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CLIMATE RECONSTRUCTION AND IMPACTS FROM THE ARCHIVES OF SOCIETIES

EDITORS
Chantal Camenisch, Sam White, Qing Pei, Heli Huhtamaa and Sarah Eggleston

PAGES

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News

6th Open Science Meeting and 4th Young Scientists Meeting
Due to COVID-19 disruptions, the OSM and YSM in May 2021 in Agadir, Morocco, have been postponed until May 2022. These are PAGES' premier events and provide an invaluable opportunity to bring the international past global change community together to share, discuss, learn, and plan for the future. For these reasons, it was decided to postpone the meetings to maximize the possibility of meeting in person. The Local Organizing Committee will keep an eye on developments and further announcements will be made in 2021: pages-osm.org

PAGES celebrates its 30th anniversary
Since 1991, PAGES has been at the forefront of paleoscience research and collaboration, bringing together international scientists to study past changes in the Earth system in order to improve projections of future climate and environment, and inform strategies for sustainability. Part of our anniversary celebrations includes a special issue of the *Past Global Changes Magazine* which will be published mid-2021. Find out more: pastglobalchanges.org/2564

PAGES Early-Career Award
PAGES is pleased to announce the inaugural PAGES Early-Career Award (ECA) recipient is Dr Alicja Bonk. Alicja is an Assistant Professor at the Institute of Geography, University of Gdańsk, Poland. All details: pastglobalchanges.org/2622

Goodbye and welcome to SSC members
After six years serving the PAGES Scientific Steering Committee (SSC), as well as time spent on the Executive Committee (EXCOM), we say thank you and farewell to Darrell Kaufman and Blas Valero-Garcés at the end of 2020. We also extend our thanks and well wishes to Stella Alexandroff, who was the PAGES Early-Career Network (ECN) SSC representative for two years. In January 2021, we welcome five new SSC members: Aixue Hu, Keely Mills, Eugenia Ferrero, Pradeep Srivastava, and ECN representative Tamara Trofimova.

New working group
A new PAGES working group, DiverseK, has been accepted and activities will begin in earnest in the new year. DiverseK focuses on integrating diverse knowledge systems for environmental policy, and will be a network of environmental and social scientists working to develop recommendations for the most pressing environmental and social justice issues. Website pages will be available soon.

New endorsed groups
PAGES endorsed two new projects – the International Paleofire Network (IPN) and the H2020 Innovative Training Network on Deep icE corE Proxies to Infer past antarctiC climatE dynamics (DEEPICE). All details: pastglobalchanges.org/2592

PAGES and ECN webinars
Jack Williams explained the Neotoma Paleoecology Database in the third PAGES webinar, held in October 2020. The previous webinars were with LiPD and WDS-Paleo. Access all PAGES webinars on our YouTube channel: youtube.com/PastGlobalChanges

The ECN webinar cluster was very active this year, in English and Spanish, and covered topics such as how to successfully apply for academic jobs and grant funding, managing international collaborations, and personal research stories. Access all the ECN webinars on its YouTube channel: youtube.com/PAGESECN

Deadline for new working groups and workshop financial support
The next deadline to propose a new PAGES working group or to apply for financial support for a meeting, workshop or conference is 12 April 2021.
All details: pastglobalchanges.org/my-pages/introduction

Apply to be on our SSC
Nominations to join the PAGES Scientific Steering Committee (SSC) are due 2 April 2021. The term starts January 2022 and would run for three to six years.
All details: pastglobalchanges.org/about/structure/scientific-steering-committee/apply

Help us keep PAGES People Database up to date
Have you changed institutions or are you about to move? Would you prefer to receive an electronic copy rather than a hard copy of our magazine? You can update your account preferences easily here: pastglobalchanges.org/people/people-database/edit-your-profile. If you have access difficulties, we can help: pages@pages.unibe.ch

Upcoming issues of *Past Global Changes Magazine*
Our next two magazines are quite special. A magazine for teens is planned for the first quarter of 2021, followed by the 30th anniversary edition, as mentioned above. Although preparations are well underway, if you would like to contribute please contact our Science Officer: sarah.eggleston@pages.unibe.ch

Calendar

VICS: Moving forward by looking back
8-10 March 2021 – Aarhus, Denmark

CRIAS: State of the Art of Historical Climatology in International Perspective
19-20 March 2021 – Hong Kong

Due to COVID-19 disruptions, these events are not guaranteed to take place in person. Check for updates here: pastglobalchanges.org/calendar

Featured products

2k Network
Bronwen Konecky et al. published "The Iso2k database: a global compilation of paleo-$\delta^{18}O$ and δ^2H records to aid understanding of Common Era climate" in *Earth System Science Data*: pastglobalchanges.org/products/13111

DICE
The former working group DICE released *The Holocene* special issue "Holocene Dust Dynamics": pastglobalchanges.org/products/13056

Early-Career Network (ECN)
Tamara Trofimova et al. published the ECN's first peer-reviewed science article, "Fundamental questions and applications of sclerochronology: Community-defined research priorities" in *Estuarine, Coastal and Shelf Science*: pastglobalchanges.org/products/13112

Floods Working Group (FWG)
FWG released the Global and Planetary Change special issue "Pluridisciplinary analysis and multi-archive reconstruction of paleofloods", which contains 18 papers covering various regions: pastglobalchanges.org/products/13077

PlioVAR
Erin McClymont et al. published "Lessons from a high-CO_2 world: an ocean view from ~3 million years ago" in *Climate of the Past*: pastglobalchanges.org/products/13105

SISAL
Working group members published the data description paper "SISALv2: a comprehensive speleothem isotope database with multiple age–depth models" in *Earth System Science Data*: pastglobalchanges.org/products/13121

VICS
Working group members found evidence connecting an unexplained period of extreme cold in ancient Rome with a massive eruption of Alaska's Okmok volcano: pastglobalchanges.org/products/13076

Cover

In historical climatology, written records of weather observations or climate proxies play an important role. Written evidence comes from many contexts, for example from the administrative field or from the historiography of noble families or political entities. This book illumination of 1484/1485 from Bern, Switzerland, depicts chronicler Konrad Justinger, who was commissioned by the Council of Bern to write the city's history. Source: Bern, Burgerbibliothek, Mss.h.h.I.16, p. 41 – Diebold Schilling, Spiezer Chronik, https://e-codices.ch/en/list/one/bbb/Mss-hh-I0016

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Recent results and new perspectives in historical climatology: An overview

Chantal Camenisch[1], S. White[2], Q. Pei[3] and H. Huhtamaa[1]

This issue of the *Past Global Changes Magazine* presents the state of research in the field of historical climatology. Its articles examine different regions of the world and review innovative methodological approaches, recent scientific results, and analyses of new source materials.

Historical climatology applies the methods and insights of historical and climate science to human records, or the archives of societies. Weather descriptions and climate proxies found in these sources, such as data on plant or ice phenology, enable the reconstruction of past climates and weather as well as their historical societal impacts.

A strength of historical climatology is the recovery of precisely located and dated information on climate and weather before the modern instrumental record. In parts of China, this information extends back more than a millennium, while in Europe evidence becomes abundant from the Late Middle Ages onwards (since ca. 1400 CE). Historical climatology research also benefits from collaboration with paleoclimatologists and climate modelers.

This issue was created in connection with the PAGES working group Climate Reconstruction and Impacts from the Archives of Societies (CRIAS; pastglobalchanges.org/crias), which started its activities in 2018. CRIAS aims to develop best practices, international collaboration, and methodological innovation in the reconstruction of historical weather and climate and their societal impacts. To this purpose, CRIAS provides a hub for researchers from different continents and different disciplines to exchange perspectives, methods, and data.

This issue opens with a selection of articles presenting research results from recent years for different world regions. Kiss et al. (p. 36) examine Southern, Central, and Eastern Europe, while Camenisch et al. (p. 38) examine recent research in Northern and Western Europe, both focusing on climate reconstruction. Williamson and Pei (p. 40) present the rich historical climatology source materials of East and Southeast Asia, as well as typical methods for their analysis. Nash and Hannaford (p. 42) provide an overview of historical climatology on the African continent.

In the second part of this issue, we present methodological considerations, innovative results, and promising new source materials. White and Pei (p. 44) discuss the integration of quantitative and qualitative perspectives when assessing the impacts of past climates and extreme events on societies. Brown et al. (p. 46) demonstrate what traditional field names in England can tell us about the history of the environment and especially the history of flooding. Jusupović and Bauch (p. 48) deal with the potential of ancient Russian sources for historical climatology. Huhtamaa et al. (p. 50) discuss the combination of tithe and tree-ring data in Scandinavia, and Ouellet-Bernier and de Vernal (p. 52) present a climate reconstruction for the Labrador region of Canada from the 18th to mid-20th centuries. Two papers deal with fantastic and rich historical sources from Arab regions. The first by Meklach (p. 54) focuses on the Maghreb, and the second by Ott (p. 56) on the Middle East during the Mamluk era. Finally, Burgdorf (p. 58) presents a comprehensive database project on early instrumental measurements.

The range of perspectives and results in this issue demonstrate the importance of the archives of societies and analysis of these documents by historical climatologists for an interdisciplinary understanding of past global changes and their human dimensions.

AFFILIATIONS

[1]Oeschger Centre for Climate Change Research and Institute of History, Section of Economic, Social and Environmental History, University of Bern, Switzerland

[2]Department of History, Ohio State University, Columbus, USA

[3]Department of Social Sciences, Education University of Hong Kong, Hong Kong

CONTACT

Chantal Camenisch: chantal.camenisch@hist.unibe.ch

Figure 1: Ancient Observatory (古觀象臺) in Beijing, China. (Photo credit: Q. Pei.)

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Recent developments of historical climatology in Central, Eastern, and Southern Europe

Andrea Kiss[1], R. Brázdil[2], M. Barriendos[3], C. Camenisch[4] and S. Enzi[5]

Historical climatology is a rapidly developing interdisciplinary field in Central, Eastern, and Southern Europe, transforming qualitative weather-related descriptions as well as phenological and physical data from documentary sources to quantitative high-resolution climate reconstructions, thus allowing for the study of the impacts of climate variability on society.

Among paleoclimate proxies, the transformation of descriptive qualitative information and documentary evidence to quantitative data (see e.g. Pfister and Brázdil 1999) has provided the highest resolution information for the reconstruction of temperature, precipitation, and other weather-related extremes over the last 500 years. Even if the time period covered is often shorter than that of most climate proxies, reconstructions may cover every month of a year. To date, Central and Southern Europe hold the largest documentary-based flood and drought collections as well as the most comprehensive and longest (index-based) local-regional temperature and precipitation reconstructions, and have played a key role in investigations where all major regions of Europe were represented (e.g. Brázdil et al. 2018; Blöschl et al. 2020). As for timescale, the temporally densest (often daily) documentation is available from Central and Southern Europe for the last 200–300 years; monthly seasonal data can be gathered for the last 400–500 years. Occasionally, representative data may cover ca. 700–800 years; however, regarding weather-related extreme events, documentary evidence in certain areas of Southern Europe may cover a period over the last two millennia or more (Camuffo and Enzi 1996).

Southern Europe

In Southern Europe, the reconstruction of hydroclimatic extremes, i.e. droughts and floods, on a multi-centennial scale is currently a large focus within flood and drought databases, sometimes reaching back two millennia. Major source types applied are narratives (esp. chronicles), church and municipal legal and economic administrative documentation, and, to a lesser extent, private and official correspondence and newspapers. Most research is concentrated on the Iberian Peninsula and Italy.

Research on the Iberian Peninsula concentrates particularly on flood- and drought-severity reconstructions over the last ca. 700 years (e.g. Oliva et al. 2018; Barriendos et al. 2019). While early research mainly draws upon municipal legal and economic records, later research primarily focuses upon rogation ceremonies, a complex social demonstration of droughts systematically preserved in the administrative sources of municipal and ecclesiastical institutions. Despite significant results in Spain and Portugal, documentary evidence still holds immense further potential; to date, only around 4% of historical sources have been exploited by historical climate research.

From the Iberian Peninsula, continuous early instrumental measurement series date back to the mid-/late 18th century; Italy holds the earliest systematically measured daily series of temperature and precipitation dating back to 1654 and 1713, respectively. Except for a 500-year rainfall reconstruction of the Iberian Peninsula, mostly individual-local and no regional-scale temperature or precipitation index reconstructions exist in Southern Europe (Camuffo et al. 2010). Southeast Europe, apart from the grand collection of medieval Byzantine weather reports (e.g. Telelis 2008) and occasional individual publications, remains underrepresented in systematic research. Besides the reconstructions of hydroclimatic extremes, long-term socio-economic impacts of changing weather conditions and weather-related extremes, especially droughts, also play a rather important role in Southern Europe (e.g. Gil-Guirado et al. 2016).

Central Europe

Central Europe is perhaps the most intensively involved area in historical climatology research within Europe. With a few gaps, index-based reconstructions of temperature, precipitation, and/or weather-related extreme events (e.g. floods, droughts, and windstorms) are available from most parts of Central Europe for the last 500 years or millennium (e.g. Glaser 2013; Brázdil et al. 2016). This is the only area of Europe where a complete regional monthly-resolution (index-based) 500-year temperature reconstruction is available: the Central European reconstruction (Dobrovolný et al. 2010), developed within the framework of the Millennium project (2006-2010), was published together with its other results as a historical climatology special issue of the journal *Climatic Change* (vol. 101, 2010). The annual resolution spring-summer temperature over the last 400-500 years were also published from most countries of Central Europe including Switzerland, the Czech Republic, Germany, Austria, and Hungary, in some cases accompanied by precipitation reconstructions. These were based on systematic daily resolution information on vine and grain phenophasis dates, such as blossoming, ripening, and grain and grape harvesting.

