sc | nat

Geosciences
Platform of the Swiss Academy of Sciences

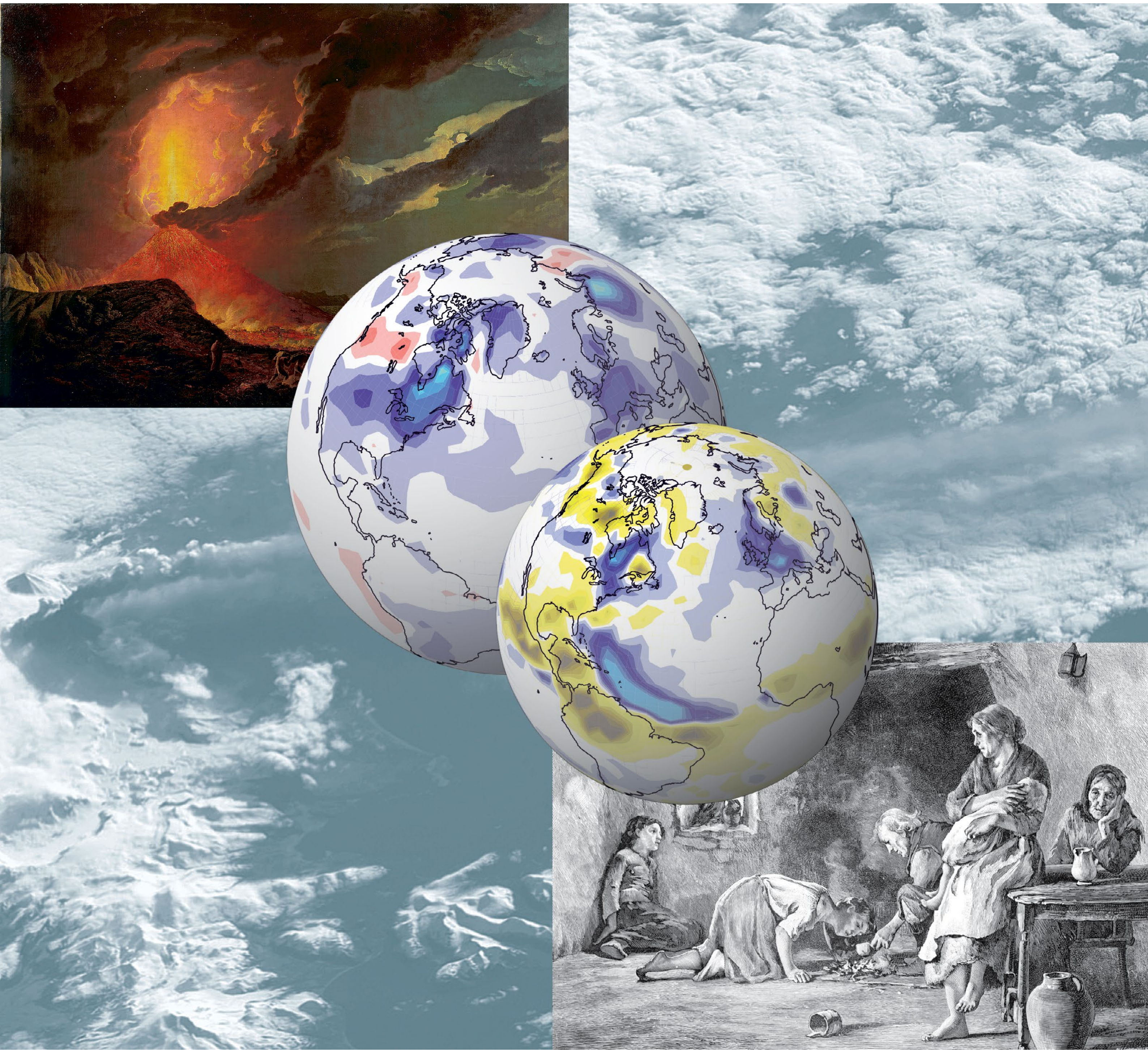
Atmospheric Chemistry and Physics ACP

UNIVERSITÄT BERN

OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

Tambora and the "Year Without a Summer" of 1816

A Perspective on Earth and Human Systems Science



GEOGRAPHICA BERNENSIA

Oeschger Centre for Climate Change Research

Tambora and the “Year Without a Summer” of 1816

A Perspective on Earth and Human Systems Science

Authors and Affiliations:

Stefan Brönnimann, Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland

Daniel Krämer, Oeschger Centre for Climate Change Research and Institute of History, University of Bern, Switzerland

Layout:

Alexander Hermann, Institute of Geography, University of Bern, Switzerland

Photo Editor:

Leonie Villiger, Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland

Language Editing and Translation:

Alena Giesche, Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland

Cover Page:

Top left: "Vesuvius in Eruption, with a view over the Islands in the Bay of Naples", oil painting on canvas by Joseph Wright of Derby (1734–1797), © Tate, London 2016. Middle: Reconstructed anomalies of temperature and precipitation in Jun–Aug 1816 relative to a contemporary reference period (see page 16), from Brönnimann (2015). Bottom right: The Irish famine 1845–1849, artist unknown, from Woodham-Smith C. 1991. *The Great Hunger*. London: Penguin Books, 510 pp. Background: Alaska's Pavlof Volcano: Photo by ISS Crew Earth Observations experiment and Image Science & Analysis Laboratory, Johnson Space Center.

Cite as:

Brönnimann S, Krämer D. 2016. Tambora and the "Year Without a Summer" of 1816. A Perspective on Earth and Human Systems Science. Geographica Bernensia G90, 48 pp., doi:10.4480/GB2016.G90.01.

ISBN: 978-3-905835-46-5

see also German version:
Brönnimann S, Krämer D. 2016. Tambora und das «Jahr ohne Sommer» 1816. Klima, Mensch und Gesellschaft. Geographica Bernensia G90, 48 pp., doi:10.4480/GB2016.G90.02.

ISBN: 978-3-905835-45-8

Printed by Publikation Digital AG, Gerlafingen, Switzerland

Preface

In April 1815, the volcano Tambora in Indonesia erupted, bringing immediate devastation to Sumbawa and the neighbouring islands. The impacts of this eruption were felt around the world for many months. In Europe and North America, 1816 became known as the "Year Without a Summer", and far over 100,000 people died worldwide.

With a certain amount of reserve, a tragic event may become an interesting one. Two hundred years later, in April 2015, numerous events and media reports around the world commemorated the bicentenary of the Tambora eruption. At least half a dozen Tambora books appeared in the years 2013 to 2015, placing the 1815 event as a landmark in the history of mankind. The extensive public attention garnered by these reports demonstrates how interesting this event remains for today's society. Furthermore the topic has an ongoing relevance for science. Many studies and review papers have been published in the last few months, and in April 2015, an international scientific conference organized by the Oeschger Centre for Climate Change Research (OCCR) of the University of Bern was held to shed light on the many interlinked aspects of the Tambora eruption.

The Tambora event is fascinating because it demonstrates how closely the Earth and human systems are connected. While the scientific interest evolves from many specific scientific questions at various interfaces within this system, it is also the "big picture" that matters. The bicentenary of the Tambora eruption 2015 was an opportunity to review our current understanding of the numerous aspects. In this process, the big picture slowly emerges. Now, for the bicentenary of the "Year Without a Summer" of 1816, the picture has become much clearer. The aim of this booklet is to draw this picture and deliver a synthesis of the Tambora eruption and the "Year Without a Summer".

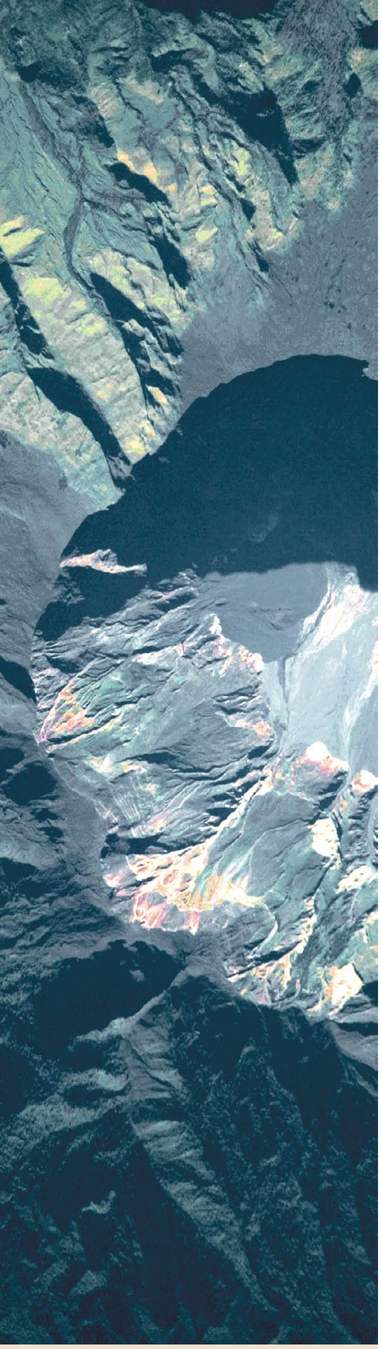
Such an undertaking is necessarily incomplete and only possible with a specific perspective. Here we focus on the perspective from Switzerland. Tambora and the "Year Without a Summer" of 1816 have close links to Switzerland. Switzerland was among the most severely affected regions: severe famine cost countless lives and desperation might have been a trigger for migration. Mary Shelley wrote "Frankenstein" during that rainy and cold summer in Switzerland. The Swiss botanist Heinrich Zollinger was the first to climb Mt. Tambora in 1847 and his report on the 1815 eruption was widely circulated. Ever since 1816, Swiss science took on a leading role in studying the Tambora eruption and the "Year Without a Summer" of 1816; from the first scientific studies on the cold climate in the Alps to the present activities of the Oeschger Centre for Climate Change Research (OCCR) at the University of Bern.

This publication was supported by the OCCR and the commission for Atmospheric Chemistry and Physics (ACP) of the Swiss Academy of Sciences SCNAT. It is the outcome of a conference supported by these two institutions as well as the Swiss National Science Foundation, the international programmes PAGES (Past Global Changes) and SPARC (Stratospheric and Tropospheric Processes and their Role in Climate), and the Fondation Johanna Dürmüller-Bol.[1]

We wish to thank all OCCR affiliated and other researchers who have helped in creating this booklet, particularly Florian Arfeuille, Renate Auchmann, Mauro Bolzern, Philip Brohan, Yuri Brugnara, Ulf Büntgen, Lucien Chabey, Mike Chenoweth, Gilbert Compo, Céline Dizerens, Hubertus Fischer, Simon Flückiger, David Frank, Jörg Franke, Jürg Fuhrer, Alena Giesche, Martin Grosjean, Gertrude Hirsch Hadorn, Alexander Hermann, Annelie Holzkämper, Gerhard Hotz, Fortunat Joos, Abdul Malik, Stefan Muthers, Christian Pfister, Christian Rohr, Karin Schleifer-Stöckli, Margit Schwikowski, Steve Self, Peter Schulthess, Michael Sigl, Willy Tinner, Leonie Villiger, Martin Wegmann, and Helmut Weissert. We also thank all participants of the Bern Conference in April 2015.

Endless rain, clouds, dreariness and cold

The year 1816 is known in Central Europe and in North America as a "Year Without a Summer." Although the link between the climatic event and the eruption of Tambora was made already a century ago, science is only now starting to uncover the many interlinkages between volcanic eruptions, atmospheric processes, climate, biophysical impacts, and societal responses. The 1815 Tambora eruption thus provides an opportunity to review our current understanding of the coupled Earth and human system.



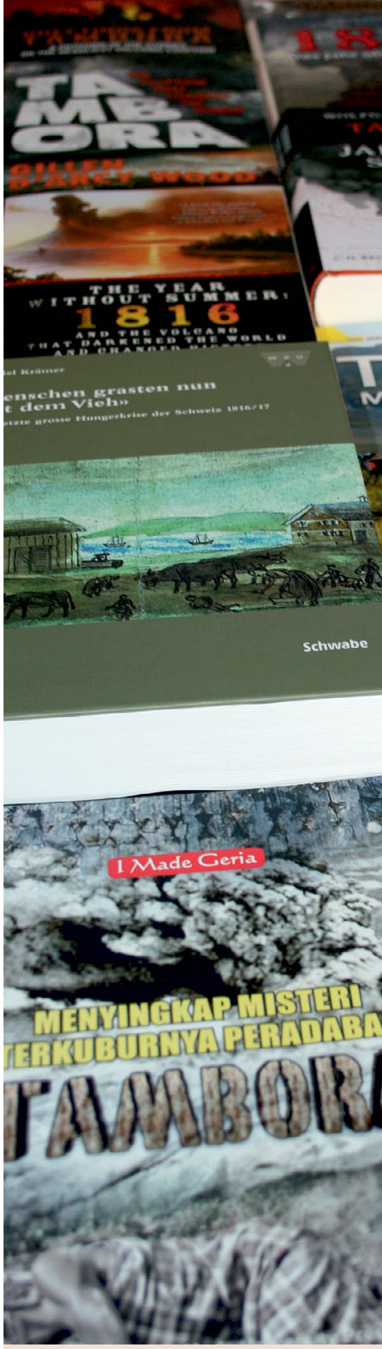
The Tambora caldera and slopes of the volcano today as seen from the International Space Station ISS

Sumbawa is an island of the Lesser Sunda Islands chain with an area of 15,448 km^2 and a population of around 1.39 million. The geology is characterised by a volcanic sedimentary succession of Late Oligocene to Quaternary age, with interbedded marine sedimentary rocks and limestones. The island still has large areas of the natural dry deciduous forest (thorn forest) and conifers at higher altitude. The coastal plains were originally savanna vegetation. The Lesser Sunda Islands are home to many endemic species, particularly birds.

Fig. 1. *Aerial view of the caldera of Tambora as seen today. It is 7 km wide and 1100–1200 m deep and has an ephemeral freshwater lake. A small active vent, called Doro Afi Toi, has formed at its base. The seismic and tectonic activity of the volcano is monitored by the Indonesian Center of Volcanology and Geological Hazard Mitigation (photo by Manuel Marty).*

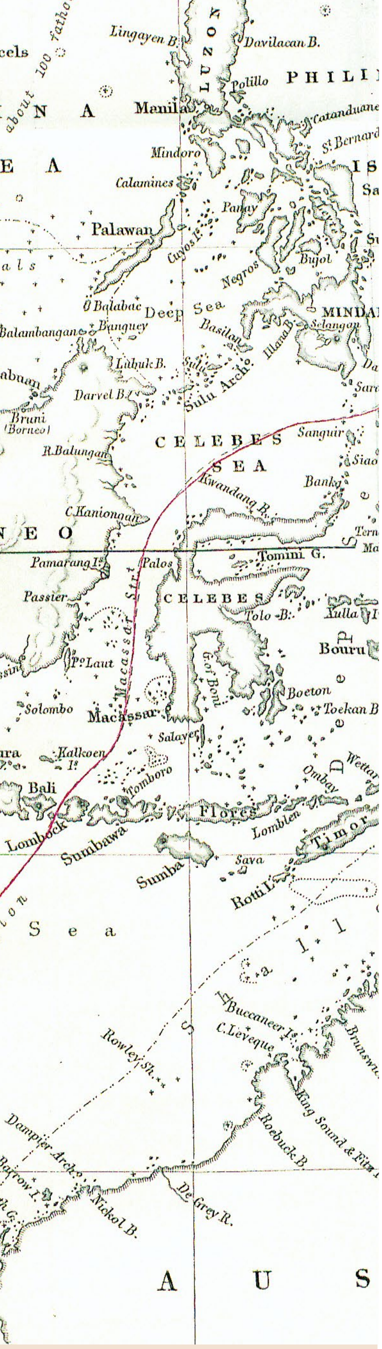
Table of Contents

Introduction	7
The Eruption	8
Box: A Tale of Indonesia and Europe	10
The Tambora Plume in the Stratosphere	12
On the Trail of the Aerosols	14
Climate Anomalies in Proxies	16
Climate Anomalies in Observations	18
Volcano Weather: Anatomy of the “Year Without a Summer” in Central Europe	20
Box: How much of the Cold Summer of 1816 in Switzerland was due to Tambora?	21
Modelled Tambora Climate	22
Indirect Climate Effects	24
Biophysical Effects	26
Crisis in Europe	28
Box: A Climate–Society Interaction Model	30
Can we measure Famine?	32
Riots	34
Box: “Memory of a Friendly Agreement on the Promotion of Hunger in the Year of 1817”	35
Aftermath	36
Culture	38
The Tambora Eruption and Science	40
A Changed World	42
Conclusions	43
Notes and References	44
Image credits of Margin Figures	48



Bicentenary books

The 1815 Tambora eruption and the “Year Without a Summer” of 1816 have seen a considerable amount of media attention in the last two years, and several books have been published in anticipation of the bicentenary. Why are both science and the public so much interested in this? The event is fascinating and frightening, entertaining and instructive. And it is still a formidable research topic.



Map of the Malay Archipelago

The Sunda Islands were relevant for the biogeographical analyses of Alfred Russell Wallace, co-founder of the theory of biological evolution. Wallace drew a line between the zoogeographical regions of Asia and Australia, which passes between Lombok and Bali (the picture shows the original drawing of the line from Wallace's 1863 paper)[4].

Mt. Tambora is one of only few landmarks on this map. Wallace's very successful 1869 book "The Malay Archipelago"[5] gives an account of the physical and human geography, volcanoes (including the 1815 Tambora eruption), and the distribution and variety of plant and animal life on the archipelago.

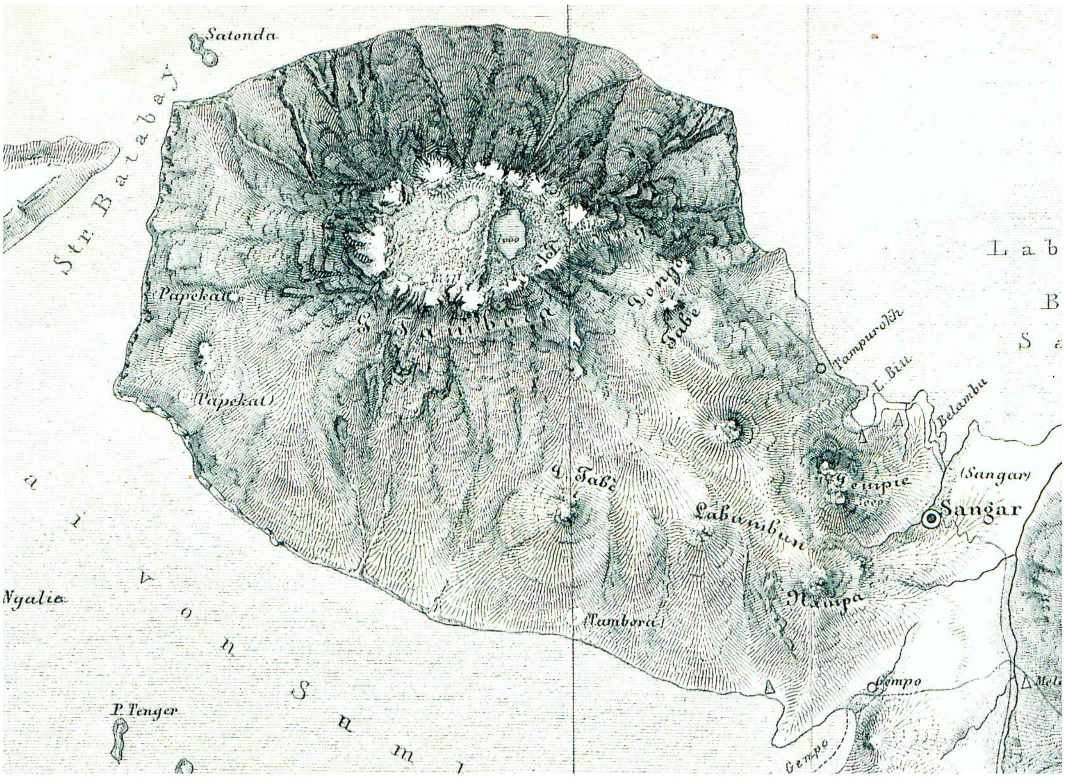


Fig. 2. *In 1847, Swiss botanist Heinrich Zollinger travelled Sumbawa and climbed Mt.Tambora. He found a large caldera with two lakes in it (the map is taken from his publication)*[2]*. Zollinger gave an extensive account of the Tambora eruption. In fact, many widely reported descriptions about the eruption go back to his work. Note the deserted settlements or ruins indicated with brackets, some of which were newly founded in a different location (Sangar, Papekat, Tambora). In fact, even away from the immediate zone of devastation, most settlements were founded after 1815 as the entire island was largely depopulated after the eruption. Interestingly, Zollinger already described the biogeographical division that later became known as the Wallace line (see figure on the left).*[3]

Introduction

Few natural events affect humanity at the global scale. One such event in relatively recent history was the eruption of Mt. Tambora (in Indonesian: Gunung Tambora or Tomboro) 200 years ago.[6,7,8] The eruption of this large volcano on the Indonesian island of Sumbawa in April 1815 was indeed devastating. Tens of thousands of people died, three local cultures vanished.[9] However, its effects were even more widespread. Global temperatures dropped significantly, making 1816 probably the coldest year of the last 250 years.[10] Monsoon precipitation decreased, causing droughts worldwide. Even more remote areas experienced a change in climate. Among the regions particularly strongly affected by the eruption were Central Europe and North America. In both regions, the summer of 1816 was much cooler than normal. The New England states experienced snowstorms as late as June.[11] Central and Western Europe suffered from endless rain, while the Iberian Peninsula was plagued by a drought.[12] The reduction in harvest yield in Europe contributed to the "last great subsistence crisis in the western world,"[13] the reactions to which were far-reaching. Some authors have gone even further, linking riots, a cholera pandemic, the precondition for drug cultivation in the Golden Triangle, economic crises in the USA and the formation of the welfare state to the Tambora eruption.[14,15] However, other socio-economic factors were already at play in Europe: The Enlightenment, proto-industrialization, war, and political changes had transformed societies in the years preceding the crisis and changes were ongoing. In any case, when the aftermath of the eruption was finally over, the world was no longer the same. Sumbawa never quite recovered from the eruption, and lives in Europe, North America, and China had changed substantially.

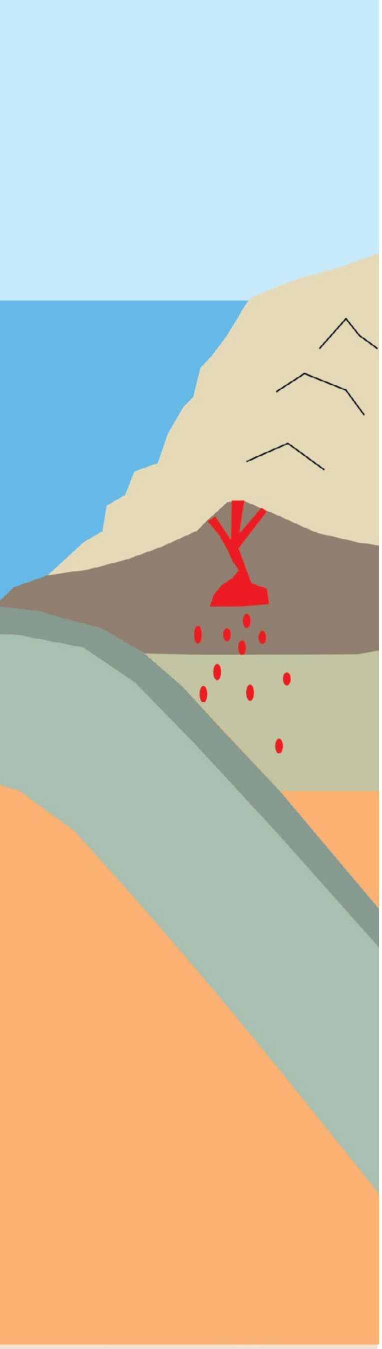
Today, the Tambora eruption still attracts the interest of scientists. Interactions in the Earth and human system can be studied exemplarily. Even after 200 years, revisiting the Tambora eruption is a challenge that continually reveals new and surprising results. Studying its climatic effects forces science to take an Earth system perspective that includes all branches of sciences; from volcanology to stratospheric chemistry, from aerosol microphysics to atmospheric dynamics. It forces scientists to combine different methods ranging from tree ring reconstructions to numerical modelling. The biophysical impacts require expertise from biologists and agronomists. Conversely, studying the effetcs on humans and society calls for historical methods as well as economic perspectives and knowledge from anthropologists and cultural scientists is needed. The real challenge, then, is to connect these approaches In view of many of the problems the world is currently facing, a combined Earth and human systems perspective such as inspired by the 1815 Tambora eruption is a highly topical approach.

A summary of the state of science on the 1815 Tambora eruption and the "Year Without a Summer" of 1816 was given in 1992 by Harington.[16] A large number of studies have been performed since that time, and very interesting aspects have come to light within the last few years. With the bicentenary of the eruption in 2015, a new opportunity to compile the big picture arose. An international conference brought together researchers from natural sciences and arts, and a review paper from that conference summarized the state of knowledge on the individual aspects of the eruption and its effects.[17] This booklet goes one step further by combining these individual perspectives into a comprehensive overview. Using Switzerland as a focus region, we pin down the Earth and human systems interaction, and, in the process, sketch the way in which scientific progress is achieved.

The Eruption of Mt. Pinatubo (Philippines) in June 1991 as seen from the Clark Air Base

Much of our current knowledge on climate effects of volcanic eruptions stems from the observation and analysis of the 1991 Pinatubo eruption, which occurred at a time when several satellites measuring gases and aerosols were in space and stratospheric model capabilities were available.

Studies of the 1815 Tambora eruption provide another rich source of information and inspiration for science, as the Tambora eruption was 3–4 times stronger, climate effects were larger, and societies were more vulnerable or vulnerable in a different way than today's societies.



The Eruption

Along the Sunda Trench south of Indonesia, the heavy Indo-Australian plate is subducting under the lighter Sunda Plate forming the Sunda Volcanic Arc. Indonesia has 147 volcanoes, of which 76 are historically active (i.e., have documented eruptions). Mt. Tambora is one of these volcanoes. It was a typical stratovolcano with a symmetrical volcanic cone and a single central vent. Even though it had been historically active Tambora was silent for more than 400 years before the eruption in 1815.

