EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 92 NUMBER 24
14 JUNE 2011
PAGES 201–208

Volcanic Versus Anthropogenic Carbon Dioxide

PAGES 201–202

Which emits more carbon dioxide (CO_2): 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_2 than human activities [*Gerlach,* 2010; *Plimer,* 2009]. In fact, present-day volcanoes emit relatively modest amounts of CO_2, about as much annually as states like Florida, Michigan, and Ohio.

Volcanic and Anthropogenic CO_2 Emission Rates

Volcanic emissions include CO_2 from erupting magma and from degassing of unerupted magma beneath volcanoes. Over time, they are a major source for restoring CO_2 lost from the atmosphere and oceans by silicate weathering, carbonate deposition, and organic carbon burial [*Berner,* 2004]. Global estimates of the annual present-day CO_2 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_2 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/).

Anthropogenic CO_2 emissions—responsible for a projected 35 gigatons of CO_2 in 2010 [*Friedlingstein et al.,* 2010]—clearly dwarf all estimates of the annual present-day global volcanic CO_2 emission rate. Indeed, volcanoes emit significantly less CO_2 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_2 emissions are comparable in the human realm to the global CO_2 emissions from flaring of waste gases (0.20 gigaton per year) or to the CO_2 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

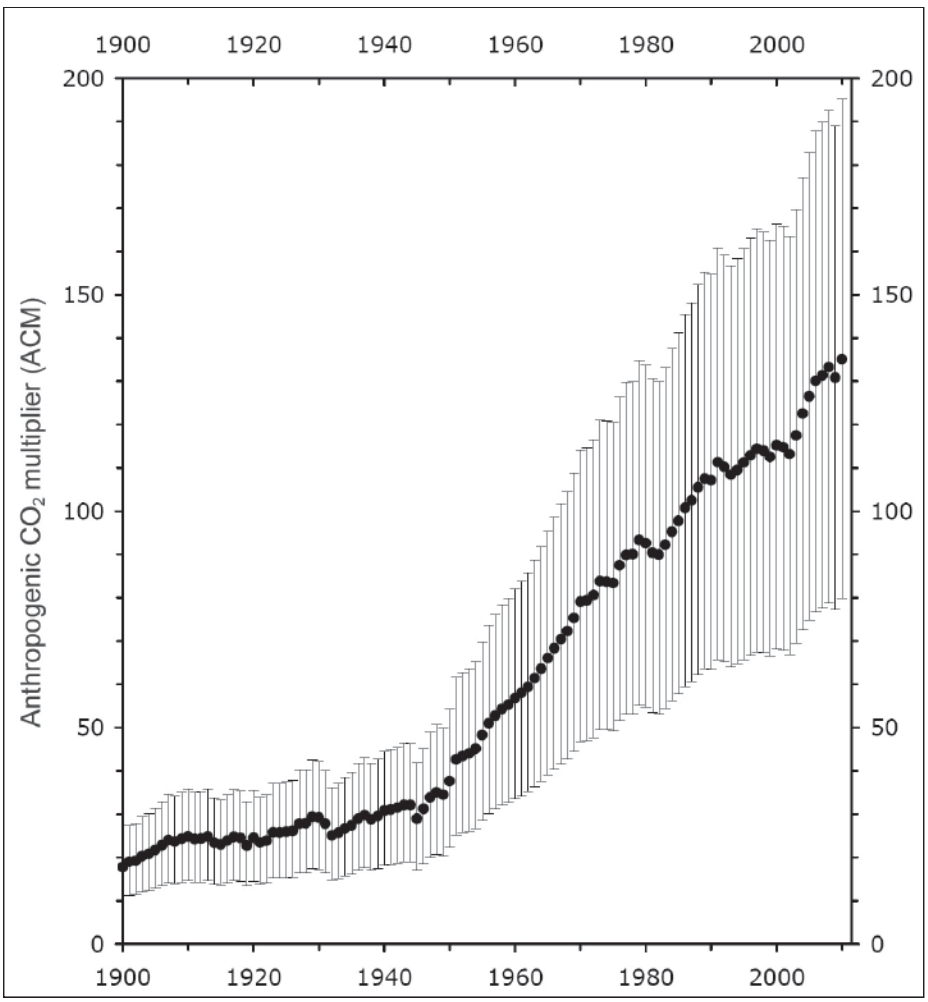

Fig. 1. Solid dots show a time series of the anthropogenic carbon dioxide (CO_2) multiplier (ACM) calculated from time series data on anthropogenic CO_2 emission rates and Marty and Tolstikhin*'s [1998] 0.26-gigaton-per-year preferred global volcanic CO_2 emission rate estimate. Bars show the spread of ACM values corresponding to* Marty and Tolstikhin*'s [1998] plausible range of global volcanic CO_2 emission rates (0.18–0.44 gigaton per year). Time series data on anthropogenic CO_2 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.esd.ornl.gov/trends/landuse/houghton/houghton.html, and http://lgmacweb.env.uea.ac.uk/lequere/co2/carbon_budget.htm.*

By T. Gerlach

CO_2 emissions of nations such as Pakistan (0.18 gigaton), Kazakhstan (0.25 gigaton), Poland (0.31 gigaton), and South Africa (0.44 gigaton). (CO_2 emissions data are for 2008 [*International Energy Agency,* 2009a, 2009b]; see also http://cdiac.ornl.gov/trends/emis/meth_reg.html, http://www.epa.gov/cleanenergy/energy-and-you/affect/coal.html, and http://lgmacweb.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_2 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_2 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_2 emissions in this article.

The projected 2010 anthropogenic CO_2 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_2 emissions defines the anthropogenic CO_2 multiplier (ACM), an index of anthropogenic CO_2's dominance over volcanic CO_2 emissions. Figure 1 shows the ACM as a time series calculated from time series data on anthropogenic CO_2 emissions and *Marty and Tolstikhin*'s [1998] preferred and plausible range of emission estimates for global volcanic CO_2. 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_2 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_2 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_2 Emissions

