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The Carbon Crater: Comparing Anthropogenic Greenhouse Gas Emissions to Historical Planetary Events

Hal T. Nelson
Portland State University

Paul Reynolds
Claremont Graduate University

Brian W. Jewett
Claremont Graduate University

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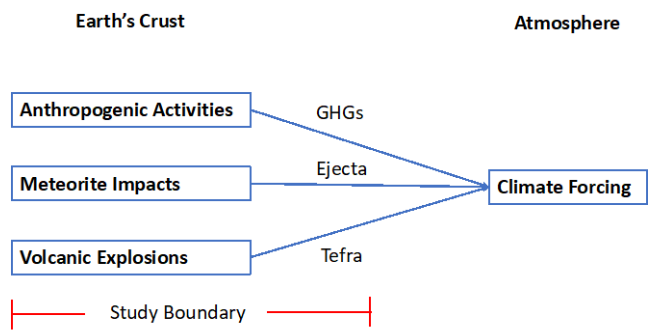
I. Introduction

There has been significant debate in the scientific community about the start date of the Anthropocene (among others, see: Luciano, 2022; Zalasiewicz et al., 2017; Waters et al., 2016; Steffen et al., 2015a; Smith and Zeder, 2013). What is not contested by recent scientific discovery is the "profound novelty" of human-induced changes on Earth systems since the 1950s (Waters et al., 2022, p. 13). Rockström et al. (2009) posit there are nine earth system processes with boundaries, that if exceeded, may lead to irreversible and catastrophic environmental change; and that humanity has already crossed three of these planetary boundaries. There is increasing evidence for boundary violations. In but one example, the ten hottest years on record have all occurred since 2014, with 2023 shattering the previous record (NOAA, 2024). The observed warming has led to public debate between leading climate scientists about whether the rate of human-induced global warming has accelerated in recent years (Hansen et al., 2023; Paddison, 2024). At the center of this debate is the role of paleoclimate data in modeling climate sensitivity to increased carbon dioxide levels.

This research investigates potential human influences on climate forcing relative to previous meteorite impacts and explosive volcanos. These two types of planetary events are appropriate to study as volcanic activity and/or meteorite impacts were responsible for the last three mass-extinction events including the Permian-Triassic, End-Triassic, and Cretaceous-Paleogene (K-T) events, all of which marked changes to the previous geological period (Bambach, 2006).

More specifically, the authors develop the following mass-balance thought experiment: *How does the mass of greenhouse gas emissions (GHG's) from* *anthropogenic activity compare to the mass of atmospheric emissions from recorded planetary events such as meteorite impacts and volcanic explosions?* As presented in Figure 1, from a mass-balance perspective, these three sources of atmospheric material deposition are identical: GHGs represent a deposition of mass from the Earth's crust into the atmosphere like ejecta from meteorite impacts and tephra from volcanic explosions.

Figure 1: Mass Balance Diagram of Study Parameters



Anthropogenic GHGs, ejecta and tephra also share temporal dimensions. On a planetary timescale, these three sources of atmospheric deposition are very short, intense transfers of mass from the Earth's crust into the atmosphere (Waters et al., 2022).

Humans have been transporting material from the Earth's crust into the atmosphere by burning fossil fuels and biomass for heat or mechanical work. These activities include electricity generation, cement production, transportation, and land clearing. Energy conversion is done at less than 100% efficiency and results in the release of waste carbon. The atmospheric waste product from the conversion process is the carbon content in the primary fuel. For example, coal has a calorific value of about 30%, meaning that on average 70% of the mass of coal is released into the atmosphere as carbon when coal is burned.

As with all thought experiments, the analysis does not introduce any new data, but rather re-assembles known data and theories to shed new light on a phenomenon (Sorensen, 1991). As shown by the study boundaries in Figure 1, this thought experiment *does not attempt* to compare, explain, or predict radiative forcing or other climate impacts from GHG emissions. Instead, the analysis rather reframes anthropogenic carbon waste in a larger, planetary perspective. Furthermore, this research does not discuss the role of terrestrial and ocean carbon sinks as they are related to climate impacts which is beyond the scope of the mass-balance analysis in Figure 1.

The paper proceeds as follows: Section II assesses how Earth System Sciences (ESS) might be informed by thought experiments as a means of scientific discovery. Section III presents the methodologies for the analyses. The results in Section IV include the aggregated mass of GHG emissions and its transformation into 1) a volume, and 2) the shape of a terrestrial impact crater, labelled the "Carbon Crater". Section IV also compares the volume of anthropogenic waste with recent volcanic explosions and discusses the limitations and possible extensions of the research. Section V offers conclusions.

II. Prior Literature

In order to understand how the interdisciplinary Carbon Crater relates to previous work on climate change requires a review of two bodies of research. The first is a brief review of climate change modeling and the need for a better representation of paleoclimate climate data. The current disagreement among leading climate scientists mentioned in the Introduction about whether an increase in the rate of human induced warming is occurring utilizes General Circulation Modeling (CGM). CGM's simulate multiple components of the Earth's systems (Cornell et al., 2012). CGM's are one component of Earth System Science (ESS) models that can also include chemical transport models (Emmons et al., 2010) and other tools.

Equilibrium Climate Sensitivity simulates the expected amount of global temperature increase following a doubling of atmospheric carbon dioxide. It is considered is a "fundamental quantitative measure of the susceptibility of Earth's climate to human influence" (Sherwood et al., 2020, p.1). Equilibrium climate sensitivity modeling is one of the primary ways to forecast the effects of anthropogenic carbon on temperature, ice sheets, rainfall, vegetation, and other phenomena. Equilibrium climate sensitivity studies are derived from three types of source data: 1) climate feedback studies, 2) historical climate change data, and 3) paleoclimate data. While a detailed review of equilibrium climate sensitivity modeling is beyond the scope of this review, see Rohling et al. (2018), as well as Zhu et al. (2021) that provide a recent evaluation of equilibrium sensitivity modeling on ice sheets. Sherwood et al. (2020) review recent modeling efforts and find that a doubling of carbon dioxide is associated with warming of 2.3-4.7 K (bounded by 5% to 95% confidence intervals of 2.0-5.7 K).

To posit that observed warming is increasing, Hansen et al. (2023) update equilibrium climate sensitivity models to include additional feedbacks, including one of the earliest and most influential approaches of Charney et al. (1979). Hansen et al. (2023) argue that existing modeling approaches using the Charney et al. assumptions are flawed due to the limitations of feedback studies and historical climate change data. Hansen et al. (2023) argue that paleoclimate data are the preferred sources of data for inferring climate sensitivities.