In Central Europe, from the Middle Ages onwards, the key source types applied are narratives (e.g. annals, chronicles, and diaries), official and private correspondence including newspapers, and partly systematic economic and legal administrative documentation (municipal accounts, council minutes, charters, accounts, and taxation records). Except for those countries with systematic historical climate research, such as the Czech Republic, Switzerland, and Germany, the latter two source types, together with specialized agricultural, weather and phenological diaries, and early instrumental records (from the early/mid-18th century) and daily weather observations, are

Figure 1: Examples of types of sources applied in reconstructions. For details, see the online version of this article.

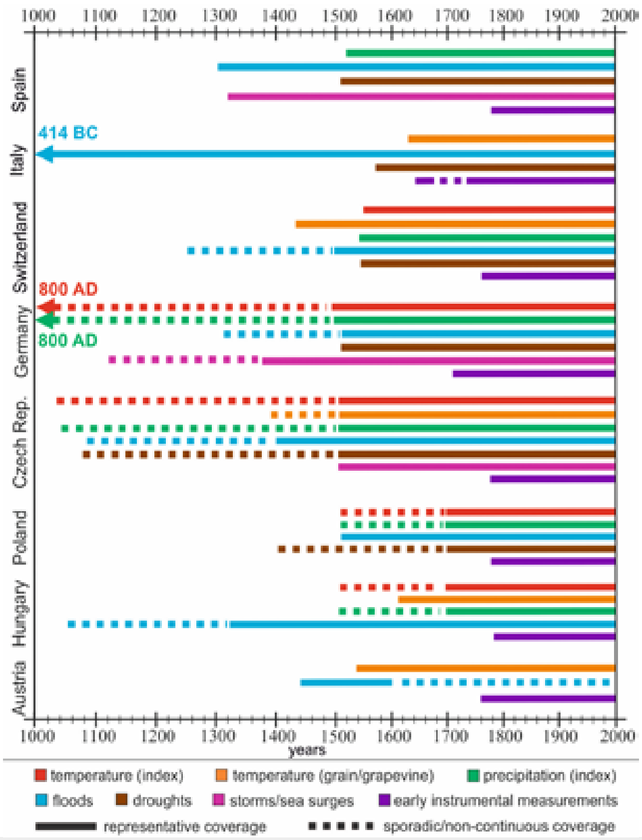

Figure 2: Long-term documentary-based flood, drought, storm, and monthly or seasonal temperature and precipitation reconstructions and grain- or grapevine-based temperature reconstruction series in Central, Southern, and Eastern Europe by country.

still to a large extent unexplored, and hold immense potential for further high-resolution multi-centennial reconstructions in the rest of Central Europe.

A further important research area is historical impact analysis of individual catastrophic weather and hydroclimatic events, anomalous periods, or long-term interactions and processes (e.g. Camenisch et al. 2016). In recent years, the attribution of major food shortages in historical times to severe weather conditions, as well as the climatic and socio-economic impacts of major volcanic eruptions in Central Europe, particularly the Tambora eruption and the Year Without a Summer, in 1816, have attracted further attention (e.g. Luterbacher and Pfister 2015).

Eastern Europe

In Eastern Europe, including Russia, the Baltic countries, Belarus, Ukraine, and Moldova, climate-history research is currently based on narrative sources, in particular chronicles and annals. Temperature, precipitation, and extreme-event reconstructions, derived from data in the major northern Russian chronicles and annals that cover most parts of the last millennium, have been carried out by Borisenkov and Pasetskiy (2002). This work has been criticized by some for the source interpretation methods used. The medieval part of this work was updated and summarized by Klimenko and Solomina (2010) in a volume discussing the historical climatology of the Polish-Lithuanian Commonwealth.

Early instrumental measurements and professional daily observations extending back to at least the mid-18th century have only been partially explored. No investigations have been carried out, so far, using other source types such as systematic legal administrative documentation, or economic sources such as accounts at the municipal, estate, district, regional, and country level; this documentation still holds great potential in Eastern Europe.

Recent highlights

While in previous decades, long-term temperature and precipitation reconstructions and early instrumental measurements were the main priority, in recent years, individual extremes and the long-term reconstruction of hydroclimatic extremes have received greater attention. Aside from individual flood and drought reconstruction papers, European and global-scale special issues on historical floods ("Floods and their changes in historical times" in *Hydrology and Earth System Sciences*: 2015-2016) and droughts ("Droughts over centuries" in *Climate of the Past*: 2019-2020, "Societal impacts of historical droughts" in *Regional Environmental Change*: 2019-2020) contain dozens of studies with new, multi-centennial reconstructions, particularly from Central and Southern Europe. Furthermore, with particular attention paid to Central and Southern Europe, regional and continental-scale online databases have been developed in the last decade(s) and opened for public use in recent years (e.g. Euro-Climhist, Tambora).

A research direction that is rapidly growing in importance is climate history that deals with the impacts of weather and weather-related extremes on the human environment, human responses on these impacts and consequent socio-economic processes, and the short- and long-term socio-economic consequences of climate variability including the complex interaction between climate and the human environment. Beyond the early modern case studies focussing on regional or European climatic extremes, there is currently a strong emphasis on the impacts of weather in anomalous periods of the (late) Middle Ages, the Late Medieval-early modern Period, and the transition from the Medieval Warm Period to the Little Ice Age, with special emphasis on Southern and Central Europe (e.g. Kiss and Pribyl 2020).

Despite intensive work over the last three decades, historical climatology and climate history are still developing fields with great further potential as, to a regionally varying extent, a large part of the documentary evidence is not yet explored. This is particularly true for Eastern and Southeast Europe, but even most areas of Central and Southern Europe still offer numerous further possibilities for future historical climatological research.

AFFILIATIONS

[1]Institute of Hydrology and Water Resources Management, Vienna University of Technology, Austria

[2]Institute of Geography, Masaryk University; Global Change Research Institute, Czech Academy of Sciences, Brno, Czech Republic

[3]Department of History and Archaeology, University of Barcelona, Spain

[4]Oeschger Centre for Climate Change Research, Department of Economic, Social and Environmental History, University of Bern, Switzerland

[5]Institute of Atmospheric Sciences and Climate, National Research Council of Italy, Padova, Italy

CONTACT

Andrea Kiss: kiss@hydro.tuwien.ac.at

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Historical climatology in Western and Northern Europe: State-of-the-art, typical documentary data and methods

Chantal Camenisch[1], H. Huhtamaa[1], N. Maughan[2] and C. Rohr[1]

Recent studies reconstructing past climates in Northern and Western Europe have employed innovative uses of natural archives and documentary data. Documentary climate proxies include plant and ice phenological data, weather-related descriptions in chronicles, newspapers, and administrative records, as well as early weather diaries and instrumental records.

Modern historical climatology as a scientific discipline has its beginnings in Western and Northern Europe. Pioneering reconstructions by Hubert H. Lamb, Emmanuel Le Roy Ladurie, and a generation later by Pierre Alexandre, Astrid Ogilvie, and Andres Tarand, focus on these regions. In the following decades, scientists have continued to be productive in studying and analyzing past climate in this part of the world. Here, we discuss the most recent climate reconstructions (since 2014) from the field of historical climatology, together with a brief overview of the most commonly used sources and methods.

France

Among the most recent reconstructions of the climate of France or parts of modern France, the work of Laurent Litzenburger (2015) deserves special mention. Litzenburger reconstructed seasonal temperature and precipitation indices for the Lorraine region as well as several extreme weather events and their impacts on society from 1400 to 1530. For this purpose, Litzenburger examined a large corpus of historical documents such as narrative sources with weather descriptions, but also plant-phenological proxies. Thomas Labbé et al. (2019) published another important summer temperature reconstruction based on grapevine phenology in Beaune from 1354 to 2018. The authors used a series of data covering 664 years to determine the beginning of the grape harvest using wage payments, newspapers, and the deliberations of a church chapter and the city council (picture of medieval grape harvest, Fig. 1). The grape harvest dates were homogenized and then calibrated and verified with a long series of early instrumental measurements from Paris. Pichard and Roucaute (2014) published a history of hydrology and flooding in the Rhone valley over the last 700 years.

Several specific extreme weather conditions and weather-related disasters have attracted attention in France in recent years. These include historical droughts, a topic which was addressed in a 2020 special issue of *Regional Environmental Change* edited by Nicolas Maughan et al. Alexis Metzger and Nicolas Jacob-Rousseau (2020) examined the 1857–1858 drought in Alsace. The authors combined narrative texts, such as letters and reports from municipal officials,

Figure 1: Grape harvest in Northern Italy in October, by Maestro Vencelsao. This fresco, painted around 1400, is located in the Eagle Tower of the Buonconsiglio Castle in Trento, Italy.
Source: https://commons.wikimedia.org/w/index.php?curid=6435756

farmers, and industries, with instrumental data derived from local rainfall stations. In Emmanuel Garnier's (2019) comparative analysis of droughts over the past 500 years from the Île-de-France, the UK, and the Upper Rhine Valley, documentary data form the backbone of the earlier part of the reconstruction. Garnier mainly uses diaries and municipal chronicles, but he stressed that historians must include all kinds of sources in their analysis. Garnier also recently reconstructed French floods and storms for case studies (Garnier et al. 2018).

The Benelux countries

One of the most comprehensive reconstructions of the last two millennia concerns the climate in Belgium and neighboring regions, with the first of several volumes published in Dutch in 1995 by Jan Buisman. The numerous and varied documentary data used for this reconstruction range from a large number of narrative sources to climate proxies and early instrumental measurements. Aryan van Engelen has transformed the text collection into semi-annual climate indices.

A number of reconstructions with a narrower focus have also been published in recent years, including a seasonal temperature and precipitation reconstruction of the 15th century by Chantal Camenisch (2015), which is based mainly on narrative sources and uses climate indices. Adriaan de Kraker (2017) applied a different approach for a reconstruction of the ice cover on Belgian canals in the period from 1330 to 1800. The author analyzed the costs for the laborers who removed the ice to enable shipping traffic on the canals, which were duly recorded in the city accounts. Alexis Metzger and Martine Tabeaud (2017) focused on winter weather conditions in a weather diary of Friesland. They analyzed temperatures and severity by comparing the duration of the wintry weather from 1594 to 1612, and by counting days of frost, rain, or snowfall in the same period.

The British Isles

Historical climatologists have also published reconstructions covering the British Isles in recent years. Kathleen Pribyl (2017) reconstructed temperatures and precipitation in Norfolk from 1256 to 1448 by analyzing grain harvest dates in medieval account books and other documentary data. Pribyl calibrated the medieval grain harvest dates with harvest dates from the 18th and 19th centuries, and with measured temperature and precipitation series. Two papers on droughts and their impact on society based on historical precipitation records from areas of the British Isles (Harvey-Fishenden et al. 2019; Murphy et al. 2020) are available, and a database called TEMPEST, on extreme weather events in the UK, is currently in progress (e.g. Veale et al. 2017).

Scandinavia and the Baltic states

The Nordic and Baltic states have a long tradition of employing ice phenological observations, such as the dates of freezing and ice breakup in harbors, rivers, and lakes. Such studies have used ice data from the ports of Stockholm, Tallinn, and Riga (Fig. 2), in addition to various stations from the German Baltic coast, although all of these studies were published prior to 2015. A recent addition to the historical ice-breakup observations from the region is a series (1749–2018) from Aura River in Turku, southwest Finland (Norrgård and Helama 2019). This series, like the earlier ice-breakup data, demonstrates strong correlation between the breakup dates and late-winter/spring temperatures. Besides temperature-sensitive written source materials, Dag Retsö and Lotta Leijonhufvud (2020) have compiled a dataset on Swedish historical droughts (1400–1800) from various documentary evidence.

Figure 2: Riga and its harbor, by Adam Olearius, 1727. This map is one of the objects being investigated to provide new insights into past climate. ETH-Bibliothek Zürich, Alte und Seltene Drucke. Source: https://doi.org/10.7890/ethz-a-000501220

Evaluation of the sources and methods

During the past years, historical climatologists in Western and Northern Europe have examined a large variety of documentary sources. Where available, notes of early instrumental measurement and weather diaries provide very detailed information useful for the calibration of other series. As several examples show, newspapers are also rich sources of data for historical climatology. For the period prior to these measurements, narrative sources, as well as account books and minutes of official and municipal institutions, provide a plethora of data for climate reconstructions. Such sources contain weather-related descriptions or plant or ice phenological information that can serve as proxies for climate variables. The examples of grape harvest dates in Beaune and canal freezing dates in the Netherlands and Belgium demonstrate the potential of such sources. Depending on the types of information derived from the documentary data, studies may either create indices or directly reconstruct meteorological conditions by applying calibration and verification processes.

AFFILIATIONS

[1]Oeschger Centre for Climate Change Research and Institute of History, Section of Economic, Social and Environmental History, University of Bern, Switzerland

[2]Pythéas Institute - Earth sciences and astronomy observatory, Foundation A*MIDEX, Aix-Marseille University, France

CONTACT

Chantal Camenisch: chantal.camenisch@hist.unibe.ch

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Archives of societies and historical climatology in East and Southeast Asia

Fiona Williamson[1] and Qing Pei[2]

Major sources of social archives for paleoclimatology in East and Southeast Asia include ancient annals and chronicles, instrumental records from government, military or missionary bodies, and private records such as diaries. Records are rich but scattered and of inconsistent quality, often requiring different forms of cross-validation and homogenization from those in the Western world.

