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Furious Mountains of Fire –

why climatologists include volcanoes in their calculations

On the evening of 5th April 1815, a loud explosion detonates over the Indonesian island of Sumbawa. Soon thereafter, a jet of fire begins shooting into the sky from the 4,300-metre peak of the Tambora volcano. Avalanches of mud cascade down the mountain flanks, burying everything in their path. But the worst is yet to come: on 10 and 11 April, several gigantic explosions blow the mountain peak to bits. Pyroclastic flows of hot gas and ash gush into the sea, and the surrounding coastal areas are devastated by tsunamis. Huge clouds of ash darken the sky. Eyewitnesses tell of „raging flames and whirlwinds that destroyed nearly every house." The inferno continues until 17 April, then the mountain finally falls silent.

When the „Benares," a ship from the British East India Company, reaches the island the next day, the crew is met with scenes of death and destruction. Thousands have lost their lives in the eruption, while many more will perish in the subsequent weeks and months, as the rain of ash has destroyed harvests and poisoned the drinking water. The explosions have shortened what was once certainly the highest volcano in the archipelago by nearly one and a half kilometres.

However the rest of the world would also suffer in the aftermath of the Tambora eruption. This once-in-a-millennium eruption so completely devastated the climate for a brief period that the year 1816 would go down in European and North American history as the „Year Without a Summer". Southern Germany was inundated by constant rainfall, and snow even fell in late July. The meagre harvests rotted and livestock died or had to be slaughtered due to fodder shortages. Grain prices sky-rocketed. Flour was supplemented with barely edible ingredients and baked into „hunger breads." As he rode through the Rhineland in the spring of 1817, General Carl von Clausewitz wrote: „I saw emaciated, barely human forms, trudging across the fields searching for half-rotten potatoes."

In many countries, hunger and illnesses such as cholera claimed countless victims and contributed to migration, unrest and even resulted in political and social changes. This catastrophe struck the population out of nowhere. People did not recognize any connection to the volcano so far away. Some even began tearing down their lightning rods, blaming them for the bad weather. Mary Shelly is said to have written her novel „Frankenstein" while at Lake Geneva in the summer of 1816, because the rains forced her to stay indoors. In Indonesia alone, up to 100,000 people died as a result of the Tambora eruption, and there were at least that many deaths in other parts of the world. How could this happen?

CONTINENTS ADRIFT

For a long time, the true nature of volcanoes was a complete mystery. Understanding first dawned in the 20th century, when research delved into the earth's interior, revealing that massive forces are at work beneath our feet. The increase in temperature and density from the earth's crust to its core induces gigantic flows of heat and material. Researchers call this circulation „convection," and in it they found the first plausible explanation for the hypothesis of **continental drift**, formulated by Alfred Wegener in 1912: Convection in the earth's mantle is the driving force for the movement of the continents. It also provides a constant supply of liquid rock from the mantle, pressing upward along the **mid-ocean ridge** and forming new crust (see also Geomax 14). This new crust moves laterally in both directions over the earth's mantle like giant plates on a conveyor belt. Mountain ranges can form where two continental plates collide. In contrast, the oceanic plates are swallowed by the earth's mantle again after no more than 200 million years. Volcanic belts form in these **subduction zones**, such as the „Ring of Fire" that encircles the Pacific Ocean. Nearly all of the spectacular eruptions recorded in centuries past have occurred in these especially unstable zones, including both Tambora (1815) and Krakatoa (1883) in Indonesia, as well as Pinatubo (1991) in the Philippines.

To measure the relative size of an eruption, geologists use the **Volcanic Explosivity Index (VEI)**, which spans a scale of 0 to 8. An eruption's size is based on the volume of ejected pyroclastic material and the height of the eruption column. An increase by one index level corresponds to an eruption that is ten times as powerful. The Tambora eruption in 1815 reached an explosivity index of 7. An eruption of this magnitude only occurs every few thousand years.

ARTIFICIAL SUNSHADES

But when does a volcanic eruption affect the earth's climate? And just what effects does it have on the climate? Claudia Timmreck and her colleagues at the Max Planck Institute for Meteorology in Hamburg are investigating questions like this. „Volcanic eruptions are natural climatic experiments," the physicist explains. „They are perfectly suited to investigating how disturbances affect the natural variability of the climate." One of the greatest challenges in climate research is to understand this variability and to distinguish it from climate change caused by humans.