Hansen, et al.'s concerns about the limitations of climate modeling assumptions are consistent with others who have posited that there is significant uncertainty in CGM projections "influenced by parameterizations and omitted or inadequate constraints on feedback processes and interactions between the geosphere and biosphere" (Steffen et al., 2020, p. 59). In ESS more generally researchers have posited a lack of attention to interactions between processes (Lade et al., 2019), the need for the inclusion of more, rather than less, complexity (Donohue, et al., 2016), and the need for more downscaling (Montoya et al., 2018).

The Carbon Crater thought experiment is applicable to this review of ESS because of the importance of paleoclimate data of equilibrium climate sensitivity. While this research is not directly transferrable to CGM modeling, relating the Carbon Crater to historical meteorite impacts and volcanic explosions that affected the paleoclimate might result in new conceptional understandings of assumptions underlying the CGM modeling.

II.A. The Role of Thought Experiments in Scientific Discovery

This short review of the need for more attention to the assumptions in ESS research in general, and for the importance of paleoclimate data in equilibrium climate sensitivity research specifically, is intended as a justification for this research. One might consider the assumptions for CGM operationalization to be mental models, defined as:

> *A representation of some domain or situation that supports understanding, reasoning, and prediction. Mental models permit reasoning about situations not directly experienced… Many mental models are based on generalizations and analogies from experience. These generalizations are not always accurate;*

researchers have identified striking cases of widespread erroneous mental models. (Gentner, 2001, 9683).

This review is not asserting that the assumptions or mental models underlying CGM modeling are erroneous, only that some of the parameters and assumptions of the state of the modeling at any given time can likely be improved. In some cases, improvements are possible by thinking outside the dominant mental models. Thinking outside of the box (mental model), is the primary purpose of performing thought experiments.

Thought experiments have been used for scientific discovery since Aristotle and hold a prestigious place science history. Aristotle used them mainly for argumentative persuasion and cases where observational data were not available (Corcilius, 2018).[1] Thought experiments are most closely associated with modern physicists who, like Aristotle, are often lacking observational data: Newton's cannonball fired into orbit (Newton & Cohen, 2004), Schrodinger's cat (Schrodinger, 1935), and Einstein's twin paradox (Debs & Redhead, 1996) are three of the more well-known thought experiments in physics.

Two well-known thought experiments in the earth sciences include 1) the Parable of Daisyworld where Watson & Lovelock (1983) developed a thought experiment that reduced the complexity of an imaginary planet in order to infer homeostasis between biotic growth and temperature. 2) More relevant to this research, is the Charney (1979) equilibrium climate sensitivity approach that Hansen et al. (2023) argue is a "Gedanken

[1] An anonymous reviewer helpfully pointed out that Aristotle's assertion that women were less intelligent than men cited purported empirical data; thereby showing that his gender bias was a bigger impediment to scientific discovery than the lack of observational data.

concept", or thought experiment, because of its extreme simplicity in assuming that ice sheets and vegetation remained fixed as atmospheric carbon dioxide doubles.

Thought experiments in science have long been used to test hypotheses, illustrate theories, simulate natural phenomena, and to uncover new phenomena (Brown, 2011). There is a considerable body of literature that posits that thought experiments are best understood as types of mental models where simulations of reality can be manipulated (p. 113). Importantly, mental models are shared intersubjectively between individuals. This "enables them to better communicate and share their learning" (Denzau and North, 1994, p. 4) which is especially relevant for complex scientific experiments. Thought experiments differ from concrete experiments in that the manipulation of real entities is not required. Nersessian (1993) argues that they are a "principal means by which scientists change their conceptual structures" (p. 292 quoted in Brown, 2011). Stuart (2018) argues thought experiments increase our understanding; composed of objective, explanatory, and practical understandings.

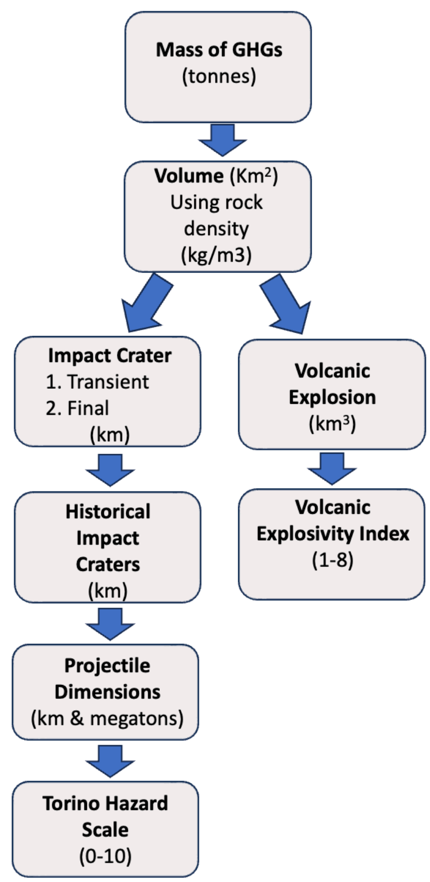
III. Methods and Data

To increase our understanding of the scale of anthropogenic waste relative to historical planetary events requires the transformation of that waste into standardized metrics. The Carbon Crater thought experiment is a multi-step research process where each step is dependent on the results of the previous step. Figure 2 shows the research process diagram. The first step in the mass-balance analysis is to aggregate the mass of historical anthropogenic carbon waste into a GHG inventory. The next step is the conversion of the mass of anthropogenic waste into volume. That volume is then transformed into the Carbon Crater using scaling laws from the planetary sciences. The volume is also used to rank of the Carbon Crater on the Volcanic Explosivity Index. Finally, the projectile (bolide) dimensions for the Carbon Crater are used to rank it on the Torino Hazard Scale of Near-Earth Objects.

III.A. The Mass of Anthropogenic Waste from the GHG Inventory

The first step in the thought experiment is to estimate the mass of atmospheric energy waste. Few attempts have been made to aggregate historical anthropogenic GHG emissions from a range of sources into a single estimate of mass.

Figure 2: Carbon Crater Process Diagram



This analysis utilizes the mass of the *waste* of the energy inputs such as coal, oil, and biomass, and not the total mass of these inputs themselves. The waste from these energy conversion processes is the release of embodied energy into the atmosphere that was previously anchored to terrestrial materials as carbon, methane, or other greenhouse gases.

