

Scientists quantify global volcanic CO2 venting; estimate total carbon on Earth

October 1 2019



Figure (a) shows the annual rate of CO_2 emitted to the atmosphere using estimates of total modern natural in-gassing and outgassing (shown in petagrams, Pg, also known as gigatonnes, Gt). Figure (b) shows the estimated annual rates of CO_2 emitted from anthropogenic sources, from the Chixculub impact in the Yucatan area of Central America 65 million years ago, and from Large Igneous Provinces. These amounts are on similar flux levels, making them important analogues to study the effects of modern anthropogenic CO_2 emissions.

Histograms of carbon influx (positive values) and outflux (negative values) to the atmosphere and the oceans. Units are in Pg C/y. (A) Carbon fluxes based on steady state models. Abbreviations: MOR = mid ocean ridge; org carbon = organic carbon. (B) Carbon fluxes as a result of large-scale perturbations to the



carbon cycle. Total outgassing refers to events listed in Figure 2A; anthropogenic is human contributions; Chicxulub (Mexico) refers to the end-Cretaceous asteroid impact and resultant mass extinction; average LIP refers to the input from large igneous provinces. Data from Kawaragi et al. (2009), Lee et al. (2019) and Black and Gibson (2019) Credit: Deep Carbon Observatory

Volcanoes, colliding and spreading continental and oceanic plates, and other phenomena re-studied with innovative high-tech tools, provide important fresh insights to Earth's innermost workings, scientists say.

Preparing to summarize and celebrate the 10-year Deep Carbon Observatory program at the National Academy of Sciences, Washington DC, Oct. 24-26, DCO's 500-member Reservoirs and Fluxes team today outlined several key findings that span time from the present to billions of years past; from Earth's core to its atmosphere, and in size from single volcanoes to the five continents.

Among many wide-ranging findings, outlined and summarized in a series of papers published in the journal *Elements:*

- Just two-tenths of 1% of Earth's total <u>carbon</u>—about 43,500 gigatonnes (Gt)—is above surface in the oceans, on land, and in the atmosphere. The rest is subsurface, including the crust, mantle and core—an estimated 1.85 billion Gt in all
- CO₂ out-gassed to the atmosphere and oceans today from volcanoes and other magmatically active regions is estimated at 280 to 360 million tonnes (0.28 to 0.36 Gt) per year, including that released into the oceans from mid-ocean ridges
- Humanity's annual carbon emissions through the burning of fossil fuels and forests, etc., are 40 to 100 times greater than all volcanic emissions



- Earth's deep carbon cycle through deep time reveals balanced, long-term stability of atmospheric CO₂, punctuated by large disturbances, including immense, catastrophic releases of magma that occurred at least five times in the past 500 million years. During these events, huge volumes of carbon were outgassed, leading to a warmer atmosphere, acidified oceans. and mass extinctions
- Similarly, a giant meteor impact 66 million years ago, the Chicxulub bolide strike on Mexico's Yucatan peninsula, released between 425 and 1,400 Gt of CO₂, rapidly warmed the planet and coincided with the mass (>75%) extinction of plants and animals—including the dinosaurs. Over the past 100 years, emissions from anthropogenic activities such as burning fossil fuels have been 40 to 100 times greater than our planet's geologic carbon emissions
- A shift in the composition of volcanic gases from smelly (akin to burnt matches) <u>sulphur dioxide</u> (SO2) to a gas richer in odorless, colorless CO₂ can be sniffed out by monitoring stations or drones to forewarn of an eruption—sometimes hours, sometimes months in advance. Eruption early warning systems with real-time monitoring are moving ahead to exploit the CO₂ to SO2 ratio discovery, first recognized with certainty in 2014

Says DCO scientist Marie Edmonds of the University of Cambridge, UK: "Carbon, the basis of all life and the energy source vital to humanity, moves through this planet from its mantle to the atmosphere. To secure a sustainable future, it is of utmost importance that we understand Earth's entire carbon cycle."

"Key to unraveling the planet's natural carbon cycle is quantifying how much carbon there is and where, how much moves—the flux—and how quickly, from Deep Earth reservoirs to the surface and back again."