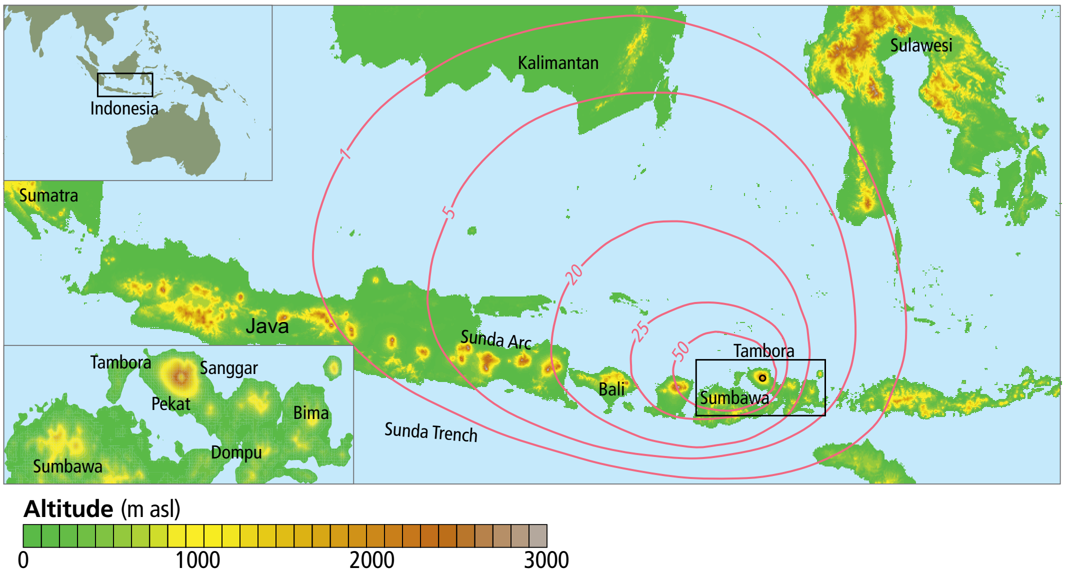


Fig. 3. *Map of Indonesia showing the location of Tambora and the thickness of ash deposits (in cm, from Self et al. 1984)*[18]*. The inset shows the six kingdoms that existed on Sumbawa prior to the eruption.*

Starting in 1812, the first signs of volcanic activity were noticed by the local population. Ash clouds were observed, but no eruptions followed. Then, on 5 April 1815, the volcano started erupting. The first, already violent eruption phase lasted 5 days and emitted large amounts of ash. It was accompanied by lahars (mudflows composed of volcanic ash, debris, and water). However, the main eruption phase was yet to come. On April 10th and 11th, Mt. Tambora literally exploded. This eruption phase generated large, devastating pyroclastic flows (fast-moving currents of hot gas and solid matter from the eruption column down the volcano slopes).[19] The explosions were heard in the entire archipelago, at places more than 1700, reportedly even 2600 km away. Within these one to two days, about 50 km^3 equivalent of dense rock material was ejected. Ash and tephra deposits covered large regions (Fig. 3), including Kalimantan, Java, and Sulawesi. This is known from contemporary reports as well as sediment cores.[20,21,22]

After April 11th, the eruption intensity decreased and came to an end on April 17th. What was once arguably the highest mountain of the archipelago was now a topless cone. The top third of Mt. Tambora had been blown away. The 1815 eruption of Tambora left a caldera of 7 km diameter and 1100–1200 m depth[23] (Figs. 1 and 2).

The 1815 Tambora eruption in numbers

Latitude	8.25° S
Longitude	117.95° E
Altitude before eruption	ca. 4300 m
Present Altitude	2850 m
Eruption Duration	Apr 5th–11th
Ejected volume	50 km^3
Amount of SO_2 injected	60–80 Mt
Volcanic Explosivity	Index 7 (out of 8)
Max. plume height	43 km
Neutral buoyancy height	23–27 km
Sound heard	2600 km
Death toll in Indonesia	~100,000
Death toll globally	100–200,000

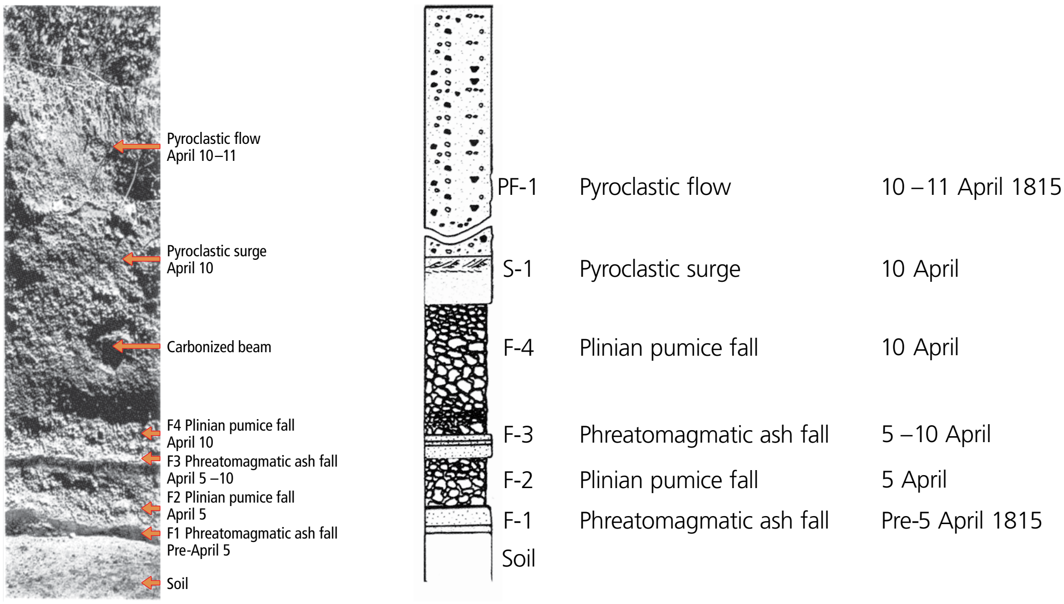


Fig. 4. *A stratigraphic column of volcanic deposits near Tambora village on the Sanggar Peninsula (from Sudrajat and Rachmat, 2015)*[24].

Today, volcanic deposits from the 1815 eruption cover the entire Sanggar Peninsula (see Fig. 3). The deposits of the 1815 eruption consist of interlayered sequences of lava and pyroclastic materials, sometimes several meters thick. A stratigraphy of deposits near Tambora village[25] is shown in Figure 4 (see also photograph on the right). The lower layers correspond to the first eruption phase and consist of ash and pumice. This layer is 40–150 cm thick. It is covered with pyroclastic deposits from the main eruption phase on 10 and 11 April, which is 1–4 m thick. At the caldera rim, the 1815 deposits are even up to 40–140 m thick. In addition to pyroclastic fall, pyroclastic flows, and lahars, Tsunamis (triggered by the pyroclastic flows into the sea) devastated the island's coasts. After the eruption had ended and the magma chamber had emptied, parts of the Sanggar Peninsula subsided. The combination of these processes reshaped the landscape of the Sanggar Peninsula.

For the local population, apparently unfamiliar with the dangers of large eruptions and with no alternatives, the eruption resulted in a humanitarian catastrophe.[26] For most people living on the peninsula, there was no escape. The three kingdoms Tambora, Sanggar and Pekat on the Sanggar Peninsula (see Fig. 3) vanished. Thousands of people died immediately during the eruption, tens of thousands in the following weeks and months as the ash fall destroyed agricultural production and poisoned the drinking water by changing the acidity and due to its fluoride content. A year later, half of the population on Sumbawa was dead, most of the other half had migrated to the neighbouring islands. But also on the islands Lombok and Bali, thousands died, and in their desperation many ended in slavery.[27] In total, an estimated 90,000 to 117,000 people died on the main islands of Indonesia due to the Tambora eruption.[28] Perhaps a similar number of people died globally in the aftermath of the eruption from famine and diseases, although one should be careful in attributing deaths solely to the Tambora eruption.

Deposits of the 1815 Tambora eruption cover large areas of the Sanggar Peninsula

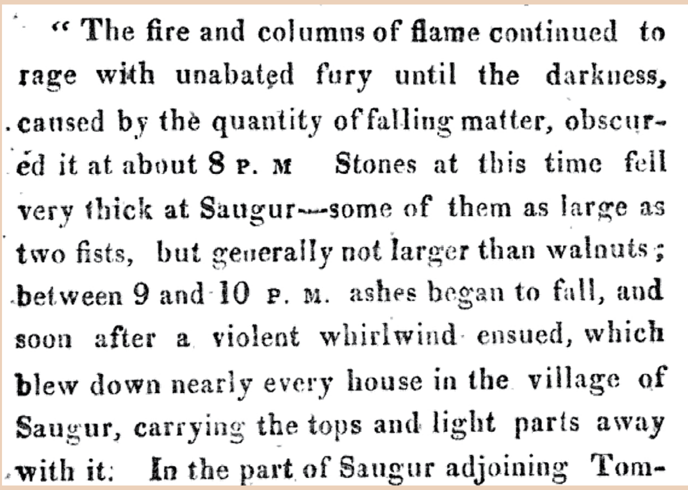
The lava flows and pyroclastic flows only spared some stripes on the southern slope of the mountain, where ancient lava flows blocked their way. This is probably the reason why the Raja of Sanggar and few of his family and entourage survived fleeing south.

Photo: Deposits of the 1815 eruption on the northwestern flank of Tambora: alternating layers of pumice and ash fall deposits are overlain by pyroclastic flow deposits.[29]

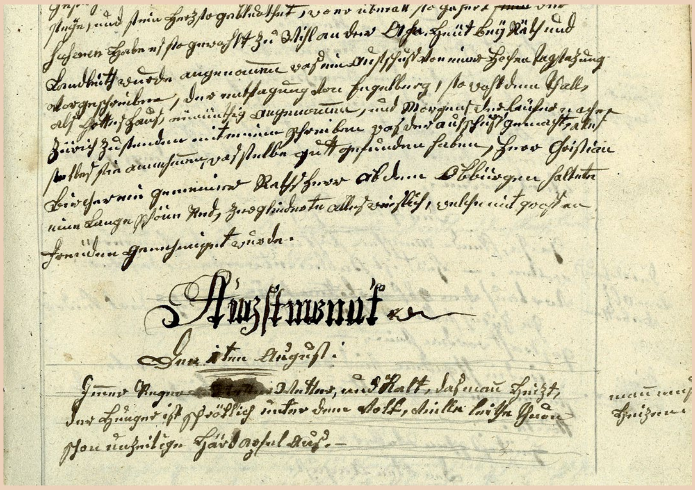
A Tale of Indonesia and Europe

Tambora affected the skies over Indonesia and Europe. Two paintings by William Turner showing (left) an eruption of Vesuvius (engraved by T. Jeavons, 1830, photo Tate, London 2016) and (right) a colourful sunset in the painting "Fighting Temeraire" from 1838, (photo National Gallery, London). Although most sunset paintings from Turner date to later, he is said to have been influenced by the intense colours of the sunsets experienced after the Tambora eruption.

The Tambora eruption in 1815 devastated the Island of Sumbawa on **Indonesia** and affected the global atmosphere. Ash clouds rose to the sky above Sumbawa and completely darkened the sky for days. While the ash settled after a few days, the gaseous emissions of Tambora continued to affect the sky globally. Sulphate aerosol particles formed from these gases and resided in the stratosphere for two to three years. They led to colourful sunsets around the worlds that inspired the romantic painters in **Europe** such as William Turner (1775–1851, see also Section "On the Trail of the Aerosols"). Though fascinated by volcanic eruptions (left), Turner was most likely not aware that he painted "volcanic skies" for many years (right) after having been inspired by colourful sunsets in 1817–1818.



" The fire and columns of flame continued to rage with unabated fury until the darkness, caused by the quantity of falling matter, obscured it at about 8 P. M Stones at this time fell very thick at Saugur—some of them as large as two fists, but generally not larger than walnuts; between 9 and 10 P. M. ashes began to fall, and soon after a violent whirlwind ensued, which blew down nearly every house in the village of Saugur, carrying the tops and light parts away with it. In the part of Saugur adjoining Tom-



The consequences of the 1815 eruption worried people in Indonesia and Europe. Eyewitness accounts as collected in Raffles' report (left)[30], speaking of flames that rage with unabated fury and whirlwinds that blew down nearly every house, and the page for August 1st, 1816, from the diary of Martin Obersteg in Switzerland (right), who mentions that one had to heat the houses in the middle of summer (Staatsarchiv Nidwalden).

The volcanic eruption in **Indonesia** must have been enormous. However, only very few people (out of a population of about 10,000 on the Sanggar peninsula) survived to provide eyewitness reports. The "Benares", a ship of the British East India Company that was anchored in Sulawesi, travelled south after explosions were heard on April 10th. The ship almost sank because of the heavy ash fall. After encountering a local sailing ship, whose crew reported the eruption that they had seen from the sea, the crew of the Benares decided to land in Sumbawa. When they arrived on 18 April, they saw complete devastation. Meanwhile in Java, explosions were heard and anxiety rose. Sir Thomas Stamford Raffles, the governor on the island for the British (who had taken over the archipelago shortly before from the Dutch), was deeply worried. He ordered a ship to be loaded with rice and water (which some call one of the first planned "disaster relief activities") and sent it eastward from Java. On Sumbawa, Lieutenant Owen Phillips, who commanded the ship, met the Raja of Sanggar, who luckily survived the eruption fleeing southward. His report was collected by Owen Phillips and remains the only eyewitness report from the immediate vicinity. Raffles commissioned a report on all accounts on the eruption and its consequences. This report was presented to the Batavian Society for Arts and Sciences in September 1815 and subsequently published. Raffles' report[31] (p. 10, left) reached Europe a few months later. Excerpts were printed widely in European newspapers.

One year later and 15,000 km away, central **Europe** suffered from a particularly cold and rainy summer. Desperate farmers struggled to survive. Life in Europe had been troubled due to the Coalition Wars. Now the constant rains and snow in early summer, no hay and the prospect of a very poor harvest threatened the very existence of many. Numerous meticulous diaries (p. 10, right) and other sources give a voice to these people and provide insight into the fears and challenges faced by them. Today we know that the rainy weather in Europe was partly a consequence of the eruption. However, the two events were not linked at that time, and the causes of the climatic anomalies in Europe would remain unknown for another century.[32]

Tambora caused death in Indonesia and Europe. Skeleton excavated in Sumbawa (left, photo by Rik Stoetman), "hunger bread" in Europe (right, photo by P. Portner, Historisches Museum Basel).

Tens of thousands of people died in **Indonesia** during the eruption and in the following months, as the ash fall destroyed crops and poisoned the drinking water. However, until 10 years ago, no bodies had been excavated. In 2004, Igan Sutawidjaja from the Center of volcanology in Bandung, Indonesia, and Haraldur Sigurdsson from the University of Rhode Island, USA, discovered two skeletons (left) and excavated several houses. Similar to the Vesuvius eruption of 79 AD, the victims seem to have been caught by surprise – one of the persons was presumably killed while preparing dinner. The authors therefore called the site the "Pompeji of the east".

In **Europe**, the cold and rainy summers indeed led to poor harvests, which was one of the factors causing famine and the last subsistence crisis of the western world. Breads became smaller and barely edible ingredients were mixed into the flour. These "hunger breads" were sold at extremely high prices (right). Malnutrition and diseases caused numerous deaths and contributed to migration, riots, political and social changes. Skeletons and hunger breads remain the silent witnesses of disaster brought about by the 1815 Tambora eruption both in Indonesia and in Europe.

Two hundred years later, many events in **Indonesia** and in **Europe** commemorated the 1815 Tambora eruption and its consequences. An international conference on the occasion of the bicentenary was held in Bern, Switzerland, 7–10 April 2015 (bottom). Scientists from all over the world gathered to share their knowledge in order to better understand the 1815 Tambora eruption and its consequences.

At the occasion of the Bern Meeting on the Bicentenary of the Great Tambora Eruption, Adjat Sudrajat from the Padjadjaran University, Bandung, Indonesia, presents a shirt to Stefan Brönnimann from the Oeschger Centre and Institute of Geography of the University of Bern, Switzerland (photo by Céline Dizerens).

The Calbuco volcano eruption plume near Puerto Montt (Chile) on 22 April 2015

Volcanic plumes rise mainly because of buoyancy. Once a hot mixture of lava, ash, air, water vapour and other gases has separated from the solid fraction, the hot (several hundred °C) plume can rise to the stratosphere. On its way up, some of the surrounding air is entrained, further fuelling the plume with water vapour.

The dynamics of volcanic plumes are complex and still not fully understood, yet this would be important for constraining the subsequent global spreading of sulphate aerosols and thus climate effects.

The Tambora Plume in the Stratosphere

The effects of the Tambora eruption reached much farther than the Indonesian archipelago. To understand Tambora's global climatic effect, we need to consider the processes taking place in a volcanic plume. It is not the impressive eruption column that we know from pictures of current eruptions that is climatically relevant, but instead it is the invisible part of the plume: the sulphur gases. The most relevant factor for global climatic impacts is the amount of sulphur reaching the stratosphere (atmospheric layer 10–50 km above the Earth's surface, the layer below is the troposphere), where such gases can remain for several years and distribute globally (for that reason, tropospheric eruptions such as the 2010 eruption of Eyjafjallajökull have a much smaller and more regional climate effect).

Tambora emitted ca. 60–80 megatons of SO_2 (sulphur dioxide) to the stratosphere.[33] This is 3–4 times as much as during the 1991 eruption of Mt. Pinatubo on the Philippines – the biggest eruption of the 20th century. In the stratosphere, the SO_2 spread across the tropics, circled the globe and was oxidized within weeks to form H_2SO_4, a substance that condenses to tiny droplets called sulphate aerosols (Fig. 5). These aerosols dimmed the sunlight and were the primary cause of the global climatic effects that followed.

One topic that scientists try to understand is the eruption height and the spreading of the aerosol cloud for the case of the Tambora eruption. Both are crucial for modelling the subsequent climate effects. Ash and tephra deposits (see Fig. 3) have been used in the past to estimate the eruption column height. A column height of 43 km has been reported for the Tambora eruption in 1815 based on the distribution of deposits[34,35] and this number is widely cited in the literature. The number might capture the overshoot height of the plume, hence, the maximum height reached during the eruption process. However, this height is not of much relevance for understanding the altitude distribution of SO_2 in the atmosphere.[36] Contrary to intuition, it is not the kinetic energy of the explosion that is the main factor determining the height at which most of the SO_2 is injected into the stratosphere, but rather buoyancy. The so-called neutral buoyancy height is therefore a better measure of the altitude of the SO_2 layer. Furthermore, the fact that the total eruption plume is the product of several individual plumes from different phases of the eruption needs to be taken into account. Often it is not the initial plume (called Plinian plume) that matters most. This plume is often too dense and collapses, forming pyroclastic flows. The secondary plumes rising from these pyroclastic flows, called "Phoenix plumes", are less dense and can also rise into the stratosphere. However, reconstructing that process for Tambora is very challenging.

Likewise, the reconstruction of the horizontal transport of Tambora aerosols is not straightforward. With the equatorial lower stratospheric winds (which are either easterly or westerly, but always close to zonal) the stratospheric volcanic cloud will circle the globe within 2–4 weeks (Fig. 5). This was first observed after the Krakatoa eruption in 1883. Textbook knowledge implies that the meridional circulation of the stratosphere will transport the aerosols of tropical volcanic eruptions towards the Polar Regions, but this circulation is much slower than the zonal circulation, such that it takes 2–5 years for an air parcel to travel from the tropical tropopause to the polar region (Fig. 5). It is not clear how efficient other transport

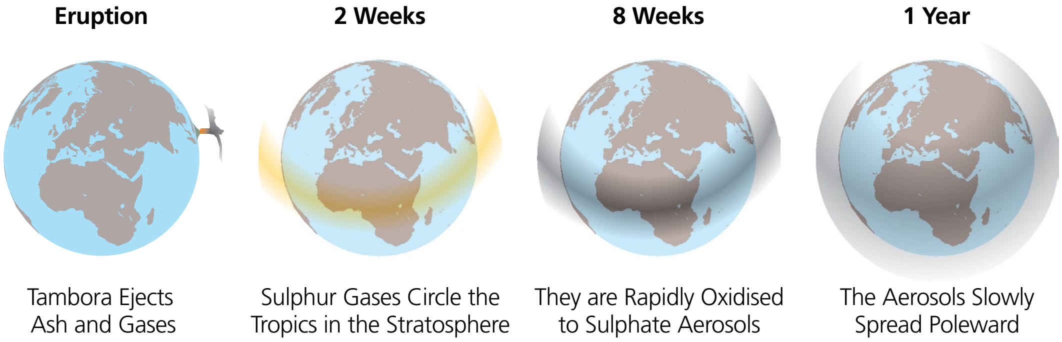


Fig. 5. *Schematic figure showing the spread of SO_2 and aerosols across the globe after the eruption of Tambora.*

pathways are. Furthermore, the hemispheric partitioning of the aerosols, which is very important for understanding climatic effects, is uncertain and not well constrained by observational evidence.

As the meridional transport is much stronger towards the respective winter hemisphere, aerosols from tropical eruptions residing in the lower stratosphere in April or May should in theory be transported to the South initially because this is the winter hemisphere. Around October, that circulation stops, and in November the northerly circulation starts. Aerosols still remaining in the tropical stratosphere at that time will go north. Modelling the transport of aerosols after Tambora using climatological stratospheric winds, Arfeuille and co-authors[37] found more aerosols in the Southern Hemisphere (Fig. 6, bottom left). However, this is at odds with the notion that climatic effects were mostly felt in the Northern Hemisphere. Uncertainties in the model are high (for instance, the model overestimates tropical aerosol amounts), but perhaps we also simply lack the information about climate effects of the eruption in the Southern Hemisphere. The following section compiles further evidence on the hemispheric partitioning of aerosols – and on the climate effect on each hemisphere.

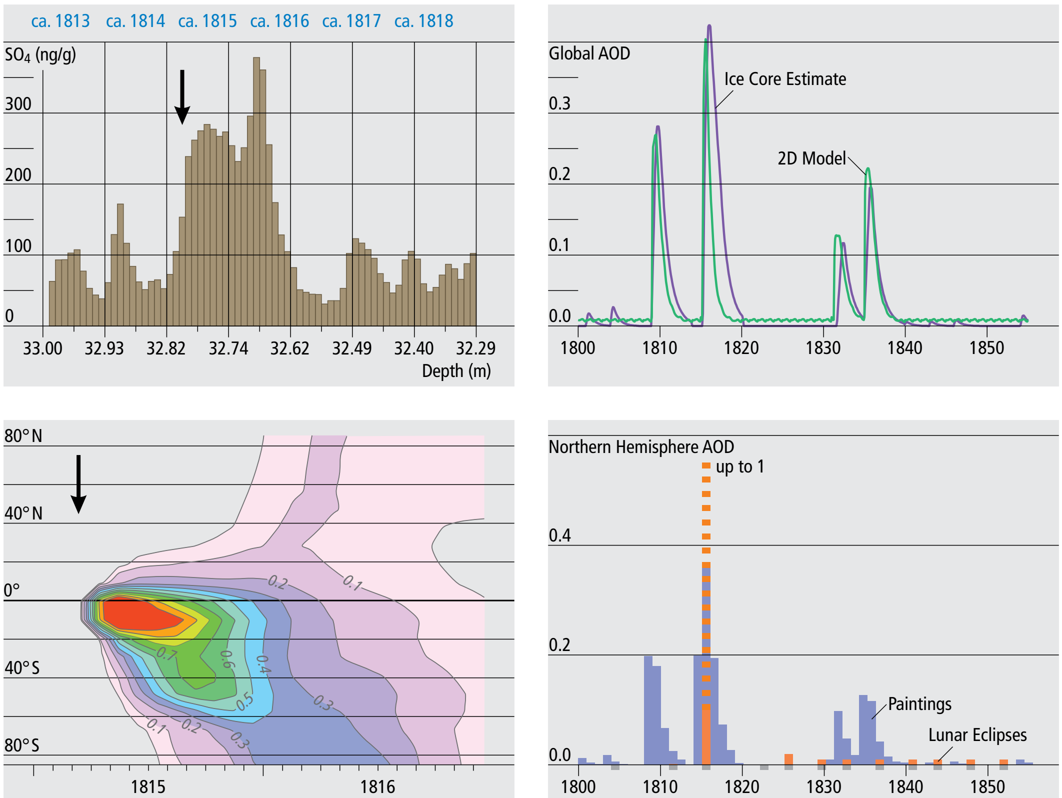


Fig. 6. *(Top left) Sulphur concentration in segments of an ice core from Greenland.*[38] *(Top right) Reconstruction of global aerosols optical depth from ice cores using statistical techniques*[39] *or a 2D aerosol model.*[40] *(Bottom left) Spread of the aerosols (zonally averaged aerosol optical depth) after the Tambora eruption in a 2D aerosol model.*[41] *(Bottom right) Estimated aerosol optical depths from paintings*[42] *and lunar eclipses*[43] *(grey indicates observed eclipses). The arrow indicates the eruption of Tambora.*

Two aerosol layers in the stratosphere two months after the 1991 eruption of Mt. Pinatubo, photographed from the Space Shuttle

Once the gaseous SO_2 of an eruption reaches the stratosphere, it spreads (after an initial overshooting) at the neutral buoyancy height and circles the globe zonally within two or three weeks. The aerosols that are formed in the stratosphere after the Pinatubo eruption appear as two thin layers at an altitude of 20–25 km. The aerosols slowly spread poleward over the next 2 years and affected the atmosphere for about 4 years.

Ice cores are an archive of volcanic aerosols from historical eruptions

Volcanic aerosols re-enter the troposphere typically at middle or subpolar latitudes, when weather systems cause an exchange of air between the upper troposphere or lower stratosphere or by falling out. The aerosols then either settle and are deposited at the Earth's surface or they are incorporated into clouds and reach the ground in the form of precipitation. The snow falling on Greenland's ice sheet therefore has traces of volcanic aerosols, which can be sampled in an ice core and analysed chemically.

Photo: Ice core of the North Greenland Eemian Ice Drilling project (NEEM).

On the Trail of the Aerosols

It would be great to either confirm or disprove the findings of Arfeuille and co-authors with independent observational evidence. Perhaps ice cores may help in this respect. All volcanic sulphate ultimately ends up in the troposphere. It settles gravitationally or is rained out and reaches the surface of the Earth. At high elevations or high latitudes, these aerosols are incorporated into the snow pack. Preserved in ice cores, we still can access and measure Tambora's aerosols today. In fact, sulphate in ice cores (next to tephra deposits) is the main source of quantitative information about past volcanic eruptions (Fig. 6, top left). For the case of Tambora, large amounts of sulphate are documented in ice cores from both Polar Regions and even in some Alpine ice cores (later eruptions are buried under the signature of industrial sulphur emissions). Due to the long stratospheric mixing time and the long atmospheric lifetime of sulfur aerosol in the stratosphere, aerosols reach the Polar Regions one to two years after the eruption, hence the signal is spread over two or more annual layers (Fig. 6, top left).

So, what do ice cores suggest in terms of hemispheric partitioning? A recent study found that the fluxes of sulphur after the Tambora eruption were higher over Antarctica than over Greenland,[44] while previous studies[45] found approximately equal partitioning. However, as for the model simulations, uncertainties in ice core estimates are high mostly because sulphate concentrations cannot be compared directly between locations. Aerosol deposition has large spatial variability, which is largely controlled by the washout of the aerosol during transport and at the site of observation. Comparing ice core records from both Polar Regions thus entails an assumption on the transport or at least some sort of "calibration". The question thus remains open whether the possible inconsistency between the hemispheric partitioning of aerosols and climate effects needs to be reconciled.

Perhaps direct information about the atmospheric aerosols could help. However, such information is very scant. The moon was practically invisible during the lunar eclipse on 10 June 1816, suggesting an aerosol optical depth (a measure for the dimming of light due to aerosols) larger than 0.1, which is a typical value for a strong tropical volcanic eruption. Other phenomena (coloured twilight glows, naked-eye visibility of sunspots, high stellar extinction) suggest even higher optical depths close to one.[46] Furthermore, the Tambora eruption, as other strong eruptions, led to colourful sunsets. Zerefos and co-authors[47] used the red-to-green ratio in hundreds of painted sunsets from the 18th and 19th century (see box "A Tale of Indonesia and Europe") to determine a time series of aerosol optical depth (Fig. 6, bottom right). The agreement between their estimates and the ice core based estimates of sulphate aerosols (top right) is very good – all data sources are in agreement with a global or northern hemispheric aerosol optical depth of ca. 0.2–0.4. Thus, paintings confirm the findings from the ice-core based estimates. However, these historical archives are not sufficient to address the issue of hemispheric partitioning. What we do know for sure is that aerosol amounts over the northern extratropics were high enough to have an effect on large-scale climate.

The main effects of volcanic aerosols on radiation and on the stratosphere are well understood. Volcanic aerosols scatter solar short-wave radiation and absorb (solar) near-infrared and (terrestrial) infrared radiation. The absorption heats the stratosphere considerably. Scattering of solar radiation diminishes solar radiation at the ground and leads to cooling. Tambora was no different than other eruptions in this regard, just bigger.

