Workshop on Impacts of large volcanic eruptions on climate and societies: proxies, models and solutions for the future

Saas Fee, Switzerland, August 11-15, 2020

Jointly organized by the University of Geneva, Switzerland, Institut Pierre et Simon Laplace (IPSL), France, University of Berne, Switzerland and University of Oslo, Norway

Workshop Program and Abstract volume

(Abstract are in alphabetical order of author name)

Workshop organizers

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Impacts of large volcanic eruptions on climate and societies:
Proxies, models and solutions for the future

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WORKSHOP PROGRAM

	Tuesday, August 11	
Afternoon	**Participants arrive in Saas Fee**	
18:30	Icebreaker, followed by supper (around 19:30)	
	Wednesday, August 12	
09:00-09:10	Welcome by the organizers and meeting objectives.	
	SESSION 1: Volcanic case studies of the Common Era ***Chairperson: Gary Lynam***	
09:10-09:30	***Samuli Helama, Natural Resources Institute (LUKE), Helsinki, Finland*** Recurrent transitions to Little Ice Age-like climatic regimes over the Holocene	**15**
09:30-09:50	***Helen Mackay, Newcastle University, Newcastle, UK*** Examining potential climatic and societal impacts from the 853 CE Mount Churchill eruption in the North Atlantic region	**22**
09:50-10:10	***Evelien van Dijk, University of Oslo, Oslo, Norway*** Impact of the 536/540 CE double volcanic eruption event on the 6th-7th century climate using model and proxy data	**34**
10:10-10:30	***Sébastien Guillet, University of Geneva, Geneva, Switzerland*** Climatic and societal impacts of a "forgotten" cluster of volcanic eruptions in 1108-1110 CE	**14**
10:30-10:50	***Lavigne Franck, University Paris 1 Pathéon-Sorbonne, France*** Did a megatsunami of volcanic origin devastate the kingdom of Tonga in the mid-15th century?	**20**
10:50-11:30	Coffee, tea, refreshments	
	SESSION 2: Climate impacts following 19th century eruptions ***Chairperson: Michael Sigl***	
11:30-11:50	***Stefan Brönnimann, University of Berne, Berne, Switzerland*** Early 19th century volcanic eruptions and their imprint in the Earth system locally and globally	**11**
11:50-12:10	***Davide Zanchettin, Unversity Ca'Foscari, Venice, Italy*** The early 19th century winter climate conundrum	**36**
12:10-12:30	***Pablo Ortega, Barcelona Supercomputing Center, Barcelona, Spain*** Climate response to the Pinatubo and Tambora eruptions in idealised experiments with EC-Earth3.2	**24**
12:30-12:50	***Claudia Timmreck, Max-Planck-Institut für Meteorologie, Hamburg, Germany*** Understanding the apparently muted climate response to the strong volcanic eruption of 1809	**32**
13:00-17:00	Free afternoon for outdoor or indoor activities	
17:00-19:30	**DISCUSSION SESSION: Super-size, ancient eruptions – the example of Toba (Leaders: C. Timmreck + K. Krüger)**	
	Introductory talk by Clive Oppenheimer, University of Cambridge, UK, on large African volcanic eruptions (20 minutes), followed by an open discussion	**23**
19:30	Evening meal	

	Thursday, August 13	
	SESSION 3: Proxies of volcanic activity and uncertainties	
	Chairperson: Sébastien Guillet	
09:00-09:20	***Peter Abbott, University of Berne, Berne, Switzerland*** Timing of Holocene volcanic eruptions and their radiative aerosol forcing	**8**
09:20-09:40	***Michael Sigl, University of Berne, Berne, Switzerland*** Towards a precise and accurate 12,000-year ice-core chronology of global volcanism	**30**
09:40-10:00	***Georg von Arx, WSL-ETHZ, Birmensdorf, Switzerland*** Using tree-ring anatomy for climate reconstruction: characterization of "blue rings"	**35**
10:00-10:20	***Patrick Fonti, WSL-ETHZ, Birmensdorf, Switzerland*** Using tree-ring anatomy for climate reconstruction: the Yamal chronology	**13**
10:20-10:40	***Marie Alexandrine Sicre, LOCEAN-IPSL, Paris, France*** Volcanic signal in marine archives	**29**
10:40-11:00	***Thomas Sheldrake, University of Geneva, Geneva, Switzerland*** Persistent volcanism recorded by coral skeletons	**28**
11:00-11:30	Coffee, tea, refreshments	
	SESSION 4: Impacts of volcanic eruptions in Scandinavia	
	Chairperson: Adrien Favillier	
11:30-11:50	***Kirstin Krüger, University of Oslo, Oslo, Norway*** Volcanic Eruptions and their Impacts on Climate, Environment, and Viking Society in 500-1250 CE	**19**
11:50-12:10	***Kjetil Loftsgarden, University of Oslo, Oslo, Norway*** The demography of Iron Age Scandinavia	**21**
12:10-12:30	***Manon Bajard, University of Oslo, Oslo, Norway*** Tracing socio-environmental dynamics and climate changes in the period 300-1300 CE in Scandinavia from lake sediments	**10**
13:00-17:00	Free afternoon for outdoor or indoor activities	
	SESSION 5: Climate responses to CE eruptions	
	Chairperson: Peter Abbott	
17:00-17:20	***Andrew Schurer, University of Edinburgh, Edinburgh, UK*** Attributing the climate response to volcanic eruptions across the last millennium and the instrumental period	**27**
17:20-17:40	***Kevin Anchukaitis, LTRR, University of Arizona, Tucson, USA*** Northern Hemisphere temperature reconstructions and the climate response to volcanic eruptions	**9**
17:40-18:00	***Markus Stoffel, University of Geneva, Geneva, Switzerland*** Possible source(s) and climatic impacts of the 1640/41 CE volcanic eruption(s)	**31**
18:00-18:20	***Julien Emile-Geay, University of Southern California, Los Angeles, USA*** Resolving the differences in the simulated and reconstructed climate response to volcanism over the last millennium	**12**
18:20-18:40	***Matthew Toohey, University of Saskatchewan, Saskatoon, Canada*** On the stratospheric residence time of volcanic aerosols	**33**
20:00	Special Conference Dinner (information will be provided during the Workshop…)	

