

## Volcanic Versus Anthropogenic Carbon Dioxide

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Which emits more carbon dioxide (CO<sub>2</sub>): Earth's volcanoes or human activities? Research findings indicate unequivocally that the answer to this frequently asked question is human activities. However, most people, including some Earth scientists working in fields outside volcanology, are surprised by this answer. The climate change debate has revived and reinforced the belief, widespread among climate skeptics, that volcanoes emit more CO<sub>2</sub> than human activities [Gerlach, 2010; Plimer, 2009]. In fact, present-day volcanoes emit relatively modest amounts of CO<sub>2</sub>, about as much annually as states like Florida, Michigan, and Ohio.

### Volcanic and Anthropogenic CO<sub>2</sub> Emission Rates

Volcanic emissions include CO<sub>2</sub> from erupting magma and from degassing of unerupted magma beneath volcanoes. Over time, they are a major source for restoring CO<sub>2</sub> lost from the atmosphere and oceans by silicate weathering, carbonate deposition, and organic carbon burial [Bernier, 2004]. Global estimates of the annual present-day CO<sub>2</sub> output of the Earth's degassing subaerial and submarine volcanoes range from 0.13 to 0.44 billion metric tons (gigatons) per year [Gerlach, 1991; Allard, 1992; Varekamp et al., 1992; Sano and Williams, 1996; Marty and Tolstikhin, 1998]; the preferred global estimates of the authors of these studies range from 0.15 to 0.26 gigaton per year. Other aggregated volcanic CO<sub>2</sub> emission rate estimates—published in 18 studies since 1979 as subaerial, arc, and mid-oceanic ridge estimates—are consistent with the global estimates. For more information, see the background, table, and references in the online supplement to this *Eos* issue ([http://www.agu.org/eos\\_elec/](http://www.agu.org/eos_elec/)).

Anthropogenic CO<sub>2</sub> emissions—responsible for a projected 35 gigatons of CO<sub>2</sub> in 2010 [Friedlingstein et al., 2010]—clearly dwarf all estimates of the annual

present-day global volcanic CO<sub>2</sub> emission rate. Indeed, volcanoes emit significantly less CO<sub>2</sub> than land use changes (3.4 gigatons per year), light-duty vehicles (3.0 gigatons per year, mainly cars and pickup

trucks), or cement production (1.4 gigatons per year). Instead, volcanic CO<sub>2</sub> emissions are comparable in the human realm to the global CO<sub>2</sub> emissions from flaring of waste gases (0.20 gigaton per year) or to the CO<sub>2</sub> emissions of about 2 dozen full-capacity 1000-megawatt coal-fired power stations (0.22 gigaton per year), the latter of which constitute about 2% of the world's coal-fired electricity-generating capacity. More meaningful, perhaps, are the comparable annual

