Paleoceanography and Paleoclimatology

RESEARCH ARTICLE
10.1029/2018PA003379

**Special Section:**
Climatic and Biotic Events of the Paleogene: Earth Systems and Planetary Boundaries in a Greenhouse World

**Key Points:**
- Rates are often time scale or denominator dependent and must be compared on the same scale of time
- Modern carbon emission rates on short time scales are 9–10 times higher than estimates for carbon accumulation during onset of the PETM
- If carbon emissions continue at increasing rates, we can expect to reach PETM accumulations in as few as 140 to 259 years

**Correspondence to:**
P. D. Gingerich,
gingeric@umich.edu

**Citation:**
Gingerich, P. D. (2019). Temporal scaling of carbon emission and accumulation rates: Modern anthropogenic emissions compared to estimates of PETM onset accumulation. *Paleoceanography and Paleoclimatology*, *34*. https://doi.org/10.1029/2018PA003379

Received 1 APR 2018
Accepted 28 JAN 2019
Accepted article online 30 JAN 2019



# Temporal Scaling of Carbon Emission and Accumulation Rates: Modern Anthropogenic Emissions Compared to Estimates of PETM Onset Accumulation

**Philip D. Gingerich**[1]

[1]Department of Earth and Environmental Sciences and Museum of Paleontology, University of Michigan, Ann Arbor, MI, USA

**Abstract** The Paleocene-Eocene thermal maximum (PETM) was caused by a massive release of carbon to the atmosphere. This is a benchmark global greenhouse warming event that raised temperatures to their warmest since extinction of the dinosaurs. Rates of carbon emission today can be compared to those during onset of the PETM in two ways: (1) projection of long-term PETM rates for comparison on an annual time scale and (2) projection of short-term modern rates for comparison on a PETM time scale. Both require temporal scaling and extrapolation for comparison on the same time scale. PETM rates are few and projection to a short time scale is poorly constrained. Modern rates are many, and projection to a longer PETM time scale is tightly constrained—modern rates are some 9–10 times higher than those during onset of the PETM. If the present trend of anthropogenic emissions continues, we can expect to reach a PETM-scale accumulation of atmospheric carbon in as few as 140 to 259 years (about 5 to 10 human generations).

**Plain Language Summary** The Paleocene-Eocene thermal maximum (PETM) is a global greenhouse warming event that happened 56 million years ago, causing extinction in the world's oceans and accelerated evolution on the continents. It was caused by release of carbon dioxide and other greenhouse gases to the atmosphere. When we compare the rate of release of greenhouse gases today to the rate of accumulation during the PETM, we must compare the rates on a common time scale. Projection of modern rates to a PETM time scale is tightly constrained and shows that we are now emitting carbon some 9–10 times faster than during the PETM. If the present trend of increasing carbon emissions continues, we may see PETM-magnitude extinction and accelerated evolution in as few as 140 years or about five human generations.

## 1. Introduction

Modern carbon release rates are known for every year from 1959 through 2015, a time series spanning 57 successive years (Figure 1). Masses of carbon are measured in petagrams, where 1 Pg is equivalent to $10^{15}$ g or $10^{12}$ kg or $10^{9}$ metric tons. Release rates have risen steadily from 2.454 Pg of carbon per year (Pg C/year) in 1959 to 9.897 Pg C/year in 2015, a fourfold increase in 56 years (Boden et al., 2016). The 57 modern release rates on 1-year intervals can be combined to yield many additional rates on time scales ranging from 2 to 57 years. Modern rates considered together (57 rates on 1-year intervals + 56 rates on 2-year intervals + … + 1 rate on a 57-year interval = 1,653 total rates) enable quantification of their dependency on interval length and categorization of the process involved. However, the rates have little meaning in isolation.

One way to appreciate the rates, process, and risk of present-day carbon release to the Earth's atmosphere and oceans is to compare current emissions to those in Earth history. The Paleocene-Eocene thermal maximum (PETM) 55.8 million years ago is an appropriate benchmark (Kennett & Stott, 1991; Koch et al., 1992; Zachos et al., 2001). During onset of the PETM some 2,300–12,000 Pg of carbon (Pg C) were released to the atmosphere from methane hydrates (Dickens et al., 1995), circumpolar permafrost (DeConto et al., 2012), and/or North Atlantic volcanism (Gutjahr et al., 2017). This happened within a span of 3 to 20 kyr (Table 1).