	Friday, August 14	
	SESSION 6: Socio-economic consequences of large eruptions	
	Chairperson: Christophe Corona	
09:00-09:20	***Felix Riede, Aarhus University, Aarhus, Denmark*** Balancing the equation – developing robust tools for understanding past human responses to volcanic eruptions and their climate perturbations	**25**

09:20-09:40	***Mario Rohrer, MeteoDat GmbH, Zurich, Switzerland*** Cascading effects of large volcanic eruptions	**26**
09:40-10:00	***Heli Huhtamaa, University of Bern, Switzerland*** Assessing the 16–17th centuries socioeconomic consequences of eruption related climatic shocks	**17**
10:00-10:30	Coffee, tea, refreshments	
10:30-13:00	**DISCUSSION SESSION: Volcanic eruptions and ENSO (Leader: M. Khodri)**	
	Introductory talk by Myriam Khodri, LOCEAN-IPSL, Paris, France on "The influence of large volcanic forcing on El Niño – Southern oscillation and global monsoons" (20' total), followed by discussion	**18**
13:00 -17:00	Free afternoon for outdoor or indoor activities	
17:00-19:00	**DISCUSSION SESSION: Characterising future eruptions to assess their impacts on global climate (Leader: T. Sheldrake)**	
	Introductory talk by Thomas Sheldrake, University of Geneva, to set the stage (20' total), followed by open discussion	
19:30	Evening meal	

	Saturday, August 15
	SESSION 7: Final plenary, wrap-up, future work
09:00-10:30	Reports from thematic sessions (5' each) and the breakout sessions (20' each)
10:30-11:00	Coffee, tea, refreshments
11:00-11:30	The way forward, future work and coordination of decisions taken
11:30-11:45	Closing remarks from the organizers, farewell
12:00	Close of the meeting
Afternoon	**Participants depart from Saas Fee (or prolong their stay for hiking, biking or sightseeing…)**

JOINING THE WORKSHOP BY ZOOM

Due to the health conditions, a Zoom session allows you to remotely join the workshop.

For the sake of convenience, a lone Zoom session will be created and maintained during the time slots defined in the Program.

Please, use the information, below, to connect to the Zoom session:
Name : Workshop Saas-Fee — 11-15.08.2020
From August 11 2020, 02:00 PM (Paris), to August 15 2020, 12:00 am.

Direct link to join the Zoom session:
https://unige.zoom.us/j/93665579418
ID: **936 6557 9418**

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Specific connection protocol:
Connect using a SIP protocol: 93665579418@zoomcrc.com

Connect using H.323 protocol
- 162.255.37.11 — USA, W. coast
- 162.255.36.11 – USA, E. coast
- 213.19.144.110 – EMEA

ABSTRACTS
AND
AUTHOR CONTACT INFORMATION

(In alphabetical order by author family name)

Abbott, P.

Timing of Holocene volcanic eruptions and their radiative aerosol forcing (THERA): Tracing tephra horizons in Greenland and Antarctic ice cores

We report on early progress within a component of the THERA project focussed on identifying horizons of volcanic ash (tephra) deposited over the Greenland and Antarctic ice sheets in the last 12,000 years. Microscopic glass tephra shards can be transported in the atmosphere over thousands of kilometres following a volcanic eruption and retain a fingerprint of their source, which can be revealed through single-shard geochemical analysis. Determining the source of tephra horizons found in ice cores in association with glaciochemical indicators of volcanic aerosol deposition allows atmospheric sulphate loadings to be directly attributed to specific volcanoes, improving understanding of the climatic impact of eruptions. In addition, if the tephra is historically dated it can constrain ice-core chronologies and improve the dating of other volcanic events.

Our search for tephra horizons is guided by co-registered, continuous records of volcanic aerosols and microparticle concentrations from Greenland and Antarctic ice cores, and once identified the key challenge is the acquisition of robust geochemical characterisations. Here we discuss the optimal characterisation approach, but also highlight alternative methods that produce less robust data but have been successfully utilised in some recent studies. Finally, we highlight a successful application using the recent identification of tephra from the 1477 CE eruption of Veiðivötn, Iceland, in a Greenlandic ice core. This identification provides the opportunity to assess the climatic impact of this eruption and using it as a chronological fix-point we can confirm the dating of two volcanic eruptions during the 1450s CE and contribute towards the debate regarding their climatic impact.

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Anchukaitis, K.

