orbital radii end up taking longer to fall, and hence have longer decline times.

Figure 13. The top left plot shows our numerically calculated values of \(\gamma\) as defined in Table 1 and derived in Appendix A, plotted vs. the numerically calculated times for our models’ populations to decline by 20% from their peak values. The black dotted line shows our analytical expression for the collapse time, derived in Section 3 and Appendix B. For contrast, the bottom left plot shows the same things yet instead for \(\gamma_{\text{eff}}\) as given by Equation (A1). The biggest difference as compared to the plot above is a net decrease in \(\gamma\) which is as expected from Equation (A2). This also has the effect of greatly reducing the deviations from our analytical predictions; that is, it adheres much more to our check-mark shaped prediction. Although, not all deviations have been solved by using \(\gamma_{\text{eff}}\). The right column shows plots of \(\gamma_{\text{eff}}\) colored by orbital distance (top) and initial global temperature (bottom). It can be seen that the models that deviate greatest from our analytical prediction are those that have large orbital radii and low initial global temperatures. As shown in Figure 10, the contour lines for pCO\(_2\) travel diagonally across the parameter space of \(a/T_0\). Thus, as a result, civilizations with a high orbital distance and a low initial global temperature could have the same value of initial pCO\(_2\) as the civilizations with a low orbital distance and a high initial global temperature. Since \(\gamma\) is principally dependent on the value of the initial pCO\(_2\), this means that these two classes of civilizations will have the same value of \(\gamma\) and hence the same value of \(\tau_{\text{coll}}\). Although, in reality, the civilizations with the higher orbital radii end up taking longer to fall, and hence have longer decline times.

Watson 2008). Schwieterman et al. (2019) emphasized that the oxidation of organic matter via free O\(_2\) is the best means of producing significant free energy via respiration. Given that O\(_2\) is the only high-potential oxidant sufficiently stable to accumulate within planetary atmospheres (Catling et al. 2005), it comprises a necessary condition for intelligent species. Based on Earth’s evolutionary history, it is clear that complex aerobic life can also be strongly impacted by CO\(_2\), with limits for animal life appearing at atmospheric conditions of pCO\(_2\) \(> 5 \times 10^4\) ppm (humans’ pCO\(_2\) lethality limit may be 10 times lower). Thus, if we take Earth’s history as a guide, atmospheres with high oxygen and low CO\(_2\) may be necessary for the emergence of intelligent civilization-building species. If this is the case then climate-dominated Anthropocenes would appear to be a generic feature of coupled planet—civilization evolution. The difficulty, however, is knowing how universal the constraints on pCO\(_2\) are for life elsewhere. Is it possible for a planet with \(10^5\) ppm of CO\(_2\) to evolve complex life that goes on to create a technological civilization? In addition, what constraints exist for energy harvesting based on combustion on high pCO\(_2\) worlds? If civilizations could occur on such planets, then our results indicate that these worlds would not undergo a climate-dominated Anthropocene. Instead, in our models, their populations climb until they reach the planet’s carrying capacity. This situation, however, presents its own difficulties and could represent a different form of negative feedback on the planet—civilization system that is not modeled in our equations. It is also possible that without rapid detrimental feedbacks from adverse climate change a civilization would reduce its population growth on its own before the carrying capacity is reached.

Future modeling efforts could explore different representations of the population growth and its coupling to the climate state and energy harvesting modality. In addition, other energy harvesting modalities such as wind or solar could also be explored. Future work should also investigate the impact of the stellar spectral type, as this will impact the climate of the planet and may also impact the ability of a civilization to utilize stellar energy (as M dwarfs have a different spectral energy distribution than G dwarfs, etc.). Finally, models that include changes in the civilization’s behavior, such as simply switching from one harvesting mode to another, could also be included in the modeling. Each of these steps would represent a further articulation of an astrobiology of the Anthropocene by exploring issues associated with the biospheric dimensions of creating a long-term sustainable civilization.

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Appendix

Appendix A: Intrinsic Timescales and Dimensionless Quantities

In analyzing the model we see that it contains three intrinsic timescales.

\[ t_G = \frac{1}{R_0} = \text{Timescale for Population Growth} \]

\[ t_T = \frac{\Delta P}{CN_{\text{max}}} = \text{Timescale for Technological Advancements} \]

\[ t_c = \frac{\Delta T}{CN_{\text{max}} D} = \text{Timescale for Climate Change} \]

where

\[ D = \frac{\Delta T}{P_0} = \left. \frac{dT}{dP} \right|_{T=T_0} = \text{Initial Climate Sensitivity} \]

as defined in Equation (9). Also, \( R_0 \) is the initial “natural” growth rate, \( \Delta P \) is the technological birth benefit, \( \Delta T \) is the civilization’s temperature tolerance, \( N_{\text{max}} \) is the carrying capacity, and \( C \) is the annual, per-capita carbon footprint. We can use these timescales to define our dimensionless quantities shown in Table 1.

\[ \gamma = \frac{t_G}{t_c} = \frac{DCN_{\text{max}}}{R_0 \Delta T} \quad \theta = \frac{t_c}{t_T} = \frac{\Delta T}{D \Delta P} \]

\[ \beta = \frac{t_G}{t_T} = \frac{CN_{\text{max}}}{R_0 \Delta T} \]