The PETM raised global temperatures by 5–8 °C, to the warmest temperatures since extinction of the dinosaurs 66 Myr ago. The PETM altered the Earth's carbon cycle, climate, ocean chemistry, and marine

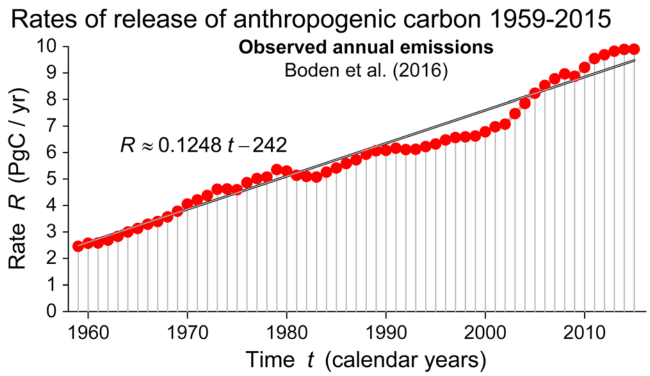


**Figure 1.** Global annual anthropogenic carbon emissions and carbon emission rates for the years 1959 through 2015 (Boden et al., 2016, in the global climate budget of Le Quéré et al., 2016). Emission rates are now nearly 10 Pg C/year on a time scale of 1 year. Line fit to the points shows the long-term trend: $R \approx 0.1248\,t - 242$.

and continental ecosystems (McInerney & Wing, 2011). Benthic foraminifera suffered a major extinction (Thomas, 1989). Salient effects on land included dwarfing, floral change, and the first appearance of mammalian groups such as artiodactyls, perissodactyls, and primates that rapidly dominated later faunas (Clyde & Gingerich, 1998; Gingerich, 1989; Secord et al., 2012; Smith et al., 2009; Wing et al., 2005).

## 2. Modern Carbon Release Rates From the Perspective of the PETM

Eight recent modeling studies quantify rates of carbon release during the onset of the PETM. Carbon accumulations are generally estimated from the masses of carbon required to explain differences in carbon isotopic ratios before and during the event. Rates of accumulation can be calculated by dividing an estimate of total accumulation with an estimate for the corresponding interval, but extracting information from the literature is complicated when authors fail to match accumulations, intervals, and rates explicitly.

1. Zeebe et al. (2009, p. 579) estimated that some 3,000 Pg C accumulated during onset of the PETM spanning some 5,000 years. The corresponding rate is 0.600 Pg C/year on a time scale of 5,000 years.
2. Cui et al. (2011, p. 483, Figure 4c, and Table S3) estimated that 2,503 to 12,974 Pg C accumulated during an onset interval of about 19,000 years. The median accumulation appears to be 7,126 Pg C, and the median rate is thus about 0.375 Pg C/year on a time scale of 19,000 years.
3. Bowen et al. (2015, pp. 44–45) estimated that some 3,000 Pg C accumulated in two pulses during an onset interval of about 3,000 years, for a rate of about 1.000 Pg C/year on a time scale of 3,000 years.
4. Kirtland Turner and Ridgwell (2016, p. 12 and Table S1) made 78 estimates of carbon release rates for different masses of carbon and different release intervals. Their estimates cover all reasonable possibilities and as a result provide little constraint on these.
5. Frieling et al. (2016, p. 12,062) estimated carbon emissions during onset of the PETM to have reached 3,000 Pg C over an interval of 5,000 years, for a rate of 0.600 Pg C/year on a time scale of 5,000 years.
6. Zeebe et al. (2016, p. 328) estimated that 2,500 to 4,500 Pg C accumulated during a PETM onset interval of 4,000 years. Median accumulation for the interval is 3,500 Pg C, and the median rate is 0.875 Pg C/year on a time scale of 4,000 years.
7. Gutjahr et al. (2017: extended data Table 1b) estimated an accumulation of 6,141 Pg C for the 20,000-year onset duration of their assumed age model, yielding an average rate of 0.307 Pg C/year on a time scale of 20,000 years.
8. Finally, in a recent review, Kirtland Turner (2018, Figure 4a and Table 1) estimated a PETM accumulation of some 4,500 Pg C in 3,000 years for a rate of 1.500 Pg C/year on a time scale of 3,000 years.