The source materials and methods that inform investigative studies of past climates can be broadly distinguished into two groups: historical climatology, which relies on the archives of societies, and paleoclimatology, which draws from the archives of nature (Brönnimann et al. 2018). While many studies often utilize evidence of both types, the archives themselves remain distinct. The archives of society are a "unit of information coded by humans which refers to weather and climate, usually from the viewpoint of individuals" (Pfister 2018). As Pfister notes, these records can be broadly categorized into three areas: instrumental weather observations, narrative accounts of weather, and human observations of climate proxies. Studies of these archives have taken several forms, such as the recovery of observational data, the correlation of extreme weather events or longer-term periods of unusual highs or lows with human activities, and reconstructive analysis based on combinations of documentary and paleoproxy data.

Sources

In East Asia, such sources of historical climate information take various forms. South Korea, for instance, has detailed narrative records of unusual or extreme weather contained in the 1st century BCE manuscripts *History of the Three Kingdoms* and *Memorabilia of the Three Kingdoms* and, later, the *Annals of the Joseon Dynasty* (1392–1897) (Chun et al. 2013). In China, too, a wealth of ancient chronicles and literature also survive, documenting both climatic conditions and natural disasters. The classical *Twenty-Four Histories* (二十四史), for example, provide a major social archive for Chinese scholars (Zhang 2004). Such archives exist because of emperors' interest in the "Mandate of Heaven" (Pei and Forêt 2018), whereby unusually bad weather or strange phenomenon could be considered the result of a ruler's failures.

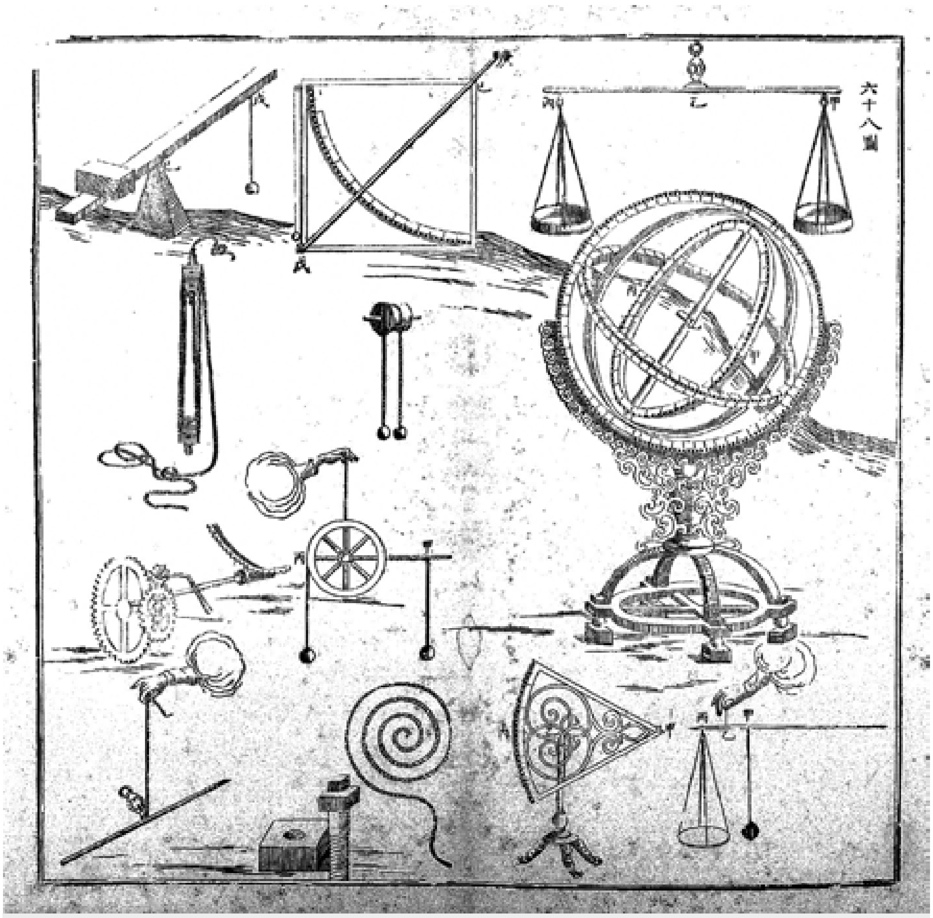

Figure 1: Illustrations of astronomical instruments, Beijing, China, by the Belgian Jesuit missionary Ferdinand Verbiest (1623–1688). Source: https://wellcomecollection.org/works/ukc9nmta

Agriculture was critically important to these ancient societies. Thus, provincial and central government records charted severe cold, frost, snow, drought, and flood events that might impact harvests, as well as incidents such as natural disasters, plagues, and famines (Zhang 2004). Due to their proclivity for extreme weather, Japan, China, and Korea were all early developers of rain- and snow-gauge technologies and in observing and keeping records of nature, such as blossoming seasons (Aono and Saito 2010). The Chinese Qing dynasty Yu-Xue-Fen-Cun (雨雪分寸) records of rain and snow (YXFC records) document how deeply rain and snow penetrated the soil (Fig. 1). Phenological records of oriental migratory locust swarms have also been reconstructed as an indicator of climate change (Huang et al. 2019). In the towns and ports of Japan and China, such as Nagasaki, Xiamen, and Beijing, meteorological records were also made by visiting traders, doctors, and missionaries and by military officials stationed at colonial outposts from the early-modern period into the early 19th century (Demarée et al. 2013).

By the late 19th century, abundant records were made across newly formed meteorological networks of registering stations and observatories, for example the China Coast Meteorological Register compiled from observations made by the China Coast Customs Service which had its headquarters in Shanghai (Fig. 2).

These records are available in sources such as government gazettes, official communications, and newspapers. Many of these are now being recovered under the aegis of major data recovery projects (ACRE: Allan et al. 2011; REACHES: Wang et al. 2018). Personal diaries and church records are also being recovered (Mikami 2008).

Southeast Asia is more reliant on the archives of nature than of society for the pre-modern period, but some records exist. Again, these take the form of ancient chronicles that chart periods of severe droughts or floods that disrupted society, such as those available from the 14th century in Burma, Cambodia, and Dai Viet (Buckley et al. 2014). For the rest of Southeast Asia, the colonial

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Figure 2: Custom House and German-Asiatic Bank, Bund, Shanghai, May 1911. Source: https://www.hpcbristol.net/visual/bl02-024

period tends to hold the best documentation on past climates, with a wealth of climate data collated by the colonial French, British, Dutch, Spanish, Japanese, and American governments. From early medical topographies that noted aspects of the climate as they related to health, to private diaries and military records, these sources became increasingly sophisticated by the end of the 19th century as meteorological science became more standardized and regulated globally.

Comments

Studies undertaken for East and Southeast Asia have tended to focus on two main areas with the bulk of research undertaken in China and later Japan: first, the correlation of climatic events with changes to human societies, for example through natural disaster or prolonged climatic instability, resulting in famine, death, warfare, or regime changes; and second, the reconstruction of climate dynamics or particular events, such as El Niño or typhoons (Kubota and Chan 2009). Chinese scholars are better known for studies extending over centuries and even millennia, whereas in Japan – although Chinese recording systems had a large influence historically – scholars have had a different focus, exploring more recent climates and explaining past variations from the perspective of explaining teleconnections and climate dynamics.

Of course, there are inherent problems in using these early records. In China, the ancient records usually entailed general patterns of phenomena or events, a recording style that translates as "Generalize Details and Absorb Them". Descriptions were qualitative rather than quantitative, for instance: big (大), medium (中), or small (小). Even the considerably more systematic Qing YXFC records contain inconsistencies, as external influences, such as the abilities of the recorder or administrative differences across regions, all impinge on their accuracy (Pei and Forêt 2018).

Even the supposedly standardized instrumental observations of the later 19th century are not without criticism. In Singapore and Malaysia, even contemporaries critiqued the pre-1920s records, blaming poorly trained staff and a lack of resources.

Cross validation of statistics and data homogenization methods are used to combat these issues (Gao et al. 2018). Current paleoclimate reconstructions based on Chinese records are typically interpreted using a five-point series following the Semantic Differential Method (Zhang 2004). Japanese scholars have used the Standard Normal Homogeneity test, the Buishand Range test, and the Pettitt test (Zaiki et al. 2006). Studies reliant on ancient chronicles may also combine the historical narratives with paleoproxy data (Buckley et al. 2014).

In spite of inaccuracies, however, reconstructions based on social archives still have the potential to span millennia and allow for amazing insights into past climates. Because studies using archives of societies for this region are significantly different from their European counterparts, the use of such archives are still gaining momentum in research and continuing to enrich the application of social archives in paleoclimatology.

AFFILIATIONS

[1]School of Social Sciences, Singapore Management University, Singapore

[2]Department of Social Sciences, Education University of Hong Kong, Hong Kong

CONTACT

Fiona Clare Williamson: fwilliamson@smu.edu.sg

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Historical climatology in Africa: A state of the art

David J. Nash[1,2] and Matthew J. Hannaford[3]

Collections of written materials from the 16th century onwards have been used to explore the historical climatology of Africa. Studies include decadal- to seasonal-scale reconstructions of past rainfall and temperature, and analyses of societal responses to historical extreme events.

Rainfall reconstructions (1500–1800)

Relative to the wealth of documentary evidence available for Eurasia, there are comparatively few collections of written materials through which to explore the historical climatology of Africa. Documents containing "climate knowledge" for periods prior to the 19th century focus on the Sahel, coastal West Africa, and pockets of southern Africa. Except for small numbers of diaries and naval accounts, few sources contain systematic weather records. Instead, entries comprise references to extreme events and generic descriptions of climates and landscapes. Information about extreme events is of most use for climate reconstruction, which is limited during these centuries to the identification of seasonal or decadal wetness and climate-related events such as locust outbreaks.

Nicholson (1978) produced centennial-scale timeseries of drought and famine for the Sahel using chronicles from Timbuktu, Bornu, Walat, and Tichitt. These chronologies identify climatic "periods" and suggest that wetter conditions interspersed by droughts prevailed from the 16th through 18th centuries, before a trend towards drier conditions began in the late 18th century. Adopting a similar approach, Norrgård (2015) produced an interdecadal-scale wetness series for coastal West Africa (from Ghana to Benin) during the late 18th century. Like the Sahel chronologies, this reconstruction suggests abrupt changes in rainfall during the 1780s (wetter) and 1790s (drier). Miller (1982) used Portuguese colonial records to produce a chronology of wetness, locusts, and epidemics for modern-day Angola from 1560 to 1830. Intense droughts were found to be present during the 1580s, 1650s, and 1790s. However, caution must be applied to parts of this chronology, since references to warfare are sometimes included as indirect evidence for drought (due to the frequent coincidence of drought and conflict). Less material exists for Mozambique than Angola, but documents are available for most decades following Portuguese settlement in 1505. A chronology of extreme events shows pronounced droughts during the late 16th century, few droughts in the 17th century, and particularly severe droughts in the 1790s and 1820s (Hannaford 2018).

Climate reconstructions (1800–1900)

The quantity of sources available for climate reconstruction in Africa during the 19th century is much greater than for earlier periods. This is mainly attributable to the expansion of European colonial activity across the continent from the late 18th century onwards. Records include colonial and missionary papers, newspapers, travelogs, personal diaries, and letter collections. Most climate information in these sources is in the form of narrative descriptions but, beginning in the 1850s, selected newspapers also included instrumental meteorological data.

Figure 1: Excerpt of a letter dated 17 February 1868, written by the missionary Rev. A. Chiswell at present-day Toamasina, showing contemporary settlements along the east coast of Madagascar. (Source: Oxford, Bodleian Libraries, United Society for the Propagation of the Gospel Papers D38.)

Information from these materials has been used to generate continent-wide and regional rainfall reconstructions based on classifications of "wetness". The main continental series (Nicholson et al. 2012) combines documentary evidence, rain-gauge data, and secondary literature – mostly relating to sites within 500 km of the coast – to explore spatio-temporal variations in historical rainfall. The most striking feature of the reconstruction is the tendency for increased aridity in the opening decades of the 19th century. A notable period of above-normal rainfall is identified in the Sahel in the 1880s and early 1890s, but drier conditions commenced elsewhere around 1880.

The greatest numbers of regional rainfall reconstructions are available for southern Africa. Some, such as Hannaford et al. (2015), use wind data digitized from ships' logbooks to capture regional atmospheric circulation and produce quantitative chronologies. Others rely mainly on narrative evidence within historical sources (Fig. 1). These include chronologies for the Kalahari, Lesotho, South Africa (including the Western and Eastern Cape, Namaqualand and KwaZulu-Natal; see Nash 2017 for sources), Malawi (Nash et al. 2018), and Namibia (Grab and Zumthurm 2018). Most studies reconstruct annual rainfall only, but where information density permits, seasonal reconstructions have been attempted. Recent work on the historical climatology of the Cape has produced a daily surface-pressure series from 1834 onwards from early instrumental records (Picas et al. 2019).

