# Climate Change Driven "Anthropocenes": Are They Common Among Exo-Civilizations?

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**Abstract**

We seek to model the coupled evolution of a planet and a civilization through the era when energy harvesting by the civilization drives the planet into new and adverse climate states. In this way we ask if "anthropocenes" of the kind humanity is experiencing might be a generic feature of planet-civilization evolution. In this study we focus on the effects of energy harvesting via combustion and vary the planet's initial chemistry and orbital radius.

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## *Are They Common Among Exo-Civilizations?*

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## Goal/Motivation

We seek to model the coupled evolution of a planet and a civilization through the era when energy harvesting by the civilization drives the planet into new and adverse climate states. In this way we ask if "anthropocenes" of the kind humanity is experiencing might be a generic feature of planet-civilization evolution. In this study we focus on the effects of energy harvesting via combustion and vary the planet's initial chemistry and orbital radius.

This project builds off of the prior work done in Frank et al (2018), which took a population biology approach to modelling the coupled evolution of exo-civilizations and host planet feedback. 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. 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.

## Energy Balance Model (EBM)

Energy balance models (EBM's) approximate planetary temperature by balancing the incoming solar radiation with the outgoing long-wave, terrestrial radiation. Our specific version of the model uses a variety of planetary inputs, such as $pCO_2$ levels, orbital semi-major axis, planetary albedo, orbital eccentricity etc. The code was 1-D in that it modeled climate as a fuction of latitude. The program then discretizes global temperatures into these bands in order to model our latitudinal heat transport as diffusion according to the equation

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

Where $C_v$ is the effective heat capacity of the surface and the atmosphere, $T$ is global temperature, $\psi$ is the solar flux, $A$ is the planetary albedo as a function of both temperature and partial $CO_2$ pressure, $I$ is the outging infrared radiation, and $\kappa$ is the diffusive parameter. Our version of the model incorporates the effect of carbon dioxide concentrations by making both $I$ and $A$ functions of temperature and partial $CO_2$ pressure. The code we used was developed by Jacob Haqq-Misra, and was most recently used in his paper *Damping of Glacial-Interglacial Cycles From Anthropogenic Forcing* (Haqq-Misra, 2014). A full description of the model and it's parameters can be found in Williams and Kastings, 1997.

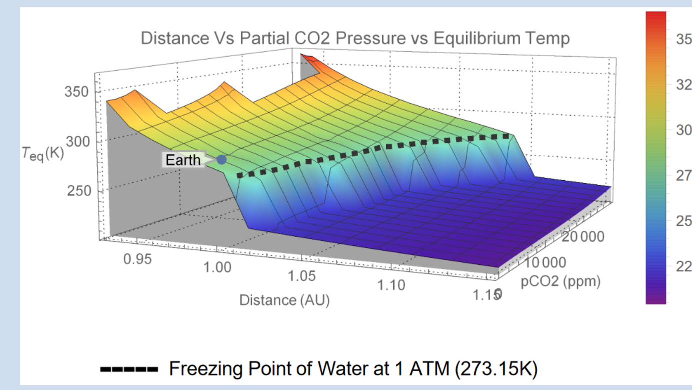


**Fig 1.** Surface Plot of our Solar Systems Habitable Zone calculated with the EBM

## Coupled 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 ($T$) across the latitudinal zones. We begin by calculating the planet's initial equilibrium temperature, which is calculated as a function of partial $CO_2$ pressure ($P$) and solar insolation, which is a function of orbital distance ($a$). Thus...

$$\boxed{\frac{dT}{dt} = EBM(P,a)} \tag{2}$$

The next step in our model is determining the global population, which is calculated as a function of the current population ($N$), partial $CO_2$ pressure ($P$), and global temperature ($T$). The dynamics of the global population are governed by the difference between the per-capita birth and death rates, denoted $A$ and $B$ respectively, which we allow to vary with time. In our simulations we assume "pre-technological" birth and death rates $A_0$ and $B_0$. As the civilization becomes more proficient at energy harvesting their 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. Since technology allows an increase in birthrate, we take $A(t)$ to be a function of $pCO_2$ ($P$) relative to the value the civilization found the planet in when it began its technological evolution ($P_0$). Thus our per-capita birth rate takes the form:

