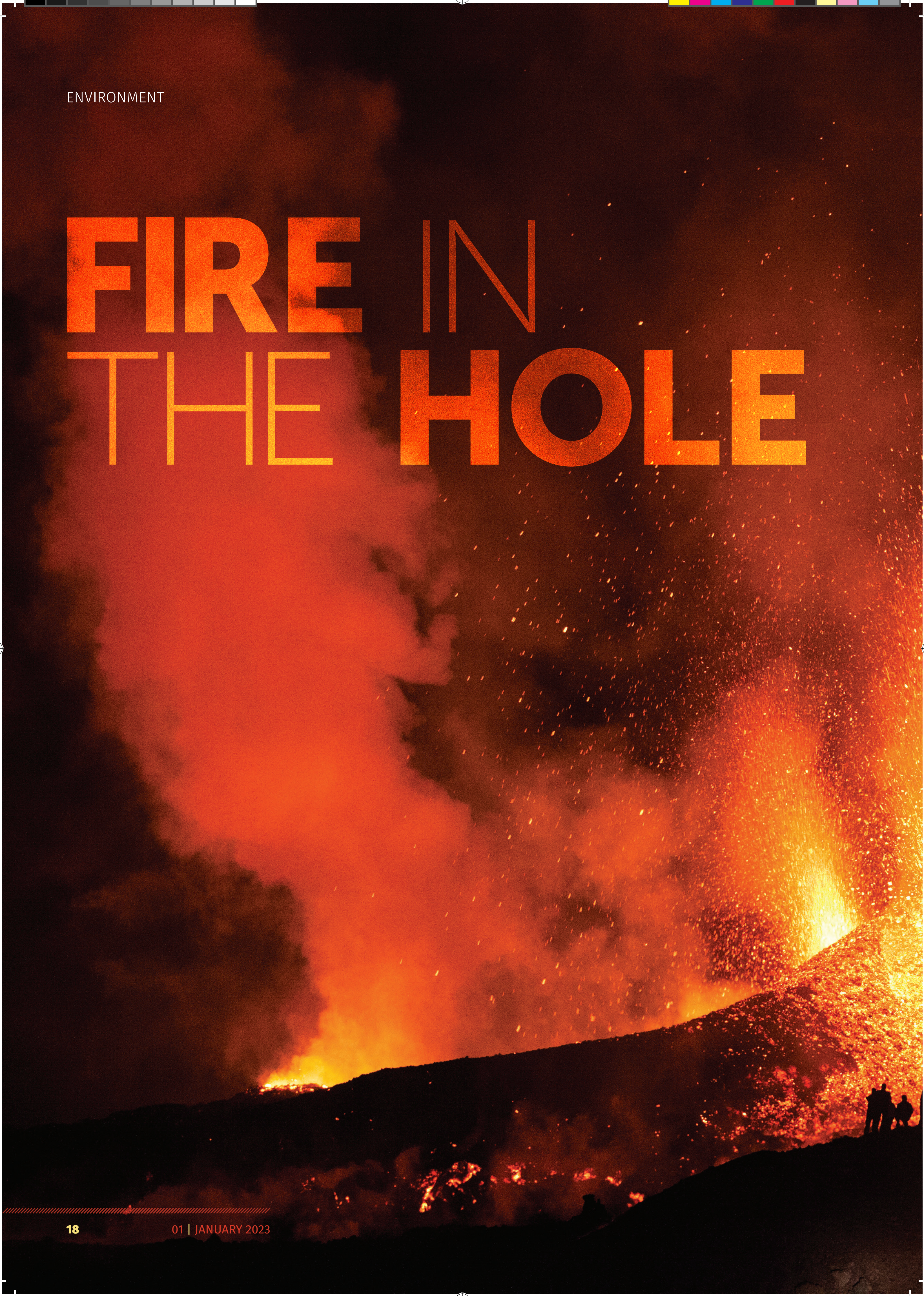
FIRE IN THE HOLE



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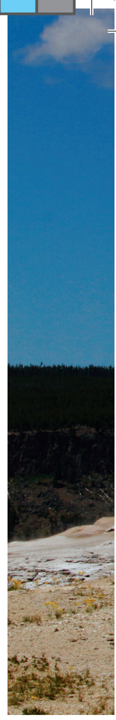
Climate scientists warn there will be at least one big volcanic eruption before the end of the century – with potentially dramatic consequences. So how well prepared are we? Asks ***Katrina Megget***