Northern Hemisphere temperature reconstructions and the climate response to volcanic eruptions

Co-authors: King, J., Wilson, R. and the NTREND Consortium

Recent long-term paleoclimate reconstructions provide new insights into the characteristics and causes of past temperature variability, allow improved fingerprinting of the contribution from radiative forcing agents including volcanic eruptions, and provide out-of-sample tests for climate models. Recent advances in our understanding of the sources of uncertainty and bias in tree-ring reconstruction in particular have resulted in improved estimates of past temperatures that capture the spatiotemporal signature of volcanic eruptions and reveal regional and continental-scale difference in past climate histories. However, climate reconstructions still differ in their representation of the climate response to volcanism, which complicated direct comparison to general circulation models. Here, we take two different ensemble-based approach to hemisphere-scale summer temperature reconstructions in order to identify the range of uncertainty and sensitivity to proxy selection and reconstruction choices. First, we apply an offline ensemble Kalman filter data assimilation (DA) approach to the NTREND tree-ring network using the full set of last millennium climate simulations as priors. Second, we use a revised and expanded network of Northern Hemisphere temperature-sensitive tree-ring chronologies to develop a suite of summer temperature reconstructions and sample across a range of potential proxy subsets. In both cases, we quantify the range of possible reconstructions associated with different methods and proxy data and compare the magnitude of the volcanic response with each parameter and predictor choice. While various inferences can be made from this range of methodological and data choices, overall the clearest evidence is that more, longer, and better data are needed to constrain the large-scale temperature response to volcanic eruptions.

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Bajard, M.

Tracing socio-environmental dynamics and climate changes in the period 300-1300 CE in Scandinavia from lake sediments

Understanding large volcanic eruptions impacts on environments and societies is necessary to consider future climate and socio-environmental interactions. Lake sediments can record these dynamics on a continuous long-time scale and include at the same time footprints from volcanic eruptions, climate changes and human activities.

We analysed the sediments of Lake Ljøgottjern, located southeastern Norway. The largest burial mound of Northern Europe was built in the mid-6th century on the shore of this lake and makes this place an ideal site to study human-environmental interactions throughout the last millennia.

Using a multi-proxy analysis of this sedimentary record, including ^{14}C dating, geochemistry, as well as palynological data, we reconstructed temperature and socio-environmental changes in this area between 300 and 1300 CE (Common Era).

We associated changes in Ca/Ti ratio with changes in temperature. The period between 300 and 800 CE was colder than the periods 200-300 and 800-1300 CE. Five abrupt cooling events seem to be linked to weakened positive NAO (North Atlantic Oscillation) phases, and two of them can also be linked to the two largest volcanic events of the period (i.e. the 536/540 CE double event, and 1257 CE eruption of Samalas).

Palynological data indicate a decrease of the human activities and reforestation of the area in the 6th century. This abandonment is consistent with archaeological findings and could be related to the 536/540 cooling event. Very little activities are then recorded between 700 and 850 CE. Agricultural activities start again strongly in the Viking age with increase in temperature.

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Brönnimann, S.

Early 19th century volcanic eruptions and their imprint in the Earth system locally and globally

A sequence of five large volcanic eruptions during the first half of the 19th century caused global cooling and led to sustained changes in the Earth system. Using climate field reconstructions and climate model simulations, we analyse different aspects ranging from monsoon systems to Pacific climate variability. Narrowing in on Europe, we suggest that these eruptions triggered the last phase of advance of Alpine glaciers. For the specific case of the Tambora eruption and Switzerland, we show severe ecological, societal, economic and even political consequences, shaping the further development to the present.

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Emile-Geay, J.

Resolving the differences in the simulated and reconstructed climate response to volcanism over the last millennium

Explosive volcanism imposes impulse-like radiative forcing on the climate system, providing a natural experiment to study the climate response to perturbation. Previous studies have identified disagreements between paleoclimate reconstructions and climate model simulations (GCMs) with respect to the magnitude and recovery from volcanic cooling, questioning the fidelity of GCMs, reconstructions, or both. Using the paleoenvironmental data assimilation framework of the Last Millennium Reanalysis, this study investigates the causes of the disagreements, using both real and simulated data. We demonstrate that the disagreement may be resolved by assimilating tree-ring density records only, by targeting growing-season temperature instead of annual temperature, and by performing the comparison at proxy locales. Our work suggests that discrepancies between paleoclimate models and data can be largely resolved by accounting for these features of tree-ring proxy networks.

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Fonti, P.

Using tree-ring anatomy for climate reconstruction: the Yamal chronology

Recent studies based on the measurements of wood cell anatomical features along tree-ring series have highlighted promising signal properties and potential for novel applications, which makes this proxy attractive for ecological, physiological and climatological studies. However, mainly due to limitations related to time-consuming and methodologically challenging wood preparation and measuring processes, studies of quantitative wood anatomy have been considered to be constrained to short temporal assessments.

In the project Caldera we address this challenge by proposing, for the first time, the construction of two multi-millennial long cell anatomical chronologies (Yamal and Tornetrask) as one of the tools to better assess the impacts of large volcanic eruption on climate and societies.

By focusing on the ongoing work related to the Yamal chronology, we present i) how we are generating wood cell anatomical data, and ii) shows first preliminary results. Particular focus will be given to highlight the peculiarities and the potential of the signal to address volcanic reconstructions.

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Guillet, S.

Climatic and societal impacts of a “forgotten” cluster of volcanic eruptions in 1108-1110 CE

Recently revised ice core chronologies for Greenland have newly identified one of the largest sulphate deposition signals of the last millennium as occurring between 1108 and 1113 CE. Long considered the product of the 1104 CE Hekla (Iceland) eruption, this event can now be associated with substantial deposition seen in Antarctica under a similarly revised chronology. The bipolar deposition episode has consequently been considered to reveal a previously unknown major tropical eruption in 1108 CE. Here we show that a unique medieval observation of a “dark” total lunar eclipse attests to a dust veil over Europe in May 1110 CE, corroborating the revised ice-core chronologies. Furthermore, careful evaluation of ice core records points to the occurrence of several closely spaced volcanic eruptions between 1108 and 1110 CE. The sources of these eruptions remain unknown, but we propose that Mt. Asama, whose largest Holocene eruption occurred in August 1108 CE and is credibly documented by a contemporary Japanese observer, is a plausible contributor to the elevated sulphate in Greenland. Dendroclimatology and historical documentation attest, moreover, to severe climatic anomalies following the proposed eruptions, likely providing the environmental preconditions for subsistence crises experienced in Western Europe between 1109 and 1111 CE.