**Table 1**
*Published Estimates for the Time Interval, Carbon Accumulation, and Carbon Accumulation Rate During Onset of the Paleocene-Eocene Thermal Maximum (PETM)*

| Source | Interval (year) | Accumulation (Pg C) | Rate (Pg C/year) | $Log_{10}$ interval | $Log_{10}$ accumulation | $Log_{10}$ rate |
|---|---|---|---|---|---|---|
| Zeebe et al. (2009) | 5,000 | 3,000 | 0.600 | 3.699 | 3.477 | −0.222 |
| Cui et al. (2011) | 19,000 | 7,126 | 0.375 | 4.279 | 3.853 | −0.426 |
| Bowen et al. (2015) | 3,000 | 3,000 | 1.000 | 3.477 | 3.477 | 0.000 |
| Frieling et al. (2016) | 5,000 | 3,000 | 0.600 | 3.699 | 3.477 | −0.222 |
| Zeebe et al. (2016) | 4,000 | 3,500 | 0.875 | 3.602 | 3.544 | −0.058 |
| Gutjahr et al. (2017) | 20,000 | 6,141 | 0.307 | 4.301 | 3.788 | −0.513 |
| Kirtland Turner (2018) | 3,000 | 4,500 | 1.500 | 3.477 | 3.653 | 0.176 |
| Maximum estimate | 20,000 | 7,126 | 1.500 | 4.301 | 3.853 | 0.176 |
| Median estimate | 5,000 | 3,500 | 0.600 | 3.699 | 3.544 | −0.222 |
| Minimum estimate | 3,000 | 3,000 | 0.307 | 3.477 | 3.477 | −0.513 |

*Note*. Accumulation estimates from Cui et al. (2011) and Zeebe et al. (2016) are medians (see text). Maximum, median, and minimum values for the estimates are tabulated in the bottom rows of each column.

The numbers here and in Table 1 for studies 1–3 and 5–8 are the masses of carbon, onset intervals, and accumulation rates extracted from each report. All should be stated and matched explicitly; however, when two of the quantities are given (e.g., mass of carbon and accumulation rate), the third (e.g., onset interval) can be calculated. Each PETM mass is an average mass for a given interval and rate, each PETM interval is an average interval for a given mass and rate, and each PETM rate is an average rate for a given mass and interval.

PETM rates range from about 0.3 to 1.5 Pg C/year. For comparison, the current rate of carbon release to the atmosphere is nearly 10 Pg C/year on a time scale of 1 year (Boden et al., 2016), which, on the face of it, exceeds all of the PETM rates by a factor of more than 6. The time scale associated with each rate is emphasized in the list above because rates are often dependent on their time scale, and this can be expected for carbon emission and accumulation rates.

Whether a median PETM rate of 0.600/year on a median PETM time scale of 5,000 years is more or less than a modern rate of 9.897 Pg C/year on a time scale of 1 year is an empirical question more subtle than some people realize. A definitive answer requires that we know how the rates scale with their corresponding time intervals (denominators of the rates), and the rates must be compared on the same time scale (comparison of rates on different scales of time is a common statistical deception).

## 3. Spatial and Temporal Scaling

Most people understand that measured geographic features, for example, river lengths, coastline lengths, and topographic relief, are scale dependent—in the sense that calculated values depend on the scale of measurement (Mandelbrot, 1967, 1983; Richardson, 1961; Steinhaus, 1954). Comparisons, to be valid, must be made on, or projected to, the same scale of measurement. It is seemingly less widely known that natural features in the temporal domain, for example, river flow, flooding, sediment accumulation, and evolutionary change, are also scale dependent—in the sense that calculated values depend on the scale of time involved (Gingerich, 1983; Hurst, 1951; Sadler, 1981). Here again comparisons, to be valid, must be made on, or projected to, the same scale of time.