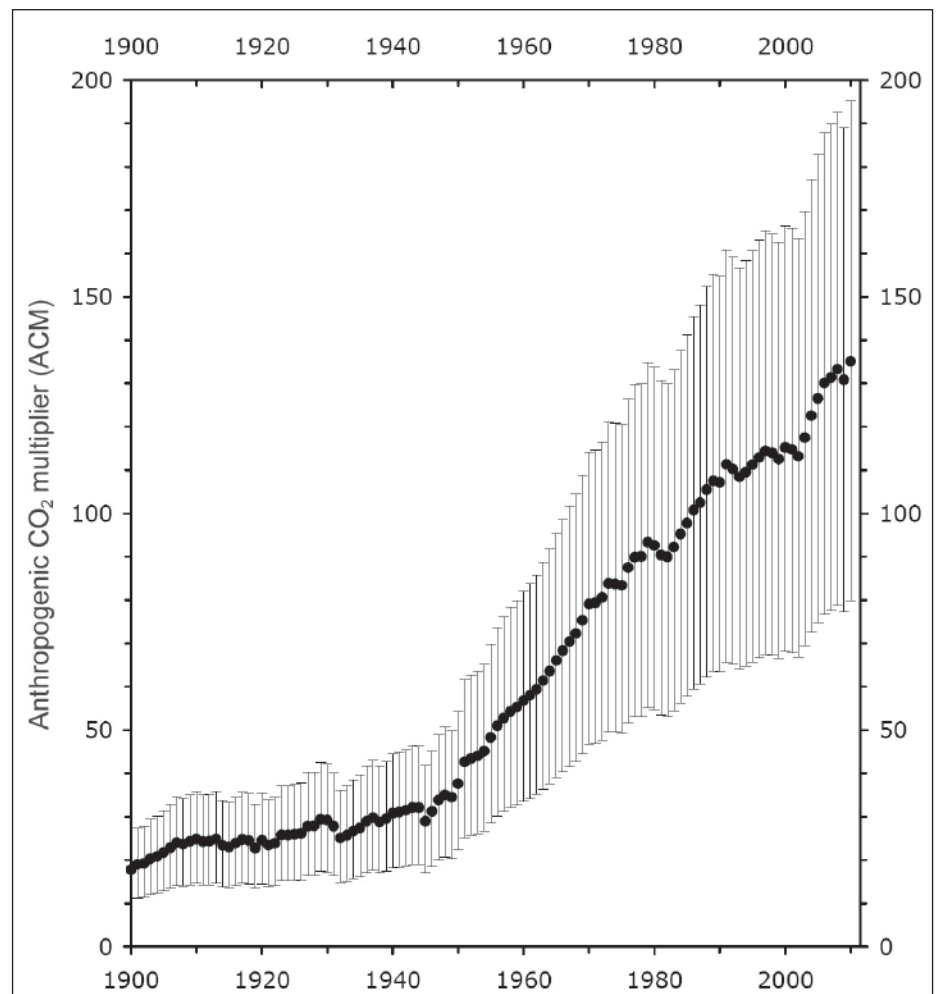


Fig. 1. Solid dots show a time series of the anthropogenic carbon dioxide (CO<sub>2</sub>) multiplier (ACM) calculated from time series data on anthropogenic CO<sub>2</sub> emission rates and Marty and Tolstikhin's [1998] 0.26-gigaton-per-year preferred global volcanic CO<sub>2</sub> emission rate estimate. Bars show the spread of ACM values corresponding to Marty and Tolstikhin's [1998] plausible range of global volcanic CO<sub>2</sub> emission rates (0.18–0.44 gigaton per year). Time series data on anthropogenic CO<sub>2</sub> include emissions from fossil fuel combustion, land use changes, cement production, and waste gas flaring [Friedlingstein et al., 2010]. Data are from [http://cdiac.ornl.gov/trends/emis/meth\\_reg.html](http://cdiac.ornl.gov/trends/emis/meth_reg.html), <http://cdiac.esd.ornl.gov/trends/landuse/houghton/houghton.html>, and [http://lqmacweb.env.uea.ac.uk/lequere/co2/carbon\\_budget.htm](http://lqmacweb.env.uea.ac.uk/lequere/co2/carbon_budget.htm).

CO<sub>2</sub> emissions of nations such as Pakistan (0.18 gigaton), Kazakhstan (0.25 gigaton), Poland (0.31 gigaton), and South Africa (0.44 gigaton). (CO<sub>2</sub> emissions data are for 2008 [International Energy Agency, 2009a, 2009b]; see also [http://cdiac.ornl.gov/trends/emis/meth\\_reg.html](http://cdiac.ornl.gov/trends/emis/meth_reg.html), <http://www.epa.gov/cleanenergy/energy-and-you/affect/coal.html>, and [http://lmgmacweb.env.uea.ac.uk/lequere/co2/carbon\\_budget.htm](http://lmgmacweb.env.uea.ac.uk/lequere/co2/carbon_budget.htm).)