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Helama, S.

Recurrent transitions to Little Ice Age-like climatic regimes over the Holocene

Holocene climate variability is punctuated by episodic cool climate events such as the Little Ice Age (LIA) predating the industrial era warming. Their dating and forcing mechanisms have however remained controversial. Even more crucially, it is uncertain whether the earlier events represent climatic regimes similar to the LIA. Here we produce and analyse a new 7500-year long palaeoclimate record tailored to detect LIA-like climatic regimes from northern European tree-ring data. In addition to actual LIA, we identify LIA-like ca. 100-800-year periods with cold temperatures combined with clear sky conditions from 540 CE, 1670 BCE, 3240 BCE and 5450 BCE onwards, these LIA-like regimes covering 20% of the study period. Consistent with climate modelling, the LIA-like regimes originate from a coupled atmosphere-ocean-sea ice North Atlantic-Arctic system and were amplified by volcanic activity, tree-ring evidence pointing to similarly enhanced cooling starting after the eruptions recorded in 1627 BCE, 536/540 CE and 1809/1815 CE. Conversely, the ongoing decline in Arctic sea-ice extent is mirrored in our data which show reversal of the LIA-like conditions since the late 19th century, our record also correlating highly (r = 0.970) with the instrumentally recorded Northern Hemisphere and global temperatures over the same period. Our results bridge the gaps between low- and high-resolution, precisely dated proxies and demonstrate the efficacy of slow and fast climate anomalies to generate LIA-like climate regimes.

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Huebner, S.

Volcanic climatic perturbation and inter-annual Nile flood variability in Roman Egypt

By combining historical sources such as historical accounts, papyri and inscriptions with paleoclimate proxies, this paper explores the potential impact of volcanic activity on Nile flood variability and Egyptian society during the Roman period. Tropical high-latitude volcanic eruptions can disturb hydroclimatic impacts by injecting sulfurous gases into the stratosphere; this causes reduced rainfall in equatorial zones such as the Ethiopian highlands where the Blue and the White Nile have their sources. Reduced monsoon rainfall in the northern Ethiopian highlands would have affected summer Nile floods, leading to gradually lower Nile floods. Studies on earlier and later periods of Egypt have shown that high-latitude volcanic eruptions caused a suppression of Nile summer flooding during the years following the eruption. During the Roman period of Egypt the two largest high-latitude tropical volcanic eruptions strong enough to have triggered a physical response from the Nile happened can be dated with ice core data to approximately 168 CE, and 266 CE; the strongest northern hemisphere volcanic eruption of the first 500 years of the Common Era has been dated to 88 CE (Sigl et al., 2015). A consecutive series of lower Nile floods resulting in diminished agricultural production could lead to subsistence crises and malnutrition, the spread of diseases, an increase in flight from Roman tax-collection, political uproar and overall economic difficulties with repercussions for the grain supply to the Roman army and the city of Rome.

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Huhtamaa, H.

Assessing the 16–17th centuries socioeconomic consequences of eruption related climatic shocks

Reduced incoming solar radiation and sudden cooling, which were associated to volcanic eruptions, caused considerable socioeconomic hardships in the 16^{th} and 17^{th} centuries Swedish Realm (modern day Sweden, Finland and Estonia). These consequences can be systemically detected from the detailed administrative accounts of the kingdom. Furthermore, the archival material indicate that the socioeconomic impacts varied within time and space, as well within the peasant society, partly due to institutional and geographical factors.

This presentation demonstrates how historical research can provide valuable evidence of the societal impacts of volcanic eruptions. This information can be utilized e.g. in policy making, if the unintended human consequences of future geoengineering solutions, like solar radiation modification, need to be assessed.

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Khodri, M.

The influence of large volcanic forcing on El Niño – Southern oscillation and global monsoons

Understanding the influence of volcanic eruptions on tropical climate variability has important societal implications as large events may have strong impacts on global monsoons and El Niño – Southern oscillation (ENSO) and may therefore yield extra predictability beyond the traditional 6-months lead time limit. Previous studies suggest that volcanically induced El Niño-like events involve a more persistent external wind forcing than classical El Niños, whose growth is dominated by internally generated wind anomalies through the Bjerknes feedback. Yet, CMIP5 models used very diverse volcanic forcing products and strategies preventing a clear consensus today about the underlying processes, whether they are linked to internal variability or result from the influence of natural external forcing. Direct observations of sea surface temperatures over the historical period and reconstructions from natural archives such as corals in the Pacific Ocean now provide windows of observations covering several centuries. A unified approach and further analyses in both models and observations are therefore needed to understand how the timing of the eruption modulates the internal ENSO cycle and its influence on the global monsoons. This contribution gives an overview of recent results and discusses the remaining stumbling blocks to ascertain the robustness of identified mechanisms across various models.

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Krüger, K.

Volcanic Eruptions and their Impacts on Climate, Environment, and Viking Society in 500-1250 CE

This multi-disciplinary project aims to understand the role of volcanic eruptions and climate change in shaping the early history of Europe. The period 500-1250 CE is characterized by natural disasters, societal unrest, Viking expansion, emerging kingship – and large volcanic eruptions evidenced by geochemical markers in natural archives.

