Bicentenary of the Great Tambora Eruption: Implications for Stratosphere-Troposphere Processes

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From 7 to 10 April 2015 an international conference organized by the Oeschger Centre for Climate Change Research and co-funded by SPARC commemorated the 200-year anniversary of the 1815 Tambora eruption. The goal of the conference was to discuss progress in our current understanding of stratosphere-troposphere processes. Around 130 scientists participated in the meeting, including four scientists from Indonesia (**Figure 5**). The conference was interdisciplinary, since the understanding of volcano-induced effects on climate requires a comprehensive 'Earth and human systems' perspective. Consequently, the speakers came from a broad range of different fields encompassing volcanology, atmospheric physics and chemistry, dynamical climatology, paleoclimatology, history, ethnology, and arts.

Three sessions were particularly relevant for the SPARC community (see the Past Global Changes (PAGES) Magazine for a conference summary focusing on palaeoclimatological aspects): the opening session, the session on plumes and volcanic aerosols, and the session on modelling volcanic effects on climate. In this report, we focus on these three sessions and our general understanding of the effect of volcanic aerosols on climate.

From the Earth's Interior to the Stratosphere

In the opening session **Clive Oppenheimer**, **Stephen Self**, and **Adjat Sudradjat** gave an overview of the Tambora eruption processes (Oppenheimer, 2003). During the 1815 eruption about 60Tg of sulfur dioxide (SO_2) were emitted into the stratosphere, where the SO_2 was oxidized to sulfate aerosols (Self *et al.*, 2004; Kandlbauer and Sparks, 2014). In the following session on plumes and volcanic aerosols, **Hans Graf** pointed to difficulties in understanding and modelling the dynamics of volcanic plumes. This is highly relevant as plume dynamics are important for estimating the vertical distribution of SO_2 emissions (Herzog and Graf, 2010). **Alan Robock** summarized what we can learn from volcanic eruptions for assessing geoengineering proposals, including the impacts of stratospheric aerosols on ozone depletion, summer monsoon failures, whiter skies, less solar energy generation, and rapid warming if stratospheric geoengineering were halted. **Susan Solomon** highlighted the role of small eruptions and the importance of considering aerosols in the lowermost stratosphere (see also Ridley *et al.*, 2014). From these presentations, the question emerged whether our current view of volcanic effects on climate is indeed correct or needs to be challenged. Is it really only large, tropical, explosive eruptions that have an effect? That only the SO_2 matters? And that only the large-scale stratospheric meridional circulation controls the aerosol amounts? Transport pathways may be more complex or more direct, smaller eruptions and high latitude eruptions may play a significant role, and even tropospheric eruptions might play a larger role than previously thought (see also Gettleman *et al.*, 2015). Perhaps also ash should be considered in order to comprehensively assess volcanic effects on the climate (**Figure 6**).

Based on the contribution of Hans, the altitude distribution of volcanic emissions is still a major source of uncertainty. One way of determining the vertical distribution of volcanic emissions is inverse modelling of volcanic plumes from satellite imagery. **Petra Seibert** and **Marie Boichu** presented such inverse modelling approaches (Seibert *et al.*, 2011; Boichu *et al.*, 2013). Further presentations in that session addressed the way in which volcanic SO_2 and aerosols can be monitored from space (**Fred Prata**, **Riccardo Biondi**).

While the above-mentioned presentations mostly focused

Figure 5: Participants of the conference "Bicentenary of the Great Tambora Eruption" in Bern, 7-10 April 2015.

on observations, this is hardly possible for eruptions as far back as Tambora, although **Christos Zerefos** demonstrated how paintings of sunsets can be used to estimate aerosol optical depth (Zerefos *et al.*, 2014). **Florian Arfeuille** presented model results suggesting that around two thirds of the stratospheric aerosols were transported to the Southern Hemisphere (Arfeuille *et al.*, 2014), in agreement with new ice core estimates (Sigl *et al.*, 2013). This is interesting in light of the fact that climate proxies from the Southern Hemisphere only show very weak signals of volcanic eruptions, including after Tambora.

Modelling Climate Effects of Volcanic Eruptions

In the session on volcanic eruptions in climate models, **Eduardo Zorita** started with an overview of volcanic effects on the climate system using model simulations of the last millennium. To broaden the view, the shift of the climate from the Medieval Warm Period to the Little Ice Age was also introduced. Modelling volcanic eruptions is not straightforward. Although the decreased short-wave radiation must lead to a cooling, which is more pronounced over land than over oceans, the magnitude and spatial patterns may be difficult to model. Factors such as cloud cover may reinforce or dampen the temperature perturbation induced by volcanic aerosols. The hemispheric or global cooling found in model simulations is often stronger than that found in proxy reconstructions. Still, it remains unclear whether this is due to a model sensitivity that is too large (*e.g.* a misrepresentation or lack of relevant processes in the models) or a proxy sensitivity that is too small (*e.g.* an inadequate selection of potentially less sensitive proxies).

