Importance of satellite-based volcanic aerosol data sets for climate simulations

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The stratospheric aerosol layer is regularly affected by volcanic eruptions, which can enhance its optical depth by several orders of magnitude and lead to a subsequent cooling of the earth surface temperature for several years. The observed upward trend in stratospheric aerosol optical depth over the past decade was mainly driven by a series of small tropical and extra-tropical mid-size eruptions (Volcanic Explosivity Index <4). These played a significant role in the global earth radiative budget with a radiative cooling of as large as -0.1W/m2 which counterbalanced up to 25 percent of global warming that would have otherwise occurred. Overall, the stratospheric aerosol layer is one of the most important natural factors of climate variability at multi-years and decadal scales.

In order to simulate accurately the climate impacts of volcanic eruptions, most global climate and earth system models required a pre-calculated volcanic radiative forcing. Satellite observations have provided almost 3 decades of global stratospheric aerosol extinction measurements from which a radiative forcing term at the top of the atmosphere was derived. The Stratospheric Aerosol and Gas Experiment (SAGE) family of instruments, which represents the longest source of measurements over the last 30 years, terminated in 2005. Herein, we use stratospheric aerosol observations by space-based stellar occultation, lidar and limb-scatter instruments to assemble a continuous and coherent record for the period after the ends of the SAGE II mission. We will present here the process by which this compilation was constructed using SAGE II, GOMOS and CALIPSO observations and how this dataset is being used in climate studies.

Impact of stratospheric volcanic aerosols on the daily temperature range (DTR) in Europe over the past 200 years: observations vs. model simulations

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Explosive tropical volcanic eruptions can affect climate and weather on many timescales and over large areas and are one of the major causes of natural climate variability. The dominant and best understood mechanism through which volcanic eruptions influence climate is the direct radiative perturbation through secondary sulfate aerosols in the stratosphere, enhancing the reflectance of solar radiation and as a consequence leading to a loss of energy at the Earth's surface. The decrease of shortwave radiation on the ground affects the energy balance during daytime only. During the night (and also during the day), even a slight increase in surface net radiation is expected due to the increase in downwelling longwave radiation. Overall, these changes in the energy balance may lead to an overall reduction of the daily temperature range (DTR). Hence, the DTR can be utilized as a quantitative measure of the radiative forcing impact through stratospheric volcanic aerosols.

We analyze this impact over Europe using long-term daily and sub-daily station records. Eight stratospheric volcanic eruptions from the instrumental period (ca. 200 years) are investigated. Seasonal all-sky DTR anomalies after volcanic eruptions are compared to contemporary (ca. 20 year) reference periods. We further use clear-sky DTR anomalies to eliminate cloud effects and better estimate the signal from the direct radiative forcing of the volcanic aerosols. We find a stronger negative signal in the clear-sky DTR anomalies compared to the all-sky case. Although the all-sky and clear-sky anomalies for different stations, volcanic eruptions, and seasons show heterogenic signals in terms of magnitude and sign, the significantly negative DTR anomalies (e.g., for Tambora) are qualitatively consistent with other studies. We quantify the impact on clear-sky DTR through stratospheric volcanic forcing, by applying a weighted linear regression model to clear-sky DTR anomalies and radiative forcing. Our estimate points to a DTR change in the order of magnitude of previously published studies for the 'global dimming' period, however being at the lower end.
This comprehensive observation based analysis quantifies, for the first time, the impact of stratospheric volcanic eruptions on clear-sky DTR over Europe, providing valuable information for geo-engineering purposes. Furthermore, we compare our results from the observations to a modeling framework, repeating the same methodology for a 30-member ensemble of ECHAM5.4 general circulation model simulations.

No persistent North Atlantic Cooling during the Little Ice Age in Paleoclimate Modelling Intercomparison Project 3 Last Millennium Simulations

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Geological evidence collected from Baffin Island in the Eastern Canadian Arctic and Iceland shows sudden and persistent cooling during the descent into the Little Ice Age (LIA), which caused ice caps to grow and remain in their expanded states until the past century. The ice cap expansions are coincident with periods of major volcanic perturbations over the past millennium, begging the question of whether successive volcanic eruptions could have triggered the descent into the LIA. Some specific modeling experiments have shown that it is possible to induce long term cooling given sea ice feedbacks, although the results are sensitive to ocean conditions at the time of eruptions.