$$A = A_0 \left[1 + \frac{P - P_0}{\Delta P}\right] \tag{3}$$

Where $\Delta P$ is a normalization constant. 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 be a corresponding increase in global temperature, dictated by equation (2). This will eventually lead to a feedback on the population. We model this feedback via the death rate which we take to be temperature dependent:

$$B = B_0 \left[1 + \left(\frac{T - T_0}{\Delta T}\right)^2\right] \tag{4}$$

Here $T_0$ is the average planetary temperature when the civilization began and $\Delta T$ describes the range of temperatures amenable to the civilization's health. This term can focus on either the biology of individuals or the functioning of the civilization as a whole.

The final governing equation for population is,

$$\boxed{\frac{dN}{dt} = min(AN,\ B_0 N_{max}) - BN} \tag{5}$$

The use of the $min$ function 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. In the classic logistic growth model

$$\frac{dN}{dt} = N\alpha(1 - \frac{N}{N_{max}})$$

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. Finally, we model the production of $pCO_2$ as a function of global population using the simple equation

$$\boxed{\frac{dP}{dt} = CN} \tag{6}$$

We terminate the simulation 20 generations after the population has peaked, where we have defined the time for a generation to be 25 years. This assumption is also what determines our growth rate, which we define as the inverse of the time for a generation.

| Parameter | Description | Earth Value |
|---|---|---|
| $N_{max}$ | Carrying Capacity | 10 Billion |
| $A_0$ | Initial Birth Rate | 0.04 $yr^{-1}$ |
| $B_0$ | Initial Death Rate | 0.036 $yr^{-1}$ |
| $\Delta T$ | Population Temp Sensitivity | $5K$ |
| $\Delta P$ | Technology Birth Benefit | 200 $ppm$ |
| $C$ | per-capita $CO_2$ generation | $2.75 \times 10^{-4} \frac{ppm}{yr \cdot 10^6 ppl}$ |

**Table 1. Input Parameters for the Model**

## Testing the Model

In order to provide both a test and a calibration of our model we test it against the recent evolution of Earth and its human population into the Anthropocene. We let the model start at $t_0 = 1820\ CE$, when the global population was $N_0 = 1.29 \times 10^9$ and the global $pCO_2$ levels were around $P_0 = 284\ ppm$. The results are shown below in Fig 2. As can be seen, the model does an excellent job of tracking both the rise in temperature and population during the last two centuries.

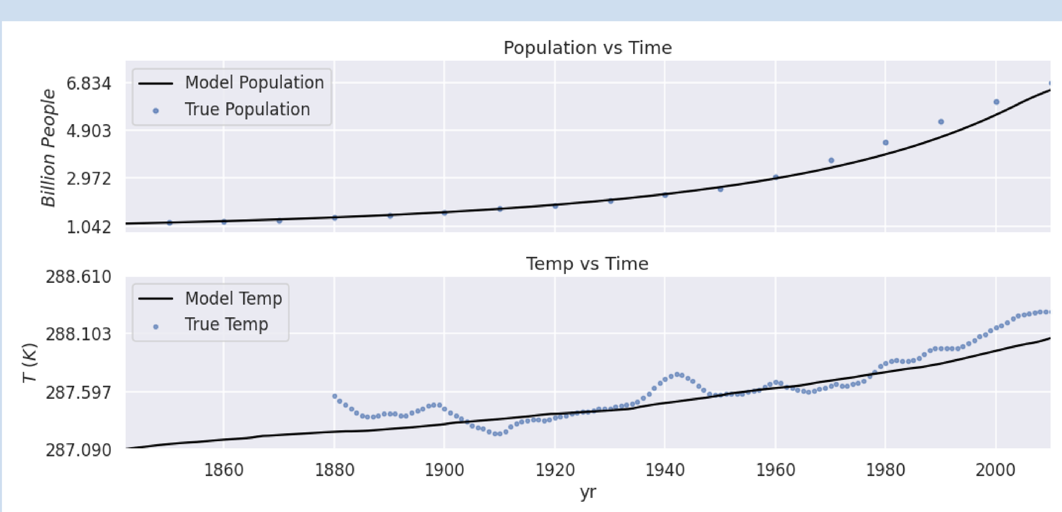


**Fig 2.** Model Output (solid black line) vs Real Global Data (dotted line)

## Analyzing the Model

In analyzing our model, we can see that the problem contains two intrinsic timescales. For the population growth, the relevant timescale is

$$\boxed{t_g \equiv \frac{1}{A_0} = Growth\ Timescale} \tag{7}$$

This describes the timescale for population growth without the added benefit of technology. It was defined under the assumption that the average timescale for a generation is around 25 years.