Two factors in particular are critical to the climatic impacts following an eruption: the quantity of sulphur dioxide (SO_2) released and the altitude to which these sulphur-containing gases rise. This is because, although the ejected ash settles back to the earth relatively quickly, sulphur dioxide undergoes photochemical oxidization in the **stratosphere** and combines with water to form droplets of sulphuric acid (H_2SO_4). These **aerosols** not only result in the colourful sunsets that inspired painters like William Turner after the Tambora eruption. „The sulphur aerosols act like an artificial sunshade," says Timmreck. „They disperse the incident sunlight back into space and also absorb thermal radiation from the Earth. This heats up the stratosphere, while cooling the layers of air near the earth's surface, as well as the oceans." **(Fig. A)**

FIG. A: EFFECT OF MAJOR VOLCANIC ERUPTIONS ON THE CLIMATE

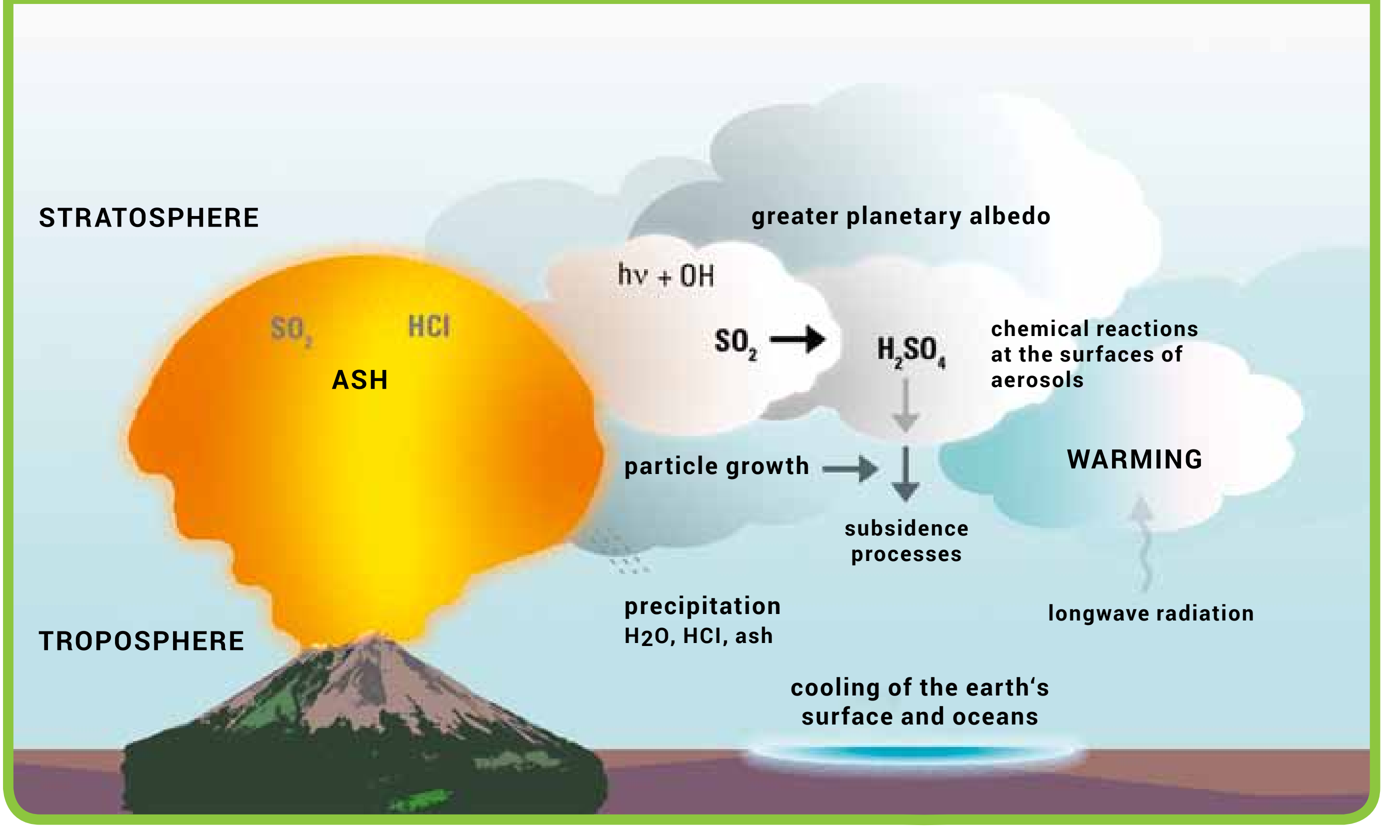
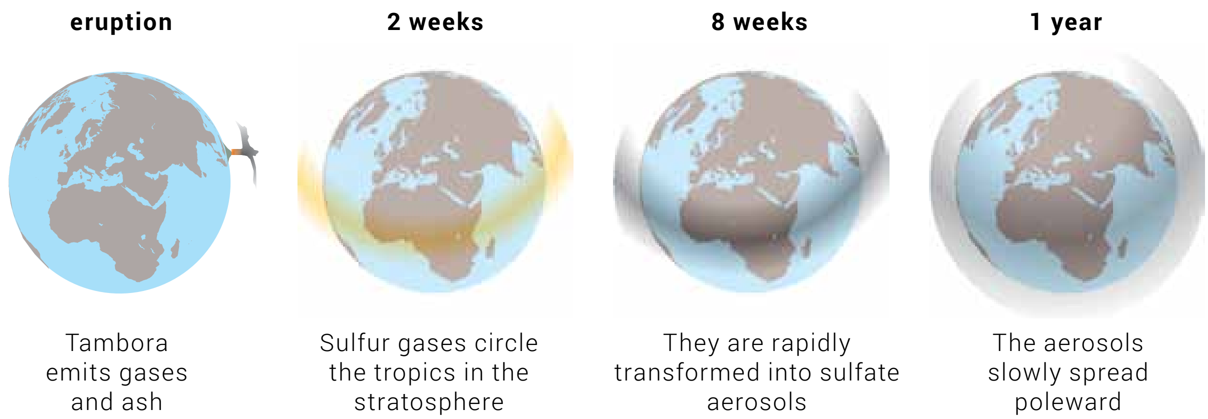