A compilation of annually resolved rainfall series for mainland southern Africa for the period 1850–1900 is shown in Figure 2. This includes seven series based on documentary evidence, three regional series from Nicholson et al. (2012) and, for comparison, a tree-ring-width-based rainfall reconstruction for western Zimbabwe (Therrell et al. 2006). All are for areas that receive most rainfall during the austral summer months (October–March). The compilation shows that relative rainfall levels were geographically variable across southern Africa. However, droughts that affected large areas can be identified (e.g. ~1850, early to mid-1860s, late 1870s, early to mid-1880s and mid- to late 1890s), in addition to a smaller number of coherent wetter years (e.g. 1863–1864 and 1890–1891). Multiproxy analyses indicate that the early to

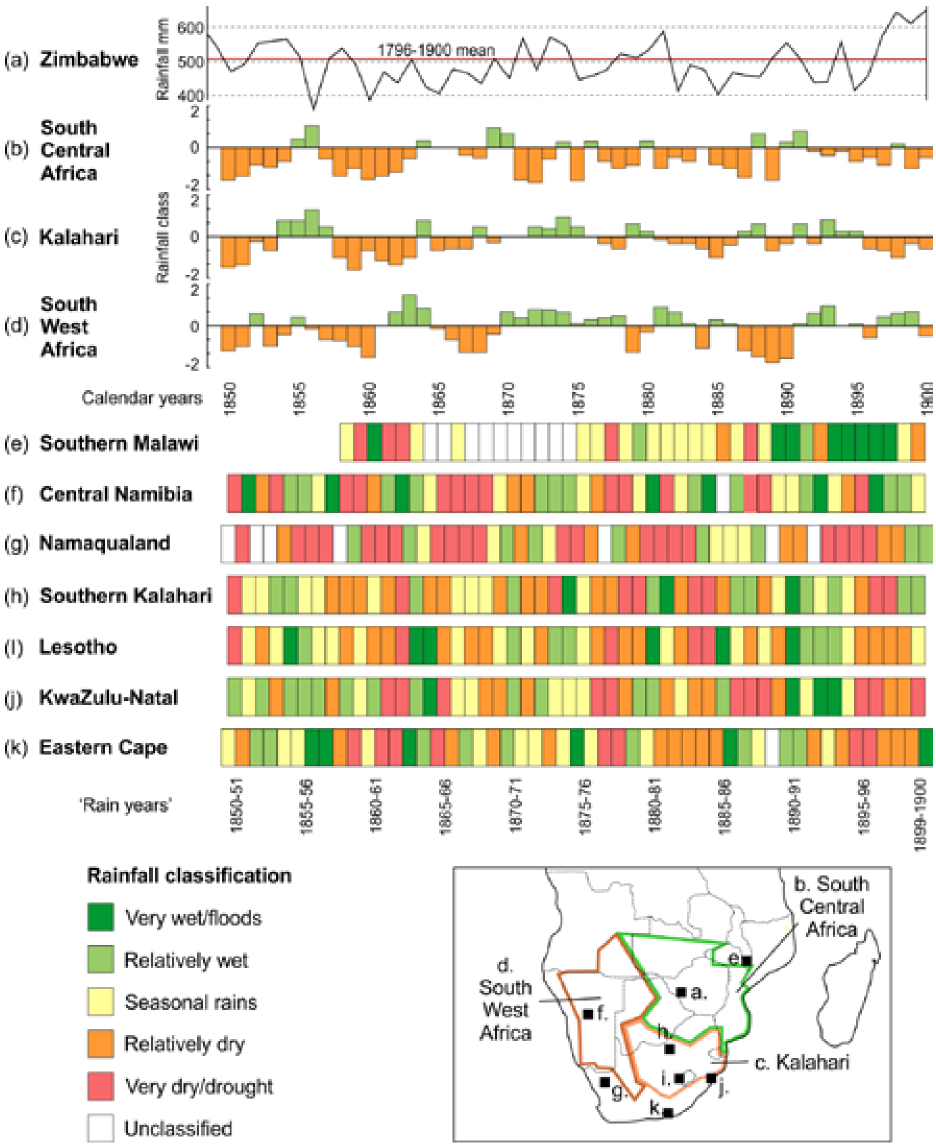

Figure 2: Annually resolved rainfall reconstructions for southern Africa during the period 1850–1900 (for more details, see the online version of this article).

mid-1860s' drought was the most severe of the 19th century, and that of the mid- to late 1890s the most protracted (see Nash 2017).

To date, the only study exploring historical temperature variations is a chronology of cold season variability for Lesotho (Grab and Nash 2010). This reveals more severe and snow-rich cold seasons during the early to mid-19th century (1833–1854) compared with the latter half of the 19th century. A reduction in the duration of the frost season by over 20 days during the 19th century is also identified.

Climate impacts and perceptions

The climate reconstructions described above provide important baselines from which to consider climate impacts, exploration of which has largely taken place within the disciplines of economic and social history. Perhaps the best documented impact of climate on society is on agricultural production. Historical studies of drought-related famine and its societal effects are reasonably widespread, with most research focusing on the 19th century and some longer-term studies back to the 16th century. Increasing use has been made of vulnerability frameworks, which consider a multitude of socio-environmental factors (including the characteristics of agro-ecosystems, diversity of human livelihoods, and level of societal organization) that shape the consequences of climatic impacts. Such approaches have demonstrated that while "material" factors such as crop diversity were important in reducing sensitivity to drought in the lower Zambezi area of southeast Africa, institutional rigidity or adaptability were the principal determinants of societal vulnerability in the long run (Hannaford 2018). The introduction of American crops, especially drought-intolerant maize, is also thought to have impacted upon food security, with implications for population growth, drought exposure, and famine vulnerability.

In relation to conflict, the period of state formation in eastern South Africa during the 18th and 19th centuries has been linked to drought-intensified competition over cattle and grazing land, in turn generating conflict and the organization of societies into defensive states (Hannaford and Nash 2016). Africa has largely been absent in pre-20th-century quantitative studies on climate and conflict, but quantitative approaches have argued that increases in slave exports during the 19th century were a result of increased temperatures in slave-exporting areas of Africa that reduced agricultural productivity (Fenske and Kala 2015).

The influences of climate on health and disease have been explored through the lens of European perceptions of African climates, who saw them as unhealthy and disease ridden, with most of the literature focused on the late 18th and 19th centuries. Some literature has explored linkages between climate and epidemics (e.g. Eldredge 1987), usually situating drought as a driver of malnutrition or contaminated water supplies, which in turn increased susceptibility to infectious diseases.

Future work

Despite the advances in African historical climatology reported here, there is still scope for future climate reconstruction work. Nicholson et al. (2012), for example, identified major spatial gaps for equatorial and arid regions of Africa. Finding documentary evidence to address these gaps may be challenging, although large collections of available primary materials may help for western and eastern Africa. By exploring links to cognate subdisciplines such as historical archaeology, future research may better contextualize climate impact analyses. Finally, there is considerable potential for using documentary sources in different regions to explore spatial variations in the signatures of global phenomena, such as El Niño, or for specific time periods such as the end of the Little Ice Age.

AFFILIATIONS

[1]School of Environment and Technology, University of Brighton, UK

[2]School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, South Africa

[3]School of Geography and Lincoln Centre for Water and Planetary Health, University of Lincoln, UK

CONTACT

David J. Nash: d.j.nash@brighton.ac.uk

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Attribution of historical societal impacts and adaptations to climate and extreme events: Integrating quantitative and qualitative perspectives

Sam White[1] and Qing Pei[2]

In this article, we identify conceptual barriers, particularly regarding causation, that divide quantitative and qualitative research relating past climate and extreme events to historical societal impacts and adaptions, and we propose solutions for better integrated research.

Discussions of societal impacts of climate and extreme events, including conflict and migration, draw on history for comparisons and insights (e.g. Adger et al. 2014). However, relevant historical research has been divided between divergent quantitative and qualitative methods and perspectives, particularly regarding causation.

Quantitative vs. qualitative perspectives

The quantitative studies in this field have come primarily from social scientists working with historical and climate datasets. Employing mainly regression methods such as Granger causality, authors have identified strong statistical associations between climate and weather phenomena and potential societal consequences over past centuries, including conflict and migration (e.g. Pei et al. 2018). Associations are typically made at multidecadal timescales over large regions, but can be at smaller scales if data coverage is adequate. These studies use five principal criteria for causation: (1) historical rationale for the statistical association; (2) strong relationship between the variables; (3) consistency in the relation between the causal variable and effect; (4) timing: the cause must precede the effect; and (5) strong predictive power of the causal variable (Zhang et al. 2011).

Qualitative studies have come primarily from historians, some in the form of monographs (e.g. White 2011), and others as multi-authored articles (e.g. Camenisch et al. 2016). The latter often involve natural scientists but less often social scientists carrying out the quantitative work described above. Most qualitative studies have focused on impacts and adaptation in individual countries and/or periods, drawing on historical and archaeological records in combination with paleoclimate and historical climatology information. Causation is primarily inferred from contemporary attribution, reasoning from actors' motives, identification of underlying causal mechanisms, and historical comparisons (i.e. methods of similarity and difference).

These contrasting approaches have produced mutual criticisms. Reviews by mainly qualitative scholars have faulted quantitative studies for uncritical use of data with uneven temporal and spatial coverage; arbitrary scales of analysis; little consideration of historical and cultural context; and deterministic causal analysis lacking adequate theory (e.g. Degroot 2018; van Bavel et al. 2019). Quantitative scholars have maintained that climate, in conjunction with subsistence pressures, operated as a root cause of impacts at a macro level, leaving room for contingency and agency and for variable triggers and outcomes in individual episodes; therefore, macro quantitative studies reveal valid underlying causal forces absent in micro or qualitative research (Lee 2020).

These criticisms appear representative of issues arising when the "two cultures" of qualitative and quantitative scholarship approach the same topic from different perspectives. Rather than providing conflicting answers to the same questions, they may answer distinct questions using different concepts. By applying up-to-date methodology and philosophy, scholars can find common ground for collaboration (Goertz and Mahoney 2012).

Key insights for integrated research

A first key insight is the pragmatic and contrastive nature of most causal explanation. Contemporary philosophical studies recognize science and humanities explanations as answers to implicit or explicit "why" questions with contrast sets (van Fraassen 1980). These contrasts are typically between units, conditions, or times. Thus, an explanation for the French Revolution of 1789 may take the form of causes for a Revolution *in France* (rather than another political unit) in 1789, a French *Revolution* (rather than peaceful condition) in 1789, or a French Revolution *in 1789* (rather than another time). The context determines the salient contrast, and confusion about the causal question may render an explanation unhelpful or misleading even if factually correct (Ylikoski 2007).

In the case of historical climate attribution, quantitative studies may claim "climate caused conflict", while qualitative studies may examine the same phenomenon and conclude "climate did not cause conflict", and both may be correct within their respective contrast set. For instance, a quantitative study may explain the higher frequency of conflict *during one period rather than another* across many units, but it may *not* explain the presence of conflict *in certain units rather than others* at the same time. By specifying the contrast set in their explanations, both qualitative and quantitative studies can formulate more targeted and defensible claims. Statistical correlation between timing of a climate variable and migration volumes may be formulated as "temporal variations in climate caused temporal variations in migration" rather than "climate caused migration"; moreover, "climate caused conflict" in the quantitative studies should be interpreted as "worse climate caused more conflicts", which correctly matches the explanation in the statistical perspective.

Second, scholars in the field use two distinct approaches to causation: effect-of-cause analysis typical of macro quantitative studies and cause-of-effect analysis usually found in micro qualitative studies and historical monographs. Effect-of-cause analysis identifies statistical relationships between two

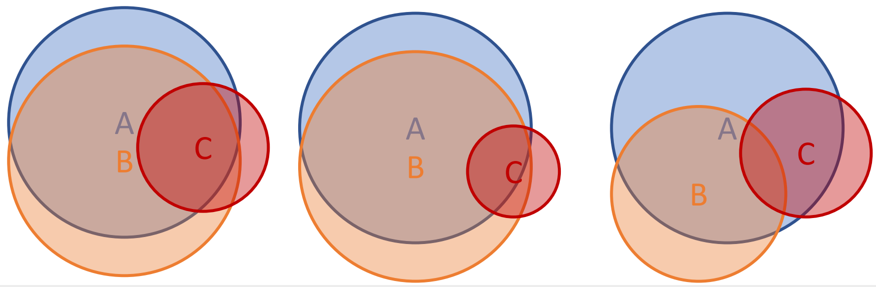

Figure 1: Schema representing frequency and co-occurrence of three INUS for historical famine, where A is vulnerable agriculture, B is inequality, and C extreme weather, and the overlap of all three indicates occurrence of famine. In typical pre-modern conditions (left), occurrence of C overlaps most with the outcome and may therefore be considered "the cause" of famines. Nevertheless, decreasing (increasing) the frequency of any INUS will decrease (increase) the frequency of the outcome (see middle and right). Thus studies concerned with climate impacts may focus on C as the causal variable, while studies concerned with economic policy may focus instead on B.