The relation between the sulphate mass residing in the stratosphere and the reduction of short wave radiation is not as straightforward as it may seem. It turns out that big eruptions do not have a proportionally bigger effect than smaller eruptions. This is another current research topic. The reason is related to the growth of aerosol particles (see Fig. 7). Larger eruptions emit larger amounts of SO_2 into the stratosphere, but the volume into which the SO_2 is injected is not much larger. As a consequence, the concentration of SO_2 increases. The number of aerosol particles is initially much larger in case of a large eruption, but these particles subsequently coagulate much more easily and grow faster than in the case of a smaller eruption.[48] This change in size affects the optical properties. The larger particles are less efficient at scattering shortwave radiation. Furthermore, large particles settle gravitationally at a more rapid pace. Therefore, in a recent model study, the extinction at the equator two years after the eruption was found to be the same for the Tambora and Pinatubo eruptions, even though the former started with four times as much SO_2 as the latter[49] (see Fig. 7). Three years after the eruption, extinction was even lower for the Tambora case than for the Pinatubo case. Large eruptions therefore might have a smaller climate effect at the ground than anticipated.

In addition to direct radiative effects, volcanic aerosols also might have indirect effects when they fall out of the stratosphere and affect the formation of cirrus clouds in the upper troposphere. However, little is yet known about this mechanism.

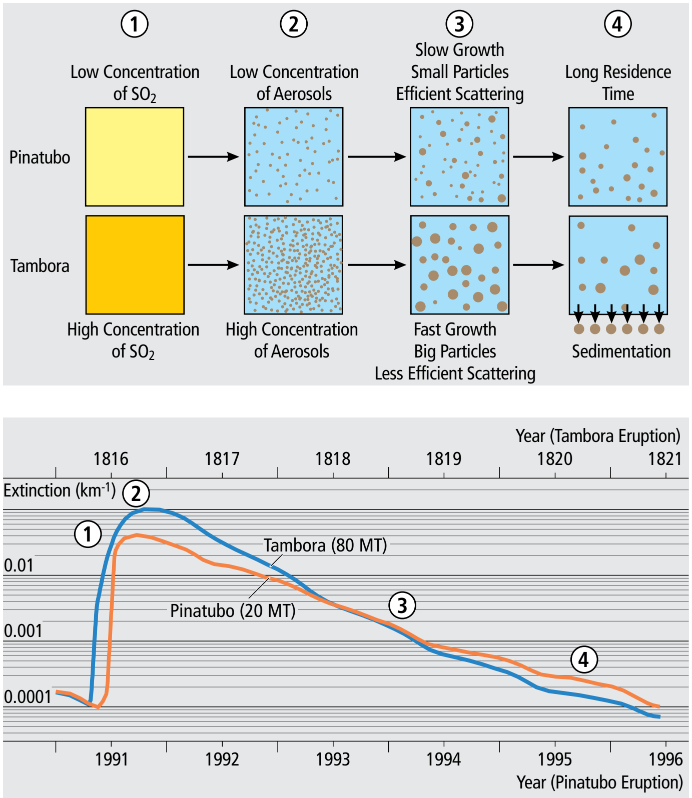


Fig. 7. *(Top) Schematic indicating the number and growth of aerosol particles after the eruptions of Pinatubo and Tambora, respectively.*[50] *(Bottom) Comparison of extinction at the equator at 20 km in model simulations after Tambora and Pinatubo.*[51]

The Tambora aerosols caused a radiative forcing of the global climate system (i.e., a change in the net radiative flux at the top of atmosphere) of about 5–6 W/m^2 for one to two years following the eruption[52,53] although this number is very uncertain and the local forcing may have been much larger. For comparison: the radiative forcing since the preindustrial era from CO_2 alone is 1.82 W/m^2 and is growing by 0.27 W/m^2 per decade.[54] The immediate volcanic forcing from the 1815 Tambora eruption was thus ca. 3 times as strong as the total CO_2 forcing since then. However, it only lasted 2 years or so, such that on long time scales, the effects of volcanic eruptions are generally small. As a first-order estimation, an increase in frequency of Tambora-sized eruptions from 1 in 400 years to 1 in 25 years would be required just to cancel the radiative effects of the current CO_2 increase (not considering any other greenhouse gases).

Lunar eclipses as a source of information on volcanic eruptions

Naked-eye observations of the average color of the totally eclipsed disk give an indication about the optical thickness of the atmosphere, which in turn may be related to the presence of volcanic aerosols. During the eclipse on 10 June 1816, the Moon appeared to vanish in a clear sky, arguable due to the Tambora aerosols.

Based on a systematic compilation of such reports, Richard Stothers[55] derived aerosol amounts in the atmosphere following major volcanic eruptions.

Photo: Lunar Eclipse on 10 December 2011. Photographed from Batticaloa, Sri Lanka.

Climate Anomalies in Proxies

The 5–6 W/m^2 negative radiative forcing in the two years after Tambora led to global cooling. However, the amount of cooling is not well constrained. Instrumental measurements are insufficient to obtain a global overview. Only the Berkeley Earth Surface Temperature data set[56] goes back that far and finds that land temperatures in 1816 were 1.4 °C cooler than the 1821–1830 average in the Northern Hemisphere; anomalies that were not reached again since that time in this data set.

However, that data set is based on only very few stations and most were located in the regions that were particularly strongly affected: Central Europe and North America. Thus, reconstructions based on indirect climate indicators (proxies) are required to obtain a hemispheric or continental view of climatic anomalies. One of the first proxy-based studies on the climate of 1816 was a paper by Briffa and co-authors.[57] Their maps of late wood density (a proxy for temperature) shows a clear decrease of temperature over northern Eurasia in the summer of 1816. Later studies confirmed these effects. Strong cooling was also found in the tropics based on tree rings[58] and corals.[59] Sparse instrumental sea-surface temperature observations, meticulously compiled by Mike Chenoweth,[60] also indicate low tropical sea-surface temperatures in 1816.

For global or northern hemispheric mean temperature, the available reconstructions[61,62,63,64] agree that 1816 was among the coldest years of the past 400 years, but they disagree quite considerably in the amplitude of the anomaly. Relative to the 1961–1990 average, the anomaly was between -0.66 and -1.9 °C for the Northern Hemispheric temperature.[65] Of course, this number also includes global warming. Compared to the preceding years, Tambora led to a cooling of around 0.5 °C globally.[66] Interestingly, according to most reconstructions of Northern Hemispheric temperature, the summer of 1816 fell into a period of already declining temperature.

As an example, the temperature reconstructions by Tom Crowley and co-authors[67] are shown in Fig. 8 (bottom), expressed relative to a contemporary reference period*. The reconstruction, which seems to emphasize decadal rather than interannual variability, shows that the year 1816 is the coldest on record globally, in the northern extratropics, and in the tropics, but not in the southern extratropics. A pronounced cold phase also occurred in the 1830s with particularly cold years after the eruptions of Babuyan Claro (Philippines) in 1831 and Cosiguina (Nicaragua) in 1835.

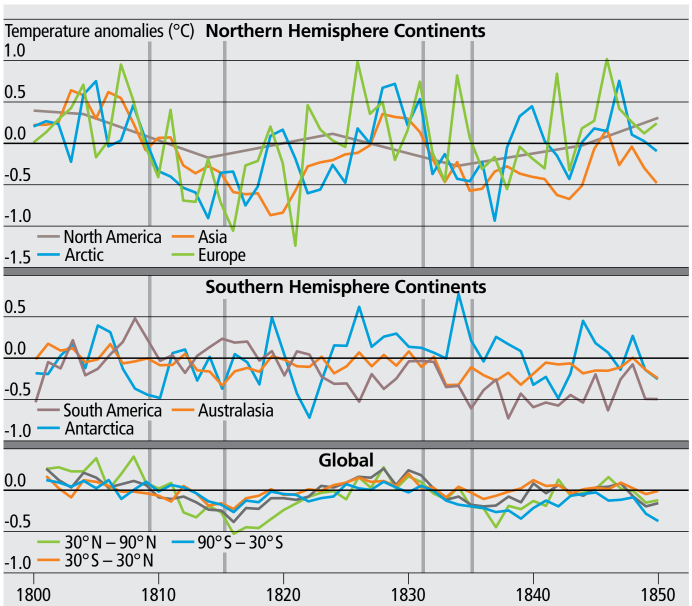
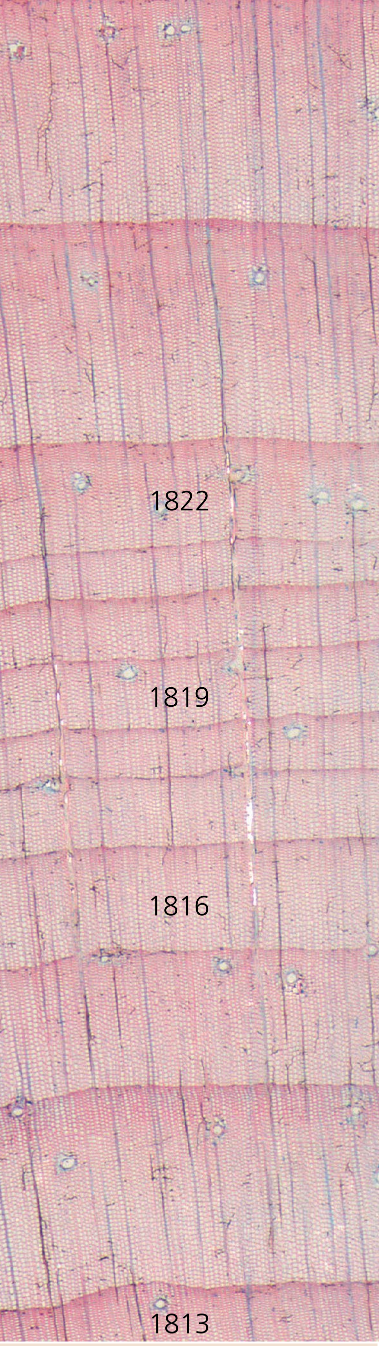


Fig. 8. Annual temperature anomalies from continental reconstructions for the Northern Hemisphere (top) and the Southern Hemisphere (middle) continents.[68] (Bottom) Annual anomalies from reconstructions of global, northern extratropical, tropical, and southern extratropical temperature.[69] Grey bars denote major tropical volcanic eruptions.*

* Following Auchmann and co-authors[vgl. ref. 101] we use the reference period 1799–1821, excluding the volcanic years 1809–1811 and 1815–1817 (note that some data sets start only in 1800) for this figure and throughout this booklet.



Thin tree rings after 1816

The annual growth rings of trees are a commonly used climate proxy. Thick rings indicate undisturbed growth while thin rings indicate adverse growth conditions. Depending on the tree species and location, growth can be limited by low temperatures or water availability. Growth generally also responds to light, and trees may not fully recover from the previous year's stress.

The combination of these factors, in this case arguably mostly the low temperature, led to small tree rings 1816 and in the following years. However, disentangling the factors remains a challenge.

Photo: Microsection from a pine sample from the Tatra Mountains.[70]

The continental-scale reconstructions from the PAGES 2k project[71] (Fig. 8, top and middle) show a more diverse picture. Reconstructions for the Northern Hemisphere continents are in general mutual agreement and also agree with the hemispheric temperature reconstructions by Crowley and co-authors[72] of hemispheric temperatures. However, unlike in the latter reconstruction, no clear impact of Tambora is seen in the Southern Hemisphere continents (Antarctica, Australasia, South America) in the PAGES 2k reconstructions. Since most of the proxy sites used in these reconstructions are coastal, there may be a sampling bias in the proxies. Nevertheless, the absence of a volcanic signal is striking, all the more so since the timing of the eruption as well as some ice core studies suggest that a greater portion of Tambora's aerosols might have moved to the Southern Hemisphere. Furthermore, the absence of a Tambora signal in the Southern Hemisphere is not reproduced by model simulations.[73] Are the records of aerosols and climate after Tambora consistent with each other? This is an open question, but its implications are more general. The general lack of correlation between Northern and Southern Hemispheric reconstructions is another big scientific puzzle.[74]

Proxies record more than just temperature. Some proxies also reveal changes in tropical precipitation after volcanic eruptions. In Central America, the Intertropical Convergence Zone (ITCZ) seems to have shifted north after Tambora.[75] Based on tree rings and other proxies as well as early instrumental data, various reconstructions of precipitation or drought indices have been performed for different regions. Figure 9 shows a compilation of these reconstructions for the boreal summer of 1816. Drought reconstructions reveal a strong drought in the Indian and Southeast Asian monsoon region, while in North America, a pronounced West-East gradient becomes apparent, with drying in the East and wet conditions in the West. Precipitation reconstructions for the Asian monsoon region confirm dry conditions in India and Southeast Asia, but not China. Further research has to clarify the severity of meteorological and hydrological drought conditions for China in 1816. No clear signals are found in winter precipitation in South Africa and annual precipitation for Australia (no gridded reconstructions are available), while precipitation reconstructions for Southern South America indicate a surplus of precipitation in the austral winter of 1816. A new reconstruction based on the combination of climate proxies and instrumental records with climate model simulations (displayed on the cover page) indicates drying in the inner tropics as well as in China.

Drought and precipitation reconstructions agree very well for Europe, where a clear increase in rainfall in the summer of 1816 is evident and is one of the main causes of the misery of the "Year Without a Summer". In the following section, we therefore focus on Europe.

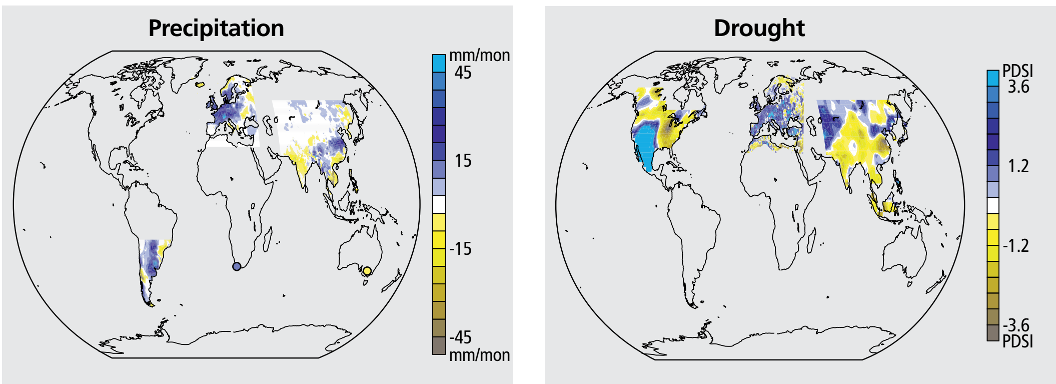
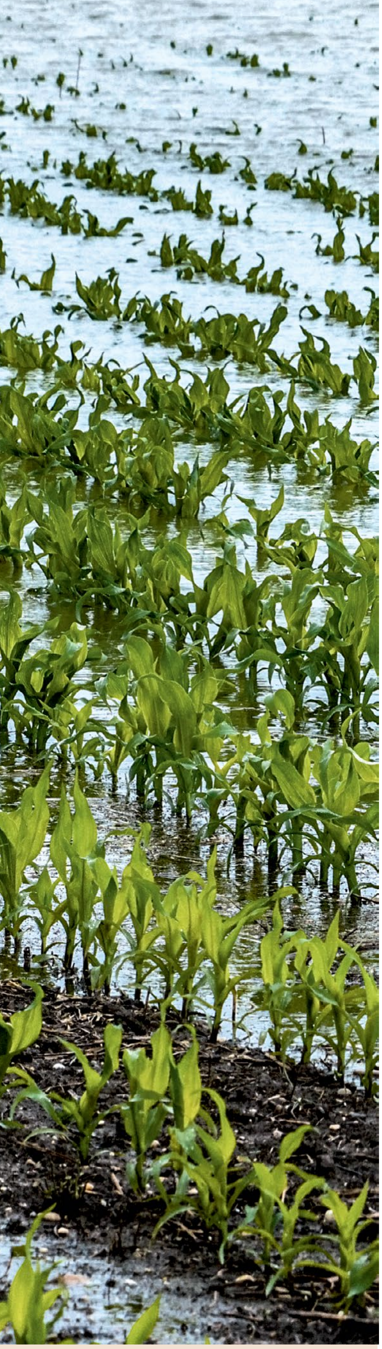


Fig. 9. *(Left) Reconstructions of precipitation anomalies in boreal summer 1816 from instrumental data and proxies for Southern South America,[76] Europe[77] (both June to August), Asia[78] (May to September), as well as point reconstructions for South Africa[79] (April to September) and Australia[80] (May top April). (Right) Tree-ring based reconstructions of the warm season Palmer Drought Severity index for North America,[81] Europe,[82] and Asia[83] for the boreal summer 1816, expressed as anomalies from a contemporary reference period (1799–1821).*

Dry in the monsoon regions

In the summer of 1816, large regions covered by the Asian monsoon arguably suffered from severe drought due to a failure of the Asian monsoon – at least this is found in climate model simulations and according to some, but not all, reconstructions. Although many improved drought reconstructions have been published for various regions of the globe in recent years, we do not yet have a complete, global picture of hydro-climate in 1816. The famine in Southwest China (Yunnan) was not only due to drought, but also due to the low temperatures, to which rice cultivation in these regions is highly susceptible.



Flooding in Central Europe

Central Europe suffered from a wet spring and summer in 1816. In some areas, rainfall was up to twice the normal amount and many floods were reported. In the northern Alpine region, even larger floods then occurred in 1817, when the accumulated snow of two winter seasons (some snow from the winter 1816 survived the summer) and the summer precipitation of 1816, which fell as snow at high altitudes, melted at once.

Photo: Flooded agriculture near Linz (Austria) after heavy rainfall in June 2013.

Climate Anomalies in Observations

For the North Atlantic-European sector, early instrumental data are abundant enough to provide an overview of the climate in 1816. Hubert Lamb, Christian Pfister, Rudolf Brazdil and numerous other climate historians of climate have compiled and studied the historical measurements and observations[84,85,86] and a book published in 1992 has compiled these works.[87] In Western and Central Europe, temperatures were by far below normal in the summer of 1816. The cooling was strongest in a region encompassing eastern France and Switzerland. While different reconstructions of climate in Western Europe agree, differences arise in Eastern Europe. Contemporary sources report high temperatures in Russia, which is supported by sparse instrumental data (Kiev, St. Petersburg). In Poland, the summer of 1816 seems to have been normal, while tree rings from the Tatra Mountains show a strong growth response.[88] It seems that the large cooling observed in western and central Europe was not a continent-wide response.

For the population of Central Europe, the endless rainfall was more problematic than the low temperature. Johann Peter Hoffmann, a farmer and magistrate from Alsace, wrote in his diary[89] in July 1816: "The rain continues, there is no day without rain. The misery is indescribable. This is the worst time in my memory." In fact, precipitation in Central Europe was 20–80 % above normal in the summer of 1816. At the same time, the Iberian Peninsula and western Russia were rather dry.[90]

A recent reconstruction of global climate obtained from combining model simulations with instrumental data and proxies (Fig. 10, see also cover page)[91] confirms the low temperatures over Central Europe and North America and higher temperatures in Eastern Europe. They also show a clear precipitation increase over Western and Central Europe (decrease over Western Russia) and a decrease in sea-level pressure centred over the British Isles.

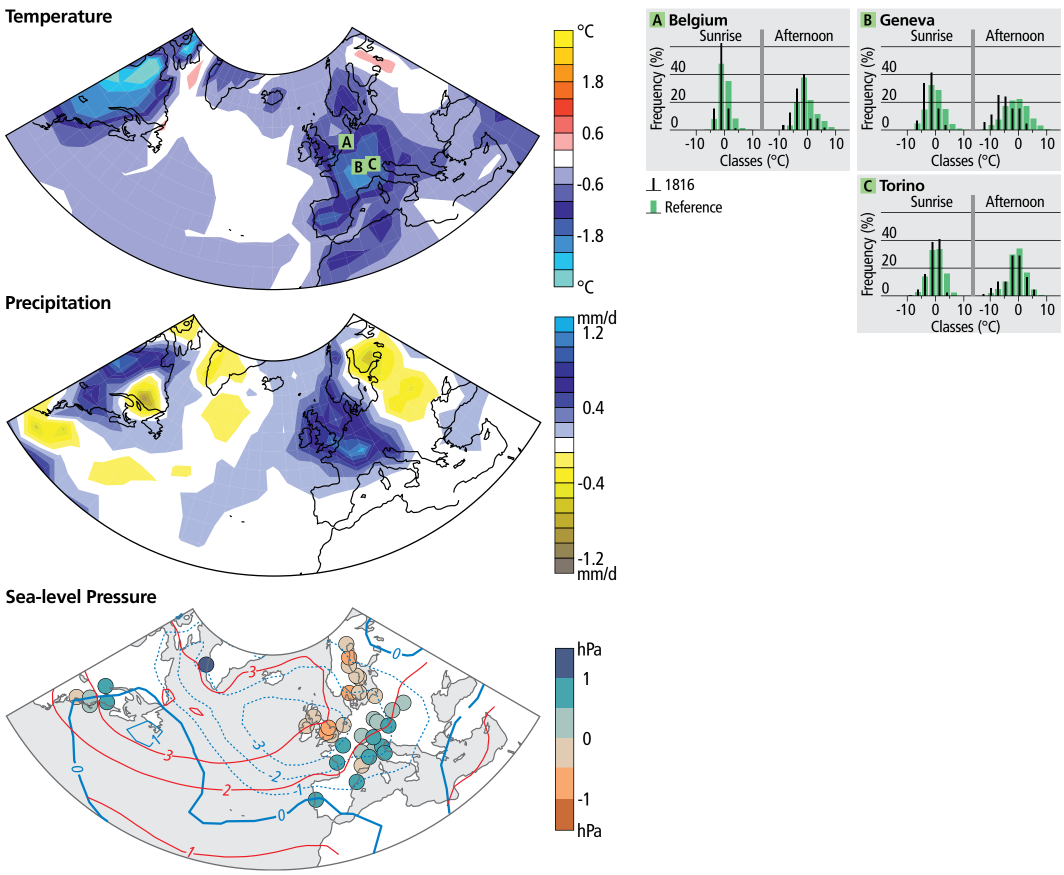


Fig. 10. *Climate in summer (Jun–Aug) 1816 expressed as anomalies from a contemporary reference observations period (1799–1821). Shown are reconstructions[92] of (top) temperature (right: frequency distributions of daily temperature anomalies from three stations), (middle) precipitation and (bottom) sea-level pressure (black contours, in hPa). Dots show the standard deviation of daily sea-level pressure, 3–6 day band-pass filtered[93] and expressed as anomalies from a present reference (1981–2010, red contours, in hPa).*

1816 was not the first cold year in Europe in the 19th century. After a warm phase around 1800, temperature dropped markedly (Fig. 11). The summer of 1816 was thus the culmination of a decade of cooling. Part of this cooling might have been due to a previous "unknown" eruption (a volcanic layer documented in ice cores, which could not yet be attributed to a known eruption) in 1808 or 1809[94], or due to low solar activity, but possibly also due to internal decadal variability in the ocean-atmosphere system.[95]

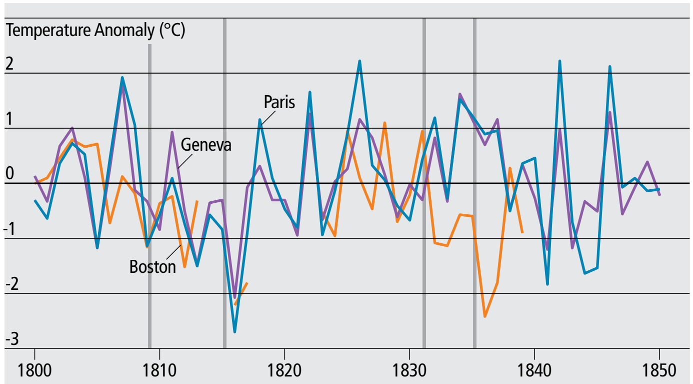


Fig. 11. June-to-August temperature in Geneva, Paris, and Boston expressed as anomalies to a contemporary reference period (1799–1821). Grey bars mark major tropical volcanic eruptions.

While several "Years Without a Summer" have been noted in Europe (examples[96] include 1529, 1588, 1601, 1618, 1628, 1675 and 1813), 1816 was the only one known as such in the USA (note, however, the cool summers in Boston in the 1830s, which also followed volcanic eruptions). Temperature anomalies in the New England States in summer 1816 (Figs. 10 and 11) were almost as strong as in Western Europe. In this region, the year of 1816 is therefore also known as "Eighteen-hundred-and-froze-to-death". After several cold spells in May, a severe snowstorm was observed as late as June, burying upstate New York, Pennsylvania, Vermont and New Hampshire with a 2–30 cm thick snow cover. Weather maps for that snowstorm, drawn by Mike Chenoweth,[97] are shown in Fig. 12. Behind the cold front moving over the Atlantic, temperatures fell to freezing levels. Interestingly, at the same time, a hurricane hit Florida (red symbol in Fig. 12) unusually early in the season. The Southeastern United States, conversely, experienced a dry spring and summer.

Farther north, unusual sea-ice conditions were reported. The ships of the Hudson Bay Company, travelling between Britain and the Hudson Bay, reported severe ice conditions in 1816. Conversely, in the Greenland Sea (east of Greenland), whaler William Scoresby Jr reported less than normal sea-ice and high temperatures in 1816 (compared to the years 1810 to 1818).[98]

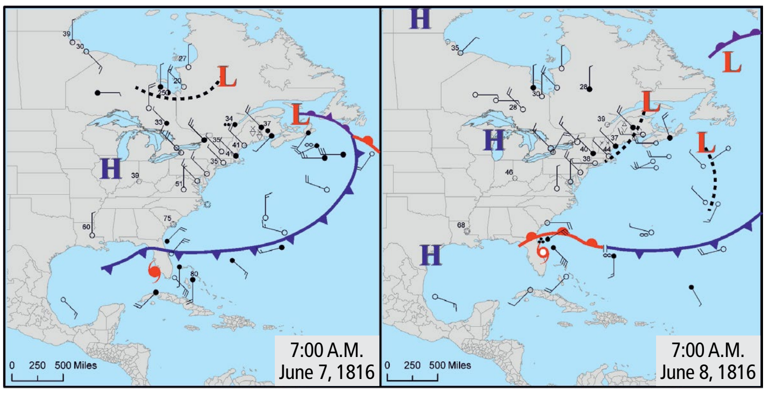
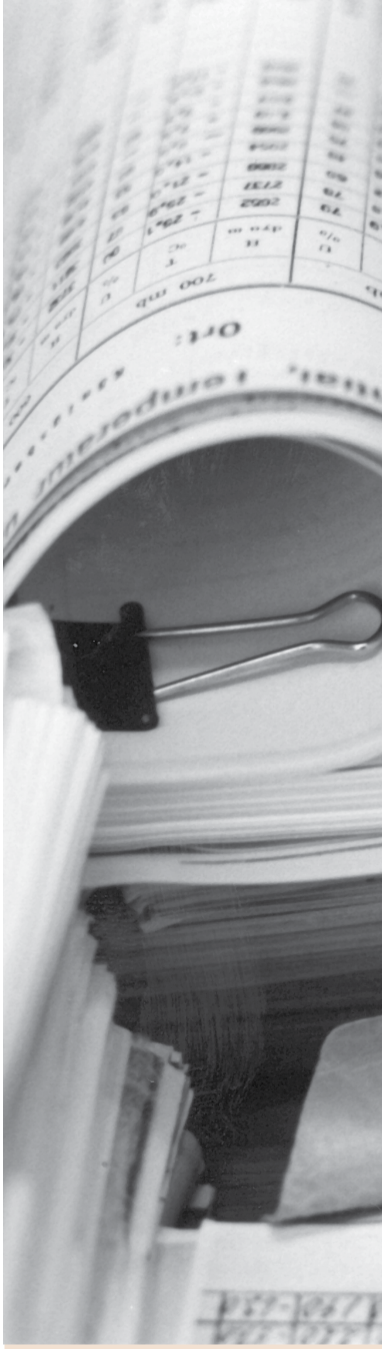


Fig. 12. Synoptic pressure charts for 7 and 8 June 1816, indicating observations of wind, temperature (°F), cloud cover (open/filled circles), and precipitation (dots or asterisks left to the wind arrows), based on a comprehensive compilation of observations by Mike Chenoweth (2009).[99]



Retrieve the Treasure

Not long ago, historical weather observations were not considered to be of much value for science. Within the last decade, however, new science questions (towards extreme events and climate impacts) as well as new numerical techniques (data assimilation) have rendered historical manuscript data valuable again. In citizen science projects such as oldweather.org, internet users can help to retrieve the treasure.