The weight of CO_2 equivalents (CO_2e) is used for the mass-balance calculations rather than the weight of carbon for three reasons: First, CO_2 equivalents represent the mass of the gases that cause climate forcing impacts, rather than the mass of the terrestrial carbon stocks themselves. Second, the use of CO_2 as a metric allows for the mass of atmospheric oxygen (O_2) that bonded with carbon during energy conversion processes to be included in the mass-balance calculations. Prior to human activity, the bonded atmospheric O_2 was an inert atmospheric gas without significant climate forcing impacts. Third, the use of CO_2 equivalents as the common metric for the analysis is appropriate because the emissions of CO_2 from land use changes and the combustion of fossil fuels represents the vast majority of anthropogenic GHG emissions.

The mass-balance analysis creates an inventory of the long-lived GHG's of CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). These gases represent the preponderance of anthropogenic emissions. The equation for the calculation of the mass of energy waste in the atmosphere is:

$$\text{Mass of GHGs} = \sum(C^t_{i\to n} + M^t_{i\to n} + N^t_{i\to n} + F^t_{i\to n}) \qquad \text{Eq.} \quad (1)$$

For countries *i* to *n*, over *t* years. Where,

- C = CO_2 emissions from the burning of fossil fuels and from land use and forestry change. The data source for this is Jones et al. (2022) Global Total CO_2 field.
- M = CH_4 emissions from fossil fuels as well as from land use and forestry changes. The data source for this is Jones et al. (2022) Global Total CH_4 field.
- N= N_2O from fossil fuels and from land use and forestry change. The data source for this is Jones et al. (2022) Global Total N_2O field
- F= F-gases include hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. F-gas data come from ClimateWatch (2023). Note that there are no emissions estimates included for F-gases prior to 1990 or after 2020.

Jones et al. (2022) is a European Commission-funded, comprehensive GHG inventory source that leverages best-available data from multiple sources including the Global Climate Project (Andrews and Peters, 2022; Andrews, 2020) and the PRIMAP-hist

HISTTP datasets (Gütschow and Pfluger, 2022; Gütschow, et al., 2016). Minx et al. (2020) review available CH_4 and N_2O inventories and note that the HISTTP scenario is centrally located with the scope of estimates.

The above methodology is likely to lead to a conservative inventory for two reasons: 1) Significant land use change occurred in many regions of the world prior to 1851. The net fluxes of CO_2 and CH_4 associated with clearing forests for urbanization and with agricultural activities before 1851 and after 2021 are not included in the above estimate. 2) F-gas data were not included prior to 1990 or after 2020.

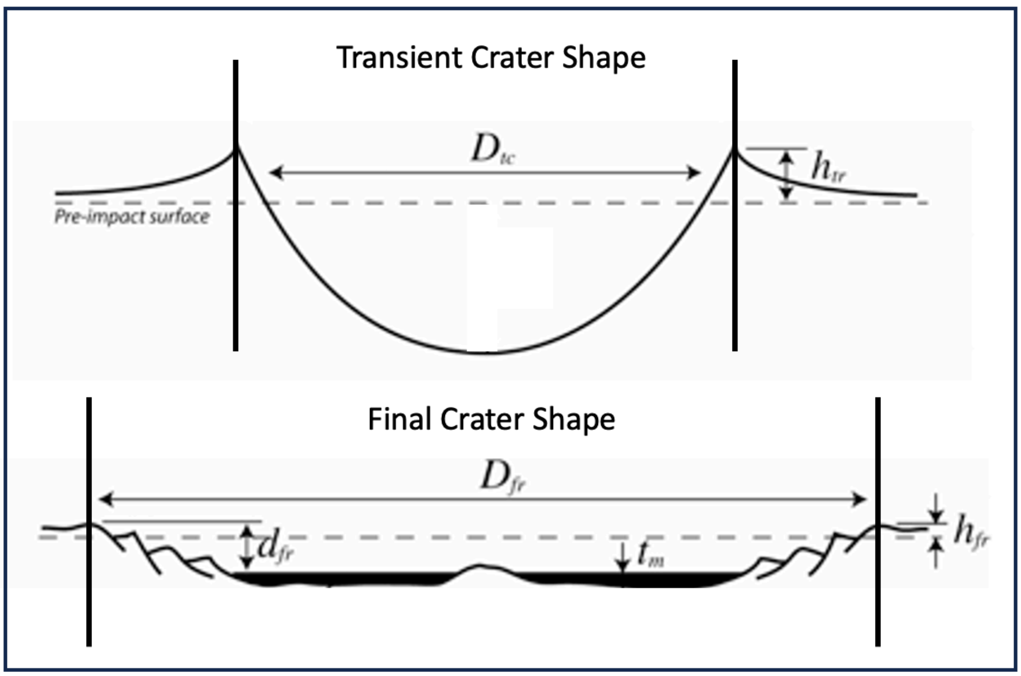
III.B. Mass to Volume Conversion

In order to compare the mass of anthropogenic energy waste to known impact events and volcanic explosions, the next step is to convert the GHG mass from III.A. into a volume. This requires an assumption relating to the density, or ratio of mass to volume, for the rock that is displaced from the impact event or volcanic explosion. For the baseline analysis, a uniform density value of 2.45 tons/m^3 for dense rock equivalent is used. This is an intermediate value between 2.40 tons/m^3 from Mason et al. (2004) and 2.50 tons/m^3 in Reinhardt, et al. (2015). 2.40 tons/m^3 is consistent with dense rock density in material surveys as well (Langer, 2006). This represents both the density of rocks found in Earth's crust as well as in volcanic structures; both of which are needed for the mass-balance thought experiment. Section IV.C explores the sensitivity of the 2.45 tons/m^3 density assumption on the Carbon Crater's estimated size.

III.C. Impact Crater Scaling Parameters

The next step in the research process in Figure 2 coverts the raw volume estimate (km^3) into a crater. To extrapolate the Carbon Crater's diameter from the volume of dense rock equivalents above requires scaling assumptions regarding the Carbon Crater's shape. The scaling parameters selected for this stage are taken from the best-available, peer-reviewed sources, including Collins et al. (2005) and Melosh (1989). Figure 3 shows the two-stage crater estimation process. The first stage calculates the shape of the crater initially following impact. Known as a transient crater, it has an approximate parabolic shape as shown in Figure 3.