Romans (2007), writing on the temporal scaling of Sadler (1981), introduced what he called a "Sadler effect" of "measurement interval bias" implying that Sadler's empirical relationship of rates and intervals is somehow an artifact. Gould (1984), writing on the temporal scaling of Gingerich (1983), labeled the scaling a psychological and mathematical artifact. The Sadler effect is not a tendency to underestimate rates when averaging over long time scales, as some believe, but rather an empirical demonstration that a rate on any time scale is determined by, and remains dependent on, the time scale represented in its denominator. Rates must be brought to the same time scale for comparison. Inverse relationships of measured differences and calculated rates to their associated intervals are not artifacts, but they are widely observed and now expected features in the natural world (Mandelbrot, 1983). Further, the relationships of such differences and rates to their spatial and temporal scales in nature are proportional—linear when plotted on log-log axes—whether the values are accumulated differences or calculated rates.

The easiest way to visualize and quantify the dependence or independence of a set of accumulated differences with regard to time is to plot the logs of the accumulations against the logs of the corresponding time intervals. Accumulations and differences are used interchangeably here because a carbon accumulation is the difference between the amount of carbon present at the start of an interval and the amount present at the end of an interval. Temporal scaling requires that at least two accumulations be measured over different intervals, or at least two rates be calculated for different intervals. There is a common understanding that change expressed as difference or accumulation depends on the length of the interval involved but a misperception that calculating rates removes this dependence. Rates are only independent of interval length in the special case when the underlying differences are wholly dependent on interval length (as when driving an automobile at a constant speed). The temporal scaling of differences and the temporal scaling of rates derived from the differences are complementary in the sense that the slopes always differ by 1 and the intercept is always the same (Gingerich, 2019).

Stationary time series have accumulated differences that scale with a slope at or near 0 on a log difference versus log interval (LDI) plot and have rates that scale with a slope at or near −1.0 on a log rate versus log interval (LRI) plot. Random-walk time series have differences that scale with a slope at or near 0.5 on an

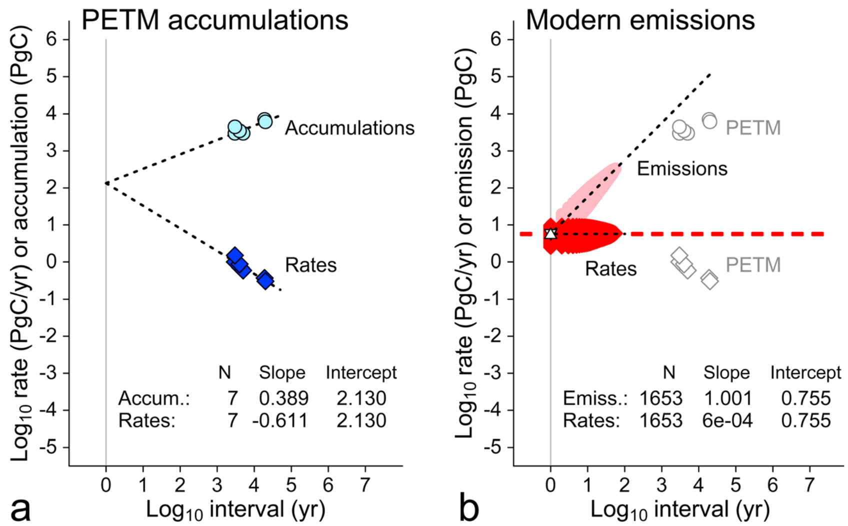


**Figure 2.** Carbon accumulations and accumulation rates estimated for the onset of the PETM compared to modern carbon emissions and emission rates. (a) Light blue circles are PETM onset accumulations that range from 3,000 to 7,126 Pg C. Dark blue diamonds are corresponding PETM onset rates that range from 0.307 to 1.500 Pg C/year (−0.513 to 0.176 on a $\log_{10}$ scale). These are rates on time scales (intervals or rate denominators) of 3,000 to 20,000 years (3.477 to 4.301 on a $\log_{10}$ scale; values from Table 1). Dotted lines are fit to PETM accumulations and rates for corresponding intervals, pointing to a common short-term PETM rate (intercept) of $10^{2.130}$ = 135 Pg C/year on a time scale of 1 year. The PETM slopes of 0.389 for accumulations and −0.611 are close to those expected for random processes (0.500 and −0.500). (b) Modern carbon emissions (light red circles) range from 2.454 to 335.5 Pg C, and modern emission rates (red diamonds) range from 2.454 to 9.897 Pg C/year (0.390 to 0.995 on a $\log_{10}$ scale) on time scales of 1 to 57 years (0 to 1.756 on a $\log_{10}$ scale; annual rates are from Boden et al., 2016). Note that the slope for accumulations or emissions and the corresponding slope for rates in each panel are complementary (differing by 1), while intercepts for the two are the same. PETM onset accumulations and rates extrapolated to an annual time scale (intercepts in panel a) are about 24 times higher than those for modern emissions (intercepts in panel b), with an uncertain confidence interval. Modern emission rates extrapolated to a PETM time scale are about 9–10 times higher than PETM rates on this time scale (open gray diamonds representing the blue diamonds in panel a), and the extrapolation has a very narrow 95% confidence interval (parallel dashed red lines). PETM = Paleocene-Eocene thermal maximum.

