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PAST GLOBAL CHANGES
MAGAZINE

VOLCANOES AND CLIMATE

EDITORS

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PAGES

GLOBAL IGBP CHANGE

News

PAGES welcomes a new Director
In August, our Executive Director of 10 years, Thorsten Kiefer, left to pursue a role at Future Earth. An article on page 43 describes his outstanding contribution to PAGES over the past decade.

In November, we welcomed Marie-France Loutre as PAGES' new Executive Director. Marie-France has a distinguished international career in past global change research, particularly in paleoclimate modeling and studying how different forcings and feedbacks influence climate. We also welcomed Angela Wade to the role of Communications and Project Officer.

PAGES farewells IGBP and formalizes relationships with Future Earth and WCRP
The International Geosphere-Biosphere Programme (IGBP), PAGES' umbrella organization since its inception in 1991, will conclude in late 2015. IGBP recently published the last *Global Change Magazine*, reflecting on IGBP's three-decade legacy to global change research.

Looking to the future, PAGES has now officially become a core project of Future Earth and established a scientific partnership with WCRP. Read more on page 44.

PAGES and IGBP at AGU 2015
The International Geosphere-Biosphere Programme (IGBP) will host a series of events at the 2015 AGU Fall Meeting to celebrate its past and the transition to Future Earth. PAGES working groups are well-represented in many of the IGBP co-sponsored sessions.
www.pages-igbp.org/calendar/all-events/127-pages/1455-agu-fall-mtng-2015

New PAGES Working Groups
Four new working groups have recently been launched:

- Pliocene climate variability over glacial-interglacial timescales (PlioVAR)
  www.pages-igbp.org/ini/wg/pliovar
- The PAGES-PMIP Working Group on the Quaternary Interglacials (QUIGS)
  www.pages-igbp.org/ini/wg/quigs
- The Floods Working Group will investigate past flood events worldwide to improve our understanding of the physical processes controlling floods.
  www.pages-igbp.org/ini/wg/floods
- Volcanic Impacts on Climate and Society (VICS) aims to improve our understanding of the impacts of volcanic forcing on climate and societies.
  www.pages-igbp.org/ini/wg/vics

Read more about PlioVAR and QUIGS in their Program News articles in this issue or you can read more about all of the groups on our website. All PAGES working groups invite participation by interested scientists anywhere in the world.

PAGES OSM & YSM 2017
The 5th PAGES Open Science Meeting (OSM) and 3rd Young Scientists Meeting (YSM) will be held in Zaragoza, Spain. The proposed dates are around early to mid-May 2017. We look forward to organizing a rewarding and memorable meeting with our hosts, the Pyrenean Institute of Ecology, Spanish National Research Council (IPE-CSIC).

Upcoming issues of PAGES Magazine
The next issue of PAGES Magazine will be on abrupt changes and tipping points. Contact the guest editors Chris Turney (c.turney@unsw.edu.au), Chris Fogwill (c.fogwill@unsw.edu.au), Tim Lenton (t.m.lenton@exeter.ac.uk) and Richard Jones (r.t.jones@ex.ac.uk), or the PAGES office to enquire about contributing to this issue.

We are also preparing an issue on climate change and cultural evolution, guest edited by our Scientific Steering Committee (SSC) members Claudio Latorre (clatorre@bio.puc.cl), Janet Wilmshurst (Wilmshurstj@landcareresearch.co.nz), and Liping Zhou (lpzhou@pku.edu.cn). Contact them or the PAGES office if you are interested in contributing or exploring ideas.

In general, if you wish to lead a special section of the magazine on a particular topic, let us know at the PAGES office or speak with one of our SSC members.

Calendar

Climate variability during the Late Pliocene
29 February - 01 March 2016 - Leeds, UK

Dynamics of socio-ecosystems
04 April 2016 - Chambéry, France

Modeling isotope ratios in proxy climate records
02-05 May 2016 - Friday Harbour, USA

Central and Eastern EU Paleoscience Symposium
23-24 May 2016 - Cluj-Napoca, Romania

Data and model estimates of hydroclimate
01-03 June 2016 - Palisades, USA

http://www.pages-igbp.org/calendar

Featured products

Already committed to 6 meters of sea-level rise?
In a recent high profile paper, Dutton et al. from PALSEA2 analyze sea-level rise due to polar ice-sheet mass loss during past warm periods (2015, *Science* 349).

2k Network studies
- Ocean2k's low resolution team found an 1800 year-long robust cooling trend in global sea surface temperatures. They linked the coolest period to an increase in volcanic eruptions (2015, *Nat Geosci* 8).
- Ocean2k's high resolution team has quadrupled the observational reach into tropical ocean temperature history (Tierney et al. 2015, *Paleoceanography* 30).
- Zhang et al. address modified climate with long term memory in tree ring proxies (2015, *Env Res Lett* 10).
- Wang et al. explore different techniques for climate field reconstructions (2015, *Geophys Res Lett* 42).

Varve research showcased
The Varves Working Group published a review of annually laminated (varved) lake sediments (Zolitschka et al. 2015, *Quat Sci Rev* 117).

Human-environment interactions
- Members of PAGES have published a special issue on the challenge of quantifying past human-environment interactions (Verstraeten (Ed.) 2014, *Anthropocene* 8).
- Dearing et al. present case studies combining paleorecords with conventional sources of historical information (2015, *Anthropocene Rev*).
- LandCover6k members synthesize the archeological record in sub-Saharan Africa to review past land use systems (2015, *Anthropocene* 9).

Reconstructions and simulations
Emerging out of the PAGES 2k/PMIP 2013 workshop, Zanchettin et al. reconcile reconstructed and simulated features of the winter Pacific/North American pattern in the early 19th century (2015, *Clim Past* 11).

Cover

Eruption of Sarychev Peak, Matua Island, Kuril Islands, Russia
Astronauts aboard the International Space Station captured this photo of the early stages of an eruption of ash and steam from Sarychev Peak in the Kuril Islands in June of 2009. Image from the Earth Science and Remote Sensing Unit, NASA Johnson Space Center (ISS020-E-9048).

PAGES pilot to chart new waters

Hubertus Fischer[1] and Alan Mix[2], Co-Chairs, PAGES Scientific Steering Committee

After 10 years of extraordinary service and success with PAGES, Executive Director Thorsten Kiefer moves on to even larger challenges at the Future Earth Global Hub in Paris.

Thorsten began his scientific life as a paleoceanographer, with a PhD from the University of Kiel in 1997, followed by postdocs first in Kiel and then at University of Cambridge. While in the UK, Thorsten honed his leadership and diplomacy skills as well as a British sense of humor, all of which made his decade with PAGES, which started in 2005 when Thorsten became director of the PAGES International Project Office in Bern, both successful and fun.

2005 was a difficult year for PAGES; although the science was strong, funding was at risk. Jumping aboard, Thorsten grabbed the PAGES wheel and began to steer. His first task was to organize the 2nd Open Science Meeting (OSM) in Beijing in August 2005. Following the Beijing OSM, Thorsten organized the 2009 and 2013 OSMs in Corvallis and Goa, and in the process made this four-yearly event a bright beacon in the global paleoscience calendar. Thorsten recognized the special needs of early-career researchers, and in 2009 he successfully launched the first Young Scientists Meeting alongside the OSM in Corvallis; this innovative model is now emulated by many other projects and societies.

Having righted the ship, Thorsten's next task was to chart a new course, guiding the development and implementation of PAGES' new Science Structure in 2006. A clear structure of foci and cross-cutting themes became the channel through which PAGES has navigated during the last 10 years, launching 40 working groups that have yielded over 157 peer reviewed journal articles and 43 special issues. Under this structure, the PAGES community grew to more than 5,500 subscribers from 125 countries.

Yet another challenge came in the past two years, with PAGES required to change course again as its former guiding star, the International Geosphere Biosphere Program (IGBP), set and a new one rose in form of the transdisciplinary sustainability program Future Earth. Again through his steady guidance of the scientific community, Thorsten helped navigate the PAGES ship safely into this new harbor. With a newly defined science structure (www.pages-igbp.org/science/intro), and a new stronger relationship both with Future Earth and the World Climate Research Programme, PAGES is perfectly positioned to continue its leadership in paleoscience while helping to contribute to Future Earth's goal of accelerating the transformation to sustainable practices. During the transition process, Thorsten has helped communicate the unique insights that paleoscience can bring regarding the long-term changes in the Earth system and how these can be of benefit in preparing for the future. Building on Thorsten's legacy, PAGES will continue its tradition of openness and inclusion, and will remain a beacon that leads the world's community of paleoscientists to meet, collaborate, and advance a coordinated agenda for globally relevant paleoscience.

In September this year, after a decade spent transforming PAGES into a polished speedboat, Thorsten moved on to assume an even larger responsibility, piloting the supertanker that is the Future Earth Global Hub in Paris. Here he will find a new chance to navigate the shallows of early program implementation and to set the course for even larger scientific vistas. For PAGES this is a great loss, but it is also a great gain. Thorsten has left PAGES with a sturdy hull and wind in its sails, and we are reassured that his deep expertise and remarkable skills will provide a steady hand on the wheel of Future Earth, and that PAGES will be well understood within the larger context.

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Transition accomplished

New setting and new structure of PAGES

Thorsten Kiefer[1], H. Fischer[2], A. Mix[3], S. Fritz[4], L. von Gunten[5] and L. Goodwin[5]

PAGES has revised its scientific structure to better align with Future Earth's philosophies of increasing interdisciplinarity and societally-relevant science. The new structure represents an integrative space between climate, environment, and humans as the key components of a sustainable Earth system.

The landscape of global change programs within which PAGES is embedded is transforming, as previous articles highlighted already (PAGES IPO 2014). The International Geosphere-Biosphere Programme (IGBP), PAGES' umbrella organization since its inception in 1991, will conclude by the end of 2015. IGBP's legacy and that of two other global change programmes, namely Diversitas and the International Human Dimensions Programme, will transfer to Future Earth, a large research platform for global sustainability that has been developing over the last few years.

Future Earth, subtitled "research for global sustainability", aims to provide the knowledge and support to accelerate our transformations to a sustainable world. To reach this ambitious goal, Future Earth intends to modify the approach taken by the predecessor programs in essentially three ways: (1) by re-directing research from addressing problems towards informing solutions to pressing societal issues, (2) by increasing the level of interdisciplinarity to an inclusiveness that reaches from the physical sciences, through the biogeochemical and ecological sciences to social sciences and the humanities, and (3) by working together with societal partners who have an interest in sustainability science (stakeholders), particularly in jointly designing initial research plans and end products.

From 2016, the former four global environmental change programs will have been boiled down into two. Future Earth will be complemented by the World Climate Research Programme (WCRP), which has formed a strong partnership with Future Earth, but will otherwise continue to coordinate its own international climate research.

In the handover from IGBP to Future Earth, IGBP's core projects, including PAGES, were invited to join the new initiative. PAGES' Scientific Steering Committee decided that PAGES would join Future Earth as a core project, while also broadening its thematic basis by establishing a scientific partnership with WCRP. Both affiliations have been formalized over recent months.

An open theme space replaces distinct foci

Since the community consultations and plenary discussions at the PAGES Open Science Meeting in 2013 in Goa, PAGES has been preparing the terrain to successfully continue the facilitation of international scientific collaboration on past global changes, while also being able to link in with the agendas of Future Earth and WCRP.

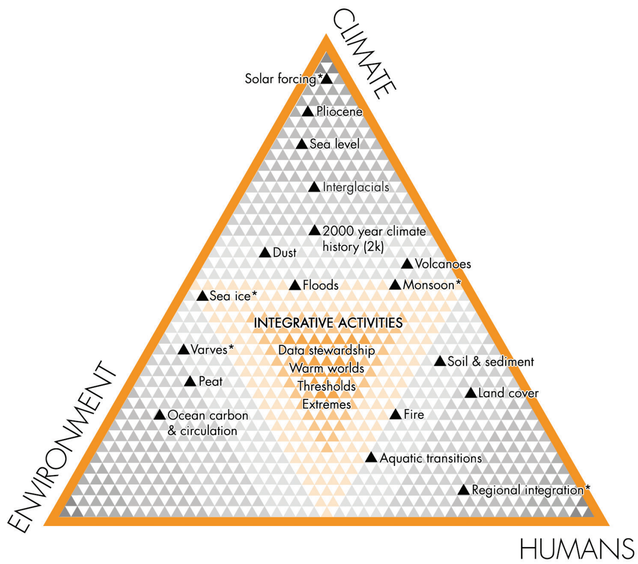

Figure 1: PAGES' science structure addresses the key components of the Earth system through the themes Climate, Environment, and Humans. The center of the triangle will hold cross-topical integrative activities, particularly suited to collaboration outside the PAGES community. Current working groups and the integrative activities are mapped on to the new science structure. The working groups marked with an asterisk are in their synthesis phase.

Accordingly, PAGES has revised its scientific structure to better align with Future Earth's philosophies of integration and societally-relevant science. PAGES' science structure addresses the key components of the Earth system through the themes Climate, Environment, and Humans (Fig. 1). These themes define our scientific scope and reflect the holistic Earth system science approach that is becoming increasingly integrated within PAGES.

- The Climate theme represents quantitative climate system dynamics from a paleo-perspective. The aims are to improve knowledge on climate forcings, sensitivity, variability, modes, non-linearities and thresholds, Earth system feedbacks, regional-scale dynamics, and how current climate models represent the various aspects of climate dynamics.
- The Environment theme addresses components of the biosphere that interact with each other and climate, and may introduce feedbacks into the Earth system. This includes biogeochemical cycling, ecosystem dynamics, and ecosystem services.
- The Humans theme addresses long-term environmental changes where humans are a major agent, e.g. through land use, pollution, fertilization, soil erosion, river damming, or landscape fragmentation, and where environmental changes have a demonstrable effect on the functioning and well-being of ecosystem services and societies.

At first glance, the change from the previous circular structure to a triangular one might not look like a major coup. And indeed, what matters most in PAGES will remain, that our working groups are excellent, active, and productive. However, the modification of the structural geometry does actually go along with changes in emphasis and conceptual thinking within PAGES.

Replacing the four foci - climate forcings, regional climate, earth system dynamics, and human-climate-ecosystem interactions - with the cornerstones of the triangle has shifted the thematic emphasis away from its dominant climate focus towards giving more equal importance to human, environmental, and climatic impacts within the framework of fundamental Earth system science.

Another measure to streamline the structure was to deemphasize research on methods by eliminating the four former cross-cutting themes on chronology, proxies, modeling, and data management. This does not mean that methodological aspects are considered unimportant. However, research on chronology, proxies, and modeling in PAGES will need to be pursued in the context of addressing specific Earth system science questions. And the data management topic has even been identified as a matter of vital importance and has hence been further highlighted in the new structure (see Fig. 2).

The most fundamental change in philosophy reflected by the new structure might be that it eliminates the previous silo-like foci by streamlining them into themes that define a boundary-free, integrative scope. Accordingly, working groups do not need to be categorized any more as belonging to one particular focus or cross-cutting theme. Instead, the open thematic space now acknowledges and encourages that all working groups and other activities address a mixture of climatic, environmental, and human aspects. Graphically, the relative importance of those aspects places each working group in a certain region of the triangle (Fig. 2).

Finally, topics that are particularly integrative between climate, environment, and humans, are now centrally placed at the heart of PAGES rather than falling between the cracks of the former foci.

A new layer of integration across working groups

Many issues of concern to society cut across the specific topics addressed in working groups under the three new themes and will benefit from being addressed with an inclusive approach. The cross-topical integrative activities, depicted in the middle of the triangle, are thus a new format in PAGES dedicated to facilitating an additional level of scientific exchange, synthesis, and outreach. They build on the results and specialist expertise of the working groups and draw on complementary scientific expertise on modern process and future projection research from the networks of Future Earth and WCRP. Outputs are expected to provide information for impact assessments and management strategies and thus to form key contributions to the scientific agendas of Future Earth and WCRP.

At present, four integrative activities with the potential to provide transformative advances in approaches to paleoscience have been identified:

- Data stewardship: PAGES aims to develop sets of best practice guidelines for data standards, archiving, and access. This will be done by soliciting broad input from the international community of experts.
- Warm worlds: As the instrumental record fails to provide estimates related to future scenarios of a world that will be warmer than today by several degrees, PAGES aims to synthesize evidence for global and regional changes in the Earth system associated with warmer periods in the past. This also entails constraining the variability of natural systems under different conditions as baselines for assessing anthropogenic impact.
- Thresholds: This activity aims to synthesize the latest insights into the existence (or lack thereof) of multiple equilibria, including thresholds and tipping points in components of the Earth system.
- Extremes: A robust risk assessment of the probability of extreme events requires extending the data record of variability beyond the instrumental and documentary time period. This activity aims to identify the diverse range of paleoclimatic and paleoecological extreme events in the Earth system to derive comparable and statistically robust probability estimates of extreme events.

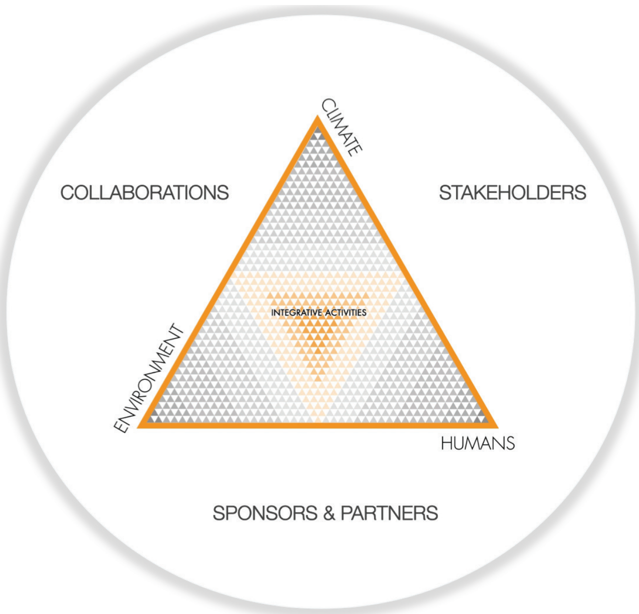

Figure 2: The PAGES science is embedded in a universe of opportunities for collaborations with the potential to enrich the diversity of research, impact of outreach, level of funding, and other aspects of the implementation of PAGES' agenda.

Streamlining on the inside, opening to the outside

The changes in scientific structure are accompanied by an evolution of internal and external organization. Internally, the working groups will remain the powerhouses of community-driven science in PAGES. To make them even more dynamic, they have gradually been streamlined in recent years by pacing their workplans into 3-year phases that conclude with syntheses.

A new management format will be required for the integrative activities. Combining the expertise from diverse working groups and loosely connected external communities will require that our Scientific Steering Committee members take on more active leadership roles and the PAGES office takes on more coordination than for the regular working groups.

The new program affiliations with Future Earth and WCRP are likely to entail more diverse and active connections to external groups of scientists and practitioners. The networks of the two programs extend the range of potential scientific contacts from the geosphere-biosphere community of IGBP to the entire range of sustainability science disciplines. Moreover, both Future Earth and WCRP will offer opportunities for highly interdisciplinary collaborative research, which should foster active collaborations across PAGES and its sister projects as well as other organizations.

Finally, a major component of Future Earth's approach to increasing the impact of science and supporting necessary transitions towards sustainability is its emphasis on collaboration with stakeholders. Core projects like PAGES are also called on to experiment with stakeholder engagement by developing approaches and building stakeholder networks. This might seem like a daunting task, but PAGES has already carried out an initial stakeholder analysis and added an encouragement to involve stakeholders to its workshop and working group proposal guidelines. We can thus expect that the orbit (Fig. 2) around the core of PAGES will rapidly populate with new people, new organizations, and new stimulating thinking.

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Volcanic eruptions and climate

Allegra N. LeGrande[1] and Kevin J. Anchukaitis[2]

Volcanic eruptions represent some of the most climatically important and societally disruptive short-term events in human history. Large eruptions inject ash, dust, sulfurous gases (e.g. SO_2, H_2S), halogens (e.g. HCl and HBr), and water vapor into the Earth's atmosphere. Sulfurous emissions principally interact with the climate by converting into sulfate aerosols that reduce incoming solar radiation, warming the stratosphere and altering ozone creation, reducing global mean surface temperature, and suppressing the hydrological cycle. In this issue, we focus on the history, processes, and consequences of these large eruptions that inject enough material into the stratosphere to significantly affect the climate system. In terms of the changes wrought on the energy balance of the Earth System, these transient events can temporarily have a radiative forcing magnitude larger than the range of solar, greenhouse gas, and land use variability over the last millennium. In simulations (Fig. 1) as well as modern and paleoclimate observations, volcanic eruptions cause large inter-annual to decadal-scale changes in climate. Active debates persist concerning their role in longer-term (multi-decadal to centennial) modification of the Earth System, however.

Societal systems are affected as well, and agriculture and infrastructure can be profoundly disturbed by these severe short-term geological and climate events, even at locations quite distant from the eruptions themselves. For instance, Puma et al. (p.66) demonstrate an association between volcanic eruptions with some of the worst famines in human history.

Despite their importance for both climate and natural hazards, there remain substantial gaps in our knowledge of the physics, magnitude, timing, and impacts of large volcanic eruptions. Robock (p.68) highlights several persistent climatic mysteries related to volcanoes and uncertainties in our understanding of processes linking eruptions to both short- and long-term changes in the climate system.

Historical accounts, geological evidence, and ice cores provide evidence of eruptions in the past that were much larger than those documented and observed since the 19th century, and volcanoes represent the most important forcing in last millennium transient climate simulations, at least until the dawn of the industrial era (Jungclaus et al. 2010). Various groups (Crowley and Unterman 2013; Gao et al. 2008; Sigl et al. 2015) have taken the initiative of estimating volcanic forcing from ice core records using the coherence of sulfate horizons in ice core records to infer volcanic eruptions. Lower (tropical) latitude and higher magnitude eruptions were inferred when there was greater coherence and higher sulfate concentrations across sites. Through a clever bit of historical work, Stothers (1984) was able to calculate the volcanic aerosol optical depth (AOD) after the 1815 Tambora eruption by digging through newspaper archives and finding mention of visible sunspots at a certain day and time, which indicated a certain minimum aerosol optical depth. Paired with the sulfate horizon observed in ice core records, it is possible to develop a conversion factor between sulfate horizon and AOD. Unsurprisingly, this process can be highly uncertain. And indeed, estimates of both the timing and magnitude of past major volcanic eruptions differ, in some cases substantially, between different ice-core derived calculations of volcanic forcing (Fig. 1; Schmidt et al. 2010). Sigl et al. (p.48) detail their latest work to establish an improved chronology for volcanic eruptions during the Common Era, in particular an improved 1st millennium record and suggest a reduced magnitude for some of the largest last millennium eruptions, including the 1250s Samalas eruption.

Early work following the Mt. Pinatubo 1991 eruption showed that global mean annual surface temperature decreased by ~0.5°C (Hansen et al. 1996). This and subsequent research on Pinatubo has been important not only because of the insights provided about the response and sensitivity of the climate system to radiative perturbations, but because knowledge of this particular eruption forms a key part of how we model the Earth System's response to other eruptions in the planet's history. Translating (parameterizing) the observed volcanic perturbation into forcing fields for global climate models (GCMs) has been accomplished, in a variety of ways with varying complexity, from exceptionally simple top-of-the-atmosphere shortwave forcing, to an intermediate complexity estimate of change in the AOD of the atmosphere, and the effective radius of the volcanic aerosol particles (R_{eff}) that have specific radiative properties to more sophisticated aerosol microphysical representation of SO_2 injection and sulfate aerosol development; with the most sophisticated treatments coming into use for the upcoming Coupled Model Intercomparison Project (CMIP6). To estimate R_{eff} for eruptions besides Pinatubo, many modeling groups follow the technique used by Sato et al. (1993), where satellite information about the co-evolution of AOD and R_{eff} by latitude after Pinatubo are generalized to prescribe R_{eff} for other eruptions given AOD. In a sense, this means that each volcanic simulation reflects a scaled version of the 1991 Mt. Pinatubo event.

Lacis describes in this issue (p.50) how particle size, not just mass or optical depth, is important for determining the radiative properties of aerosols. These particles not only scatter incoming shortwave radiation (as expected from reduced surface temperatures following volcanic eruptions), but also absorb and re-emit some energy, giving a positive thermal forcing, and warming the stratosphere. Mann G. and others show in detail (p.52) the importance of getting this size distribution, R_{eff}, correct, and the shortcomings of previous efforts in this regard.

Timmreck et al. (2009), amongst others, have demonstrated that our representation of volcanoes is likely oversimplified, which has important consequences for how we simulate the climate impacts of past volcanic eruptions. By implication, modeling estimates of possible geoengineering solutions using solar radiation management are likewise incomplete. Each climate modeling group makes its own decisions about how to apply and simulate volcanic eruptions – past, present, and future; for example, which atmospheric layers to specify, how many latitude bands, and how to define and apply estimates of AOD and R_{eff}. There is a substantial need for greater coordination and communication regarding these modeling efforts. CMIP6 will include a coordinated project focusing on volcanic eruptions ("VolMIP"), which Zanchettin and others describe in this issue (p.54).

The 1991 Mt. Pinatubo eruption was the largest eruption of the 20th century, and even the simplest of parameterizations in GCMs provides a reasonable approximation of this event that the model was designed to produce. However, to provide out-of-sample validation for models, tree rings and other paleoclimate proxies can be used to estimate past temperature and precipitation changes following large eruptions. For instance, Churakova et al. (p.64) show multiple lines of proxy evidence for the large 6th century eruption in Siberian tree-ring chronologies.

However, for large events (greater than the 1991 Mt. Pinatubo event), there are in some cases stark differences between the simulated GCM and reconstructed climate response (Anchukaitis et al. 2012; Mann M.E. et al. 2012; Zanchettin, this issue). For instance, climate models simulate extremely large (>1°C) cold excursions following the mid-to-late-thirteenth century volcanic eruptions, including the 1250s eruption of Samalas (which the CMIP5 forcing reconstructions estimate at roughly 10x the magnitude of the 1991 Mt. Pinatubo event; Fig. 1). The proxy reconstructed temperature response is generally smaller and less spatially coherent than the global cooling pattern (global cooling 50-200% larger than Pinatubo) simulated by GCMs. Identifying the source of this mismatch is of paramount importance in understanding the impacts of large eruptive events and building climate models capable of reproducing them. Timmreck et al. (2009) and English et al. (2013) have explored possible modeling reasons for this, and Sigl et al. (p.48) suggest a new, reduced magnitude for the 1250s eruption. St. George and Anchukaitis (p.60) explore this potential mismatch from the proxy point of view of the large 19th century eruption of Tambora. Stine

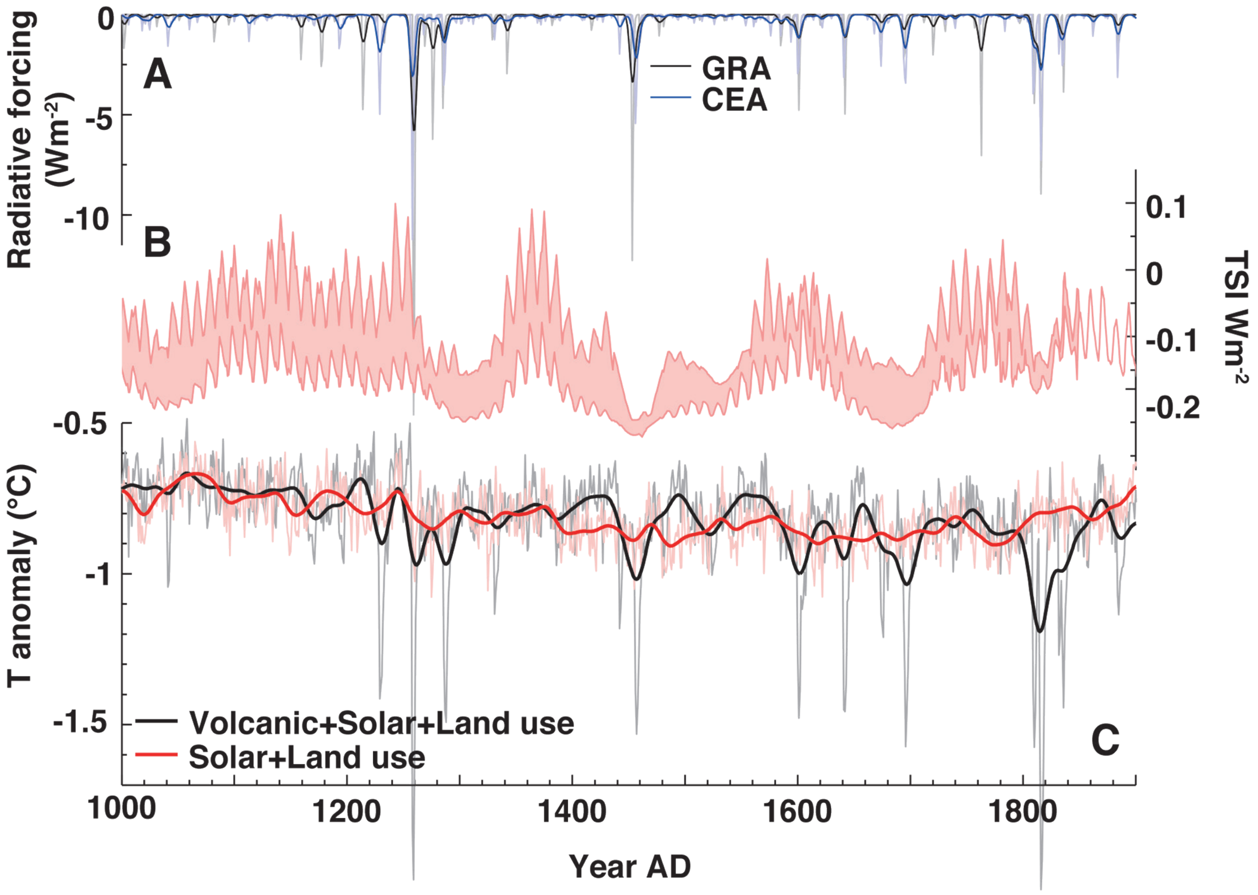

Figure 1: Last millennium climate forcing and modeled global mean annual temperature response. **(A)** Two time series of global annual radiative forcing estimated by scaling global sulfate loading (GRA: Gao et al. 2008 and CEA: Crowley et al. 2008 & Crowley and Untermann 2013) via aerosol optical depth (Schmidt et al. 2012, light lines) and a 10-year Gaussian smooth through these values (thick lines). **(B)** The full range of estimated PMIP3 annual total solar irradiance (TSI) anomalies (excluding those of Shapiro et al. 2011) relative to a 1976-2006 baseline (Schmidt et al. 2012). **(C)** Global mean annual average surface air temperature response in the GISS-E2 last millennium (CMIP5) experiment forced with given anthropogenic land use (Pongratz et al. 2008), solar variability (Steinhilber et al. 2009), and with (Crowley and Unterman 2013) or without (red) volcanic forcing.

et al. (p.62) investigate the possible role of changing light conditions in influencing the growth response of trees after certain volcanic eruptions, which could modulate the inferred magnitude of post-event cooling.