Figure 3: Transient and Final Crater Shapes



Source: Adapted from Collins et al. (2005)

The transient crater is assumed to be approximately parabolic (Melosh, 1989). The formula for the volume (V_{tc}) of a transient crater comes also from Melosh (1989):

$$V_{tc} = \frac{\pi H_{tc} D_{tc}^2}{8} \qquad \text{Eq. (2)}$$

- Where height is estimated at 1/3.4 of diameter (D_{tc}).

Recall that the goal of this section is to estimate the Carbon Crater size (km). The model requires solving for diameter (D_{tc}), given the above Carbon Crater volume estimated in III.B. from the GHG mass and density assumption:

$$D_{tc} = \left[\frac{8V}{0.294\pi}\right]^{1/3} \qquad \text{Eq. (3)}$$

This transient crater diameter can now be used in the second stage that transforms the transient crater shape to the shape of observed impact structures on Earth that allows for an apples-to-apples comparison with the Carbon Crater shape. This requires the estimation of the final, or complex, crater diameter. The final crater diameter is larger than the transient crater diameter for two reasons. First, post impact erosion causes the compressed rock walls to slough off into the crater as shown in Figure 3. Second, the final crater diameter is measured from rim-to-rim, not from the pre-existing surface level. The scaling law for the ratio of final crater D_{fr} to the transient crater is described by Collins et al. (2005):

$$D_{fr} = 1.17\frac{D_{tc}^{1.13}}{D_{c}^{0.13}} \qquad \text{Eq. (4)}$$

where D_c = 3.2 km, which is the size of a crater on Earth at which the transition to a final crater occurs. The final crater diameter is the size of the Carbon Crater which can then be used to compare to known Earth impact structures.

III.D. Projectile Parameters: Size and Kinetic Energy

The next question investigates the size of the projectile and the associated kinetic energy that is necessary to create the final Carbon Crater. These parameters are necessary to rank the Carbon Crater on the Torino Hazard Scale in Section III.E. below. Melosh (1989) notes that this simple question does not have a simple answer. Our direct knowledge of impact processes is limited. Given the wide range of parameters that affect the projectile-crater relationship, the assumptions employed in this analysis to extrapolate the projectile size are typical, or *most probable*, values. The characteristics of asteroids are used because they comprise the bulk of near-Earth objects. Similarly, dense rock asteroids are more common than iron asteroids (Chapman, 2004). Using the projectile scaling law from Collins et al. (2005):

$$D_{tc} = 1.161\left(\frac{\rho_i}{\rho_t}\right)^{1/3} L^{0.78} v_i^{0.44} g_E^{-0.22} \sin^{1/3}\theta \qquad \text{Eq.} \quad (5)$$

To estimate projectile diameter (L), Equation 5 is transformed to solve for (L):

$$L = \left[\frac{1.161\left(\frac{\rho_i}{\rho_t}\right)^{1/3} v_i^{0.44} g_E^{-0.22} \sin^{1/3}\theta}{D_{tc}}\right]^{\frac{-.1}{.78}} \qquad \text{Eq.} \quad (6)$$

Where:

- ρ_i = density of dense rock projectile at 3000 kg/m^3
- ρ_t = density of target crystalline rock at 2450 kg/km^3
- v_i = velocity of typical asteroid of 17km second
- g_E = Earth's surface gravity in (meters/second)^2
- θ = most probable impact angle of 45 degrees

The kinetic energy (E) of the projectile can be then estimated using Equation 7 (Collins et al., 2005):

$$E = \frac{1}{2} m_i v_i^2 = \frac{\pi}{12}\rho_i L^3 v^2 \qquad \text{Eq.} \quad (7)$$

Where:

- m_i = the mass of an approximately spherical asteroid

Finally, the estimated reoccurrence time (T) for a Near Earth Object with a given kinetic energy in megatons (Mt) of TNT can be estimated using Equation 8 (Collins et al., 2005):

$$T_{RE} \approx 109E_{Mt}^{0.78} \qquad \text{Eq. (8)}$$

III.E. Torino Scale and Volcanic Explosiveness Index

In addition to comparisons with individual impact craters, the Carbon Crater can also be compared mathematically to the flux of comets and asteroids hitting the Earth and their associated kinetic energy. The flux methodology compares Lunar craters with Earth records and a census of Earth-crossing asteroids and comets (Chapman and Morrison, 1994).

The Torino Scale adapts the 1994 Chapman and Morrison methodology to create a 0-10 Hazard Scale that was developed to communicate the risks from Near-Earth Objects. The Torino Scale consists of two coupled parameters that jointly describe the risks to Earth from Near-Earth Objects (Binzel, 2000). The first parameter is the probability of impact of the object with Earth, and the second is the kinetic energy of the object. The lower boundary of 0 on the Scale is associated with an object that is so small that it would not reach the Earth's surface intact as it would be incinerated by the Earth's atmosphere. The upper boundary of 10 on the Torino Scale is an object with a near certain impact and the kinetic energy of the Chixculub impact associated with the K/T boundary event (10^8 megatons of TNT equivalent).

The Volcanic Explosivity Index (VEI) is a comparable risk metric to the Torino Scale but was instead developed to measure the explosive magnitude of historical volcanic events. The VEI measures the relative explosiveness of volcanic eruptions on a scale of 1 to 8. Each increase of one unit in the index translates to a ten-fold increase in eruption power (Newhall and Self, 1982). The VEI has been assigned to over 8,000 historical eruptions and no explosive events of VEI 7 or 8 have been identified since the

1500's (Newhall and Self, 1982). It is described as "a general indicator of the explosive character of an eruption" and does not indicate specific attributes of volcanic eruptions such as destructive potential, dispersive power, or intensity (Newhall and Self, 1982, pp. 1233-1234). This aggregated nature of the VEI makes it a very suitable index to compare against the static Carbon Crater by comparing the volumes of material displaced by the two very different phenomena.

IV. Results

The first required result is the mass of GHG emissions that will be used as an intermediate input to the Carbon Crater volume calculation used for comparison with Earth impacts. Using Equation 1, the three sources of historical GHG emissions yield an inventory with an estimated mass of 3.59 trillion tons of CO_2e emissions. Figure 4a shows the time series of annual and cumulative CO_2e emissions. Figure 4b shows the components of the total GHG emissions.