FIG. B: SPREAD OF SULPHUR DIOXIDE AND AEROSOLS FOLLOWING THE TAMBORA ERUPTION



The altitude to which the sulphur particles rise is determined by various factors, including the explosiveness of the eruption and local weather conditions affecting that rise. If the particles reach an altitude of more than twelve kilometres and therefore enter the stratosphere, they can then spread over the entire globe as aerosols over the course of several months and remain there for several years **(Fig. B)**. Major volcanic eruptions near the equator have a particularly large global impact, because their aerosols can drift from there across both the northern and southern hemispheres. In contrast, eruptions close to the poles affect only one hemisphere, regionally limiting the impact on the climate. Because the aerosols spread only gradually at first, the global system experiences a delayed reaction after an eruption. „Maximum cooling is normally reached after six to twelve months. After that, the effect can be observed for several more years," says Timmreck.

Max Planck researchers run computer simulations of both historical and modern eruptions to better understand their effects on the climate. Their goal is to be able to forecast the effects of future eruptions as accurately as possible. For example, what would happen if an eruption like Pinatubo in 1991 were to occur today? The eruption had an explosivity index of 6 and briefly reduced the global surface temperature by an average of 0.5 °C. (For comparison: the global surface temperature was reduced by an average of roughly 1 °C in the Tambora eruption.) This may not seem like much, but it was clearly felt due to the large range of fluctuations in some locations. The eruption also altered atmospheric circulation, and stratospheric ozone concentration was temporarily reduced by up to 50 percent. This is due to various chemical reactions that proceed on the surface of the aerosols, destroying the protective ozone layer. The Pinatubo eruption in 1991 was the most recent volcanic event that had a global impact on the earth's climate. In contrast, although other eruptions were spectacular, they had no climatic significance. This was the case for the eruption of Eyjafjallajökull in Iceland, which paralysed air traffic over Europe in April of 2010. The eruptions of Kilauea in Hawaii and Merapi in Indonesia (both in the spring of 2018) were not relevant for the climate either. Unlike Tambora, no sulphur-containing compounds reached the stratosphere during any of these eruptions.

To simulate a volcanic eruption realistically, the researchers have to supply their computer models with the best, most accurate data on the released quantity of sulphur dioxide. „Nowadays we primarily rely on satellite measurements," says Timmreck. „The on-board sensors determine what is known as extinction, which indicates how much light is absorbed at a certain wavelength. The quantity and size of the particles can then be calculated from this measurement. Research balloons also provide us with data about the size distribution of the particles."