Schnee oder Regen.

Nachts.	Vormittags.	Nachmittags.
—	—	Reg. 3
Regen	Regen	Regen
Regen	—	Regen
Regen	Regen	Regen
—	Regen	Regen
Regen	—	—
—	—	Reg. 3
Regen	Regen	—
—	—	Stbr. 7
—	Reg. 12	Regen
Regen	Reg 11	Regen
Regen	Regen	Regen
Regen	Regen	Regen
Regen	Regen	—
—	—	Reg. 4
—	—	Regen
Regen	Regen	Regen
Regen	Regen	—
Regen	—	—
—	—	—
—	—	—
Regen	—	Regen
—	—	—
Regen	Reg. 12	Regen
Regen	—	Reg. 6
—	—	Reg 1
Regen	—	—
—	—	Stbr. 7
Regen	Regen	Regen
Regen	Regen	Rg. Hl.
Regen	Regen	Regen

Weather Observations from Aarau, Switzerland, July 1816

The German (later Swiss) scientist, author, and reformer Heinrich Zschokke performed instrumental measurements and weather observations three times per day in Aarau, Switzerland, during the years 1807 to 1816.[105] The data sheet from July 1816 indicates rain (in German: "Regen") on 28 out of 31 days, mostly all day long.

During the current climatological norm period (1981–2010), the station Buchs/Aarau had on average 11.5 days with >0.1 mm precipitation in the month of July.

Volcano Weather: Anatomy of the "Year Without a Summer" in Central Europe

"Volcano weather" was the title of Henry and Elizabeth Stommel's classic text[100] on the "Year Without a Summer" of 1816. In fact, the early instrumental data from Central Europe now allow for a detailed look not only at climate, but at daily weather during 1816, based on sub-daily measurements. This analysis firstly reveals that, while weather was not extreme in 1816, climate was. This means that it was the frequency of adverse weather situations rather than their intensity that characterised the extreme summer of 1816.[101]

Precipitation frequency strongly increased over Switzerland, whereas intensity did not change at all. Essentially, this means Switzerland simply experienced more rainy days, each with no more rain than usually falls in a day. However, precipitation is difficult to measure and locally variable. Other Central European sites show only small anomalies in the precipitation of 1816, despite the notion of widespread flooding. In Switzerland, snow fell repeatedly down to the valley bottoms into the early summer of 1816 (and even stronger floods occurred in 1817 due to the melting of the snow, see Section "Aftermath").

Sub-daily temperature observations also give indications as to the underlying processes causing the cold summer of 1816. For instance, afternoon temperatures in Central Europe dropped more strongly (the maximum decrease in summer temperature relative to neighbouring decades is 3.8 °C in Geneva, Switzerland) than those at sunrise (1.8 °C; Fig. 10, top). This is most likely due to an increase in cloud cover, which can be confirmed by an increase in cloudiness in observations.[102] Clouds lead to a cooling during the day by reducing solar radiation, but to a warming during night by preventing emission of longwave radiation. Furthermore, the frequency distributions of temperature anomalies changed in such a way that warm sunrises were mostly missing, while very cold sunrises were not more frequent in 1816 than in other years (small diagrams in Fig. 10, top) – again a consequence of an increased cloud cover. For plant growth, this increased cloud cover and change in the temperature frequency distribution has a large negative effect (see Section "Biophysical effects"). South of the Alps (e.g., Torino, Fig. 10, top) cloud cover did not increase.

Combining sub-daily temperature and cloud information even allows us to address the clear-sky diurnal temperature range. This measure may serve as a proxy for the direct effect of the volcanic aerosols; the response to the shortwave forcing is expected to affect daytime temperatures more directly than nocturnal temperatures, thus reducing the diurnal temperature range. In fact, relative to neighbouring years, a decrease of 0.6 °C in the clear-sky diurnal temperature range was found over Central Europe, in good agreement with climate model simulations.[103] While this shows that a direct effect of Tambora aerosols existed, it explains only a small part of the 1.5–3 °C of cooling in Central Europe (see box "How much of the Cold Summer of 1816 in Switzerland was due to Tambora?"). Most of the change needs to be explained by changes in weather. In fact, a weather type classification for Geneva, Switzerland, based on pressure, pressure tendency, and wind indicates an increase of low-pressure types by a factor of 2.5 and an almost complete absence of high-pressure situations.[104] Based on station data for all of Europe, the band-passed filtered standard deviation of pressure (variations that occurs on time scales of 3–6 days) can be analysed as a measure for storminess or synoptic activity. In fact, a band of increased synoptic activity is found, stretching over France, Switzerland, and Central Europe (Fig. 10, bottom, green colours). This means that during the summer of 1816, one depression after the other moved from the Channel across France and Switzerland. The systems brought frequent rain, low temperature, high cloud cover, almost no sunny days and no long fair weather spell until August of 1816. The main cause of the cold weather thus was not direct radiative forcing, but a change in the weather types. However, this change in the weather types is probably also partly due to the volcanic aerosols (Section "Indirect effects").

Scandinavia, on the other hand, experienced less pressure variability (although the average pressure was below normal). Also, temperature and precipitation effects were less pronounced there.

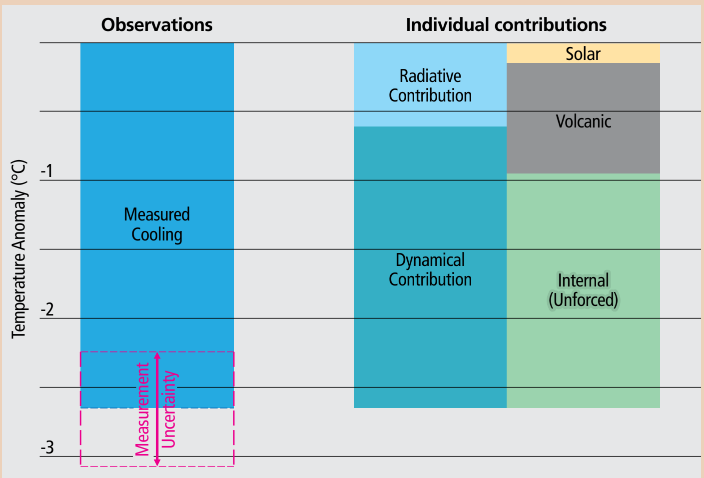
How much of the Cold Summer of 1816 in Switzerland was due to Tambora?

Lord Byron spent the summer of 1816 in the Villa Diodati close to Geneva, joined by Percy Bysshe Shelley and Mary Godwin (who later became Mary Shelley). The bad weather forced the young writers to stay inside – where they passed the time by talking, drinking, and writing ghost stories. Mary Shelley's novel "Frankenstein" and Lord Byron's poem "Darkness" were among the outcomes. This is one of the often-told Tambora anecdotes.

It is true that temperatures in Geneva and neighbouring areas were ca. 2.5–3 °C lower in the summer of 1816 than during the period 1799–1821. But how much of the cooling was really due to Tambora? An estimation of the direct radiative cooling can be gained from the reduction of diurnal temperature range on clear sky days, which, for a set of Central European stations, amounted to ca. 0.6 °C.[106] This observation-based estimate is in agreement with large-scale cooling in model simulations. A small fraction of this radiative cooling might not have been due to Tambora aerosols but rather due to the reduced solar irradiance during the so-called "Dalton Minimum" of solar activity from 1790 to 1830 (the number is very small if a contemporary reference period is chosen). However, the Tambora influence encompasses more than just the direct radiative effects. Atmospheric model simulations that include volcanic aerosols suggest that the unequal land and ocean cooling (land cools faster than ocean) also changes the position of the cyclone track over the North Atlantic (see Sections "Volcano Weather: Anatomy of the 'Year Without a Summer' in Central Europe" and "Indirect Effects"). As a consequence, some regions such as central Europe experience an additional cooling due to a shift in weather types. In climate model simulations, this additional cooling is confirmed but is rather small, at least on average. In all, around 0.7–1 °C of the temperature decrease can be attributed directly or indirectly to the Tambora eruption.

Villa Diodati near Geneva (photo by Robert Grassi).

This is still far less than the observed 2.5–3 °C of cooling. This means that most likely, random internal variability of the climate system also contributed significantly. In fact, the largest contribution to the cooling in Switzerland remains unexplained in the models. To what extent this was just a coincidence, or whether it represents an amplification of the indirect volcanic effects due to some unknown processes, remains open. The fact is, not all strong eruptions cause a "Year Without a Summer" as in 1816, neither in the model, nor in the real world (conversely, not all "Years Without a Summer" are volcanic). Thus "Frankenstein" and "Darkness" were not only the result of Tambora, but also of random weather variability – and of course of the imagination of the "young romantics".[107]



Contributions of direct and indirect Tambora effects and of internal (unforced) variability to the temperature anomaly in the summer of 1816 in Geneva. The quantification is based on the observed diurnal temperature range on clear sky days as well as model results.[108]

Modelled Tambora Climate

While observations and reconstructions can inform us about what happened, model simulations can help us to find out why it happened. Models simulate the basic processes in the atmosphere (or the ocean) such as atmospheric circulation or radiation based on principal equations. Volcanic aerosols can be prescribed in these simulations, and the response is then studied in the model world (Fig. 13). Alternatively, one can use a model of the atmosphere only and prescribe sea-surface temperatures (e.g., using reconstructions) as boundary conditions (see Fig. 15).[109] In most of the coupled (ocean-atmosphere) climate model simulations, global mean temperature drops by around 0.5–1 °C after the Tambora eruption, which is at the upper edge of what is estimated from reconstructions. As an example, Figure 14 shows an ensemble of coupled simulations for the period 1800–1850, which comprises four large eruptions. In these model simulations, global (land and ocean) temperatures decreased by 0.5 °C after the Tambora eruption, which is consistent with reconstructions. These simulations used the modelled aerosol concentrations[110] shown in Figure 6 (bottom left), in which most of the aerosols are transported south. It is therefore not surprising that the modelled cooling is stronger in the Southern Hemisphere than in the Northern Hemisphere for Tambora.

The agreement between model simulations and reconstructions in terms of global mean temperature is noteworthy. Previous studies had reported a discrepancy between the modelled and reconstructed magnitude of the temperature response, and both were blamed to be inaccurate.[111,112] Recent studies have, however, found a better agreement.[113,114]

In the stratosphere, volcanic eruptions lead to a pronounced warming, which is relevant for stratospheric processes (although it does not directly affect the climate on the ground). The lower stratosphere warmed by as much as 2.5 °C – on a global average! – after the eruption of Pinatubo in 1991. Tambora was ca. 3 times stronger than Pinatubo. According to the model simulations, Tambora caused an increase of globally averaged lower stratospheric temperature of 6 °C. Similar as for global mean temperature near the ground, previous model simulations have tended to overestimate the stratospheric response to volcanic eruptions, at least for Pinatubo,[115] but a 6 °C warming after Tambora is not unrealistic.

The direct effect of volcanic eruptions through the change in radiation also affects other variables. The oceans take up less energy and hence the global upper ocean heat content decreases. In the simulations, Tambora's signature in ocean heat content persisted for 15 years and had not fully recovered when the next eruption occurred. Conversely, the heat content was already strongly reduced when Tambora erupted due to the strong, "unknown"

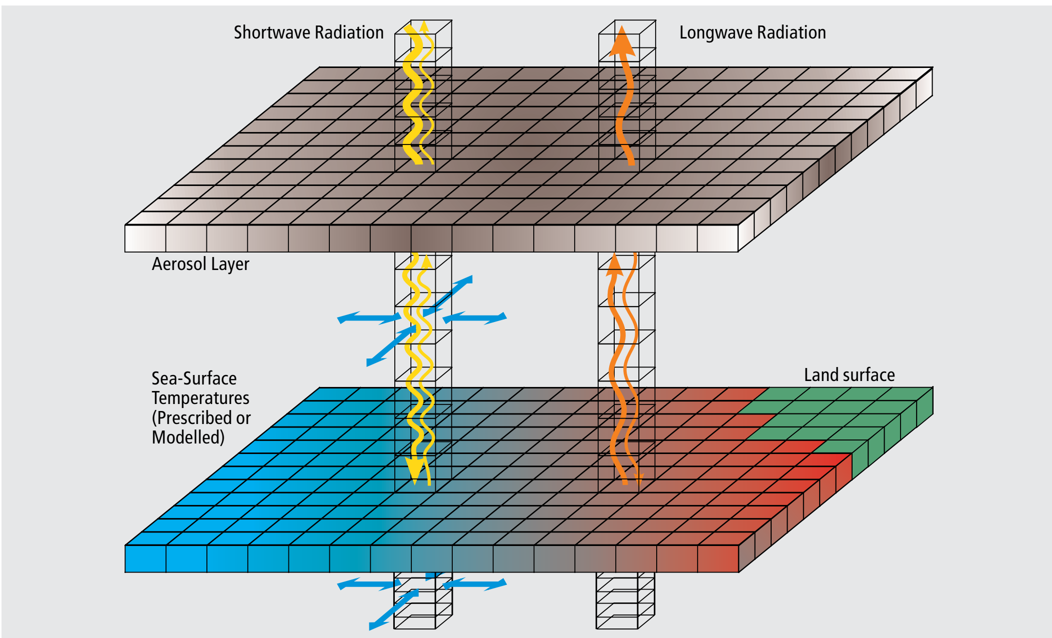


Fig. 13. A schematic climate model.

Supercomputers have become indispensible tools for paleoclimatology

Volcanic eruptions are a test case for our understanding of the climate system. To the extent that this understanding is captured in climate models, scientists can use models to simulate possible responses to past eruptions. However, as random climate variability also plays an important role, a large number of simulations need to be performed before a signal emerges. Massive amounts of data need to be processed – paleoclimatology becomes a "big data" science.

Photo: Climate data storage of the Oeschger Centre for Climate Change Research (OCCR).

1808/09 eruption.[116] In fact, values such as those around 1800 were not reached again for the next 60 years in the model simulations (not shown). The effect of double eruptions may be larger than that of two single eruptions, and may trigger a response of the ocean circulation, which affects climate for a longer time after the eruption. Furthermore, solar activity was low at the same time, known as the so-called Dalton Minimum of solar activity (ca. 1790 to 1830).[117]

The simulations also show a slight increase in global sea ice after Tambora and other eruptions, which is expected from the general cooling. However, unlike the response in the ocean heat content or stratospheric temperatures, these increases were of the same order as the typical interannual variability.

Due to the reduced solar radiation, evaporation is also reduced after eruptions and hence the entire water cycle is slowed down. Global annual mean precipitation decreases by 3–4 % after the eruption in the model simulations. This is considerably more than interannual variability. Spatial patterns reveal that the decrease in global precipitation is dominantly seen in the tropics – which fits well with the reconstructions shown in Figure 9.

So, on the first order, volcanoes are expected to lead to cool, dry climate. Why, then, was it cold and wet over Europe in 1816? This counterintuitive behaviour cannot be understood as a direct effect, but as an indirect effect. Therefore, in the next section we look more closely at indirect effects of volcanic eruptions in general, and of Tambora in particular.

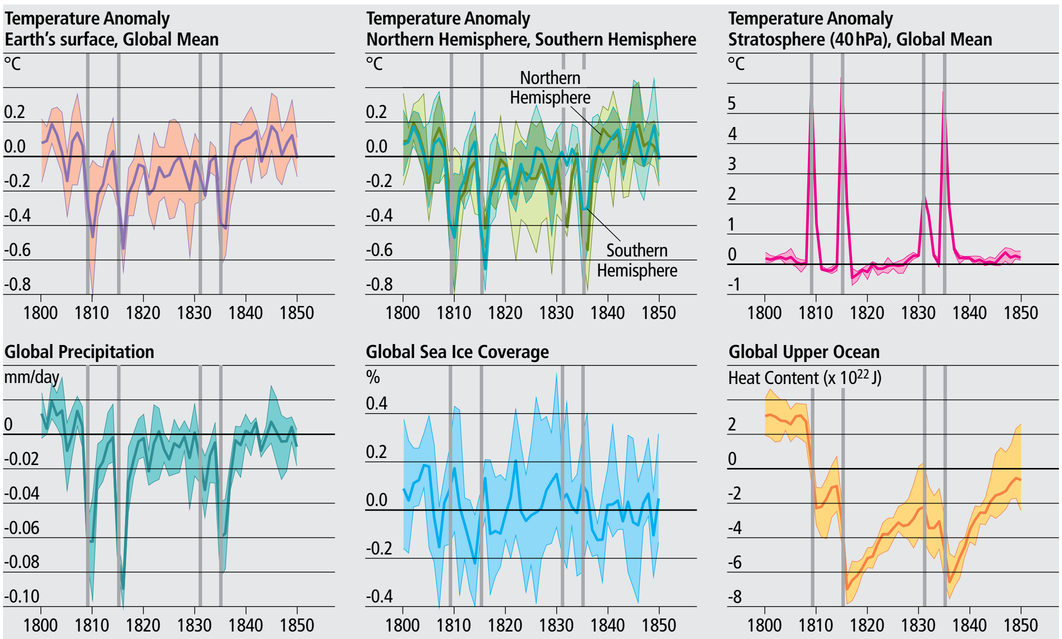
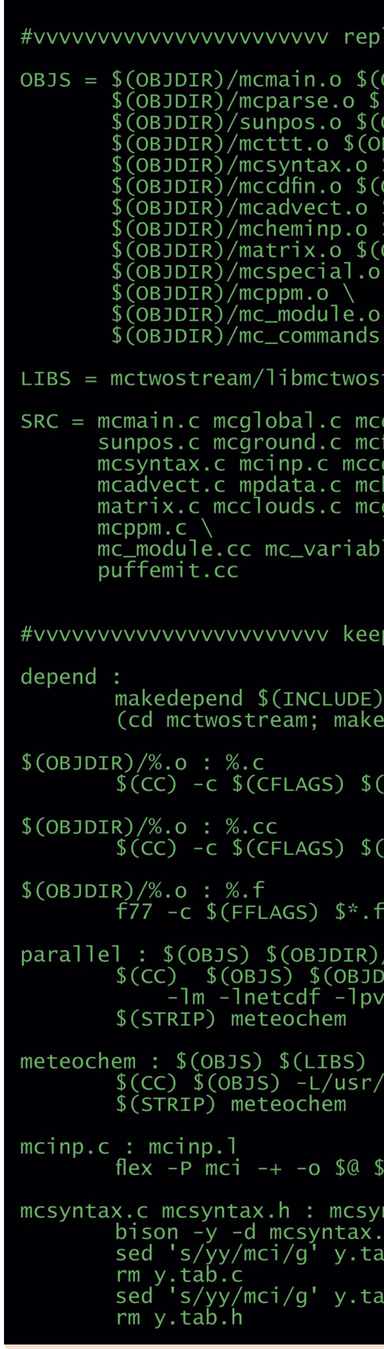


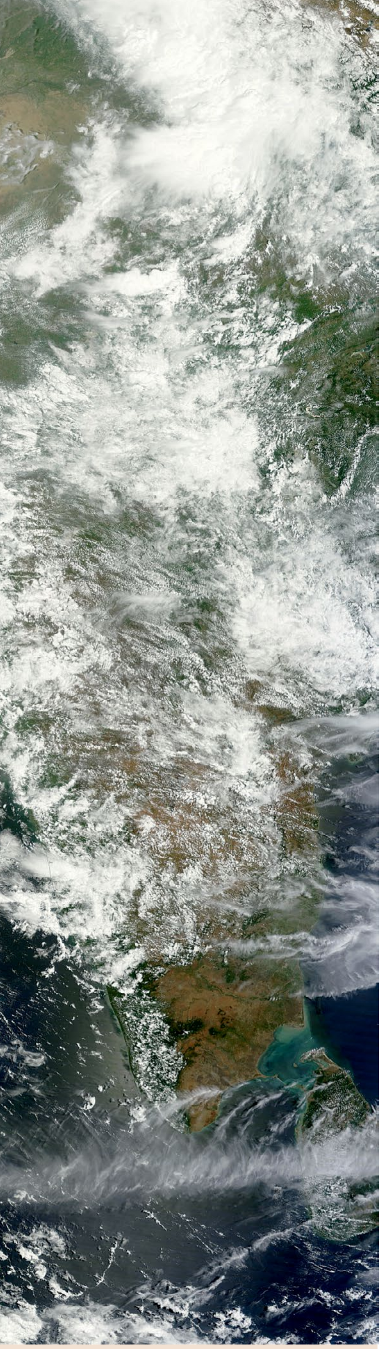
Fig. 14. Time series of global mean values of temperature at the Earth's surface (as well as in the Northern and Southern Hemisphere) and in the stratosphere, global mean values of precipitation, sea ice coverage, and upper ocean (0–700 m) heat content from four climate simulations performed with an ocean-atmosphere chemistry-climate model,[118] expressed as anomalies from a contemporary reference period (1799–1821). The thick lines indicate the mean of the four simulations, the shading indicates the spread. Two simulations differ from the other two by a different solar forcing, among themselves by different initial conditions.[119] Grey bars mark major tropical volcanic eruptions.



Climate models are based on complex computer code, which transfers our knowledge of the climate system into numerics

Perhaps the first model study of Tambora effects was performed by Krishna Rao Vupputuri,[120] who used a one-dimensional coupled chemistry-climate model. Today scientists use three dimensional models of the atmosphere and ocean (coupled models) of atmospheric physics and chemistry (chemistry-climate models) or of atmosphere, ocean, vegetation, and ice sheets (Earth system models).

Photo: Makefile of the model METPHOMOD.



Indirect Climate Effects

Direct effects (i.e., those due to decreased radiation, such as cooling, less evaporation, less precipitation) only make up part of the volcanic effects on climate. Many further effects are indirect, i.e., they emerge through spatially inhomogeneous cooling and subsequent changes in atmospheric circulation. For instance, as the land surface cools more rapidly than the oceans, the large-scale land-sea thermal gradient changes. This is important for the monsoon circulations, which are driven by the continental-scale summertime land-sea thermal gradient. Consequently, many (though not all) model simulations show a weakening of the monsoon systems in response to strong volcanic forcing.[121] Some evidence for this is found in the reconstructions shown in Fig. 9, albeit with uncertainties.

Atmospheric model simulations for the summer of 1816, in which sea-surface temperatures are prescribed, are shown in Fig. 15. Here we show the anomaly averaged over 30 simulations, i.e., a large part of the random weather variability is averaged out and what remains is mainly the forced signal that is due to volcanic aerosols and low sea-surface temperatures (which are both prescribed).[122] The simulations confirm the strong cooling of the continents (top left). The strong southwesterly monsoon winds blowing towards West Africa and India were reduced (bottom left; wind anomalies are easterly). This might also have been the case in the real world.

With less moisture and a weaker monsoon circulation, precipitation (shown in the top right panel) decreases over the monsoon regions of Africa, East Asia, and North America. While a precipitation decrease and drought over Asia is also seen in some reconstructions (Fig. 9), this is not the case for North America (no reconstructions are available for Africa). Along with precipitation, cloud cover is also lower in the typical monsoon regions. Therefore, embedded in the continental scale cooling that gives rise to weaker monsoons, many model simulations exhibit zones of warming due to less clouds. This is also seen in the atmospheric simulations (Fig. 15, top left).[123,124]

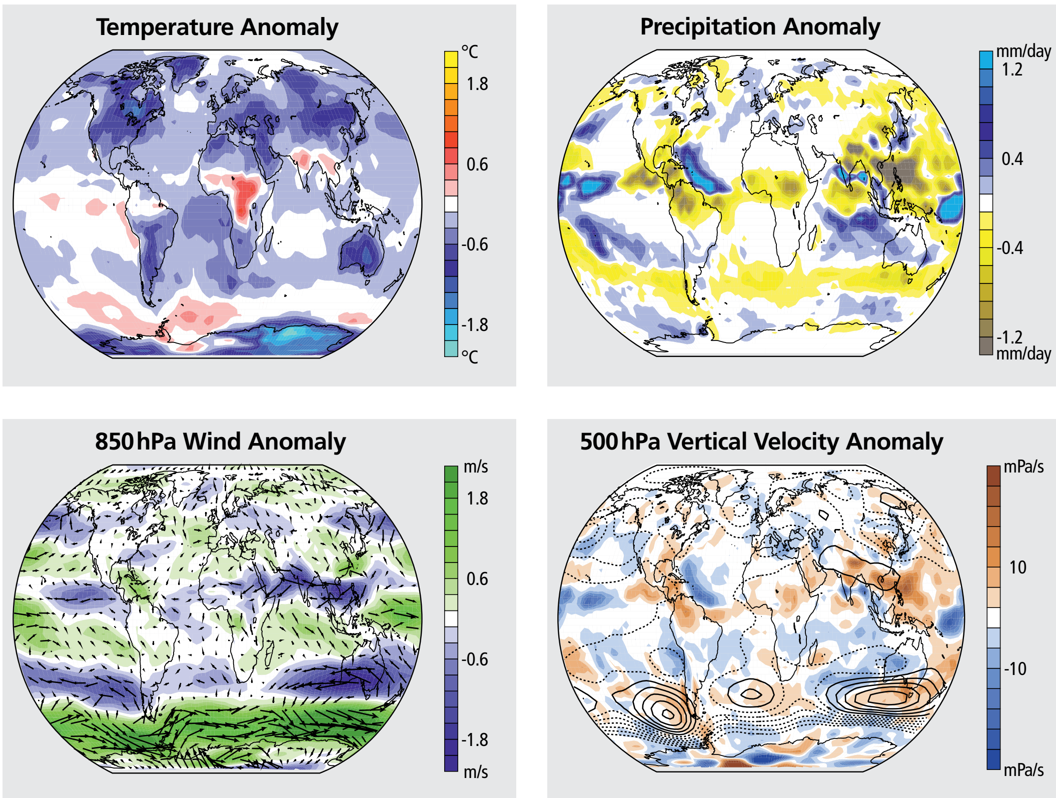


Fig. 15. *Modelled anomalies[125] of (top left) temperature at the Earth surface, (top right) precipitation, (bottom left) wind at 850 hPa (ca. 1.5 km altitude; colours indicate the zonal wind) and (bottom right) vertical velocity (colours) and geopotential height at 500 hPa (ca. 5.5 km altitude; contours, 6 gpm spacing symmetric around zero, negatives are dashed) in Jun–Aug 1816, expressed as anomalies from a contemporary reference period (1799–1821). Shown is the average over 30 individual simulations (ensemble members).*

Monsoon systems react sensitively to perturbations in radiation such as volcanic eruptions

The summer monsoons are essentially driven by the stronger heating of the subtropical land masses as compared to the surrounding oceans. Land masses react more rapidly to volcanic cooling, thus leading to a slowdown of the monsoon.

Understanding monsoons is also relevant with respect to future climates, as the response of the monsoon systems to changes in greenhouse gases, aerosols, interaction with midlatitude circulation, snow cover and other factors is not well known.

Photo: Satellite image of India during monsoon.