Figure 4a: Annual (L) and Cumulative (R) Anthropogenic Pg (Billion Tons) CO2e Emissions

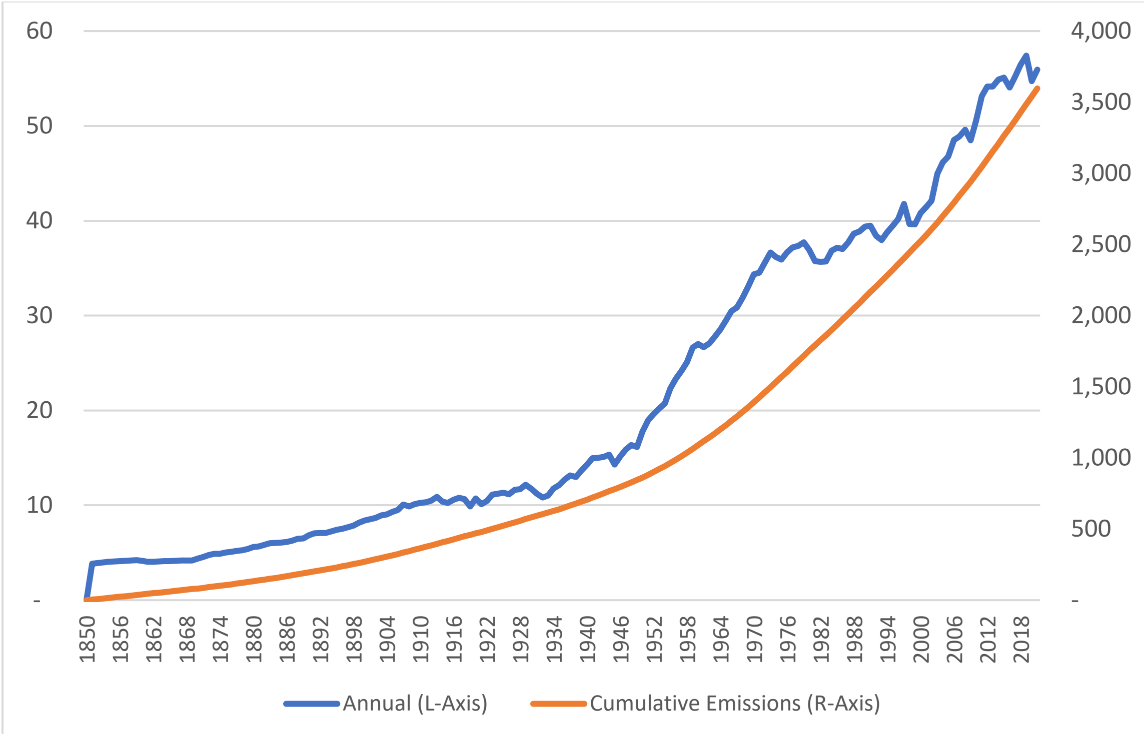


Figure 4b: Source Gas Pg (Billion Tons) CO2e Emissions

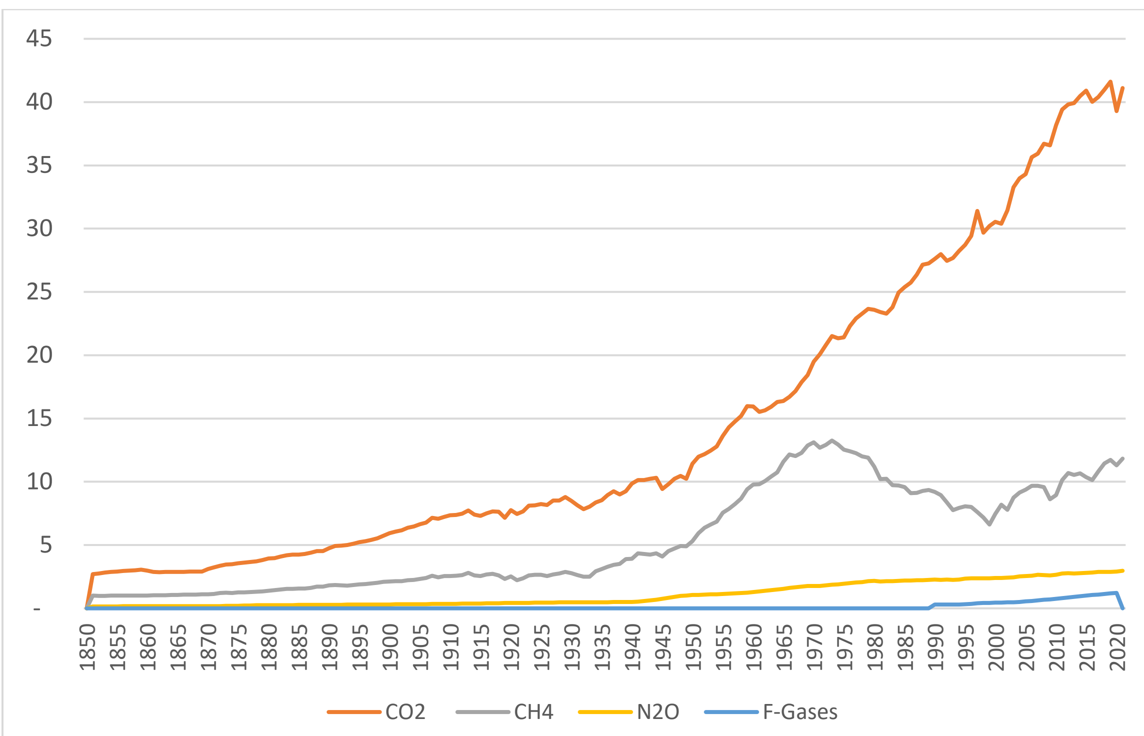
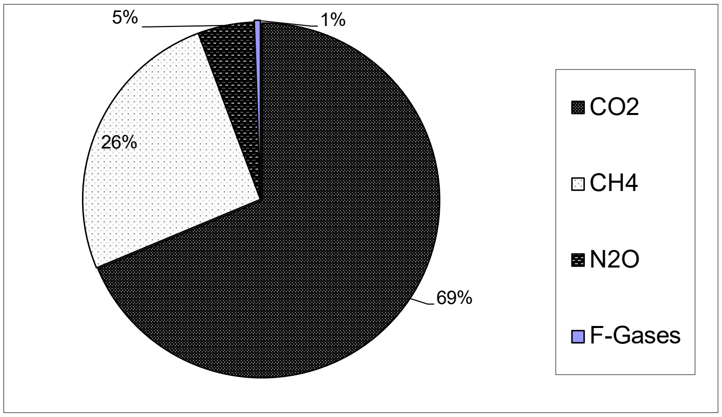


Figure 5 shows the relative contribution of the three sources of GHGs to the total (totals may not add up to 100% due to rounding).