Contemporary reports of a mysterious cloud which dimmed the light of the sun for at least a year were written at the dawn of the Middle Ages which marked the beginning of an unusual cold period in the mid of the 6th century due to the double volcanic eruption event in 536/540 CE. The social structure of Scandinavian society was radically changed between 500 and 750 CE. Population levels were reduced by plague and agriculture had to be adapted to a colder climate. Tree ring and climate model data from Scandinavia identify a prolonged period of cooling which may have lasted over a century. Following is a period of volcanic activity which was thought to be more quiescent in a global sense and is marked by the onset of the medieval warm period (c. 950 -1250 CE). However, volcanic eruptions in Iceland were frequently active during 700 to 1100 CE and must have had severe impacts on climate, environment and society in Northern Europe, which is not supported by available records.

This presentation aims to shed more light into the background of this early Common Era period based on revised volcanic forcing, complex earth system climate model, proxy, and archaeology data.

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Lavigne, F.

Did a megatsunami of volcanic origin devastate the kingdom of Tonga in the mid-15th century?

Co-authors: F. Lavigne, J. Morin, P. Wassmer, O. Weller, T. Kula, A. Maea, F. Mokadem, K. Kelfoun, M.N.Malawani, M. Benbakkar, C.M. Vidal, S. Saulnier-Copard.

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Loftsgarden, K.

The demography of Iron Age Scandinavia

Prehistoric demographic patterns have long remained hidden, but the availability of large data sets and new tools and methods has given us the opportunity to look behind the veils of the past and uncover the demographics of the Iron Age.

Although it is often stated that abrupt changes in climate had severe societal impacts, these are seldom explicitly defined or quantified. In this paper, I will make use of a systematic approach to large archaeological datasets to identify and understand the long-term societal responses to sudden shifts in climate. Specifically, I will explore the ebb and flow of the past populations in Scandinavia in the period 200–1000 AD, and how these relates to climate and environmental changes.

In Scandinavia, non-Christian burials were used up until the 11th century. This comparatively homogenous grave material gives a unique, and largely unused, approach to uncover relative changes in population size and density. In addition, I will analyse large datasets of radiocarbon dates from archaeological sites. The method is predicated on that the modelled radiocarbon data will reflect variations in human activity.

Never before have archaeologists been so well-equipped to recognize and understand the major changes in the Iron Age societies and settlements. Large-scale archaeological excavations and surveys have generated a vast amount of archaeological data for further research. In addition, most databases have been digitised, making available descriptions and spatial information for millions of archaeological finds and sites.

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Mackay, H.

Examining potential climatic and societal impacts from the 853 CE Mount Churchill eruption in the North Atlantic region

The 853 CE Mount Churchill eruption, Alaska, was one of the largest first millennium volcanic events. Ash fallout from this eruption was extensive, with the cryptotephra – White River Ash east (WRAe) – extending eastwards into Europe. However, the estimated stratospheric sulfur injection from this event, based on Greenland ice core sulfate records, was minor (ca. 2.5 Tg S). Proximal ecosystem disturbances have been linked with this eruption, but wider eruption impacts on climate and society are unknown. This study uses palaeoenvironmental reconstructions, historical records and modelled climate data to assess the potential contribution of the Mount Churchill eruption to climate and societal change.

Precise comparisons of palaeoenvironmental records from eastern North America and western Europe, facilitated by the WRAe isochron, demonstrate that there were no lasting (multi-decadal) impacts from the Mount Churchill eruption on climate in the North Atlantic region. Whilst historical evidence in Europe for subsistence crises demonstrate a degree of temporal correspondence on interannual timescales, the extent to which this relationship is correlative rather than causal is unclear owing to the frequency and persistence of climate and societal perturbations during the 9th century. Reconstructed climate data demonstrate that Northern Hemisphere summer temperatures cooled by <1oC between 851–854 CE. Did this cooling trigger crop failures or did food crises stem from the coincidence of multiple environmental anomalies and societal stresses? We examine the implications of understanding the temporal relationship of the eruption to precisely dated records whilst even a small age uncertainty for the ice cores remains.

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Oppenheimer, C.

Late Quaternary volcanism in Africa: human and climate entanglements

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Africa tends not to be the first continent that comes to mind when thinking about sources or impacts of volcanism. However, it hosts many Late Quaternary volcanoes, notably in the rift valley systems, and in regions of North and West Africa. Evidence for Holocene volcanism is catalogued for around 150 volcanoes, though very few have been systematically studied (Lenhardt and Oppenheimer, 2014). A few significant historical eruptions have been documented, including those of Nabro in 2011 (Goitom et al., 2015) and Dubbi in 1861 (Wiart and Oppenheimer, 2000), and there are well-known sources of prodigious sulphur degassing into the atmosphere such as Nyamuragira (Carn et al., 2003). Recent geochronological studies also indicate that several of the large caldera-forming eruptions evident in the Ethiopian Rift Valley and Afar and the Tibesti occurred in the Middle Pleistocene (e.g., Hutchison et al., 2016). To date very little work has been carried out on their volatile inventories but some of these episodes are likely to have been of hemispheric-scale atmospheric and climatic significance. It is probable that African volcanism has a signature in polar ice cores that is yet to be discovered. A further motivation for deeper studies of Late Quaternary volcanism in Africa stems from the intercalation of distal tephra horizons in stratigraphic contexts replete with archaeological and/or palaeoenvironmental information. Of note, there are exceptional archives in some of the lakes of East and North Africa, and these include both medial, distal and ultradistal tephra records (e.g., Lane et al., 2013; Martin-Jones et al., 2017). Here, an improved geochronological framework built on the tephrastratigraphic lattice and anchored by radiometric dating of correlated proximal deposits can be of especial importance in understanding the pace and phasing of environmental changes. Lastly, regions of North and East Africa offer opportunities to investigate the entanglements of human lifestyles with volcanic terrains, resources (e.g., obsidian) and activity (e.g., Blegen, 2017; Oppenheimer et al., 2019).