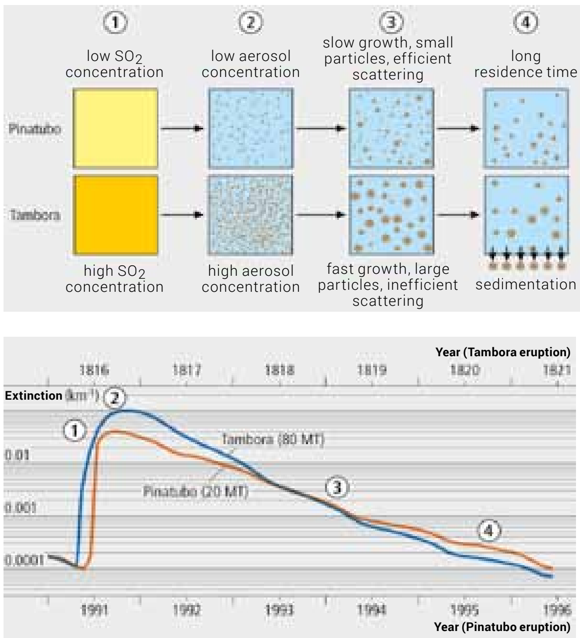
CLIMATE DETECTIVES AT WORK

Measuring past eruptions, however, requires detective work. For this, scientists from various disciplines work together, including meteorologists, geologists and botanists. Climatic development during bygone eras can be deciphered from tree rings: for example, they document when growth was hindered by an extremely cold summer. The researchers determine sulphur dioxide levels based on ice cores drilled from the Arctic and Antarctic. The temperatures of earlier epochs can be reconstructed from the concentrations of water isotopes contained in the cores, and the air trapped in the ice provides information on the composition of the atmosphere. All of this information is archived in practical, chronological order. The deeper the climate chronologists drill, the further they travel back in time, but also the more uncertain and inaccurate their data become.

For example, in preparing their analyses, the researchers have to account for the fact that only a certain percentage of the sulphur dioxide from an eruption in the tropics will reach the poles. „We can estimate this percentage based on the fallout from nuclear tests in the 1960s," says Timmreck. To account for local variations, the scientists always analyse multiple cores from different locations.

The Max Planck researchers in Hamburg are continually receiving new data from their colleagues, which they use to further substantiate and extend their models. By varying different parameters – such as local weather conditions and air currents, or global circulation anomalies like El Niño – and then comparing the results with direct observations, they obtain increasingly realistic estimates of the impact of volcanoes on the climate. The researchers use the high-performance computer at the German Climate

FIG. C: EFFECT OF VOLCANIC AEROSOLS



Top: Number and growth of aerosol particles following Pinatubo and Tambora eruptions. **Bottom**: Comparison of aerosol extinction (= effect on short-wavelength radiation), based on model simulations. The diagram shows conditions at the equator at an altitude of 20 kilometres. The relationship between the concentration of sulphates in the stratosphere and the reduction in short-wavelength radiation is non-linear. A large eruption like Tambora therefore does not have a proportionately larger effect than a smaller eruption like Pinatubo. This is due to the growth of the aerosol particles (top).

Computing Center (DKRZ) for their highly complex simulations. „Using the quantity of sulphur dioxide determined from ice cores, numerical models can be used to determine the global spread and residence time of the volcanic cloud and the associated volcanic **radiative forcing**," says Timmreck. This value is a measure of how factors affecting the climate – such as sulphur aerosols or greenhouse gases – affect the energy balance between the earth and the atmosphere by shifting the equilibrium between incident solar radiation and thermal radiation reflected by the earth. Radiative forcing is expressed in units of Watts per square metre (W/m2). Incidentally, a single volcanic eruption would be nowhere near enough to slow human-induced climate change. „That would take five to seven Pinatubos – every year!" says Timmreck.

However if a „normal" volcano is already enough to affect the global climate, what would be the effect of an index 8 supervolcano eruption, such as occurred roughly 640,000 years ago in the Yellowstone area of Wyoming in the United States? **Supervolcanoes** are extremely large volcanic eruptions that eject more than 1 trillion tons of material – roughly 150 times as much as from Pinatubo in 1991. At that time, the Yellowstone eruption covered large portions of the continent with a layer of ash ten centimetres thick (see also video tips).

„Another factor comes into play for large eruptions that release very large quantities of sulphur dioxide," says Timmreck. „The sulphur particles form clumps, thereby changing their radiation properties. Larger particles are also heavier and fall out of the atmosphere more quickly." This means that the effect of large eruptions on the climate does not increase proportionately with the quantity of sulphur dioxide they release. However, previous models did not account for this and usually overestimated radiative forcing (Fig. C).

Based on this, the Toba eruption in Indonesia 74,000 years ago may also have had less dramatic consequences than previously assumed. According to the so-called Toba catastrophe theory, a majority of the human population living at the time is thought to have perished in the aftermath of the eruption. However, this eruption could not have caused the so-called „genetic bottleneck", i.e. the limited genetic variability among modern humans. In their simulations of the Toba eruption, the climate researchers in Hamburg based their calculations on a quantity of sulphur that is one hundred times that from the Pinatubo eruption. This yielded a maximum global cooling of 3.5 °C. Too little to endanger the continued existence of Homo sapiens – even though life must have been quite unpleasant in many parts of the world over the years following the eruption.

Keywords

aerosols, continental drift, mid-ocean ridge, radiative forcing, stratosphere, subduction zone, supervolcano, Volcanic Explosivity Index

Further reading

- *Hans-Ulrich Schmincke, Vulkanismus, Wissenschaftliche Buchgesellschaft, 2015*

Links

- *Tambora and the „year without summer" 1816*, (in German)
  www.mpg.de/g231 > PDF

Video-Tipps

- *Volcanic eruption simulations*, (in German)
  www.mpg.de/232 > youtube
- *Yellowstone Supervulcano*
  www.mpg.de/g233

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