Adds colleague Tobias Fischer of the University of New Mexico, U.S.: "The Deep Carbon Observatory has advanced understanding of the inner workings of Earth. Its collective body of more than 1500 publications has not only increased what is known but established limits to what is knowable, and perhaps unknowable."

"While we celebrate progress, we underline that deep Earth remains a highly unpredictable scientific frontier; we have truly only started to dent current boundaries of our knowledge."

How Much Carbon does Earth Contain?

Scientists have long known that carbon inside Earth exists as a diverse array of solids, fluids, and gases. Some of these materials involve combinations of carbon with oxygen (e.g. carbon dioxide), with iron (e.g., carbides), with hydrogen (e.g., kerogen, coal, petroleum, and methane), and other elements (e.g., silicon, sulfur, and nitrogen), in addition to elemental carbon (e.g., graphite and diamond).

Deep Carbon Observatory scientists underline that knowledge of total carbon in lower mantle and core is still speculative and the numbers are sure to evolve in accuracy as research continues. That said, experts (notably Lee *et al.*, 2019) estimate reservoirs of carbon on Earth as follows:

By the numbers: Best current estimates, carbon on Earth

1.85 billion gigatonnes (1.85 x 1 billion x 1 billion tonnes): Total carbon on Earth





Gas sampling at Lastarria Volcano (northern Chile) during the Trail by Fire expedition (trailbyfire.org) Credit: Yves Moussallam, Lamont Doherty Earth Observatory

Breakdown:

- 1,845,000,000 (1.845 billion) Gt: total carbon below surface
- 1,500,000,000 (1.5 billion) Gt: Carbon in the lower mantle:
- 315,000,000 (0.315 billion) Gt: Carbon in the continental and oceanic lithospheres
- 30,000,000 (0.03 billion) Gt: Carbon in the upper mantle
- 43,500 Gt: total carbon above surface—in the oceans, on land, and in the atmosphere (2/10ths of 1% of Earth's total carbon)



- 37,000 Gt: Carbon in the deep ocean (85.1% of all above surface carbon)
- 3,000 Gt: Carbon in marine sediments (6.9%)
- 2,000 Gt: Carbon in the terrestrial biosphere (4.6%)
- 900 Gt Carbon in the surface ocean (2%)
- 590 Gt: Carbon in the atmosphere (1.4%)

Release of CO₂ from volcanoes

Earth's total annual out-gassing of CO_2 via volcanoes and through other geological processes such as the heating of limestone in mountain belts is newly estimated by DCO experts at roughly 300 to 400 million metric tonnes (0.3 to 0.4 Gt).

Volcanoes and volcanic regions alone outgas an estimated 280-360 million tonnes (0.28 to 0.36 Gt) of CO_2 per year. This includes the CO_2 contribution from active volcanic vents, from the diffuse, widespread release of CO_2 through soils, faults, and fractures in volcanic regions, volcanic lakes, and from the mid-ocean ridge system.

In many world regions, tectonic outgassing (emissions from mountain belts and other plate boundaries), particularly in cool night temperatures, can cause dangerous levels of CO_2 close to the ground—enough to suffocate livestock.

According to DCO researchers, with rare exceptions over millions of years the quantity of carbon released from Earth's mantle has been in relative balance with the quantity returned through the downward subduction of tectonic plates and other processes.

Carbon catastrophes

While the volume of carbon buried through subduction and what's



released from volcanoes and tectonic fractures are normally in steady state, about four times over the past 500 million years this balance has been upended by the emergence of large volcanic events—1 million or more square kilometers (the area of Canada) of magma released within a timeframe of a few tens of thousands of years up to 1 million years.

These "large igneous provinces" degassed enormous volumes of carbon (estimated at up to 30,000 Gt—equal to about 70% of the estimated 43,500 Gt of carbon above surface today).

Carbon cycle imbalance can cause rapid global warming, changes to the silicate weathering rate, changes to the hydrologic cycle, and overall rapid habitat changes that can cause mass extinction as the Earth rebalances itself.

Similar carbon catastrophes have been caused by asteroids / meteors (bolides), such as the massive Chixculub impact in the Yucatan area of Central America 65 million years ago—an event to which extinction of the dinosaurs and most other plants and animals of the time has been attributed.