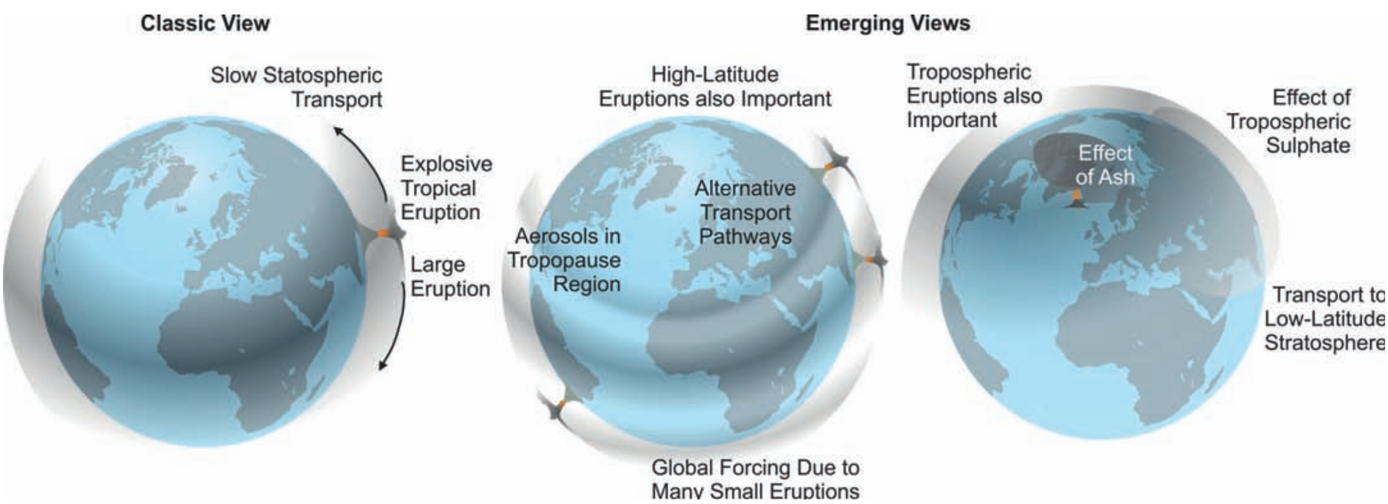

Figure 6: The classic view that only large, tropical volcanic eruptions affect climate perhaps needs to be revised.

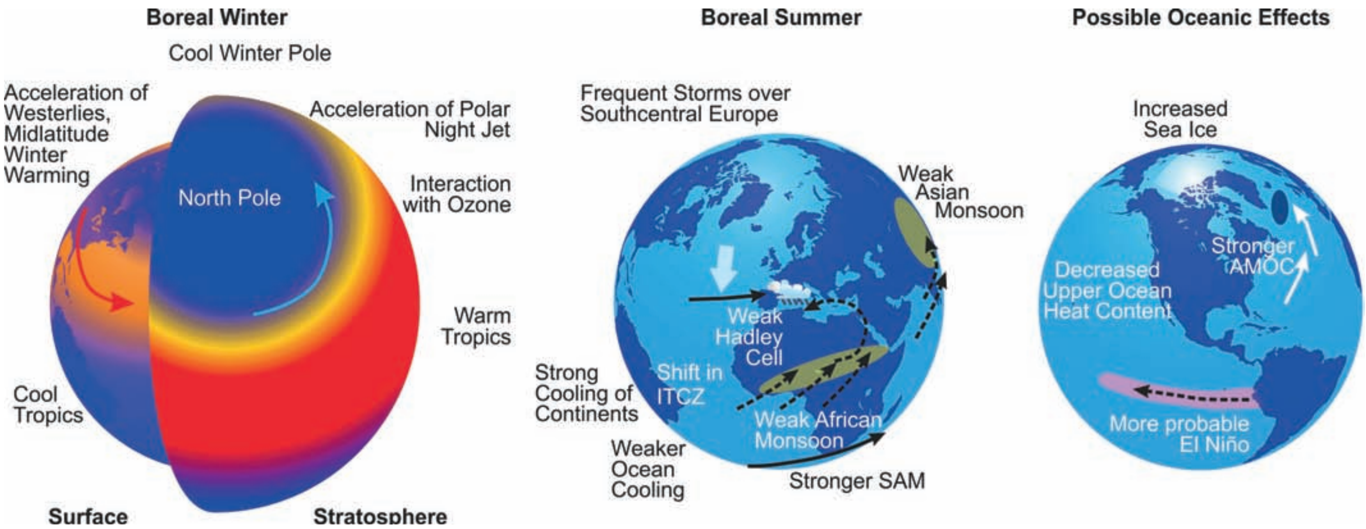

Figure 7: Possible effects of volcanic eruptions on the circulation of the stratosphere and troposphere (left and middle) and on ocean and sea ice (right) discussed at the Bern meeting.