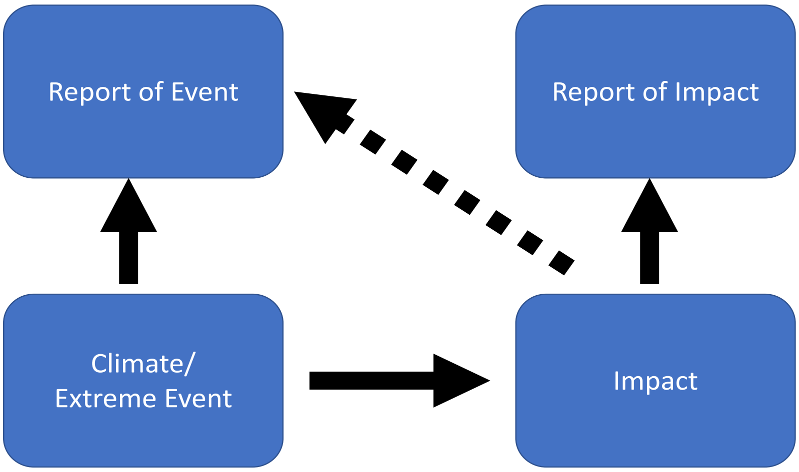

Figure 2: Example of biased reporting. In certain historical circumstances, extreme events were more likely to be reported when they produced impacts (dashed arrow) than when they did not, generating a positive bias in statistical associations.

variables in order to attribute control of one over the other. In historical climate attribution, studies may use regression or potential outcomes analysis to relate a climate or weather variable to the past frequency or magnitude of a quantifiable societal impact, and then interpret this relation in causal terms. Cause-of-effect analysis, on the other hand, identifies logical relationships of necessity and sufficiency – that is, whether some event or condition had to occur for, or was enough to bring about, a particular outcome (Goertz and Mahoney 2012). For historical climate attribution, this approach usually requires inferences derived from historical evidence, comparisons with like cases, and counterfactual reasoning about outcomes if climate had been different.

When quantitative studies identify control of a climate variable over a societal impact, the finding does not imply that climatic factors were necessary or sufficient for each instance of that impact. For example, a study may identify a large-scale statistical relationship between lower temperatures and the frequency of conflict and give this relationship a causal interpretation without implying that climatic change was the cause of any one particular conflict. The process tracing that may accompany such studies is illustrative rather than a complete or deterministic picture of causation in each instance (e.g. Zhang et al. 2011). Conversely, when qualitative studies identify a climatic factor as necessary or sufficient for a historical case of a societal impact, the finding does not imply that the climate variable regularly influenced that type of societal impact. For instance, a study may find that a particular drought was or was not the cause of a single historical migration without concluding that drought frequency or severity influenced migration volumes at larger scales. Thus, these two types of causal analysis are complementary rather than contradictory. When drawing lessons from history, effect-of-cause studies indicate typical past relationships between climate variables and impacts, whereas cause-of-effect studies may indicate causal mechanisms underlying those relationships and the necessary and sufficient conditions for those relationships to persist in the present or return in the future.

A third key insight is that historical outcomes depend on the co-occurrence of insufficient but necessary components of unnecessary but sufficient sets of conditions, or INUS (Mackie 1965). For instance, extreme weather, vulnerable agriculture, and social inequalities did not each cause famines alone, but combined (along with other background conditions) to produce famines on particular occasions. This raises a classic philosophical dilemma: which of these factors should be analyzed as "the cause" of those famines (Hart and Honoré 1985, pp. 36-37)? An intuitive approach is to identify the INUS condition most nearly necessary *and sufficient* for the outcome, as indicated by greatest predictive power over the outcome or occurrence that most nearly overlaps with the outcome (Mahoney et al. 2009). In the case of historical famines described above, the INUS selected as "the cause" will often be extreme weather, because its occurrence predicted the timing of famines better than vulnerable agriculture or inequalities, which were more constant. However, causal selection has unavoidable normative implications (Garfinkel 1981), and studies may emphasize the causation of other INUS conditions due to their policy or ethical relevance (Fig. 1). Historical climate attribution studies may address criticisms of insensitivity to policy or ethical issues by explicitly justifying analysis of climate as "the cause" and specifying the role of other INUS conditions.

These insights clarify when limited datasets are problematic for quantitative impact studies. Contrast set, scale, type of causation, and standard for causal selection determine whether gaps and inconsistencies invalidate causal inferences. In effect-of-cause analyses focused on temporal variations of impacts at large scales, statistically valid results may depend more on wide spatial and temporal coverage than on consistency within that coverage; or else studies may compensate for data inconsistencies by using statistical methods or by expanding the study area and duration. Nevertheless, it remains important that the scale of analysis be grounded first in theory and that the data are suitable for the chosen scale. Systematic biases in evidence can also invalidate causal inferences. In particular, studies based on statistical associations must establish that reporting of climate or weather events and their supposed impacts were truly independent of one another, a determination requiring knowledge of the underlying historical reporting and record-keeping processes (Fig. 2).

These considerations indicate possibilities to overcome conceptual barriers between quantitative and qualitative historical attribution research. Each approach has limitations, which may be partially compensated by better communication across studies and collaboration within studies. Publications could minimize confusion by specifying cause and effect contrast sets, distinct effect-of-cause and cause-of-effect inferences, justification for (not) analyzing climate or extreme events as the key causal variable, and grounds for the scale of analysis. Collaboration may capitalize on the division of labor between qualitative methods of inference from and about historical evidence and quantitative methods of modeling and statistical induction, as well as the complementary functions of effect-of-cause and cause-of-effect analysis, in order to achieve integrated evaluation of historical climate attribution suited to informing policy.

AFFILIATIONS
[1]Department of History, Ohio State University, Columbus, USA
[2]Department of Social Sciences, Education University of Hong Kong, Hong Kong

CONTACT
Sam White: white.2426@osu.edu

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Flood hazard assessment from alluvial sediments: Data from sedimentology to place names

Antony G. Brown[1,2], B. Pears[2], P. Toms[3], J. Carroll[4], J. Wood[3] and R. Jones[5]

Floods are a natural component of our environment, and are constantly changing due to both natural and human factors. However, they leave physical and societal evidence in sediments and place names.

An increase in late 20th- and 21st-century river floods in the UK and other parts of Europe, including France, Spain, Poland, and the Czech Republic, highlights the urgent need to better understand flood magnitudes and return frequencies across short (decadal to sub-centennial) to medium (centennial to millennial) timescales in order to prepare for future events. Key to generating robust predictive models is the ability to track, with greater precision and across greater expanses of time, the nature of past floods and to set these against the various climatic and anthropogenic factors that contributed to their occurrence. For the UK, the timeline for the formal recording of empirical observations revealing magnitude and reach of individual flood events is woefully short, rarely providing reliable data before the 17th century CE (Macdonald and Sangster 2017). Other evidence is needed to extend this record back through time. Since every flood leaves a physical signature of its passing, constructing chronostratigraphic models from alluvial sediments gives direct insight into fluvial activity potentially over millennia. Less obviously, we can draw upon the observations made by early medieval communities of river behaviors, initially communicated through, and now preserved within, the names they gave to riverside settlements.

Sedimentary histories

The use of fluvial sediments as flood archives has a long history. These are usually reconstructed in bedrock reaches where channel stability permits the cross-sectional area of floods to be calculated. This is more problematic in non-bedrock alluvial systems characteristic of lowland Britain and much of Europe. But where channels have stabilized, a flood archive is sometimes preserved in deep floodplain sediments. With advances in optically stimulated luminescence (OSL) dating, reliable to ±10% (1σ), these clastic sequences can be dated in the absence of organic material and, when analyzed using high-resolution proxies including X-ray fluorescence (XRF), provide insights into fluvial depositional conditions and flood events (Brown et al. 2013; Pears et al. 2020a; Pears et al. 2020b; Pears et al. in prep).

Recent research at Powick, Worcestershire, UK, at the Severn-Teme confluence (Pears et al. 2020b) demonstrates channel stabilization from ca. 3500 years before present followed by unabated vertical floodplain accretion from the Middle Iron Age onwards (ca. 300 BCE). The results show subtle variations in depositional character from the start of the medieval period, with a dramatic increase in fluvial activity from the 16th century CE. Similar chronologies and fluvial signatures at other sites across the Severn catchment demonstrate broad correspondences in depositional character (Brown et al. 2013; Pears et al. 2020a). These can be set against the historical climate record and potential contributory anthropogenic factors, including land-use change, agriculture, and embanking (Lewin 2013; Macklin et al. 2014).

At Kempsey (Fig. 1), south of Powick, a recently analyzed sediment sequence contains exceptionally well-preserved coarse flood laminations (Pears et al. in prep). These laminae can be correlated with relative confidence to historically attested major floods between ca. 1600 and ca. 1840 CE and to other unrecorded flood events (Macdonald and Sangster 2017). Tellingly, a correlation can be demonstrated between flood-rich periods and the two significant solar minima of this period, the Maunder Minimum (ca. 1645–ca. 1715 CE) and Dalton Minimum (ca. 1790–ca. 1830 CE), indicating solar activity as a potentially significant contributory factor in the behavior of the Severn. Critically, these laminae permit us to estimate the discharges of some of the largest recorded historic events. They also indicate that the return frequency of floods might vary significantly across time. The Severn's response to Maunder and Dalton differed. This has implications for understanding future flooding, particularly since it is predicted that we are entering the next Grand Solar Minimum.

Name histories

Many British river names tell us something about their general geomorphological and hydraulic characteristics. These include names which describe channel sinuosity and rates of flow (Fig. 2b). However, more specific and localized information is more often encountered in riverside settlement names. Place names originated as meaningful descriptions which arose in everyday speech or within administrative contexts. In England, most town and village names were formed between the 8th to 11th centuries CE in early varieties of English (Old English) and Scandinavian (Old Norse). They inform on the historic landscape, including riverine behavior (Jones 2016; Jones et al. 2017). Place names record types of watercourse (e.g. Southwell: "south spring"), water behavior (Averham: "[settlement] at the floods") and wetland areas (various settlements named Ham: "wetland, water-meadow"). Place names also record wetland-loving flora (Kersal: "cress nook"), fauna (Frostenden: "frog valley"), and suggestive geology (Slapton: "slippery place"). Names of riverine settlements relate to river form and topography. For example, names containing Old English hamm: "land hemmed in by water or marsh" (Gelling and Cole 2000) typically refer to locations in lower reaches within areas of shallow gradient and dominant river meanders. These sites are still subject to prolonged flooding with much of the floodplain underwater for extended periods (Gelling 1984). In contrast, names containing terms for "river crossings", Old English ford and Old Norse vath, are found where gradients become steeper, resulting in shallower river depth, and are often associated with weirs.

Landscape terms within place names were used with a high degree of specificity. Some speak directly of flooding. Old English wæsse, "land which floods and drains quickly" (Gelling and Cole 2000), is attached to key locations in the West Midlands where there is a distinctive change in floodplain morphology. It is found in Buildwas, where

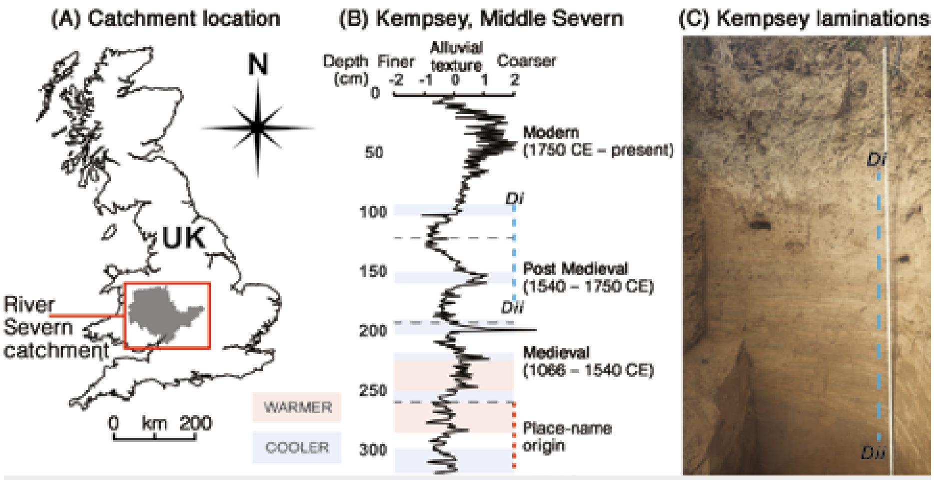

Figure 1: (A) Map showing the catchment area. **(B)** Sediment record from Kempsey (Middle Severn). **(C)** Visible sub-horizontal alluvial laminations between 0.6–1.4 m. For more details, see the online version of this article.