Year-round monitoring at five volcanoes revealed that the level of carbon dioxide relative to sulfur dioxide in volcanic gases systematically changes in the hours to months before an eruption. Here Deep Carbon Observatory volcanologist Brendan McCormick installs a DECADE (Deep Earth Carbon DEgassing) subgroup MultiGAS monitoring device at Rabaul Volcano, Papua New Guinea. Credit: Emma Liu, University of Cambridge

According to Australian researchers Balz Kamber and Joseph Petrus: "The Chicxulub event ... greatly disrupted the budget of climate-active gases in the atmosphere, leading to short-term abrupt cooling and medium-term strong warming."



"Thus, some large bolide impacts are comparable to those observed in the Anthropocene in terms of rapidly disrupting the C (carbon) cycle and potentially exceeding a critical size of perturbation."

Wiring up volcanoes

DCO experts estimate that about 400 of the 1500 volcanoes active since the last Ice Age 11,700 years ago are venting CO_2 today. Another 670 could be producing diffuse emissions, with 102 already documented. Of these, 22 ancient volcanoes that have not erupted since Pleistocene epoch (2.5 million years ago to the Ice Age) are outgassing. Thus all volcanoes, the young and very old, may be emitting CO_2 .

Today's CO_2 , sulphur dioxide and hydrogen sulphide emissions rates are now quantified for many of the world's most active volcanoes thanks in part to the development of miniature, durable, inexpensive instruments.

And several volcanoes have been wired up with permanent gas instrument monitoring stations to obtain real time data readings, improving monitoring by governments and universities in the U.S., Italy, Costa Rica, and elsewhere. About 30 collaboratively operated gasmonitoring stations on volcanoes across five continents now exist, which continually monitor emissions.

Pioneered by scientists with DCO's DECADE (Deep Earth Carbon DEgassing) subgroup, the technologies and installations have helped revolutionize data collection within inaccessible or dangerous volcanic places. The data obtained are combined with readings from longestablished ground and satellite systems.

Recent research has revealed the number of volcanoes thought to be outgassing measurable amounts of CO_2 today. Estimated at 150 in 2013, DECADE researchers confirm that more than 200 volcanic systems



emitted measurable volumes of CO_2 between the years 2005 and 2017. Of these, several super-regions of diffuse degassing have been documented (e.g., Yellowstone, U.S., the East African Rift, Africa, and the Technong volcanic province in China, to name a few). Diffuse degassing is now recognized as a CO_2 source comparable to active volcanic vents.

Among the DCO's legacies: a new database (<u>http://www.magadb.net</u>) to capture information on CO_2 fluxes from volcanic and non-volcanic sources around the world.

Volcanic whispers: Changes in ratio of vented SO2 to CO₂ can forewarn of eruptions

Research at a growing number of well-monitored volcanoes worldwide has provided important new insight about the timing of eruptions relative to the composition of volcanic outgassing.

Year-round monitoring at five volcanoes revealed that the level of carbon dioxide relative to sulfur dioxide in volcanic gases systematically changes in the hours to months before an eruption. Volcanoes where such patterns have been documented include Poas (Costa Rica), Etna and Stromboli (Italy), Villarica (Chile), and Masaya (Nicaragua).

Likewise the CO_2 to SO2 ratio changed dramatically months to years prior to large eruptions at Kilauea (Hawaii) and Redoubt Volcano (Alaska), in the U.S., suggesting that monitoring gas composition, often in invisible plumes, offers a new eruption forecasting tool that, in some cases, precedes increases in <u>volcano</u> seismicity or ground deformation.

More information: Giancarlo Tamburello et al. Global-scale control of extensional tectonics on CO2 earth degassing, *Nature Communications* (2018). DOI: 10.1038/s41467-018-07087-z



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Provided by Deep Carbon Observatory

Citation: Scientists quantify global volcanic CO2 venting; estimate total carbon on Earth (2019, October 1) retrieved 1 May 2024 from <u>https://phys.org/news/2019-10-scientists-quantify-global-volcanic-co2.html</u>

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