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Ortega, P.

Climate response to the Pinatubo and Tambora eruptions in idealised experiments with EC-Earth3.2

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Explosive volcanic eruptions cause episodes of strong negative radiative forcing in the climate system by injecting large amounts of sulphur dioxide into the stratosphere, producing an aerosol which reflects part of the incoming solar radiation. This negative radiative forcing causes a global surface cooling, although there is substantial uncertainty in the magnitude and in the regional climate response in climate models and observations are limited. The aim of this work is to analyse and compare the climate response to the Pinatubo (1991) and Tambora (1815) eruptions, the latter being a significantly greater eruption than the former, in an ensemble of experiments done with the ECEarth3.2 atmosphere-ocean general circulation model (AOGCM). Both the Pinatubo and Tambora volcanic forcings have been estimated with the Easy Volcanic Aerosol (EVA, Toohey et al., 2016) tool, and the Pinatubo forcing has been validated against the CMIP6 estimate. Previous studies have shown that the background climate conditions may mask the climate response to volcanic eruptions of similar magnitude to Pinatubo, making it difficult to detect dynamical signals (e.g. Ménégoz et al., 2017).

Our results show that atmospheric temperature anomalies (tropospheric and stratospheric) in response to the Tambora eruption are significantly greater in magnitude and persist longer, thus making the volcanic imprints more detectable. This is particularly true for global temperatures, for which the response to the forcing seems to be linear. Important differences between the Tambora and Pinatubo eruptions emerge for the dynamical responses. While for the second no significant response have been identified for the main modes of variability, the Tambora eruption consistently leads to an acceleration of the polar vortices, evolving into positive phases of the North Atlantic Oscillation (NAO) and the Southern Anmular Mode phase, respectively in the first boreal winter and the second austral winter. Tambora eruptions also promote the development of el Niño events in the second austral summer, followed by a negative SAM phase one month later.

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Riede, F.

Balancing the equation – developing robust tools for understanding past human responses to volcanic eruptions and their climate perturbations

Recent years have witnessed major leaps in our understanding of past volcanic eruptions and their downstream impacts on climate. Aided by major efforts at integrating various datasets and underwritten by sophisticated computational methods, these new results implicate volcanoes in some profound climatic perturbations. These new insights have also given rise to many high-profile suggestions of associated societal impacts. Such claims are, however, contested by members of the natural scientific and the historical communities. How could such disagreements be resolved? Rooted in the initial results of the ERC CoG project CLIOARCH (http://cas.au.dk/en/ERC-clioarch/), I argue that one way forward is afforded by upgrading the computational dimensions of human science data derived from historical and archaeological sources. By integrating numerous such datasets with digital elevation and climate models within so-called distribution models, the effects on human populations can be investigated, using 'biggish' data, at the landscape scale. Focusing on the Last Glacial-Interglacial Transition and the potential impacts of the Laacher See eruption, I present a workflow that seeks to interrogate the human impacts of this volcanic event as mediated by its climatic perturbations versus impacts caused by tephra deposition and its ecological effects. I argue that the time is right to move the study of volcanic impacts on society from exploratory and loosely correlative approaches towards more ambitious hypothesis-testing ones that balance the size, scale and sophistication of the climatic part of the equation with matching ones from the societal side.

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Rohrer, M.

Cascading effects of large volcanic eruptions

Large volcanic eruptions often trigger secondary impacts like Tsunamis (cf. Anak Krakatau Dec. 2018) which may affect even more people as the eruption itself. Moreover, beside local and regional effects, large volcanic eruptions may have worldwide consequences, as air traffic disruptions or - in extreme cases - a relevant large-scale dimming of the solar radiation with a subsequent cooling of surface air-temperatures and a change in precipitation pattern and its seasonal repartition. These climatic changes may in turn strongly influence agricultural production, solar and hydro-energy production, and eventually flows of refugees, to only mention a few further possible impacts.

It's tried to draft an event-based pathway approach to point out how the impacts of large volcanic eruptions may evolve into a cascade with several branches. These pathway schemes may then serve as a basis for a better preparedness, this not only locally, but also regionally and worldwide.

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Schurer, A.

Attributing the climate response to volcanic eruptions across the last millennium and the instrumental period

This presentation reviews results from detection and attribution of volcanically induced climate change in palaeoclimate archives and instrumental records. Volcanic eruptions can cause periods of rapid climate change even over decades, as evidenced in the early 19th and early 20th century, as confirmed by attributed global temperature signals. Volcanic forcing is also implicated in deviations in rate of warming from what is expected by anthropogenic forcing. Estimates of the magnitude of the model simulated response to volcanic forcing in data tend to find an overestimate of the climate model simulated signal. However, this may be misleading, as incorporating memory as present in treering data in a fingerprint for the volcanic response can reconcile the amplitude of the volcanic cooling as well as its extent. Over the instrumental period, the amplitude of the observed response to volcanism is consistent with climate model simulations when synchronizing El Nino in models and data. This shows that the episodic nature of volcanic forcing causes unique challenges with sampling the observed response in the presence of climate variability. Volcanic eruptions also cause detectible changes in aspects of the watercycle, and these not only extend to the shift of the ITCZ but also to a tendency to dry wet regions and wetten dry regions.

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Sheldrake, T.