Infrequent large paroxysmal volcanic explosions can cause significant positive deviations from the 0.26-gigaton-per-year preferred volcanic CO_2 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_2 emissions. For example, the 18 May 1980 paroxysm of Mount St. Helens is estimated to have released only about 0.01 gigaton of CO_2. Smaller and somewhat larger paroxysms probably also emit CO_2 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_2 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_2 per year to the global volcanic CO_2 emission rate. For more on CO_2 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_2 emission rates of about 0.001 and 0.006 gigaton per hour, respectively. Intriguingly, the anthropogenic CO_2 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_2 than human activities. But volcanic paroxysms are ephemeral, while anthropogenic CO_2 is emitted relentlessly from ubiquitous sources. On average, humanity's ceaseless emissions release an amount of CO_2 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_2 emissions.

Problematic Implications

Several dilemmas arise from the belief that volcanic CO_2 emissions exceed the 35-gigaton-per-year anthropogenic CO_2 emission. For example, a global volcanic CO_2 output exceeding 35 gigatons per year would imply that the annual mass of volcanic CO_2 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_2 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_2. This much CO_2 would probably make all volcanism tremendously explosive, and it conflicts with abundant evidence that the primary CO_2 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_2 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_2. 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_2 into the ocean would overwhelm the observed acid-buffering capacity of seawater and contradict seawater's role as a major sink for atmospheric CO_2 [*Walker,* 1983; *Khatiwala et al.,* 2009].

In short, the belief that volcanic CO_2 exceeds anthropogenic CO_2 implies either unbelievable volumes of magma production or unbelievable concentrations of magmatic CO_2. These dilemmas and their related problematic implications corroborate the observational evidence that volcanoes emit far less CO_2 than human activities.

Volcanic Analogs of Anthropogenic CO_2 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_2 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_2 emissions may already exceed the annual CO_2 emissions of several continental flood basalt eruptions, consistent with the findings of *Self et al.* [2005].

Scaling up CO_2 releases of volcanic paroxysms to the 35-gigaton anthropogenic CO_2 emission level is also revealing. For example, scaling up the 0.05-gigaton CO_2 release of the 15 June 1991 Mount Pinatubo paroxysm to the current anthropogenic CO_2 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_2 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_2 emissions may exceed the CO_2 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_2 than present-day human activities, volcanic quiescence would be a rare experience.