Volcanic eruptions affect the hydrological cycle as well as temperatures. In this issue, Iles et al. (p.56) show that global rainfall decreases by up to 0.04-0.05 mm per day following large eruptions. Focusing on the Asian monsoon region, Gao (p.58) illustrate the reductions in monsoon rains in the years following an eruption may be an order of magnitude larger than the global average.

The papers in this issue collectively represent not just a summary of the current science, but also more importantly a series of implicit and explicit challenges to the modeling, observation, and paleoclimate communities. Robock (p.68) directly sets out a series of tantalizing questions, and it is clear that a consilience of simulated and reconstructed temperature response has not yet been achieved. Likely explanations for these differences lie at least in part on our representation of the processes governing the climate consequence of eruptions in state-of-the-art GCMs, including aerosol processes, as well as precise knowledge of the timing and magnitude of past events. Paleoclimate proxies are a filter through which we peer into the past, and thus the biological, chemical, and physical mechanisms that give rise to these records need to be better understood. Addressing these myriad and extant uncertainties will require close coordination between those specializing in paleoclimate reconstruction, Earth System modeling, and present observations of the climate system: scientists with domain knowledge in aerosol and particulate behavior in the atmosphere, geologists and ice core specialists with knowledge of both atmospheric processes and geochronology, social scientists and engineers who understand the coupled human and natural systems impacted by eruptions, and climate modelers. Volcanic eruptions and their influence on coupled Earth systems cut across traditional disciplinary boundaries, and will continue to require collaboration and a high degree of international cooperation.

PAGES has recently organized the "Volcanic Impacts on Climate and Society" (VICS) working group. The principal aims of this group are to improve radiative forcing; understanding of volcanically induced climate variability; and understanding of societal impacts of volcanic eruptions. The group hopes to extend our current volcanic forcing datasets, largely limited to the last millennium back to the beginning of the Holocene. This work will facilitate model-to-data inter comparisons such as those of SSiRC (Stratospheric Sulfate and its Role in Climate), PMIP4 (Paleoclimate and Modeling Intercomparison Project, Phase 4), and VolMIP (Model Intercomparison Project on the Climatic Response to Volcanic Forcing). In addition to editors Allegra LeGrande and Kevin Anchukaitis, the PAGES VICS working group will be lead by Michael Sigl, Matthew Toohey and Francis Ludlow.

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The history of volcanic eruptions since Roman times

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We discuss the timing of volcanic eruptions and quantify atmospheric sulfate loading using an array of ice cores from Greenland and Antarctica. We demonstrate that throughout the Common Era volcanic activity was the main driver for abrupt summer cooling in Europe.

Volcanic eruptions impact climate through the injection of large amounts of ash and sulfur gas into the atmosphere (Fig. 1a). This gas is converted to sulfate aerosols, which reflect solar radiation in the stratosphere, decreasing the amount of solar radiation reaching the Earth's surface. The primary result is a cooling of the Earth's surface. Volcanic sulfate is mixed and transported within the stratosphere, and eventually travels downward into the troposphere, where it is finally deposited to the surface of the Earth. Sulfate deposition over the ice sheets is preserved in annually accumulating ice layers, allowing for reconstruction of the magnitude and timing of past volcanic events with the help of ice cores (Fig. 1b-d). The impact of volcanic eruptions is also clearly seen in other paleoclimate records. Temperature reconstructions predominantly obtained from tree-ring chronologies (Fig. 1e,f; Fig. 2) spanning previous centuries show the influence of a number of volcanic events (D'Arrigo et al. 2001; PAGES2k Consortium 2013; Salzer et al. 2014); however, a number of apparent mismatches between paleoclimate reconstructions and previously reconstructed volcanic forcing records have been noted (e.g. Mann et al. 2012). Striving towards better agreement between proxy-based climate reconstructions and model simulations is an important component of current climate research (Toohey et al. 2013). The paleoclimate record – i.e. reconstructions of past climate variables such as temperature and precipitation, produced from analysis of proxies such as tree rings, ice cores, and marine sediments – is essential for understanding the Earth system's response to various forcing agents.

Sulfate measurements in ice cores

Because a major driver of climate variability over the past centuries is the impact of volcanic eruptions, the ability of climate model simulations to accurately recreate past climate is tied directly to the accuracy of the volcanic forcing time series used in the simulations. Presently, all volcanic forcing estimates used in paleoclimate model simulations is derived from ice cores. Time series of sulfate deposition from ice cores are translated into estimates of atmospheric sulfate aerosol loading, and corresponding estimates of radiative forcing. Volcanic forcing sets typically used in modern paleoclimate simulations span the years 500/800-2000 CE (Crowley and Unterman 2013; Gao et al. 2008), although the limited number of ice cores used to derive the forcing in the early years of the data set limits the accuracy of the estimated forcing (Sigl et al. 2014). The limited number of records currently included in volcanic forcing sets is explained by the time-intensive discrete measurement techniques that are often used to measure sulfate in ice. Newly developed state-of-the-art analytical techniques allow for a variety of elements (including sulfur) and chemical species to be analyzed simultaneously in real time while slowly melting the ice on a heated melter plate (McConnell et al. 2014; Fig. 1d). Further, the high measurement resolution of these analyses also allowed some ice cores from Antarctica with high annual snowfall rates to be dated by counting annual cycles in the impurity content of the snow and ice (Sigl et al. 2013).

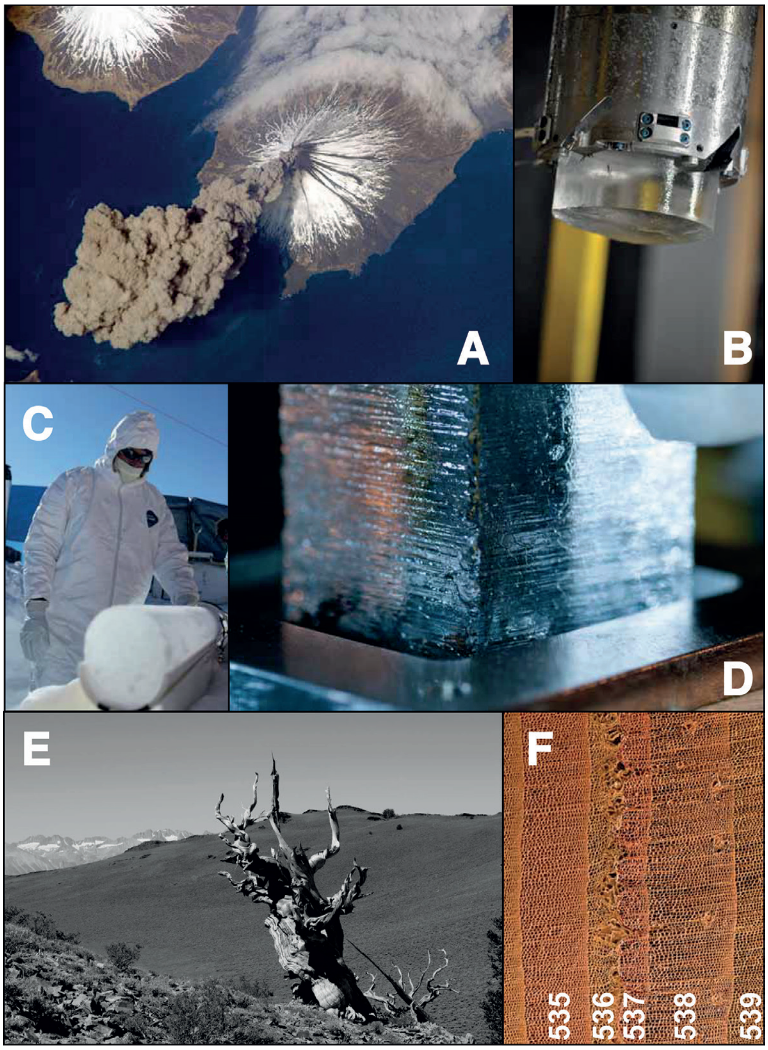

Figure 1: (A) Injection of ash and aerosols into the atmosphere; **(B)** ice core section from WAIS Divide (Antarctica) sticking out of the core barrel. High annual snowfall at this site enables individual annual layers to be identified and counted; **(C)** ice core section from TUNU (Greenland) that contains a record of volcanic sulfate aerosols; **(D)** the ice is slowly melted and a variety of elements and chemical species are simultaneously analyzed; **(E)** bristlecone pine ring-width minima indicate that summer cooling often occurred when major volcanic eruptions dimmed the Earth's surface; **(F)** frost rings from a Siberian pine in Mongolia. The narrow, distorted rings for 536 and 537 CE indicate a drastic cooling in the northern hemisphere which was caused by a large volcanic eruption. Image credits, A-F: NASA, M. Twickler, M. Sigl, S. Masclin, M. Sigl, D. Breger (Micrographic Arts).

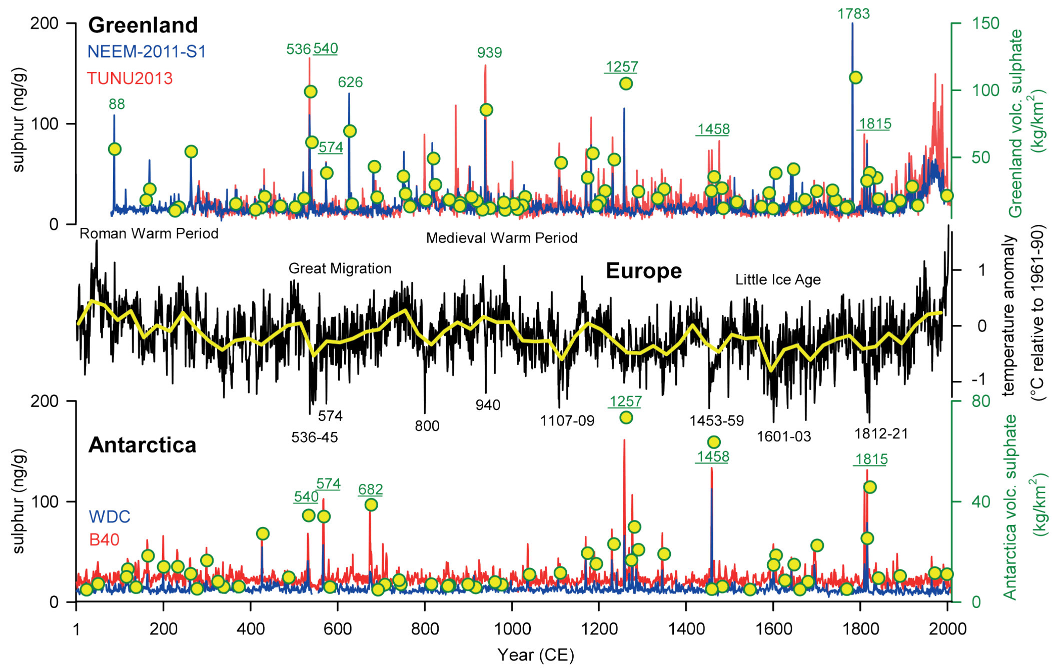

Figure 2: Ice-core records of sulfur from two ice cores in Greenland and two ice cores in Antarctica (Sigl et al. 2013, 2014), used among others to infer atmospheric deposition (yellow circles). More than 100 individual eruptions are reconstructed and attributed to either mid-to high latitude eruptions (e.g. Iceland, Alaska) and low-latitude eruptions (underlined for selected events) based on the timing of sulfate deposition over the ice-sheets. Reconstructed dates are given for some large volcanic eruptions (Sigl et al. 2015) as are time periods of strong summer cooling in Europe indicated by tree-ring reconstructions (black curve, PAGES-2k Consortium 2013).

A comprehensive array of ice cores from Antarctica

Methodological advances have enabled much more accurate reconstructions of the history of volcanic sulfate deposition in Antarctica over the last 2,000 years (Sigl et al. 2014). This has become possible by combining a number of new ice core sulfate records with pre-existing ones to provide better sampling over Antarctica, important due to the high spatial variability in sulfate deposition. The number of long-term records reaching back approximately 2,000 years has therefore been significantly increased compared with past compilations and this has meant a composite deposition index could be based on a quasi-static ensemble size over the length of the record. Also, the new record benefits from an improved timescale and better synchronization of the different ice core records; consequences of the very high temporal sampling resolution of the newly drilled West Antarctic Ice Sheet Divide Ice Core (WDC).

The new record of Antarctic sulfate deposition (Sigl et al. 2014) shows a number of improvements compared with previous reconstructions (Crowley and Unterman 2013; Gao et al. 2008). Firstly, the magnitude of a number of events is significantly adjusted, including a lessened estimate of the magnitude of the 1257 CE Samalas eruption. Secondly, the history of volcanism in the earliest centuries of the record is drastically altered, with updated dates and magnitudes of eruptions often differing greatly from prior estimates.

Revised ice-core chronologies

During the first millennium, inconsistencies were identified between the reconstructed timing of sulfate deposition on the ice-sheets and tree-ring records indicating widespread cooling. It was suggested that the ice-core chronologies were biased towards ages that were too old during that time, potentially caused by an incorrect link of the ice-core chronologies to the historic Vesuvian eruption in the year 79 CE (Baillie and Anneny 2015). By using a multi-disciplinary approach that integrates state-of-the-art continuous ice core aerosol measurements, automated objective ice-core layer counting (Winstrup et al. 2012), tephra and radioisotope (beryllium-10) analyses, and detailed examination of historical archives, we revised the ice-core chronologies for Greenland (NEEM-2011-S1) and Antarctica (WDC) and thus resolved these inconsistencies back into Roman times (Sigl et al. 2015). Other existing long-term sulfate records (e.g. those from NGRIP, GISP2, TUNU, DFS10, B40, NUS8-5) can be synchronized to the new timescales by matching their sulfate profiles (Fig. 2). This way, robust estimates of the ice-sheet mean deposition can be achieved (yellow circles in Fig. 2), allowing volcanic forcing to be estimated.

Post-volcanic summer cooling

With these revised ice-core chronologies, major volcanic eruption dates are in agreement with tree-ring reconstructed cooling extremes that occurred in the immediate aftermath of large volcanic eruptions throughout the Common Era (Fig. 2). The exceptionally cold summers reconstructed in parts of Europe (and other regions) in the years 1816, 1601, 1453, 1109, 574, and 541 CE all followed major volcanic eruptions, thus confirming that volcanic activity is an important driver of natural climate variability on inter-annual timescales. Strong summer cooling is not limited to tropical eruptions but is also observed frequently following eruptions located in the high latitudes of the northern hemisphere, as in the years 940, 800, and 536 CE. The largest volcanic eruption in terms of atmospheric sulfate loading (Samalas, 1257 CE) did not, however, appear to induce strong cooling in Europe. This confirms that for individual eruptions the temperature response to the forcing is spatially heterogeneous and may also be dependent on background conditions of the climate system such as the state of ENSO.

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Volcanic aerosol radiative properties

Andrew Lacis

Large sporadic volcanic eruptions inject large amounts of sulfur bearing gases into the stratosphere which then get photochemically converted to sulfuric acid aerosol droplets that exert a radiative cooling effect on the global climate system lasting for several years.

Volcanic aerosol consists mainly of concentrated sulfuric acid (75% H_2SO_4), although the bulk of the erupted volcanic material consists of large ash particles which fall out rapidly, leaving the sulfur bearing gases to form the more enduring volcanic aerosol. It is this longer lasting aerosol that causes cooling of the global surface temperature (solar albedo effect), and warming of the lower stratosphere (greenhouse effect). More generally, the magnitude of the surface cooling, and the degree of stratospheric warming depend in detail on the aerosol composition, its optical depth, particle size, and the height of the aerosol in the stratosphere.

Aerosol radiative properties can be calculated accurately for any aerosol size and composition using Mie scattering theory, which is an exact theory of how light is scattered by homogeneous spherical particles. Figure 1A shows that the effective cross-section (expressed per unit mass) of atmospheric aerosols can differ greatly relative to the particle's geometric size. According to Mie theory, particles exhibit their peak scattering efficiency at a characteristic size that depends on the aerosol composition. In moving toward ever larger sizes, the mass-specific cross-section diminishes inversely with size, while in the small particle limit (i.e. the Rayleigh limit where particles are much smaller than the wavelength of incident radiation), the effective cross-section for non-absorbing particles such as sulfuric acid, aluminum oxide, sea salt, sulfates, nitrates, goes to zero (thus making them invisible), while the strongly absorbing particles (e.g. black carbon), retain most of their peak absorption efficiency even as the particle size approaches zero.

Effect of particle size

For non-absorbing aerosols, the cross-section per unit mass is largest for aerosols with effective radii near 0.25 µm. Particle size is also important considering that aerosol residence time in the stratosphere is governed by particle fallout speed, which is proportional to the particle radius squared. In their formative stage, volcanic aerosols are exceedingly tiny, which translates into negligible fallout speed and a negligible scattering cross-section as dictated by the small particle Rayleigh limit of Mie theory. Mature volcanic aerosols tend to be in the 0.25 µm effective radius size range, and at that size they have a stratospheric residence time of about a year at the nominal volcanic aerosol altitude of 25 km. For strongly absorbing aerosols such as black carbon, the Rayleigh limit has minimal effect on the particle's absorption efficiency. For more exotic aerosol compositions, such as metallic aluminum (for which the imaginary refractive index is much larger than unity), the particle surface becomes reflective, resulting in scattering characteristics that are similar to non-absorbing aerosols (Fig. 1A). The peak radiative efficiency for both black carbon and metallic particles occurs at less than half of the particle radius compared to non-absorbing aerosols. Basically, absorbing aerosols can be effective in cooling the ground surface if their absorption occurs high in the stratosphere, but they produce strong local heating that adversely impacts stratospheric ozone.

The principal radiative effect of volcanic aerosols is the solar shortwave (SW) cooling of the surface temperature (green dashed line and left-hand scale, Fig. 1B) computed with zero feedback magnification for a single-layer aerosol at 27-29 km altitude (with a mass density of 0.01 gm^{-2}, 75% H_2SO_4 composition) as the aerosol effective radius is varied from zero to 1 µm. The aerosol effect can also be expressed equivalently as Wm^{-2} of radiative forcing (blue and red dashed lines for the SW and net radiative forcings, right hand scale). Also shown at the bottom of Figure 1B by the dotted and solid green lines is the LW (greenhouse effect) forcing of the volcanic aerosol. Notably, the LW forcing

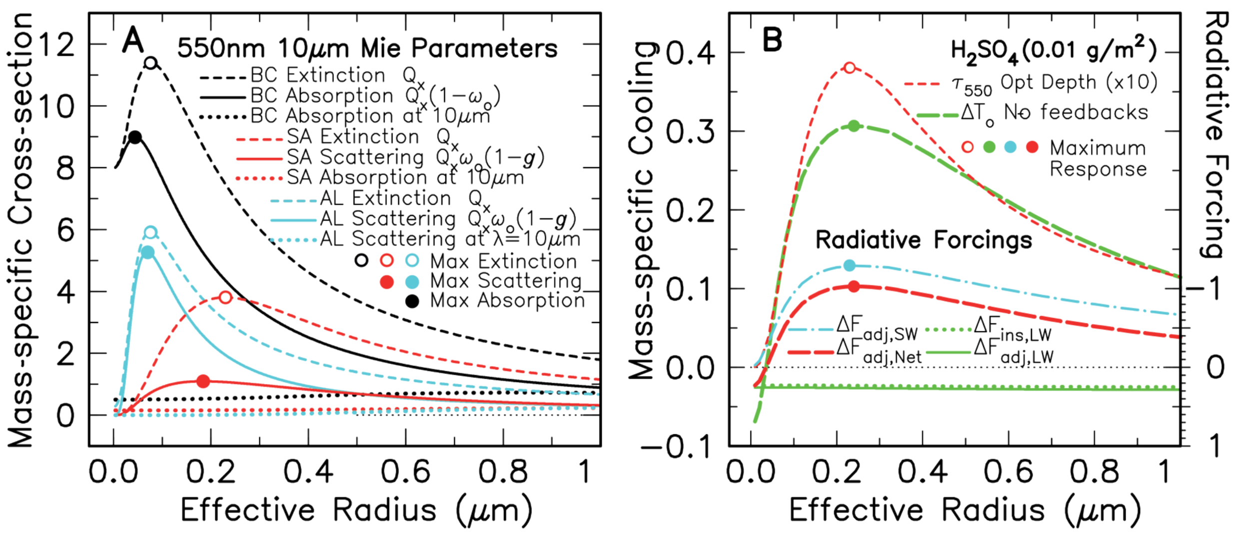

Figure 1: (A) Mass-specific cross-sections (m^{2}g^{-1}) at 550 nm and 10 µm for black carbon (BC), sulfuric acid (SA), aluminum (AL) aerosols as functions of aerosol size. Dashed lines are Mie extinction efficiency factors Q_x. BC absorption cross-section is solid black. Solid red and blue lines depict effective scattering cross-sections of SA and AL aerosols. Black and red dotted lines are BC and SA absorption cross-sections at 10 µm. Blue dotted line is AL scattering at 10 µm. **(B)** Mass-specific cooling for SA aerosol for mass density 0.01 gm^{-2} as functions of aerosol size. Dashed red line is SA optical depth (x10). Long-dash green line depicts no-feedback surface temperature (cooling) change. Radiative forcings use right-hand scale. The long-dash red line depicts adjusted forcing with solar only (SW) component given by the dot-dash cyan line. The green lines are LW instantaneous and adjusted forcings.

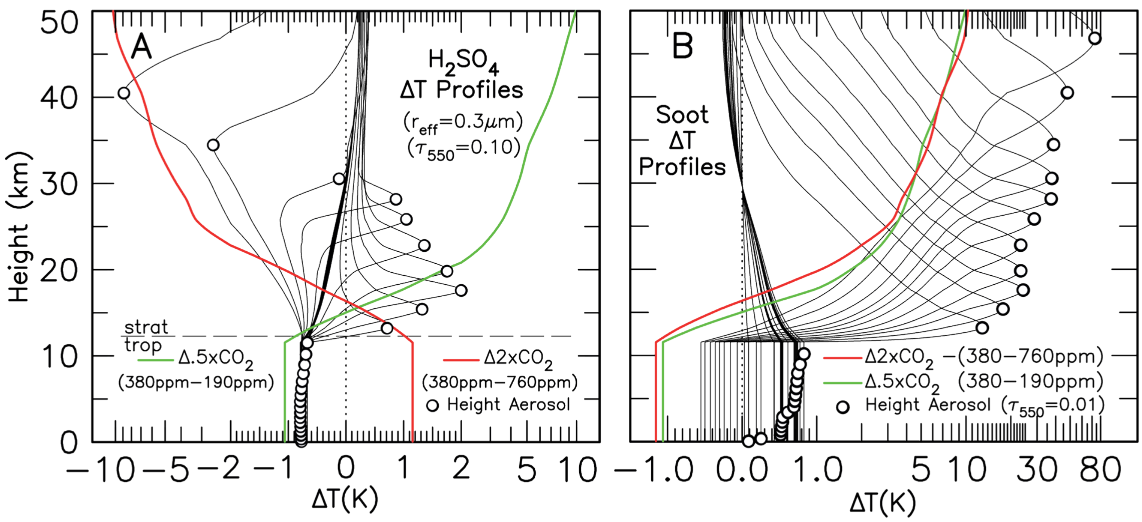

Figure 2: (A) Atmospheric heating and cooling profiles for sulfuric acid (H_2SO_4) aerosol for optical depth τ_{550}=0.10 as functions of aerosol height. Aerosol height is denoted by the open circles. ΔT scale is linear from -2.0 to 2.0, logarithmic otherwise. Atmospheric temperature changes for $2xCO_2$ (red line) and $0.5xCO_2$ (green line), are included for comparison. **(B)** Atmospheric heating and cooling profiles for black carbon (soot) aerosol for optical depth τ_{550}=0.01 as functions of height (open circles). The ΔT scale is linear from -1.0 to 1.0, otherwise logarithmic. For comparison, the temperature response for $2xCO_2$ and $0.5xCO_2$ are plotted as a negative temperature change.

is virtually independent of particle size. This happens because sulfuric acid aerosol is strongly absorbing at thermal wavelengths, and for the size range shown, the aerosol is effectively within the Rayleigh limit relative to the wavelength of thermal radiation (hence there is only minimum change in the LW absorption cross-section with size).

A simple estimate of the aerosol potential climate impact is the instantaneous radiative forcing ΔF_{ins} which is just the change in LW net flux at the tropopause calculated with and without the aerosol. A more accurate estimate is the adjusted radiative forcing ΔF_{adj}, which is obtained by allowing the stratosphere to equilibrate with ground and tropospheric temperatures kept constant. The radiative/convective equilibrium response can also be expressed as a surface temperature (ΔT_o) change representing the radiative forcing in temperature equivalent units without feedback effects being included. To estimate the full-equilibrium surface temperature response (ΔT_{eq}), with climate system feedback contributions included, ΔT_o is multiplied by a climate feedback factor, which, in the case of the GISS climate GCM with 2.7°C sensitivity for $2xCO_2$, is *f* ~2.3 (Lacis and Mishchenko 1995).

The perception that if aerosols are very small, they will have little or no LW radiative effect is not accurate. This is because for strong LW absorption, e.g. H_2SO_4, the absorption cross-section remains largely independent of particle size in the Mie scattering Rayleigh limit for absorbing aerosols. Thus, volcanic H_2SO_4 aerosols will produce some surface warming when the aerosol size is smaller than r_{eff}=0.04 µm. Also, when H_2SO_4 aerosols are larger than 2.2 µm, the LW radiative heating contribution exceeds the SW scattering component to produce surface warming.

Effect of vertical aerosol distribution

Typically, volcanic aerosols absorb little SW solar radiation. Hence, the vertical distribution of the aerosol has minimum impact on the surface cooling. However, the aerosol height does have an important bearing on the stratospheric heating. Figure 2A demonstrates the radiative effect of volcanic aerosol height on atmospheric temperature by stepping the H_2SO_4 aerosol layer-by-layer from the ground to the mesosphere. The largest heating occurs in the lower stratosphere, where the stratosphere is the coldest, and where the absorbed LW radiation exceeds the local LW emission by the largest margin. H_2SO_4 does absorb strongly at near-IR wavelengths beyond 3 µm, but there is little solar energy there to be absorbed in this spectral region (Lacis et al. 1992).

At altitudes higher than about 30 km, where stratospheric temperatures are comparable to ground surface temperatures, the H_2SO_4 aerosols exhibit substantial stratospheric cooling. However, the radiative forcing that drives the global surface cooling (ΔT_o) is largely independent of height, and is equal to approximately -0.7°C (Fig. 2A). For comparison, the equilibrium response of stratospheric temperature to $0.5xCO_2$ (380-190 ppm) and $2xCO_2$ (380-760 ppm) is shown by the heavy green and red lines, respectively.

In contrast to the behavior of H_2SO_4 aerosols, Figure 2B shows the atmospheric heating and cooling profiles characteristic for strongly absorbing black carbon (soot) aerosol. Because of its greater surface cooling efficiency, optical depths (τ_{550}=0.01) an order of magnitude smaller are used for soot than for H_2SO_4. A principal characteristic of strongly absorbing aerosols is their strong tropospheric and surface warming if the soot aerosol is deployed within the troposphere. Significant cooling of the ground surface is possible when the soot aerosol is deployed at high altitude, approaching -1.86 Wm^{-2} surface cooling for soot deployed at 44-50 km altitude. This behavior is similar to what happens in nuclear winter scenarios when the thermal back-warming from the stratosphere is much diminished by the increasing height of the aerosol. Predictably, soot that is deployed high in the stratosphere will generate extreme stratospheric heating, which is an undesirable bi-product. In summary, the radiative impact of soot on the surface temperature is strong heating for soot deployed within the troposphere, but when deployed at high altitudes in the stratosphere, soot can also produce strong cooling of the ground surface.

Considerations for geoengineering applications

Large volcanic eruptions have been valuable radiative forcing experiments to test climate model response to stratospheric aerosol injections. Based on this, aerosols have also been suggested for geoengineering applications to counteract global warming. For this purpose, the non-absorbing aerosols would appear to be the logical choice in that they could mimic the radiative effects of naturally occurring volcanic aerosols. But among the drawbacks would be the need to maintain millions of tons of scattering aerosols in the stratosphere since particles that are large enough to scatter efficiently tend to fall out from the stratosphere within a year. Thus, for non-absorbing aerosols, maintaining the optimum aerosol size would be critical – if the aerosols are too large, they fall out too fast, if they are too small, their scattering efficiency becomes too small. The results presented here also demonstrate that strongly absorbing aerosols could efficiently cool the ground surface, but that the accompanying stratospheric heating would be exceedingly large.