Here we analyze the most recent suite of Last Millennium simulations (850-1850 C.E.) from the Paleoclimate Modelling Intercomparison Project 3 (PMIP3) and the Coupled Model Intercomparison Project 5 (CMIP5) to determine if the current state-of-the-art models capture the sudden onset and persistence of the LIA cold period inferred from geological records in the North Atlantic region. We find that snow cover over Baffin Island does not show the sudden expansion as seen in the proxy records. This is likely a result of the models' inability to capture the critical plateau elevations that hold the ice caps. Sea ice expansion is seen in some PMIP3/CMIP5 models after single large eruptions, however none of these models produce significant centennial-scale effects. This is likely caused by biases in the mean climate; average hemispheric temperatures range by more than 3 K between models, while NH sea ice extent is consistently lower in the models than in reconstructions over the past millennium. This has critical consequences on ice and snow persistence in regions such as the Arctic where temperatures are near the freezing point and small temperature changes can induce feedbacks, such as ice-albedo, which could cause dramatic climate changes.

Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate

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Observations and models have shown that continuously degassing volcanoes have a potentially large effect on the natural background aerosol loading and the radiative state of the atmosphere. We use a global aerosol microphysics model to quantify the impact of these volcanic emissions on the cloud albedo radiative forcing under pre-industrial (PI) and present-day (PD) conditions. We find that volcanic degassing increases global annual mean cloud droplet number concentrations by 40% under PI conditions, but by only 10% under PD conditions. Consequently, volcanic degassing causes a global annual mean cloud albedo effect of -1.06 W m^{-2} in the PI era but only -0.56 W m^{-2} in the PD era. This non-equal effect is explained partly by the lower background aerosol concentrations in the PI era, but also because more aerosol particles are produced per unit of volcanic sulphur emission in the PI atmosphere. The higher sensitivity of the PI atmosphere to volcanic emissions has an important consequence for the anthropogenic cloud radiative forcing because the large uncertainty in volcanic emissions translates into an uncertainty in the PI baseline cloud radiative state. Assuming a -50/+100% uncertainty range in the volcanic sulphur flux, we estimate the annual mean anthropogenic cloud albedo forcing to lie between -1.16 W m^{-2} and -0.86 W m^{-2}. Therefore, the volcanically induced uncertainty in the PI baseline cloud radiative state substantially adds to the already large uncertainty in the magnitude of the indirect radiative forcing of climate.

Reference:

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The role of volcanic forcing on northern hemisphere decadal to multidecadal climate variability and future carbon cycle

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Decadal to multidecadal climate variability is an important feature of the observed northern hemisphere climate record. For instance, decadal variations in Atlantic SSTs have been suggested to affect a number of important regional climates, such as North American droughts, summer temperatures in Europe, changes in the monsoon systems and the intensity of hurricanes. In addition, decadal-scale SST variations in the North Pacific, the so-called Pacific Decadal Oscillation (PDO), have been associated with low-frequency changes of climate patterns over North America, Australia and East Asia. The ultimate causes and governing mechanisms for these observed decadal to multidecadal SST variations are not fully understood, although they are likely caused by a combination of changes in forcing, atmospheric and oceanic processes. Here, we present findings from historical simulations with Bergen Climate Model (BCM) covering the last 600 years highlighting the potential important role played by natural and anthropogenic forcing factors in modifying and controlling these patterns. In particular, the results suggest that volcanoes play an important role in decadal SST variations in the Atlantic through their direct radiative forcing on tropical SSTs. In addition, volcanic eruptions tend to strengthen the Northern polar vortex, which in turn forces a positvie response of the so-called North Atlantic Oscillation (NAO) at the surface. A more positive NAO is associated with increased production of intermediate to deep water masses in the high northern sinking regions (i.e. Labrador Sea) and thus leads to a post-volcanic strengthening of the Atlantic thermohaline circulation. In the North Pacific, it is found that volcanic eruptions tend to push the simulated PDO into its cold phase. Finally, idealized simulations are used to assess the potential role of volcanic eruptions on future projection of climate change and its associated carbon cycle feedback. The analysis show that potential future eruptions induce positive feedbacks (i.e., more carbon sink) on both the terrestrial and oceanic carbon cycle.

Deciphering the climatic effects of volcanic aerosols: what will happen when the next Tambora-like event occurs?

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The twentieth century was perhaps unusually free of explosive eruptions that affected highly populated Northern Hemisphere regions, where about 90 percent of global residents live, thus our informed historic perspective on aspects of widespread volcanic-aerosol-induced climatic changes is limited. Because future eruptions will occur that will generate dense aerosol clouds, it will serve society well if we understand the climatic impact of past eruptions. Which eruption type and size should be considered in this regard? What is the most severe climatic impact that we can expect from an eruption? Highly explosive eruptions up to VEI 6 (Krakatau-size, bigger than Pinatubo), with a mean frequency over the past millennium of about 2 per century, cause ash and aerosol clouds that affect global climate, weather, and possibly communications; aerosol-induced cooling is small (less than 1 degree C).