The 1991 eruption of Mount Pinatubo in the Philippines caused global temperatures to drop by 0.5°C on average. In 1815, the eruption of Tambora in Indonesia saw global temperatures drop 1°C on average, resulting in the 'year without a summer' in 1816. It wiped out 75% of UK agriculture.

Now scientists believe the chances of an eruption this century with a similar or greater impact on the climate is as little as one in six – in other words, the roll of a die. Writing in the journal *Nature* in August 2022 (*Nature*, 2022, **608**, 469), two volcano risk experts believe the world is 'woefully underprepared'. They say the volcanic eruption in Tonga in January, the largest eruption to be instrumentally recorded, should be a wake-up call. Had the eruption lasted longer, emitted more ash and gas, and occurred in a more populated area with essential infrastructure, like the Med, they say the impact would have been graver.

'This isn't scaremongering. We're not talking about an extinction risk but a large eruption would cause a large amount of destruction,' says Mike Cassidy, Professor of volcanology at the University of Birmingham, UK. That destruction could include a volcanic winter and effects on agriculture, global trade, finance and migration. 'We would see the cooling of the earth by a degree or several degrees and we would see this shift within six months. It would be an abrupt change in temperature and weather patterns. We estimate the cost of destruction would run into the multi-trillions.'

The main culprit in this potential destruction is sulfur dioxide. When this gas is ejected high into the atmosphere during an eruption, it combines with water vapour to form sulfuric acid aerosols, which can stay in the atmosphere for several years. These tiny droplets form a cloud-like haze, which has the ability to reflect sunlight back into space thereby reducing the surface temperature of the earth, potentially leading to a volcanic winter. In the case of Pinatubo, the volcano ejected 15-20m t of sulfur dioxide 25-30km into the atmosphere.



Prediction and monitoring

But volcanic eruptions cannot be predicted and all volcanoes are different. For instance, January 2022's eruption of the undersea Hunga Tonga-Hunga Ha'apai volcano in Tonga only ejected 400,000t of sulfur dioxide – considerably less than volcanologists were expecting. But it did spew enough water 50km into the stratosphere to fill 58,000 Olympic-sized swimming pools, and detections from a NASA satellite suggest the extra water vapour, which traps heat, is likely to have temporarily warmed the planet. Scientists don't yet know but speculate the reduction in sulfur dioxide is somehow due to the amount of seawater that was emitted in the eruption.

Besides a volcano's ability to cool and heat the planet, volcanic aerosols can also react with and temporarily destroy ozone. They have also been found to cause drought, impact the number of hurricanes, and impact precipitation and the monsoon season.

Furthermore, research in 2021 from the University of Cambridge and the UK Met Office (*Nature Commun.*, 2021, **12**, 4708), suggests that as the planet warms, large-magnitude eruptions will have a greater impact on the climate as warming will encourage gas and ash to rise higher in the atmosphere and spread faster over the globe. The scientists believe this will amplify the temporary cooling caused by the eruption by 15%.

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>
> **Mike Cassidy** *Professor of volcanology, University of Birmingham, UK*

'When you put the potential of a large-magnitude eruption [10 or 100 times larger than the Tonga eruption] in the context of a roll of a dice, it makes it more prescient,' says Lara Mani, a Research Associate at the UK's University of Cambridge Centre for the Study of Existential Risk and co-author of the *Nature* paper. 'We should be chatting more and engaging policy leaders about this risk which currently isn't prioritised.'