Figure 5: Source Categories of Anthropogenic GHG Emissions 1851-2021



IV.A. Dense Rock Volume and Carbon Crater Dimensions

Given this mass balance result from Section IV.A, it is now possible to estimate the volume of the Carbon Crater. Using the uniform density value of 2.45 tons/m^3 for dense rock equivalents from Section III.B., the 3.59 trillion tons of mass deposited in the atmosphere is equivalent to an estimated volume of 1,467 km^3 (352 $miles^3$).

Next, the transient impact crater diameter associated with a volume of 1,467 km^3 of dense rock is calculated using the crater shape assumptions in Equations 2 and 3. The transient impact crater associated with anthropogenic CO_2 emissions is approximately 23.3 km (14.5 miles) wide.

In order to compare the transient crater to known Earth impact craters requires converting the transient crater diameter to a final crater diameter using Equation 4. This results in a Carbon Crater diameter of 35.5 km (22.0 miles). This is considered the baseline result, using most probable assumptions from the literature.

IV.B. Evaluation of the Carbon Crater Results

As with any simulation, it is important to validate the modeling results. Validation in modeling are typically performed to corroborate model results to real-world conditions (Sornette, et al., 2007; Hillborn and Mangel, 1997). For this application, validation of the Carbon Crater size to real world events is not possible. Instead, validation against other simulation studies is performed. Recall that the goal of the above methodology is to estimate the diameter of the Carbon Crater using the volume of material transported from Earth's crust into the atmosphere. In contrast, most Earth impact studies start with an assumption of the size and composition of the meteorite that strikes Earth; instead of the size of the observed crater.

In order to reconcile these different starting points, as well as to validate the Methodology from Section III and the Results from Section IV, a validation test was performed. The baseline Carbon Crater assumptions were submitted to the Imperial College London/Purdue University Earth Impact Effects Program (Marcus et al., 2023). When the baseline assumptions were entered into the online calculator it estimated a final Carbon Crater size of 34.5 km (21.3 miles), which is nearly identical to the baseline 35 km Carbon Crater results presented above. The similarity of the results between the online calculator and the calculations presented here should give the reader confidence in the methodology and calculations for the baseline Carbon Crater.

Sensitivity analyses of the Carbon Crater baseline assumptions are also included. The ability of an experiment in general, and thought experiments in particular, to create new knowledge or understanding relies on the validity of its "background assumptions" (McAllister, 2006). For the Carbon Crater thought experiment, there are two different types of assumptions. The first assumption is the validity of the estimated annual anthropogenic 1851-2021 GHG inventory in Equation 1 that constitute the mass-balance analysis. The development of uncertainty analyses on the GHG inventory data proceeded conservatively. It is not the function of a thought experiment to generate new empirical data (Norton, 1991). These GHG data have been compiled by multiple research teams over decades.

Statistical measures of dispersion such as standard deviation are often used for uncertainty analysis. Nonparametric measures of dispersion on *cumulative* GHG emissions are inappropriate because of the right skewness of the data (See Figure 2) which renders indicators such as the median (645 gigatons) and interquartile range (1^{st}: 214 gigatons, 3^{rd}: 1,689 gigatons) meaningless.

The second type of assumption in this thought experiment are ones that go into the Carbon Crater calculations including the density of the rock that is displaced as well as the crater shape formula in Equations 2-4. There is not adequate empirical evidence to create probability distributions for the crater shape parameters which rules out the use of statistical measures of dispersion for uncertainty analysis.

Given these two attributes of the GHG source data, the uncertainty analysis included the following sensitivity tests:

1. Substituting crystalline rock (1,500 kg/m^3) instead of dense rock (2,450 kg/m^3) as the terrestrial target material: This resulted in a final Carbon Crater diameter of 39.5 km (24.5 miles) (+20%) compared to the baseline Carbon Crater size of 32.9 km.

2. Substituting 100m water depth plus soft rock (1,000 kg/m^3) instead of dense rock (2,450 kg/m^3) as the terrestrial target material: this simulation utilized the online Earth Impact Effects Program (Marcus et al., 2023), along with the baseline parameters listed in Equation 6; specifically an asteroid diameter of 2,640 meters of dense rock (3,000 kg/m^3) This resulted in a final Carbon Crater diameter on the seafloor of 32.6 km (20.3 miles). This very close to the baseline Carbon Crater size of 35 km.

The uncertainty analysis was developed that utilizes a +/- 28% confidence interval. This is *one standard deviation* (sigma) of the right-skewed cumulative GHG inventory or about 1,010 Pg CO_2e. A one sigma confidence interval is larger than the +20% sensitivity analysis for rock density. Therefore, the 28% confidence interval represents a compromise between several analyses and encompasses uncertainty for: a) the GHG inventory, b) crater shape parameters, and c) rock density. A one sigma (28%) confidence interval yields a crater ranging from 25.5 km (15.8 miles) to 45.2 km (28.1 miles). Interested readers can calculate other confidence intervals for the ~35 km Carbon Crater.

IV.C. Comparing the Carbon Crater with Terrestrial Impact Events

Given the results of the sensitivity analyses, the Carbon Crater results can proceed to be compared against historical planetary events. Using the most-likely crater size of ~35 km Carbon Crater would rank as the 23rd largest-known terrestrial impact structure in the Earth Impact Database (Planetary and Space Science Centre, 2023). Table 1 shows the list of known structures with a similar range of crater diameters. Considering the +/- 28% confidence interval from above, the Carbon Crater's range of diameters would range from 31st up to the 14th largest impact structure.

