Limited Climate Response of Very Large Volcanic Eruptions

Extremely large volcanic eruptions have been linked to global climate change, biotic turnover, and, for the Younger Toba Tuff eruption 74,000 years ago, near-extinction of modern humans. One of the largest uncertainties of the estimated climate effects in previous model studies involves the aerosol size distribution. A huge sulfate load causes higher collision rates, larger particle sizes, and rapid fall out, which in turn greatly affects radiative feedbacks. Incorporating aerosol microphysical processes into global model simulations results in a smaller climate effect than estimated before.

1. Climate Response of Large Volcanic Eruptions

One of the great challenges in climate research is to differentiate between natural climate variability and anthropogenic climate change. Therefore it is crucial to understand natural climate variability. Natural variability is evoked by the climate system's internal variations and by external factors such as the variability of solar radiation or large volcanic eruptions. The latter causes large although temporary perturbations in the solar forcing.

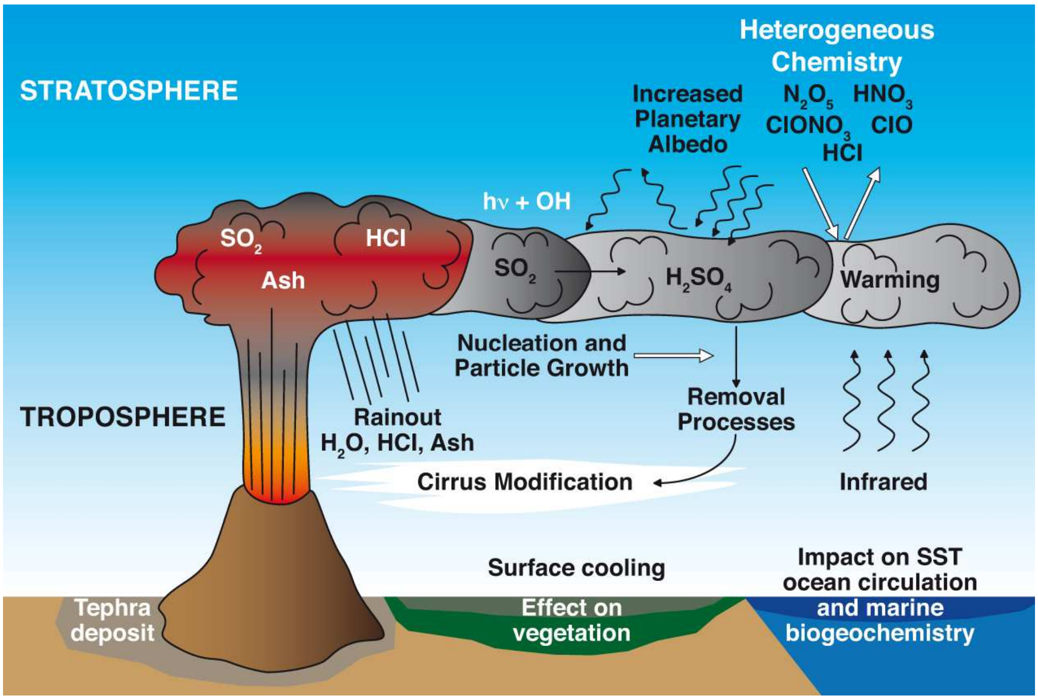

Fig. 1: Schematic overview of the climate response of large volcanic eruptions

Volcanic eruptions can inject great amounts of gases and solid particles (ash) into the upper atmosphere. Due to its size and mass, the volcanic ash rapidly falls out of the atmosphere again. Therefore, the volcanoes' climate response mostly results from the emission of sulfurous gases and the resulting aerosol particles.

Their concentration can exceed the stratospheric background aerosol by several magnitudes. Stratospheric aerosols influence the global climate system in many ways **(Fig. 1)**: By scattering the incoming solar radiation and absorbing the Earth's thermal radiation, they directly influence the radiation. As a consequence, the aerosol-containing layers in the stratosphere warm up whereas the near-ground air layers as well as the ocean cool down. Moreover, heterogenic chemical reactions take place at the surface of the volcanic aerosol particles leading to chlorine activation and thus to the depletion of the ozone layer.