15-20m t

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Geoengineering

Cassidy and Mani call for more volcano monitoring, forecasting and preparedness, but they also suggest for the first time that there should be increased research into volcano geoengineering as a possible means of curtailing a volcanic winter. This could include studying how to counter the aerosols released by an eruption or research into magma manipulation.

'Geoengineering to counter the impact of a volcanic eruption is not even being talked about so this is very much in its infancy,' says Cassidy. 'We're not advocating to do geoengineering but we are advocating for research into it and its feasibility.'

Cassidy and Mani note there may be costs and side effects, as well as ethical questions, but they add there could also be large potential benefits. While research into geoengineering to dampen the effects of a warming climate is a concept that has been considered for years, there is very little on countering a devastating volcanic eruption. A fact that spurred a research team from Norway

Cooling the planet

The idea of interfering with, or geoengineering, the climate to deliberately cool the planet has grown in interest recently as global warming continues.

One of the most popular concepts is solar radiation management (SRM), which is based on the cooling concept of volcanic eruptions. This would see airplanes or balloons pumping sulfur gases into the stratosphere, where they would work like volcanic aerosols to reflect sunlight back out to space.

In October 2022, the US White House Office of Science and Technology Policy announced it was co-ordinating a five-year research plan to study ways of modifying the amount of sunlight that reaches the earth in order to dampen the effects of global warming. Included in this plan is an assessment of SRM alongside other climate interventions and their impact.

The UN Environment Programme too has touched on the topic for the first time, dedicating a chapter in a recent report to the ozone impacts of stratospheric aerosol injection.

However, the topic is highly controversial. Earlier in 2022, more than 60 researchers published an open letter calling for an international non-use agreement on solar geoengineering technologies (*WIREs Climate Change*, 2022, 13, e754). This would include banning outdoor experiments, prohibiting national funding agencies from providing financial support and refusing patents for these technologies. 'The debate on solar radiation management is a dangerous distraction from current efforts to mitigate climate change and to drastically reduce our emissions,' says Frank Biermann, Professor of global sustainability governance at Utrecht University, The Netherlands, one of the letter's authors. 'Any artificial interference in the climate system by SRM is risky and potentially extremely harmful.'

Some scientists claim the letter is an attempt to stifle scientific progress. Biermann disagrees, noting several restrictions on technological developments such as human cloning and mining in Antarctica. But others argue it may be necessary to research SRM even if it's never used. 'There's plenty of reasons why we should examine SRM – one thing is to understand it better,' says Jim Haywood, professor of atmospheric science at the University of Exeter, UK.

'Most of my research is about the perils and pitfalls of SRM. We've shown there's a bunch of potential negative consequences, but the consequences of global warming are so severe that research into combatting its effects is surely warranted. That's what keeps me coming back to SRM. What is required is a balanced research programme of both pros and cons so we can make informed policy decisions.'

Old Faithful, Yellowstone National Park, US

ANDREW CULSHAW

and the UK. 'We were discussing traditional geoengineering and one of us wondered if there was any research done on the... occurrence of a future, powerful volcanic eruption,' says Bjørn Samset, a physicist at Norway's Centre for International Climate Research. 'It turned out we couldn't find anything and since we had the tools available to look into it, we set up some simulations to see what would come out. Our research showed that it would be possible in principle [to counter the aerosols from a volcanic eruption].'

Using a global climate model and simulations, the team showed the cooling from a large volcanic eruption could theoretically be balanced using the warming effects of the greenhouse gas HFC-152a (*Geophys. Res. Lett.*, 2014, **41**, 8627). This hydrofluorocarbon, which is used in refrigerators, does not damage ozone and is known to break down and be removed from the atmosphere rapidly.

The researchers calculated that 1.25bn t of HFC-152a would be needed in the first year to match the cooling emissions from a hypothetical volcanic eruption three times that of Pinatubo. That is roughly the size of the 1815 Tambora eruption in terms of the amount of sulfur emitted.