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Evolving particle size is the key to improved volcanic forcings

Graham Mann[1,2], S. Dhomse[2], T. Deshler[3], C. Timmreck[4], A. Schmidt[2], R. Neely[1,2] and L. Thomason[5]

Accurate volcanic forcing estimates are pivotal for robust simulation of global mean surface temperature trends. Interactive stratospheric aerosol microphysics models calculate aerosol-radiation interactions and sedimentation rates consistently with a globally varying particle size, which improves the fidelity of simulated climate impacts.

Major volcanic eruptions inject sulfur dioxide (SO_2) into the stratosphere, abruptly increasing the stratospheric aerosol burden, with the decay back to pre-eruption conditions taking several years (Fig. 1). The aerosols have long-lasting global impacts on climate (e.g. Robock 2000), principally surface cooling through increased scattering of solar radiation, which is partially offset via increased absorption of terrestrial radiation, heating the stratosphere. Accurately characterizing these shortwave and longwave radiative effects is critical for robust attribution of anthropogenic climate change.

The injected SO_2 oxidizes to sulfuric acid vapor causing new particle formation and condensation onto existing particles, which, together with ongoing coagulation, grows aerosol particles to larger sizes than in quiescent conditions (e.g. Deshler 2008). The size shift increases the solar scattering efficiency and controls the stratospheric heating since only coarser particles absorb solar near-infrared and terrestrial longwave radiation (Lacis et al. 1992). Larger particles also fall faster, which causes a vertical gradient in the particle size distribution and limits the impacts from very large eruptions (e.g. Pinto et al. 1989).

In the case of major tropical eruptions, such as the 1991 Pinatubo eruption, the stratospheric heating enhances the equator-to-pole temperature gradient in the lower stratosphere causing a stronger polar vortex and inducing chemical and dynamical changes with complex associated short-term climate responses (e.g. Graf et al. 1993). For example, mid-latitude North America and Eurasian winters were warmer following major 20th century eruptions (Robock and Mao 1992).

Microphysical processes therefore play a key role in determining volcanic impacts on climate, and Timmreck (2012) identified the need for model intercomparisons and greater evaluation against observations to better constrain radiative forcings.

Prescribed volcanic forcings may cause biases

All but one of the climate models that performed CMIP5 historical simulations used prescribed volcanic radiative forcing datasets based on observationally-derived reconstructions of aerosol optical depth following major eruptions (e.g. Sato et al. 1993). Many also calculate radiative effects assuming a globally uniform particle size distribution, which may have overestimated volcanic cooling in the simulations (Canty et al. 2013). Indeed, deficiencies in prescribed volcanic forcings have been identified as a likely contributor to discrepancies between climate model and observed global mean surface temperature (GMST) trends (Marotzke and Forster 2015).

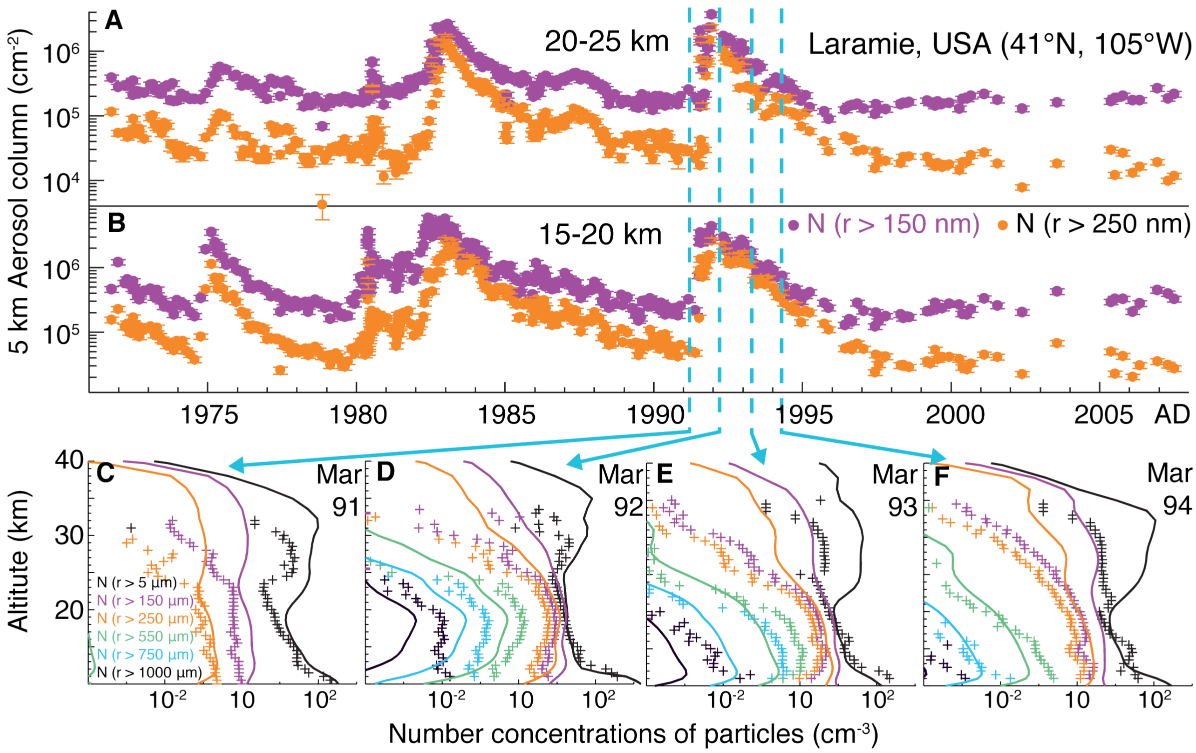

Figure 1: The 30+ year record of column-integrated size-resolved stratospheric aerosol particle concentrations at altitudes of **(A)** 20-25 km and **(B)** 15-20 km from balloon soundings at Laramie, USA (from Deshler 2008). **(C-F)** Example evaluation of the UM-UKCA model (Dhomse et al. 2014) simulated particle size distribution (dashed lines) before (C) and after (D, E, F) the June 1991 Pinatubo eruption compared to measured particle concentrations (crosses) larger than different size thresholds (colors) and total particle concentrations larger than 5 nm radius (black).

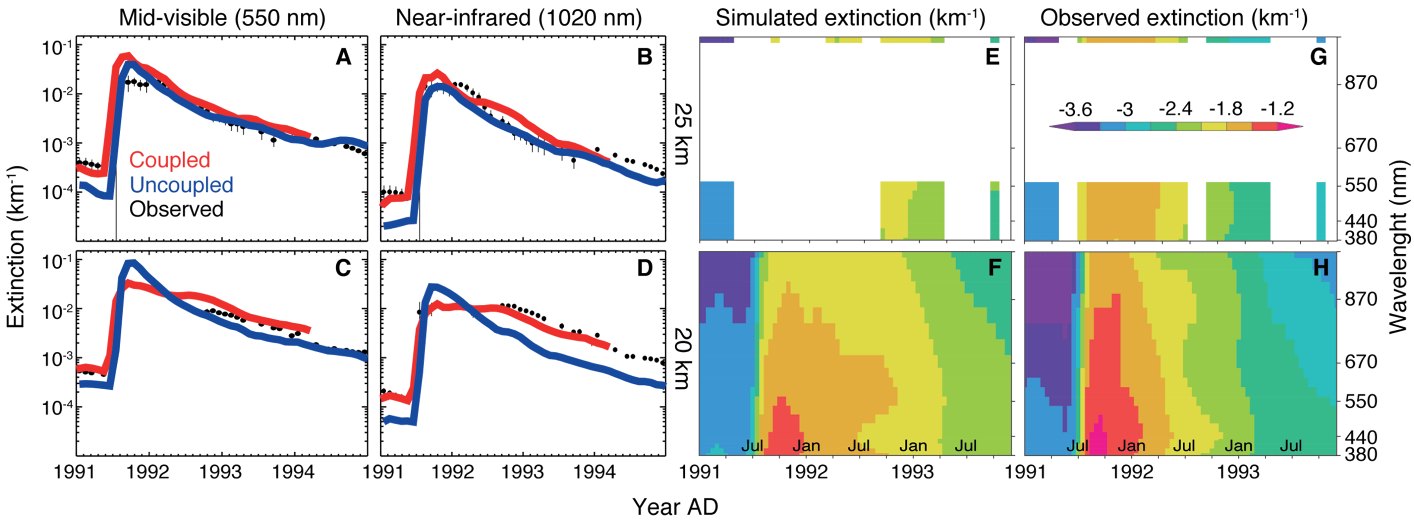

Figure 2: The SAGE-II timeseries of tropical-mean (0-15°N) aerosol extinction in the mid-visible (550 nm) and near-infrared (1020 nm) at 25 km **(A, B)** and 20 km a.s.l. **(C, D)** compared to radiatively coupled (red) and uncoupled (blue) Pinatubo simulations where 10 Tg of SO_2 was injected. The evolution of the simulated extinction across the shortwave spectrum at the two altitudes is shown in panels E and F, alongside that observed by SAGE-II v7.0 **(G, H)**.

The CMIP5 models tend to overestimate the post-Pinatubo stratospheric warming and generally fail to capture the dynamical response and associated winter warming (Driscoll et al. 2013), which may partly be due to omission of global size variations.

Climate models with interactive stratospheric aerosol

There has been a significant advance in model capability recently with the development of a new generation of composition-climate models (CCMs) that treat the stratospheric aerosol interactively (e.g. Niemeier et al. 2009; Dhomse et al. 2014). Many of these models also include aerosol microphysical modules to calculate sedimentation rates and aerosol-radiation interactions consistently with simulated global variations in particle size distribution. Such models therefore have great potential to improve the accuracy of modeled volcanic impacts on climate and thereby increase the reliability of simulated GMST trends.

Interactive stratospheric aerosol CCMs have demonstrated capability in reproducing observed variations in particle size distribution after the Pinatubo eruption. For example, in Figure 1, the model captures the observed feature that optically active sizes (larger than 150 nm, colored lines) were enhanced for all size channels measured by the particle counter, whereas total particle concentrations (black) were not greatly perturbed by the eruption.

Figure 2 demonstrates the potential of the models to produce new volcanic forcing datasets and illustrates how the heating of the plume strongly influences its own dispersion and subsequent radiative effects. The warming enhances upwelling in the tropics, which lofts particles to high altitudes generating a kink in the 20 km extinction timeseries: a minimum in early 1992 and a second maximum at the end of the year. The latter peak is likely due to particles sedimenting from the main plume, which at that time is present at higher altitudes. Combining the models and measurements may also help close a key observation gap in the post-Pinatubo SAGE-II solar occultation record. For several months following the eruption the volcanically enhanced aerosol was opaque enough to prevent measurements of aerosol extinction below 23 km in the tropics (e.g. Hamill et al. 2006).

A recent study of the Pinatubo eruption (Dhomse et al. 2014) showed that the satellite-observed post-eruption increase in mid-visible aerosol optical depth is consistent with a considerably lower mass of sulfuric acid in the aerosol when variations in particle size are simulated. The study also emphasized that satellite estimates of the peak global sulfur burden in the particles are around 50% lower than the measured gas phase sulfur burden shortly after the eruption. Further analysis suggests that the coarse spatial scales used in global models may miss important loss pathways in the first days following the eruption. This could have implications on the modeling of SO_2 emissions in the CCMs in order to make the simulated stratospheric aerosol properties consistent with observations.

Quantifying uncertainty in volcanic forcings

These issues will be investigated in a new "Historical Eruption SO_2 Emission Assessment" experiment within the model intercomparison activity of the current "SPARC Stratospheric Sulfur and Its Role in Climate" initiative (SSiRC). The activity will involve evaluating simulations of the Agung, El Chichón, and Pinatubo eruptions from a range of interactive stratospheric aerosol models and assessing how much SO_2 is required to match with available observations.

Another analysis within the modeling component of SSiRC is the "Pinatubo Emulation in Multiple modelS" (PoEMS) experiment, which will quantify the uncertainty in volcanic forcings predicted by interactive aerosol CCMs. By applying novel statistical techniques (Lee et al. 2011), contributions to the overall forcing uncertainty will be attributed to a range of parameters, varied within the ensembles carried out by each participating model. In so-doing, the initiative seeks to identify to which parameter uncertainties (injection settings, chemical conversion or microphysical processes) simulated volcanic forcings are most sensitive. The SSiRC intercomparison experiments are complimentary to the VolMIP initiative for CMIP6, which will investigate climate responses to common prescribed volcanic forcings (see Zanchettin et al., this issue).

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A coordinated modeling assessment of the climate response to volcanic forcing

Davide Zanchettin[1], C. Timmreck[2], M. Khodri[3], A. Robock[4], A. Rubino[1], A. Schmidt[5] and M. Toohey[2,6]

Simulating volcanically-forced climate variability is a challenging task for climate models. The model intercomparison project on the climate response to volcanic forcing (VolMIP) defines a protocol for idealized volcanic-perturbation experiments to improve comparability of results across different climate models.

Stratospheric aerosols originating from volcanic sulfur emissions are a critical part of the natural forcing driving interannual-to-multidecadal climate evolution. In its 2013 assessment report, the Intergovernmental Panel on Climate Change (IPCC) affirms strong advances had been made in understanding volcanic aerosols and constraining associated forcing estimates compared with previous assessments (Myhre et al. 2013). Challenging the high confidence in volcanic forcing estimates reported by the IPCC (see Table 8.5 in Myhre et al. 2013), climate model results show some gaps in our understanding of the climate's response to volcanic eruptions. For example the largest uncertainties in the estimates of radiative forcing from historical simulations performed using state-of-the-art climate models occur during periods of strong volcanic activity (Santer et al. 2014); climate models generally do not produce robust dynamical responses to volcanic eruptions (e.g. Driscoll et al. 2012; Ding et al. 2014) and tend to overestimate the observed post-eruption global surface cooling (Marotzke and Forster 2015); and simulated temperatures around major volcanic events of the last millennium often disagree with corresponding reconstructed changes (e.g. Mann et al. 2012; Anchukaitis et al. 2012).

The key question then is whether the lack of robustness in models' behavior mostly depends on insufficient representation of climate processes, or other substantial sources of uncertainty, such as the imposed volcanic forcing. The lack of agreement between model results is mainly due to differences in the model's characteristics, such as spatial resolution and implementation of volcanic forcing (e.g. Timmreck 2012). Nevertheless, whereas recent volcanic eruptions have been well observed and forcing estimates relatively well constrained, uncertainties grow considerably for events that occurred in the more remote past. For such eruptions, which contribute substantially to our understanding given the few instrumentally observed events, forcing characteristics must be reconstructed based on indirect evidence. This implies a lack of detail and large uncertainties regarding the climatically relevant parameters related to the source (especially the magnitude of the eruption), and to the stratospheric aerosol properties such as spatial extent of the cloud, optical depth, and aerosol size distribution (e.g. Timmreck 2012). All these large uncertainties are reflected in the occasionally substantial inconsistencies between available volcanological datasets (Sigl et al. 2014). Furthermore, internal climate variability and the presence of other forcing factors contribute to determine which mechanisms are activated in response to individual events (e.g. Zanchettin et al. 2013). It is therefore difficult to constrain the simulated responses to eruptions that occurred before the instrumental period, for which knowledge about the background climate conditions is poor.

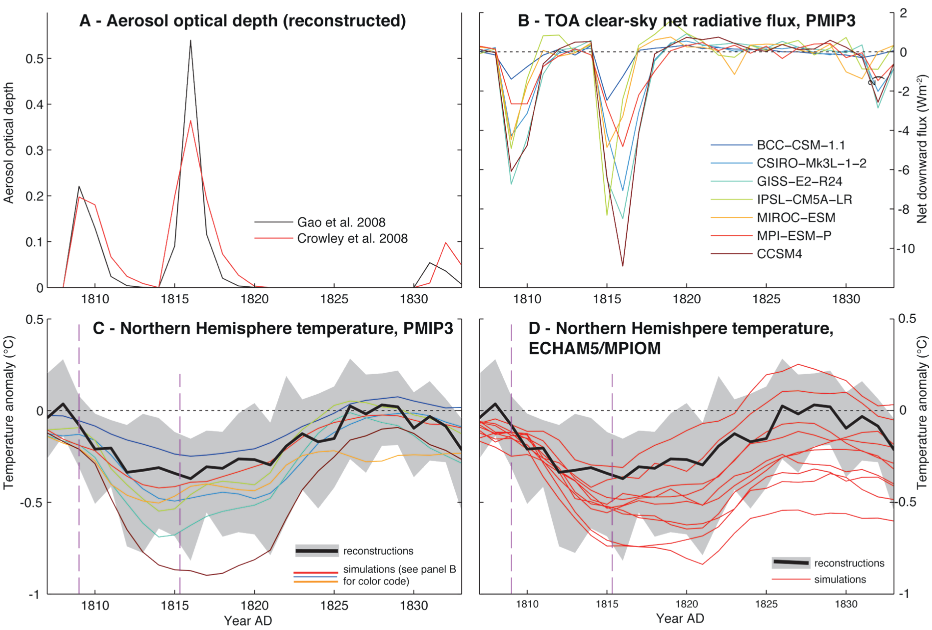

Figure 1: Uncertainty in radiative forcing and climate response for the early-19th-century eruptions. **(A)** Two estimates of annual-average global aerosol optical depth at 550 nm (AOD). **(B)** Top-of-atmosphere (TOA) annual-average net clear-sky radiative flux anomalies for a multi-model ensemble of last-millennium simulations (PMIP3; Braconnot et al. 2012). **(C)** Comparison between simulated (PMIP3, 11-year smoothing, colors) and reconstructed (black line: mean; shading: 5th-95th percentile range) Northern Hemisphere average summer temperature anomalies (from 1799-1808). **(D)** Same as (C), but for a single-model ensemble (ECHAM5/MPIOM; Zanchettin et al. 2013). The models tend to overestimate the reconstructed early-19th-century cooling, yet both simulation ensembles are compatible with the reconstruction; different models and forcing inputs (C) and internal climate variability (D) similarly contribute to simulation-ensemble spread.

It is thus unsurprising that different simulations, either performed with different climate models or with the same climate model, and climate reconstructions tell different, often divergent stories about the post-eruption climate evolution. This occurred, for instance, in the case of the 1815 Tambora event, the largest-magnitude volcanic eruption of the past five centuries (Fig. 1).

Coordinated model intercomparisons

The continuing development of more accurate histories of past eruptions (e.g. Sigl et al. 2014) and more realistic volcanic forcing datasets (e.g. Arfeuille et al. 2013) promises to improve climate model simulations of past volcanic events. This alone, however, is not enough to discern the individual contributions to uncertainty from the bulk of the varied factors illustrated above. It is also necessary to frame modeling activities within standardized experiments designed to systematically tackle specific uncertainty factors.

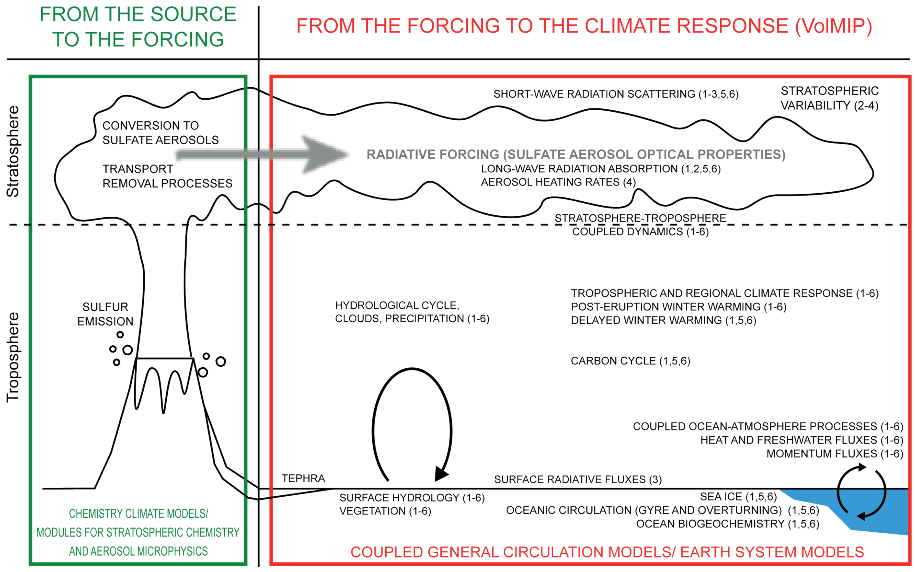

Figure 2: Dominant processes illustrating the link between volcanic eruptions and climate response, with an overview of VolMIP experiments as submitted to the World Climate Research Program for CMIP endorsement (1-4: mandatory; 5,6: non-mandatory). VolMIP experiments: (1) Tambora-like tropical eruption [VolLongS60EQ]; (2) Pinatubo-like tropical eruption [VolShort20EQfull]; (3) Pinatubo-like eruption, prescribed perturbation to shortwave radiative flux [VolShort20EQsurf]; (4) Pinatubo-like eruption, prescribed perturbation to aerosol heating rates [VolShort20EQstrat]; (5) Laki-like high-latitude eruption [VolLongS100HL]; (6) 19th century-like cluster of tropical eruptions [VolLongC19thC].

The ongoing Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP) has defined a common protocol to subject coupled climate models to the same volcanic forcing, thus aiming for negligible across-model differences in the applied radiative forcing (e.g. Fig. 1b) in order to focus on the climate response. The coordinated experiments will assess the causes of across-model spread linked to the different treatment of physical processes, and separate such model uncertainties from uncertainties in the forcing and internal variability.

VolMIP focuses on the simulated processes that determine two main aspects of climate response to large volcanic eruptions: (i) the immediate dynamical alteration of atmospheric circulation triggered by the volcanically-induced stratospheric thermal anomaly and the associated variations in regional near-surface responses; and (ii) the decadal-scale response of the oceanic thermohaline and gyre circulations and associated long-term changes in heat transport and ocean-atmosphere coupling.

The VolMIP experiments

VolMIP defines a set of idealized volcanic perturbations based on historical eruptions. In this context, "idealized" means that the volcanic forcing is derived from radiation parameters of documented eruptions and the experiments do not include information about the actual climate conditions when these events occurred. The experiments are designed as ensemble simulations, with sets of initial climate states sampled from an unperturbed preindustrial simulation. By exploring very different initial conditions, VolMIP aims to constrain the range of post-eruption evolutions that arise from the interplay between ongoing internal climate variability and the imposed radiative perturbation, thus clarifying how much an accurate knowledge of background climate conditions matters when reproducing past volcanic events. Specific attention is given to the concomitant phasing of two dominant modes of climate variability: the El Niño-Southern Oscillation, the most important source of interannual climate variability, and the Atlantic meridional overturning circulation, a measure of the strength of the oceanic thermohaline circulation.

The proposed core and sensitivity experiments (Fig. 2) reflect VolMIP's twofold strategy:

- VolShort: a set of experiments focusing on the seasonal-to-interannual atmospheric response to a 1991 Pinatubo-like volcanic eruption. The goal is to discriminate between the uncertainties that are due to internal variability (within-model spread) and those due to model characteristics (across-model spread). The core full-forcing experiment is supported by sensitivity experiments designed to determine the roles of surface cooling and stratospheric warming – the two main features of short-term post-eruption climate variability – in controlling the dynamical response of the atmosphere. Additional experiments address the impact of volcanic forcing on seasonal-to-interannual climate predictability.
- VolLong: a set of experiments addressing the long-term (up to the decadal time scale) climate response to volcanic eruptions featuring a high signal-to-noise ratio in the global-average surface temperature response. Focus is on the signal propagation pathways of volcanic perturbations within the coupled atmosphere-ocean system, the associated determinant dynamical processes and their representation across models. The 1815 Tambora eruption is chosen as reference for the core experiment, as available climate-proxy data provide information on both eruption characteristics and climate response. A 1783 Laki-like, high-latitude eruption and idealized volcanic clusters (close successions of large volcanic eruptions) are also contemplated in this set of experiments. Provision of forcing input data for these simulations is an integral part of VolMIP.

Conclusions

Improvement in understanding the dominant mechanisms behind simulated post-eruption climate evolution crucially depends on coordinated modeling activities that address the individual sources of uncertainty separately. By subjecting different models to well-constrained volcanic forcing, VolMIP promises to make significant progress in our knowledge of the physical processes that determine the climate's response to volcanic forcing. By further clarifying the relative role of internal and externally-forced climate variability during periods of strong radiative forcing, VolMIP can enhance our ability to accurately simulate past, as well as future, climates.

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Volcanic eruptions and the global hydrological cycle

Carley E. Iles, G.C. Hegerl and A.P. Schurer

Large, explosive volcanic eruptions cause a decrease in global precipitation and shifts in the position of the Intertropical Convergence Zone. Regionally, the most significant changes include decreases in precipitation in monsoon areas, and more precipitation in dry tropical ocean regions.

Large, explosive volcanic eruptions are an important driver of climate variability. For instance, the 1815 eruption of Mount Tambora in Indonesia was followed, by "the year without a summer" in Europe and North America (Stothers 1984). Volcanic eruptions have also caused decreases in hemispheric and regional temperature over the last millennium, particularly over the Little Ice Age (e.g. Schneider et al. 2009; Schurer et al. 2013), and are even speculated to have contributed to its onset (Miller et al. 2012). Climatically relevant eruptions operate through injecting SO_2 into the stratosphere, where it is oxidized into sulfate aerosols, which reflect incoming solar radiation. These aerosols spread out globally following tropical eruptions, or over the hemisphere of eruption for high latitude ones, with a lifetime in the stratosphere of a couple of years. The result is a global cooling response lasting a few years (e.g. Robock 2000 and references therein).

Global precipitation decrease

Volcanic eruptions also affect other components of the climate system, by changing atmospheric circulation, increasing sea ice extent, and reducing global precipitation (e.g. Robock 2000; Timmreck 2012). Precipitation decreases have been found in both observational records and in climate model simulations forced with observed records of volcanic aerosols (e.g. Iles et al. 2013; Iles and Hegerl 2014; Trenberth and Dai 2007). They occur because less shortwave radiation reaches the surface, thereby reducing evaporation and stabilizing the atmosphere, whilst the cooler atmosphere contains less water vapor. This pattern is modulated on regional scales by circulation changes, for example weakened monsoon winds can result from larger post-eruption cooling of the land relative to the ocean, reducing precipitation in monsoon regions (e.g. Joseph and Zeng 2011; Schneider et al. 2009).

Isolating the effect of volcanic eruptions is more difficult for precipitation than for temperature because it demonstrates less spatial and temporal coherence. A technique used to overcome this is termed "superposed epoch analysis" and involves averaging the precipitation response across multiple eruptions in order to reduce climate noise (e.g. Fischer et al. 2007).

Iles et al. (2013) examined the precipitation response to volcanic eruptions using this technique in both observational data and simulations of the last 600 years using the climate model HadCM3. Figure 1 shows that the model simulated precipitation response over the ocean is longer lived than that over land. Further investigation showed that this is a phenomenon that occurs in all historical simulations of the coupled climate models submitted to CMIP5 (Coupled Model Intercomparison Project Phase 5; Iles et al. 2014). Iles et al. (2013) found that the timing of the ocean precipitation response matched the timing of the post-eruption cooling response over the oceans, implying that precipitation changes could be driven through changing sea surface temperatures. Over land, precipitation reacted faster than temperature, its timing instead consistent with a reduction in land-ocean temperature gradient and the increase in aerosol optical depth, suggesting links to weakening monsoons and a directly forced component respectively.

Spatial pattern of the precipitation response

Figures 2a-d show the spatial patterns of precipitation response to five 20[th]-century eruptions (1902 Santa Maria, 1912 Novarupta, 1963 Agung, 1982 El Chichón, and 1991 Pinatubo) for the CMIP5 multi model mean (a,b) and observational gauge data (c,d) for the cold (Nov-April) and warm (May-Oct) seasons. Model simulated precipitation decreases strongly in tropical-subtropical wet regions (contour lines), including in monsoon regions in their summer season (including SE Asia, central Africa, Northern South America, and Indonesia-northern Australia). Surrounding areas get wetter, and high latitudes get drier (Fig. 2a,b). The tropical drying response shifts between seasons,

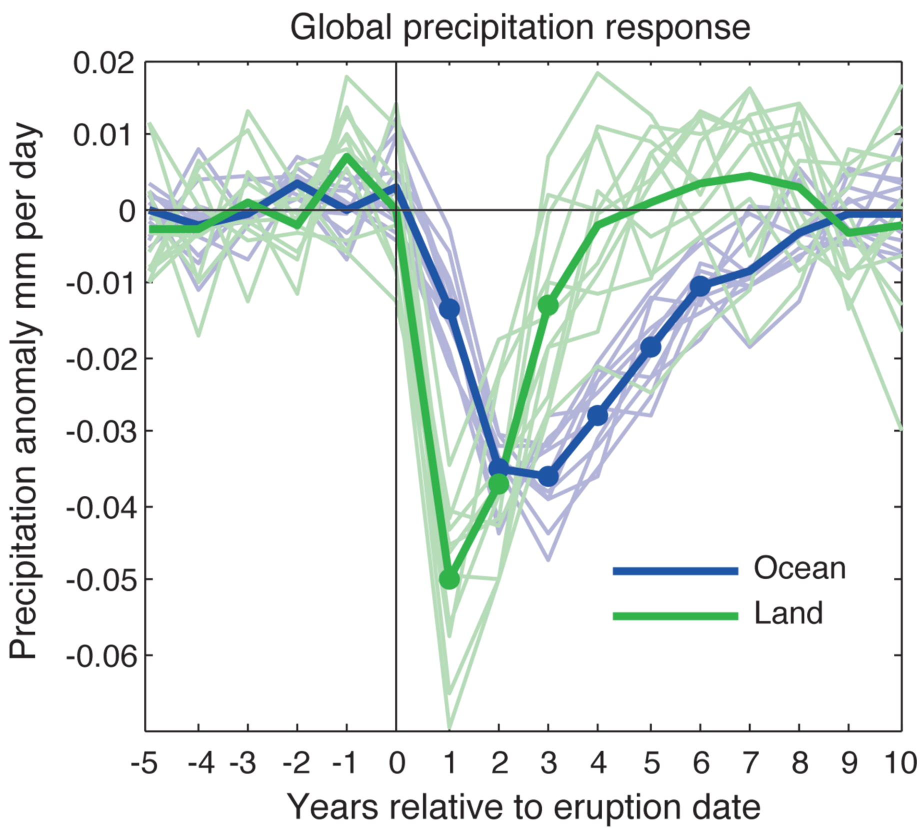

Figure 1: Global land and ocean precipitation response averaged over 18 low latitude eruptions and 11 ensemble members of the climate model HadCM3. Thick lines are ensemble means and thin lines are individual ensemble members. Dots indicate where the ensemble mean response is significant against internal variability at the 5% level. Figure modified from Iles et al. 2013.