Since the first historical known link between a volcanic eruption (Etna volcano, 44 BC) and a subsequent change by(Plutarch [1]), the climate response of volcanoes have been object of manifold studies, reaching from atmospheric and geological measurements over the analysis of ice cores and proxy data to climate modeling. Direct observations of volcanic aerosols have been existing for only a few decades and basically span two volcanic eruptions affecting our climate – the eruptions of El Chichòn in April 1982 and Pinatubo in June 1991. In the last few years these two eruptions have helped us essentially improve our understanding of how volcanoes affect our climate. But some basic questions regarding the impact of volcanoes on natural climate variability on different time scales (paleontological, historical, decadal) still remain unresolved.

In order to answer these questions and – in particular - to understand the effects of very large volcanic eruptions on our climate and the Earth system, a large crosscutting project called "Super Volcano" was established at the Max Planck Institute for Meteorology (MPI-M) some years ago. This project investigates the effects of very large volcanic eruptions by employing a complex climate model encompassing all relevant areas of our Earth system (Earth System Model).

2. Volcanic Super Eruptions

Extremely large volcanic eruptions emitting more than 10^{15} kg of material (~150 times the quantity of the Pinatubo eruption) are defined as super eruptions [2]. These super eruptions occur with an average frequency of 1.4 events in one million years, though there have been episodes in the Earth's history with a higher frequency. Super eruptions mainly occur in areas of subduction zones and continental hot spots. Active volcanoes which would be capable of producing super eruptions these days, for example, are the Yellowstone Volcanic System and the Phlegraean Fields, situated west of Naples / Italy. Such volcanic super eruptions have utterly devastating consequences for the immediate neighboring areas. So-called pyroclastic flows can cover ten thousands of square kilometers with thick hot ash layers which make life impossible. However, super eruptions do not only have regional effects but can also be responsible for a decrease in the global temperature by several degrees – having far-reaching climatological consequences.

One of the scientifically most interesting super eruptions is the Young Toba Tuff (YTT) eruption 74,000 years ago which is also considered to be the reason for a possible population bottleneck [3]. The degree of global cooling after the YTT, however, is unknown. Previous atmosphere-ocean models [4, 5] have calculated a decadal cooling by more than 10 K in the global mean. But these results do seem contradictory to the high survival rate of mammals in South-East Asia [6].

The climate response of volcanic eruptions is mainly dependent on the amount of stratospheric sulfur emissions. For the YTT, this calculation varies by more than one magnitude (between 10 to 360 times the amount of sulfur emitted during the Pinatubo eruption) [3]. For the calculations that

led to the above-mentioned cooling by 10 K, 100-times the amount of sulfur had been estimated. Besides the quantity of emitted sulfur, the particle size distribution of the resulting volcanic aerosol determines the climate response's strength [7]. If the sulfur concentration in the stratosphere is increased, the particles become larger. These large particles have different radiation properties than the smaller background aerosol particles and fall out of the atmosphere more quickly. This fact directly influences the volcanic radiative forcing. Previous calculations of the YTT climate response did not include the temporal development of the particle size distribution which may be a fundamental reason for a very strong cooling in these previous calculations. In the frame of the Super Volcano project we have taken into account the formation and temporal development of the volcanic aerosol distribution in an Earth System Model (ESM) simulation of the YTT eruption in order to thoroughly examine the effects of the eruption on climate and life [8].

3. Earth System Model Simulation of the Young Toba Tuff Eruption

For the MPI-ESM YTT simulations, a two-step method was applied. As a first step, the formation and development of volcanic aerosol and its optical properties were calculated with an aerosol model, estimating that the initial stratospheric sulfur emission was 850 MT sulfur (100 x Pinatubo). As a second step, the previously calculated volcanic aerosols' radiative forcing was integrated into the MPI-ESM [8].