The second intrinsic timescale describes how the climate responds to this population growth, thus is called a collapse timescale. In determining this, we first define a new parameter to measure how global temperatures change as a function of partial $CO_2$ pressure, called climate sensitivity ($D \equiv dT/dP$). Using $D$ we can define our climate response time as

$$\boxed{t_c \equiv \frac{\Delta T}{C N_{max} D} = Collapse\ Timescale} \tag{8}$$

Using these two timescales, we can define a dimensionless parameter $\gamma$.

$$\boxed{\gamma \equiv \frac{t_g}{t_c} = \frac{DCN_{max}}{A_0 \Delta T} = \frac{Timescale\ for\ Population\ Growth}{Timescale\ for\ Climate\ to\ Change}} \tag{9}$$

$\gamma$ serves as a measure of when an "anthropocene" can be expected. For our purposes we define an anthropocene to be changes in climate occurring on timescales that are short with respect to the populations own evolution.

- $\gamma << 1 \Longrightarrow$ Climate will change on timescales much longer than the average generation. Corresponds to a civilization having a low risk for an Anthropocene.
- $\gamma = 1 \Longrightarrow$ Climate will change within one generation.
- $\gamma >> 1 \Longrightarrow$ Climate will change on timescales much shorter than the average generation. Corresponds to a civilization having a high risk for an Anthropocene.

If $\gamma = 1$, then the growth and the collapse timescales are equivalent. The value of the carrying capacity required to accomplish this is then representative of the number of people required to force the climate out of equilibrium in a single generation. This quantity is thus called the "anthropogenic population":

$$\boxed{N_A \equiv \frac{N_{max}}{\gamma} = \frac{A_0 \Delta T}{DC}} \tag{10}$$

## References

- Haqq-Misra, J. (2014), Damping of glacial-interglacial cycles from anthropogenic forcing, J. Adv. Model. Earth Syst., 06, doi:10.1002/ 2014MS000326
- Frank et al. (2018), The Anthropocene Generalized: evolution of exo-civilizations and their planetary feedback http://doi.org/10.1089/ast.2017.1671
- Williams, D. M., & Kasting, J. F. 1997, Icarus, 129, 254

## Conclusions

We find that our models lead either to climate driven anthropocenes (large die-off via change in $T$) or the species hits its planet's carrying capacity which is likely to drive other versions of an anthropocene.

## Experiment #1: Constant Composition ($P_0 = 284\ ppm$)

In this experiment, we define the "habitable zone" by the range of distances that will result in temperatures below boiling and above freezing. This requirement and the resulting range of semi-major axii ($a_{habitable}$) are shown below.

$$373.15\ K < T_{habitable} < 273.15\ K$$

$$\boxed{0.94\ AU < a_{habitable} < 1.02\ AU}$$

As can be seen, this requirement results in a very small range of habitable distances. To see how civilizations in this range would evolve, we chose 5 distances uniformly distributed in this range and let them all evolve, the resulting evolution of population is shown below.