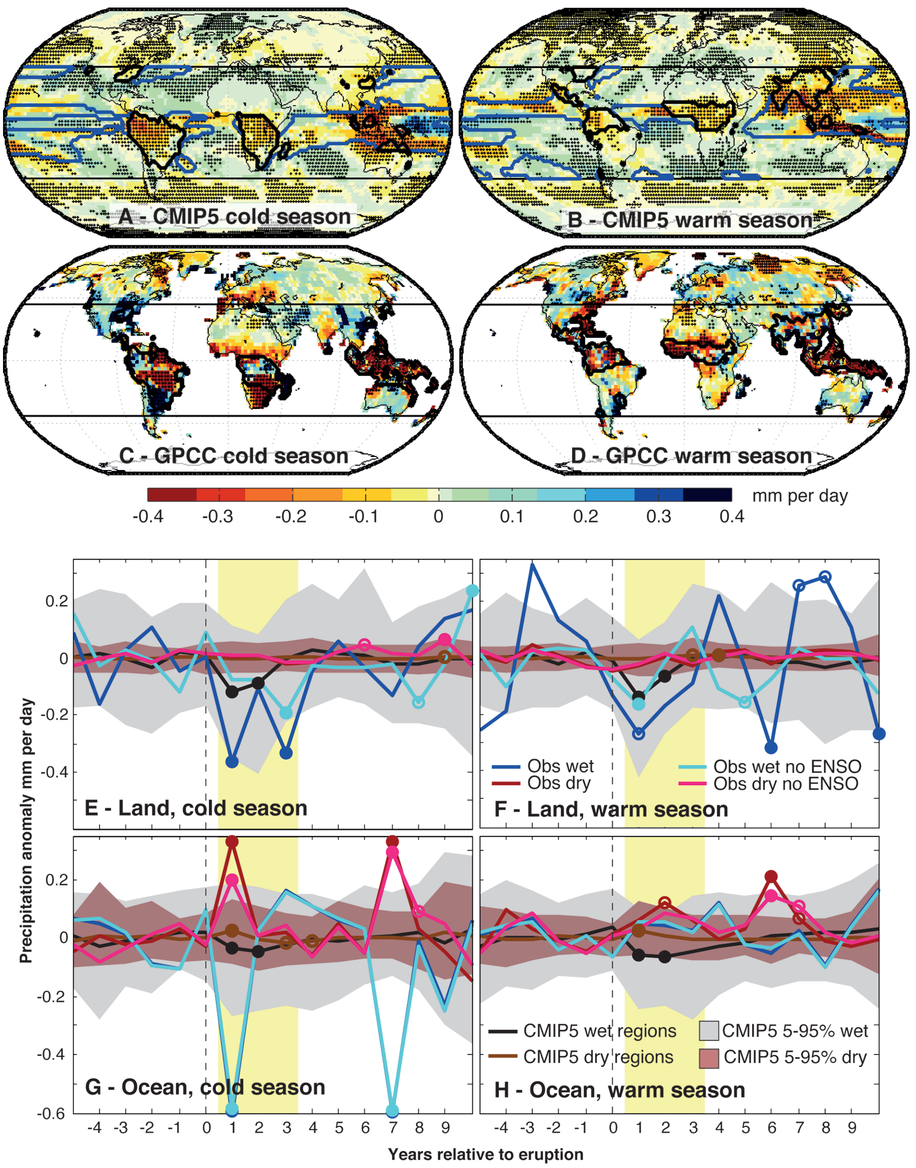

Figure 2: Average precipitation response across the first two years following five volcanic eruptions for **(A)** and **(B)** CMIP5 multi model mean, **(C)** and **(D)** observational data over land. Stippling indicates significance at the 90% level. Contour line denotes tropical-subtropical wet regions, blue for ocean and black for land. **(E-H)** Precipitation response averaged across wet and dry tropical-subtropical regions. Black line denotes the CMIP5 multi model mean over wet regions; brown for the dry regions. Shading denotes the 5-95% range of the results for individual ensemble members. Blue and red lines are the observed response over the wet and dry regions, respectively, with (darker line) and without (lighter line) the influence of ENSO. Circles indicate significance at the 80% level (open) and 90% level (filled) for post-eruption years. Yellow shading indicates when a response is expected. (A-F) are averaged over 5 eruptions and (G-H) over two (1982, 1991 eruptions). Figure modified from Iles et al. 2014.

following the migration of the Intertropical Convergence Zone (ITCZ) and monsoon regions. Observational records also show a drying response in monsoon regions, with the exception of Southeast Asia (Fig. 2c,d).

Figures 2e-f show the precipitation response averaged across the wet tropical-subtropical regions and dry regions over land and ocean separately. Wet regions get significantly drier in models and observations over both land and ocean, with the exception of observed ocean precipitation in the warm season. This observational decrease is robust to the removal of the influence of the El Niño Southern Oscillation (ENSO), which also has a large influence on precipitation, tending to shift it from land to ocean during El Niño years. Three of the five 20th-century eruptions examined are followed by El Niño events. Conversely, dry ocean regions get wetter in both the models and the observations, although this phenomenon is less detectible over land. Models appear to underestimate the size of the response in the cold season, with the observations lying outside of the 5-95% range of the ensemble members (Fig 2e,g), a finding confirmed through a detection analysis by Iles et al. (2014). In response to individual eruptions, Iles et al. (2014) found that in the CMIP5 multi model mean, the ITCZ shifts away from the hemisphere with the higher concentration of volcanic aerosols.

A positive phase of the North Atlantic Oscillation (NAO) has been observed on average in the winters following tropical eruptions, with associated winter warming over northern hemispheric continents (e.g. Robock and Mao 1992). Figure 2c shows a positive NAO precipitation pattern in observational data, with drying over southern Europe and wetter conditions over Northern Europe. However, consistent with other studies (e.g. Driscoll et al. 2012), this is not captured in the CMIP5 models (Fig. 2a).

Volcanic eruptions have also been found to affect global streamflow, with a significant decrease observed following the 1991 eruption of Mount Pinatubo, and more moderate decreases following the 1963 Agung and 1982 El Chichón eruptions (Trenberth and Dai 2007). Flow in the Nile and Niger rivers has been observed to decrease following high latitude eruptions (Oman et al. 2006). Recent research suggests a discernible influence of eruptions on observational streamflow records at regional scales over the instrumental period, largely consistent with model-simulated patterns of the precipitation response (Iles and Hegerl 2015).

Conclusion

Volcanic eruptions have caused detectible changes in precipitation. The response appears to be larger than simulated by present climate models, at least in some regions, which contrasts evidence that the temperature response in observations is smaller than simulated (e.g. Schurer et al. 2013), a discrepancy that needs to be understood. When analyzing regional precipitation change, it has proven useful to consider the expected pattern of volcanic response in climate models in order to make best use of the noisy response in observational records. Better understanding of the water cycle response to volcanic eruptions is important in understanding past variations in precipitation and to improve predictions of the impact of future eruptions, as well as that of shortwave geoengineering schemes (e.g. Tilmes et al. 2015), on global water availability.

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Volcanic monsoon influence revealed from multi-proxy evidence

Chaochao Gao

High-resolution hydrological reconstructions incorporating multiple proxies from diverse monsoonal regions provide improved understanding of how monsoon precipitation responds to volcanic eruptions and the underlying mechanisms.

Large volcanic eruptions inject sulfate gases into the stratosphere to form aerosols and cool the Earth's surface by reflecting sunlight. This effect on temperature has been well acknowledged and has inspired proposals for stratospheric sulfate aerosol injection as a potential way to reduce global warming. However, precipitation responses to volcanic perturbation, especially in monsoon regions, are just as crucial. Land precipitation and runoff showed a substantial reduction after the 1991 Pinatubo eruption, causing widespread drought for a large number of people in the world (Trenberth and Dai 2007). The 1912 Katmai and 1982 El Chichón eruptions preceded three of the four driest Sahelian summers during the last century, with the last drought attributed to up to 250,000 deaths and 10 million refugees (Haywood et al. 2013).

Ice-core reconstructions (Gao et al. 2008; Sigl et al. 2014) suggest that over the past 2000 years, volcanic eruptions can be even larger than the aforementioned events. For example, the 1257 Samalas, 1452-53 Kuwae and 1815 Tambora eruptions are estimated to have produced three to eight times more sulfate aerosols than Pinatubo. What impact did these historical eruptions have on the monsoon system? And what are the underlying mechanisms at work?

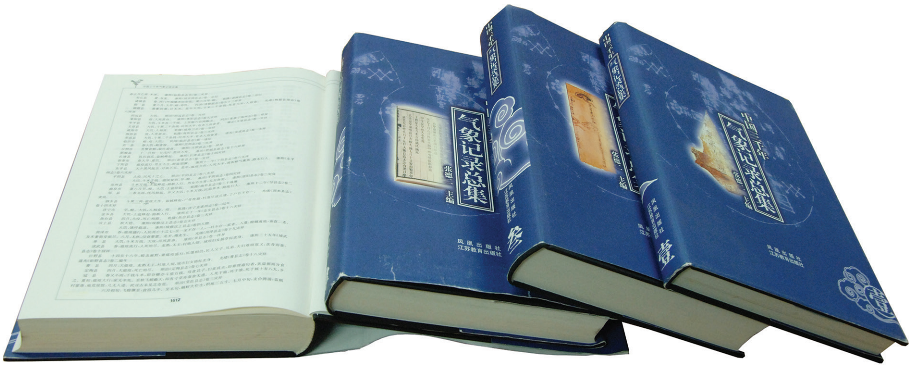

Figure 1: *"A Compendium of Chinese Meteorological Records of the Last 3,000 Years"* compiles the most comprehensive collection of Chinese official records including state annals, provincial annals, and county annals.

Multi-proxy evidence of volcanic monsoon influence

Recent progress on paleo-hydrological reconstructions provides a great opportunity to tackle these questions. Derived from over 300 precipitation, sensitive tree-ring records, the Monsoon Asia Drought Atlas (MADA; Cook et al. 2010) offers a major reconstruction of summer monsoon precipitation over the past seven centuries in Asia. Using MADA, Anchukaitis et al. (2010) found conditions drying significantly in eastern and northern China, but wetter conditions in Southeast Asia, after large volcanic eruptions. The South Asian summer monsoon index (SASMI; Shi et al. 2014), based on 15 tree-ring chronologies, also shows that volcanic perturbations lead to a weak South Asian summer monsoon in the second post-eruption year. This, in combination with temperature reductions, may be responsible for 69% of the historical droughts and famines in India over the last millennium (Shi et al. 2014).

Historical documents offer another independent line of evidence, and one of the best-preserved historical archives can be found in China. Shen et al. (2007) compiled a 500-year drought and flood index from historical rainfall descriptions in 120 stations across China, and found that the three most severe drought events in eastern China were triggered or amplified by volcanic eruptions. Zhuo et al. (2014) took the disaster records from a comprehensive collection of county, provincial, and state annals, and compiled an annual and county specific drought index over China for the past 700 years (Fig. 1). Overlapping MADA and this human archive with two independent multi-ice-core reconstructions of past volcanism, they studied the effects of volcanic eruptions on monsoon China over the past seven centuries. They found that large Northern Hemisphere eruptions cause notable drought in eastern China, and the severity increases with the injected amount of sulfate aerosols (Fig. 2). These Chinese annals adopt uniform recording standards and are rich in precipitation records, and therefore are a direct complement to the tree ring data. Similar studies utilizing historical records were conducted in various monsoon regions such as Sri Lanka and India (Sinha et al. 2011).

Proxy-model comparison and hints about the underlying mechanisms

Iles and Hegerl (2014) showed monsoon regions dried significantly after large volcanic eruptions in the Coupled Model Intercomparison Project Phase 5 (CMIP5-model ensemble results), and Man et al. (2014) reported a coherent summer precipitation reduction centered in central eastern China in the Max Plank Institute Earth System Model. In a preliminary superposed epoch analysis with the Community Earth System Model (CESM) and the Community Climate System Model (CCSM4) millennial outputs, we found a notable (significant at 95% confidence level) summer precipitation decrease in year 0-1 following the eruptions (Fig. 2). Therefore, proxy reconstructions and model simulations tend to agree on the average sign of monsoon response to large eruptions.

The summer monsoon contributes about 70% of the annual rainfall in eastern China, and it is affected by three airflows at 850 hPa: strong southwesterly winds from the Indian summer monsoon, a moderate

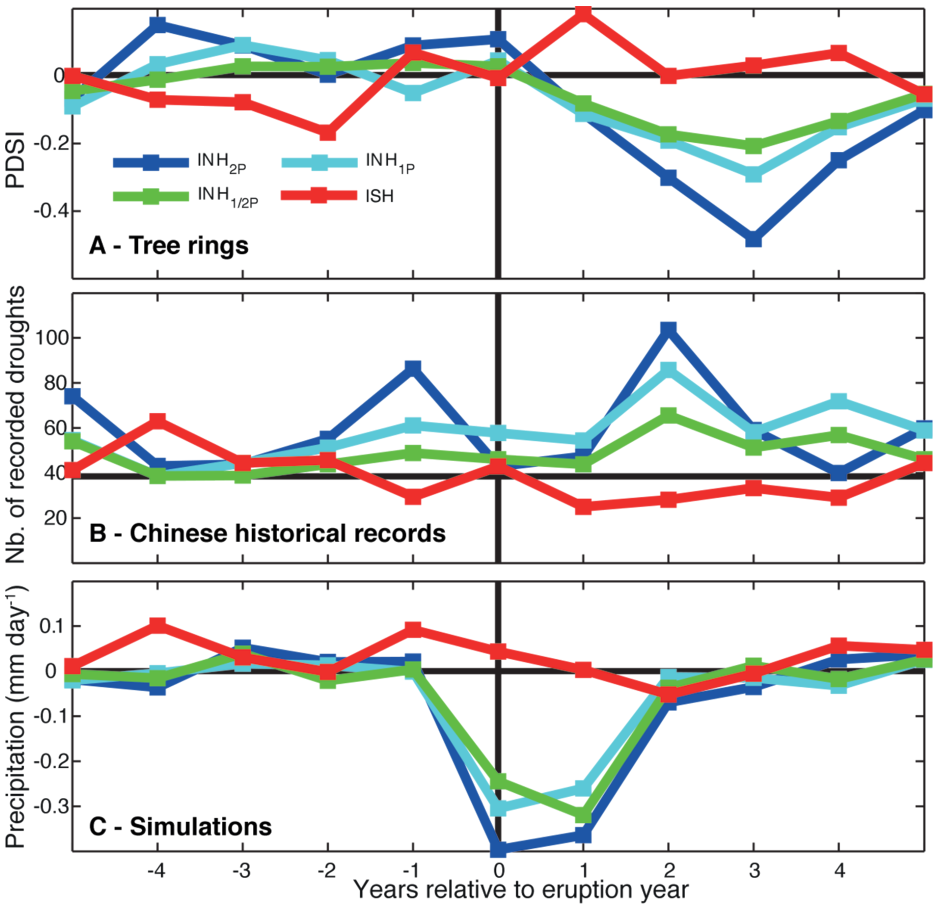

Figure 2: Average summer rainfall response in China to volcanic perturbations, revealed from **(A)** tree rings (Monsoon Asia Drought Atlas), **(B)** Chinese historical records (CHI), and **(C)** CESM and CCSM4 millennium simulations. Plotted are the superposed epoch analysis results for eruptions with Northern Hemisphere sulfate injection of more than half (INH1/2P), equal (INH1P), and double (INH2P) that of the 1991 Pinatubo eruption and SH-only (ISH) injection during AD 1300-1850. (A) and (B) are adapted from Zhuo et al. (2014); (C) is the precipitation anomaly with respect to the AD 1300-1850 mean.

southeast Asian monsoonal airflow from the west Pacific, and a weak cross-equatorial airflow from Australia. Model simulation shows significant reduction in water-vapor transport by both the southwesterlies and the southeasterlies after large tropical eruptions, therefore suggesting that the mechanism may be that volcanic-induced cooling reduces the zonal and meridional land–sea thermal contrast which leads to a weaker summer monsoon circulation.

Proxy evidence of a volcano-monsoon mechanism

A rapidly emerging body of proxy data (Sinha et al. 2011) suggests that, in addition to acting like a continental scale thermally-driven sea breeze, regional monsoons are interactive components of a singular global system tied to the seasonal migration of the intertropical convergence zone (ITCZ). Cooler temperature anomalies in the extratropical Northern Hemisphere could strengthen the NE trade winds in the Atlantic and Pacific basins, and force a southward shift of the ITCZ (Broccoli et al. 2006). The shift of ITCZ not only suppresses the mean state of the monsoon, but also intensifies the ENSO variability that further weakens the Asian Monsoon (Sinha et al. 2011).

The drying tendency after the Northern Hemisphere eruptions and wetting tendency after Southern Hemisphere ones (Haywood et al. 2013; Zhuo et al. 2014) indicate that volcanic aerosols may move the ITCZ toward the warmer hemisphere. A 500-year stalagmite $\delta^{13}C$ reconstruction of rainfall in southern Belize (Ridley et al. 2015) identified nine drying events associated with large Northern Hemisphere eruptions, and conversely increased rainfall after Southern Hemisphere eruptions. As the site is located near the northern edge of the ITCZ and therefore sensitive to even minor shifts in the ITCZ's position, these results tend to confirm that asymmetric distribution of volcanic aerosols could cause short-lived ITCZ migration to the warmer hemisphere.

On the other hand, Hong et al. (2015) synthesized diverse rainfall archives from both the Asian and Australian monsoon regions and found synchronized retreat of ITCZ in both areas during the Little Ice Age. The authors suggested that a reduction in effective solar irradiance, including volcanically-induced events, supplemented by the unique continent-marine distribution in the west Pacific, could cause a contraction of the ITCZ and reduced seasonal extremes in monsoon moisture transport.

Outlook

Analyzing proxy records provides a valuable approach to exploring the monsoonal response to volcanic perturbations, and for the pre-instrumental period, the only approach. The monsoon region is home to more than half of the world's population, and results from the proxy analyses reveal how damaging volcanic monsoonal responses could be. Nevertheless, proxy reconstructions can be limited by spatial-temporal coverage and the sensitivity towards the parameters under examination. Integrating multiple proxies, including tree rings, ice and lake sediments, speleothems, and historical records, from all of the monsoon regions is therefore crucial to obtaining a better understanding of the impact of volcanic events on the monsoon regime, before the next big eruption or prior to any attempts at climate engineering through deliberate release of sulfate aerosols into the stratosphere.

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On the AD 1815 Tambora eruption and the matter of misplaced tree rings

Scott St. George[1] and Kevin J. Anchukaitis[2]

A debate about volcanic eruptions and missing tree rings has spurred new research into the integrity of tree-ring dating and the impact of exceptionally cold summers on arctic and alpine forests.

On 10 April 1815, Mount Tambora erupted, sending "three columns of flame" into the sky above Sumbawa, Indonesia (Stothers 1984). By the time the volcano returned to slumber, 50 km^3 of rock had been vaporized, 71,000 people in Indonesia had died, and roughly 60 Mt of sulfur had been injected into the stratosphere (Oppenheimer 2003). In terms of total atmospheric loading, Tambora ranks as the third-largest volcanic event of the last 1500 years, eclipsed only by the 1257 Samalas and 1453 Kuwae eruptions (Gao et al. 2008).

The brilliant red, purple and orange sunsets seen in London during the following summer and autumn (Stothers 1984) were among the first signs the effects of this eruption would extend far beyond the Dutch East Indies. For many Europeans and North Americans in 1816, aberrant weather became the norm. Snow fell across Quebec, Maine, and New York state in June, mid-summer frosts extended as far south as New Jersey, and incessant cold and rain prevailed across England and central Europe (Oppenheimer 2003). The unseasonable weather, shortened growing season, and widespread crop failures led to 1816 being memorialized as the "Year Without a Summer".

Exactly how much cooling occurred in 1816 and how much was due to Tambora remains a point of contention nearly two centuries later. Limited instrumental measurements suggest Northern Hemisphere temperatures dipped 0.7 to 0.8°C in 1816 (Stothers, 1984), but few weather stations were active at this time and most were in Europe (D'Arrigo et al. 2013). Both proxy reconstructions and climate simulations show strong cold anomalies in 1816, but some model experiments (Mann et al. 2012) produce more cooling than supported by proxies.

The Year Without a Ring?

The mismatch between proxy reconstructions and climate simulations could be due to one of several potential causes, including estimates of Tambora's stratospheric aerosol loadings being too high or models exhibiting an excessively strong thermodynamic response to explosive volcanism. But one study proposed that proxies are the root cause of this disagreement and specifically called to question the ability of tree rings to track exceptionally cold years. Mann et al. (2012) argued the Year Without a Summer was so frigid that trees near their thermal limit in arctic and alpine forests remained dormant throughout the entire growing season and, as a result, did not form a ring for that year. If that were so, the ring for 1816 would be missing, paleotemperature estimates for 1816 would be incorrectly based on the 1815 ring, and prior to the Tambora eruption, tree-ring records would have a one-year chronological error.

The "missing 1816" scenario was initially criticized for its implementation of a tree-ring-growth model and a lack of empirical evidence for dating errors in tree-ring chronologies (Anchukaitis et al. 2012). More recently, this debate has provided the motivation for new research investigating how trees react to extreme cold and testing whether extraterrestrial influences on radiocarbon production can be used to corroborate or refute the current tree-ring timeline. In this Highlight article, we report on some of this latest work and discuss its implications for our understanding of Tambora and the sensitivity of the Earth's climate system to major volcanic eruptions.

Hunting the invisible

Every year, trees in boreal and temperate forests produce a new growth ring. But acute environmental stress, such as moisture deficits, wildfire, or insect attacks, can sometimes cause a portion of the tree's vascular cambium, the source of new wood, to remain dormant throughout the entire growing season. In those cases, the new growth ring will be discontinuous along the stem, present in some positions (usually near the crown) and absent at others (usually near the ground). The possibility that some years may be missing is one of the main reasons why tree-ring dating is accomplished through pattern-matching and not ring counting.

Perhaps because identifying missing rings is a routine step in chronology building, most tree-ring studies do not report how often they occur or where and when they are common. To address this shortcoming, St. George et al. (2013) produced a synthesis of locally absent rings across the Northern Hemisphere during the last millennium drawing upon 2,359 tree ring-width records. Absent rings did occur frequently across the American Southwest during severe droughts, but were extremely rare in tree-ring records from high-latitude or high-elevation sites. Based on their hemispheric survey, St. George et al. (2013) established that, in order for the "missing 1816" scenario to be valid, a wide swath of the boreal forest would have needed to exhibit a reaction to environmental stress that has never been observed anywhere at any time during the last millennium.

Validating the tree-ring calendar

But what if the 1816 rings were actually missing? Esper et al. (2012) conducted an experiment by modifying several tree-ring density records from Northern Scandinavia and the European Alps so that 1816 was entirely absent, the rings originally placed at 1816 were re-assigned to 1815, and the dates of all prior rings were shifted earlier by one year. The altered tree-ring sequences showed no correspondence with either temperature measurements from early weather stations or a five-century long summer temperature reconstruction for central Europe derived from documentary evidence. They concluded that, unless the tree-ring series, instrumental climate data, and historical reconstructions all share precisely the same dating error, the original tree-ring chronologies must be correct.

D'Arrigo et al (2013) also explored the consequences of making revisions to the tree-ring timeline. Density records from Labrador, Canada and the Scottish Cairngorms are excellent surrogates for summer temperature, but inserting a missing ring at 1816 destroys the correlation between local weather observations made in the late 1700s and early 1800s and the tree-ring series. They also pointed out that the lowest density value in the entire Labrador record occurred in 1816. If we assume that year was missing, this extreme

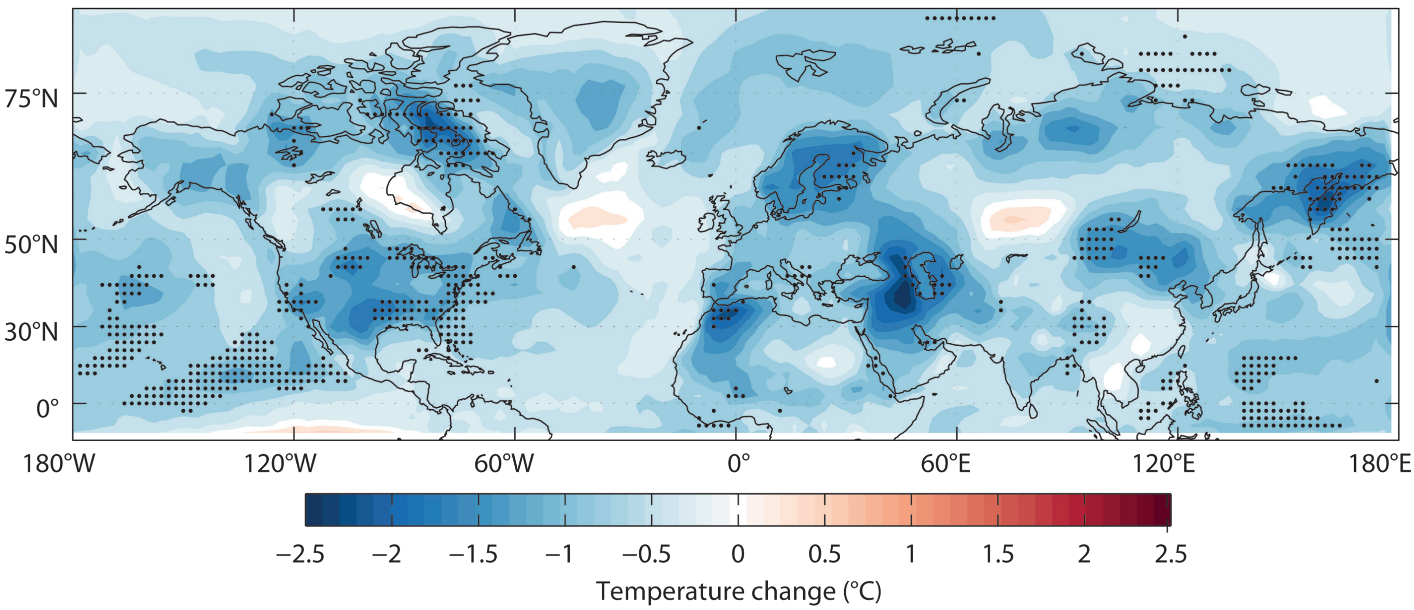

Figure 1: Simulated cooling during the northern summer (JJA) of AD 1816, as estimated by the Coupled Model Intercomparison Project Phase 5 (Taylor et al. 2012). The shading represents the multi-model mean temperature difference between the northern summer of 1816 and 1815, and stippling illustrates locations where at least seven of eight model ensemble members agree on the sign of the temperature change.

value would be re-assigned to 1815, which was not a particularly cold summer.

The other novel line of evidence affirming the tree-ring calendar emanates from an extraterrestrial source. Miyake et al. (2012) announced that tree rings from two Japanese cedars exhibited a rapid increase in radiocarbon content from AD 774 to 775, and argued this enrichment was evidence of a short-lived global surge in atmospheric ^{14}C production provoked by a cosmic-ray event. The AD 774-775 spike in radiocarbon content has subsequently been detected in Germany (Usoskin et al. 2013), Siberia and California (Jull et al. 2014), the Austrian Alps (Büntgen et al. 2014), and New Zealand (Güttler et al. 2015). Other researchers have argued this radiocarbon excursion was due to a different type of extraterrestrial event, such as an exceptional solar flare, a cometary impact on the sun, or a gamma-ray burst. But regardless of its origin, the fact that the same ^{14}C signature is discernible in chronologies from both temperature- and moisture-limited settings confirms the accuracy of tree-ring dating over (at least) the last twelve centuries.

More tests for the trees?

There are still other ways to verify the fidelity of tree-ring dates prior to the Tambora eruption. Rutherford and Mann (2014) singled out specific tree-ring records they believed to have chronological errors caused by volcanic cooling: Tornetraesk (northern Sweden), Taymir (far-northern Siberia), and the Gulf of Alaska (United States). For those regions or records hypothesized to have been most strongly affected by the Tambora eruption, it may be worthwhile to verify their dating by testing for the presence of the radiocarbon excursion in their AD 775 rings. Dissecting complete trees along their stem, sampling trees that would have been juvenile in 1816, or tracing the 1816 ring from cold, marginal forests to more hospitable environments downslope or towards the forest interior, could also help confirm the integrity of the tree-ring timeline.

But at this point, it is questionable what will be gained by additional efforts expended to refute a hypothesis that 1816 is missing from any portion of the global tree-ring network. Trees growing in high-latitude and high-elevation forests are adapted to cool summers and short growing seasons, and almost never skip rings under any circumstances. Forcing a missing ring at 1816 causes the well-established association between summer temperature and tree-ring width and density at thermally-limited sites to vanish. The ubiquity of the 8th century ^{14}C marker demonstrates the Year Without a Summer was not a year without a ring. It also refutes the proposition that the larger Samalas or Kuwae eruptions caused widespread shutdowns at treeline forests in the Alps, California or northern Siberia.