In addition to the change in the monsoons, the model also produces associated changes in the northern Hadley cells (the large-scale, meridional overturning circulations of the tropics, consisting of ascent in the ITCZ, poleward flow, descent in the subtropical highs and return flow at the surface in the form of trade winds). Over Africa, the weakened convection over the Sahel-Sudanese region (which constitutes the ascending branch of the Hadley cell in this region; reddish colours in the bottom right panel) also weakens the overall circulation, including its downwelling branch over the Mediterranean (bluish colours). The subtropical high is weaker (dashed lines). As a consequence, the storm track shifts southward in the model – as in the observations (Fig. 10). Although this result only emerges when averaging a large number of simulations (many of the individual simulations do not show this behaviour) and although the magnitude in the model is very much weaker than in observations, this confirms that part of the change in weather types is actually volcanically driven – via a weakening African monsoon. [126]

The existence of such remote effects is something science learned from Tambora and other volcanic eruptions. The connection between European precipitation and eruptions (see also Fig. 16) is not the only example. Model simulations suggest that volcanic eruptions affect coupled oceanic-atmospheric modes of variability. Volcanic eruptions tend to coincide with El Niño events (although discussed controversially) [127] and in models they tend to strengthen the Atlantic Meridional Overturning circulation (AMOC). [128,129] Although more evidence is required (including for the Tambora case), the indirect effects of volcanic eruptions via the oceans deserve further attention and are thus another active research area related to Tambora.

Another indirect and counterintuitive effect of volcanic eruptions is the warming of winters in northeastern Europe. Although the winter of 1815/1816 was not particularly anomalous, the winter warming is well documented from many eruptions. [130] It is reproduced in atmospheric model simulations [131] (although coupled models struggle) [132] and is at least partly understood. [133,134] The effect proceeds via the stratosphere (Fig. 16), where very strong temperature gradients develop between the tropics (where the infrared radiation from the surface is higher and thus also its absorption in the stratospheric aerosol layer) and the Polar Regions. This difference accelerates the strong westerly winds of the polar stratosphere. The wind anomaly may propagate down to the ground [135] and lead to stronger westerly winds. These winds bring mild Atlantic air to northeastern Europe. A similar mechanism might also operate in the Southern Hemisphere, also causing a strengthening of the westerly winds. This is predicted in model simulations (Fig. 15).

Figure 16 schematically summarises the indirect effects of volcanic eruptions on atmospheric circulation and climate. It is not known whether all of these effects occurred after the Tambora eruption. Some of the effects are well known, some are discussed, and some indirect effects are likely yet to be discovered.

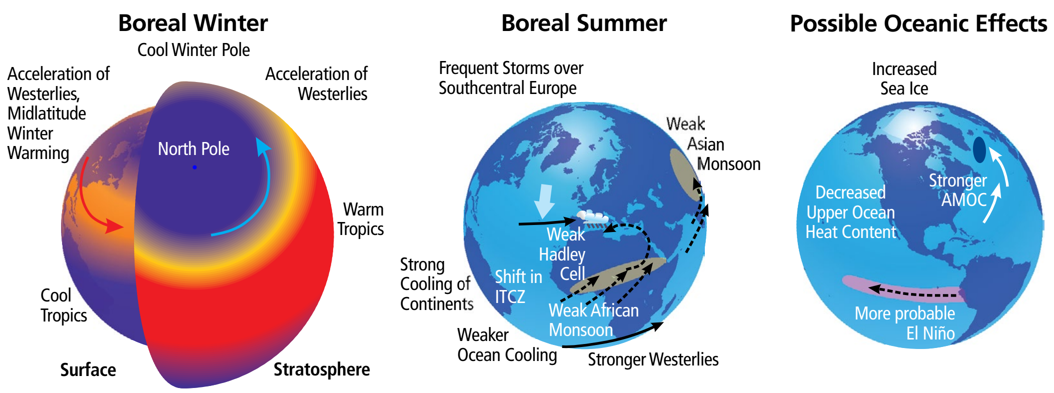
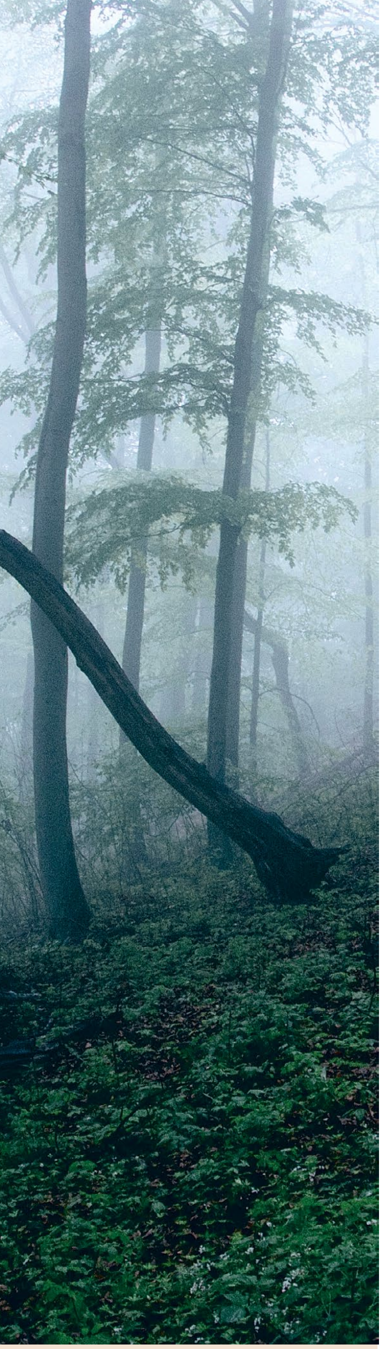


Fig. 16. *Schematic depiction of some mechanisms by which volcanic eruptions affect climate indirectly via changes in atmosphere circulation or the ocean.* [136]

Sea ice increases after volcanic eruptions and might trigger further feedback mechanisms

Volcanic eruptions have been suspected to be the trigger of the "Little Ice Age", via feedback mechanisms involving sea ice. [137] After the Tambora eruption, sea ice conditions were severe in the Baffin Bay but little ice was found in the Greenland Sea. However, whether there is any relation to the Tambora eruption remains unknown.



Biophysical Effects

The 1815 Tambora eruption also affected the biosphere. On Sumbawa and neighbouring islands, the products of the eruption altered biogeochemical cycles. Ash deposits destroyed the crops and changed the water pH and composition, which further affected plant and animal life. Farther away, Tambora's climatic as well as radiative effects influenced the land biosphere. In monsoon regions, the decreased precipitation led to drought and affected growth, and in other regions the rainy weather adversely affected the plants. Apart from the severe regional effects, some of which are discussed in the following pages, one may wonder whether Tambora affected the global carbon cycle.[138,139] Several mechanisms might be important for the land biosphere: low temperature slows growth, increased diffuse radiation may stimulate photosynthesis of some plants, and changes in precipitation may also affect growth on a global scale. Lower temperature and associated changes in soil moisture may lead to a decrease in heterotrophic respiration. Furthermore, the ocean uptake may be altered due to changing winds, temperature, and ocean circulation. While the relative roles of individual factors remain unclear, it has been suggested that the net effect of volcanic eruptions is a small uptake of CO_2.[140]

On a regional scale the effects on crops are of particular relevance. For instance, due to the missing monsoon, droughts and cooling for three years in a row led to bad harvests and famine in the Yunnan region of China in 1816.[141] Here, people reportedly started to eat clay, as the rice had been destroyed completely. India also suffered from droughts and heatwaves[142] (this somewhat counterintuitive occurrence – heatwaves despite volcanic cooling – can be explained by cloud cover anomalies as discussed in Fig. 15). Droughts furthermore might have occurred in Africa, although documentation is lacking.

Climate factors such as temperature, radiation and precipitation affect quantity and quality of the harvest, but also the timing. Delayed growth means that crops are exposed to pests, hail and other incidences for a longer time. Hence, as for climate, biophysical effects may go beyond the direct effects.

Puma and co-authors[143] recently studied the effect of a Tambora-type eruption on a globally connected market in order to assess the stability of the global food system. They found that such an event could be a trigger for a global systemic disruption of the food system.

In Switzerland, according to model simulations[144] the reduced temperature and low solar radiation (increased cloud cover) slowed plant growth and led to low harvested biomass. Depending on the crop, losses of around 10–40 % are modelled (e.g., for potatoes). In addition, historical sources show that excessive wetness led to rotting crops, a factor that is not explicitly taken into account in the model. Reportedly, yields were lower by about 20–30 % in 1816, and the quality of the crops was low. Wine grapes were harvested unripe in November before the winter came.

Note that the adverse weather also indirectly affected the availability of food in the months after the harvests. In the early 19^{th} century, losses along the consumption chain were large, and they were even larger in 1816. The wet weather certainly affected storage. Crops not only rotted on fields but also in granaries because grains were harvested wet. In addition, transportation was affected by the weather, as will be discussed in the next section. Finally, the weather also affected the demand of resources (e.g., of fire wood).

The effect of the adverse weather in Central Europe in 1816 on animal life is not well studied. Due to the effects on the harvest yields, the fodder for animals was similarly affected in terms of availability, price, and quality. Horses and cattle that could not be fed were eaten. Furthermore, oat and potatoes were eaten by humans as substitutes rather then being used as fodder.

A further indirect biophysical effect of the Tambora eruption concerned pathogens. It has been argued that Tambora was the cause of the first pandemic: the Bengal cholera (Fig. 17), which started in 1817 in the Bengal region and then spread during subsequent years.[145] Perhaps the Tambora climate was favorable for some pathogens in some regions. But certainly, the

Did Tambora also affect the global carbon cycle?

The response of forest ecosystems to volcanic eruptions was studied after the 1991 Pinatubo eruption. Growth was affected negatively due to cooling, leading to a browning of the vegetation. Conversely, deciduous forests were reported to have increased photosynthesis due to the increase of diffuse light. Other compartments such as the soils or the oceans also changed.

Although the effect of the Tambora eruption on the CO_2 concentration in the atmosphere was small, the response of the global carbon cycle to such a disturbance is an interesting test of our understanding.

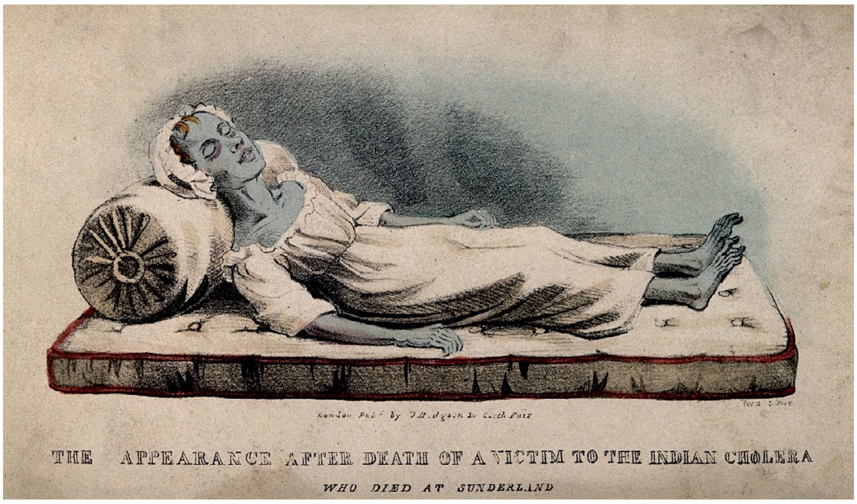


Fig. 17. *Cholera victim in Sunderland, 1832. Coloured lithograph, (photo Wellcome Library, London CC BY 4.0).*

changed health condition and behaviour of humans and cattle was. The weakened individuals were more susceptible to diseases. In desperation, many people left their villages and moved to the cities, where diseases could spread much more easily. The military activities in these years (war between the British East India Company and the Maratha Empire in India) also played a role in spreading diseases. Similarly, cattle diseases perhaps could spread more easily.

Are these biophysical effects of the eruption or are they rather related to changes in the human behaviour? Prices of food, feed and firewood as well as famines, health issues or migration are economic, political, or societal mechanisms rather than biophysical effects.[146] Therefore, in the remaining part of this brochure, we focus on the human system. Before doing that, however, we give a brief summary of the Earth system effects of the Tambora eruption (or volcanic eruptions in general) in Fig. 18. The effects encompass volcanological phenomena, plume dynamics, chemical, microphysical and radiative processes in the atmosphere, dynamical changes of atmospheric circulation, and biophysical effects. The Tambora eruption thus truly calls for a system view: In order to understand "Tambora's" effects we need the expertise of geologists, physicists, chemists, climatologists, and biologists. We need field studies, collections of proxies, numerical modelling, and dynamical analyses. Even then, we might be strongly misled as to the effect on society. In fact, we not only need an Earth system perspective, but an Earth and human systems perspective.

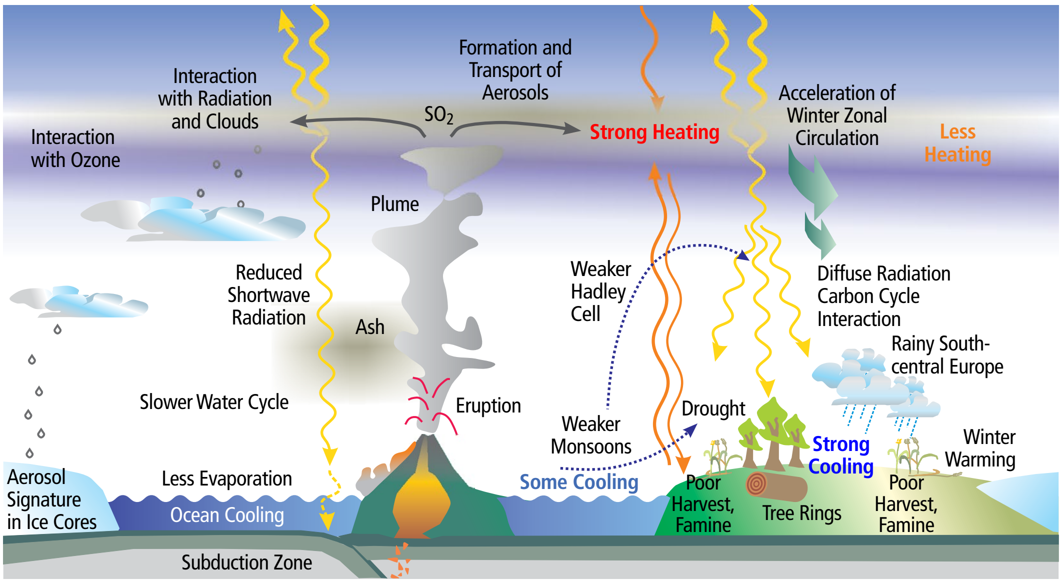


Fig. 18. *Processes in the Earth system related to volcanic eruptions.*

Cholera bacterium Vibrio cholerae

Before bacteria were discovered as causes of illnesses, doctors often attributed illnesses to climatic conditions. Although our view of the infectious diseases has changed dramatically, impacts of climatic changes on the spreading of pathogens is an important research topic.

Did the Tambora eruption affect the cholera outbreak or its spread?

In 1816, Europe was still recovering from the Coalition Wars

Napoleon's defeat restored hopes for people in Europe. After all the adversities of war, all the additional compulsory labour, and the extraordinary taxes, people longed for a peace dividend. A text on the oddities of the years 1816 and 1817 stated: "The first year of peace in the political world became a war year in the physical world."

Photo: Excerpt from painting "Sortie de la garnison de Huningue le 20 août 1815" of Edouard Detaille.

Crisis in Europe

The previous sections have addressed the chain of processes leading from the eruption of a subduction zone volcano to reduced crop harvest. However, the Tambora eruption was not the only reason for the global climate anomalies or the endless rain in Switzerland. Furthermore, the climatic conditions may not have been the only reason for low harvest yields. Finally, the poor harvest was not the only reason for the crisis.

The "Year Without a Summer" hit Europe at an untimely moment. After the Napoleonic Wars (1792–1815), great economic crises began in France, the Netherlands, the Italian states, and Spain.[147] The wars had changed economic structures: on the one hand, the naval blockades cut off the colonial powers from their overseas territories, and on the other hand, the war economy instigated a structural change in agriculture in many states. The blockades had guaranteed much higher grain prices for farmers, and the absence of foreign competition led to an expansion of cultivated land. When the prices fell after the wars, the farmers lost their war pensions. England reacted to the drop in grain prices with the introduction of new Corn Laws in 1815.[148]

The post-war depression was strengthened by several factors: the saturated labor markets that could not absorb all of the demobilized soldiers, the limited negotiating powers of states due to rising debts, and the political post-war reordering of states whose territories had become substantially larger. In addition, a far-reaching structural change in the textile industry occurred, affecting continental centers in particular.[149] In Switzerland alone, around 60,000 jobs in hand spinning were lost between 1787 and 1820 due to the mechanization of the weaving loom. Their fate was finally sealed by the lack of protection after the lifting of the Continental Blockade and the famine years of 1816/17. In the Canton of Zurich, no less than 30,000 unemployed cotton spinners were counted in 1817.[150,151]

People throughout many parts of Europe were hoping for large harvests after the Napoleonic Wars precisely because of these difficulties. Their reserves were exhausted after the ongoing quartering of troops, requisitions, and plundering. When the harvests of the "Year Without a Summer" turned out badly both in amount as well as quality in many regions, the well known mechanisms of price inflation were set into motion. The annual average prices in many European markets doubled or quadrupled between 1815 and 1817.[152] In Switzerland, the price increase ranged between 220 % in Geneva and almost 600 % in Rorschach.[153] During a time in which the majority of people had to spend 60–70 % of their income on food, many households could no longer afford their daily bread.[154]

The purchasing power of consumers sank further during the inflation crisis. The lower and middle classes could barely afford food; the earning opportunities for day laborers and farmhands disappeared with the failure of crops; sales collapsed in the textile industry, and no contracts were made in trade and commerce while inflation consumed incomes.[155] This, in part, led John D. Post to speak of the "last great subsistence crisis in the Western world".[156]

In central Europe, a strikingly uniform canon of coping strategies had existed since the end of the Middle Ages, which included market interventions to regulate supply and demand and "steer" the times of need, as it is often referred to in the sources.[157] At the beginning of the 19th century, measures to stabilize prices, regulate the use of foodstuff, and increase production had priority. The promotion of grain imports and the restriction or even prohibition of grain exports was added to these measures.[158] Rationing was still rare, but in the city of Nuremberg, for example, persons in need were given bread cards.[159] While the collection of private food stocks was the harshest measure, the early purchases of grain from abroad, the establishment of soup kitchens, and the arrangement of public relief works proved to be the most effective coping strategies.[160] Finally, in the Kingdom of Wurttemberg and the Grand Duchy of Baden, migration along the Rhine and the Danube were among the most commonly employed strategies on an individual basis.[161,162]

The severity of need surpassed the imagination of many people. Failed harvests stoked fears of revolutions, the army of beggars grew, the polarization between poor and rich increased, prisons filled, sicknesses such as typhus and pellagra spread, doomsday scenarios found many followers, and the specter of usury led not only to social tensions, but also gave life to the stereotype of the Jewish grain profiteer.[163] The memory of the inconceivable was kept alive in countless descriptions, illustrations, depictions, caricatures, "Teuerungsmedaillen" (inflation medals), and price tables.[164,165,166]

In Switzerland, many patterns were revealed by the crisis. First, the crisis was not as severe on the southern side of the Alps as on the northern side. In the summer of 1816, the cool and moist air accumulated on the northern slope of the Alps and rained out. The southern side of the Alps and the central Alps were more sheltered, which is why these regions were much less affected by the climate anomalies of the "Year Without a Summer" than the regions on the northern side of the Alps. Along with the low population density due to land use and the agro-pastoral production method based on managed risks and subsistence, the favorable climate improved the resistance of the region, despite it being poorly developed and largely unbound to supra-regional markets. The peripheral and "backward" regions in transition from an agrarian to an industrial society were therefore not as vulnerable as the integrated and "progressive" areas of the Swiss Plateau.[167,168,169]

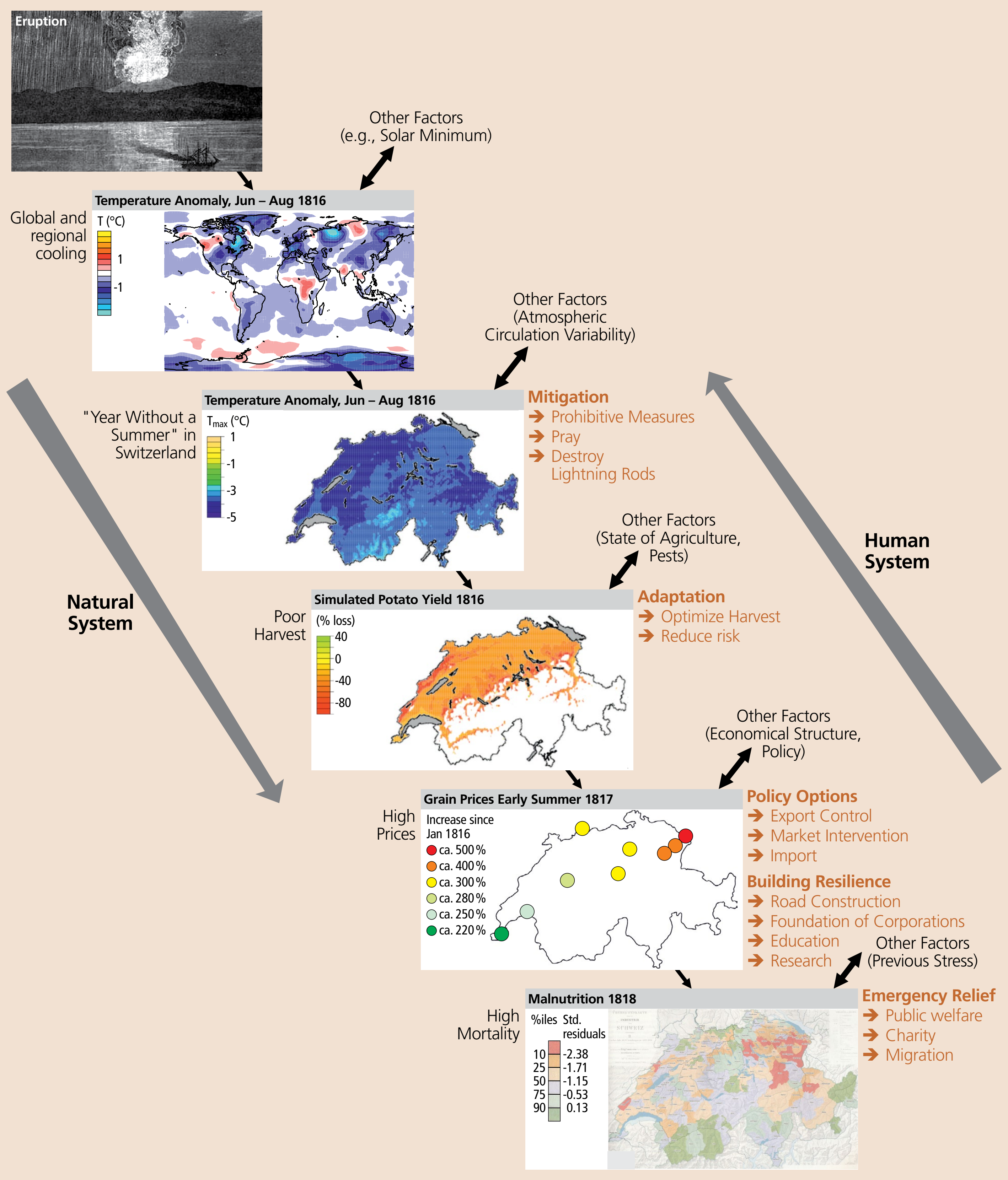
Second, large differences between eastern and western Switzerland were apparent. One of the characteristics of this pattern included the higher mortality rate, the price gap between both regions (see above) and the unequal sizes of their industrial centers. The textile sector spread earlier throughout eastern Switzerland and employed more workers than in western Switzerland. In part because of this, the population density in eastern Switzerland was higher than in the regions of the western part of the Swiss Plateau, the pre-Alps, and the valleys of the Jura. At the same time, the industry had expanded at the cost of agriculture, explaining why the level of self-sufficiency was lower than in the western part of the Swiss Plateau. Ultimately, as southern Germany became the breadbasket of the cantons of eastern Switzerland, an integrated grain market emerged around Lake Constance. The spinners, the weavers, and the winders had become dependent on the market in a dual sense: on the one hand, they relied on an economic boom in the textile industry, and on the other hand, they had to hope for good harvests because the market supplied them with grain. When the agricultural and industrial crises overlapped in the years of 1816 and 1817, they were left with nothing.[170]

Third, the famine crisis did not have solely structural causes. Famine was and is always political.[171] While the cantons of western Switzerland intervened in markets earlier and bought grain from abroad in the fall of 1816 in order to lower prices and curb inflation, the cantons in eastern Switzerland waited longer. Being the younger cantons, they not only possessed less experience with subsistence crises, but they also did not have the same financial resources. In part, the political will to deploy all available resources was also lacking. The budget of the canton of Thurgau ended with a surplus in 1817. The "aimless struggle" against the rapidly growing distress was criticized in a report of the cantonal commission of the poor – the crisis was managed instead of fought.[172,173]

Souvenirs of the Crisis

The crisis 1817 was a memorable event that people described for later remembrance. Many leaflets were printed and medals were coined. A part of this commemorative culture is this cupboard in Appenzell. The photo shows scenes of a hunger year and lists of prices during the 1817 crisis.

A Climate–Society Interaction Model



Tambora, its climate effects and its societal effects addressed as a coupled Earth and human system. With the aid of quantitative approaches, many of the effects of the Tambora eruptions can be linked to each other. Top: Tambora eruption. Second from top: global Jun–Aug temperature anomalies in reconstructions[174] *(see also cover page). Third from top: Jun–Aug temperature anomalies in Switzerland (relative to the period 1800–1820) based on a daily analogue reconstruction approach.*[175] *Third from bottom: Simulated loss in potential potato yield in Switzerland in 1816 (relative to the period 1800–1820) based on daily weather reconstructions.*[176] *Note that actual land use is not considered, as are many other factors that influence the actual yields such as soil wetness, pests or diseases. Second from bottom: Prices for the main grains in Switzerland in early summer 1817 relative to January 1816.*[177] *Bottom: Map of malnutrition in Switzerland in 1818 (representation of people born in 1818 relative to other years, displayed as standardized residuals and percentiles based on a cohort census performed in 1860).*[178]

The effects of the eruptions on and response of society to a climatic event can be characterised by a climate–society interaction model of the type introduced by Ingram[179] and refined by Pfister and Brazdil[180] and others.[181,182] In this model, climatic anomalies have biophysical effects (such as low harvest yields), which then affect society. In trying to cope with the consequences, society interferes with not only with the socioeconomic and political, but also the biophysical world.

For the case of the effects of the 1815 Tambora eruption on famine in Switzerland, many aspects of climate-society-interaction can be further specified and – at least to some extent – even quantified. Furthermore, societal responses can be grouped using this model, as is sketched in the figure. Here, the natural system encompasses the upper left part of the figure, the human system the lower right part. They interact mostly in the middle of the figure, where the biophysical system is situated. It is important to note that the figure does not promote a deterministic, monocausal view, but at each level we focus on one cause-effect relation that must be seen in the context of many other influences.

The 1815 Tambora eruption caused a cooling of the globe. It is shown here in terms of climate reconstructions, as on the cover page.[183] However, other factors (e.g., the previous 1808/09 eruption, low solar activity, or oceanic variability modes) also contributed to global cooling (in fact, global temperature had already been on the decline when Tambora erupted). Likewise, the "Year Without a Summer" in Switzerland (here expressed as a high-resolution temperature reconstruction for Switzerland based on an analogue resampling approach)[184] was only partly an effect of the Tambora eruption. Random atmospheric circulation variability contributed most likely the largest share (see box "How much of the Cold Summer of 1816 in Switzerland was due to Tambora?"). These climatic anomalies influenced crop growth and potential yields. This is shown in the figure by means of model simulations with a crop model based on the above displayed daily weather reconstruction.[185] Again, the adverse weather was likely not the only effect on crop yields. Agricultural practices, political and other factors contributed equally. The reduced yields led to increased prices of the main grains, particularly in 1817, as is shown here from historical data. This increase was far larger in the eastern part of Switzerland than in the West, which can hardly be explained climatically. Again, many other factors – empty storages and a challenged economy after the Coalition Wars, market policies, etc. – contributed. Finally, the increased prices led to malnutrition, again much stronger in eastern Switzerland. This is here derived from cohort statistics (i.e., a statistical analysis of the year-of-birth of all people in the first Swiss census in 1860). Again, various other factors, e.g., previous stress and increased vulnerability, played a role.