Perhaps VEI 7 explosive eruptions (bigger than Tambora 1815) should concern us more? They are under-reported in the record of past eruptions, with a greater than 10 percent chance of one occurring in the next century. However, the radiative effects of aerosols derived from Tambora's approximately 60 Mt release of sulphur dioxide may have been limited by rapid aerosol droplet growth and sedimentation from the stratosphere; estimates of the hemispheric or global aerosol-induced cooling are quite small (1-2 degrees C). In order to assess what lies in our future, further modelling is required to attempt to isolate the effects of volcanic stratospheric aerosols from the influences of other forcings that lead to climatic variability. This is especially important for the types and sizes of eruptions in the VEI 6-7 range, that have a high likelihood of happening in the next century.

Our society should not be overly concerned about newsworthy but rare super-eruptions (greater than VEI 8); the probability of one occurring in the foreseeable future is negligible and expected climatic impacts may not be as severe as past studies have suggested, but may be prolonged above the usual 2-3 years of cooling and other effects. The magmas typically causing super-eruptions probably have low S contents, meaning that masses of sulphate aerosols may be limited. Positive effects of future eruptions include possible offset of global warming via radiatively effective stratospheric aerosols and ash-fall onto oceans, which may help decrease atmospheric carbon dioxide.

Volcanic eruptions as an analog for geoengineering

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In response to the global warming problem, there has been a recent renewed interest in geoengineering "solutions" involving "solar radiation management" by injecting particles into the stratosphere, brightening clouds or the surface, or blocking sunlight with satellites between the Sun and Earth. This talk addresses stratospheric geoengineering, the topic that has produced the most discussion. While volcanic eruptions have been suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog also argues against geoengineering because of ozone depletion, regional hydrologic responses, and other negative consequences. I will show climate model calculations that evaluate stratospheric geoengineering, and then give volcanic examples that can inform us about their validity. Volcanic eruptions are an imperfect analog, since solar radiation management proposals involve the production of a permanent stratospheric aerosol layer, while volcanic layers are episodic. Nonetheless, we can learn much from the volcanic example about the microphysics of stratospheric sulfate aerosol particles; changes in atmospheric circulation, producing regional climate responses, such as changes to the summer monsoon; atmospheric chemistry; changes of the partitioning of direct and diffuse insolation; effects on satellite remote sensing and terrestrial-based astronomy; and impacts on the carbon cycle. By the way, I now have 26 reasons why geoengineering may be a bad idea, and nine reasons why it might be a good idea. Much more research is needed before we can quantify each of these, so that policymakers in the future can make informed decisions about whether to ever implement stratospheric geoengineering. This research needs to develop additional observational programs to take advantage of future volcanic eruptions to inform us about the potential impacts of geoengineering. Given what we know today, global efforts to reduce anthropogenic emissions and to adapt to climate change are a much better way to address anthropogenic global warming.

Climate forcing by very large basaltic eruptions - Insight from oxygen isotopes of biogenic silica from the finely laminated diatomite of the Fur Formation, Denmark

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The sensitivity of oxygen isotope composition of biogenic minerals to the temperature of seawater invites investigation of possible climate change in periods of extensive volcanic activity by high-resolution studies of suitable stratigraphic sections. Here we present the initial results from a study of the oxygen isotope composition of finely laminated (<0.25 mm - 4 mm) diatomite deposited in direct contact with tephra layers within the Fur Formation, Denmark. More than 200 layers of volcanic tephra of predominantly basaltic composition are exposed in the Fur Formation (Mo-clay), Denmark. The tephra layers are associated with the explosive volcanism following the extensive flood basalt volcanism during continental break up in the North Atlantic.

Historic volcanic events have shown to affect average global temperatures significantly, e.g. 0.5-0.6℃ cooling following the Pinatubo eruption in 1990 and 1℃ drop in northern hemisphere average temperatures in 2-3 years following the Laki eruption in 1783-1784. The climatic effect of the volcanic eruptions associated with the Fur formation is expected to be significantly greater.

In a shallow ligated inland sea as the sea for deposition of the Mo-clay, it is assumed that temperature variations in the sea waters are reflected in the oxygen isotope composition of the diatom silica.

The temperature influence on the oxygen isotope fractionation during formation of the diatom silica is anticipated to give a difference in $\delta^{18}O_{diatom}$ of approx. 0.2 ‰(relative to SMOW) per 1℃ change of temperature with an uncertainty of the temperature coefficient of $\pm$0.05 ‰. However, quantitative paleoclimate applications are indeed limited by uncertainties about the nature and the magnitude of the temperature influence on the oxygen isotope fractionation during formation of the diatom silica.