There are many reasons why proxies and models might disagree on the magnitude of cooling caused by Tambora. All models show the Northern Hemisphere was cold during the summer of AD 1816 (Fig. 1) but, at a regional scale, they disagree on the pattern and magnitude of cooling and in some cases run counter to instrumental temperature measurements (for example, in Scandinavia). It is also true that trees are not solely influenced by one aspect of climate but instead integrate the influence of several environmental factors prior to and during the growing season. Because volcanic aerosols enhance the forward scattering of incoming solar radiation, major eruptions might actually cause trees to photosynthesize more efficiently, offsetting the negative effects of short-term cooling. But whatever the source of the apparent differences between proxies and models, an overwhelming body of evidence shows the Tambora eruption did not interrupt the yearly calendar kept by trees around the globe.

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Illuminating the volcanic signal in tree rings

Alexander R. Stine[1], M.P. Tingley[2] and P. Huybers[3]

Comparison of the signature of volcanism in tree rings with thermometers indicates that tree rings overestimate volcanic cooling. The timing and spatial expression of the tree-ring response indicate that decreased light availability contributes to the tree-ring response to volcanism.

Volcanic eruptions that loft aerosols into the stratosphere offer natural experiments by which to explore the response of the climate system to short-term changes in radiative forcing. In the one to two years following the largest volcanic eruptions of the past century, we observe a decrease in the solar radiation received at the Earth's surface, as well as cooler than usual surface temperatures (Robock et al. 2007). Volcanic eruptions also offer an opportunity to explore the response of tree-ring proxies to changes in solar radiation and temperature. Most tree-ring chronologies from temperature-limited high-northern latitude regions show a decrease in tree-ring width or density following a major explosive volcanic eruption. This response has historically been interpreted as an exclusive result of the cooler summertime temperatures that are observed following such eruptions – a cooling that is understood to be induced by scattering from volcanic aerosols in the stratosphere that reduce the amount of shortwave radiation reaching the Earth's surface.

An emerging line of evidence supports the hypothesis that high-latitude tree-ring growth also responds to variability in light, independent of the influence of light on temperature (Stine and Huybers 2014; Tingley et al. 2014). The notion that large-scale tree-ring growth may respond to changes in photosynthetic light availability is not new (Briffa et al. 1998). Indeed, the well-established Vaganov-Shashkin (VS) model of tree-ring growth includes a term whereby the growth rate is proportional to variations in daily average light intensity (Vaganov et al. 2006).

Here we discuss two lines of evidence for a direct tree-ring response to volcanic dimming. Each relies on aggregating the tree-ring response to large volcanic eruptions over distinct regions of the Arctic, so as to isolate the effects of reduced light from the effects of cooler temperatures (Stine and Huybers 2014; Tingley et al. 2014).

Evidence that light affects trees
One line of evidence that tree rings respond to changes in the light environment is provided by comparing the volcanic temperature response inferred from tree rings to that measured by thermometers. Consider the response to the 1883 Krakatoa and 1912 Novarupta eruptions - the two largest eruptions that occurred late enough to be reasonably well-monitored by instrumental thermometers, but early enough to be unaffected by the late-20th century decline in Arctic tree-ring width and density relative to temperature referred to as the divergence phenomenon (Briffa et al. 1998). Both Krakatoa and Novarupta resulted in strong reductions in atmospheric transmissivity, leading to a reduction in surface solar radiation intensity which was recorded by contemporary pyrheliometer measurements (Kimball 1918). In both cases, post-eruption temperature anomalies inferred from tree-ring densities show a larger amplitude response than is consistent with the degree of cooling found in thermometer measurements (Fig. 1; Tingley et al. 2014). Furthermore, the cold bias is larger in magnitude in high-latitude regions where photosynthesis is inferred to be more limited by light (Nemani et al. 2003), supporting the hypothesis that trees respond directly to decreases in light availability. Pyrheliometer measurements indicate that the atmospheric transmissivity was reduced for substantially longer following Krakatoa (~3 years) than following Novarupta (~1 years; Kimball 1918). In both cases the tree-ring cold bias persists for a period similar to the period of reduced atmospheric transmissivity (Fig. 1e,f).

Whereas the instrumental period contains only a small number of eruptions with a clear response in both the instrumental and tree ring records, 32 major eruptions were recorded in the northern hemisphere ice-core record in just the last 700 years (Gao et al. 2007). Across the high-northern latitudes a close correspondence exists between the magnitude of the tree-ring response to volcanism and estimates of the relative importance of light availability in limiting plant growth (Fig. 2c; Nemani et al. 2003). The reduction in tree-ring density following the major volcanic eruptions of the last 700 years was, on average, twice

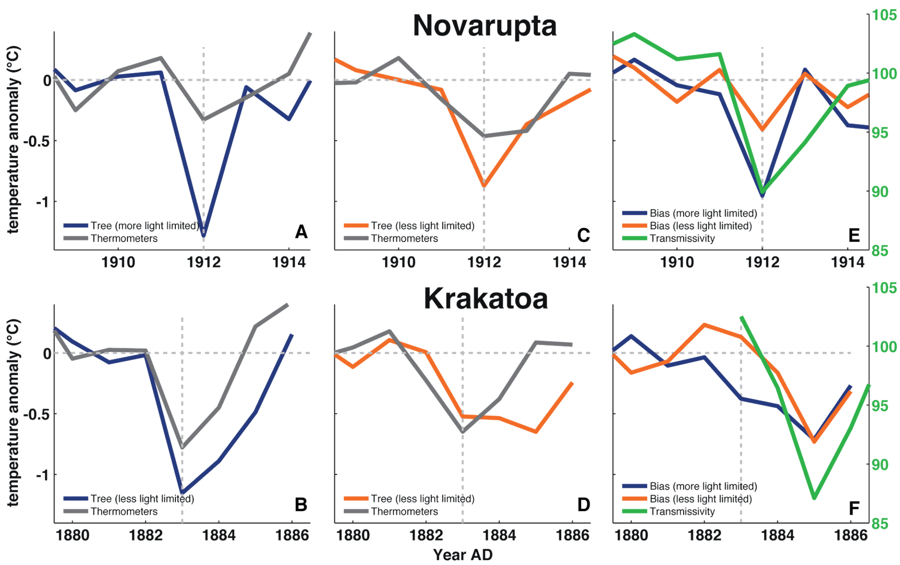

Figure 1: Comparison of the volcanic cooling recorded by boreal tree rings with volcanic cooling recorded by thermometers. Tree rings are calibrated into temperature units using a Bayesian approach (Tingley et al. 2014). Top row shows response for 1912 Novarupta eruption and bottom row for 1883 Krakatoa eruption. **(A and B)** Comparison for relatively strongly, and **(C and D)** for relatively weakly light-limited boreal regions. **(E and F)** The bias in the tree-ring response from regions of relatively strong (blue) and weak (orange) light-limitation compared with the anomaly in atmospheric transmissivity inferred from contemporary pyrheliometers (green; Kimball 1918).

as large in high-northern latitude regions where light-limitation on photosynthesis is strong, compared with regions where light limitation on photosynthesis is weaker (Fig. 2a). Similar results are found for tree-ring widths (Stine and Huybers 2014). The concordance between the volcanic response and patterns of light limitation to growth suggests that, in the boreal regions that are more strongly light limited, tree growth responds directly to both the reduction in temperature and the reduction in photosynthetically available radiation.

Light and growth

There are a number of different frameworks for thinking about the role of light variability in modulating productivity, not all of which can be considered entirely consistent with each other. Manipulation studies have directly shown that tree-ring growth in the tropics increases in response to increased light availability (Graham et al. 2003). The Carnegie Ames Stanford Approach (CASA) carbon cycle model treats productivity as directly proportional to light availability, multiplied by a growth limitation term which may be controlled by temperature or moisture availability depending on local environmental conditions (Potter et al. 1993). The VS model of tree-ring growth incorporates this formulation as well (Vaganov et al. 2006). Satellite-based estimates of productivity assume proportionality to surface insolation and infer the efficiency at which this light is used from the spectra of surface reflectance (Running et al. 2004). Global climate models include light limitation as one of several competing forms of environmental limitation that can modulate carbon uptake. Laboratory-based studies of photosynthesis, in contrast, tend to emphasize the ability of photosynthesis to proceed at a constant rate across a broad range of light intensities (Long et al. 1994).

Global dimming

Two lines of evidence – the spatial pattern of the volcanic tree-ring response, and the difference between this response in tree rings and in thermometer measurements – support the notion that a reduction in solar radiation will lead to a decrease in growth in some tree-ring records.

From 1955-1975, a reduction in shortwave radiation was observed in many regions of the world, including at high-northern latitudes (Wild 2009). Over this same period, tree-ring density in many boreal regions exhibited a negative trend relative to temperature. Interestingly, the pattern of these trends in tree-ring growth relative to temperature is correlated with the pattern of tree-ring density anomalies following volcanic eruptions (Fig. 2b,d).

A competing interpretation exists, which indicates that divergence results from methodological and data treatment decisions (Esper et al. 2010). However, a simulation using synthetic data showed that the imprint of a global dimming on tree-ring growth is more clearly detectable when, instead of using a difference methodology (Esper et al. 2010), a regression approach is employed to isolate non-temperature components in the tree-ring record (Stine and Huybers 2014). This regression approach indicates a significant imprint of global dimming on Arctic tree-ring growth over the period of divergence. Further work testing for the presence of divergence and its characteristics is warranted.

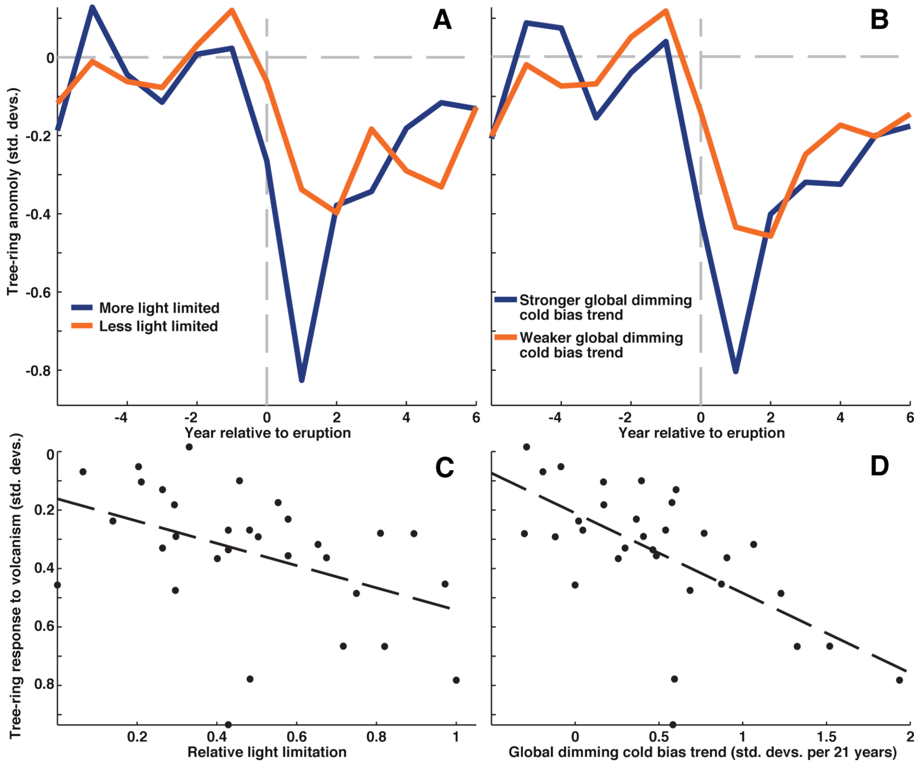

Figure 2: Comparison of the tree-ring density response to volcanic eruptions of the last 700 years with local estimates of light limitation and spatial variability in the response to global dimming (Stine and Huybers 2014). **(A)** Volcanic response in strongly (blue) and weakly (orange) light-limited regions. **(B)** Volcanic response in regions with strong (blue) and weak (orange) decline in density relative to temperature during period of global dimming. Comparison of volcanic tree-ring response to **(C)** light limitation and to **(D)** global dimming across the boreal region.

Outlook

The signature of a changing light environment in the tree-ring record implies that tree rings reflect both the climatic cooling in response to volcanism, and, via dimming, the forcing itself. Tree-ring scientists have traditionally worked hard to isolate trees that respond primarily to a single environmental control, maximizing the ability to reconstruct that variable. Increasingly, however, advances in tree-ring science allow interpretation of multiple proxies from the same cores. For example, stable carbon isotope ratios record variability in stomatal conductance, which may be controlled by light availability and moisture stress (Gagen et al. 2011). Wood anatomy measurements of features such as cell lumen area and cell wall thickness, can reveal environmental information distinct from that inferred from tree-ring width. These indications of the contribution of light variability to high-latitude tree-ring records makes it only more important that tree-ring scientists continue to develop these new proxies, so that we can more fully separate the signature of light variability from temperature variability in the tree-ring record.

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Siberian trees: Eyewitnesses to the volcanic event of AD 536

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The AD 536 volcanic eruption caused a drastic decrease in tree-ring widths, cell wall thickness, carbon and oxygen isotopic values in larch tree cellulose, and frost-ring formation, effects which are without an analogue over the past 2000 years in Siberia.

The new annual ice-core chronologies for volcanic sulfate in Greenland and Antarctica (Larsen et al. 2008; Sigl et al. 2014) can be compared with the annually dated Siberian (Russian) tree-ring chronologies to investigate the impact of major volcanic eruptions that occurred around AD 536.

We discuss the effects of volcanic eruptions on trees growing in the permafrost zone in Siberia and the trees' physiological response to such extreme environmental events. Using multiple lines of evidence, we discuss how tree-ring width (TRW), cell wall thicknesses (CWT), and stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes in tree-ring cellulose of larch trees were affected by extreme climate conditions during the period AD 516-560. We analyze the response of Siberian trees growing at the high-latitude sites in northeastern Yakutia (YAK; Sidorova and Naurzbaev 2002), eastern Taimyr Peninsula (TAY; Naurzbaev et al. 2002), and at a high-altitude site in the Russian Altai (ALT; Myglan et al. 2009; Fig. 1) to climatic changes after the major volcanic eruption of AD 536, which has no analogue over the past 2000 years in Siberia (Churakova (Sidorova) 2014), with the aim of improving our understanding of the physiological adaptation of trees to extreme environmental impacts.

Many scientists have investigated the "AD 536 dust-veil or unknown event" (e.g. Stothers 1984). This volcanic event likely lead to one of the most severe cold episodes in the Northern Hemisphere high-latitudes during the last two millennia (Briffa et al. 1998; Larsen et al. 2008), is despite the fact that ice-core acidity records from Antarctica suggest that, globally, much stronger volcanic peaks occurred at other times (Plummer et al. 2012).

Tree-ring width and stable carbon and oxygen isotope composition ($\delta^{13}C$ and $\delta^{18}O$) are indicators for both temperature and moisture regime changes, where fractionation processes during CO_2 uptake are important for $\delta^{13}C$, while for $\delta^{18}O$ changes in the soil and leaf water isotope ratio are determining factors (McCarroll and Loader 2004). We hypothesized that the volcanic eruption of AD 536 would lead to strong decreases in tree-ring width and cell wall thickness as a result of the combined effect of reduced incoming solar radiation and related temperature decrease. In addition, we assumed that the temperature decrease and reduced vapor pressure deficit could have led to decreased stable carbon and oxygen isotopic ratios in tree rings for both high-latitude and high-altitude sites. To test our hypothesis, we examined our tree-ring width chronologies from 21 years before and 24 years after the AD 536 event. They showed a pronounced narrowing of tree-ring widths from well-replicated, >2000 year-long chronologies. TRW, CWT, $\delta^{13}C$, and $\delta^{18}O$ isotope chronologies were measured on four cross-sections of relict wood at each site (Fig. 2).

Differences in tree response among the study sites

At all three studied sites, we observed that the period AD 516-560 was characterized by the strongest decrease in tree radial growth over the past 2000 years (Churakova (Sidorova) et al. 2014). The strikingly low $\delta^{18}O$ values at ALT in AD 536 (Fig. 2) reflect a low condensation temperature of precipitation water supplied to trees. Furthermore, low temperatures lead to low vapor pressure deficit and thus to low needle water enrichment. This $\delta^{18}O$ leaf water signal is transferred to the cellulose, although part of the leaf oxygen isotope enrichment is lost in the stem during cellulose formation by the exchange with less enriched xylem water. Low $\delta^{18}O$ values in cellulose associated with thin cell walls and a low numbers of cells (in AD 536 only two cells were counted) indicate that reconstructed June-July air temperatures dropped by ca. 4°C relative to the mean June-July air temperature which was around 9°C at YAK for the last 2000 years (Sidorova et al. 2005; Churakova (Sidorova) et al., unpublished data).

The tree's response to decreased light intensity and low temperatures caused by volcanic dust veils is also visible in ring width, but with a delay of three years, which may be due to the ability of the trees to use

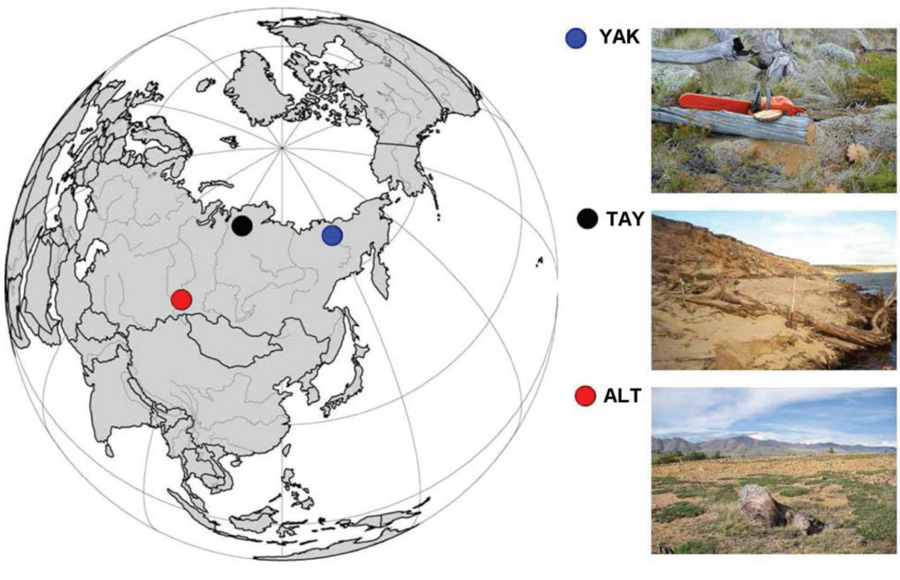

Figure 1: Map with locations and photos of the study regions in the high-latitude sites in northeastern Yakutia (69°N, 148°E; YAK), Taymir Penninsula (70°N, 103°E; TAY), and high-altitude site in the Russian Altai (50°N, 89°E; ALT).

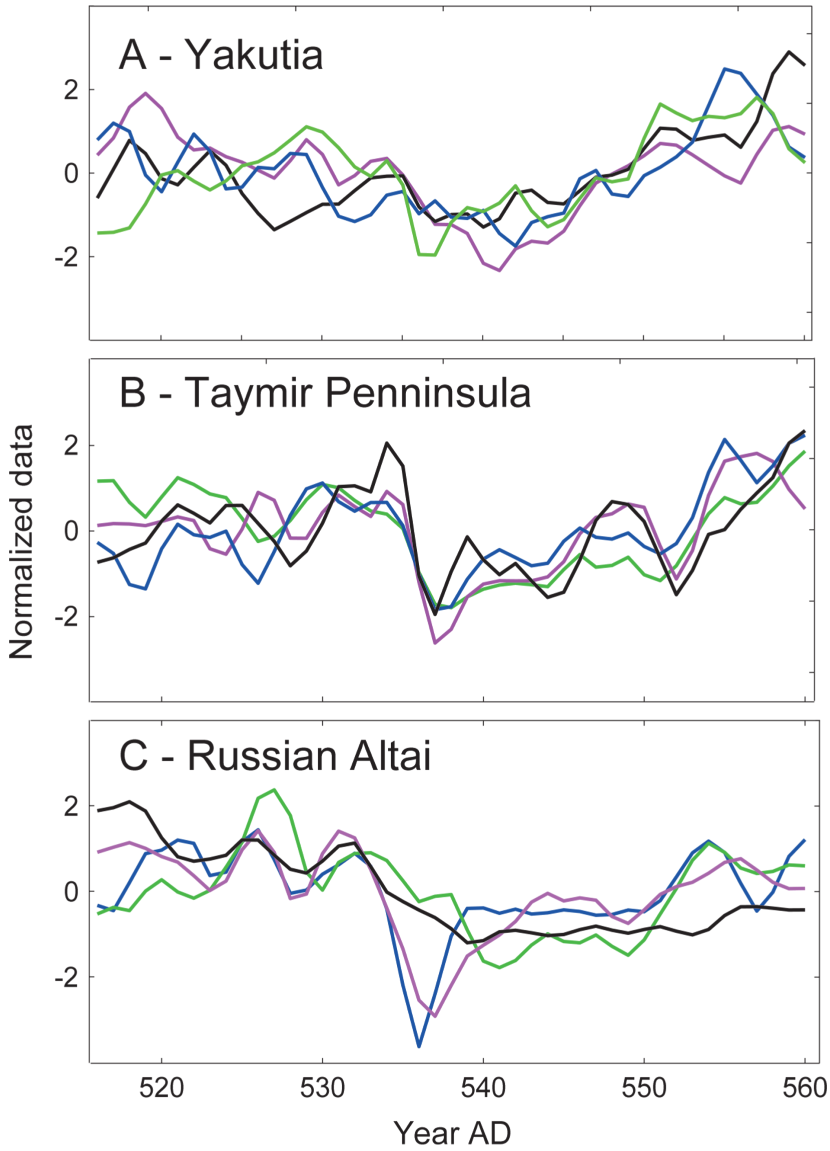

Figure 2: Normalized by 3-year smoothed δ^{13}C (green), δ^{18}O (blue), tree-ring width index (black), and cell wall thickness (pink) chronologies for the three study regions **(A)** Yakutia (YAK), **(B)** Taymir Penninsula (TAY), and **(C)** Russian Altai (ALT).

their carbohydrate reserves during early wood formation.

At the high-elevation ALT site, there was no clear reduction of TRW after AD 536, although the lowest values are observed in AD 539. There were reductions in CWT (AD 537) and, rather dramatically, in δ^{18}O cellulose for the year of AD 536, which rebounded strongly the next year. This is a clear difference between the sites near the northern tree limit, and the more southern, high-elevation site. Although the AD 536 event has not been recorded immediately in the TRW series at ALT, it would be associated with low maximum latewood density given the observed low cell wall thickness in AD 536 and AD 537 (Churakova (Sidorova) et al., unpublished data).

The advantage of multi-proxy studies

The study of multiple parameters like tree-ring width, latewood density, cell wall thickness and stables isotopes in tree rings from markedly different locations provides new insight into understanding the effects of volcanic eruptions in eco-physiological and climatological aspects. In particular, increased δ^{13}C indicates drought or high vapor pressure deficit, which is often coupled with limited water availability, while decreased δ^{13}C is an indicator for cold and moist conditions during the growing season. Reduced light intensity, as produced by a volcanic dust veil, can reduce photosynthesis, which will lead to an increase in the leaf intercellular CO_2 concentration, and thus also lower δ^{13}C (Farquhar et al. 1989). Therefore, if we take reduced δ^{13}C as an indication of stress in the trees, we can infer stressed growth conditions at both northern sites, but less so at ALT, in AD 536. This is consistent with the very low tree-ring widths in the North in those years, and frost rings at ALT in AD 536. The strikingly low cellulose δ^{18}O values (20‰, compared with the mean value 28.1‰ for the period from AD 520 to AD 560) at ALT in AD 536, associated with thin cell walls, strongly indicates a very cold or short growing season, even though the response in ring width is delayed by three years.

At the two sites closest to the northern limit of tree growth on the Taimyr Peninsula and in northeastern Yakutia, sharp declines of already small tree-ring widths, latewood density, and cell wall thickness occur in AD 536, and are accompanied by simultaneous drops in cellulose δ^{13}C. At the high-elevation, more southern Altai site, the reduction in TRW was delayed by three years, whereas very low values of δ^{18}O in AD 536, and reduced cell wall thickness in AD 536 and AD 537 (Churakova (Sidorova) et al. 2014).

Tree-ring parameters such as tree-ring width, cell wall thicknesses, and stable carbon and oxygen isotopes in tree cellulose, compared with other multi-proxy records such as ice cores and historical archives are useful proxies and complement each other perfectly. Using a multi-proxy approach would help to improve the quality of climate reconstructions in the past.

ACKNOWLEDGEMENTS

We dedicate this article to our co-author Mukhtar M. Naurzbaev, who sadly is not with us anymore. Not only will we remember him for his enthusiasm for subarctic forest ecosystem research, and for searching for and sampling long living trees in Taimyr and Yakutia, but, first and foremost, as a respected and helpful colleague and friend.

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Exploring the potential impacts of historic volcanic eruptions on the contemporary global food system

Michael J. Puma[1,2], S. Chon[3] and Y. Wada[1,2]

A better understanding of volcanic impacts on crops is urgently needed, as volcanic eruptions and the associated climate anomalies can cause unanticipated shocks to food production. Such shocks are a major concern given the fragility of the global food system.

Our global food system will face great pressures in the coming decades due to increases in food demand, depletion of groundwater resources in major agricultural regions, and possibly more extreme weather anomalies as the climate changes (e.g. Godfray et al. 2010; Foley et al. 2011). A suite of strategies has been proposed to deal with these challenges, which includes increasing crop yields on underperforming lands, improving the efficiency of agricultural resources use (i.e. water, fertilizers and pesticides), changing diets, and reducing food waste (Foley et al. 2011). While these strategies are sound, they do not directly address the vulnerability of the global food system to major food supply disruptions.

Any substantial disruption to the world's food supply would, all else being equal, lead to spikes in food prices. International food trade is vulnerable to such price fluctuations, especially because countries are likely to impose trade restrictions to protect domestic markets (as happened during the 2008 global food crisis). Such trade restrictions could propagate through the system, causing a systemic disruption to global food supply. Consequently, catastrophic shortages in national-level food supply can occur, because many countries depend on international trade for even their staple food supply (Puma et al. 2015). From this perspective, the global food system can be regarded as a fragile system that is susceptible to systemic disruptions.

Extremes and volcanic eruptions

Crops are highly sensitive to extreme climate anomalies including floods, droughts, and high and low temperatures. Farmers do have the ability to deal with some weather and inter-annual climate variability, depending on local farming practices, infrastructure, and experience (Gornall et al. 2010). However, there are important limits to their coping capacity. For example, if sudden temperature extremes coincide with critical stages of plant development (e.g. the flowering stage), crop yields reduce dramatically (e.g. Gornall et al. 2010). Likewise, regional precipitation shifts in monsoon Asia can lead to substantial crop losses, especially considering the highly concentrated rice production in this region.

Large volcanic eruptions are known to cause extreme climate and weather variations (e.g. Volcanic Explosivity Index, VEI ≥ 4); however, the climate response is known to vary substantially (e.g. Kasatkina et al. 2013), depending on numerous factors including the location of the volcanic eruption, the eruption's VEI, the timing and duration of the eruption, and the baseline state of the climate system (e.g. El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation phase).

Methods

We explore the potential impacts of historic volcanic eruptions on the contemporary global food system by: (1) selecting major

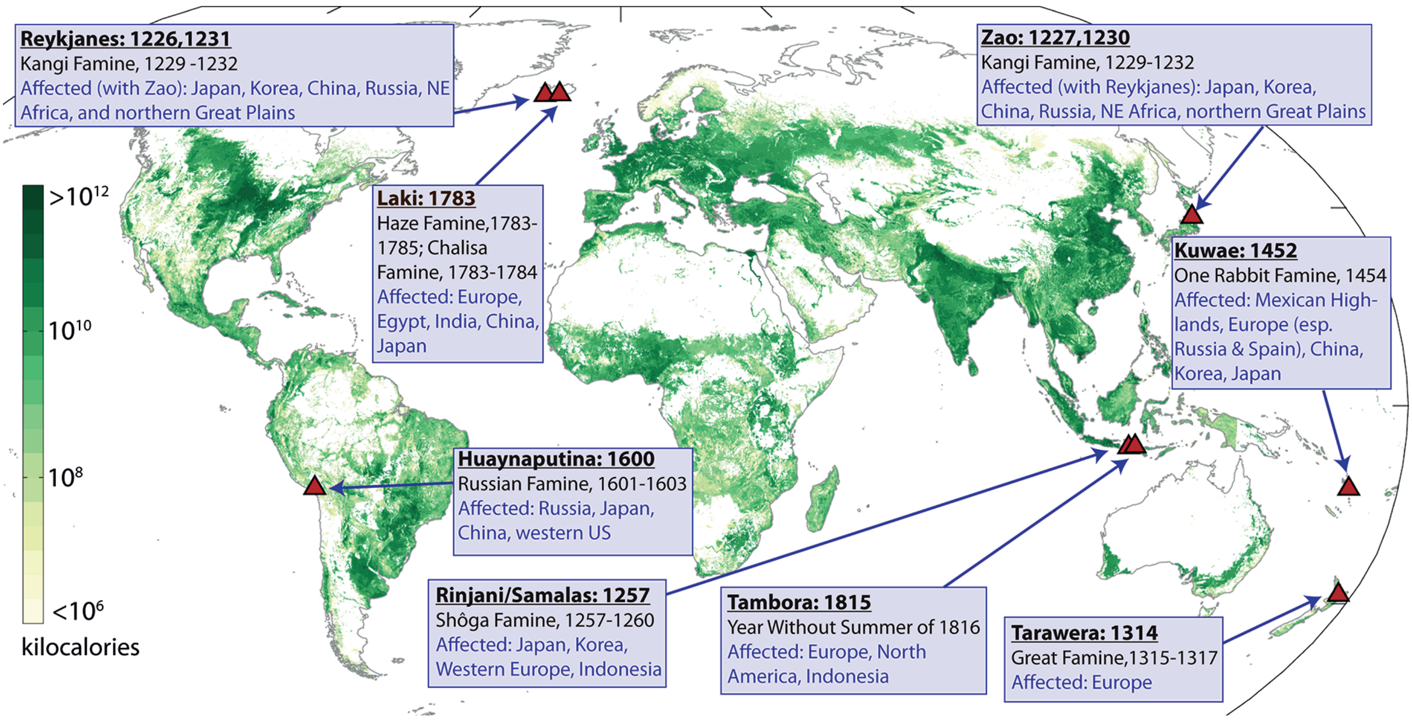

Figure 1: Crop production and select volcanic eruptions (with associated famines and crop failures) over the last millennium that had major impacts on food supplies. Global crop production for the year 2005 in kilocalories based on SPAM (You et al. 2014) and estimates of the caloric content of different crops from UN's Food and Agriculture Organization.