LDI plot and have rates that scale with a slope at or near −0.5 on an LRI plot. Directional time series have differences that scale with a slope at or near 1.0 on an LDI plot and have rates that scale with a slope at or near 0.0 on an LRI plot. Temporal scaling on LDI and LRI plots shows whether and how differences and rates are influenced by corresponding intervals of time. This is true for longitudinal time series such as modern carbon emissions and emission rates and for cross-sectional equivalents such as PETM accumulations and accumulation rates when estimates are available for independent intervals.

## 4. PETM and Modern Carbon Emissions and Rates

Figure 2a is a combined LDI-LRI plot for temporal scaling of the seven PETM onset carbon accumulations and rates listed in Table 1. The seven PETM rates range from 0.307 to 1.500 Pg C/year, on time scales or intervals (rate denominators) of 3,000 to 20,000 years. A common pattern is evident: the higher rates are those calculated on shorter time scales, and the lower rates are those calculated on longer time scales. A line fit to the PETM rates (blue diamonds in Figure 2a) has a slope of −0.611, which is close to the slope expected for a random time series. A line fit to the PETM accumulations (light blue circles) has a slope of 0.389 (the complement of −0.611). Lines fit to the PETM rates and to the PETM accumulations, both on time scales ranging from 3,000 to 20,000 years, have an intercept of 2.130. This common intercept corresponds to a predicted PETM rate of $10^{2.130}$ = 135 Pg C/year on a time scale of 1 year.

The problem with this prediction is that it is based on relatively few (seven) PETM accumulation estimates, or rate estimates derived from these, all characterizing a single PETM onset event. Multiple estimates represent the event itself and the associated accumulation, interval, and rate values, but they do not constrain extrapolations of accumulations or rates to different scales of time. Thus, the extrapolated PETM rate of

10.1029/2018PA003379

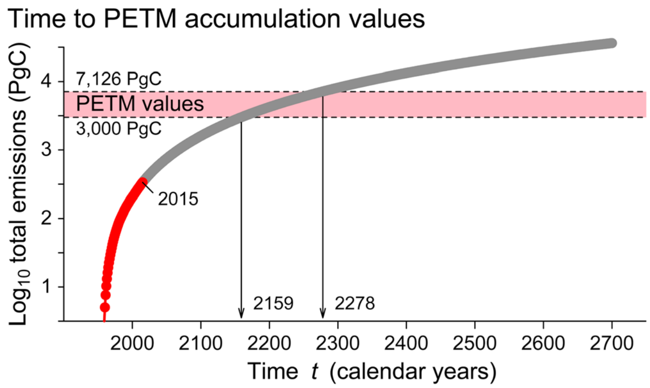


**Figure 3.** Model for carbon accumulation as the sum of carbon emissions, based on the steady increase in emissions and emission rates shown in Figure 1. Red circles are annual accumulations through 2015. If the recent trend in emissions continues, we can expect to reach the minimum estimate for PETM-scale carbon accumulation in the year 2159 and the maximum estimate for PETM-scale carbon accumulation in the year 2278. The light red band illustrates the range of PETM values for carbon accumulation (Table 1). The range of PETM values brackets the mass of carbon thought to remain in fossil fuel reserves (Archer et al., 2009). Finally, the petagrams of carbon trajectory shown here, logged, resembles the upper bound for carbon emissions in the Representative Concentration Pathway or RCP 8.5 model of the Intergovernmental Panel on Climate Change (Ciais et al., 2013). PETM = Paleocene-Eocene thermal maximum.