While there is a direct link from the Tambora eruption to the malnutrition, its role diminishes at each step (i.e., each panel in the figure above). Conversely, at each step, other factors contribute, and in many cases presumably dominate. It would thus be unwise to frame the famine in Switzerland in terms of Tambora eruption. Its role was arguably minor. Nevertheless, Tambora helps us to understand all different factors leading to famine.

Humans do not face their fate passively. They interact with the sketched natural-human system. They take decisions in order to relieve the suffering, adapt to the adverse conditions, or mitigate the cause of suffering in order to improve their well-being. The interactions can now be placed in this figure. For instance, on the level of malnutrition, several emergency relief strategies were used, ranging from public welfare to charity to decisions on the individual level such as to migrate or to abstain from marriage and reproduction. On the level of the prices, policy measures were taken in many places. Among them were market interventions or export regulations, which directly affected the prices during the crisis. Other measures were more directed towards the future and could be summarized as "building resilience". They included the construction of roads, the foundation of corporations and savings banks[186] or the stimulation of education or of research. On the level of the agricultural yields, strategies to minimise the risk, improve yields, and lower the risks of maximum losses were sometimes pursued, obviously within narrow boundaries due to the available technology and information. Finally, some measures were put into place for mitigating the adverse weather conditions. Among them are the prohibition of dancing in some Swiss cantons, praying, or tearing down lightning rods from houses as observed in Germany and Switzerland. In fact, in parts of Switzerland and southern Germany, lightning conductors (thus the notion of anthropogenic climate change) were blamed by parts of the population for having caused the rainy weather.[187]

Mitigation, adaptation, policy options, building resilience, disaster relief – the responses of society in the "Year Without a Summer" can be analysed with the same categories that we use to characterise present-day climate–society interaction. In this way, the 1815 Tambora eruption and its aftermath might even help us to better understand today's interaction between climate change and society. As in 1816 and 1817, future crises may occur in situations in which climatic changes concur with many other unfavorable circumstances. Reactions will be accordingly multifaceted.

Can we Measure Famine?

Medal of the hunger crisis

Another expression of the culture of remembrance are votive medals or coins, of which many were issued in 1817. This photo shows a medal coined in Nürnberg, 1817. Inscription: "O gieb mir Brod mich hungert" and "Verzaget nicht – Gott lebet noch" (Oh give me bread I am hungry – Do not be disheartened, God still lives).

The intensity and extent of the famine during the years 1816 and 1817 can hardly be "measured". Unlike in natural sciences, famine researchers have not, as of yet, had any success in developing a scale to portray the sensory experience or physiological consequences of famine.[188] Therefore, besides price data, demographic studies are often used to indirectly depict the situation through rising mortality rates and declining birth rates. In addition, the rise of minor misdemeanors during inflation crises and the development of average body height can be used to understand the effects of the subsistence crisis. As these are all indirect indicators, none can claim mathematical accuracy, and they simply convey a sense of the intensity of the hardship.[189] Although all four indicators were affected by the indirect and biophysical impacts of the Tambora eruption, the political, social, and cultural factors must be more heavily weighted, as shown by the interaction model between climate and society (see box "A climate–society interaction model").

In Switzerland, thefts rose along with grain prices during the famine years. This was the general rule in all of Europe during the transition from an agricultural to a civil-industrial society, even if there may have been single exceptions in the "Year Without a Summer." More than half of the people who had warrants out for their arrest in the years 1816–1818 were suspected of theft. These numbers were confirmed by the canton of Aargau: in the years of 1816 and 1817, judges almost exclusively imposed penalties on thieves; this made up more than 90 % of convicted persons.[190]

The famine also affected the development of the average body height. Social and societal inequalities such as the distribution of food within a household, as well as regional differences, were mirrored by this measure. The body is very sensitive to agricultural and industrial crises during its growth phase, since the uptake of nutrients was still very dependent on the economic conditions during the beginning of the 19th century. The average body height of persons born between 1800 and 1809 decreased significantly in the passport registrar of Entlebuch District in the canton of Luzern. They suffered from both the war years as well as the famine. Surprisingly, the average body height of the middle class decreased more than that of the lower class.[191] It is possible that they were less likely to request help in overcoming the crisis than members of the lower classes, due to a fear of social stigmas. A similar scenario occurred in Swiss cities a good hundred years later during the First World War.[192]

The decreasing number of baptisms during the years of the crisis also points to the vulnerability of the Swiss society. During famines, a scissor-like demographic change could be observed in the rising mortality rate and decreasing number of baptisms. Over a long-term perspective, annual birth rates do not fluctuate as strongly as annual mortality rates, and researchers therefore regard birth rates as the more reliable indicator. A cohort census from the year of 1860 enabled the reconstruction of the development of the cohort at a district level in the entire nation. Vulnerability in the famine years proved to be dynamic rather than static: in the first year of the crisis, the climate-sensitive wine-growing regions by the large lakes of the Swiss Plateau, the cities, and the canton of Bern were particularly vulnerable. In the second year, the crisis moved to eastern Switzerland and the valleys of the Jura, where the jewelry and watchmaking industry had expanded. Statistically seen, while only sufficient food was lacking in western Switzerland, a true famine prevailed in eastern Switzerland.[193] In the canton of Appenzell Innerrhoden, single communities lost around one ninth of their population, not even counting emigration. It was very likely "the worst demographic crisis since the pest of 1629".[194]

Famine is a complex phenomenon, where climate is one factor out of many. On the one hand, hardly any event besides a famine affects a society so comprehensively. On the other hand, many processes precede the event by influencing the vulnerability of the society and confer a structure to the famine itself. This paradox makes a uniform approach to understanding the various manifestations of a famine more difficult, and has caused a communication problem in research. The field of research is therefore not only unclear, but there is also no consensus as to how the phenomenon should be approached.[195]

The various approaches to the phenomenon of "famine" have led to the development of two theories that are diametrically opposed. On the one hand, famine is seen as a consequence of "natural" causes such as climatically-determined crop failures. From this perspective, famine is perceived as a problem of supply, and is solely reduced to production (Food Availability Decline Theory). On the other hand, political factors, such as unequally distributed access (entitlement) are highlighted as the cause of famine. From this perspective, the distribution of food plays a central role (Food Entitlement Decline Theory).[196] When analysing famine, regardless of the approach, it makes sense to differentiate between three levels: region, household, and the individual. The causes, consequences, short term adjustments, as well as long term adaptations can vary, based on these levels.[197,198]

The last great subsistence crisis of the western world after the eruption of Tambora counts as an ideal case study in historical climatology, used to understand the interactions between climate and society.[199] The abundance of resources enables not only a concerted examination of the interactions between climate, nutrition, and politics, but also allows for a differentiated picture of human reactions to climatic extreme events to emerge.

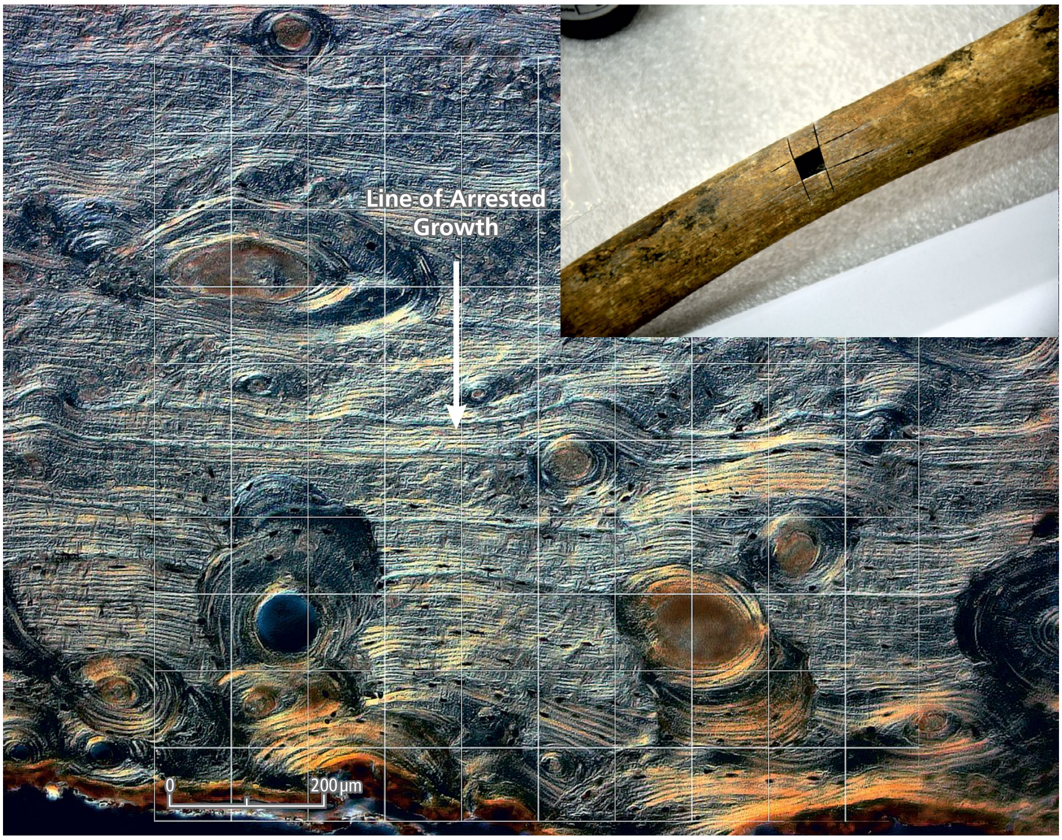
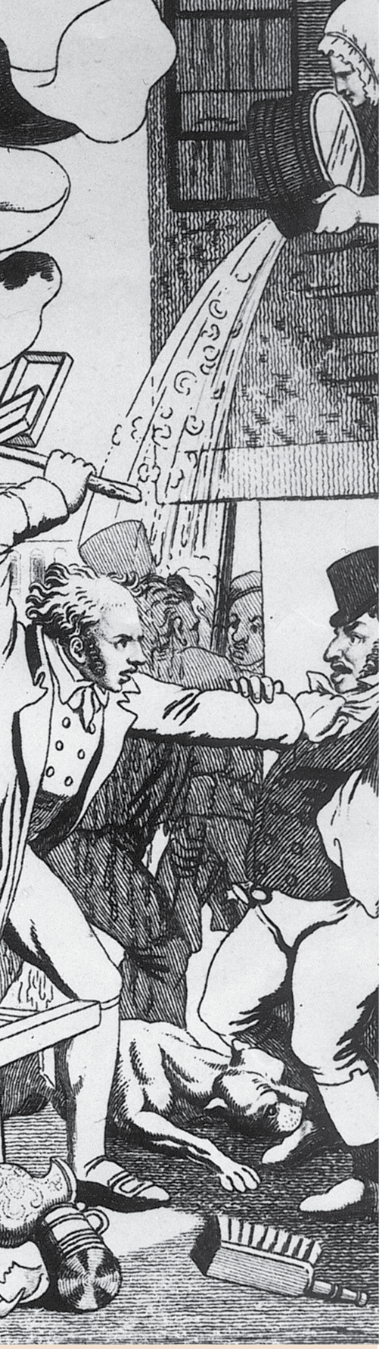


Fig. 19. *Thigh bone of Susanna Hunziker-Widmer (ca. 1799–1853), who had experienced the famine as an 18-year-old woman. Imprints can be seen in the bone microstructure. The marked white line in the middle of the photograph shows a line of arrested growth (LAG) that coincides with crisis and famine of 1816 and 1817. Histological section and photograph by Stefanie Doppler.*[200]

The famine in 1817 caused death and desperation

The crisis of 1817 had considerable demographic effects. On the one hand, the mortality rate increased, on the other hand the birth rate decreased. In Appenzell Innerrhoden individual communites lost up to one ninth of their population.

Photo: "Zum Andenken an die grosse Theurung und Hungersnoth im Jahr 1817" Coloured illustration in "art brut" style of an angel, with maximum prices of the main grains in 1817.



Riots

In the early 19th century, riots were a form of self-help for the common people. They fought for fair prices. In search for the responsibles of the crisis, many anti-Semitic riots broke out. The photo shows the violent Hep-Hep riots in 1819, as the crisis continued, and was directed against jews.

Photo: Johann Michael Voltz, Grafik der Hep-Hep-Unruhen in Frankfurt am Main, 1819.

Riots

Inflation riots became more frequent in the years 1816–1818. Although studies for single regions are lacking, the political scene became charged and served to balance the powers within the country. The prevention of famines was both justified by natural law as well as one of the oldest sources of legitimization of sovereignty. Nevertheless, collective food riots were among the most important forms of social protests in the 19th century in Europe. The consumers called for a market that would be regulated for their protection during crises. If concessions of the government were absent and if unfair practices were suspected, then this "moral economy" would enable the collective to take the law into their own hands: the consumers ambushed transports or plundered storage warehouses and set "fair prices" for the essential goods required to fulfil daily needs. Since the legal consequences of such forms of protest were difficult to predict, social tensions did not always lead to inflation riots.[201,202,203] In the famine years of 1816 and 1817, the violence reached a state comparable to the times of "The Great Fear" during the French Revolution.[204]

France became the center of the protests and riots. The resistance initially remained passive, however, in the spring of 1817, raids on farms and granaries as well as the forcible occupation of entire villages became more frequent. Two things were obvious: first, a political dimension was generally lacking, and second, the local authorities reacted in a surprisingly pragmatic manner. Even though the riots were quelled by force and single deaths and injuries resulted, the use of violence on both sides did not lead to bloody excesses.[205]

Famine was no equalizer. Protests also took place in the rest of Europe. In the kingdom of Bavaria, five riots were suppressed with military help, and in Koblenz and Mainz the military also had to step in. In England, the protests reached their peak in the summer of 1817, leading the Tory government to hold on to the suspension of the Habeas Corpus Act. Protests were also recorded in Scotland, Ireland, Wales, Norway, northern Italy, Spain, and northern Africa. It is unclear what happened outside of Europe. Nevertheless, we know of anti-colonial uprisings in Asia.[206,207]

Even though riots did not occur in the United States, the failed harvests still changed the face of the country. The number of immigrants shot up and the expansion into the west accelerated. The inflation and famine had a political toll during the congressional elections in the fall of 1816. Around 70 % of the members of Congress were not reelected. The Compensation Act of 1816 was one reason for the dissatisfaction of the people: in the midst of the malaise, members of congress approved an increase of their salaries retroactive to May of 1815.[208]

Although no country suffered as terribly as Switzerland during the "Year Without a Summer", protests remained a rarity.[209] In the canton of Vaud, impoverished families from the Jura planned a march to Lausanne in March of 1817 in order to stock up on food. The government sent two trusted men into the region who were able to calm down the situation.[210] Only in Geneva did a demonstration with plundering and violence occur, in October 1817, ignited by the rising potato prices. Not only the timing but also the location of this demonstration was a surprise. In comparison to the cities in eastern Switzerland, Geneva seemed to have overcome the crisis relatively well, and the demonstration occurred when the greatest moment of need had already passed. Thus, besides exposing the underlying social unrest and dissatisfaction, the demonstration also illustrated a fear of more inflation and its accompanying misery.[211]

“Memory of a Friendly Agreement on the Promotion of Hunger in the Year of 1817”

Aquatint by Rudolf Tanner: Swiss gourmandizers in the famine of 1817 about to be led to hell. Source: Kunsthaus Zürich, Grafische Sammlung, Gr.Inv.A.B.1111. German Text: Erinnerung an die freundschaftliche Übereinkunft zur Beförderung des allgemeinen Hungers im Jahr 1817 / Sag was macht der Barometer? Regen, zeigt er ohne maass / So ihr Herren: das heisst gut Wetter. Frisch jezt eins aus meinem Fass! / Nein, ruft jener von dem Haufen: Geb ich euch ganz andern her; / Den mein Famulus läst laufen, Lernts’ von Meister Luzifer. // Mögs’ euch brennen in der Seele; Hartes wucherndes Geschmeiss! / Seht ihr jenen in der Hölle? Dursten, sie ist jezt noch heiss. / Was schert uns dein Bibel deuten? Bursche jagt die Engel raus / Tod! Fahr ab mit diesen Leuten: Hier ist Mammon Herr im Haus.

The aquatint by Rudolf Tanner tells the observer a story of greed, heartlessness and sin. In the centre of the graphic is a well-dressed man sitting on a barrel – probably a cask of wine. He is holding a barometer in his hand that indicates endless rain. The climatic conditions of the “Year Without a Summer” led to overall crop failures in Central Europe. To the profiteers – in the eyes of the people these were often grain merchants, bakers, millers, large farmers (Grossbauern), and landlords – the climatic anatomy of this year meant good news: they could make a profit from the rising grain prices. Just below the window, there is a man studying a table – the observer might wonder if he is mulling over rising prices. However, he stands for the Janus face of raising prices.

On the one hand, large farmers who could sell their grain on the market, as well as profiteers and speculators, could make a very good living from the economically bad years, and they did not hesitate to flaunt their wealth. Sacks of wheat, a pile of potatoes, wine and bread with cheese or butter illustrate the well-being of this rich, greedy, heartless and sinful scum in the picture (see the original text above). They are supported by devils and a watchdog. Finally, the man with a hooked nose sitting at the table represents the widespread anti-Semitic prejudice of the so-called “Kornjude” (Jewish grain merchant).

The skeleton on the right symbolizes Rudolf Tanners last wish (last line of text). “Oh, death,” the poor exclaim, “we want to get rid of this scum. Take them to hell! Money reigns here.” The curtain is symbolical too: On the left side, the curtain is closed and conceals the poverty of the middle and lower classes. On the right side, an angel opens the curtain as well as the window. Light is shed on the gluttony and the owl sitting on the windowsill carries out its duty as the bringer of bad tidings.

Aftermath

When climatic conditions returned to normal after the eruption of Tambora, the world was not the same anymore. The island of Sumbawa was barely habitable for the next years. Only slowly did the population grow again and did life develop. When the Swiss botanist Heinrich Zollinger (Fig. 2) arrived in 1847, life on the island was still much influenced by the 1815 eruption. Some even say that Sumbawa could never quite recover from the eruption. In fact, most settlements were founded after 1815, since the older locations were deserted after the eruption. Thus, the current settlement structure still bears the evidence of the eruption (Fig. 20).

In Yunnan, China, life also did not return to the state of subsistence agriculture that dominated before the famine. Farmers started to plant opium poppy as a cash crop because it was more robust. From the Yunnan region, the opium farmers then spread south into the region that would later become known as the Golden Triangle, one of the world's largest producer of drugs. A Tambora effect?

The Bengal cholera spread from the Indian subcontinent across Eurasia. It reached Persia in 1823. Cholera then turned up again in Russia in 1829 and Western Europe in 1830. In North America, the first cases occurred in 1832, and in the same year cholera spread in Africa. It is debated whether this was one single pandemic or whether the first pandemic ended in 1824 and a second pandemic, also originating from the Bengal region, started in 1826 and then spread to Europe and North America. Was the Bengal cholera another Tambora effect?

In Central Europe, climatic conditions improved in 1817. However, the hazard was not over. Part of the winter snow of 1816 in the Alps did not melt in the summer of 1816. Even worse, at elevations above 2000 m asl precipitation fell as snow also in summer, thus adding another snow pack on top of the winter snow. The snow from winter and the particularly cold spring 1817 then added to this snow pack, such that in June 1817, a huge snow pack was melting at once. Triggered by a strong precipitation event in June, a large flooding[212] occurred north of the Alps. It was the highest ever reported level of Lake Constance (Fig. 21) and affected waterways for weeks. Climate thus once again affected society and transport of food imports.

Even if things returned to normal in 1818, several years of cold and wet weather left traces in the environment. Most notably, many glaciers in the Alps grew in length with some years of delay and reached maximum lengths around 1820. The "Year Without a Summer" thus contributed to the second last glacier maximum of the "Little Ice Age".

The "Year Without a Summer" also left other traces in the landscape. In the wake of the event, existing networks were extended and improved, and new roads were constructed across the Alps in order to facilitate transport of grain from Southern Europe in case of future famines. In general, the extension and the improvement of the road networks increased not only overall transport capacities, but also offered novel opportunities for trade over longer distances due to its higher reliability and regularity. Furthermore, the floods promoted an older plan by the engineer Johann Gottfried von Tulla to straighten the river Rhine between Basel and Worms. Yet another Tambora effect?

Better supply channels for future hunger crises

Some of the measures taken after the crisis of 1817 aimed at increasing the resilience towards future hunger crises. After the famine of 1816/17, several pass roads such as the Splügen or the San Bernardino were improved to better supply the area of Graubünden with grains imported from southern Europe. In 1820–1826, the Julier Pass road was built, thus adding another navigable pass road.

Photo: Passengers crossing the Julierpass with horse-dawn carriage.

Fig. 20. *Rice fields on the island of Sumbawa in 1998 (photo by Lawson Speedway).*

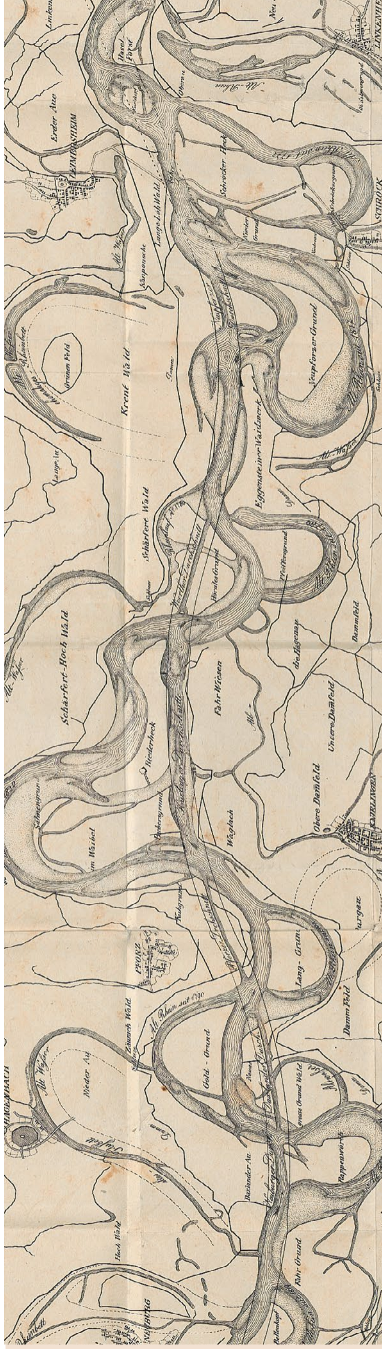
Fig. 21. *High-water mark in Bregenz during the flooding of 1999, the highest lake level of the 20th century (the mark for 1817 should be ca. 5 cm higher than indicated due to settling of the stone),[213] (photo Amt der Vorarlberger Landesregierung, Abteilung Wasserwirtschaft).*

The subsistence crisis revived large-scale emigration. According to John Dexter Post, a hundred thousand desperate Europeans responded to the increasing distress. However, a significant number of emigrants never reached their destination. Either they were forced to return to their old homeland because they could no longer support themselves on the journey or they died during the journey. In the United Kingdom, the number of emigrants to extra-European states noticeably increased between 1816 and 1819. There as well as in France, in the German states and in Switzerland, emigration to the Americas and to Russia was mostly economically motivated. In North America, the fear of a hunger crisis hastened the migration to the West and paralleled the European migration.

The economy also changed: The agricultural sector was volatile, and that volatility could prompt economic downturns. After the bad harvests of 1816, the cultivated area was extended considerably in response to rising agricultural prices. This played an important role in the trade cycles after the subsistence crisis. The expanded capacity for the production of agricultural staples led to falling prices and a longstanding agricultural depression which lasted until the mid-1820s. The United States were able to export grain to Europe during the years 1816 and 1817. However, once harvests in Europe returned to normal values, prices dropped in the USA as well, causing a minor economic crisis. If the high food prices were a matter of concern during the hunger years, from 1819 to 1825 the main economic problem had shifted to the depressed agricultural prices.

Nevertheless, the famine contributed to the ongoing agricultural modernization. Stable feeding all year round, collection of dung-water in covered basins below stables, crop rotation, cultivation of clover, abolition of fallow and conversion of commons into potato fields increased the productivity in the long run significantly. After the subsistence crisis, in Bavaria, Wurttemberg and Switzerland model farms were founded to accelerate the reform processes in the agricultural sector and festivals for agricultural exhibitions were initiated (see also the following two sections).

At the political level, European governments were confronted with a wide range of challenges in the aftermath of the Congress of Vienna: political dislocations, popular disturbances, social unrest, administrative problems, economic depression and protectionism, unemployment, hunger, rioting, looting, begging, vagrancy and large-scale emigration. The high level of anxiety created an environment that favoured conservative and repressive policies. Citizens' rights and fundamental rights were usually restricted and liberal movements were in difficulty. However, the hunger years, the social unrest, the begging and the vagrancy underpinned the need for in-depth reforms of the social welfare systems. In any case, the "Year Without a Summer" left traces, not only in the environment and in the built landscape, but also in society as a whole.



Less frequent floods and navigable rivers

After the floods of 1816 and 1817, river engineering structures were built, for instance the straightening of the river Rhine between Basel and Worms (which had been planned before) by Ing. Johann Gottfried Tulla, aiming at navigation and flood protection.

Photo: Map of the straigthening of the river Rhine near Karlsruhe from a publication of Tulla.[214]

Frankenstein

Mary Shelley's novel became a modern myth as it created an almost inexhaustible supply of images. The novel was translated into almost all languages of the world, was adapted for plays and countless movies.

Photo: Frankenstein observing the first stirrings of his creature, from the 1831 edition of Shelley's novel.[215]

Culture

Many authors argue that the 1815 Tambora eruption also affected European culture. Mary Shelley's "Frankenstein" (see box "How much of the Cold Summer of 1816 in Switzerland was due to Tambora?"), Lord Byron's poem "Darkness" or John William Polidori's "The Vampyre" are then used as examples. Other examples are the sunset paintings by William Turner or John Constable's skies (Fig. 22). These may be famous models, but the effects on culture and society were generally more subtle. In the climate–society interaction model (see box above) cultural impacts are only a faint echo of the eruption of Mt. Tambora.

Fig. 22. *Weymouth Bay with Approaching Storm. Painting by John Constable (1816), (photo Victoria and Albert Museum, London).*

In Central Europe, the culture of remembrance assured that the event is not forgotten. The sufferings of the memorable years 1816 and 1817 – the year without a summer and the scourge of hunger – were written down not only on paper (see page 33), but also on medals (see page 32) or even on cupboards (see page 29). Especially the wave of price increases remained in the people's consciousness. Memorial and satirical prints, commemorative coins, medals and copperplates, coloured illustrations and tables of the rising grain prices, inscriptions in walls, reverse painting on glasses, showcases with breads and monuments were common and produced in large quantities.

In 1817, the return of the first waggon with harvest (Erntewagen) was not only a popular motif, but was also celebrated in many places (Fig. 23). In fact, in some places the celebrations or special worships have survived as tradition since that time, such as the "Cannstatter Volksfest" near Stuttgart which is still celebrated today. Finally, philanthropists such as Ruprecht Zollikofer or Peter Scheitlin published impressive books about the destitution of these years in Eastern Switzerland. Others created utopias – places called "corn valley" (Korntal) or "village of gold makers" (Das Goldmacherdorf). And last but not least, diaries kept the memories of hardship alive. However, it must be stated that this commemorates the "Year Without a Summer", or perhaps more adequately the crisis of 1817 and its end, but not the 1815 Tambora eruption.