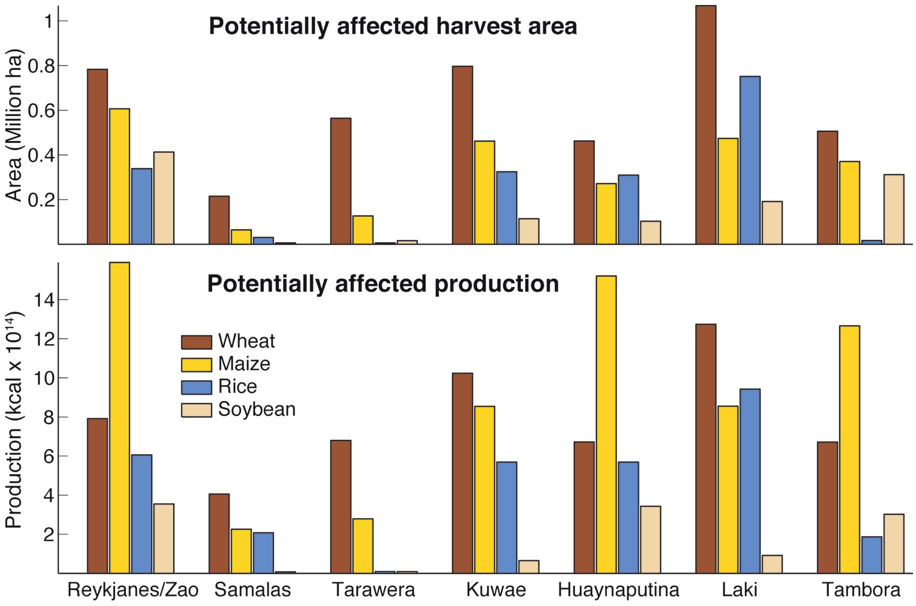

Figure 2: Potential impacts of historical volcanic eruptions on contemporary global wheat, maize, rice, and soybean. (Top) Harvest area and (bottom) crop production that would potentially be affected if the severe historical weather anomalies, associated with the identified historical volcanic eruptions, affected each crop. To put these numbers in perspective, the potential annual production losses from the Laki eruption are equivalent to the annual food consumption of 2.9 billion people on a caloric basis, assuming a diet of 2940 kcal per capita per day (world average for 2015; www.who.int/nutrition/topics/3_foodconsumption/en/).

volcanic eruptions over the past millennium that likely contributed to climate anomalies associated with significant crop failures; (2) identifying the geographic regions that were impacted by the associated climate anomalies; and (3) estimating present-day crop production that would potentially be affected based on the historical extent of these anomalies.

To estimate the potentially affected crop production, we use the Spatial Production Allocation Model (SPAM; You et al. 2014). This model produces an estimate of global harvest area and crop production for 42 crop groups at a five-minute resolution for the year 2005. These production estimates are in metric tons, which we then convert to calories in order to aggregate the different crop groups. In Figure 1, we present total crop production for the world's main food crops (wheat, maize, rice, soybean, potato, cassava, etc.). Next, we compute the potential impacts by identifying regions that experienced historic crop failures and then summing modern-day country-level harvest area and production values for the set of affected countries (Fig. 2).

Selected historical events

We select a total of seven historical periods with widespread weather extremes and crop losses that have been linked to volcanic eruptions (Fig. 1). We emphasize that these volcanic eruptions were not likely the sole cause of the weather anomalies. The interactions of volcanic emissions with large-scale climate patterns such as ENSO are likely to have contributed to each event.

The earliest period of major crop losses and famine that we consider is AD 1227-1232 (Atwell 2001). Three volcanoes, in particular, are thought to have contributed to climate anomalies: Iceland's Mt. Reykjanes and Mt. Reykjaneshryggur erupted in 1226 and 1231, respectively, and Japan's Mt. Zao in Japan erupted in AD 1227 and 1230. Extreme flooding, drought, and temperature fluctuations impacted crop production throughout the Northern Hemisphere. Later in the 13th century, another period (AD 1257-1260) of anomalous climate occurred in response to the 1257 eruption of the Samalas volcano on Lombok Island, Indonesia (Lavigne et al. 2013). Contemporary historical sources reveal that an unprecedented cold summer and extreme flooding affected crops throughout Western Europe and part of Asia (Stothers 2000).

One of the more speculative connections is the link between the multi-year eruption episode of Mt. Tarawera (Nairn et al. 2004) and Europe's Great Famine of AD 1315-1317. During this period, anomalous wet and cool conditions devastated crops throughout Europe, especially the torrential downpours of the summer of 1315 (Lucas 1930). A better link has been established between the eruption of Mt. Kuwae, Vanuatu and weather anomalies in Europe, East Asia, and Mexico, although a strong warm ENSO event and other volcanic activity could jointly be responsible for the anomalies (Briffa et al. 1998; Atwell 2001). Later, Peru's Mt. Huaynaputina erupted in 1601, which likely contributed to what might have been the coldest Northern Hemisphere summer in the past 600 years (Atwell 2001).

The most recent volcanic eruptions considered here are Iceland's Laki and Indonesia's Tambora eruptions. The 1783 Laki eruption produced a dry fog veil that spread throughout much of the Northern Hemisphere, causing unusual and extreme weather throughout (Thordarson 2009). In 1815, Tambora erupted resulting in severe local and global impacts. In North America and Europe, the summer of 1816 was extremely cold, resulting in a devastating famine throughout Europe (Oppenheimer 2003).

Possible impacts on today's crops

In Figure 2, we present the harvest area and production of the world's major crops (wheat, maize, rice and soybean) that would be potentially affected by each of the historical volcanic eruptions should they happen today. Potential crop impacts vary substantially across the volcanic events, depending on spatial distribution of the climate anomalies and crop production. For example, the impacts of the Mt. Reykjanes and Zao eruptions would potentially be greatest for maize, while the Laki eruption would be largest for wheat and rice. Although we would generally not expect total crop failure, even if failure in the affected regions were a small percentage (say 10%), we should expect to see spikes in global food prices.

Outlook

Volcanic eruptions are a threat to the global food system. History has shown that these sudden, unpredictable events can severely disrupt crop production across the globe. Unfortunately, the global food system is not well-positioned to deal with such disruptions, especially considering the tight relationship between global food supply and demand (Rosegrant et al. 2013). New research is needed, which combines our understanding of the global food system as a complex interconnected network with our improving insight into volcanic impacts on climate and crops. These findings must then be incorporated into food policies at the national and global levels.

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Important research questions on volcanic eruptions and climate

Alan Robock

While we understand much about how the climate system responds to volcanic eruptions, there are still a number of outstanding research questions, including on aerosol microphysics, observational capabilities, and climate responses on seasonal to century time scales.

On the 200th anniversary of the largest volcanic eruption of the past 500 years, that of Mt. Tambora in Indonesia, it might be useful to summarize what we still do not know about the impacts of volcanic eruptions on climate. That the April 10, 1815 Tambora eruption was responsible for the 1816 "Year Without a Summer" is well accepted, as large volcanic eruptions produce stratospheric sulfate aerosol clouds that reflect sunlight and cool Earth. Lord Byron wrote *Darkness*, Mary Shelley wrote *Frankenstein*, and John Pollidori wrote *The Vampyre* that summer, inspired by the cold, gloomy weather in Geneva. As I pondered in a review (Robock 1994) of the book by Harington (1992, The Year Without a Summer? World Climate in 1816), "The purpose of the book reviewed here is to address the question of whether Shelley and Byron were making too much of the weather that summer. The summer in New England that year also had extreme weather. Was 1816 truly a 'Year Without a Summer' globally or just a local European and New England phenomenon? What were the causes of these extreme climate anomalies? Were they the result of the Tambora volcanic eruption in April 1815, in Indonesia, or caused by solar variations, El Niño/Southern Oscillation (ENSO) events, or random weather variations?"

Many of these details are still unknown. What exactly is the spatial and temporal pattern of response to a large volcanic eruption, and how well will we be able to predict that response in the seasons and years to come once the next one erupts? How well will our current observing system measure the important parameters needed to make this prediction, as well as to understand the important processes? These and many of the questions presented in Robock (2002) are still unanswered. So if you are looking for a Ph.D. dissertation topic or an important scientific question for your next proposal, in addition to the questions above, here are my candidates:

Are stratospheric sulfate aerosols larger following large SO_2 injections? This is important because it determines their lifetime and their impact on radiation per unit mass, both of which make larger aerosols have a smaller negative radiative forcing and climate impact. Size also determines their ability to destroy ozone, which would be less for larger particles. This mechanism is also important to understand for evaluating proposals for stratospheric geoengineering. Pinto et al. (1989) provided the theoretical explanation for this process, which was used by Crowley (2000) and Crowley and Unterman (2013) to convert ice core records of sulfate deposition into volcanic radiative forcing, and a number of recent papers have assumed that this theory is true. However, there are no observations to support this theory. How can it be verified?

Did volcanic eruptions at the end of the 13th Century, reinforced by the 1452 Kuwae eruption, produce the Little Ice Age? Miller et al. (2012) used observations of ice sheet persistence on Baffin Island and general circulation model (GCM) simulations to propose a mechanism whereby feedbacks between large volcanic cooling and oceanic energy transport into the Arctic Ocean resulted in a colder climatic state after a series of large eruptions. But this mechanism depended on the initial state of the climate model and does not occur in some simulations. So how robust is this mechanism and what are the details of the climate system response?

Why was the summer of 1783 so warm in Europe? Was it caused by the Laki eruption in Iceland? Was it just a coincidence that it was so warm in Europe during the summer of 1783? If it was caused by the Laki eruption, what was the mechanism? Was it radiative, or did the radiative forcing produce a strong southerly advection? How?

Why do climate models have such a hard time producing winter warming over Northern Hemisphere continents after large tropical eruptions? As Stenchikov et al. (2006) and Driscoll et al. (2012) have shown, GCMs have a hard time simulating the observed winter warming (Robock and Mao 1992) following large tropical volcanic eruptions. Why?

Are we ready to monitor the next big volcanic eruption, or geoengineering outdoor experiments or implementation? Specific scientific questions that can be addressed include the size distribution of sulfate aerosol particles, how the aerosols will be transported throughout the stratosphere, and how temperatures change in the stratosphere as a result of the aerosol interactions with shortwave (particularly near IR) and longwave radiation. What observational needs must be met to provide information that would help us produce seasonal and decadal forecasts? Is the total SO_2 enough, or do we need more precise measurements of altitude, or the small tephra particles and subsequent sulfate aerosol clouds? If there is an influence on cirrus and other clouds as the sulfate leaves the stratosphere, do we have good enough observations of potential indirect effects on tropospheric clouds? Do we have enough measurements to evaluate changes in the chemical composition of the atmosphere?

How much seasonal, annual, and decadal predictability is possible following a large volcanic eruption? How large does an eruption have to be to produce a detectable response, and how does this depend on the location and time of year of the eruption? Are the amplitudes of global cooling patterns, winter warming, and summer monsoon precipitation reductions linear with respect to stratospheric aerosol loading?

There are still many interesting research questions with respect to volcanic eruptions and climate, and answering them will allow us to be prepared to address the impacts of the next large eruption, and to better separate natural and anthropogenic climate responses from each other.

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Lessons from Tambora

Stefan Brönnimann, M. Grosjean, F. Joos, W. Tinner and C. Rohr

Bicentenary of the Great Tambora Eruption, Bern, Switzerland, 7-10 April 2015

In April 1815, the Indonesian volcano Tambora awakened. The main eruption phase starting on 10 April was one of the strongest in recent history. It devastated the island of Sumbawa and killed thousands of people. In the following year, the eruption led to global cooling and to climatic changes in the tropics, Europe, and North America. Disease and famine claimed tens of thousands of lives (Oppenheimer 2003).

Among the most affected regions was Switzerland, where the cold and rainy summer of 1816 contributed to the last famine. Two hundred years later, on 7-10 April 2015, about 130 scientists gathered in Bern, Switzerland, at an international conference co-funded by PAGES. Even after 200 years, science can learn from analyzing the Tambora eruption and its climatic and societal consequences. However, this requires a comprehensive Earth System perspective (Fig. 1). Correspondingly, the participants came from a broad range of fields, encompassing volcanology, atmospheric physics and chemistry, biogeochemistry, dynamical climatology, paleoclimatology, history, ethnology, and the arts. Only with such combined expertise can the event and all its consequences be understood.

The individual sessions touched on all these aspects. During the 1815 eruption, 30-50 km^3 equivalent of dense-rock material was ejected (Self et al. 2004). Around 60 Tg of SO_2 reached the stratosphere and formed sulphate aerosols; the cause of the subsequent climatic changes (see SPARC Newsletter 45, 2015, for a conference summary focusing on stratospheric aspects). The hemispheric distribution of aerosols is poorly constrained, although the time of year suggests that the major part went to the Southern Hemisphere.

Globally, the top-of-atmosphere radiative forcing of the eruption equaled 5 Wm^{-2} (Timmreck 2012). The sulphate ultimately entered the troposphere and can be traced in ice cores. The dating of the cores as well as the quantification of sulphur deposition are areas of substantial recent methodological improvement. As to the ability of tree rings to capture volcanic cooling, several contributions showed a clear signal over northern Eurasia. However, it remains unknown why a cooling signature, although well documented in the Northern Hemisphere, is not seen in proxies from the Southern Hemisphere (Neukom et al. 2014).

Several speakers highlighted the Tambora eruption in the context of other strong eruptions of the past millennium. Hubertus Fischer, PAGES Co-chair, explored the interest in the community to engage in a PAGES volcanic forcing working group (PAGES has subsequently launched the VICS working group - www.pages-igbp.org/ini/wg/vics).

Reconstructions allow the climate in Europe (and increasingly also other regions) in 1816 to be analyzed. The strongest cooling is found in Western Europe, while data sources disagree on temperatures in Eastern Europe. In the North Atlantic-European sector, sub-daily instrumental observations suffice to address changes in weather and atmospheric circulation. For instance, a dynamical reanalysis of 1815-1817 within the "Twentieth Century Reanalysis" framework was presented (Gilbert Compo, Univ. Colorado/CIRES-NOAA, USA; Philip Brohan, Met Office, UK). Low-pressure weather types and increased cyclonic activity dominated over western France and Switzerland (Auchmann et al. 2012) and caused increased precipitation. For the tropics, information is scant and the effects on the Asian monsoon remain unclear.

In Europe, the summer of 1816 fell into a period of declining temperatures, perhaps in part due to the unknown eruption of 1808 (but solar activity was also weak). Several presentations highlighted the particularly strong effect of double eruptions. In this context, the role of the ocean was also addressed.

Model studies find strong global cooling and stratospheric warming as well as a weakening of the monsoons after Tambora (Kandlbauer et al. 2013). In fact, the weakened African monsoon is a possible cause of rainy summers in South-Central Europe following strong eruptions due to a weakened Hadley circulation, weak subtropical highs, and an altered North Atlantic storm track (Wegmann et al. 2014). Proxies also reveal changes in tropical precipitation after volcanic eruptions, which are interpreted as changes in the Intertropical Convergence Zone.

Tambora also affected the carbon cycle; however, the relative roles of changes in precipitation, temperature, and diffuse radiation (increasing photosynthesis) on carbon stocks remain unclear. The effect of volcanic eruptions on the carbon cycle is an interesting test of our system understanding. The conference also addressed the historical and social aspects as well as the effects on culture and arts. The combination of these aspects is attractive also for a wider audience as evidence by the extensive media coverage of our conference and the bicentenary.

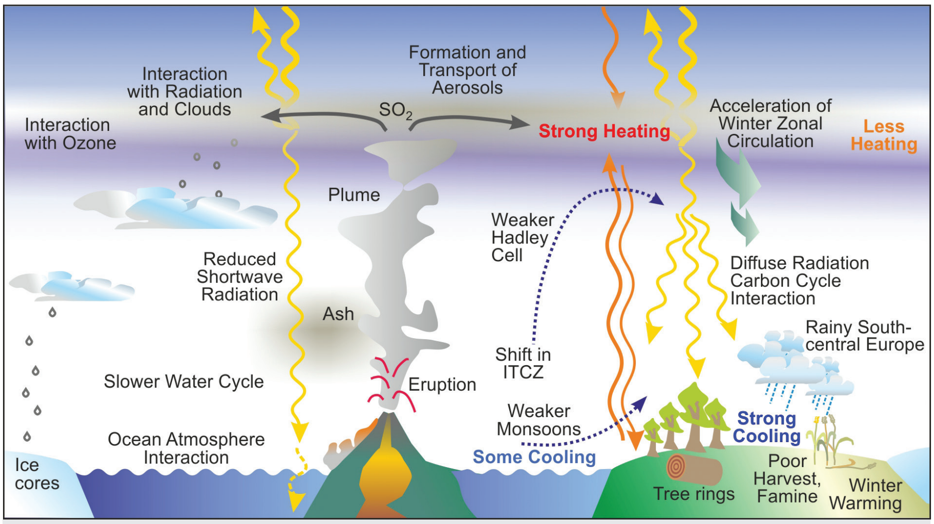

Figure 1: An Earth system perspective of the 1815 Tambora eruption and its consequences.

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Integrating records of aquatic change: existing evidence and missing data

Keely Mills[1,2,3] and Peter Gell[2]

Nottingham, UK, 22-24 April 2015

Forty scientists met at the British Geological Survey (Keyworth, UK) to attend the inaugural workshop of the Aquatic Transitions Working Group. This three-day meeting brought together established and early-career researchers from across Europe, North America, South America, China, South East Asia and Australia to discuss the notion of transitions in aquatic ecosystems, the evidence for regime shifts, and the nature and cause of these shifts, interspersed with many a cautionary tale!

Human activities have negatively impacted aquatic ecosystems and the services they provide through the release of contaminants and the abstraction and regulation of waters. Coupled with these anthropogenic stressors are those associated with long-term changes in temperature and hydro-climate. Many aquatic systems exhibit a non-linear response to these pressures, with ecosystems either responding abruptly or showing a level of resilience until a (internal) threshold is breached. Many of these observed changes have existed in the past and so research on major transitions in aquatic systems represents a significant field of enquiry that demands contributions from both ecology and paleoecology. Further, long-term records of change provide evidence of the ecosystem dynamics that have occurred in the past leading up to a threshold change and reveal early warning signals that may provide lessons to prioritize intervention measures for future management (Fig. 1).

In light of this, the overarching goal of the Aquatic Transitions Working Group is to integrate regional records of change in aquatic systems to provide a global synthesis of site sensitivity to critical stages of human and natural impact. Specifically, the meeting addressed two major topics:

- First human impact in sediment records – how do we identify them?
- Regime shifts – are people the cause and do sediment records really reveal this?

The workshop design was fluid, but aimed to provide a mix of presentations interspersed with breakout sessions in which participants could discuss the key themes arising from the talks in small groups, and then provide feedback in a wider context to the plenary.

The first presentations were focused on short regional overviews and the recording of 'first human impact' in lake sediment records from Europe (Rick Battarbee), Canada (Irene Gregory-Eaves), USA (John Anderson on behalf of Jasmine Saros), South America (Doriedson Gomes), Australia (Peter Gell), China (Xuhui Dong), South-East Asia (Ngoc Nguyen) and Africa (Dirk Verschuren). The final presentations of the day were dedicated to regime shifts in aquatic systems, with a range of examples and explanations from Mike Reid, Rong Wang, Marie Perga, Tom Davidson and Carl Sayer.

This workshop also laid the foundations for the future activities of the working group as a whole. This naturally led to discussions on the collation of databases, papers, and meta-data, but there was also a clear focus on outputs and goals. As a result, a number of papers were tabled and part of the workshop was given over to outlining and planning these. Riding on the wave of a number of future outputs, the drive was on to produce our first tangible output as a working group. With clear leadership (and some perspiration), the group managed to pull together an eleventh-hour session proposal "Sedimentary records of threshold change in ecosystems" for the 2015 AGU Fall Meeting, cementing the support, collaborative spirit, and momentum of those at the meeting.

Looking to the future of Aquatic Transitions, there was a one-day workshop preceding the International Paleolimnology Symposium in Lanzhou (August 2015) to follow up and welcome new collaborators to the group. The next workshop is likely to be held in 2016 in the southern hemisphere. A decision on the exact location will be decided soon.

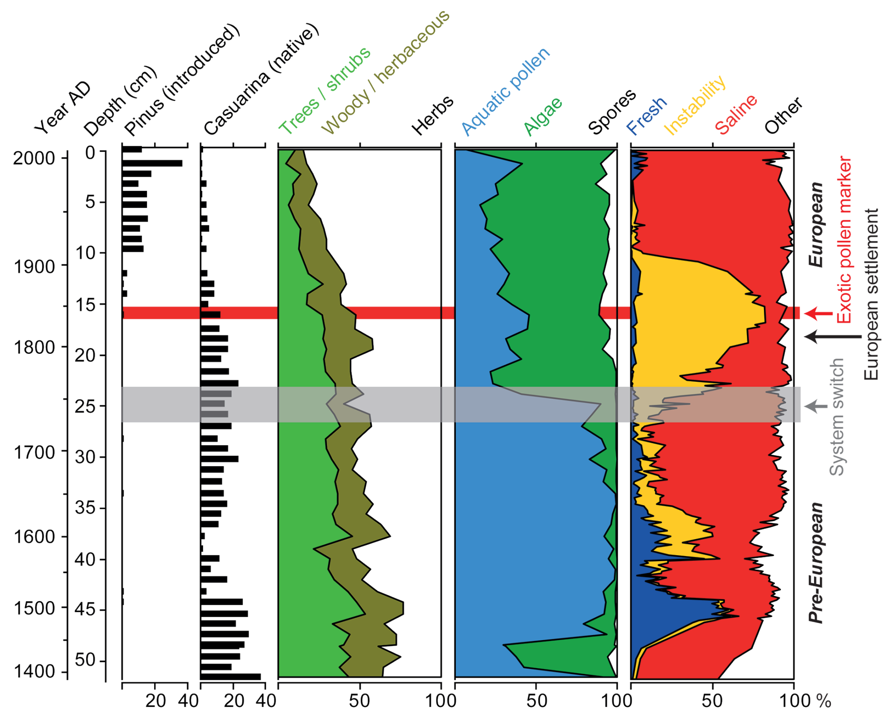

Figure 1: A summary diagram from Lake Colac (western Victoria, Australia) showing (from left to right) terrestrial plants, aquatic plants, and diatom habitat preferences. Two switches in the lake's ecosystem are observed: one prior to early European settlement (AD 1750) and one post-AD 1900. This is an example where despite the clear impact of Europeans on the landscape (e.g. decline in native tree taxa [e.g. *Casuarina*] and the introduction of exotic species [*Pinus*]), the aquatic ecosystem is resilient to human-caused perturbation and climate change drivers are the overriding dominant signal (Mills and Gell, unpublished data). This work was funded by Land and Water Australia and Rural Industries Research and Development Corporation, 2009-2011.

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We thank PAGES and the British Geological Survey for financial support. Thanks are due to all of the participants who shared their enthusiasm, thoughts, and data across the three days. Finally, a special thanks is extended to the group scribes: Zofia Taranu, Antonia Law, Jean-Philippe Jenny, Elodie Brisset, and Daniel Schillereff.

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Global Soil and Sediment Transfers in the Anthropocene (GloSS)

Thomas Hoffmann[1], D. Penny[2], V. Vanacker[3], G. Stinchcomb[4] and Lu Xixi[5]

Bonn, Germany, 19-21 August 2015

The aim of the open kickoff meeting of the PAGES working group GloSS was to set the boundary conditions for GloSS to meet its scientific goals within the next three years. The workshop focused on the development of a list of proxies and indices of human impacts on soil and sediment transfers that will support the compilation of a global soil and sediment database.

A total of 30 participants from different disciplines (geomorphology, geology, soil science, ecology, (paleo)limnology, hydrology, and geoarcheology) and four continents contributed to the workshop.

The first one and a half days were dedicated to continental reviews of proxies of human impacts on soils and sediment transfers. The regional reviews were complemented by a keynote, which provided a global view on sediment production and export, and a videoconference contribution on the experiences of the PAGES 2k-team building the PAGES 2k database.

During the second and third days, the workshop participants (i) developed a concept to organize proxies of human impact on soil and sediment dynamics for hillslopes, floodplains, lakes, and deltas covering different timescales during the Holocene, (ii) discussed the structure, requirements, and potential stakeholders of a GloSS database, and (iii) developed a project road map for the next three years.

The participants of the breakout discussion group on human impact proxies agreed that the first version of the dataset should only include proxies and indices of soil erosion and of sediment transport and deposition. Other proxies such as pollen or diatoms, which are not directly related to sediment transport, will not be included. While quantitative volumetric and mass balance proxies are generally favored compared to length-per-time proxies (such as sedimentation or erosion rates given in mm per year), it was nevertheless noted that the latter are invaluable for reconstructing sediment budgets and that for many study sites complete quantitative inventories are not available. Despite their limitations, length-based rates data will also be collected, but will be interpreted with care due to timescale biases that arise from comparing datasets that average over different timescales. Regarding the considered timescale, the Holocene was considered to be the adequate time frame for the GloSS datasets, as it allows the study of anthropogenic disturbances as well as natural baseline conditions.

The discussion on the GloSS database content and structure resulted in the following statement: The database should focus on soil erosion and sediment transport and deposition of hillslopes, floodplains, and channels, lakes, and deltas (Fig. 1). At this point, there is no need to populate the database with other available paleo-environmental information. Instead, the database should be linked to other existing databases to avoid redundancy where possible.

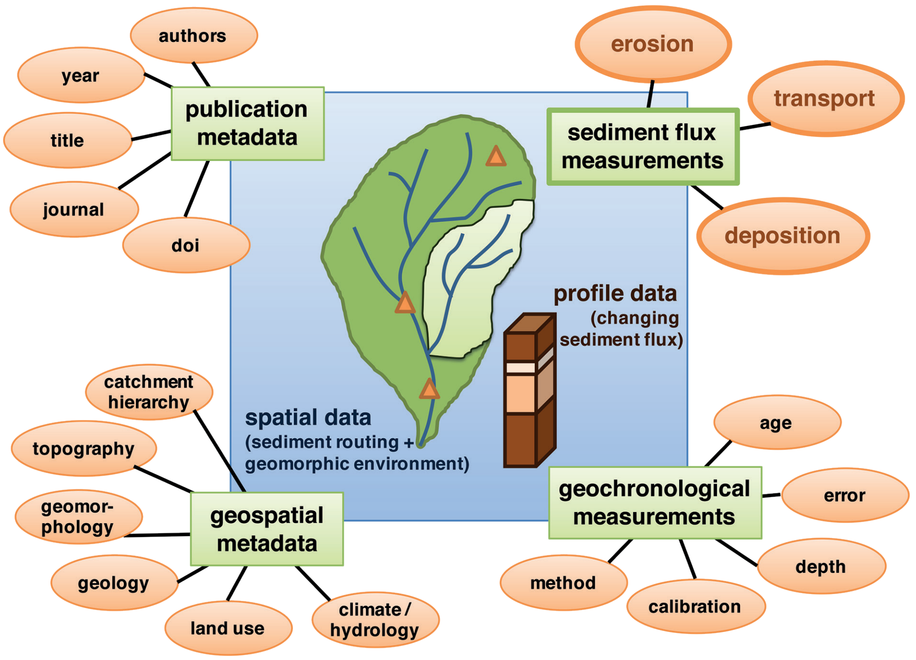

Figure 1: Planned structure of the global GloSS database focusing on human impact on soil erosion, sediment transport and deposition during the Holocene.

The participants agreed that human impact on the above-mentioned environments is best described by the changes in erosion, transport, and deposition. Thus, at minimum, two time slices, before and after human impact for those three variables, are necessary. Due to the major challenges of defining what human impact actually is and when it starts in different regions of the earth, it was argued that the number of time slices should be larger to allow flexible interpretations without constraining what the user can interpret from inferred changes (e.g. climate versus human impacts).

To set the boundary conditions for the first three years of the GloSS working group, a roadmap, seven regional task forces, and a database task force were built.

The regional task forces and their leaders are: Europe and Mediterranean (Gert Verstraeten), South Asia (Rajiv Sinha), SE Asia (Dan Penny), Australia and New Zealand (Bob Wasson, Duncan Cook), East and Central Asia (Hongming He, Lu Xixi), North America (Jane Willenbring, Gary Stinchcomb), South and Central America (Juan Restrepo), and Africa (Klaus Martin Moldenhauer, to be confirmed).

The database task force includes Jane Willenbring, Gary Stinchcomb, Veerle Vanacker, Dan Penny, Lishan Ran, Jean Philippe Jenny, Nick Mackay, Kim Cohen, and Thomas Hoffmann.

If you would like to participate in any of these activities, visit the GloSS webpage at (www.pages-igbp.org/ini/wg/gloss).