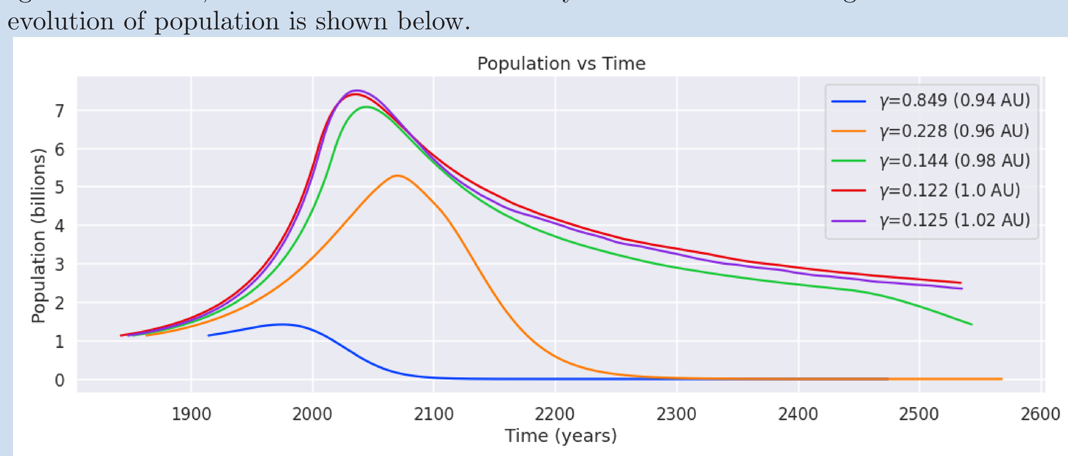


**Fig 3.** Population Evolution for Civilizations in this Range

We can see how $pCO_2$ and temperature evolve as a result by focusing in on one distance. This plot is shown below.

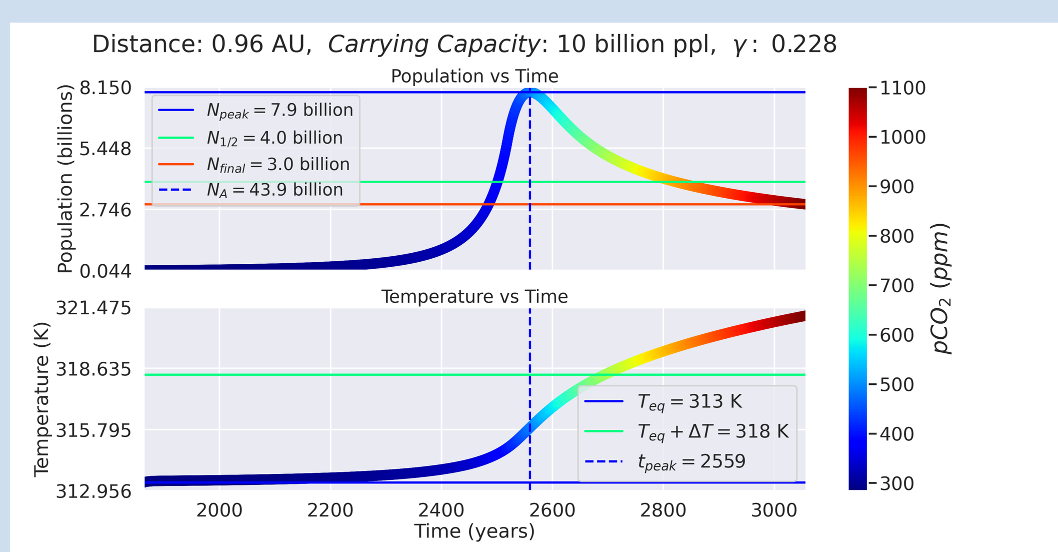


**Fig 4.** Population/Temperature/$pCO_2$ vs Time for $0.96 AU$

## Experiment #2: Constant Temperature ($T_0 = 287K$)

In this experiment, we define the habitable zone by the range of distances that have temperatures approximately equal to the pre-anthropocene temperature of our planet ($287.09K$); with corresponding values of $pCO2's$ greater than 10ppm and less than $10^5$ppm. The lower limit was chosen as it represents the lowest value allowed by our simulation. The upper limit was chosen as it corresponds to an atmosphere composed of 10% $pCO_2$. The resulting evolution of population is shown below. This requirement and the resulting range of semi-major axii ($a_{habitable}$) are shown below.

$$10\ ppm < pCO2_{habitable} < 10^5\ ppm$$

$$\boxed{0.975\ AU < a_{habitable} < 1.105\ AU}$$

As can be seen, this requirement results in a slightly larger range of habitable distances as compared to the first experiment. To see how civilizations in this range would evolve, we chose 5 distances uniformly distributed in this range and let them all evolve, the resulting evolution of population is shown below.