Another focal point was the water cycle response to volcanic eruptions. **Gabi Hegerl** analysed precipitation and temperature in climate model simulations and streamflow in observations. The deceleration of the global water cycle is a direct effect of the decrease in surface net shortwave radiation. Using model simulations of very strong eruptions, **Claudia Timmreck** investigated, amongst other things, volcanic effects on ocean dynamics, the carbon cycle, and marine and terrestrial biogeochemistry. She pointed to the importance of the microphysical treatment of volcanic aerosol size distribution, which is mostly neglected in current modelling exercises (Timmreck, 2011). **Thomas Frölicher** summarized the state of knowledge of the volcanic effect on carbon stocks, highlighting the importance of changes in precipitation, temperature, and diffuse radiation (increasing photosynthesis) for the carbon cycle. The results presented showed that the effect of volcanic eruptions on the carbon cycle is an interesting test of our system understanding and may deliver an additional constraint on Earth system models.

Volcanic eruptions also affect the climate system indirectly through changes in atmospheric circulation. The well-known winter warming that occurs from Central Europe to Russia following tropical volcanic eruptions (**Figure 7**), which is known from direct observations and reconstructions (*e.g.* Fischer *et al.*, 2007), is not well reproduced by climate models. Although the winter warming is primarily induced by changes of the temperature gradient in the stratosphere, the role of the interaction with planetary waves and the role of the background state of the stratosphere need further investigation (Muthers *et al.*, 2014). This indicates that we may not have fully understood all processes. Using model simulations, **Kirstin Krüger** presented evidence that very large explosive volcanic eruptions can lead to a strengthening of the Southern Annular Mode.

The 1815 Tambora eruption was preceded by an unknown eruption that occurred arguably in late 1808 (Guevara-Murua *et al.*, 2014). **Matthew Toohey** presented the effect of such 'double eruptions', which have often been followed by decadal-scale climate anomalies. An interesting conclusion was that two closely spaced eruptions of Tambora-magnitude could have a larger cumulative climate impact than a single very large eruption, perhaps triggering abrupt climate change. One reason for this behaviour is the reduced ocean heat uptake (see Figure 6). Although volcanic eruptions cool the land more than the ocean, the effect on the ocean is longer lasting and may trigger interactions with the ocean circulation. Furthermore, sea-ice increases in model simulations after eruptions and may trigger feedback processes with ocean circulation and salinity. It has been suggested that volcanic eruptions are able to excite El Niño events in the tropical Pacific (Adams *et al.*, 2003) or that they favour a positive mode of the Atlantic Meridional Overturning circulation (AMOC, Stenchikov *et al.*, 2009). **Didier Swingedouw** found in model simulations and observational data from the last millennium that volcanic forcing excites bidecadal variability in the North Atlantic, leading to constructive or destructive interferences for recent volcanoes (last 60 years), potentially explaining two Great Salinity Anomalies as well (Swingedouw *et al.*, 2015).

Because of the stronger cooling of landmasses than the ocean surface, summer monsoons generally weaken in model simulations after volcanic eruptions, including Tambora (Kandlbauer *et al.*, 2013), and the ITCZ may shift to the hemisphere that cools less. Using climate model simulations, **Martin Wegmann** (University of Bern, Switzerland) found that the weakening of the African monsoon and thus of the northern Hadley circulation also weakens the Azores high. This may be the cause for the increased rainfall in south-central Europe after volcanic eruptions due to more convection and a southward shift of the Atlantic storm track (Wegmann *et al.*, 2014).

Learning from Tambora

Have we understood volcanic effects on climate sufficiently well? A brief overview of some proposed volcanic effects on the climate system is given in Figure 7. Understanding them requires understanding stratosphere-troposphere coupling, teleconnections in the atmosphere, ocean-atmosphere-sea-ice interactions, and interactions with the global biogeochemical cycle. Not all of these effects are well understood and some are clearly speculative. Studying the Tambora eruption forces us to consider the entire Earth system and all interactions – as well as the human system, which was discussed in several other sessions. Science has already learned a lot from studying the Tambora eruption, and it will learn more in future.

The conference also addressed future undertakings of the scientific community. To study volcanic effects on climate with a consistent modelling protocol, the VolMIP initiative (Model Intercomparison Project on the climatic response to volcanic forcing) was started and advertised at the meeting. VolMIP is endorsed by CMIP6, the latest Climate Modelling Intercomparison Project. The meeting also showed the links between SPARC and the PAGES, which also co-sponsored the meeting. PAGES co-chair **Hubertus Fischer** explored the interest in the community to engage in a PAGES 'Volcanic Forcing Working Group'. This might open interesting points of contact with SPARC's SSiRC activity (Stratospheric Sulphate and its Role in Climate), again demonstrating the Earth system perspective entailed by the study of volcanic eruptions and perhaps bringing two international projects a little closer together.

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