The average sedimentation rate associated with the deposition of the Mo-clay is prudently estimated to 1 mm/decade. The finely laminated nature of the Mo-clay indicates high-frequency environmental change through time; however it is not believed to be annual rhytmites. This is rather interpreted as multiannual phenomena such as extraordinary external nutrient loading or upwelling of nutrient rich waters with following phytoplankton blooms as a result of tropical rainfall regimes associated with intense storms.

To ensure high resolution climate studies on this 55 Ma old formation a sampling protocol has been designed to enable sampling of layers down to less than 0.1 mm thick and a highly specialized separation protocol including chemical attack, sieving, heavy-liquid separation and ultra sound treatment has been designed to handle sample sizes of down to about 20 mg. Thus obtained samples are expected to represent a resolution of down to 1 year per sample.

Climate and carbon cycle response to the 1815 Tambora volcanic eruption

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The sulphur released by the 1815 Tambora eruption resulted in a global cooling of the earth surface, and is believed to have at least partly caused "the year without summer" in 1816. A series of simulations have been performed using HadGEM2-ES Earth system model to assess the climate and carbon cycle responses to the 1815 Tambora eruption. The model simulates a global mean temperature decrease of 1℃ and reduced precipitation by about 4% the year after the eruption. The northern hemisphere shows generally colder temperatures than the southern hemisphere likely due to the larger continental area in the north. Precipitation patterns are dominated by tropical regions, where a southwards shift in the ITCZ leads to drier than usual conditions north of the Atlantic equator, and wetter conditions in the south. The climatic conditions after the eruption lead to an overall increase in terrestrial net primary productivity (NPP), mainly due to a strong reduction in plant respiration which more than compensates for a reduction in gross primary productivity (GPP). Globally, the land carbon inventory is increased, implying a small drawdown of atmospheric CO_2. The soil carbon pool takes up most of the carbon especially in tropical regions. The results suggest that the carbon uptake in the tropics is caused by increased litter carbon input, with only a small reduction in soil respiration. A carbon sink is found in the northern high latitudes, associated primarily within the vegetation pool. In this region the reduced litter carbon loss is not strong enough to compensate the greatly decreased carbon input from NPP. Looking into the carbon cycle in more detail, to the C3 and C4 plants and crop productivity respectively, the results show globally decreased C4 plant productivity in 1816-18 (though with large regional variability) and more uniform pattern of increased C3 plant productivity for the 1818-22 time period. These findings could improve understanding of crop responses after a large volcanic eruption.

Sulphur yield and climatic impact of the AD 1835 eruption of Cosigüina volcano, Nicaragua

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The January 1835 eruption of Cosigüina volcano, Nicaragua, produced a bulk tephra volume of ~6 km^3 and ranks among the Americas' largest and most explosive historical eruptions. Ice cores from both the Arctic and Antarctica commonly show a prominent sulfate spike near AD 1835, suggesting that the Cosigüina eruption injected ~13 Tg of sulphur into the stratosphere. New electron microprobe data on matrix glasses and melt inclusions reveal that syn-eruptive devolatilisation of the 1835 magma alone released 2.2-3.3 Tg S. Most of the sulphur discharged during the eruption was probably derived from a sulphur-rich gas phase stored in the magma chamber beforehand. Temperature-sensitive tree-ring chronologies indicate significant cooling in 1836 and 1837 due to the eruption. The climatic impact of the Cosigüina eruption was thus likely sizable and comparable to or even larger than that of the 1991 eruption of Pinatubo.

Volcanic and anthropogenic contributions to stratospheric aerosol changes from 2000 to 2009

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Major volcanic explosive eruptions can significantly perturb stratospheric aerosol. However, a persistent background aerosol layer is present in the stratosphere even during periods without large explosive eruptions, as was the case during the last decade. Observational data indicates that the stratospheric aerosol layer was actually increasing during this timeframe. Since variations of the stratospheric aerosol can have long-term climate effects, it is important to understand the underlying causes for such a variation. Two potential sources for this increase have been suggested, namely numerous volcanic eruptions which have occurred during this period, and the growth of anthropogenic SO2 emissions in Asia. We present results from a study which we performed with the global chemical transport model GOCART in conjunction with observations from both satellite-based instruments (OMI, CALIOP, SAGE II) and ground-based lidar data (MPLNET, EARLINET). In our analysis, we assess the relative contributions of volcanic and anthropogenic SO2 emissions to the stratospheric aerosol loading and its variability from 2000 to 2009.