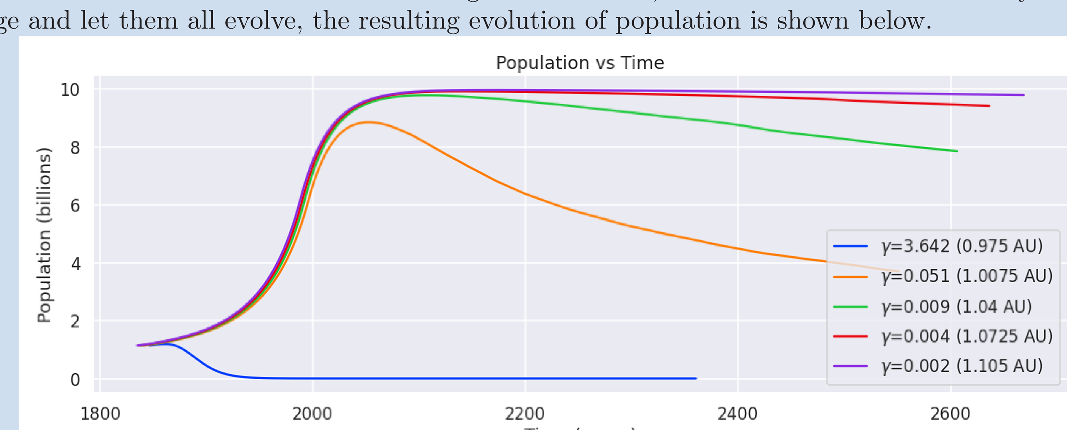


**Fig 5.** Population Evolution for Civilizations in this Range

## Exploring the Model

To explore the broad dependence on initial conditions we chose 40 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 below. 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 these locations produced a runaway greenhouse effect that made it unable for our EBM to reach an equilibirum. The top right part of the plots are grey because the value of $pCO_2$ required there was greater than $10^5 ppm$, which corresponds to an atmosphere composed of 10% $CO_2$, a level we have deemed uninhabitable for intelligent civilizations.