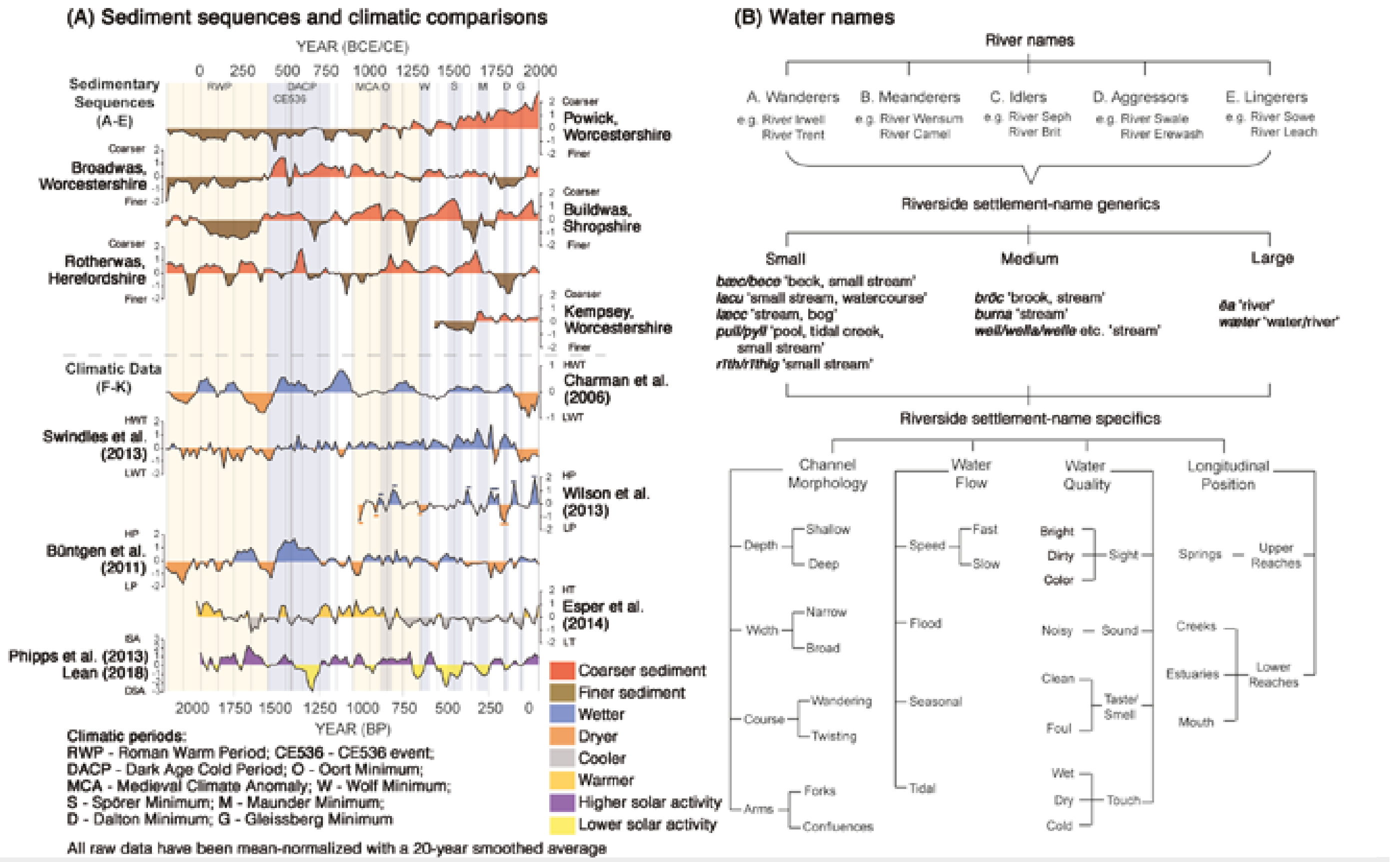

Figure 2: (A) Comparison of Severn-catchment decadal sediment deposition models modeled against upland peatland watertable depth and proxy wetter/drier conditions in the UK and Ireland; precipitation in Southern and Central England and Central Europe; Northern European temperatures and solar activity (Pears et al. 2020b). **(B)** Hydrological information relating to flowing water retained within river and place names (adapted from Jones 2016).

the Severn enters the Ironbridge Gorge, in Broadwas, at a distinctive widening on the Teme, and in Rotherwas on the Wye, as it meets the Lugg. Such names comment on historical riverine behaviors, and, when assessed with geoarchaeological evidence, the responses of inhabitants to those behaviors.

Place names and sedimentological analysis

Those who coined place names 1000 years ago knew that wæsse-sites flooded. Flooding remains a frequent occurrence in these locations. But what was the specific character of flooding in these places that merited the use of a special term, seemingly inappropriate for floodable areas elsewhere? Sedimentological analysis has revealed the fluvial characteristics of the rivers – the Severn, the Teme, and the Wye – at these locations from the Iron Age to the present day (Fig. 1). Consequently, it is possible to set this early medieval flood term against the contemporary physical record for flooding (Pears et al. 2020a).

Coarse alluvial sediments at Broadwas and Buildwas indicate that high-energy river deposition conditions characterized, albeit with some chronological variation, the period from the 5th to the 13th centuries CE. A more mixed picture emerges at Rotherwas where the Wye appears to have been particularly energetic during the 6th and 7th centuries CE and again from the 14th century (Pears et al. 2020a). Noteworthy in all three cases is that the onset and conclusion of individual flood events appears to have occurred rapidly, even if floodwaters inundated the entire floodplain. It would appear that it was the fast rising and quick draining in these locations that place-namers sought to convey in the term wæsse.

In combination, place names and sedimentological analysis therefore permit the reconstruction of a longer and more-precise chronology of floods, and help to assess their nature and magnitude. River behaviors can thus be correlated with potential climatic drivers, particularly the influence of solar irradiance (Phipps et al. 2013; Lean 2018), but also fluctuations in temperature (Büntgen et al. 2011; Esper et al. 2014), precipitation (Charman et al. 2006; Swindles et al. 2013; Wilson et al. 2013), and storminess – especially during the Dark Age Cold Period (400–750 CE), and Medieval Climate Anomaly (900–1300 CE) – as well as anthropogenic factors such as woodland clearance and arable expansion (Fig. 2a).

Future perspectives

Our work helps to determine non-stationarity in flood series and better integrate natural and societal evidence to understand depositional regime change over time. This potentially enables us to recalculate, or better define, major flood return intervals under certain climatic conditions. These may be significantly lower than previously estimated, with obvious future design and flood management implications. Despite their age, warnings of flood-prone locations and other indications of riverine activity communicated through historic place names can also be shown to be relevant today. These insights from the past can help us better prepare for the future.

AFFILIATIONS

[1]The University Museum Tromsø, Arctic University of Norway, Norway
[2]School of Geography and Environmental Science, University of Southampton, UK
[3]Luminescence Dating Laboratory, School of Natural and Social Sciences, University of Gloucestershire, Cheltenham, UK
[4]Institute for Name-Studies, University of Nottingham, UK
[5]Centre for English Local History, University of Leicester, UK

CONTACT

Tony Brown: antony.g.brown@uit.no

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Surprising eastern perspectives: Historical climatology and Rus'ian narrative sources

Adrian Jusupović[1] and Martin Bauch[2]

Narrative sources of the medieval period from the historic lands of the Rus' principalities, which include parts of modern-day Russia, Ukraine, Belarus, and Eastern Poland, provide a trove of historical weather information. The long tradition of Russian climate historical research is rather unknown outside of this region.

From the 12th to the 16th centuries, the Kievan Rus' (existing from the 9th century) consisted of self-governing principalities ruled by descendants of the Rurikid dynasty and is considered the historical precursor to modern-day Russia, Ukraine, and Belarus. While academic scholarship has paid considerable attention to the ethnic origins (Norse and/or Slavic) of their elite groups, the potential of Rus'ian historiography for the reconstruction of climatic conditions of the High Middle Ages in Eastern Europe has been largely ignored outside Russia. This article focuses on climate history but aims to shed more light on this historical period and region as well.

Medieval Rus'ian narrative sources

Beginning in the mid-10th century, Rus'ian chroniclers recorded information about weather and natural extreme events, many of which they witnessed firsthand. The scriptoria functioned next to the episcopates. In the 12th century, chronicling started to become a more common practice not only in Kiev and Novgorod but also in the self-governing principalities (e.g. the city of Vladimir, today 200 km east of Moscow).

The following excerpt about a severe winter in January 1287 from the *Chronicle of Halych-Volhynia* serves as an example of the kind of information on meteorological conditions included in these sources: "[The Tatars] remained in Lev's principality for two weeks, living off the fat of the land. They did not engage in open warfare, but neither did they let anyone leave the city for food. [Of those that dared] leave the city, they would kill some, capture others, and rob [still] others, [releasing] them stark naked [to die] from the cold, because there was a very severe winter [that year]" (Perfecky 1973, p. 97). The Rus' sources do not only provide information about their own territory, but also report on unusual weather events from other parts of Europe, such as the St. Lucia's Day flood along the North Sea coast on 14 December the same year: "[It was rumored] that in the land of the Germans the sea overflowed its bank and inundated the country because of God's wrath. More than sixty thousand people drowned and one hundred and eleven stone churches were inundated, not counting those made of wood" (Perfecky 1973, p. 98).

Historiography of Russian climate history

In the latter half of the 1700s, scholars at the St. Petersburg Academy of Sciences began analyzing the wealth of climatic information recorded over centuries in Russian sources. In the first decades of the 19th century, Russian researchers were preparing statistical summaries about Russian climate from 147 temperature measurement sites throughout Russia. Konstantin Veselovskij collected this data and compared it with historical information extracted from different types of sources, going back as far as the era of Herodotus up to his contemporary age (1857; Zhogova 2013). Mikhail Bogolepov continued this pioneer work in climate history around the turn of the 12th century by collecting and analyzing information from published Cyrillic and Latin sources dating from the 10th century onwards (Bogolepov 1907; 1908). This body of Russian scholarship on climate history includes studies about anomalous weather (e.g. Borisenkov and Paseckij 1983; Borisenkov 1988); reconstructions showing fluctuations in Russian climate (e.g. Liakhov 1984; Borisenkov 1988; Klimanov et al. 1995; Klimenko et al. 2001; Slepcov and Klimenko 2005; Klimenko and Solomina 2010); fluctuations in river levels (Oppokov 1933); and famine years in Russia (Bozherianov 1907). The available information dates as far back as the early 11th century (see Fig. 1), though there is a significant drop in documentation in the 1230s and 1240s, likely due to the Mongol invasion of Rus' principalities in 1237.

Figure 1: Number of meteorological extreme events, famines, epizootics, and epidemics mentioned in Rus'ian narrative sources between 1000 and 1300 CE in decadal values, according to Borisenkov and Paseckij (1983, pp. 79, 82, 86).

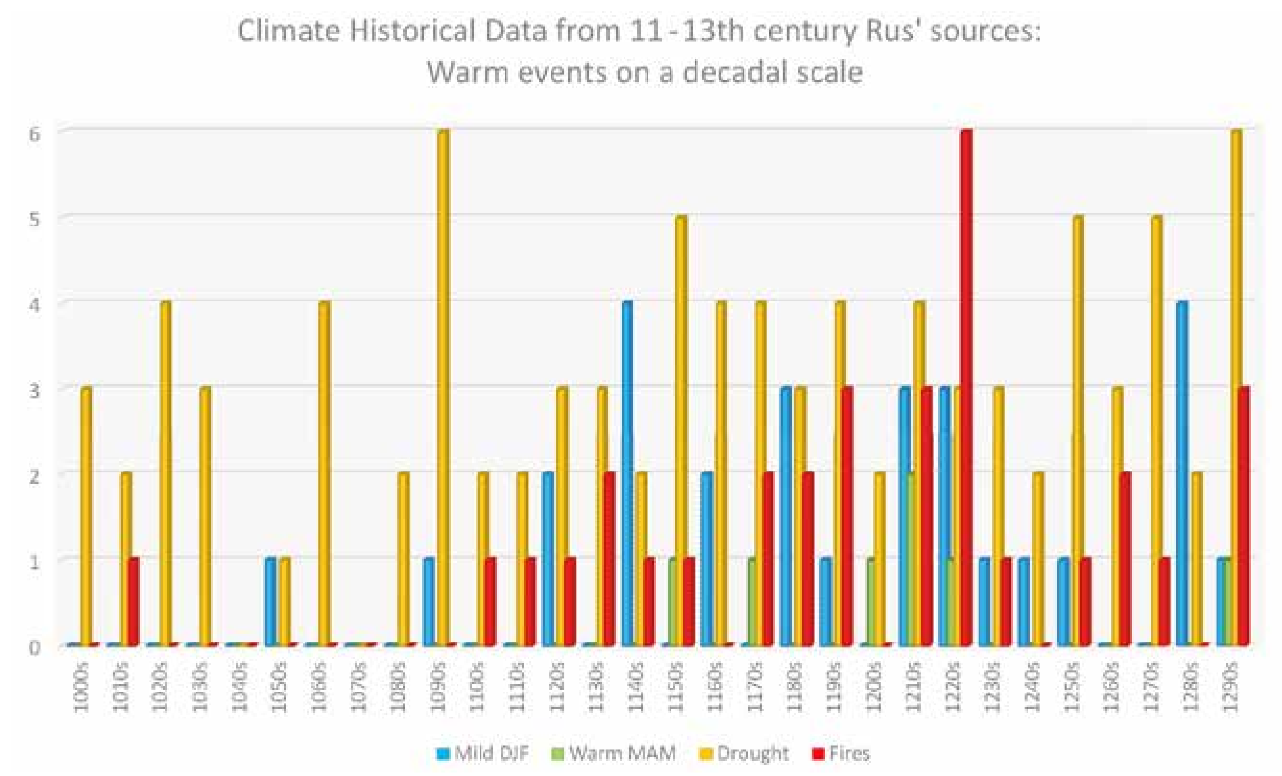

Figure 2: Number of meteorological extreme events related to warm conditions and numbers of city fires in Rus'ian narrative sources between 1000 and 1300 CE in decadal values according to Borisenkov and Paseckij (1983, pp. 79, 82, 86).