*Marty and Tolstikhin* [1998] give a preferred estimate of 0.26 gigaton per year for the present-day global volcanic CO<sub>2</sub> emission rate and a range for plausible estimates of 0.18–0.44 gigaton per year (see the online supplement). Their study—an evaluation of CO<sub>2</sub> emissions from divergent plate (spreading center), intraplate (plume), and convergent plate (arc) volcanism—is the most comprehensive and probably the most cited of the global estimate studies, and its broad range of plausible estimates reflects a realistic assessment of uncertainties. What's more, *Marty and Tolstikhin's* [1998] assessments give the highest preferred, minimum, and maximum global estimates, making them appropriate high-end volcanic limits for the comparisons with anthropogenic CO<sub>2</sub> emissions in this article.

The projected 2010 anthropogenic CO<sub>2</sub> emission rate of 35 gigatons per year is 135 times greater than the 0.26-gigaton-per-year preferred estimate for volcanoes. This ratio of anthropogenic to volcanic CO<sub>2</sub> emissions defines the anthropogenic CO<sub>2</sub> multiplier (ACM), an index of anthropogenic CO<sub>2</sub>'s dominance over volcanic CO<sub>2</sub> emissions. Figure 1 shows the ACM as a time series calculated from time series data on anthropogenic CO<sub>2</sub> emissions and *Marty and Tolstikhin's* [1998] preferred and plausible range of emission estimates for global volcanic CO<sub>2</sub>. The ACM values related to the preferred estimate rise gradually from about 18 in 1900 to roughly 38 in 1950; thereafter they rise rapidly to approximately 135 by 2010. This pattern mimics the pattern of the anthropogenic CO<sub>2</sub> emissions time series. It reflects the 650% growth in anthropogenic emissions since 1900, about 550% of which has occurred since 1950. ACM plots related to the preferred estimates of global volcanic CO<sub>2</sub> in the four other studies (not shown) exhibit the same pattern but at higher values; e.g., the 2010 ACM values based on their preferred estimates range from 167 to 233, compared to the 135 based on *Marty and Tolstikhin's* [1998] preferred estimate.

### Paroxysmal Volcanic CO<sub>2</sub> Emissions

Infrequent large paroxysmal volcanic explosions can cause significant positive deviations from the 0.26-gigaton-per-year preferred volcanic CO<sub>2</sub> estimate. But contemporary paroxysms, when added to all other eruptions, are unlikely to have breached the upper limit of 0.44 gigaton per year for global volcanic CO<sub>2</sub> emissions. For example, the 18 May 1980 paroxysm of Mount St. Helens is estimated to have

released only about 0.01 gigaton of CO<sub>2</sub>. Smaller and somewhat larger paroxysms probably also emit CO<sub>2</sub> at levels that do not overrun the upper limit. Even the Mount Pinatubo paroxysm on 15 June 1991—one of the three largest eruptions of the twentieth century—with an estimated CO<sub>2</sub> release of about 0.05 gigaton, would not have overrun the upper limit. It would take more than three equivalent Pinatubo paroxysms per year to exceed the upper limit. Prorated over a 100-year recurrence interval, the 1991 Pinatubo paroxysm adds only 0.0005 gigaton of CO<sub>2</sub> per year to the global volcanic CO<sub>2</sub> emission rate. For more on CO<sub>2</sub> emissions of the Mount St. Helens and Mount Pinatubo eruptions, see the online supplement.

The nearly 9-hour duration of both the Mount St. Helens and Pinatubo paroxysms gives average CO<sub>2</sub> emission rates of about 0.001 and 0.006 gigaton per hour, respectively. Intriguingly, the anthropogenic CO<sub>2</sub> emission rate of 35 gigatons per year—equivalent to 0.004 gigaton per hour—is similar. So, for a few hours during paroxysms, individual volcanoes may emit about as much or more CO<sub>2</sub> than human activities. But volcanic paroxysms are ephemeral, while anthropogenic CO<sub>2</sub> is emitted relentlessly from ubiquitous sources. On average, humanity's ceaseless emissions release an amount of CO<sub>2</sub> comparable to the 0.01 gigaton of the 1980 Mount St. Helens paroxysm every 2.5 hours and the 0.05 gigaton of the 1991 Mount Pinatubo paroxysm every 12.5 hours. Every 2.7 days, they emit an amount comparable to the 0.26-gigaton preferred estimate for annual global volcanic CO<sub>2</sub> emissions.