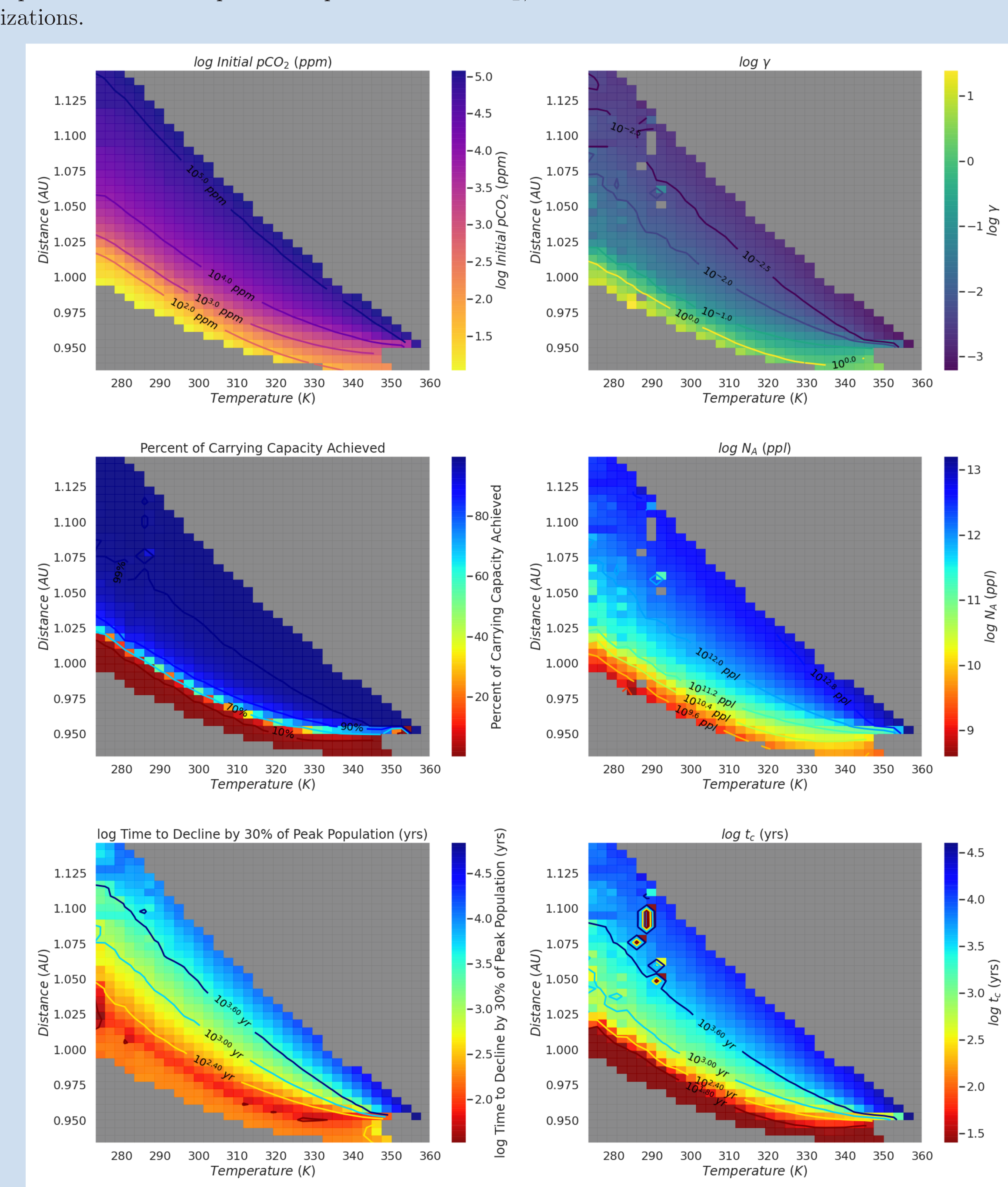


**Fig 6.** Parameter Sweeps using the model described above.

We continued to further explore the model by repeating this process for multiple values of $\Delta T$. 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.

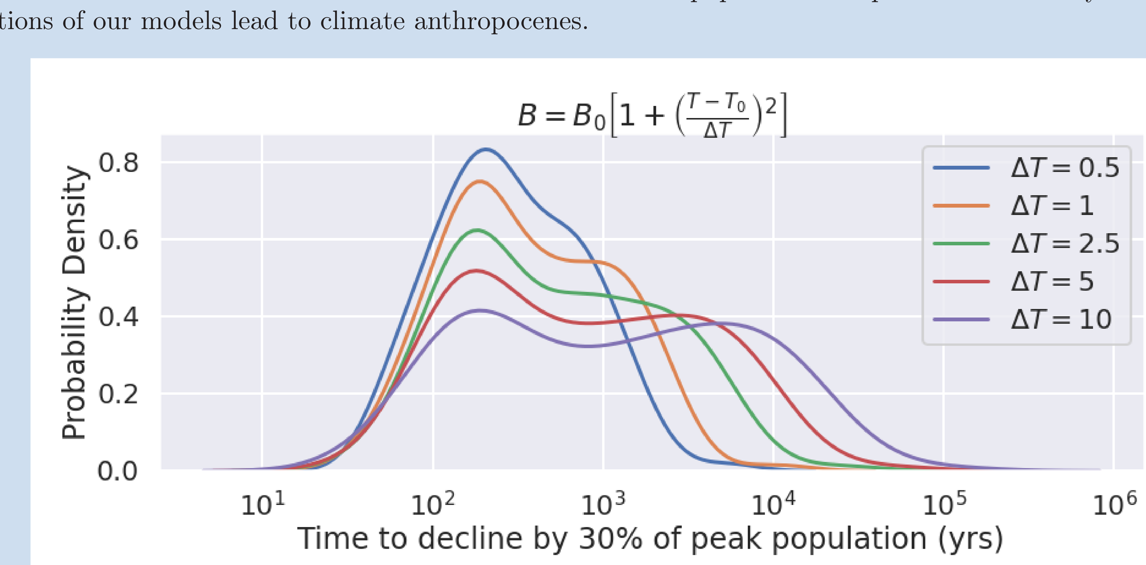


**Fig 7.** Fraction of Models with a "die-off" vs $\Delta T$