Note that \( \beta = \theta \gamma \). Since we have defined \( \gamma \) to be approximately constant, based on the initial climate sensitivity, we can define an “effective” \( \gamma \) to be based on the value of the climate sensitivity when the population reaches its peak value, which occurs approximately when global temperatures have deviated from their initial values by \( \Delta T \).

\[ \gamma_{\text{eff}} \equiv \left( \frac{CN_{\text{max}}}{R_0 \Delta T} \right) \left. \frac{dT}{dP} \right|_{T=T_0+\Delta T} \]

As defined by Equation (9), this means that

\[ \gamma_{\text{eff}} = \left( \frac{CN_{\text{max}}}{R_0 \Delta T} \right) \Delta T e^{-\Delta T / \Delta T} \]

\[ \equiv \left( \frac{DCN_{\text{max}}}{R_0 \Delta T} \right) e^{-\alpha} = \gamma e^{-\alpha} \]

where we have defined \( \alpha \equiv \Delta T / \Delta T \). Thus, as temperatures increase, the civilization’s effective \( \gamma \) will drop from its fiducial value. See Figure 13 to visualize this effect. Furthermore, the value of the carrying capacity that makes \( \gamma = 1 \) is indicative of the number of people required to force the climate out of equilibrium in a single growth timescale \( (t_c) \). This quantity is called the civilization’s “anthropogenic population”

\[ N_A \equiv \frac{\gamma}{N_{\text{max}}} = \frac{R_0 \Delta T}{DC} = \text{Anthropogenic Population}. \]

### Appendix B: Derivation of Collapse Time for High Climate Forcing

For high climate forcing (\( \gamma \gg 1 \)) we find that the collapse time is given by

\[ \tau_{\text{coll}} = \frac{1}{\max\left(\frac{\gamma}{2}, \theta \right)} = \begin{cases} 
1/\sqrt{2}, & \theta \ll 1 \\
1/\theta, & \theta \gg 1 
\end{cases} \quad (B1) \]

We can derive this from our linearized model as follows. If \( \gamma > 1 \), then \( t_c < t_G \), so the climate changes on a much faster rate than the population does. This is the region of the climate-dominated Anthropocene, which means that global temperatures will begin to increase death rates before civilizations reach their carrying capacity. A consequence of this is that civilizations in this region never reach their maximum growth rate, \( \eta \ll 1 \), which implies that \( 1 - \eta > \eta(1 + \theta \epsilon) \), so their population growth equation will have the form

\[ \dot{\eta} = \eta(1 + \theta \epsilon) - \eta^2 = \eta(1 + \theta \epsilon - \epsilon^2) = d\eta / d\tau. \]

We can set \( \dot{\eta} = 0 \) and solve for \( \epsilon \) to determine what the environmental state is at the point when population begins to collapse (i.e., the moment when \( \dot{\eta} \) drops below zero). We call this value of \( \epsilon \) its critical value, which we find to be

\[ \epsilon_c = \theta / 2 + \sqrt{1 + \left(\theta / 2\right)^2} \]

We can also find the timescale for the population to decline after it reaches this peak. Since these civilizations do not reach their carrying capacity, their growth rate as they enter the Anthropocene dictates what their collapse rate will be directly after. Thus, we use the freefall time for civilizations as their collapse rate

\[ \tau_{\text{coll}} = \left( \frac{\eta}{\dot{\eta}} \right)_{\eta=0} \quad (\gamma \gg 1). \]

We can use our population growth rate equation to find this second derivative

\[ \dot{\eta} = \eta(\theta \dot{\epsilon} - 2 \epsilon \dot{\epsilon}) \]

where we let \( \dot{\epsilon} \equiv d\epsilon / d\tau \). When the population begins to decline, global temperatures continue to rise exponentially. Thus, at this point, the rate of increasing temperatures is approximately equal to its critical value \( \dot{\epsilon} \approx \epsilon_c \). It follows that at this point, directly after \( \eta = 0 \),

\[ \dot{\eta} \approx (2 \epsilon^2 - \theta \epsilon_c). \]

As a result, the collapse timescale for \( \gamma \gg 1 \) is given by

\[ \tau_{\text{coll}} = (2 \epsilon^2 - \theta \epsilon_c)^{-1/2} \quad (\gamma \gg 1). \]

This can further be broken down into two cases, dependent on \( \theta \).

1. Low Technological Growth Acceleration: If \( \theta \ll 1 \), then \( \epsilon_c \to 1 \) and \( \tau_{\text{coll}} = 1/\sqrt{2} \). In this case, the civilizations’ technological abilities are not advanced enough to increase their growth rates. Also, the fastest timescale is that for climate change. Since their rate of technological
advancements is negligible and their rate of climate change exceeds that for population growth, these civilizations will have negligible population growth before entering their Anthropocene. As a result, their growth rate as they enter the Anthropocene will be approximately equal to its initial “natural” value. Thus, all civilizations in this area will also collapse with a constant “natural” collapse rate.  

2. High Technological Growth Acceleration: If \( \theta \gg 1 \), then \( \epsilon_c \to \theta \) and \( \tau_{\text{coll}} = 1/\theta \). In this case, the civilizations’ technological abilities are able to accelerate their growth rates. Thus, these civilizations enter their Anthropocene with an accelerated growth rate due to their technological abilities. This accelerated growth leads to an accelerated decline, which means that these civilizations collapse at a faster than natural rate.

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