$10^{2.130}$ = 135 Pg C/year on a time scale of 1 year is poorly constrained and may or may not be significantly greater than modern carbon emissions on a time scale of 1 year.

Figure 2b is a combined LDI-LRI plot for temporal scaling of the 1,653 modern carbon emissions and emission rates based on the 57 annual values published by Boden et al. (2016). The 1,653 modern rates range from 2.454 to 9.897 Pg C/year (0.390 to 0.996 on a $\log_{10}$ scale), on time scales or intervals (rate denominators) of 1 to 57 years. A line fit to the modern rates (red diamonds in Figure 2b) has a slope of 6e−04 or 0.001, which is almost exactly the slope (0.000) expected for rates in a directional time series. A line fit to the modern accumulations (light red circles) has a slope of 1.001 (the complement of 0.001 and again the slope expected for differences in a directional time series). Both have an intercept of 0.755. This common intercept yields a predicted modern rate of $10^{0.755}$ = 5.689 Pg C/year, on a time scale of 1 year. The intercept for modern emissions has a narrow bootstrapped confidence interval, with limits (dashed red lines in Figure 2) ranging from $10^{0.727}$ = 5.338 to $10^{0.781}$ = 6.038 Pg C/year.

When the modern rate of $10^{0.755}$ = 5.689 Pg C/year on a time scale of 1 year is projected to a median PETM time scale of 5,000 years, the modern rate on this time scale is still approximately 5.689 Pg C/year. Thus, compared on the same scale of time, the modern rate of carbon emissions is significantly different and 9–10 times the median PETM rate of 0.600 Pg C/year on a PETM time scale (Table 1). Figure 2b shows this graphically by the vertical distance between the dashed double-red-line confidence interval and the open gray diamonds. Extrapolation of modern emissions (light red circles) to a PETM time scale in Figure 2b yields a similar result, where modern emissions are again projected to be some 9–10 times greater than PETM emissions (open gray circles).

## 5. Modern Carbon Emissions Projected Forward in Time

The temporal scaling slope of modern carbon emission rates is 0.001, which is almost exactly the slope (0.000) expected for a directional process. There is nothing stationary or random about modern carbon emissions. Emissions may change in the future, but the 57-year record of anthropogenic carbon emissions shows that we have been adding carbon to the atmosphere at annual rates increasing steadily through time (Figure 1). The process being directional means we are, in effect, manufacturing carbon and adding it to the atmosphere as efficiently as any factory makes widgets.

Where will this lead? The increase in rates of modern emissions shown in Figure 1 is linear with slight deviations, and $R \approx 0.1248\,t - 242$ is a reasonable model for the time series as a whole. If the present trend of increasing emissions continues, how long will it take to reach a PETM-magnitude carbon accumulation? A simple extrapolation is illustrated in Figure 3. Emission rates for the years from 1959 through 2015 are shown in red. The sum of carbon emissions for the years from 1959 through 2015 is 335 Pg C (2.53 on the $\log_{10}$ ordinate of Figure 3). Projecting emissions forward in time, we can expect to reach the estimated minimum PETM accumulation value of 3,000 Pg C (3.477 on a $\log_{10}$ scale) in the year 2159, and we can expect to reach the maximum PETM accumulation value of 7,126 (3.853 on a $\log_{10}$ scale) in the year 2278. The year 2159 is only 140 years or about five human generations in the future, while 2278 is 259 years or about 10 generations in the future. To put these intervals in perspective, my grandfather was born 140 years ago, and Benjamin Franklin was inventing the three-wheel clock showing hours, minutes, and seconds some 259 years ago.

## 6. Conclusions

Temporal scaling of emission and accumulation rates can be used to compare present-day carbon emissions to carbon accumulations in the geological past. The PETM raised global temperatures by 5–8 °C, the warmest temperatures of the past 66 Myr, and the PETM altered the Earth's carbon cycle, climate, ocean chemistry, and marine and continental ecosystems. Temporal scaling of PETM onset carbon accumulation rates on long time scales might lead one to expect higher carbon emission rates than we see today on short time scales. However, the PETM rates are relatively few, and temporal-scaling projection of these is poorly constrained.