### Problematic Implications

Several dilemmas arise from the belief that volcanic CO<sub>2</sub> emissions exceed the 35-gigaton-per-year anthropogenic CO<sub>2</sub> emission. For example, a global volcanic CO<sub>2</sub> output exceeding 35 gigatons per year would imply that the annual mass of volcanic CO<sub>2</sub> emissions is more than 3 times greater than the likely annual mass of erupted magma (~10.8 gigatons per year [Crisp, 1984]). While not believable, this implication is a telling perspective on the size of humanity's carbon footprint. Furthermore, the degassing of more than 35 gigatons of CO<sub>2</sub> from the ~81 gigatons per year [Crisp, 1984] of global magma production—volcanic plus plutonic—would imply a global magma supply containing on average more than 30-weight-percent CO<sub>2</sub>. This much CO<sub>2</sub> would probably make all volcanism tremendously explosive, and it conflicts with abundant evidence that the primary CO<sub>2</sub> concentrations of mid-ocean ridge, plume, and subduction zone magmas are less than or equal to about 1.5 weight percent (see the online supplement).

Further, to create more than 35 gigatons per year of volcanic CO<sub>2</sub> would require that magma across the globe be produced in amounts exceeding 850 cubic kilometers per year, even for magma hypothetically

containing 1.5-weight-percent CO<sub>2</sub>. It is implausible that this much magma production—more than 40 times the annual mid-ocean ridge magma supply—is going unnoticed, on land or beneath the sea. Besides, the release of more than 35 gigatons per year of volcanic CO<sub>2</sub> into the ocean would overwhelm the observed acid-buffering capacity of seawater and contradict seawater's role as a major sink for atmospheric CO<sub>2</sub> [Walker, 1983; Khatiwala et al., 2009].

In short, the belief that volcanic CO<sub>2</sub> exceeds anthropogenic CO<sub>2</sub> implies either unbelievable volumes of magma production or unbelievable concentrations of magmatic CO<sub>2</sub>. These dilemmas and their related problematic implications corroborate the observational evidence that volcanoes emit far less CO<sub>2</sub> than human activities.

### Volcanic Analogs of Anthropogenic CO<sub>2</sub> Emissions

It is informative to calculate volcanic analogs that elucidate the size of humanity's carbon footprint by scaling up volcanism to the hypothetical intensity required to generate CO<sub>2</sub> emissions at anthropogenic levels. For example, using the 2010 ACM factor of 135 (Figure 1) to scale up features of present-day volcanism, Kilauea volcano scales up to the equivalent of 135 Kilauea volcanoes; scaling up all active subaerial volcanoes evokes a landscape with the equivalent of about 9500 active present-day volcanoes [Siebert et al., 2010]. Similarly, the seafloor mid-ocean ridge system scales up to the equivalent of 135 such systems. Of particular interest, though, is the roughly 4 cubic kilometers per year of current global volcanic magma production [Crisp, 1984], which would scale up to about 540 cubic kilometers per year. This significantly exceeds the estimated average magma output rates of continental flood basalt volcanism [Self, 2010], which range from about 10 to 100 cubic kilometers per year. Thus, annual anthropogenic CO<sub>2</sub> emissions may already exceed the annual CO<sub>2</sub> emissions of several continental flood basalt eruptions, consistent with the findings of *Self et al.* [2005].

Scaling up CO<sub>2</sub> releases of volcanic paroxysms to the 35-gigaton anthropogenic CO<sub>2</sub> emission level is also revealing. For example, scaling up the 0.05-gigaton CO<sub>2</sub> release of the 15 June 1991 Mount Pinatubo paroxysm to the current anthropogenic CO<sub>2</sub> emission level requires 700 equivalent paroxysms annually. Accordingly, Pinatubo's explosively erupted magma, which amounts to about 5 cubic kilometers (see the online supplement), would scale to 3500 cubic kilometers of magma—enough annually for about eight supereruptions, defined as eruptions yielding more than 450 cubic kilometers of magma [Self, 2006]. Similarly, scaling the 0.01-gigaton CO<sub>2</sub> release of the 18 May 1980 Mount St. Helens paroxysm requires 3500 equivalent paroxysms annually, each involving about 0.4 cubic kilometer of magma (see the online supplement) and thus yielding 1400 cubic