Methodological approaches and difficulties in Russian climate history

While the source density of meteorological information from Rus' sources is considerable, most of the research does not use the original editions or appraise them critically. Instead, modern scholars have relied for the most part on Evgenij Borisenkov and Vasilij Paseckij's quantitative evaluation (1983), which incorporates only some of the available sources. The most important collection of Russian narrative sources is what is known as the ПСРЛ [Complete Collection of Rus'ian Chronicles]. Spanning 43 published volumes, these chronicles report on events such as insect infestations, droughts, unusually wet summers and autumns, early and late frosts, famines, floods, and storms. When Borisenkov and Paseckij compiled their statistics (which also includes data from Western Europe, i.e. from England, France, Germany, and the Netherlands), only 37 volumes of the ПСРЛ had been published; furthermore, Borisenkov and Paseckij frequently referred to later literary mentions rather than the original sources. It is thus not clear how they defined a drought, in which seasons it occurred, and which regions were affected (Fig. 2).

As a result, this study, as valuable as it is as the backbone of all reconstructions from documentary data in pre-modern Russia and a pioneering work, should be used with extreme caution. Borisenkov and Paseckij tried to reconstruct the Russian climate over the course of the last 1000 years, albeit with a descriptive approach rather than by applying quantitative methods such as climate indices. The existing historiography on the written sources published thus far for the territory of modern Russia must accordingly be deemed patchy and insufficiently analytical, and none of these studies incorporates the quantitative approaches established in climate history, nor do they meet the basic requirements of modern historical scholarship with regard to source criticism. In the last few years the approach to reconstructing Russian climate has changed, as researchers have looked beyond historical sources and included tree-ring reconstructions, palynological data, lake sediment records, and biostratigraphic analyses (e.g. Klimenko and Solomina 2010; Klimenko 2016).

Objectives for the near future

Closer collaboration between climate historians and specialists on early Russian narrative sources would provide a critical, up-to-date catalog of extreme events and weather-related information, not only from Rus'ian chronicles, but for the whole territory of modern-day Russia and its immediate neighbors in Eastern Europe and Central Asia. Careful English translations of original sources would allow the international community of historical climatologists to work with documentary data of Rus' and Russian origin, which could later become part of established databases such as www.tambora.org or www.euroclimhist.unibe.ch. Such an endeavor would fill the geographical gap between the dense repositories of climate-historical information for the countries of Western and Central Europe and the rich compendia organized by Chinese scholars.

AFFILIATIONS
[1]Institute of History, Polish Academy of Sciences, Warsaw, Poland
[2]Leibniz Institute for the History and Culture of Eastern Europe, Leipzig, Germany

CONTACT
Adrian Jusupović: ajusupovic@ihpan.edu.pl

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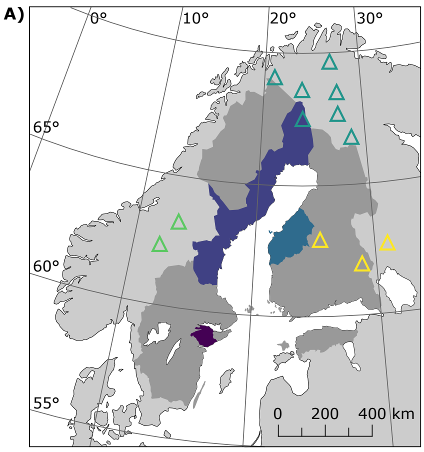
Combining the archives of nature and society: Tree rings and tithes

Heli Huhtamaa[1], S. Helama[2], L. Leijonhufvud[3] and F. Charpentier Ljungqvist[4]

Combining information from proxy materials stored in natural and man-made archives helps to gain a more comprehensive understanding of past climate–society relationships. This is demonstrated here with an example from tree-ring and tithe data from the 16th- to 17th-century Swedish Realm.

The impacts of future climate change on agriculture form a crucial issue for food security. Valuable insights into this topic can be gained by studying the impacts of past climate on crop cultivation – not only in recent history, but also over past centuries. Use of only the most recent data increases the risk of addressing symptoms rather than deep-rooted causes (Adamson et al. 2018). Yet, such deeper historical dimensions are not extensively examined in the literature. This is likely because direct statistical data on climate and agricultural production become available mainly from the 19th century onwards. Nevertheless, for periods further back in time, we can use indirect, i.e. proxy, data to study the relationships between climatic and agricultural fluctuations. These proxy data can be found in either the "archives of nature", such as ice layers and tree rings, or in the "archives of society", composed of written documents. This article discusses some of the main issues in combining proxy data from both types of archives by presenting a case study on temperature and grain harvest fluctuations from the 16th- to 17th-century Swedish Realm (comprising roughly the area of modern-day Sweden, Finland, and Estonia).



Proxies of temperature and grain yields

Meteorological data and countrywide agricultural statistics are both available from 19th-century Sweden and Finland. Analysis of these series has previously revealed that temperatures and yields of principal grains generally show positive and statistically significant correlations, with warmer conditions bringing higher yields (Holopainen et al. 2012; Huhtamaa et al. 2015). Prior to this "statistical era", the availability of crop-yield and instrumental temperature data decreases dramatically. For annual harvest data, some sporadic yield-ratio series are available from the 16th and 17th centuries. Yet these commonly indicate the yield ratios of manorial estates, i.e. the productivity of fields owned by the nobility. The great majority (>80%) of the population in Sweden and Finland were, however, peasants. Nevertheless, grain tithes can provide an alternative source to detect annual yield fluctuations. The tithe was a tax that every land-holding peasant was obliged to pay in the 16th- to 17th-century Swedish Realm. Although collection practices varied slightly across the kingdom, each peasant household, in general, was supposed to pay approximately 10% of their annual grain harvest as tithes. The tithes commonly consisted of roughly equal shares of barley and rye, but in the northernmost areas, the tithes were paid almost entirely in barley. Here we use tithe data from three old administrative areas: the province of Södermanland and the land of western Norrland in Sweden (Leijonhufvud 2001), and the province of southern Ostrobothnia in Finland (Huhtamaa and Helama 2017a).

In addition to using documentary evidence, crop yields and temperatures could be reconstructed using tree-ring data available from both countries (Fig. 1). Here we use maximum latewood density (MXD) chronologies of Scots pine (*Pinus sylvestris* L.) tree rings from Lapland (Matskovsky and Helama 2014), southern Finland (Helama et al. 2014), and Jämtland (Sweden; Gunnarson et al. 2011). All of these reconstructions explain around 60% or more of the total variance in the measured annual warm season temperatures. Furthermore, the Finnish MXD chronologies reliably indicate relative variations in grain yields in central and northern Finland (Huhtamaa and Helama 2017b).

Tree rings and tithes

The years with strong drops in MXD-based growing season temperatures were found to match the years when all the tithe series indicated poor harvests. These years include 1587, 1601, and 1614 (Fig. 1). This suggests that although the harvest was influenced by local environmental conditions and man-made factors, at least during the years representing relatively average

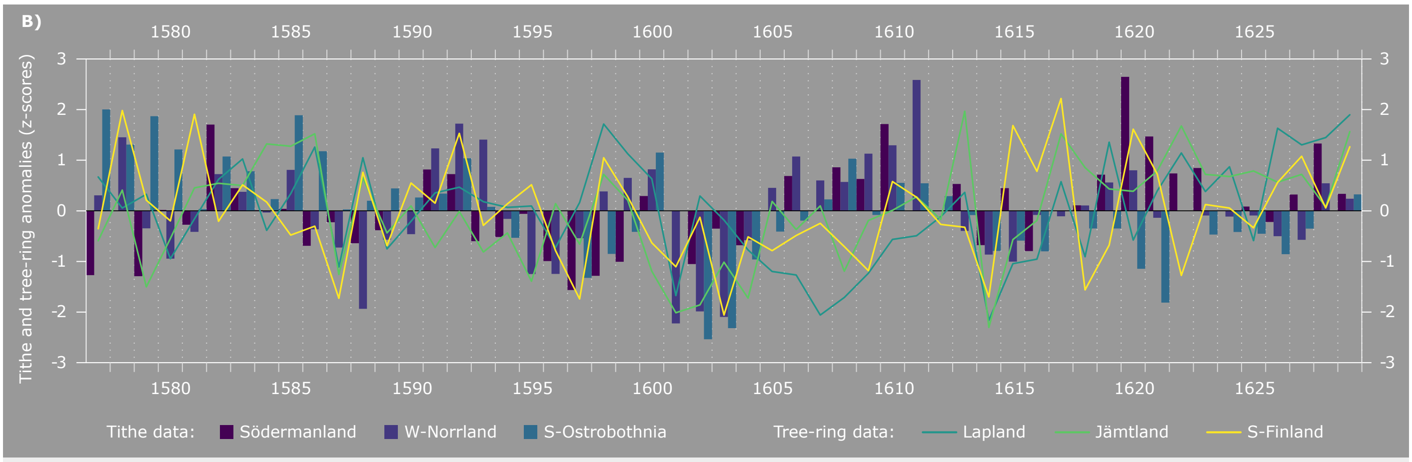


Figure 1: (A) Three historical districts for the tithe data (coloring) and the average sampling sites of the tree-ring data (triangles). The darker grey area illustrates the extent of the Swedish Realm in 1600. **(B)** Annual tithe variations and tree-ring reconstructed temperature variability (standardized over the period 1577–1629).

"The tithe that annually are due, are now for this year [1]602 not fulfilled, since the frost devastated the fruit [i.e. the crops]. The entire land therefore needs no taxation on the previously mentioned tithe grain as the sealed evidence tell within the bound [book of] annual rent. Date February 5 year [1]603."

Figure 2: The year 1601, evidenced in tree-ring samples from Finnish Lapland and written material from northern Finland. As the tithes were collected the following winter, the tithe year 1602 actually reflects the harvest year 1601.

climatic conditions, severe kingdom-wide harvest failures were likely driven by climate extremes. In this regard, the climatic "downturn" of 1601–1604 following the 1600 Huaynaputina volcanic eruption is especially visible in both types of data (Fig. 2). In fact, the 1601 harvest failure was so complete that in many provinces the authorities decided not to collect grain tithes at all (Huhtamaa and Helama 2017a).

Furthermore, the comparison of the MXD and tithe data reveals that harvests remained poor for at least one year after the year of poor harvest – even if climatic conditions would have supported higher yields (e.g. year 1588 in Fig. 1). The early modern Swedish Kingdom expected peasants to be self sufficient regarding seed grain. Thus, the harvest year following the crop failure remained poor as well, as only part (if any) of the fields could be sown due to empty grain stores. Consequently, insufficient preparedness to cope with large-scale crop failures, as well as inadequate seed grain storage, worsened the agricultural impacts.

The MXD measurements do not correlate as strongly with the 16th- to 17th-century tithe data as with the 19th-century yield data. This is hardly surprising, however, as the latter provide an indication of relative productivity fluctuations, whereas tithes can be more illustrative of the total quantities of grain harvest output. The total amount of taxed harvest may, in turn, have been influenced by several factors other than climate, such as the quantity and quality of seed grain, the size of the arable fields, and even the strictness of individual tax collectors. Moreover, the tithe series from Södermanland agreed least with the MXD-based temperature reconstructions (Fig. 1). This is likely due to the long distance between the province and MXD sites. Additionally, northern grain yields, like MXD, were more sensitive to the length and thermal conditions of the growing season than yields in southern Sweden, where winter temperatures and summer precipitation markedly influenced the harvest (Edvinsson et al. 2009).

Discussion and conclusions

Data from both natural and man-made archives are needed when studying climate and grain harvest fluctuations in the era preceding official statistics. Meaningful comparisons require natural and written materials representing the same climate variables and similar spatio-temporal coverage and resolution. Thus, for example, temperature-sensitive tree-ring data from Sweden and Finland are not suitable to explore climate–harvest relationships in precipitation-sensitive agricultural areas further south. Moreover, when studying annual harvest fluctuations, the natural materials used for comparisons need to be dated to absolute calendar years to demonstrate inter-annual variability comparable to historical data. Among the different natural proxy types, only tree-ring chronologies are routinely converted to calendar years, making them directly comparable to historical data, with no need to speculate on dating issues.

The natural and man-made archives shown here (MXD and tithes, respectively) both serve as proxy materials, i.e. data indirectly indicative of past variations in climate and crop yields. In this sense, tree-ring data can be used to demonstrate climatic impacts on crop yields, whereas grain tithes indicate the quantity of the harvest. Additionally, when further information is needed, yield ratios, for example, can indicate the relative productivity variations and grain prices the fluctuations in grain availability. None of these different types of data alone provides us with a comprehensive picture of past harvest fluctuations. Combining these sources, however, provides us with a much more detailed understanding of the past.

AFFILIATIONS
[1]Oeschger Centre for Climate Change Research and Institute of History, University of Bern, Switzerland
[2]Natural Resources Institute Finland, Rovaniemi, Finland
[3]Department of Historical Studies, University of Gothenburg, Sweden
[4]Department of History and Bolin Centre for Climate Research, Stockholm University, Sweden

CONTACT
Heli Huhtamaa: heli.huhtamaa@hist.unibe.ch

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Winter freeze-up and summer break-up in Nunatsiavut, Canada, from 1770 to 1910

Marie-Michèle Ouellet-Bernier[1] and Anne de Vernal[2]

Historical sources provide unique information on sea ice in a coastal Labrador Sea region. Data extracted from missionary journals permit differentiation of the winter and summer signals. Decadal variations marked winter conditions during the 19th century.