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Large-scale climate variability in Antarctica and the Southern Ocean and links to extra-polar climate

Sarah Gille[1], J. Jones[2] and H. Goosse[3]

La Jolla, USA, 24-26 March 2015

Given the short length of the observational record at the high latitudes of the Southern Hemisphere, modern instrumental data are not sufficient to describe the regional state and variability of the climate system. Data rescue of early observations, instrumental data, and proxy records are needed even more here than in other regions. Furthermore, the links between atmosphere, ocean, and sea ice are strong in the southern polar region. The objective of this workshop was to study changes in large-scale patterns of Antarctic climate variability over the last decades to centuries, as well as extrapolar-polar connections, by combining proxy records, historical data, and instrumental records that cover the atmospheric, land, and oceanic domains, with model results.

The workshop was attended by an international group of 30 scientists, including early-career scientists. It brought together expertise from the atmosphere, ocean, and sea ice communities, along with expertise in satellite, observational, historical and paleoclimate data, and modeling. It was jointly supported by PAGES and the World Climate Research Programme (WCRP) as part of the WCRP Polar Climate Predictability Initiative (PCPI). The PCPI has a focus on polar regions and their role in the global climate system, and aims to improve predictability of the climate system on all timescales by improving understanding of the underlying physical mechanisms and their representation in climate models.

After reviewing our current knowledge, participants focused on discussing the difficulty in determining the magnitude and causes of decadal-scale variability in climate system changes in the Southern Ocean and Antarctic region. For example, for data types such as those indicated in Figure 1, we considered how to determine whether trends in recent decades are unprecedented or within the range of natural variability. These difficulties are both due to our incomplete understanding of the dynamics of the system and the lack of data. In particular, modern instrumental records in the ocean typically represent isolated point observations, not extended time series, and these records extend back only a few years. Furthermore, paleoclimatic records of sufficiently high resolution are scarce. This severely limits our ability to estimate the natural multi-decadal variability.

Participants found the workshop to be stimulating and would definitely encourage similar jointly supported PAGES and WCRP activities in the future. Workshops such as these provide a rare opportunity for communities that do not normally meet (paleoclimate, instrumental, modeling) to share their expertise covering all aspects of the problem (atmosphere, ocean, sea ice) and to focus on specific issues. Data scarcity was recognized as a crucial limitation for Southern polar climate studies, and the importance of new work that needs to be done to obtain data for oceanic areas in the Southern Hemisphere was stressed, namely by developing new proxies using cold corals and mollusks, and also by imaging, digitizing, and processing meteorological observations from ships' logbooks. The need for better estimates of the uncertainties in current reanalysis products and for a coupled reanalyses dataset focused on high southern latitudes were also underlined.

The meeting achieved its aims of taking stock of current knowledge and determining key questions. Participants developed concrete plans for a publication summarizing the meeting findings. The meeting also sowed the seeds for a number of future collaborations, and we have been working to collect information about these emerging collaborative efforts, which we would be happy to share.

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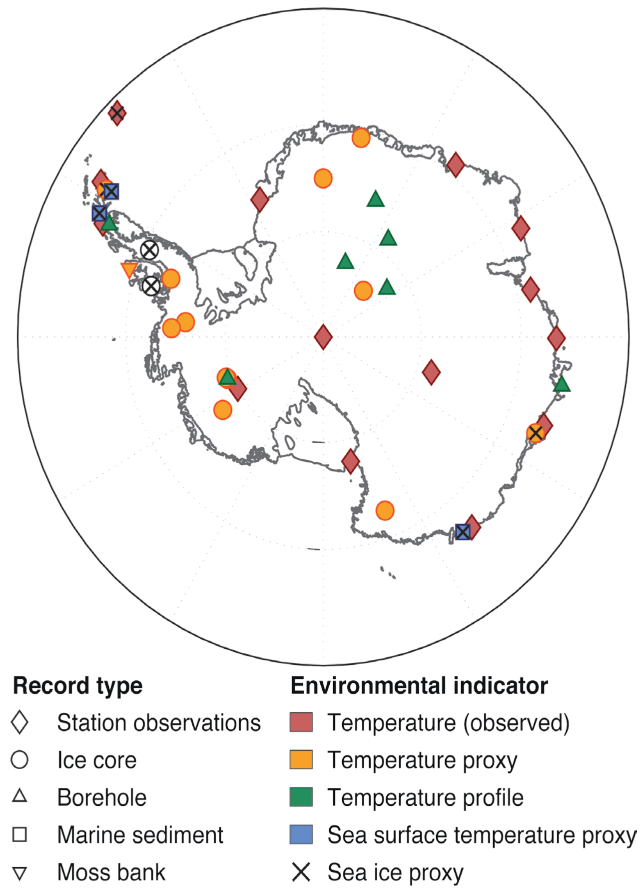

Figure 1: Location and type of climate and environmental information covering the last 200 years in Antarctica (Figure from Nerilie Abram).

Quantifying global sea level during warm periods

Gaylen Sinclair[1], B.S. Lecavalier[2] and K.L. Vyverberg[3]

PALSEA2 Workshop, Tokyo, Japan, 22-24 July 2015

In July, the third meeting of the second PALeo constraints on SEa level rise (PALSEA2) working group convened at the University of Tokyo, with the goal of integrating data and model-based reconstructions of paleo climate, cryosphere, and sea level. Presentations focused on past warm periods (mainly the late Pliocene, the last interglaciation (LIG), and the Holocene) and periods of rapid change during the last glacial cycle.

Due to the fragmentary record of the Miocene and Pliocene, and chronological uncertainties with existing records, delegates agreed that obtaining accurate sea-level rates for this period is impossible; efforts should focus on better constraining the maximum amplitude (Fig. 1). Sea-level changes due to dynamic topography must also be considered at these timescales to accurately estimate global ice volume from the sea-level reconstructions; current model results show that the contribution from this process can be tens of meters and may account for the spatial variations in Pliocene sea-level fluctuations (Rovere et al. 2015).

For the LIG, model-corrected relative sea-level records indicate peak global mean sea levels of around six to nine meters (Fig. 1), although the timing and number of highstands differs between reconstructions.

In several areas, including the Seychelles, detailed study of fossil coral facies and lithology reveal sub-orbital sea-level fluctuations consistent with previous inferences from the Bahamas and the Red Sea (Thompson et al. 2011; Rohling et al. 2008). A single, global-mean sea-level reconstruction should enable eventual reconciliation of these disparate sea-level estimates, accounting for different sources of sea-level rise, including potentially different timings of retreat of the major ice sheets.

The Holocene sea-level history is relatively well constrained, although there is room for improvement in delimiting the spatial and temporal variability of sea levels. A primary source of uncertainty is the contribution from the Antarctic Ice Sheets due to the relative paucity of observational control and the difficulty in obtaining accurate dates from cosmogenic methods. For the past 2,000 years, application of a Gaussian process model supports the existence of sub-millennial changes in global mean sea level (Cahill et al. 2015); but the processes responsible for those changes remain a target for future research.

Several techniques for improving climatic forcings in models were also debated, highlighting differences between modeled LIG climates and compilations of ocean-temperature data. Coupling of ice-sheet and climate models is increasingly feasible, and critical for understanding reconstructed sea-level histories. The importance of developing transient simulations of past warm periods was stressed as a means to improve understanding of the spatial and temporal variability observed in ice-sheet and sea-level reconstructions.

While new paleoclimate data at present are often archived online, they are rarely compiled into intuitive databases that can be easily accessed by all end users, particularly the modeling community. Significant progress has been made since the last PALSEA2 meeting in developing a framework for new databases for use by paleoclimate and paleo sea-level communities (Düsterhus et al. 2015). Discussions continued at this meeting, where delegates stressed the importance of including all metadata for a given data point to facilitate standardization of data and accommodation of future interpretations and calculations. Discussions during the conference to clarify the uncertainties of various data and model outputs highlighted the importance of being more rigorous about reporting and explaining uncertainties. Such transparency will facilitate the interpretation and application of climate, cryosphere, and sea-level reconstructions, and will be critical to advancing data-model comparisons, as well as interdisciplinary collaborations.

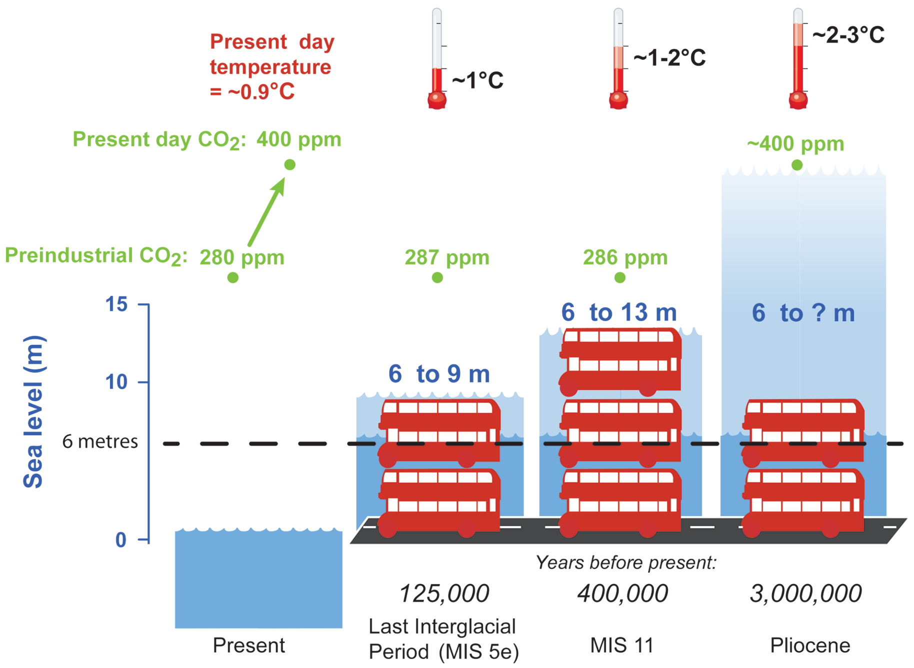

Figure 1: Summary figure of global mean sea level during past warm periods, global mean temperature relative to 1890 CE, and atmospheric CO_2 levels. Adapted from Dutton et al. (2015)

ACKNOWLEDGEMENTS

Funding was provided from PAGES, INQUA, and the Atmosphere and Ocean Research Institute (AORI) at the University of Tokyo. We thank all the delegates and the local hosts – Yusuke Yokoyama, Ayako Abe-Ouchi and their research groups – for making the workshop a success.

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Social-ecological dimensions of forest bark beetle disturbances: Past, present, and future

Jesse Morris[1,2], J. Clear[3], S. Cottrell[4], W. Hansen[5], K. Mattor[4], A. Seddon[6] and H. Seppä[7]

Santa Fe, USA, 2-3 April 2015

Since the late 1980s, native bark beetles (Curculionidae: Scolytinae) have caused widespread tree mortality in forests throughout North America and Europe. From a historical perspective the spatial scale and intensity of this disturbance has never been observed before. The outbreaks have been attributed to warm and dry climate conditions, which accelerate beetle reproduction cycles and diminish host tree defenses. During the past two decades, over 47 Mio ha of coniferous forest have been affected in western North America (Raffa et al. 2008).

An international group of ecologists and social scientists concerned with bark beetles met to identify priority research questions about the past, present, and future dynamics of beetle infestations, and the implications for society and the environment. The workshop ran alongside the Western Forest Insect Work Conference (www.wfiwc.org) in which all of the 17 workshop participants gave a short-format oral presentation. These research talks facilitated rich discussions among participants and representatives of several land-management agencies, including the US Forest Service and US Fish and Wildlife Service.

The workshop discussions addressed several major research themes pertaining to the social-ecological dimensions of bark beetle disturbances:

1) Ecological impacts

Tree mortality in western North America has been caused primarily by the mountain pine beetle (Dedroctonus ponderosae) and spruce beetle (D. rufipennis), while in Europe the spruce bark beetle (Ips typographus) has been most active. A key discussion point was how best to determine the precedence of recent outbreaks through the analysis of lake sediment and peat records. Discussions centered on applications of pollen, non-pollen palynomorphs, insect macrofossils, and biogeochemical proxies to detect past outbreaks with an emphasis on integrating sediment proxies with tree-ring records and forest inventories (Morris et al. 2015).

2) Ecosystem services

Ecosystem services provide a variety of important benefits to society, though many of these services remain unquantified. Severe beetle outbreaks pose challenges to society, including harmful effects on human health due to diminished air and water quality, by shifting property values, by causing declines in merchantable timber, and by negatively affecting landscape aesthetics causing reductions in tourism revenues (Flint et al. 2009). However, bark beetle disturbances can also lead to increases in the provision of ecosystem services, including improved wildlife viewing and increases in stream flow. These costs and benefits must be managed and measured in the face of change through strategies designed to improve and facilitate resilience (sensu Hollings 1973) and the adaptive capacity of the system. Workshop discussions aimed to identify common metrics, such as carbon biomass, that could aid in assessing the impacts and recovery of ecosystems from beetle disturbances over multiple spatial and temporal scales.

3) Human behavior

Of particular interest was how human perspectives shape policy and management response to large-scale outbreaks. For instance, recent studies demonstrate that beetle-impacted forests do not increase fire hazard, yet US management policies still allocate hundreds of millions of dollars annually to reduce fuel loads in beetle-affected forests (Hart et al. 2015). Additionally, changing property values are of concern as communities that were once surrounded by lush forests now find themselves in expansive landscapes of gray, standing dead trees known as "ghost forests" (Fig. 1). However, following salvage logging operations some communities surprisingly realize net increases in real estate values due to enhanced viewsheds (Hansen and Naughton 2013).

Priority research questions identified at the workshop will provide the basis for a forthcoming journal article and a research proposal planned for fall 2015 submission.

Figure 1: View of gray stage lodgepole pine forest, or "ghost forest", resulting from a mountain pine beetle outbreak in the Rocky Mountains, USA.

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Late Pleistocene and Holocene climatic variability in the Carpathian-Balkan region

Marcel Mîndrescu[1,2] and Ionela Grădinaru[1,2]

CBW2014, Cluj-Napoca, Romania, 6-9 November 2014

Prior to the last decade, the Carpathian region was largely unrepresented in large data reviews (Akinyemi et al. 2013) on well-dated, high-resolution investigations of past climate and environmental conditions and in studies on human impact on the local and regional environment. However, more recently, as new paleoclimatic records are continuously being generated, the area has ceased to be regarded as a blank spot in regional and continental-scale climate reconstructions (e.g. Feurdean et al. 2014). Undoubtedly, improving knowledge of the region in terms of past and current climate change research, biodiversity patterns and dynamics, or human spread and related cultural-technological interchanges will be accomplished only through a denser network of multi-proxy investigations (Veres and Mîndrescu 2013).

In 2011, a workshop co-sponsored by PAGES and the Mountain Research Initiative (MRI), and focusing on climatic variability in the Carpathian-Balkan region (Carpathian-Balkan Workshop, CBW2011, Suceava, Romania) was an early and successful attempt to create a network of paleoscientists in the region (Mîndrescu 2012). An initial product from this new network was a special volume in *Quaternary International* on the advances in Pleistocene and Holocene climate changes research from the Carpathian-Balkan region (Veres and Mîndrescu 2013).

The latest workshop, CBW2014, was another step forward for paleo-research in the region. The outcomes of several collaborations emerging from CBW2011 were presented, and new international research topics were discussed. Furthermore, the event provided a platform for young scientists to introduce and discuss their results to an international and multidisciplinary audience.

Sixty-two researchers from 11 countries (Canada, UK, Switzerland, Germany, Poland, Hungary, Ukraine, Bulgaria, Bosnia and Herzegovina, Serbia, and Romania) conducting studies in the Carpathian-Balkan region presented over 60 contributions covering the timeframe from the Late Pleistocene to the present. Topics included climate and vegetation changes inferred from lacustrine and riverbed sediments, tree rings, speleothems, loess-paleosol sequences, and glaciers and glaciation; refining research techniques for paleoenvironmental investigations; human impacts; archeological findings; etc. The abstracts and extended abstracts were published prior to the event in an open-access special issue of *Georeview* (http://georeview.ro/ojs/index.php/revista/issue/view/CBW-2014).

The range of data from recent research in the region presented at the workshop (including two datasets on glacial lakes, http://atlas.usv.ro/geoconcept/webcarpath2/ and glacial cirques from the Romanian Carpathians, http://atlas.usv.ro/geoconcept/glaciar/) is in itself an accomplishment as those records contribute in covering previously "uncharted" territory. Further, the meeting participants envisaged using the new datasets as a basis for new research endeavors which could integrate and relate data from this growing network of sites (see Fig. 1).

The more advanced contributions presented at the meeting will be published in a special volume in *Quaternary International*, to be guest edited by the organizers of the workshop: more than 30 author groups have already committed to submitting a paper.

Finally, in the plenar discussion, the participants agreed that without better data coverage and expertise exchange, difficulties will remain in understanding local-scale environmental changes and developing regionally significant paleoclimate reconstructions, which would assist in proposing plausible predictions of future climate evolution.

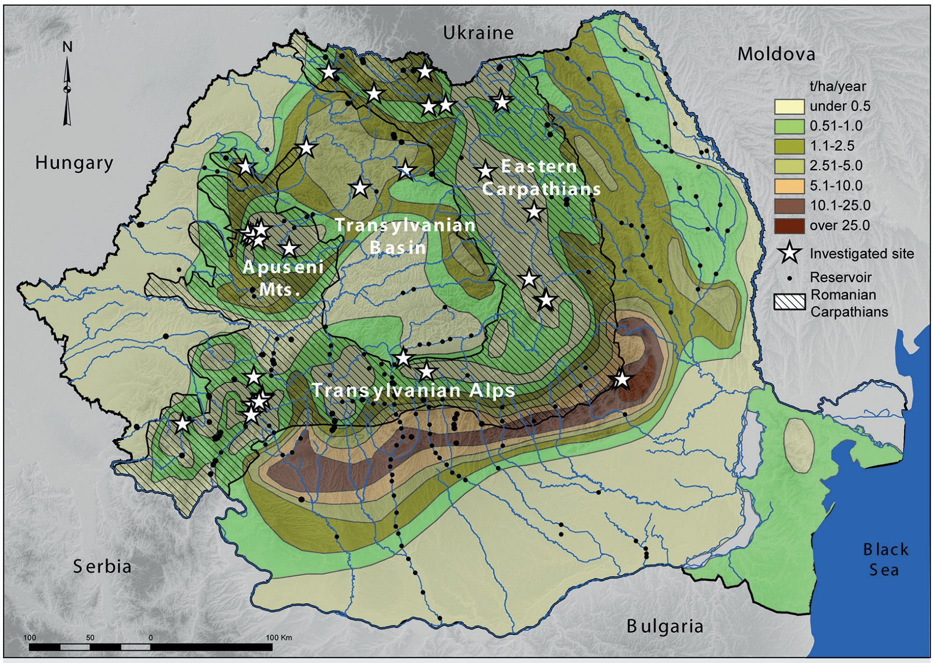

Figure 1: Location of sites with lacustrine sediment records in the Romanian Carpathians (modified from Mîndrescu et al., in press).

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Quaternary fluvio-lacustrine environments and human settlements in West Africa

N'dji dit Jacques Dembele

Bamako, Mali, 27-31 October 2014

The West African Quaternary Research Association (WAQUA) was established in 2009 to promote Quaternary Sciences in the West African region through the capacity building, mentoring and motivation of early-career scientists and the fostering of collaborative research, exchange of information and networking opportunities. Eighty quaternary scientists, mainly early-career scientists of the West African region and Democratic Republic of Congo, gathered in Bamako to share their research results and experiences on quaternary fluvio-lacustrine environments.

Fifty oral presentations were given in the following five sessions: (1) Quaternary fluvio-lacustrine sediments: paleoclimates and paleoclimatology; (2) Past and contemporary human settlements in relation to fluvio-lacustrine systems; (3) Paleoecological evidences from fluvio-lacustrine deposits; (4) Current environmental issues arising from the use of fluvio-lacustrine systems; (5) The methods of research of quaternary fluvio-lacustrine complexes in West Africa.

Figure 1: Laminated lacustrine deposits of the Niger River south bank at Bamako, Mali, visited during the conference field trip.

During the first session, the fluvio-lacustrine deposits of the Niger River in Mali and in Nigeria; the stratigraphy of fluvial deposits of the Falemé River, tributary of the Senegal River; and the paleoenvironment and paleoclimates of the Kivu River in the Democratic Republic of Congo during the late Pleistocene and Holocene were introduced. This session showcased the great potential to use fluvial deposits to reconstruct the quaternary climatic variation and paleohydrology of West Africa. However, because the scientists in that region do not use the same stratigraphic framework, comparing the individual studies is difficult. Building such regional comparable chrono- and climatostratigraphies is only possible through collaborative research efforts. In the discussion, the participants also agreed that local stratigraphic climatic stages such as the Ogolian (a dry period of the late Pleistocene) could not be generalized to all of West Africa without further research and stratigraphic correlation.

During the second session, the prehistoric settlement of the Sahelian region of West Africa in Burkina Faso, in the Niger Inland Delta region and in Nigeria; the Holocene settlement of the Dogonland of Mali; and the effect of current climate change on migration were presented. The discussion focused on the effect of quaternary climate variability on human settlements and population migrations. The participants recognized that understanding quaternary climate variation, and especially the succession of dry and humid periods, should be one of the foci of quaternary research in the region.

The third session covered the evolution of quaternary vegetation in the Niger Inland Delta in Mali and in Nigeria and an explanation of the causes of the "Dahomey Gap", a region of savanna separating the West African tropical forests. Pollen analyses provide evidence of the effect of climate change and human settlement on West African ecosystems. The attendees recommended the use of more paleoecological research methods such as phytoliths and quaternary fossil assemblages analyses to complement pollen analysis.

The fourth session focused on the impacts of current climate change on the West African fluvial and lacustrine ecosystems; anthropogenic pressure; the use and management of fluvial and lacustrine resources; flash floods; the use of fluvial and lacustrine systems for tourism; and the impact of off-season rainfalls. In this session's discussion, the use of the concept of "climate change" was discussed and whether one can talk of climate change or climate variability in only a 30-year framework. Climatologists of the region were asked to address this question by providing a temporal perspective on the use of these two concepts in the West African context.

During the last session quaternary research methods in the West African fluvio-lacustrine context were discussed. Methods based on pollen analysis, computer modeling, and GIS were introduced.

To help the early-career scientists improve their research capacity, training sessions were organized on the topics "Paleoecology and palynology of quaternary fluvio-lacustrine deposits" and "The use of heavy minerals in quaternary fluvial and lacustrine deposits, and in geoarcheology".

ACKNOWLEDGEMENTS

The organizing committee express their sincere gratitude to PAGES, INQUA, PAST (Palaeontological Scientific Trust), AUF (Agence Universitaire de la Francophonie), and USSGB (Université des Sciences Sociales et de Gestion de Bamako) for their financial and material support, and encouragement.

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Quaternary paleoecology: Reconstructing past environments

Sonia L. Fontana[1] and Keith D. Bennett[2]

Mar del Plata, Argentina, 4-15 August 2014

The 2nd Latin American paleoecology workshop took place at the University of Mar del Plata, Argentina and was attended by 37 participants from Mexico, Ecuador, Colombia, Brazil, Chile, Uruguay and Argentina. This intensive two-week course was designed for postgraduate students and early-career scientists undertaking research in paleoecology, with an emphasis on microfossil analysis. Thus the workshop stimulated the interaction of students and young scientists with a broad range of expertise, including palynology, the analysis of diatoms, ostracods, cladocera, charophytes, plant macrofossils, bryophytes, as well as geochemistry, archeology, and geomorphology.

The course focused on state-of-the-art methodological approaches and techniques applied to diverse paleoresearch issues in chronology and proxy development. The event was organized into different activities: lectures, practical classes, poster presentations, a field trip, and the development of a joint research project. These activities addressed the interaction of different external (e.g. climate variations, human activities) and internal forcing factors (e.g. population dynamics, dispersal, resilience) responsible for ecosystem changes. They also looked at the spatial and evolutionary responses of organisms to long-term climatic changes.

Participants designed a multi-disciplinary research project based on the analyses of sediment cores recovered in shallow lakes of the Pampa region. The cores were described and sub-sampled for different analyses during the course, and the analysis of the samples is now taking place at the participants' home institutions. Findings from this research will be communicated to all other participants. In this way, we are building a network of young scientists in Latin America: Synergy Latina. The main goal of this particular project is to contribute to the understanding of the regional changes in climate and the environment during the Holocene. Paleoenvironmental reconstructions from the Pampa region are important for understanding this large ecosystem, which has been completely converted into agricultural land, apart from the costal dunes (Fontana 2005). In addition, sediment records from this region also offer the opportunity to look at changes in trophic states of lakes through time (Stutz et al. 2012), applying the ecological theory of alternative stable states of the aquatic systems on long time scales (Scheffer et al. 1993, 2001; Fig. 1). The outcome of this project will contribute significantly to understanding the drivers of pampean lake dynamics on a long-term perspective.

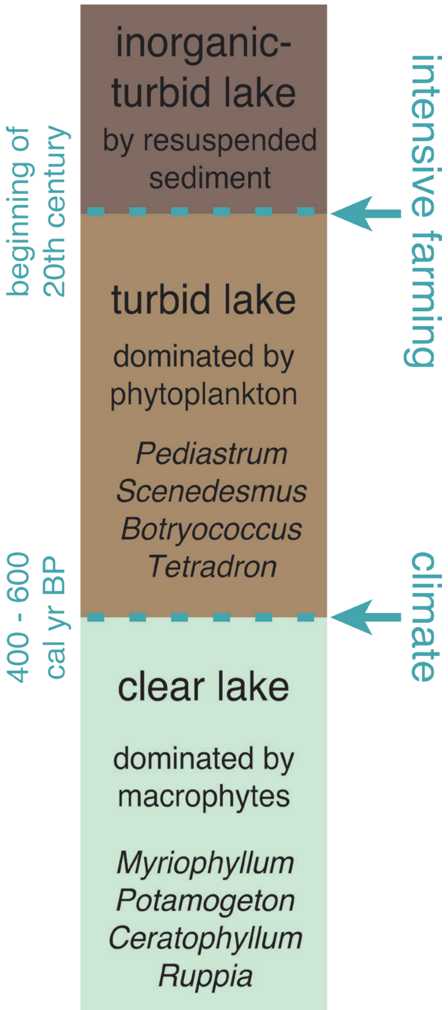

Figure 1: Schematic representation of Holocene changes in trophic states of shallow lakes from the Pampa plain in Argentina (Stutz et al. 2012). Arrows indicate ecological thresholds, points at which there are abrupt changes in the aquatic system, and the drivers identified.

The workshop also aimed to promote social and scientific exchange between research groups from different Latin American countries, while enhancing the skills and knowledge of all of the participants through field, laboratory, and computer exercises. Because the number of applicants far exceeded the available workshop slots, the organizing committee is now considering offering this course on an annual basis.

In addition to the financial support from PAGES, participants obtained support from their home institutions, universities and research councils. A personal grant from the Ministry of Science and Technology of Argentina, Milstein-raíces program, to SLF helped develop the workshop. The ^{14}CHRONO Centre at Queen's University Belfast, UK, supported the Synergy Latina project by providing radiocarbon dating of the sediment records. We would like to thank Silvina Stutz, Alejandra Marcos and Marcos Echeverria for coordinating the different activities during the meeting. The full program of activities, including abstract presentations can be viewed at: www.uni-goettingen.de/en/413062.html

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Spatiotemporal distribution of temperature and hydroclimate proxy data in the Arctic

Anne Hormes[1], J. Werner[2], K. Husum[3] and N.J. Steiger[4]

Arctic2k meeting, Vienna, Austria, 13 April 2015

The Arctic2k working group met for an open meeting during the European Geosciences Union (EGU) General Assembly 2015 to discuss the current state of the group and future activities. Twenty-five participants attended the meeting.

Johannes Werner reported on the status of the database and the plans for creating regional temperature reconstructions. As the Arctic2k region already had a well-developed database for the first phase of the temperature reconstructions (see PAGES2k Consortium 2013; McKay and Kaufman 2014), only a few new temperature records have become available since then. The largest "gap" identified in the current temperature database is a number of tree ring records, mainly from Scandinavia and Russia, that have not yet been included. Hans Linderholm is currently quality checking and formatting these records.

One problem identified in recent temperature field reconstruction attempts is the poor skill over Greenland (e.g. Anchukaitis and McKay 2014), which is surprising given the relatively good coverage of ice core records. Thus, to find the source of the problem, Valerie Masson-Delmotte has volunteered to coordinate an activity to check the quality and climatic interpretation of the ice core data, and their correlation with the regional meteorological records.

Another project proposed by Jostein Bakke aims to prepare a funding application for additional ^{210}Pb and ^{14}C dating of existing sedimentary climate records. This would serve two purposes: data that could, up until now, not be included in the 2k database could then pass the dating selection criteria, and data already included would be improved.

Hydroclimate

A breakout discussion, lead by Anne Hormes, focused on the hydroclimate and the type of proxy records available. As a first step, the group decided to work on a paper reviewing the available records in the Arctic and discussing which hydroclimate parameters could be reconstructed. The linked proxy record database will be completed by the second half of 2015, to allow enough time to create a hydroclimate reconstruction for the 2k Network synthesis in 2016. Please contact Hans Linderholm or Anne Hormes if you want to contribute to the collection and quality control of the proxy records, or to contribute to the review article.

Reconstruction methods

A second group, lead by Johannes Werner, discussed the spatial temperature and precipitation reconstructions themselves. Although the spatial density of data in the Arctic is low, the group will attempt a circumarctic spatial temperature reconstruction. However, it was noted that great care must be taken in communicating the reconstruction quality and uncertainties that would change through time and space. A promising method for doing this was recently showcased by the NOAA 20th Century Reanalysis Project, and consists of clouding out areas that do not fulfil the criteria for trustworthy reconstructions. Johannes Werner and Nathan Steiger offered to lead the reconstruction effort, using Data Assimilation and Bayesian hierarchical models. Contributions from other reconstruction groups are encouraged.