Persistent volcanism recorded by coral skeletons

The aragonite skeleton that is precipitated by a coral polyp provides a record of the chemistry of the water column in which it resides. For example, elements such as Sr have long been used as proxies for sea surface temperature and hence used to infer the state of the climatic system. Corals are commonly found on the submarine flanks of volcanic islands located within the tropics. Here, we investigate the ability of corals to record disturbances to the water column due to volcanic eruptions. We focus on corals located in distal locations, as corals located proximally to a volcanic centres are likely to be destroyed or significantly damaged by intense ash fall, gravitational collapses of the volcanic edifice or pyroclastic flows that enter the ocean. Analysing a coral sample that is located approximately 100km from a volcanic centre, we systematically measure the geochemical profile along the growth axis of the coral skeleton using LA-ICP-MS. We show that impurities in the coral skeleton record the pattern and duration of eruptive activity. The prevalence of these signals varies along the skeleton reflecting changes in the style of volcanic activity.

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Sicre, M.-A.

Volcanic signal in marine archives

Historical or proxy records can help understand the effects of tropical volcanism on ocean variability at decadal to multi-decadal timescales. However, very few marine archives (marine sediments and corals) meet the needs for an accurate assessment of the ocean response to volcanic eruptions owing to methodological limitations. Here, we show the value of high-resolution climate reconstructions developed on marine sediments utilizing robust dating approaches, such as tephrochronology, for the detection of decadal-scale ocean changes and their comparison with numerical simulations to investigate the link between discrete volcanic eruptions and oceanic signals. We provide examples of sub-decadal scale variations documented by sea surface temperature and sea ice reconstructions from marine cores located in the subpolar North Atlantic induced by decadally-paced explosive tropical volcanic eruptions that took place during the second half of the thirteenth century. We discuss trends, as well as short- and long-term variability seen in marine paleo-records and compare them with simulation of the IPSL-CM5A LR model. We also show the potential of deep-sea corals to record the impact of volcanism on mid-depth ocean circulation using water mass circulation geochemical tracers. We show how the Nd isotopic composition (εNd) of long-lived coral Lophelia pertusa in Rockall Through was able to record a brief excursion at 1250 AD witnessing a change in the North Atlantic circulation after the Samalas eruption. This abrupt rise of mid-depth seawater εNd, from −14.4 to −11.8, occurring in less than 20 years is coherent with a change of the subpolar gyre dynamic.

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Sigl, M.

Towards a precise and accurate 12,000-year ice-core chronology of global volcanism

Due to its high resolution and well-constrained chronology (WD2014), the West Antarctic Ice Sheet (WAIS) Divide ice-core record provides a master record of past climatic changes throughout the Last Interglacial–Glacial cycle in the Southern Hemisphere. By synchronizing ice core records between regions, hemispheres and proxy archives by means of volcanic fallout (tephra, sulphate), cosmogenic radionuclides (10Be, 14C) and greenhouse gases (CH4) we are able to gain detailed insights into the time-transgressive nature of abrupt climate changes on decadal-to-centennial timescales. A total of 900 new stratigraphic markers identified between the sulphate records of WAIS, EDML, EDC, Talos Dome (all Antarctica) and GISP, GRIP (Greenland) provide the backbone of a new volcanic reference chronology over the Holocene. We further examine the potential that tephra isochrones, and in particular non-visible ash layers (cryptotephras), might offer for synchronising paleo-records with a greater degree of finesse and help underpin a more evolved tephra 'lattice' that links paleo-records between the high- and mid-latitudes. Finally, we evaluate the dating precision of the Holocene volcanic record through comparison with ultra-long tree-ring chronologies and discuss the climate impact potential of colossal volcanic eruptions (VEI≥6) throughout the Holocene using selected examples.

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Stoffel, M.

Possible source(s) and climatic impacts of the 1640/41 CE volcanic eruption(s)

Co-authors: Christophe Corona, Chaochao Gao, Sébastien Guillet, Samuli Helama, Heli Huhtamaa, Katrin Kleemann, Francis Ludlow, Michael Sigl, Matthew Toohey

This contribution will look into the volcanic eruptions around the mid-17th century and look into the impacts they have had on climate. The time period between 1630 and 1650 AD shows three distinct volcanic sulphur peaks in Greenland associated with volcanic eruptions with concentrations peaking in AD 1637, 1641-42 and 1646. A smaller sulphur peak observed in NEEM in AD 1640, but not in the two other ice cores. During the same time window only one unambiguous sulphate spike is recorded in Antarctica peaking in AD 1642. We attribute the sulphate peak in AD 1641-1642 observed in both polar regions primarily to the eruption of Parker Peak (6°N, Philippines, 26.12.1640). Volcanic sulphate emitted from the eruption of Koma-ga-take (42°N, Japan, 31.7.1641) potentially also contributed to the observed increase in sulphate concentrations in Greenland (and to a lesser extent in Antarctica too). The radiocarbon-dated (AD 1650 ±10) eruption of Sheveluch (56°N, Kamchtaka) is a potential candidate for the signal in AD 1646. No results of tephra analyses have been reported for any of the mid-17th century sulphate peaks in ice cores from Greenland or Antarctica that would allow to match the geochemical composition with those from the potential source volcanoes. Written sources and proxy data are used along with model output to quantify their climatic impacts and consequences on societies.

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Timmreck, C.

Understanding the apparently muted climate response to the strong volcanic eruption of 1809

The early 19th century was the coldest period of the past 500 years and is therefore of special interest for the study of inter-decadal climate variability. It encompasses a cluster of strong volcanic eruptions, including the unidentified 1808/1809 eruption of unknown location and the Tambora eruption in 1815. In contrast to the Tambora eruption not much is known about the 1809 eruption. Although ice core data suggest for the latter a best estimate for the stratospheric sulfur injection of 19.3 TgS, twice the current upper estimate of the 1991 Pinatubo eruption, climate anomalies in 1809 and 1810 were weak.