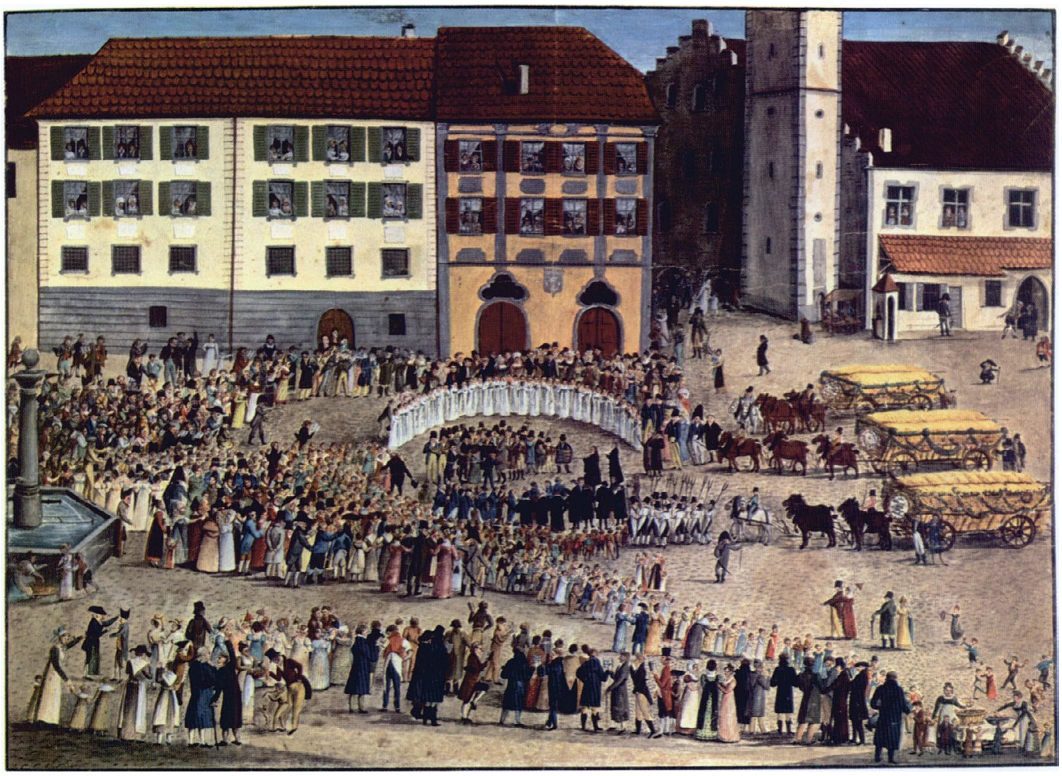


Fig. 23. *Arrival of the first harvest waggons after the famine in Ravensburg on 4 August 1817 (Gouache by G. J. Edinger, 1817, photo Stadtarchiv Ravensburg).*

Another example of how the "Year Without a Summer" of 1816 changed culture and even our everyday lives was the invention of a walking machine by Karl Drais in 1817 (called "draisine"; Fig. 24). The invention was triggered by the fact that many horses were eaten or died otherwise during the hunger crisis because of the high prices for fodder. Furthermore, oat had become a precious good, hence keeping horses had become expensive and nourishment focused on humans. The draisine was invented to provide a fast and efficient mode of transportation. Nowadays kids again enjoy walking bikes, but the draisine was not a direct precursor of today's bicycle, which was only invented decades later.

Are the invention of the modern vampire stories or the draisine just some curiosities, or did Tambora really influence European culture? Again, it would be unwise to see the 1815 Tambora eruption as a major driver or rupture, but it would be equally unwise to completely neglect the "Year Without a Summer".

Fig. 24. *Karl Drais' walking machine (patent, 1817). The high prices for oat in the "Year Without a Summer" inspired Karl Drais to invent a "walking machine" without horses. This seemed to be a promising alternative in view of the increased costs for keeping and feeding horses.*[216]

Like a Bike

Balance bikes are very popular today among children. The invention of balancer bikes goes back to Karl Drais (Fig. 24), whose "walking machine" however was not very successful.

Blame the lightning rods

In parts of Switzerland and Germany lightning conductors were blamed for having caused the bad weather of the summer 1816. After incidences of property damage, the Zurich government passed a decree, which foresaw high penalties for property damage (NZZ, 9 June 1816).

Photo: Lightning rod in Hudlice, Czech Republic.

The Tambora Eruption and Science

Seen over the long term, the Tambora eruption also affected science and research. Immediately, however, scientists had no explanations to offer for the cold and rainy weather in Europe. In the popular imagination, sunspots, lightning conductors, or a passing comet were blamed. For others, good and bad years lay in God's hands. Reports of large masses of ice drifting in the northern North Atlantic by Scoresby (see Section "Climate Anomalies in Observations") were discussed as a possible cause for the cold summer. Although the ultimate cause of the cold and rainy weather remained unknown – or perhaps even because of that – science was stimulated by the event in the following years.

In Switzerland, the cool weather in 1816 prompted the newly founded Swiss Natural Sciences Society to launch the prize question "Is it true that the high Alps have become progressively cooler over the last years?"[217] The answer did not come from meteorology, a discipline which had no position as a science, had no large community, and suffered from a reputation problem (weather was the domain of astrology). Rather, it was an engineer who won the price by studying past glacier positions, concluding that the recent cooling had come to an end: Ignaz Venetz.

This episode is typical in that it shows that established communities such as natural history or geology were able to put the event in the context of their already existing ideas and theories. Although they could not explain the "Year Without a Summer", the research conducted by Venetz on glacial variations was useful and became a strong impetus for the ice age theory.[218] Tambora thus sparked scientific discoveries of a very different nature. Likewise, discoverers used Scoresby's report to obtain funds for new expeditions. Meteorologists, however, remained silent. They had no theory to offer. Despite this, they started several new measurement series and thus also promoted science over the long run. Furthermore, to be able to study the weather anomalies of the summer 1816, Heinrich Wilhelm Brandes suggested weather maps as a diagnostic tool – a very successful suggestion indeed.

Another reaction of science was more strongly guided by practical needs. In Stuttgart, Germany, the University of Hohenheim (Fig. 25) was founded as an academy for forestry (another already established branch of science) in the wake of the "Year Without a Summer" of 1816. Likewise, in Switzerland, the "Strickhof" in the Canton of Zurich was founded in 1818 as an institution of "agricultural education for the poor".

Interestingly, although the Tambora eruption was reported, the link between the bad weath-

Fig. 25. *The University of Hohenheim was founded as an agricultural institution in 1818 as a reaction to the famine of 1817, (photo by Eric. A. Lichtenscheidt, Universität Hohenheim).*

er and the eruption was not made. Only after the next big eruption, that of Krakatau in 1883, did scientists began to study atmospheric effects of volcanic eruptions in a systematic way.[219] The first study relating the "Year Without a Summer" of 1816 to the Tambora eruption was published only in 1913 by William Jackson Humphreys.[220]

From today's perspective, the Tambora eruption can be seen as an "experiment of nature"; an interference with the normal flow of things in the coupled Earth and human system. The experiment may provide answers to various questions, and as the questions posed change over time, science can revisit the experiment again and again.[221] In fact, the Tambora eruption was revisited many times in the past. The first studies put it in the context of the Ice Age Theory,[222] in the 1960s the evolving discipline of historical climatology analysed societally relevant volcanic eruptions including Tambora.[223] In the early 1980s the context was set by the interest in asteroid impacts (the Dinosaur extinction) and nuclear winter.[224] More recently, the discussion on geoengineering has prompted scientists to revisit Tambora. Science keeps learning from studying that same 200-year-old eruption.

Why do scientists today study Tambora? The 1815 eruption is perceived as a worst-case scenario for climate variability, as an analogue for geoengineering, an opportunity for improving seasonal forecasts, a test case of Earth and human systems interactions, and much more. So, in case a future eruption should occur, having studied Tambora helps us to generate seasonal forecasts, and even before an eruption occurs, it may help us defining the monitoring needs. The "Year Without a Summer" of 1816 has also been used as a reference for analysing current food security,[225] and historians study the event to learn more about societal vulnerability and resilience.

Finally, Tambora provides an opportunity to develop tools and methods to study past climate events. In paleoclimatology, the year 1816 is a test bed for reconstruction approaches. For instance, at the occasion of the 200th anniversary year of the event, a new global reanalysis of the period 1815–1817 was released, providing a 6-hourly, 3-dimensional weather reconstruction. In this approach, a weather prediction model is treated such that it provides weather fields that are both physically consistent and consistent with the sparse observations and their errors. As an example, Fig. 26 shows fields of lower tropospheric temperature, geopotential height, wind and uplift as well as precipitation for 29 July 1816, 18 UTC. This is an average of 56 members, i.e., 56 equally likely realisations. These data can be used to interpret the weather events of 1816 in great detail, here showing a front that passes Western and Central Europe and, amplified by strong uplift on the front side of the trough and ahead of the Alps, brought intensive rainfall. The latter was indeed observed in Switzerland (see page 20, left). Behind the front, the figure shows the inflow of cold air, which forced people in Switzerland to heat their houses (see diary entry for 1 Aug 1816 on page 10).

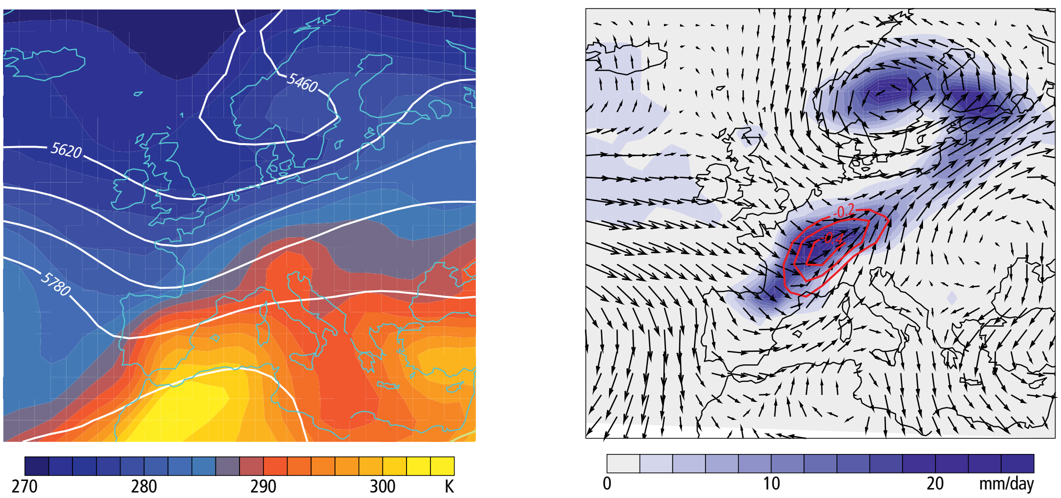
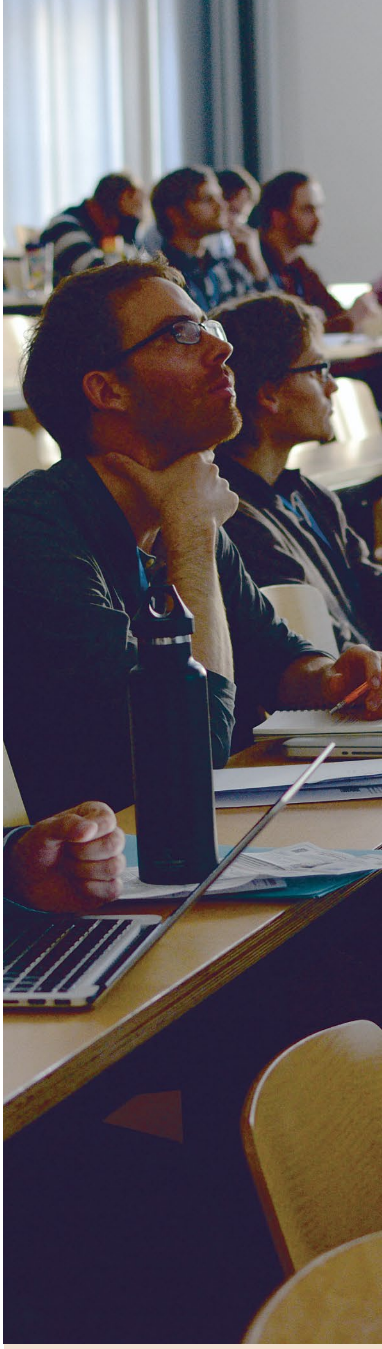


Fig. 26. *(left) Temperature at 850 hPa (colours) and geopotential height at 500 hPa and (right) precipitation (colours), 850 hPa wind (arrows) and vertical motion (Pa/s, negative means upward, only contours -0.2, -0.3 and -0.4 are shown) on 29 July 1816, 18 UTC in the "Twentieth Century Reanalysis" (ensemble mean).*



Even after 200 years we learn from the Tambora eruption

The participants of the Bern Conference on the 200th anniversary year of the 1815 Tambora eruption, 7–10 April 2015 came from various research areas. The conference speakers addressed topics as diverse as aerosol microphysics, agreement of proxies and models, possible hemispheric asymmetry of aerosol spreading and climate effects, implications for the carbon cycle, societal impacts, narratives, and cultural effects.

Photo: Participants at the Bern conference.

The Dutch Colonial reign in Indonesia

Indonesia was only ruled by the British for a short time. In 1816, the Dutch took over again and ruled Indonesia until the Second World War, when it was occupied by Japan. Indonesia obtained independence in 1945.

Photo: Andrees Handatlas, Bielefeld and Leipzig, 1893.

A Changed World

Every catastrophe is perceived as a rupture. For the individual or for society, the world is not the same anymore. Many authors argue that Tambora changed the world.[226,227] It changed Indonesia by killing tens of thousands of people. It affected China and India by drought. It affected the entire world by a cholera pandemic. It changed Europe due to the rainy weather and North America due to the cold air outbreaks. A schematic map is shown in Fig. 27, showing global climatic, biophysical, socio-economic and political effects on a map. Climatic effects, aggravated by other factors, triggered biophysical effects which then, aggravated by other factors, led to societal effects. Seen in this way, Tambora caused approximately 200,000 deaths around the world and changed societies profoundly. D'Arcy Wood,[228] Behringer[229] and others go even further, by linking the tradition of drug cultivation in the "Golden Triangle", social politics in the British Empire or Germany, economic crises in the USA (after the recovery of the European grain market) and many other factors to the eruption of Tambora.

The brochure also shows how science was, and still is, learning from the event. European culture was affected, and even today, an everyday item – the bicycle – reminds us of Tambora.

How far should one go in attributing effects to Tambora? Is it justified to link the migration from Europe to North America (or towards the West within the USA) to Tambora? Many would argue against a "climate deterministic" viewpoint, though acknowledging that climate – and the Tambora eruption – played a role. Thus, it is helpful not to forget the Tambora eruption when studying each of these impacts, but it is certainly not helpful to attribute each of them to one cause – Tambora.

It is clear that all these effects must be analysed in their own, specific contexts. Most likely, other factors were at least as important. However, when adding them up, a truly global picture emerges, which coincides with other ongoing societal changes. So, whether or not Tambora was the cause, the world was different after 1815.

__Fig. 27.__ Schematic map of the impacts of the 1815 Tambora eruption (blue: climate effects, green: biophysical effects, orange: socio-political or economic effects).

Conclusions

The eruption of Mt. Tambora in 1815 devastated Sumbawa and neighbouring islands. It affected the global atmosphere through a sequence of chemical, microphysical and radiative processes, leading to a cooling of the Earth's surface. The radiative changes, both in the stratosphere and troposphere, altered atmospheric dynamics and changed circulation patterns. The perturbations influenced the oceans, sea ice, and biogeochemical cycles. The entire Earth system was affected, and an Earth's system perspective is required to understand the event in its full complexity.

But first and foremost, humans were affected. Tens of thousands died in Indonesia. People in Central Europe suffered from a cold, rainy summer, bad harvests, increasing prices, and famine. The societies that were already vulnerable due to the political instability and the preceding Napoleonic Wars had to deal with the crisis. In some places, riots broke out. In short, the Tambora eruption of 1815 and the "Year Without a Summer" of 1816 had lasting effects on the economic, social, political, technical, cultural and, last but not least, scientific environment since that time. However, there is no monocausal explanation for the effects – no deterministic chain leading straight from the eruption to the famines. At each step, many other factors contributed: other climate factors, random weather variability, the political and economic situation of the European countries, and a stressed population.

From this we can also learn for future climate impacts: Crises might not be primarily climatically caused, but there will always be unfortunate coincidences, in which climatic effects after all might contribute to a crisis. The model of Earth and human systems interaction introduced here helps to understand such phenomena. This makes the Tambora eruption of 1815 attractive as many of today's grand challenges such as dealing with global climate change and food security require an Earth and human systems perspective. Studying Tambora, scientists gain knowledge about the specific process in their own field, while interacting with others to get the big picture.

What would happen today after a Tambora-type eruption? Perhaps such an eruption could be forecasted and people could be warned, but this is not always possible.[230] Even then, global climate could be affected in nearly the same way as in 1816: by a global cooling and slower water cycle (although the exact effect on the monsoon might depend on the season and latitude of the eruption). This could have disruptive impacts on the global food system.[231] However, unlike the societies in 1816, we would be able to predict at least some of the long term climatic consequences of a large eruption, and be able to adjust our response.

Concerning Europe, it is important to note that not all strong eruptions lead to "Years Without a Summer". A lot of random variability is also needed. If a "Year Without a Summer" should occur, we would be less vulnerable. While bad weather would still affect the harvest (and prevent farming with heavy machines), imports would replace the losses (as long as the harvest failure is not global). Furthermore, emergency plans exist and good information would alleviate the effects. Seasonal predictions would help anticipating the bad harvests and medium range weather forecasts would help to plan agricultural activities even in a very bad summer. Finally, as the proportion of income spent on food is much less than in 1816, a shortage (and higher prices) would affect the population less severely. Thus, in isolation, the effects on Central Europe would arguably be manageable.

Nevertheless, a future "Year Without a Summer" could also be just one additional stress factor added to many others – social, political, economic. Together, these factors might nevertheless lead to profound transformations. Science then would perhaps again turn to the 1815 Tambora eruption. One thing is certain: Revisiting the Tambora eruption in 50 years time, we will realize that we have solved many of the issues, but perhaps we will also come away with new questions.

A national Park

On April 11th, 2015, the Tambora area was declared as a National Park by the president of Indonesia, Joko Widodo at the occasion of the bicentenary of the eruption. The plan is to include it in the Global Geopark Network and to stimulate mild tourism in the area.

Notes and References

1 The research presented here was supported, among others, by the Swiss National Science Foundation (project FUPSOL-II), the European Programme HORIZON2020 (Project "EUSTACE") as well as the cogito Foundation.

2 Zollinger H. 1855. *Besteigung des Vulkanes Tambora auf der Insel Sumbawa und Schilderung der Eruption desselben im Jahr 1815.* Winterthur: Wurster, 22 pp.

3 Wanner H. 1984. *Heinrich Zollinger 1818–1859. Ein Zürcher Schulmann als Naturforscher und Pflanzer in Indonesien: sein Leben und seine Zeit.* Zürich: Orell Füssli, 32 pp.

4 Wallace AR. 1863. On the physical geography of the Malay Archipelago. *J Royal Geogr Soc* **7:**205-212.

5 Wallace AR. 1869. *The Malay Archipelago: The land of the orang-utan, and the bird of paradise. A narrative of travel, with sketches of man and nature.* London: Macmillan, 515 pp.

6 Oppenheimer C. 2003. Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Prog Phys Geogr* **27:**230-259.

7 Stothers RB. 1984. The great Tambora eruption in 1815 and its aftermath. *Science* **224:**1191-1198.

8 Klingaman WK, Klingaman NP. 2013. *The year without summer: 1816 and the volcano that darkened the world and changed history.* New York: St Martin's Press, 338 pp.

9 Sudrajat A, Rachmat H. 2015. *Greetings from Tambora. A potpurri of the stories on the deadliest volcanic eruption.* Bandung: Geological Museum, 173 pp.

10 Crowley TJ, Obrochta SP, Liu J. 2014. Recent global temperature 'plateau' in the context of a new proxy reconstruction. *Earth's Future* **2:**281-294.

11 Chenoweth M. 1996. Ships' logbooks and "the year without a summer". *Bull Am Meteorol Soc* **77:**2077-2094.

12 Trigo RM, Vaquero JM, Alcoforado MJ, Barriendos M, Taborda J, Garcia-Herrera R, Luterbacher J. 2009. Iberia in 1816, the year without a summer. *Int J Climatol* **29:**99-115.

13 Post JD. 1977. *The last great subsistence crisis in the Western World.* Baltimore: Johns Hopkins University Press, 240 pp.

14 Wood GD. 2014. *Tambora: the eruption that changed the world.* Princeton: Princeton University Press, 293 pp.

15 Behringer W. 2015. *Tambora und das Jahr ohne Sommer. Wie ein Vulkan die Welt in die Krise stürzte.* München: C.H.Beck, 398 pp.

16 Harington CR. 1992. *The year without a summer? World climate in 1816.* Ottawa: Canadian Museum of Nature, 576 pp.

17 Raible CC, Brönnimann S, Auchmann R, Brohan P, Frölicher TL, Graf HF, Jones P, Luterbacher J, Muthers S, Neukom R, Robock A, Self S, Sudrajat A, Timmreck C, Wegmann M. 2016. Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. *WIREs Clim Change* (accepted).

18 Self S, Rampino MR, Newton MS, Wolff JA. 1984. Volcanological study of the great Tambora eruption of 1815. *Geology* **12:**659-663.

19 Self S, Gertisser R, Thordarson T, Rampino MR, Wolff JA. 2004. Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora. *Geophys Res Lett* **31:**L20608.

20 Sigurdsson H, Carey S. 1989. Plinian and co-ignimbrite tephra fall from the 1815 eruption of Tambora volcano. *Bull Volcanol* **51:**243-270.

21 Kandlbauer J, Sparks RSJ. 2014. New estimates of the 1815 Tambora eruption volume. *J Volcanol Geotherm Res* **286:**93-100.

22 Self et al. 1984, op. cit.

23 Sutawidjaja IS, Sigurdsson H, Abrams L. 2006. Characterization of volcanic depostis and geoarchaeological studies from the 1815 eruption of Tambora volcano. *Jurnal Geologi Indonseia* **1:**49-57.

24 Sudrajat and Rachmat 2015, op. cit.

25 Sudrajat and Rachmat 2015, op. cit.

26 Sudrajat and Rachmat 2015, op. cit.

27 Wood 2014, op. cit.

28 Sutawidjaja et al. 2006, op. cit.

29 Gertisser R, Self S. 2015. The great 1815 eruption of Tambora and future risks from large-scale volcanism. *Geology Today* **31:**132-136.

30 Raffles, TS. 1816. *Narrative of the effects of the eruption from the Tomboro mountain, in the island of Sumbawa on the 11th and 12th of April 1815.* Netherlands: Batavian Society for Arts and Sciences (Bataviaasch Genootschap der Kunsten en Wetenschappen), 25 pp.

31 Raffles 1816, op. cit.

32 Humphreys WJ. 1913. Volcanic dust and other factors in the production of climatic changes, and their possible relation to ice ages. *Bull Mt Weath Obs* **6:**1-34.

33 Kandlbauer and Sparks 2014, op. cit.

34 Sigurdsson and Carey 1989, op. cit.

35 Arfeuille F, Weisenstein D, Mack H, Rozanov E, Peter T, Brönnimann S. 2014. Volcanic forcing for climate modeling: a new microphysics-based dataset covering years 1600–present. *Clim Past* **10:**359-375.

36 Herzog M, Graf HF. 2010. Applying the three-dimensional model ATHAM to volcanic plumes: Dynamic of large co-ignimbrite eruptions and associated injection heights for volcanic gases. *Geophys Res Lett* **37:**L19807.

37 Arfeuille et al. 2014, op. cit.

38 Bigler M, Wagenbach D, Fischer H, Kipfstuhl J, Miller H, Sommer S, Stauffer B. 2002. Sulphate record from a northeast Greenland ice core over the last 1200 years based on continuous flow analysis. *Ann Glaciol* **35:**250-256.

39 Crowley TJ, Unterman MB. 2013. Technical details concerning development of a 1200-yr proxy index for global volcanism. *Earth Syst Sci Data* **5:**187-197.

40 Arfeuille et al. 2014, op. cit.

41 Arfeuille et al. 2014, op. cit.

42 Zerefos CS, Tetsis P, Kazantzidis A, Amiridis V, Zerefos SC, Luterbacher J, Eleftheratos K, Gerasopoulos E, Kazadzis S, Papayannis A. 2014. Further evidence of important environmental information content in red-to-green ratios as depicted in paintings by great masters. *Atmos Chem Phys* **14:**2987-3015.

43 Stothers RB. 2005. Stratospheric transparency derived from total lunar eclipse colors, 1801–1881. *Publ Astron Soc Pac* **117:**1445-1450.

44 Sigl M, McConnell JR, Layman L, Maselli O, McGwire K, Pasteris D, Dahl-Jensen D, Steffensen JP, Vinther B, Edwards R, Mulvaney R, Kipfstuhl S. 2013. A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years. *J Geophys Res* **118:**1151-1169.

45 Gao C, Robock A, Ammann C. 2008. Volcanic forcing of climate over the last 1500 years: An improved ice-core based index for climate models. *J Geophys Res* **113:**2517-2538.

46 Stothers 2005, op. cit.

47 Zerefos et al. 2014, op. cit.

48 Timmreck C, Lorenz SJ, Crowley TJ, Kinne S, Raddatz TJ, Thomas MA, Jungclaus JH. 2009. Limited temperature response to the very large AD 1258 volcanic eruption. *Geophys Res Lett* **36:**L21708.

49 Arfeuille et al. 2014, op. cit.

50 Brönnimann S. 2015. *Climatic changes since 1700.* Adv Global Change Res, Vol 55. Switzerland: Springer International Publishing, xv+360 pp.

51 Arfeuille et al. 2014, op. cit.

52 Timmreck 2009, op. cit.

53 Crowley et al. 2014, op. cit.

54 Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima N, Robock A, Stephens G, Takemura T, Zhang H. 2013. Anthropogenic and Natural Radiative Forcing. In: Stocker TF, Qin D, Plattner DK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, New York: Cambridge University Press, pp. 659-740.

55 Stothers 2005, op cit.

56 Rohde R, Muller RA, Jacobsen R, Muller E, Perlmutter S, Rosenfeld A, Wurtele J, Groom D, Wickham C. 2013. A new estimate of the average earth surface land temperature spanning 1753 to 2011. *Geoinfor Geostat: An Overview* **1:**1.

57 Briffa KR, Jones PD, Schweingruber FH, Osborn TJ. 1998. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature* **393:**450-455.

58 D'Arrigo R, Wilson R, Tudhope A. 2009. The impact of volcanic forcing on tropical temperatures during the past four centuries. *Nat Geosci* **2:**51-56.

59 Wilson R, Tudhope A, Brohan P, Briffa K, Osborn T, Tett S. 2006. Two-hundred-fifty years of reconstructed and modelled tropical temperatures. *J Geophys Res* **111:**C10007.

60 Chenoweth M. 2001. Two major volcanic cooling episodes derived from global marine air temperature, AD 1807–1827. *Geophys Res Lett* **28:**2963-2966.

61 Crowley et al. 2014, op. cit.

62 Mann ME, Zhang ZH, Rutherford S, Bradley RS, Hughes MK, Shindell D, Ammann C, Faluvegi G, Ni FB. 2009. Global signatures and dynamical origins of the Little Ice Age and medieval climate anomaly. *Science* **326:**1256-1260.