kilometers of magma—enough for about three supereruptions annually. Supereruptions are extremely rare, with recurrence intervals of 100,000–200,000 years; none have occurred historically, the most recent examples being Indonesia's Toba volcano, which erupted 74,000 years ago, and the United States' Yellowstone caldera, which erupted 2 million years ago. Interestingly, these calculations strongly suggest that present-day annual anthropogenic CO<sub>2</sub> emissions may exceed the CO<sub>2</sub> output of one or more supereruptions every year.

Humans currently live in a time of volcanic quiescence [Plimer, 2009, pp. 149, 211, 225]. But if the Earth's volcanoes were emitting more CO<sub>2</sub> than present-day human activities, volcanic quiescence would be a rare experience.

### Looking Ahead

Improving estimates of the present-day global volcanic CO<sub>2</sub> emission rate is a principal goal of the Deep Carbon Observatory White Paper: Deep Carbon Reservoirs and Fluxes (<https://dco.glcw.edu/resources/dco-reports>), an international research plan to advance understanding of the deep-Earth carbon cycle. While such efforts are of great scientific importance, the clear need to communicate the dwarfing of volcanic CO<sub>2</sub> by anthropogenic CO<sub>2</sub> to educators, climate change policy makers, the media, and the general public is also important. Discussions about climate policy can only benefit from this recognition.

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# NEWS

## Limiting Invasive Species in Ballast Water

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Ballast water is often intentionally loaded onto cargo ships and other vessels to provide weight necessary for safe maneuvering. However, this practice can unintentionally transport exotic organisms to parts of the world where populations of these organisms can establish themselves in new habitats as invasive and environmentally and economically disruptive species. Each year, an estimated 196 million metric tons of ballast water are discharged into U.S. coastal waters and the Great Lakes alone from an average of more than 90,000 visits of commercial ships greater than 300 metric tons, according to a 2 June report by the U.S. National Research Council (NRC) of the National Academies.

The problem of how to limit the transport of invasive species—which could range from bivalves and worms to sea grasses, dinoflagellates, and viruses—in ballast

water can seem daunting because of the sheer number of ships and amount of ballast water, the differences in source and recipient regions, the diversity and abundance of organisms entrained in ballast water, and the lack of sufficient ballast water data and adequate models of discharge standards, according to the NRC report, entitled *Assessing the Relationship Between Propagule Pressure and Invasion Risk in Ballast Water*.

Prepared by a committee of the NRC's Water Science and Technology Board, the report outlines the complexity of the problem and recommends measures to study and limit the number of propagules, which are defined as any living biological material transported from one location to another. The report, sponsored by the U.S. Environmental Protection Agency (EPA) and the U.S. Coast Guard, comes out at a time when ballast management programs of these agencies are being revised with a focus on setting specific post-treatment discharge

standards. It also was released prior to the International Maritime Organization's International Convention for the Control and Management of Ships' Ballast Water and Sediments coming into force.

The report's stated goal is to inform ballast water regulation through a better understanding of the relationship between the concentration of propagules and the probability of their establishing populations in U.S. waters. It notes that ballast water exchange reduces concentrations of live coastal organisms by about 88–99% and that the implementation of ballast water treatment systems would further reduce the concentrations, and perhaps diversity, of organisms in ballast water.

The report states that EPA and the Coast Guard are developing standards to limit the density of organisms in ballast water discharged to U.S. waters “in an effort to go beyond the protectiveness afforded by ballast-mediated transfers of species.” The agencies requested that NRC provide technical advice “to help inform the derivation of numeric limits for living organisms in ballast water for their regulatory programs.”

“It is abundantly clear that significantly reducing propagule pressure will reduce the probability of invasions, when controlling for all other variables,” the report states. “There