Table 1: Known Impact Structures and the Carbon Crater

Structure Name	Diameter (km)	Rank	Structure Name	Diameter (km)	Rank
Vredefort	160	1	Chesapeake Bay	40	19
Chicxulub	150	2	Araguainha	40	20
Sudbury	130	3	Carswell	39	21
Popigai	90	4	Clearwater West	36	22
Acraman	90	5	**Carbon Crater**	**~35**	
Manicouagan	85	6	Manson	35	23
Morokweng	70	7	Saqqar	34	24
Kara	65	8	Keurusselkä	30	25
Beaverhead	60	9	Yarrabubba	30	26
Tookoonooka	55	10	Slate Islands	30	27
Charlevoix	54	11	Shoemaker (formerly Teague)	30	28
Siljan	52	12	Mistastin	28	29
Kara-Kul	52	13	Clearwater East	26	30
Montagnais	45	14	Strangways	25	31
Woodleigh	40	15	Steen River	25	32
Saint Martin	40	16	Kamensk	25	33
Puchezh-Katunki	40	17	Tunnunik (Prince Albert)	25	34
Mjølnir	40	18	Ries	24	35

Source: Adapted from Planetary and Space Science Centre, 2023

The Carbon Crater diameter is situated between two well-known craters: the 24 km Ries crater in Germany and the 35 km Manson crater in the state of Iowa (United States). These craters are well-known because of the intensity of the meteorites' impact. The Ries crater is remarkable because the stones quarried from the crater to construct local buildings contain small diamonds, formed because of compression of the graphite rock from the meteorite's impact. The comparably sized Manson crater (35 km) is notable as it was initially a suspect in the Cretaceous-Paleogene (K-T) extinction event (Koeberl and Anderson, 1996).

To compare the hypothetical Carbon Crater to known impact events should be done carefully due to uncertainties in measuring existing impact structures. Grieve (1997) cautions, '[q]uantitative interpretations based on data compilations of rim diameters of terrestrial impact structures should be regarded with some caution' because estimates are subject to considerable revision. Also, because of variation in scaling 'laws', caution should be used when comparing scaled craters against existing impact craters. Even with these caveats, some insights are likely to be gleaned as to the scale of the anthropogenic transfer of mass into the atmosphere through such a comparison.

IV.D. Projectile Results

Now that the Carbon Crater diameter has been estimated, the size of the projectile (meteorite) required to generate such a crater can be calculated. Recall that the projectile size and associated kinetic energy are required to rank the Carbon Crater on the Torino Scale. Given the most probable, or typical, input parameters presented above in Equation 6, an asteroid of 2.66 km (1.65 miles) is required to create the baseline 35 km complex crater. The kinetic energy (E) associated for an asteroid with the most probable input assumptions is estimated in Equation 7 at 1,024,060 megatons of TNT (1.20E+06). The reoccurrence time (T) associated with an asteroid with this kinetic energy from Equation 8 is estimated at once every 5.3 million years.

Note that atmospheric entry has "no significant influence on the shape, energy, or momentum of impactors with a mass that is much larger than the mass of the atmosphere displaced during penetration" according to Collins et al. (2005, pp. 819-820). Thus, for impactors greater than 1 km, the impact energy at the atmosphere is functionally equivalent to the impact energy at the surface of the Earth.

IV.D.1. Torino Scale Ranking

Given the estimated kinetic energy for the Carbon Crater's ~2.6 km projectile is E = 1.20E+06. This ranks the Carbon Crater's risk as a 10 on the Torino Scale, the most serious (red) category. The description for a 10 is:

> *A collision is certain, capable of causing global climatic catastrophe that may threaten the future of life as we know it, whether impacting land or ocean.* (Binzel, 2000, p. 301).

The Carbon Crater 's 2.6 km projectile is nearly 50 percent larger than the "nominal global threshold" projectile size of 1.5 km (Chapman and Morrison's, 1994).

IV.E. Volcanic Explosions

From a mass balance perspective, the volume of the Carbon Crater represents can also be compared to other planetary events. Table 2 compares the volume of airborne material (tephra) released from several volcanic eruptions to the volume of the baseline Carbon Crater, estimated above at 1,467 km^3. The volcanic events of Krakatau, Novarupta, Mount St. Helens, and Pinatubo were chosen because these events: 1) occurred during in the study period, 2) are widely known, and 3) were highly explosive.

The results below indicate that the volume of anthropogenic waste released into the atmosphere from the baseline Carbon Crater dwarves the largest volcanic eruptions in modern history. Anthropogenic activity has transferred into the atmosphere a volume of material over 1,200 times the amount of tefra from Mount St. Helens and 73 times that of Krakatau.

Table 2: Comparisons between the Carbon Crater and Recent Volcanic Events

Volcanic Event	Start Date	Stop Date	Mean Tephra Volume km3	Volcanic Explosivity Index	Ratio of Volumes: Carbon Crater / Volcanic Event (+/- 25%)
Krakatau	1883 May 20	1883 Oct 21	20.0	6	73 (53-93)
Novarupta	1912 Jun 6	1912 Oct ?	28.0	6	52 (37-67)
Mt. Saint Helens (tefra only)	1980 Mar 27	1986 Oct 28 ± 3 days	1.2	5	1223 (881-1565)
Mt. Saint Helens (tefra plus debris avalanche)	1980 Mar 28	1986 Oct 28 ± 3 days	N/A	5	358 (258-458)
Mt. Pinatubo	1991 Apr 2	1991 Sep 2	11.0	6	133 (96-170)

Sources: Adapted from the Smithsonian Institution's Global Vulcanism Program (2023) and authors' calculations.

Table 2 also calculates the relative magnitude of the volume of the Carbon Crater to Mount St. Helens with tephra plus the debris avalanche of 2.9 km^3 (Glicken, 1996). The mass of the avalanche was more than just magma from the volcano and also included ice, water, and debris. The Mount St. Helen's landslide was widely responsible for many of the 57 deaths and much of the property damage.

IV.E.1 Volcanic Explosivity Index

Ranking the volume of material transferred by the Carbon Crater on the Volcanic Explosivity Index illustrates the scale of human activity compared to over 8,000 known volcanic eruptions. The volume of "erupted products' associated with the Carbon Crater (1,467 km^3) would place it well above the 1,000 km^3 cutoff for the largest VEI rating of 8, which is qualitatively described as "mega-colossal" (Newhall and Self, 1982). Examples of VEI 8 events include the Yellowstone Eruption 640,000 years ago and Toba, Indonesia eruption 75,000 years ago (Mason et al., 2004). The Carbon Crater's

VEI of 8 is approximately 100 times bigger than largest volcanic event listed in Table 2 with a maximum rating of 6. VEI 8 events are expected to occur only 2 times per 100,000 years (USGS, ND).