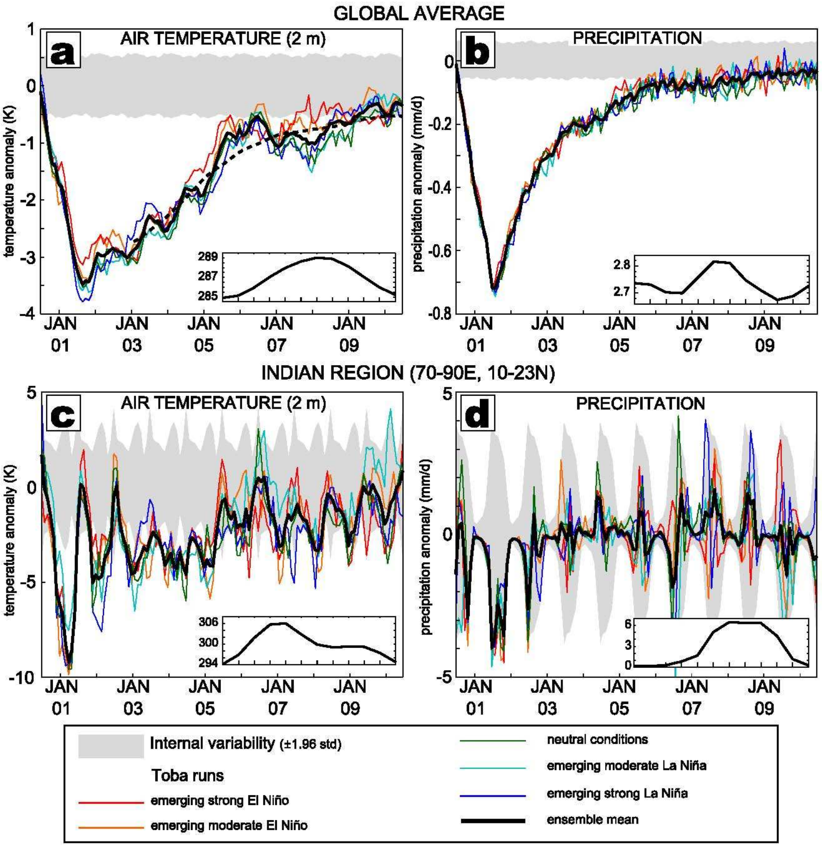

Fig. 2: Mean temperature and (b, d) precipitation anomalies for the globe (figures 2a and 2b) and the Indian region (figures 2c and 2d) for the ensemble mean and individual simulations. The shaded areas denote ±1.96 standard deviations of the control run. The inserts are sketches of the respective climatological annual cycles of the control run. The dashed line in figure 2a depicts a 3-year running average.

The MPI-ESM simulations of the YTT eruptions show a significant decrease in the global surface temperature and the global mean precipitation within the first nine years **(Fig. 2)**. While the spread of the precipitation anomalies is small, the different initial conditions imply a large spread of the temperature signal. The cold ocean surface temperatures tend to prolong the weak negative global mean temperature anomalies to year ten, i. e., beyond the immediate radiative impact. Maximum global mean cooling is −3.5 K, for the ensembles mean, but ranges between 3.8 K and 3.1 K in the individual simulations, depending on the initial conditions.

The development of temperature and precipitation after the YTT eruption is particularly interesting over the Indian subcontinent as paleoarchaeologists are currently controversially discussing to what extent modern humans survived the Toba eruption in India [10]. The MPI-M Earth system model simulations show a distinct temperature decrease over India **(Fig. 2)**, but the absolute temperatures are still in a two-digit range. Strikingly, the summer temperature anomalies in the first two years after the eruption remain in the range of the natural variability and drop significantly only afterwards. The reason for that is a reduced formation of clouds and precipitation within the first two summers which counteract the negative radiant power anomalies as they lead to reduced evaporation and less reflection of solar radiation. After three years, the precipitation anomalies do not differ anymore from the natural variability. Then the radiation-induced cooling becomes the dominating factor again and causes lower summer temperatures in the following years.