63 Frank DC, Esper J, Raible CR, Büntgen U, Trouet V, Stocker B, Joos F. 2010. Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature* **463:**527-530.

64 Brönnimann 2015, op. cit.

65 Raible et al. 2016, op. cit.

66 Raible et al. 2016, op. cit.

67 Crowley et al. 2014, op. cit.

68 PAGES 2k Consortium. 2013. Continental-scale temperature variability during the last two millennia. *Nat Geosci* **6:**339-346.

69 Crowley et al. 2014, op. cit.

70 Büntgen U, Trnka M, Krusic PJ, Kyncl T, Kyncl J, Luterbacher J, Zorita E, Ljungqvist FC, Auer I, Konter O, Schneider L, Tegel W, Štěpánek P, Brönnimann S, Hellmann L, Nievergelt D, Esper J. 2015. Tree-ring amplification of the early-19th century summer cooling in Central Europe. *J Clim* **28:**5272-5288.

71 PAGES 2k Consortium 2013, op. cit.

72 Crowley et al. 2014, op. cit.

73 Neukom R, Gergis J, Karoly DJ, Wanner H, Curran M, Elbert J, Gonzalez-Rouco F, Linsley BK, Moy AD, Mundo I, Raible CC, Steig EJ, van Ommen T, Vance T, Villalba R, Zinke J, Frank D. 2014. Inter-hemispheric temperature variability over the past millennium. *Nat Clim Change* **4:**362-67.

74 Neukom et al. 2014, op. cit.

75 Ridley HE, Asmerom Y, Baldini JUL, Breitenbach SFM, Aquino VV, Prufer KM, Culleton BJ, Polyak V, Lechleitner FA, Kennett DJ, Zhang MH, Marwan N, Macpherson CG, Baldini LM, Xiao TY, Peterskin JL, Awe J, Haug GH. 2015. Aerosol forcing of the position of the intertropical convergence zone since AD 1550. *Nat Geosci* **8:**195-200.

76 Neukom R, Luterbacher J, Villalba R, Kuttel M, Frank D, Jones PD, Grosjean M, Esper J, Lopez L, Wanner H. 2010. Multi-centennial summer and winter precipitation variability in southern South America. *Geophys Res Lett* **37:**L14708.

77 Pauling A, Luterbacher J, Casty C, Wanner H. 2006. 500 years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. *Clim Dyn* **26:**387-405.

78 Feng S, Hu Q, Wu Q, Mann ME. 2013. A gridded reconstruction of warm season precipitation in Asia spanning the past half millennium. *J Clim* **25:**2192-2204.

79 Neukom R, Nash DJ, Endfield GH, Grab SW, Grove CA, Kelso C, Vogel CH, Zinke J. 2014. Multi-proxy summer and winter precipitation reconstruction for southern Africa over the last 200 years. *Clim Dyn* **42:**2713-2726.

80 Gergis J, Gallant AJE, Braganza K, Karoly DJ, Allen K, Cullen L, D'Arrigo R, Goodwin I, Grierson P, McGregor S. 2012. On the long-term context of the 1997–2009 "Big Dry" in South-Eastern Australia: insights from a 206-year multi-proxy rainfall reconstruction. *Clim Change* **111:**923-944.

81 Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW. 2004. Long-term aridity changes in the Western United States. *Science* **306:**1015-1018.

82 Cook ER, Seager R, Kushnir Y, Briffa KR, Büntgen U, Frank D, Krusic PJ, Tegel W, van der Schrier G, Andreu-Hayles L, Baillie M, Baittinger C, Bleicher N, Bonde N, Brown D, Carrer M, Cooper R, Čufar K, Dittmar C, Esper J, Griggs C, Gunnarson B, Günther B, Gutierrez E, Haneca K, Helama S, Herzig F, Heussner KU, Hofmann J, Janda P, Kontic R, Köse N, Kyncl T, Levanič T, Linderholm H, Manning S, Melvin TM, Miles D, Neuwirth B, Nicolussi K, Nola P, Panayotov M, Popa I, Rothe A, Seftigen K, Seim A, Svarva H, Svoboda M, Thun T, Timonen M, Touchan R, Trotsiuk V, Trouet V, Walder F,Ważny T, Wilson R, Zang C. 2015. Old World megadroughts and pluvials during the Common Era. *Science Advances* **1:**e1500561.

83 Cook ER, Anchukaitis KJ, Buckley BM, D'Arrigo RD, Jacoby GC, Wright WE. 2010. Asian monsoon failure and megadrought during the last millennium. *Science* **328:**486-489.

84 Lamb HH. 1970. Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Phil Trans R Soc A* **A266:**425-533.

85 Pfister C. 1999. *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995).* Bern, Stuttgart, Wien: P. Haupt, 304 pp.

86 Brazdil R, Řezníčková L, Valášek H, Dolák L, Kotyza O. 2016. Effects on the Czech Lands of the 1815 eruption of Mount Tambora: responses, impacts and comparison with the Lakagígar eruption of 1783. *Clim Past Discuss* (in review).

87 Harington 1992, op. cit.

88 Büntgen U, Trnka M, Krusic PJ, Kyncl T, Kyncl J, Luterbacher J, Zorita E, Ljungqvist FC, Auer I, Konter O, Schneider L, Tegel W, Stepanek P, Brönnimann S, Hellmann L, Nievergelt D, Esper J. 2015. Tree-ring amplification of the early nineteenth-century summer cooling in Central Europe(a). *J Clim* **28:**5272-5288.

89 Diary of Johann Peter Hoffmann (1753–1842), farmer and magistrate of Lützelstein (Alsace), resident of Petersbach, transcribed 1987–1992 by Dieter W. Hoffmann, Uster, shortened version by Hartmut Moos-Gollnisch.

90 Trigo et al. 2009, op. cit.

91 Brönnimann 2015, op. cit.

92 Brönnimann 2015, op. cit.

93 Brugnara Y, Auchmann R, Brönnimann S, Allan RJ, Auer I, Barriendos M, Bergstrom H, Bhend J, Brazdil R, Comp GP, Cornes RC, Dominguez-Castro F, van Engelen AFV, Filipiak J, Holopainen J, Jourdain S, Kunz M, Luterbacher J, Maugeri M, Mercalli L, Moberg A, Mock CJ, Pichard G, Reznckova L, van der Schrier G, Slonosky V, Ustrnul Z, Valente MA, Wypych A, Yin X. 2015. A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the "year without a summer" 1816. *Clim Past* **11:**1027-1047.

94 Guevara-Murua A, Williams CA, Hendy EJ, Rust AC, Cashman KV. 2014. Observations of a stratospheric aerosol veil from a tropical volcanic eruption in December 1808: is this the Unknown 1809 eruption? *Clim Past* **10:**1707-1722.

95 Anet JG, Muthers S, Rozanov EV, Raible CC, Stenke A, Shapiro AI, Brönnimann S, Arfeuille F, Brugnara Y, Beer J, Steinhilber F, Schmutz W, Peter T. 2014. Impact of solar vs. volcanic activity variations on tropospheric temperatures and precipitation during the Dalton Minimum. *Clim Past* **10:**921-938.

96 Pfister 1999, op. cit.

97 Chenoweth M. 2009. Daily synoptic weather map analysis of the New England cold wave and snowstorms of 5 to 11 June 1816. In: Dupigny-Giroux LA, Mock CJ (eds.). *Historical Climate Variability and Impacts in North America.* Netherlands: Springer, pp. 107-121.

98 Brohan P, Ward C, Willetts G, Wilkinson C, Allan R, Wheeler D. 2010. Arctic marine climate of the early nineteenth century. *Clim Past* **6:**315-324.

99 Chenoweth 2009, op. cit.

100 Stommel HM, Stommel E. 1983. Volcano Weather. The Story of 1816, the Year Without a Summer. Newport: Seven Seas Press, 177pp.

101 Auchmann R, Brönnimann S, Breda L, Bühler M, Spadin R, Stickler A. 2012. Extreme climate, not extreme weather: the summer of 1816 in Geneva, Switzerland. *Clim Past* **8**:325-335.

102 Auchmann et al. 2012, op. cit.

103 Auchmann R, Arfeuille F, Wegmann M, Franke J, Barriendos M, Prohom M, Sanchez-Lorenzo A, Bhend J, Wild M, Folini D, Stepanek P, Brönnimann S. 2013. Impact of volcanic stratospheric aerosols on diurnal temperature range in Europe over the past 200 years: Observations versus model simulations. *J Geophys Res Atm* **118:**9064-9077.

104 Auchmann et al. 2012, op. cit.

105 Zschokke H. 1817. Meteorologische Beobachtungen vom zweiten Halbjahr 1816; nebst den Krankheitsgeschichten dieses Zeitraums. *Archiv der Medizin, Chirurgie und Pharmazie* **3:**209-227.

106 Auchmann et al. 2013, op. cit.

107 Hay D. 2010. *Young Romantics: The Shelleys, Byron and other tangled lives.* New York: Farrar, Straus and Giroux, 364 pp.

108 Auchmann et al. 2013, op. cit.

[109] Bhend J, Franke J, Folini D, Wild M, Brönnimann S. 2012. An ensemble-based approach to climate reconstructions. *Clim Past* **8:**963-976.

[110] Arfeuille et al. 2014, op. cit.

[111] Brohan P, Allan R, Freeman E, Wheeler D, Wilkinson C, Williamson F. 2012. Constraining the temperature history of the past millennium using early instrumental observations. *Clim Past* **8:**1551-1563.

[112] Mann ME, Fuentes JD, Rutherford S. 2012. Underestimation of volcanic cooling in tree-ring-based reconstructions of hemispheric temperatures. *Nat Geosci* **5:**202-205.

[113] Anet et al. 2014, op. cit.

[114] Stoffel M, Khodri M, Corona C, Guillet S, Poulain V, Bekki S, Guiot J, Luckman BH, Oppenheimer C, Lebas N, Beniston M, Masson-Delmotte V. 2015. Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years. *Nat Geosci* **8:**784-788.

[115] Thompson DWJ, Baldwin MP, Wallace JM. 2002. Stratospheric connection to Northern Hemisphere wintertime weather: Implications for prediction. *J Clim* **15:**1421-1428.

[116] Guevara-Murua et al. 2014, op. cit.

[117] Anet et al. 2014, op. cit.

[118] Muthers S, Anet JG, Stenke A, Raible CC, Rozanov E, Brönnimann S, Peter T, Arfeuille FX, Shapiro AI, Beer J, Steinhilber F, Brugnara Y, Schmutz W. 2014. The coupled atmosphere–chemistry–ocean model SOCOL-MPIOM. *Geosci Model Dev* **7:**2157-2179.

[119] Muthers et al. 2014, op. cit.

[120] Vupputuri RKR. 1992. The Tambora eruption in 1815 provides a test on possible global climatic and chemical perturbations in the past. *Natural Hazards* **5:**1-16.

[121] Iles CE, Hegerl GC, Schurer AP, Zhang X. 2013. The effect of volcanic eruptions on global precipitation. *J Geophys Res* **118:**8770-8786.

[122] Wegmann M, Brönnimann S, Bhend J, Franke J, Folini D, Wild M, Luterbacher J. 2014. Volcanic influence on European summer precipitation through monsoons: possible cause for "years without summer". *J Clim* **27:**3683-3691.

[123] Joseph R, Zeng N. 2011. Seasonally modulated tropical drought induced by volcanic aerosol. *J Clim* **24:**2045-2060.

[124] Kandlbauer J, Hopcroft PO, Valdes PJ, Sparks RSJ. 2013. Climate and carbon cycle response to the 1815 Tambora volcanic eruption. *J Geophys Res* **118:**12497-12507.

[125] Wegmann et al. 2014, op. cit.

[126] Wegmann et al. 2014, op. cit.

[127] Maher N, McGregor S, England MH, Sen Gupta A. 2015. Effects of volcanism on tropical variability. *Geophys Res Lett* **42:**6024-6033.

[128] Stenchikov G, Delworth TL, Ramaswamy V, Stouffer RJ, Wittenberg A, Zeng FR. 2009. Volcanic signals in oceans. *J Geophys Res* **114:**D16104

[129] Frölicher TL, Joos F, Raible CC. 2011. Sensitivity of atmospheric CO_2 and climate to explosive volcanic eruptions. *Biogeosciences* **8:**2317-2339.

[130] Fischer EM, Luterbacher J, Zorita E, Tett SFB, Casty C, Wanner H. 2007. European climate response to tropical volcanic eruptions over the last half millennium. *Geophys Res Lett* **34:**L05707.

[131] Wegmann et al. 2014, op. cit.

[132] Driscoll S, Bozzo A, Gray LJ, Robock A, Stenchikov G. 2012. Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. *J Geophys Res* **117:**D17105.

[133] Graf HF, Kirchner I, Robock A, Schult I. 1993. Pinatubo eruption winter climate effects: model versus observations. *Clim Dyn* **9:**81-93.

[134] Robock A. 2000. Volcanic eruptions and climate. *Rev Geophys* **38:**191-219.

[135] Baldwin MP, Dunkerton TJ. 2001. Stratospheric harbingers of anomalous weather regimes. *Science* **294:**581-584.

[136] Brönnimann 2015, op. cit.

[137] Miller GH, Geirsdottir A, Zhong YF, Larsen DJ, Otto-Bliesner BL, Holland MM, Bailey DA, Refsnider KA, Lehman SJ, Southon JR, Anderson C, Bjornsson H, Thordarson T. 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophys Res Lett* **39:**L02708.

[138] Frölicher et al. 2011, op. cit.

[139] Kandlbauer et al. 2013, op. cit.

[140] Frölicher et al. 2011, op. cit.

[141] Wood 2014, op. cit.

[142] Wood 2014, op. cit.

[143] Puma MJ, Bose S, Chon SY, Cook BI. 2015. Assessing the evolving fragility of the global food system. *Environ Res Lett* **10:**024007.

[144] Flückiger S. 2015. *Tambora 1815: Impacts of a volcanic eruption on climate and crop yields in Switzerland.* MSc. Universität Bern, 80 pp.

[145] Wood 2014, op. cit.

[146] Luterbacher J, Pfister C. 2015. The year without a summer. *Nat Geosci* **8:**246-248.

[147] Craig L, García-iglesias C. 2010. Business Cycles. In: Broadberry S, O'Rourke KH (eds.). *The Cambridge Economic History of Modern Europe Volume 1: 1700–1870.* Cambridge: Cambridge University Press, pp. 122-144.

[148] Post 1977, op. cit.

[149] Krämer D. 2015. «*Menschen grasten nun mit dem Vieh». Die letzte grosse Hungerkrise der Schweiz 1816/17.* Basel: Schwabe, 527 pp.

[150] Dudzik P. 1987. *Innovation und Investition. Technische Entwicklung und Unternehmerentscheide in der schweizerischen Baumwollspinnerei 1800 bis 1916.* Zürich: Chronos-Verlag, 634 pp.

[151] Humair C. 2004. *Développement économique et état central (1815–1914): Un siècle de politique douanière suisse au service des élites.* Bern: Peter Lang, 870 pp.

[152] Post 1977, op. cit.

[153] Krämer 2015, op. cit.

[154] Buchheim C. 1997. *Einführung in die Wirtschaftsgeschichte.* München: C.H.Beck, 173 pp.

[155] Plumpe W. 2010. *Wirtschaftskrisen. Geschichte und Gegenwart.* München: C.H.Beck, 127 pp.

[156] Post 1977, op. cit.

[157] Collet D, Krämer D. 2016. Famines in Austria, Germany and Switzerland – natural and political environments. In: Alfani G, Ó Gráda C (eds.). *Famine in Europe*. Cambridge University Press (in print).

[158] Krämer 2015, op. cit.

[159] Vasold M. 2001. Das Jahr des grossen Hungers. Die Agrarkrise von 1816/17 im Nürnberger Raum. *Zeitschrift für bayerische Landesgeschichte* **64:**745-782.

[160] Pfister C. 1998. Deregulierung. Vom Paternalismus zur Marktwirtschaft 1798–1856. *Berner Zeitschrift für Geschichte und Heimatkunde* **60:**160-175.

[161] Bade KJ. 2000. *Europa in Bewegung. Migration vom späten 18. Jahrhundert bis zur Gegenwart.* München: C.H.Beck, 510 pp.

[162] Grabbe HJ. 2001. *Vor der grossen Flut. Die europäische Migration in die Vereinigten Staaten von Amerika 1783–1820.* Stuttgart: Franz Steiner Verlag, 458 pp.

[163] Behringer 2015, op. cit.

[164] Specker L. 1993. Die grosse Heimsuchung. Das Hungerjahr 1816/17 in der Ostschweiz (1. Teil). *Neujahrsblatt* **133:**7-42.

[165] Bayer D. 1966. *O gib mir Brot. Die Hungerjahre 1816 und 1817 in Württemberg und Baden.* Ulm: Deutsches Brotmuseum, 132 pp.

[166] Spamer A. 1916. Bayerische Denkmale aus der «theueren Zeit» vor 100 Jahren. *Bayerische Hefte für Volkskunde* **3:**145-266.

[167] Netting RM. 1981. *Balancing on an Alp. Ecological change and continuity in a Swiss mountain community.* Cambridge: Cambridge University Press, 278 pp.

[168] Ostrom E. 1990. *Governing the commons. The evolution of institutions for collective action.* Cambridge: Cambridge University Press, 280 pp.

[169] Mathieu J. 2015. *Die Alpen. Raum – Kultur – Geschichte.* Ditzingen: Reclam, 254 pp.

[170] Krämer 2015, op. cit.

171 Devereux S. 2007. Introduction: from "old famines" to "new famines". In: Devereux S (ed.). *The new famines. Why famines persist in an era of globalization.* London: Routledge, pp. 1-26.

172 von Greyerz T. 1918. Das Hungerjahr 1817 im Thurgau. *Thurgauische Beiträge zur vaterländischen Geschichte* **57/58:**64-171.

173 Soland R. 2011. Johann Conrad Freyenmuth (1775–1843) und seine Tagebücher. *Thurgauische Beiträge zur vaterländischen Geschichte* **146**.

174 Brönnimann 2015, op. cit.

175 Flückiger 2015, op. cit.

176 Flückiger 2015, op. cit.

177 Krämer 2015, op. cit.

178 Krämer 2015, op. cit.

179 Ingram MJ, Farmer G, Wigley TML. 1981. Past climates and their impact on man: A review. In: Wigley TML, Ingram MJ, Farmer G (eds.). *Climate and history.* Cambridge: Cambridge University Press, pp. 3-50.

180 Pfister 1999, op. cit.

181 Krämer 2015, op. cit.

182 Luterbacher and Pfister 2015, op. cit.

183 Brönnimann 2015, op. cit.

184 Flückiger 2015, op. cit.

185 Flückiger 2015, op. cit.

186 Behringer 2015, op. cit.

187 Anonymus. 1816. Untitled. In: *Neue Zürcher Zeitung* June 21, 1816 and July 9, 1816.

188 Ó Gráda C. 2009. *Famine. A short history.* Princeton: Princeton University Press, 327 pp.

189 Krämer 2015, op. cit.

190 Krämer 2015, op. cit.

191 Krämer 2015, op. cit.

192 Staub K. 2016. Der vermessene menschliche Körper als Spiegel der Ernährungs- und Gesundheitsverhältnisse am Ende des Ersten Weltkrieges. In: Krämer D, Pfister C, Segesser DM (eds.). *«Woche für Woche neue Preisaufschläge». Nahrungsmittel-, Energie- und Ressourcenkonflikte in der Schweiz des Ersten Weltkrieges.* Basel: Schwabe (in print).

193 Krämer 2015, op. cit.

194 Schürmann M. 1974. *Bevölkerung, Wirtschaft, und Gesellschaft in Appenzell Innerrhoden im 18. und frühen 19. Jahrhundert.* Appenzell: Historischer Verein Appenzell, 356 pp.

195 Millman S. 1990. Hunger in the 1980s. Backdrop for policy in the 1990s. *Food Policy* **15:**277-285.

196 Devereux S. 1993. *Theories of famine.* New York: Harvester Wheatsheaf, 288 pp.

197 Millman S, Kates RW. 1990. Toward understanding hunger. In: Newman LF (ed.). *Hunger in history. Food shortage, poverty, and deprivation.* Oxford: Basil Blackwell, pp. 3-24.

198 Krämer D. 2012. Vulnerabilität und die konzeptionellen Strukturen des Hungers. Eine methodische Annäherung. In: Collet D, Lassen T, Schanbacher A (eds.). *Handeln in Hungerkrisen. Neue Perspektiven auf soziale und klimatische Vulnerabilität.* Göttingen: Universitätsverlag, pp. 45-65.

199 Pfister C. 2010. The vulnerability of past societies to climatic variation. A new focus for historical climatology in the twenty-first century. *Clim Change* **100:**25-31.

200 Doppler S. 2008. *Alters-, Aktivitäts- und Krankheitsmerkmale in der menschlichen Knochenmikrostruktur: Eine vergleichende Studie einer individualaltersbekannten historischen Population mit rezenten Menschen.* Diss. Ludwig-Maximilians-Universität München, 503 pp.

201 Thompson EP. 1991. The moral economy reviewed. In: Thompson EP (ed.). *Customs in common.* London: The Merlin Press, pp. 259-351.

202 Gailus M, Volkmann H. 1994 (eds.). *Der Kampf um das tägliche Brot. Nahrungsmangel, Versorgungspolitik und Protest 1770–1990.* Opladen: Westdeutscher Verlag, 477 pp.

203 Randall A, Charlesworth A. 2000. The moral economy. Riot, markets and social conflict. In: Randall A, Charlesworth A (eds.). *Moral economy and popular protest: crowds, conflict and authority.* Basingstoke: Macmillan, pp. 1-32.

204 Post 1977, op. cit.

205 Behringer 2015, op. cit.

206 Post 1977, op. cit.

207 Behringer 2015, op. cit.

208 Skeen CE. 1981. "The year without a summer". A historical view. *J Early Repub* **1:**51-67.

209 Post 1977, op. cit.

210 Henrioud M. 1917. L'année de la misère en Suisse et plus particulièrement dans le canton de Vaud (1816–1817). *Revue historique vaudoise* **25:**21-22.

211 Krämer 2015, op. cit.

212 Wetter O, Pfister C, Weingartner R, Luterbacher J, Reist T, Trosch J. 2011. The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence. *Hydrol Sci J* **56:**733-758.

213 Arbeitsgruppe Wasserstandsvorhersage Bodensee. 2011. Ermittlung des Extremwasserstandes (ca. HW1000) für den Bodensee (Ober- und Untersee). URL: http://www.bodensee-hochwasser.info

214 Tulla JG. 1825. *Ueber die Rektifikation des Rheins von seinem Austritt aus der Schweitz bis zu seinem Eintritt in das Grossherzogtum Hessen.* Karlsruhe: Chr. Fr. Müller's Hofbuchdruckerey, 60 pp.

215 Shelley MW. 1831. *Frankenstein: Or, the modern Prometheus.* London: Colburn and Bentley, 163 pp.

216 Lessing HE. 2003. *Automobilität. Karl Drais und die unglaublichen Anfänge.* Leipzig: MAXIME Verlag Maxi Kutschera. 527 pp.

217 Bodenmann T, Brönnimann S, Hadorn GH, Krüger T, Weissert H. 2011. Perceiving, explaining, and observing climatic changes: An historical case study of the "year without a summer" 1816. *Meteorol Z* **20:**577-587.

218 Krüger T. 2006. *Die Entdeckung der Eiszeiten. Internationale Rezeption und Konsequenzen für das Verständnis der Klimageschichte.* Diss. Universität Bern, 619 pp.

219 Dörries 2005, op. cit.

220 Humphreys 1913, op. cit.

221 Dörries 2005, op. cit.

222 Humphreys 1913, op. cit.

223 Lamb 1970, op. cit.

224 Stommel and Stommel 1983, op. cit.

225 Puma et al. 2015, op. cit.

226 Wood 2014, op. cit.

227 Behringer 2015, op. cit.

228 Wood 2014, op. cit.

229 Behringer 2015, op. cit.

230 Self S, Gertisser R. 2015. Tying down eruption risk. *Nat Geosci* **8:**248-250.

231 Puma et al. 2015, op. cit.

Image Credits of Margin Figures

p.3 Photo by Andrea Kaiser

p.4 NASA / Photo ID: ISS020-E-6563

p.5 Photo by Andrea Kaiser

p.6 Russel WA. 1863. On the Physical Geography of the Malay Achipelago. *The Journal of the Royal Geographical Society of London* **33:**217-234.

p.7 Photo by Richard P. Hoblitt (United States Geological Survey / Cascades Volcano Observatory)

p.8 Image by Stefan Brönnimann

p.9 © Geology Today / Photo by Katie Preece / In: Gertisser R, Self S. 2015. The great 1815 eruption of Tambora and future risks from large-scale volcanism. *Geology Today* **31:**132-136.

p.12 Photo by Carolina Barría Kemp (CC BY SA 2.0)

p.13 NASA / Photo ID: STS043-22-23

p.14 © North Greenland Eemian Ice Drilling project (NEEM)

p.15 Photo by Anton Croos (CC BY SA 3.0) / URL:https://commons.wikimedia.org/wiki/File:Lunar_Eclipse_on_10th_of_December_2011.jpg#filelinks

p.16 Photo by Ulf Büntgen / In: Büntgen U et al. 2015. Tree-Ring Amplification of the Early-19th Century Summer Cooling in Central Europe. *J Clim* **28:**5272-5288.

p.17 (CC0 1.0) / URL:https://pixabay.com/en/drought-earth-desert-aridity-711651/

p.18 Fotolia / Image ID: #53651446 / Photo by Gina Sanders

p.19 Photo by Andrea Kaiser

p.20 Zschokke H. 1817. Meteorologische Beobachtungen vom zweiten Halbjahr 1816; nebst den Krankheitsgeschichten dieses Zeitraums. *Archiv der Medizin, Chirurgie und Pharmazie* **3:**209-227.

p.22 Photo by Andrea Kaiser

p.23 Image by Céline Dizerens

p.24 NASA / LANCE: Rapid Response Image of FAS_India4 Subset 08 August 2015

p.25 NOAA NMFS SWFSC Antarctic Marine Living Resources (AMLR) Program / Photo by Dr. Mike Goebel, NOAA NMFS SWFSC.

p.26 (CC0 1.0) / URL:https://www.pexels.com/photo/forest-trees-dark-fog-6992/

p.27 © Neueste medizinische Nachrichten

p.28 © RMN-Grand Palais (musée d'Orsay) / Christian Jean / Hervé Lewandowski / Sortie de la garnison de Huningue le 20 août 1815, c.1892, Edouard Detaille (1848–1912)

p.29 © Stiftung für appenzellische Volkskunde, Herisau

p.32 Photo by Alexander Basok

p.33 Verein "Projekt 1816"

p.34 © bpk – Bildagentur für Kunst, Kultur und Geschichte / Hep-Hep-Krawalle in Frankfurt am Main, 1819, Johann Michael Voltz (1784–1858)

p.36 Postkarte "Die Juliersäulen am Julierpass". Engadin Press Co., Samaden. 10800

p.37 (CC0 1.0) / URL:http://www.e-rara.ch/doi/10.3931/e-rara-20159

p.38 © Wellcome Library, London (CC BY 4.0) / Image ID: L0027125 / Frankenstein observing the first stirrings of his creature. Engraving by W. Chevalier after Th. von Holst, 1831.

p.39 Fotolia / Image ID: #21730996 / Photo by Jörn Buchheim

p.40 Photo by ŠJů (CC BY SA 3.0) / URL:https://commons.wikimedia.org/wiki/File:Hudlice,_Jungmannova_18,_hromosvod.jpg

p.41 Photo by Céline Dizerens

p.42 Geographische Anstalt von Velhagen und Klasing in Leipzig. 1893. *Andrees Handatlas*, Dritte Auflage, Verlag von Velhagen und Klasing, Bielefeld and Leipzig.