The statistical advantage of projecting forward from the present to anticipated PETM onset values in the future is that the modern samples are many, and the temporal scaling of this projection is tightly constrained. Modern carbon emission rates are increasing steadily. If this continues, we can expect PETM onset values of carbon accumulation within 140 to 259 years. A second PETM-scale global greenhouse warming event is on the horizon if we cannot lower anthropogenic carbon emission rates.

**Acknowledgments**
I thank Gabriel Bowen and Peter Lippert for organizing the Snowbird CBEP 2017 meeting and inviting me to participate. Reviews by Scott Wing and one or more anonymous Editors and reviewers improved the manuscript. All data are available from published sources.

## References

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., et al. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences*, *37*(1), 117–134. https://doi.org/10.1146/annurev.earth.031208.100206

Boden, T. A., Marland, G., & Andres, R. J. (2016). Fossil emissions by fuel type, in Le Quéré et. al., Global carbon budget 2016. *Earth System Science Data*, *8*(2), 605–649. https://doi.org/10.5194/essd-8-605-2016

Bowen, G. J., Maibauer, B. J., Kraus, M. J., Röhl, U., Westerhold, T., Steimke, A., et al. (2015). Two massive, rapid releases of carbon during the onset of the Paleocene-Eocene thermal maximum. *Nature Geoscience*, *8*(1), 44–47. https://doi.org/10.1038/ngeo2316

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V. C. J., Chhabra, A., et al. (2013). Carbon and other biogeochemical cycles. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 465–570). Cambridge: Cambridge University Press. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter06_FINAL.pdf

Clyde, W. C., & Gingerich, P. D. (1998). Mammalian community response to the latest Paleocene thermal maximum: An isotaphonomic study in the northern Bighorn Basin, Wyoming. *Geology*, *26*(11), 1011–1014. https://doi.org/10.1130/0091-7613(1998)026<1011:MCRTTL>2.3.CO;2

Cui, Y., Kump, L. R., Ridgwell, A. J., Charles, A. J., Junium, C. K., Diefendorf, A. F., et al. (2011). Slow release of fossil carbon during the Palaeocene-Eocene thermal maximum. *Nature Geoscience*, *4*(7), 481–485. https://doi.org/10.1038/ngeo1179

DeConto, R. M., Galeotti, S., Pagani, M., Tracy, D., Schaefer, K., Zhang, T., et al. (2012). Past extreme warming events linked to massive carbon release from thawing permafrost. *Nature*, *484*(7392), 87–91. https://doi.org/10.1038/nature10929

Dickens, G. R., O'Neil, J. R., Rea, D. K., & Owen, R. M. (1995). Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography*, *10*(6), 965–971. https://doi.org/10.1029/95PA02087

Frieling, J., Svensen, H. H., Planke, S., Cramwinckel, M. J., Selnes, H., & Sluijs, A. (2016). Thermogenic methane release as a cause for the long duration of the PETM. *Proceedings of the National Academy of Sciences*, *113*(43), 12,059–12,064. https://doi.org/doi10.1073/pnas.1603348113

Gingerich, P. D. (1983). Rates of evolution: Effects of time and temporal scaling. *Science*, *222*(4620), 159–161. https://doi.org/10.1126/science.222.4620.159

Gingerich, P. D. (1989). New earliest Wasatchian mammalian fauna from the Eocene of northwestern Wyoming: Composition and diversity in a rarely sampled high-floodplain assemblage. *University of Michigan Papers on Paleontology*, *28*, 1–97. http://hdl.handle.net/2027.42/48628

Gingerich, P. D. (2019). *Rates of evolution: A quantitative synthesis*. Cambridge: Cambridge University Press.

Gould, S. J. (1984). Smooth curve of evolutionary rate: A psychological and mathematical artifact. *Science*, *226*(4677), 994–996. http://www.jstor.org/stable/1693378. https://doi.org/10.1126/science.6505682

Gutjahr, M., Ridgwell, A., Sexton, P. F., Anagnostou, E., Pearson, P. N., Pälike, H., et al. (2017). Very large release of mostly volcanic carbon during the Palaeocene-Eocene thermal maximum. *Nature*, *548*(7669), 573–577. https://doi.org/10.1038/nature23646

Hurst, H. E. (1951). Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers*, *116*, 770–808.