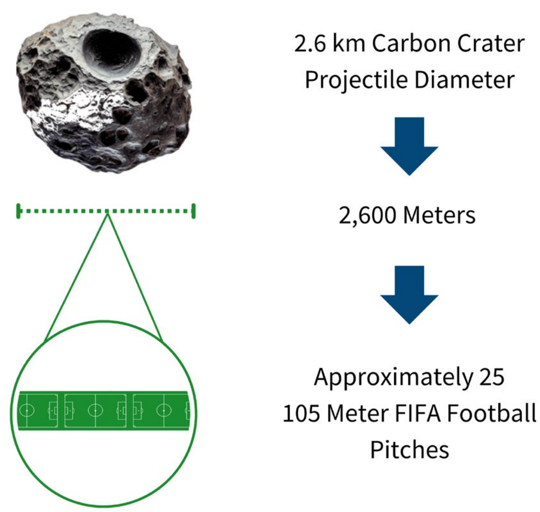
IV.F. Discussion

The results presented here for the Carbon Crater show substantive support for the comparative mass-balance research question posited in the introduction. The scale of anthropogenic atmospheric deposition is directly comparable to large historical planetary events. Despite these substantive findings, the theoretical implications for ESS and CGM research are indeterminant. ESS needs additional theories and empirics on the complexities of Earth's systems, not simplifications (Steffen et al., 2020). In this way, the Carbon Crater thought experiment is somewhat like the Watson and Lovelock's (1983) thought experiment that reduced the complexity of a biotic system in order to test inferences about homeostasis. The Carbon Crater results likely confers few direct implications for the study of the paleoclimate that are important for equilibrium climate sensitivity modeling (Hansen et al., 2023). However, the Carbon Crater does develop a conceptual correlation between anthropogenic carbon waste and two types of planetary events that influenced paleoclimate change.

Changing human conceptions and existing mental models about existing systems is one of the primary functions of thought experiments (Nersessian, 1993). Watson and Lovelock (1983) have over 700 citations on Google Scholar. But the long-term implications for thought experiments are difficult to measure. The implications of this research are more likely to apply to our conceptual understanding of atmospheric human waste. To better explicate these implications, additional empirical research such as focus groups, experiments, and survey research are required to understand the potential impact of the Carbon Crater on conceptual change. It is likely that the Carbon Crater concept could affect conceptual change for consumers of science to a greater degree than for scientists. Since GHGs are invisible, and anthropogenic climate change is occurring against natural climate variability, the tangible image of the Carbon Crater might make climate change more salient to non-scientists. This is important because there is some evidence that scientific literacy can affect attitudes and behaviors (Allum et al., 2008) and subsequent support for pro-environmental policies and candidates. However, empirical research designs would need to control for the average person's poor understanding of science and history (Moore, 2015).

Reframing anthropogenic depositions to the atmosphere as a Carbon Crater and comparing it to historical impact and volcanic events could help clarify non-scientists understanding of climate forcing. Social math can help improve understanding about complex phenomena (Yocco and Pulli, 2016). Presenting the Carbon Crater 's diameter of ~35 km as an area and comparing it to known landmarks is one possible social math representation. Figure 6 compares the area of the ~35 km Carbon Crater to the approximate area for the city of Berlin, Germany: the hypothetical impact crater is larger than the size of the capital of Germany. Figure 6 also shows the width of the 2.6 km meteorite as the approximate width of 25 football pitches combined. These are two simple examples of how the scale of the Carbon Crater could be communicated to non-scientists via social math.

Figure 6: Comparisons of the Carbon Crater with Terrestrial Structures



Sources: Authors

Like those that have come before it, this study is not without limitations. As shown in Figure 1, a direct comparison of the climate influences from the Carbon Crater versus conventional impact craters and volcanic explosions is beyond the focus of this thought experiment. Furthermore, drawing meaningful conclusions from such a comparison would be difficult for two reasons. First, anthropogenic emissions of GHGs are associated with global warming while the climate effects of impact events and volcanic explosions are varied. Large terrestrial impact events are initially associated with regional or global cooling as incoming solar radiation is reflected back into space from particulates or ash from fires started by the event. The ejecta and ash from the 150 km Chicxulub crater likely resulted in global cooling of up to 10^{o} C for up to decades immediately following the impact (Schulte et al., 2010). Surviving organisms were likely then subjected to extreme *heat* as carbon dioxide released from the projectile's impact into limestone rock warmed the surface of the planet. The climate effects from the Pinatubo explosion were also varied with warming of the lower troposphere over North America, Europe and cooling over the Middle East and China (Robock, 2002). Thus, the effects of conventional planetary processes can be indeterminate, while the Carbon Crater predicts potential global warming. Furthermore, the climatic effects of the waste materials that created the Carbon Crater have been moderated due to their uptake by ocean and terrestrial carbon reservoirs (Denman et al., 2007).

The second difference between the sources of climate change is related to a temporal dimension. The climate effects from a conventional impact event or volcanic explosion are felt soon after the event occurs. In contrast, the Carbon Crater "occurred" over the last 150 years, with most of the emissions occurring during the last several decades as shown in Figure 4.

V. Conclusions

The geophysical comparisons presented here provide us with another method of understanding the *potential* impacts from anthropogenic activities. The mass-balance analysis indicates that anthropogenic activities have transported approximately 3.60 trillion tons of material from the Earth's crust to the atmosphere. Converting the mass of GHGs into an impact crater volume equates to a crater with an estimated diameter of about 35 km. The Manson impact event of 35 km is of a similar size as the Carbon Crater and at one point was a suspect in the KT event 66 million years ago that caused the extinction of non-avian dinosaurs.

The Carbon Crater's 2.6 km projectile has an estimated reoccurrence time of once every ~5.3 million years. An interval of this time in Earth's history predates *homo sapiens*. It is associated with the fossil hominoid *Ardipithecus,* an important predecessor to existing ape and human hominoids (Almécija, et al., 2021). The paper that served as the scientific foundation of the Torino scale (Chapman & Morrison, 1994) stated "There is a 1-in-10,000 chance that a large (~2 km diameter) asteroid or comet will collide with Earth during the next century, disrupting the ecosphere and killing a large fraction of the world's population." (p. 33). While the Climate Crater's 2.6 km conceptual meteorite has not killed a large fraction of the world's population, anthropogenic climate change is increasingly being attributed to extreme weather events (National Academies of Sciences, Engineering, and Medicine, 2016). These extreme events are causing excess human deaths, destruction of the built environment, and incalculable harm to animal species. Future extensions of this research can identify how the Climate Crater thought experiment might influence human conceptions of anthropogenic climate change.

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