To understand the muted climate response of the 1809 eruption, we have performed a series of MPI-ESM1.2-LR simulations with different volcanic forcing estimates and compared them with proxy records. Our results show that global mean temperature anomalies are for all forcing scenarios within the observational range but there are significant differences between the scenarios, approximately half of the signal. The climate signal of the 1809 eruption is small in tree ring reconstructions and relative high in model simulations. Comparisons with tree ring data suggest therefore the lower bound of the sulfate estimates from ice core data for the 1809 eruption. Our studies further indicate that the weak climate signal of the 1809 eruption can be a result not only of the forcing strength but also of the forcing structure. Disentangle the differences between the effects of volcanic forcing strength and structure will be a future challenge.

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Toohey, M.

On the stratospheric residence time of volcanic aerosols

The cumulative radiative impact of major volcanic eruptions depends strongly on the length of time volcanic sulfate aerosols remain in the stratosphere. Observations imply that residence time depends on the latitude of the volcanic eruption, with tropical eruptions producing aerosol loading that persists longer than that from extratropical eruptions, however, the combined role of latitude and injection height is not well understood. Here we use satellite observations and model experiments to explore the relationship between eruption latitude, injection height and resulting residence time of stratospheric aerosols. We find that contrary to earlier interpretations of observations, the residence time of aerosol from major tropical eruptions is on the order of 24 months. Model results suggest that the residence time is greatly sensitive to the height of the sulfur injection, especially within the lowest few kilometers of the stratosphere. As injection heights and latitudes are unknown for the majority of eruptions over the common era, we estimate the impact of this uncertainty on volcanic aerosol forcing reconstructions.

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van Dijk, E.

Impact of the 536/540 CE double volcanic eruption event on the 6th-7th century climate using model and proxy data

The mid of the 6th century is an outstanding period and started with an unusual cold period that lasted several years to decades, due to the 536/540 CE double eruption event. Multiple tree ring records from the Alps to the Altai Mountains in Russia identified a centennial cooling lasting from 536 up to 660 CE. A previous Earth System Model (ESM) study with reconstructed volcanic forcing found that the double eruption led to a global decrease in temperature and an increase in Arctic sea-ice for at least a decade. However, the simulations were too short to fully investigate the multi-decadal cooling and the atmospheric forcing from this double volcanic eruption alone may not be enough to sustain such a prolonged cooling.

To better understand forced versus internal decadal climate variability we have performed ensemble simulations with the MPI-ESM1.2 for the 520-680 CE period using the evolve2k volcanic forcing. The ensemble consists of 10 realizations, which were branched from the MPI-ESM1.2 PMIP4 Past2k run.

Here, we present results of this new set of MPI-ESM simulations in comparison with available paleo-proxies. Surface temperatures reveal a remarkable agreement with available tree-ring data. Duration, strength and the possible mechanism for a long lasting volcanic induced cooling will be investigated based on sea ice/ocean changes. Special focus is placed on the impact of the 536/540 CE double volcanic eruption event on the surface climate of the Northern Hemisphere and Scandinavia comparing model data with new tree-ring and lake sediment proxies from south-eastern Norway.

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von Arx, G.

Using tree-ring anatomy for climate reconstruction: Characterization of “blue rings”

Time series of cell anatomical features (“tree-ring anatomy” or “dendroanatomy”) have long been considered a promising method to extract novel and high-resolution environmental information from tree-rings, because of mainly three arguments: i) the sequential radial progression of cell growth from earlywood to latewood allows matching intra-ring cell position with intra-annual timing of cell formation; ii) xylem cell structure responds sensitively to environmental influences during formation, which typically takes between two weeks and two months; iii) xylem cell structure and function are linked, which allows mechanistic interpretation of this high-resolution archive of plant internal processes and external drivers such as climate variability and extremes.

A tree-ring feature attaining increasing interest when investigating extreme events are “blue rings”. Using standard anatomical sample preparation protocols, a blue band at the end of the latewood indicates interrupted lignification, which is the last cell maturation step. This could be due to an early cold spell towards the end of the growing season as induced by climate variability or volcanic forcing. However, “blue rings” may be not always visible even if lignification did not complete, which constrains the use of “blue rings” for diagnostic purposes.

Here, we quantify cell anatomical features of visible blue rings in Scots pines from Northern Finland to show that, indeed, thickness of cell walls in the latewood is much reduced in “blue rings” and may be even thinner than in the earlywood, which is the opposite from a normal tree-ring. Dendroanatomy may thus improve reconstruction of extreme events.

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Zanchettin, D.

The early 19th century winter climate conundrum

The exceptionally cold decades in the early 19th century mark one of the climatically most relevant interdecadal periods of the last millennium. It left enduring imprints on Earth's and human history. But, "how cold" or "why" we cannot tell with enough confidence, as available observations, reconstructions and simulations provide only sparse, uncertain and often inconsistent information about the climate of this recent past. A cluster of very strong volcanic eruptions and a grand solar minimum were its natural forcing players; but, their relative roles and that of internal climate variability remain highly controversial, as do the underlying physical mechanisms. Gaps of knowledge especially concerns winter climates (e.g., Zanchettin et al., 2015, *Clim. Past.*).

In this contribution I will present an updated reconstruction-simulation comparison using a probabilistic approach and pseudo-reconstructions to assess key aspects of the early 19th century winter climate, using the available PMIP4-past1000 and VolMIP-volc-long/cluster experiments. I will discuss progress (or lack thereof) compared to analyses with PMIP3 data, with a focus on volcanic forcing, interdecadal anomalous phases of winter PNA and NAO, and inter-season asymmetries.

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