Kennett, J. P., & Stott, L. D. (1991). Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, *353*(6341), 225–229. https://doi.org/10.1038/353225a0

Kirtland Turner, S. (2018). Constraints on the onset duration of the Paleocene-Eocene thermal maximum. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2130), 1–16. https://doi.org/10.1098/rsta.2017.0082

Kirtland Turner, S., & Ridgwell, A. (2016). Development of a novel empirical framework for interpreting geological carbon isotope excursions, with implications for the rate of carbon injection across the PETM. *Earth and Planetary Science Letters*, *435*, 1–13. https://doi.org/10.1016/j.epsl.2015.11.027

Koch, P. L., Zachos, J. C., & Gingerich, P. D. (1992). Correlation between isotope records in marine and continental carbon reservoirs near the Palaeocene-Eocene boundary. *Nature*, *358*(6384), 319–322. https://doi.org/10.1038/358319a0

Le Quéré, C., Andrew, M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., et al. (2016). Global carbon budget 2016. *Earth System Science Data*, *8*(2), 605–649. https://doi.org/10.5194/essd-8-605-2016

Mandelbrot, B. B. (1967). How long is the coast of Britain? Statistical self-similarity and fractional dimension. *Science*, *156*(3775), 636–638. https://doi.org/10.1126/science.156.3775.636

Mandelbrot, B. B. (1983). *Fractal geometry of nature*. San Francisco, CA: W. H. Freeman. https://doi.org/10.1119/1.13295

McInerney, F. A., & Wing, S. L. (2011). The Paleocene-Eocene thermal maximum: A perturbation of carbon cycle, climate, and biosphere with implications for the future. *Annual Review of Earth and Planetary Sciences*, *39*(1), 489–516. https://doi.org/10.1146/annurev-earth-040610-133431

Richardson, L. F. (1961). The problem of contiguity: An appendix to statistics of deadly quarrels. *General Systems, Yearbook of the Society for the Advancement of General Systems Theory* (Vol. 6, pp. 139–187). Ann Arbor, MI.

Romans, B. (2007). Sediment accumulation rates and bias: The Sadler effect. Wired.com *(Science)*, *2007*, 1–5. https://www.wired.com/2007/07/sediment-accumulation-rates-and-bias-the-sadler-effect/

Sadler, P. M. (1981). Sediment accumulation rates and the completeness of stratigraphic sections. *Journal of Geology*, *89*(5), 569–584. https://doi.org/10.1086/628623

Secord, R., Bloch, J. I., Chester, S. G. B., Boyer, D. M., Wood, A. R., Wing, S. L., et al. (2012). Evolution of the earliest horses driven by climate change in the Paleocene-Eocene thermal maximum. *Science*, *335*(6071), 959–962. https://doi.org/10.1126/science.1213859

Smith, J. J., Hasiotis, S. T., Kraus, M. J., & Woody, D. T. (2009). Transient dwarfism of soil fauna during the Paleocene-Eocene thermal maximum. *Proceedings of the National Academy of Sciences USA*, *106*(42), 17,655–17,660. https://doi.org/10.1073/pnas.0909674106

Steinhaus, H. (1954). Length, shape and area. *Colloquium Mathematicum, Warsaw*, *3*(1), 1–13. https://doi.org/10.4064/cm-3-1-1-13

Thomas, E. (1989). Development of Cenozoic deep-sea benthic foraminiferal faunas in Antarctic waters. *Geological Society Special Publication*, *47*(1), 283–296. https://doi.org/10.1144/GSL.SP.1989.047.01.21

Wing, S. L., Harrington, G. J., Smith, F. A., Bloch, J. I., Boyer, D. M., & Freeman, K. H. (2005). Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science*, *310*(5750), 993–996. https://doi.org/10.1126/science.1116913

Zachos, J. C., Pagani, M., Sloan, L. C., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, *292*(5517), 686–693. https://doi.org/10.1126/science.1059412

Zeebe, R. E., Ridgwell, A., & Zachos, J. C. (2016). Anthropogenic carbon release rate unprecedented during the past 66 million years. *Nature Geoscience*, *9*(4), 325–329. https://doi.org/10.1038/ngeo2681

Zeebe, R. E., Zachos, J. C., & Dickens, G. R. (2009). Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene thermal maximum warming. *Nature Geoscience*, *2*(8), 576–580. https://doi.org/10.1038/ngeo578