Whether this geoengineering would work in the real world would require real-world studies, Samset says, and that's not something he and his colleagues are advocating. There are a number of practical, economic, political and ethical issues that would make it unfeasible in the real world and which may rule it out as a credible strategy, he notes.

For instance, 'there are other effects of volcanic ash that we wouldn't be able to fix in this way; notably the reduction in sunlight, which our crops need to grow'. In addition, it would be expensive – in the order of trillions of dollars. Alongside HFC-152a production and storage issues, there could be unintended side effects, for instance, on rainfall.

In 2015, NASA's Jet Propulsion Laboratory considered drilling 10km down inside the Yellowstone super-volcano and pumping in cold water in order to absorb heat and cool the magma. They believed this would make the magma more viscous and less likely to rise, reducing the risk of an eruption.

58,000

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'This is only the very first start of such a discussion,' he says, adding that a major damaging eruption is likely so there is a need for scientists to look into solutions to mitigate this sort of scenario. 'It's good if the discussion can continue – and if more sophisticated work than ours can be done to provide policymakers with information if and when they need it.'

Another future geoengineering concept could be magma manipulation. In 2015, German researchers demonstrated experimentally that a significant part of the sulfur dissolved in magma is incorporated in the calcium-based, sulfur-bearing mineral anhydrite, which can form in certain magmatic conditions. It essentially acts as a natural sulfur-binding sponge, sucking the sulfur out of the magma and locking it within its crystalline lattice.

That means when the volcano erupts, the sulfur is locked in the anhydrite crystals rather than being released as gas. 'Thus, anhydrite limits the release of sulfur into the atmosphere [and limits the climatic impact of subaerial volcanic eruptions],' says Marcus Nowak, Professor of experimental mineralogy at the Universitaet Tuebingen, Germany. This could also explain why some volcanoes don't release as much sulfur dioxide gas as predicted, he says.

However, Nowak says manipulating the system would not be a feasible geoengineering tool 'either now or in the near future, if ever'. This is largely because of the challenges accessing magma chambers deep beneath the earth's surface where the temperature and pressure is high, making it impossible to change the composition of the magma before an eruption occurs, he says. In addition, the response of the magma chamber to such geoengineering would not be predictable.

Yet geoengineering magma has been considered by NASA. In 2015, the organisation's Jet Propulsion Laboratory considered drilling 10km down inside the US Yellowstone super-volcano and pumping in cold water in order to absorb heat and cool the magma. They believed this would make the magma more viscous and less likely to rise, reducing the risk of an eruption.

The scientists concluded the theory could work with the bonus of superheated water pumped out that could generate electric power. However, it was deemed a non-starter because of the 16,000 year time period needed to sufficiently cool the volcano to a safe level at a cost for the infrastructure of $3.46bn. The scientists also admitted such action could trigger an eruption.

But the potential challenges are not stopping others. Mani points to one project known as Magma Outgassing During Eruptions and Geothermal Exploration. It aims to assess the possibility of manipulating magma to moderate an eruption and has European Research Council funding until 2026. Meanwhile, in 2024, researchers plan to drill into a magma pocket at the Krafla test bed in Iceland to provide a 'long-term magma observatory'. While that project is not specifically for geoengineering, the insights could pave the way for future research.

And that's the point, Cassidy and Mani stress. 'We want to ask the genuine question. Can we do geoengineering? Can we remove sulfur from the atmosphere?' Mani says. 'This question has never been put on the table before. We think we should be having a conversation about this. And such a conversation requires rigorous theoretical and experimental research to underpin it.'

She admits volcano geoengineering is 'blue-sky thinking' and might seem inconceivable, but as Cassidy and she write in *Nature*: 'So did the deflection of asteroids until the formation of NASA's Planetary Defense Coordination Office in 2016.'