Climatically coherent regions that are well covered in terms of proxy data will also be identified. Generating regionally averaged reconstructions over these regions will provide a valuable second set of reconstructions that can be compared with the spatial reconstructions.

The group agreed that a reconstruction should be more than an updated version of already available spatio-temporal climate reconstructions. One novel aspect could be improving the communication and visualisation of the spatio-temporal uncertainties of the reconstruction. Additionally, a fortuitous fact is that the landmasses surrounding the North Atlantic basin are relatively well covered in terms of proxy records, and preliminary results show that good reconstruction skill over this region is possible. A North Atlantic reconstruction should enable the comparison of atmospheric circulation changes that can then be linked to high-resolution marine archives. Several decadal resolution sediment archives are available, and new sclerochronological records will hopefully become available in time for the final comparison.

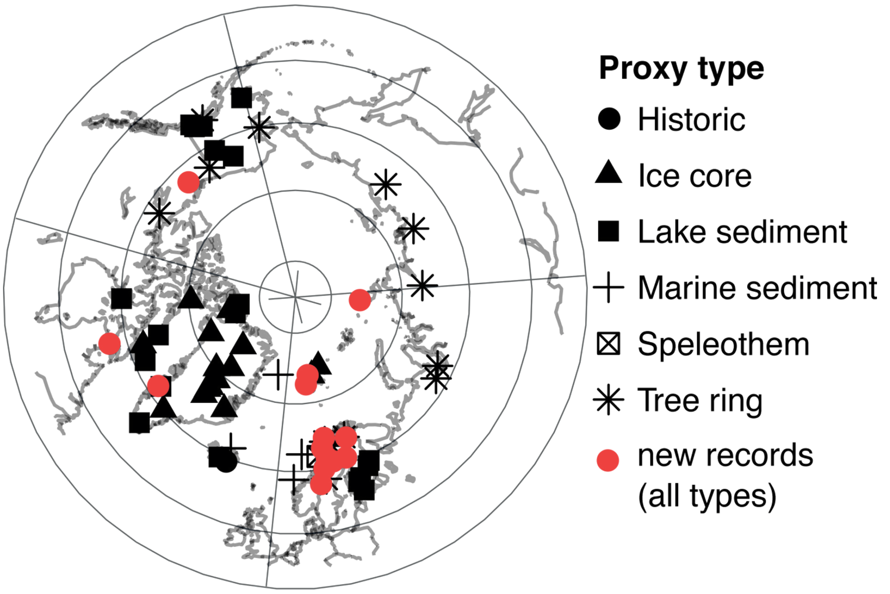

Figure 1: Overview of temperature proxy archives in the Arctic2k database, new records are highlighted in red.

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Toward an Asian hydroclimate field reconstruction

Takeshi Nakatsuka

4th Asia 2k workshop, Kyoto, Japan, 19-20 March 2015

The Asia 2k working group met at the Research Institute for Humanity and Nature in Kyoto, Japan, to coordinate its phase 2 activities i.e. collecting Asian paleo-records and integrating them into climate, in particular hydroclimate, reconstructions for the past two millennia.

Historical hydroclimate variability, such as severe droughts and floods, has played a key role in people's welfare in Asia. However, creating the hydroclimate field reconstruction (HFR) needed to better understand this natural variability is a significant challenge due to the heterogeneous nature of precipitation over the Asian monsoon region. Data coverage is still scarce for hydroclimate indicators over Asia, and the statistical models still have a challenge integrating the available multi-proxy records with various temporal resolutions. Thus, new data have to be found to fill the spatial gaps, realistic HFR targets set, and the best methods to achieve these discussed; these points were at the center of the discussions at this meeting.

Almost 40 researchers, including 10 graduate students and postdoctoral fellows, participated in the workshop. Many Asian and non-Asian countries were represented: Japan, China, Russia, India, Pakistan, Nepal, Sri Lanka, Germany, USA, New Zealand, and Switzerland. After an opening remark on the application of Asia 2k's phase 1 results (Cook et al. 2013) in an inter-disciplinary research project (Fig. 1), the first day of the meeting was dedicated to participants' reports on their expertise and research related to Asia2k. On the second day, discussions focused on the goals and timeline of the working group, the status of the data collection, and devising the integration strategies required to achieve the climate field reconstructions.

Although creating spatial hydroclimate reconstructions is a challenge in the monsoon region, the region has also many advantages, especially thanks to the various types of proxy records available. For example, tree ring chronologies in Asia have great potential to reconstruct past hydroclimate. Many new tree-ring oxygen isotope chronologies were recently published; these can record past changes in regional summer precipitation and relative humidity (e.g. Xu et al. 2013).

In Asia there are also several stalagmite, coral, sediment, and ice core series recording various aspects of the hydroclimate. Together with the tree ring data, all of these proxies can serve as a strong basis for the creation of hydroclimate records. Chinese documentary records on flood and drought covering more than two millennia are also very promising proxies, as well as those from Japan covering the last millennium. Because hydroclimate reconstructions need more densely distributed proxy data than temperature reconstructions and no millennial-long tree-ring chronologies are available from the more populated areas like eastern China, the inclusion of documentary data is crucial.

In a first step, the group has been working on an updated version of the Monsoon Asia Drought Atlas (MADA; Cook et al. 2010). The new MADA will serve as a benchmark for comparison with planned multi-proxy reconstructions, and its tree ring database is the basis for the new data collection. Currently, the group is collecting hydroclimate records and adding them to the database using the same selection criteria and format as used by the 2k Network for its global temperature database. The goal is to produce a gridded reconstruction of monsoon precipitation using a Bayesian approach. If the data coverage is too sparse for a full spatial reconstruction, index reconstructions of sub-regions will be targeted. Independent data, such as glacier extents will be considered for validation purposes.

In addition to its main focus on hydroclimate, the group has also produced a first version of a multi-proxy spatial temperature reconstruction (Shi et al. 2015). The final version of the temperature reconstruction will be based on several reconstruction methods and integrate high- and low-resolution records.

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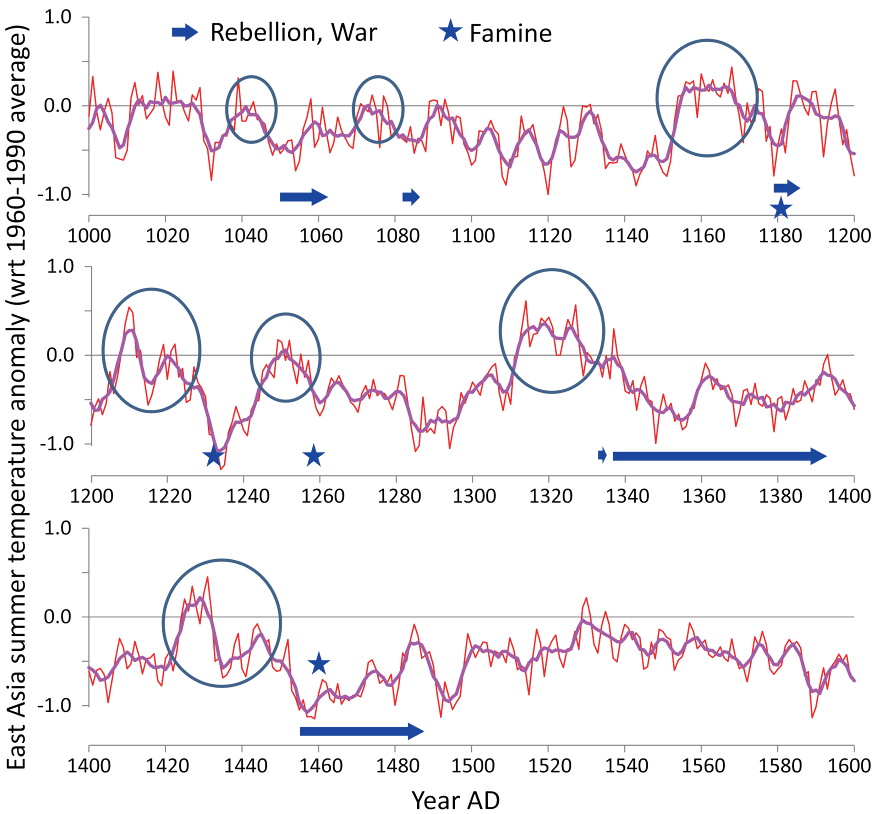

Figure 1: The Asia 2k East Asia summer temperature record (Cook et al. 2013) has enabled the detailed comparison of climate and Japanese history over the last millennium and has stimulated an interdisciplinary research project between paleoclimatologists and historians on societal adaptation to climate change (http://www.chikyu.ac.jp/rihn_e/project/H-05.html). Major medieval famines and warfare often occurred at times of sudden cooling after multi-decadal warmth.

Climate variability and human impacts in Central and Eastern Europe during the last two millennia

Wojciech Tylmann[1] and Martin Grosjean[2]

Gdansk, Poland, 17-19 June 2015

Proxy-based comprehensive regional climate reconstructions for the past 2000 years provide critical insight into the fundamentals of natural climate variability and the detection and attribution of anthropogenic climate change in the 20th century. Moreover, it is increasingly recognized that anthropogenic land-use and land-cover changes over the same period of time have played an important role in modifying the regional atmosphere and ecosystem development. Although Europe has better paleoclimate data coverage than many other parts of the world, information from Central and Eastern Europe is still scarce and mostly missing in comprehensive regional climate reconstructions (PAGES 2k Consortium 2013). However, the extraordinarily rich sources of early instrumental and documentary data from historical climatology, recent discoveries of many varved lake sediments in Poland (Tylmann et al. 2013), new developments of quantitative hydroclimatic proxies from peat bogs (Lamentowicz et al. 2011), and new insights into anthropogenic vegetation and land-cover changes have drawn the attention of paleoecologists and paleoclimatologists to Central and Eastern Europe.

Under the umbrella of the three PAGES working groups, Euro-Med2k, the Varves Working Group and LandCover6k, 90 scientists from 14 countries gathered at the University of Gdansk, Poland, to (i) discuss existing and new data sets from Central and Eastern Europe; (ii) explore ways the scientific community from this part of Europe could be better involved in ongoing PAGES activities, and (iii) stimulate research along the agendas of the three PAGES working groups. More precisely, the conference aimed to fill regional data gaps in Central Europe, to improve the quality of paleoclimate data sets (calibration, resolution, chronology, interpretation), to work towards data synthesis and comprehensive multi-site, multi-proxy climate reconstructions, and build our understanding and ability to discriminate between the multiple influences on ecosystems (climate, human, ecosystem evolution, etc.).

Several oral and poster presentations demonstrated the potential of tree-ring research along W-E and N-S transects across Central and Eastern Europe. Within this area, trees are sensitive both to temperature and humidity, and this sensitivity varies across the seasons. Additionally, the challenges of temperature reconstructions derived from temperate lowland trees were addressed.

Taking advantage of the momentum and methodological developments generated by the Varves Working Group in recent years, progress in very high-resolution (annually to seasonally resolved) quantitative climate reconstructions and reconstructions of environmental and vegetation change from varved lake sediments was shown. Robust quantitative paleoclimate signals can be extracted from biological proxies (chironomids, chrysophyte stomatocysts), while most of the biogeochemical and sedimentological proxies contain mixed signals and are more difficult to interpret and quantify. Separating climate variability from anthropogenic impacts still remains a challenge.

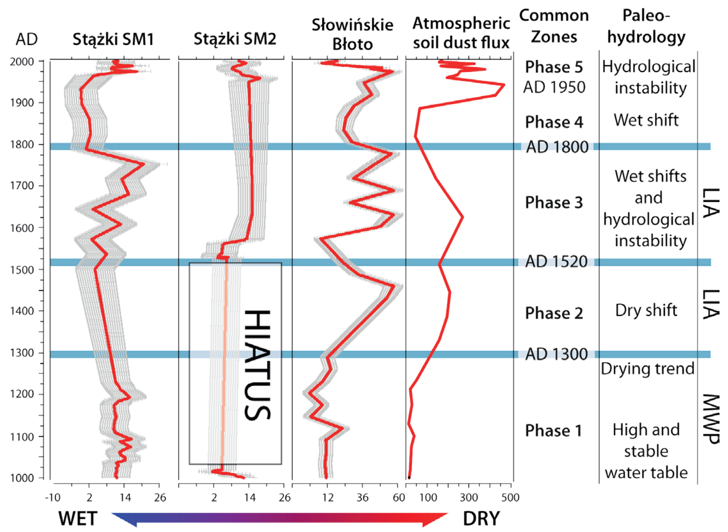

Figure 1: Hydroclimate variability of the last millennium reconstructed from northern Polish bogs using testate amoebae transfer functions (courtesy of Mariusz Lamentowicz).

This part of Europe is very rich in peat bogs. Several presentations demonstrated the potential of testate amoebae transfer functions for quantitative reconstructions of bog humidity (Depth to Water Table DWT) and, thus hydroclimate (Fig. 1). The currently available records show systematically dry conditions and hydrological instability during the Little Ice Age (14-19th centuries), which is in contrast to conditions in Western Europe during this period. It appears that there is more spatial heterogeneity in hydroclimatic conditions across Europe than previously thought.

The aims and plans of the recently established LandCover6k working group were presented during the meeting. The importance of land-atmosphere coupling is increasingly recognized, in particular the effect of land-use and land-cover change (LUCC) on regional temperatures. Central and Eastern Europe is a key site for the study of past land-atmosphere couplings, mainly because of the very large number of sites that have been studied for pollen and vegetation changes. These data, in combination with very rich and detailed information about past land-cover changes and hydrological modifications from historical cartography and other documentary sources, might make Central Europe a suitable test bed for calibrating and verifying pollen-based LUCC reconstructions and investigating land-cover feedbacks on the regional atmosphere in the past.

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Launching workshop of PAGES' working group LandCover6k

Marie-José Gaillard[1], A.-M. Lézine[2], K. Morrison[3] and LandCover6k Steering Group[4]

Paris, France, 18-20 February 2015

The goal of PAGES' new LandCover6k Working Group is to achieve Holocene land-cover and land-use reconstructions that can be used to evaluate and improve the scenarios of anthropogenic land-cover change (ALCC) by Klein Goldewijk et al. (2011; HYDE) and Kaplan et al. (2009; KK) for the purpose of climate modeling studies (Gaillard et al. 2015). LandCover6k focuses on the last 6000 calendar years, i.e. the period in the Holocene when anthropogenic deforestation occurred in most continents, but it will also cover older periods in regions where significant human impact on vegetation occurred earlier. LandCover6k has links to other research programs, in particular IHOPE (Intergrated History and Future of People on Earth), GLP (Global Land Project), PMIP (Palaeoclimate Modelling Intercomparison Project), and PAGES' GPWG (Global Paleofire Working Group).

This workshop was attended by 50 participants from 17 countries. Its purpose was to summarize the state of the art in land cover studies in the Americas, Europe, Africa, Asia, and Oceania, and to discuss the working group's strategy for achieving its goals. The first part of the workshop was devoted to lectures and discussions on (i) the problems related to current descriptions of past land cover in climate modeling studies, (ii) the ALCC scenarios, (iii) the methods used to reconstruct past land use and land cover, (iv) the status of the pollen databases, and (v) existing land-use and land-cover reconstructions. The second part of the workshop was devoted to organizing the working group, planning the strategy, and creating a timeline for the first three-year phase, including the next workshops and scientific products.

The participants decided that the LandCover6k research activities would be divided into two major areas, Land Cover, coordinated by Marie-José Gaillard, and Land Use, coordinated by Kathleen Morrison. Furthermore, the group is divided into nine subgroups each with one or several coordinators. The nine subgroups are (1) N America, (2) Latin America, (3) Europe, (4) Africa, (5) Asia, Australia, Oceania, (6) Land use (from archeological and historical data), (7) Methodology focused on the tropics, (8) Anthropogenic Land Cover Change (ALCC) modeling (i.e. revision of the ALCC scenarios KK and HYDE), and (9) Pollen productivity estimates (PPE).

LandCover6k will first focus on three time windows, 6000 BP, 450 BP, and 100 BP, as an intermediate product to test the methods and strategies. Additional time windows will be added at the end of the first three-year phase. Reconstructions of past land use will be achieved mainly by the community of archeologists and historians, and will include the challenging effort of upscaling archeological and historical information into maps of past major land-use systems. Reconstructions of past land cover at the global spatial scale will be achieved using pollen data and various methods including the modern analogue approach (e.g. Blois et al. 2011), biomization (e.g. Fyfe et al. 2013) and the REVEALS model (e.g. Trondman et al. 2015).

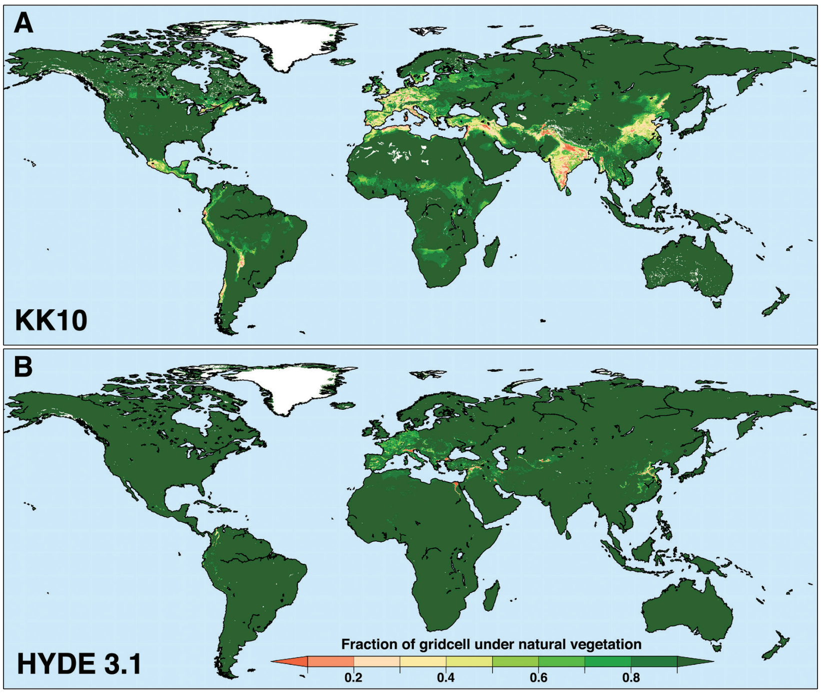

Figure 1: A comparison of human land use estimates (fraction of deforestation) around AD 1 from **(A)** the KK10 scenario (Kaplan et al. 2009) and **(B)** HYDE 3.1 (Klein Goldewijk et al. 2010). LandCover6k aims to improve the KK and HYDE scenarios and decrease their discrepancies using land-use reconstructions based on archeological and historical data, and quantitative land-cover reconstructions based on pollen records (forested versus deforested land).

Of the meetings planned at the February workshop, several have already happened, including a working and information meeting at INQUA 2015, Japan; a Land-Use workshop in October 2015 in Paris, France organized by Kathleen Morrison; a steering group meeting in November 2015; and a training workshop on pollen-based reconstructions of land cover in September 2015 in Reading, UK. There will be a Landcover6k sessions at AGU (2015) and EGU (2016). We also plan sessions at the International Congress of Palynology (IPC) in 2016, and at the next PAGES Open Science Meeting (OSM) in 2017, as well as a number of workshops in 2016.

Further details on the organization of the working group, coordinators and key participants, and future activities can be found on the LandCover6k website: www.pages-igbp.org/ini/wg/landcover6k.

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Pliocene climate variability over glacial-interglacial timescales (PlioVAR) working group

Erin McClymont[1], P. Dekens[2], H. Dowsett[3], L. Dupont[4], A. Haywood[5], A. Rosell-Melé[6] and U. Salzmann[7]

The Pliocene epoch (~2.6-5.3 million years ago) is arguably the best-resolved example of a climate state in long-term equilibrium with current or predicted near-future atmospheric CO_2 concentrations. It was characterized by a globally warmer climate (Fig. 1), reduced continental ice volume, and reduced ocean/atmosphere circulation intensity. Data derived from natural archives can be constrained in time to the Pliocene by multiple stratigraphic frameworks. Orbital forcing of solar radiation is known precisely, and many of the species extant today were also present then. As a result, detailed understanding of climate forcings and feedbacks is possible through both data analysis and data-model integration.

Pleistocene paleoclimate studies have demonstrated the value of understanding climate variability on orbital timescales, whereby the unique spatial and temporal signatures of individual interglacials or glacial-interglacial cycles highlight sensitive regions or climate systems. Recent modeling work confirms that such variability (and regional non-synchronicity) should also be expected in the Pliocene. However, Pliocene data density is lower than for the Pleistocene, and stratigraphical correlation may be more challenging (e.g. benthic $\delta^{18}O$ oscillations are more muted). To create a globally distributed, orbitally-resolved synthesis of Pliocene climate variability a community effort is required, ensuring high quality data sets can be integrated using a robust stratigraphy, which is essential to underpin future data-model comparisons.

The PlioVAR working group

The overall aim of PlioVAR is to coordinate a synthesis of terrestrial and marine data to characterize spatial and temporal variability of Pliocene climate. We are seeking datasets and scientific expertise with global reach, to increase our understanding of climate sensitivity to forcings in the past with both regional and global perspectives. We will examine marine and terrestrial evidence for e.g. temperature change, hydrology, and nutrient cycling, with the aim of understanding the interactions between different components of the climate system, including ocean-atmosphere circulation and continental ice volume. Within PlioVAR we also aim to explore the biotic response to Pliocene climate variability, and the links between marine and terrestrial ecosystems.

Our program builds on key priorities identified by the community at a PAGES-sponsored workshop in Barcelona, 2014 (Rosell-Melé et al. 2015). Our initial focus will be the late Pliocene, for which we have the greatest data density and constraints for model simulations, but the longer-term goal is to extend these efforts to earlier intervals of the Pliocene epoch. We have three over-arching goals:

- Synthesize late Pliocene climate data with orbital and sub-orbital scale resolution.
- Examine tools and experimental design for new climate modeling studies to characterize Pliocene climate variability, including transient model simulations.
- Identify early Pliocene intervals to which the approaches of (1) and (2) can be applied in later stages of PlioVAR, to compare and contrast the long-term evolution of Pliocene climate and consider the role of ocean gateways and CO_2 forcing in the evolution of the Earth system.

Within PlioVAR we aim to create a database of late Pliocene marine and terrestrial data, which enables regional and global syntheses of spatial and temporal climate variability. This will include coordinating efforts to address missing data, evaluating chronostratigraphic tools and their constraints, and recommending protocols on stratigraphic reporting for database metadata. We will quantify and compare uncertainties in proxies, and develop methods for assigning and reporting confidence in proxy records for database metadata. Finally, we aim to quantify late Pliocene climate variability over time and at both regional and global scales through data synthesis, modeling experiments, and data-model integration.

We will shortly be circulating a white paper to PlioVAR members that addresses the chronostratigraphic tools and approaches used in Pliocene research, and which will make recommendations for the PlioVAR data synthesis. A workshop to discuss Pliocene modeling approaches is also scheduled for early 2016 in Leeds, UK, and we plan several proxy-led workshops for data synthesis and discussion. To learn more about PlioVAR and to join the working group please see our webpages (www.pages-igbp.org/ini/wg/pliovar) or contact any of the members on the PlioVAR steering committee.

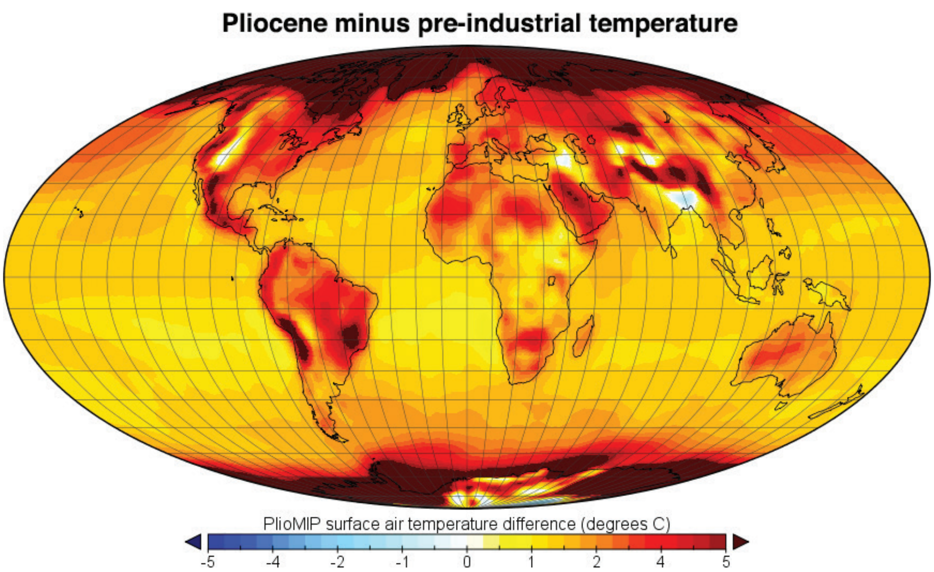

Figure 1: Annual mean surface air temperature change in Celsius (Pliocene minus pre-industrial) from the PlioMIP ensemble (redrawn from Haywood et al. 2013).

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New PAGES-PMIP working group on Quaternary Interglacials (QUIGS)

Chronis Tzedakis[1], E. Capron[2], A. de Vernal[3], B. Otto-Bliesner[4] and E. Wolff[5]

Past interglacials can be thought of as a series of natural experiments in which boundary conditions, such as the seasonal and latitudinal distribution of insolation, the extent of continental ice sheets and atmospheric greenhouse gas concentrations, varied considerably with consequent effects on the character of climate change. Documenting interglacial climate variability, therefore, can provide a deeper understanding of the physical climate responses to underlying forcing and feedbacks, and of the capabilities of Earth System Models to capture the patterns and amplitudes of the responses. These considerations provided the impetus for a comprehensive comparison of interglacials of the last 800,000 years within the context of the PAGES working group on past interglacials (PIGS; 2008-2015). While PIGS synthesized the current state of understanding on interglacials of the last 800,000 years, it also identified a number of research issues that need to be solved if further breakthroughs are to be made (Past Interglacials Working Group of PAGES, in press):

- There is no simple astronomical cause for differences in the intensity of interglacials, which seems to arise at least partly from the patterns observed in atmospheric CO_2 concentrations. This emphasizes the need to better understand and model the carbon cycle across glacial cycles.
- Chronological advances, both in assessing absolute ages relative to astronomical forcing, and in aligning different proxies and locations, are essential if we are to assess the dynamics of interglacials and their termination and inception.
- The paucity of long and continuous terrestrial records precludes the assessment of many important aspects of the climate.
- While existing records suggest that sea level was higher than present in some interglacials, better knowledge of the contribution of the Greenland and Antarctic ice sheets is critically needed.
- Identifying the controls on intra-interglacial variability remains a challenge.

Within the so-called "zoo" of interglacials (Fig. 1), the Last Interglacial (LIG, MIS 5e) has been the most intensively studied, but modeling of earlier interglacials remains limited. In particular, much more needs to be done to better characterize and understand (1) warm extremes, (2) cool versus warm interglacials of the last 800 ka, and (3) interglacials in the 41 ka-world vs those in the 100ka-world.

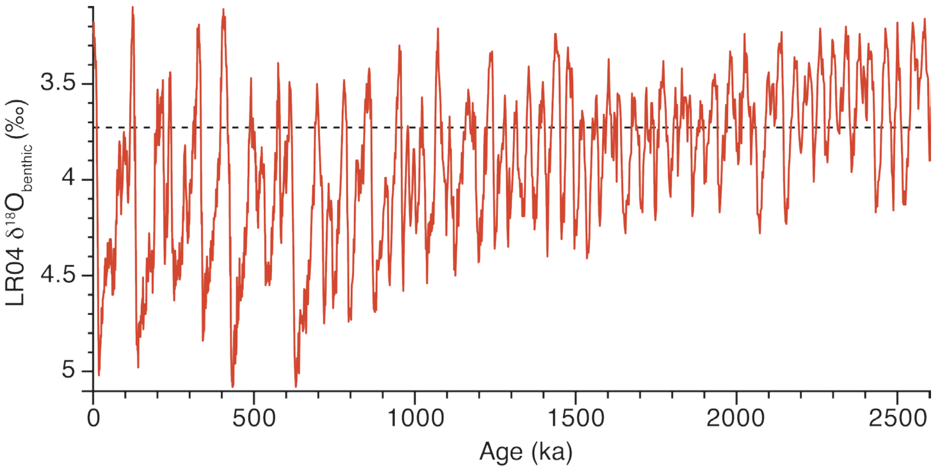

Figure 1: "LR04" stack (graphic correlation of 57 records) benthic $\delta^{18}O$ over the Quaternary (modified from Lisiecki and Raymo 2005). Interglacials occur above the dotted horizontal line. See Past Interglacials Working Group of PAGES (in press) for more information.

The objectives of QUIGS are to:

- document and synthesize data on the temporal and spatial patterns of climate responses during Quaternary interglacials and assess the governing processes using numerical models;
- assess the relevance of interglacials to understanding future climate change.

The drive towards a systematic understanding of interglacials requires targeted model exercises as well specific data sets with improved chronologies (some of which are not available yet). QUIGS will promote closer collaboration between the modeling (Paleoclimate Modelling Intercomparison Project; PMIP) and data communities, who together will provide expertise on experimental design, data compilations and syntheses, model-data comparisons, and interpretation of results.

The first workshop on "Warm extremes" took place in Cambridge, UK, 9-11 November 2015. It specifically examined the LIG and MIS 11, identified by PIGS as the warmest interglacials of the last 800 ka. While both interglacials have been considered by previous projects, our aim is to stimulate the work needed for PMIP. Thus, during this first workshop, we assessed emerging data syntheses and recent model experiments. This will allow us to highlight data gaps, and promote and initiate specific efforts to fill these gaps. In particular, we will identify critical datasets needed and define the much needed model protocols (including transient simulations).

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