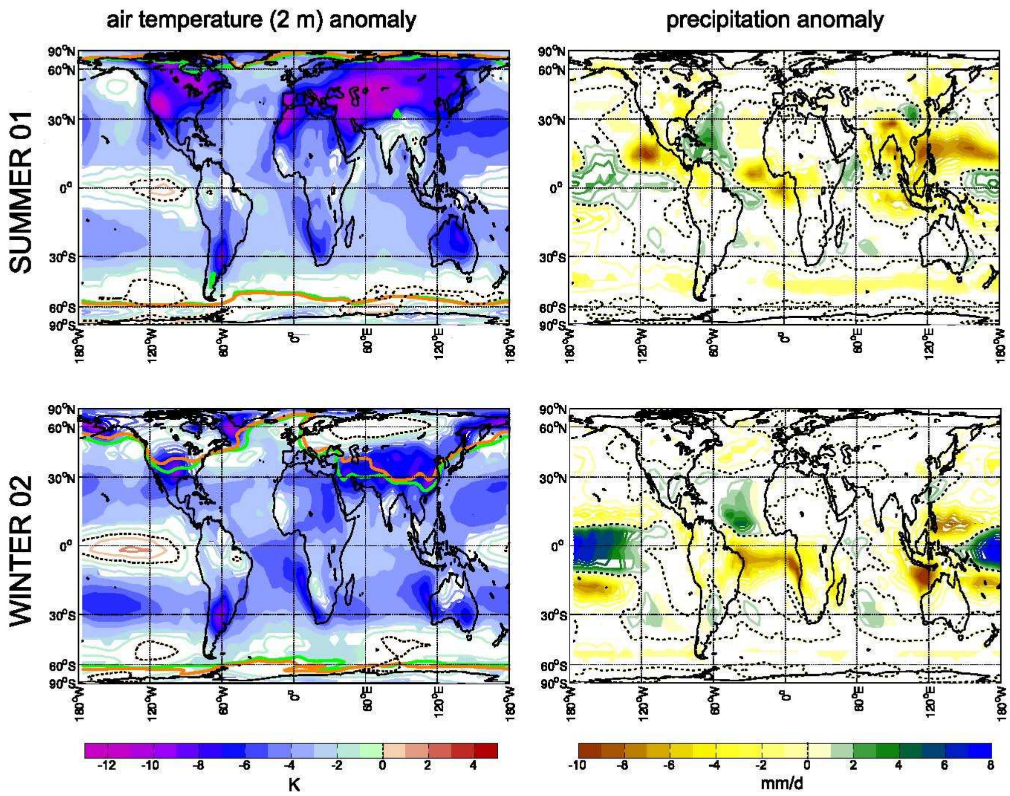

Fig. 3: Temperature (left) and precipitation (right) anomalies for the 1st summer (top) and 2nd winter (bottom) after the eruption for the ensemble mean. The frost line is included (orange for the control climate and green for the simulations). Line (filled) contours individuate regions where the anomaly is within (exceeds) the thresholds of natural variability, defined as the ±1.96 standard deviations evaluated for the control run. Contours are drawn at 1-unit intervals.

Global temperature anomaly patterns indicate that the largest summer temperature anomalies occur one year after the volcanic eruption when a large-scale decrease by more than 6 K with peak values of 12 K can be observed over the Northern hemisphere continents **(Fig. 3)**. Over the tropical ocean, the cooling is generally less severe and depends on the local sea surface temperatures at the time of the eruption. In the tropical Pacific Ocean the natural temperature variability is particularly strong due to the ENSO (El Niño-Southern Oscillation) phenomenon. Positive temperature anomalies over the Northern part of Eurasia can be found during winter. In this region, advection of mild humid air coming from the Atlantic overrides the effect of radiation-induced cooling. This fact was also observed after most historic volcano eruptions. The relatively small shifts of the frost line suggest no severe change in environmental conditions that could induce dramatic global scale alterations in the biosphere. Consistent with temperature changes, precipitation changes are mostly confined to the tropical regions.

The MPI-ESM simulations of the YTT eruption show a strong negative feedback process, which had not been taken into account for earlier calculations of the climate response of extremely large volcanic eruptions. This effect results from aerosol microphysics and concludes that the climate response of very large eruptions is far smaller than previously assumed. With regard to the YTT eruption this implies that most species might have survived the eruption.

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