Looking Ahead

Improving estimates of the present-day global volcanic CO_2 emission rate is a principal goal of the Deep Carbon Observatory White Paper: Deep Carbon Reservoirs and Fluxes (https://dco.gl.ciw.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_2 by anthropogenic CO_2 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.

Acknowledgments

I thank several U.S. Geological Survey and *Eos* reviewers for their comments and suggestions.

References

Allard, P. (1992), Global emissions of helium-3 by subaerial volcanism, *Geophys. Res. Lett., 19*(14), 1479–1481, doi:10.1029/92GL00974.
Berner, R. A. (2004), *The Phanerozoic Carbon Cycle,* 150 pp., Oxford Univ. Press, New York.
Crisp, J. A. (1984), Rates of magma emplacement and volcanic output, *J. Volcanol. Geotherm. Res., 20*(3-4), 177–211, doi:10.1016/0377-0273(84)90039-8.
Friedlingstein, P., R. A. Houghton, G. Marland, J. Hackler, T. A. Boden, T. J. Conway, J. G. Canadell, M. R. Raupach, P. Ciais, and C. Le Quéré (2010), Update on CO_2 emissions, *Nat. Geosci., 3*(12), 811–812, doi:10.1038/ngeo1022.
Gerlach, T. M. (1991), Present-day CO_2 emissions from volcanoes, *Eos Trans. AGU, 72*(23), 249, 254–255.
Gerlach, T. M. (2010), Volcanic versus anthropogenic carbon dioxide: The missing science, *Earth, 55*(7), 87. [Available at http://www.earthmagazine.org/earth/article/371-7da-7-1e.]
International Energy Agency (2009a), *CO_2 Emissions From Fuel Combustion: 2009 Edition*, 530 pp., Paris.
International Energy Agency (2009b), *Transport, Energy and CO_2: Moving Toward Sustainability*, 400 pp., Paris.
Khatiwala, S., F. Primeau, and T. Hall (2009), Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean, *Nature, 462,* 346–350, doi:10.1038/nature08526.
Marty, B., and I. N. Tolstikhin (1998), CO_2 fluxes from mid-ocean ridges, arcs and plumes, *Chem. Geol., 145*(3-4), 233–248, doi:10.1016/S0009-2541(97)00145-9.
Plimer, I. (2009), *Heaven and Earth: Global Warming—The Missing Science*, 504 pp., Taylor Trade Publ., Lanham, Md.
Sano, Y., and S. N. Williams (1996), Fluxes of mantle and subducted carbon along convergent plate boundaries, *Geophys. Res. Lett., 23*(20), 2749–2752, doi:10.1029/96GL02260.
Self, S. (2006), The effects and consequences of very large explosive eruptions, *Philos. Trans. R. Soc. A, 364,* 2073–2097, doi:10.1098/rsta.2006.1814.
Self, S. (2010), Extent and emplacement of continental flood basalt lava flow fields, *Geol. Soc. Am. Abstr. Progams, 42*(5), Paper 55-4.
Self, S., T. Thordarson, and M. Widdowson (2005), Gas fluxes from flood basalt eruptions, *Elements, 1*(5), 283–287, doi:10.2113/gselements.1.5.283.
Siebert, L., T. Simkin, and P. Kimberly (2010), *Volcanoes of the World*, 3rd ed., 551 pp., Smithson. Inst., Washington D. C.
Varekamp, J. C. R., R. Kreulen, R. P. E. Poorter, and M. J. Van Bergen (1992), Carbon sources and arc volcanism, with implications for the carbon cycle, *Terra Nova, 4*(3), 363–373, doi:10.1111/j.1365-3121.1992.tb00825.x.
Walker, J. C. G. (1983), Carbon geodynamic cycle, *Nature, 303,* 730–731, doi:10.1038/303730b0.

Author Information

Terry Gerlach, Cascades Volcano Observatory (Emeritus), U.S. Geological Survey, Vancouver, Wash.; E-mail: tgerlach@usgs.gov

NEWS

Limiting Invasive Species in Ballast Water

PAGES 202–203

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