Snow and ice are fundamental in the description of subarctic and Arctic environments. In Nunatsiavut, the autonomous territory of the Labrador Inuit, the land-fast ice forms seasonally along the coast. It is considered as an extension of the land. Land-fast ice is thus very important for cultural activities, communications, mobility, and livelihood (Cuerrier et al. 2015). Usually, land-fast ice forms in mid-December and ice breaks up in mid-June, while drift ice can remain along the coast until late July (Canadian Ice Service 2013; Fig. 1). The historical sources provide punctual information that may help to document the natural variability of sea-ice freeze-up and break-up during the 19th century and before. Attention is specifically directed towards written sources.

Human occupation

Dorset people arrived from the Central Arctic and settled along the Labrador coast about 650 BCE. They depended on marine resources, and their presence in a region is often associated with extended sea ice (D'Andrea et al. 2011). Migrating from Alaska, the Thule colonization of Labrador began much later, around 1200 CE. It is likely that both Dorset and Thule cultures occupied the Labrador coast from about 1200 to 1500 CE. The Dorset group occupation ended at about 1500 CE; the reason for their disappearance is still unclear. It could be linked to warmer climate and more variable sea-ice conditions, or to competition with the Thule (McGhee 1997). During the 17th century, a transition occurred from Thule to Inuit culture (Kaplan and Woollett 2000). Moravian missionaries established their first mission station in Nunatsiavut in 1770 and started to document their environment and keep written archives (Demarée and Ogilvie 2008). On 18 September 1771, they noted: "In December all is frozen far out to sea and the ice remains until June, or even until July, for they all go wes[t]" (Nain Diary 1771).

Sea-ice freeze-up and break-up

The first record of freeze-up and break-up dates was extracted from Nain Diaries encompassing the period 1771–1808. A transcript is held at the Them Days archive center in Happy Valley-Goose Bay, Labrador. In addition to direct mention of winter freeze-up, the first hunt on ice is considered to be an indicator of ice presence. A correction to the estimate of freeze-up dates was made by taking into account the fact that based on the historical data, the first hunt took place on average five days after the ice formed. The first kayak arrival was taken as an indicator of ice break-up in summer. Here, too, a correction was applied, as the first kayak arrived on average seven days later.

The second set of data was extracted from the Moravian Periodical accounts spanning 1816–1910, which were presented as yearly reports to the Moravian Church headquarters in London (Fig. 2). Freeze-up and break-up dates were noted in Hopedale, Nain, Okak, and Hebron (located at latitudes of 55° to 58°N; Fig. 1). Additional comments regarding exceptional situations were also made. Freeze-up and break-up dates have been standardized for each village in order to remove local climate effects (Fig.2). The duration of sea-ice cover was calculated from freeze-up and break-up dates when both were available. From 1771 to 1910, the mean freeze-up date was 5 December, ranging from 27 October to 10 January; the mean break-up date was 19 June, ranging from 30 May to 20 July. The mean length of sea-ice season represents a total of 196 days (28 weeks; Fig. 2).

Early freeze-up and late break-up dates were recorded from 1770 to 1810, which corresponds to the end of the "Little Ice Age" (D'Arrigo et al. 2003). Then, a warming trend was observed from the beginning of the 19th century. From 1800 to 1810, break-up anomalies showed a positive trend, representing early break-up dates. Early sea-ice formation was recorded from 1817 to 1824, whereas thaw occurred in early summer. An asynchronous pattern was observed again between 1839–1848 and 1855–1864 with late freeze-up and late break-up. From tree-ring

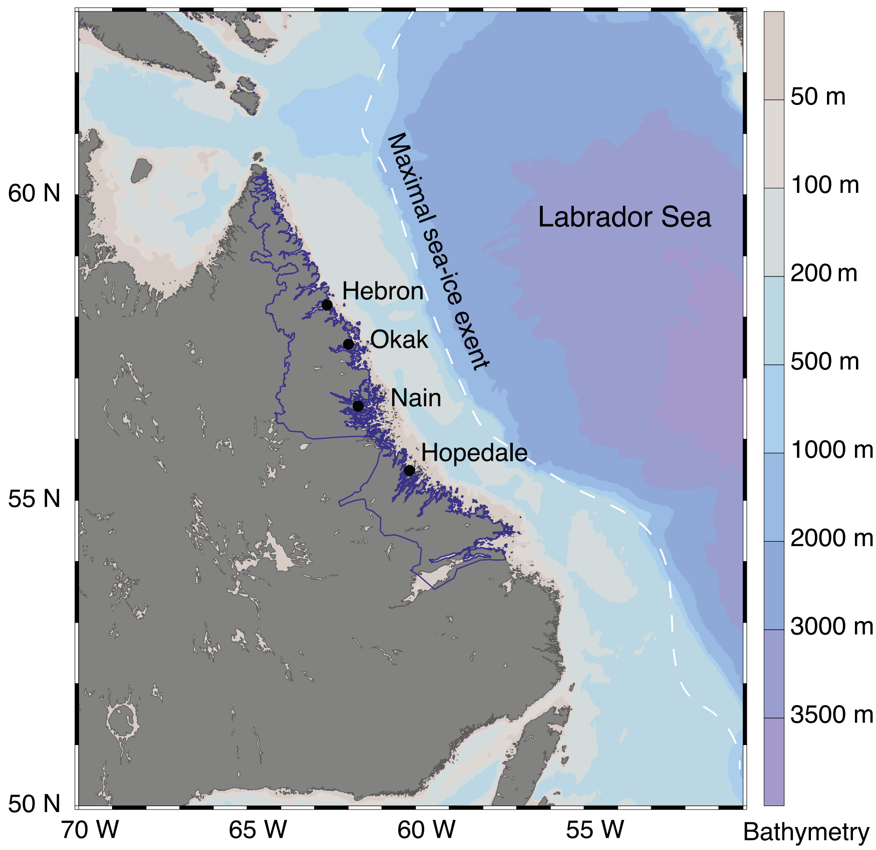

Figure 1: Map showing the location of sites mentioned in the text and the maximum extent of sea ice as recorded from satellite imagery in March 2019 (National Snow and Ice Data Center, nsidc.org). Nunatsiavut territory is delimited in blue.

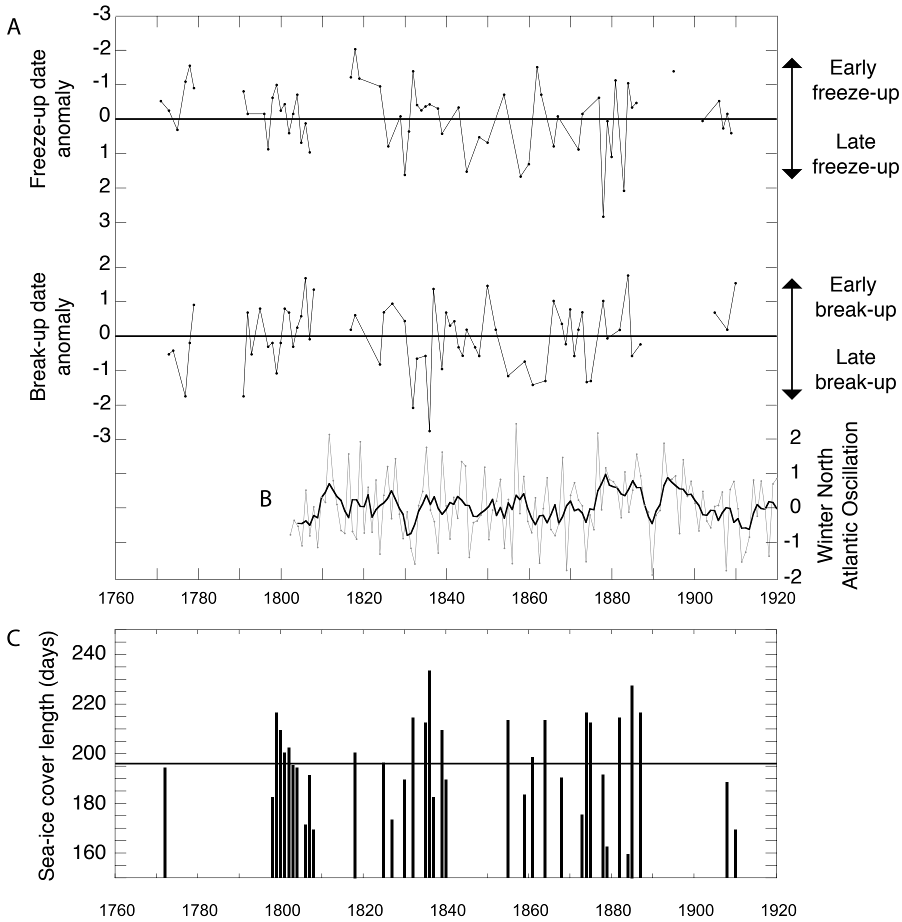

Figure 2: (A) Break-up and freeze-up date normalized anomalies in Nunatsiavut. A positive (negative) freeze-up anomaly represents a late (early) freeze-up, and a positive (negative) break-up anomaly represents an early (late) break-up. **(B)** Winter North Atlantic Oscillation normalized index (Jones et al. 1997). Black curve shows a five-year running mean. **(C)** The duration of the sea-ice season (calculated as the number of days between freeze-up and break-up). Horizontal black line shows the mean value over the period.

density records, D'Arrigo et al. (2003) suggested that the increase in climatic variability during the first half of the 19th century was accompanied by the occurrence of extreme conditions. From 1865 to 1885, variations between late freeze-up/early break-up and early freeze-up/late break-up resulted in shorter sea-ice cover duration in some years and longer in others (Fig. 2). Afterwards, and until the 20th century, there was almost no mention of ice freeze-up and thaw. The Nunatsiavut population was severely affected by epidemic and food scarcity; therefore, Moravians reported on the humanitarian situation instead of climatic parameters (e.g. Periodical accounts 1895, vol. 3, no. 25).

A unique window into past winters

The first standardized instrumental winter temperature measurements were made in 1880 (First International Polar Year initiative; Demarée and Ogilvie 2008). The use of historical sources is thus very valuable as it provides an overview on winter conditions before 1880. It is rarely possible to reconstruct winter climate conditions from proxy sources such as tree-ring data, which mostly represent spring and summer (e.g. D'Arrigo et al. 2003). Along the Labrador coast, the sea-ice freeze-up relates to atmospheric and oceanic conditions. Early freeze-up is usually associated with cool temperatures and fresh surface waters in the summer and early autumn (Close et al. 2018). The freeze-up date varied independently from the summer break-up date. The retreat of sea ice usually relates to advection of warm air masses from the south with strong southerly winds (Crane 1978). Summer break-up dates must be used carefully as remaining drift ice along the coast can induce a bias in observation. Strong dominant northwesterly winds can block the Labrador coast with ice for a longer period (Banfield and Jacobs 1998). From long-term observational data, Walsh et al. (2017) demonstrated that Arctic sea-ice variations are driven by air temperature, wind forcing, radiative forcing, and ocean heat fluxes.

Intra- to multi-annually resolved information

Historical sea-ice information offers the possibility to develop records with intra-annual temporal resolution and to provide both summer and winter perspectives on climate states. However, multiple years are missing in the historical records, as missionaries do not always refer to climate in the periodical accounts.

A relationship between winter temperature and sea-ice cover in the Labrador Sea/Baffin Bay area and the North Atlantic Oscillation (NAO), which is calculated from the surface sea-level pressure difference between the Azores and Iceland, was supported by Hurrell and Deser (2010). In our study, winter freeze-up shows large amplitude variations, which might be linked to the NAO. Winter NAO was in a positive mode during the 1830s, which corresponds to enhanced sea-ice duration and extent, and a low sea-surface temperature. Our calculations indicate that sea ice was present more than 200 days per year in 1831, 1834, 1835, and 1838.

Outlook

From 1770 to 1810, freeze-up and break-up dates show long sea-ice seasons characterized by both early freeze-up and late break-up. From 1816 to 1880, the length of the sea-ice season varied considerably, with the freeze-up and break-up dates showing no relationship. From 1875 until the early 20th century, a trend to later freeze-up in winter and earlier break-up in summer is observed, which probably results from regional climatic warming. As winter temperature data are typically not available from natural proxies such as tree-rings, historical data from written sources offer a unique perspective on winter and summer onset in Nunatsiavut dating back to 1770.

AFFILIATIONS
[1]Institute of Environmental Sciences, University of Quebec in Montreal, Canada
[2]Department of Earth and Atmospheric Sciences, University of Quebec in Montreal, Canada

CONTACT
Marie-Michèle Ouellet-Bernier: ouellet-bernier.marie-michele@courrier.uqam.ca

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ADDITIONAL RESOURCE
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Arab Islamic historical documents as a climatological source in the Maghreb

Yassin Meklach

Arab historiographical studies can provide detailed climatic data and information on natural disasters through the exploitation of academically revised and re-edited ancient manuscripts. Maghrebian scholars have written valuable chronicles and annals that can form the basis of relevant paleoclimatic series.

Documentary data from all over the world can contribute to our understanding of the climate of the past. Such data are found in the archives of societies, and it is the aim of historical climatologists to give these documents voice and credibility. Progress in codicology and paleography has made it possible to examine old manuscripts more efficiently (Mathisen 2008). In particular, critical source editions and transcription projects have made these handwritten texts accessible to researchers from disciplines outside of the historical sciences. Apart from this indisputable progress, however, uncountable manuscripts still remain unexplored in archives and libraries around the world (Zaydān 1997). The first attempts to make such manuscripts accessible to a broader audience were made by Benedictine Monks in the 17th century. Frenchman Bernard de Montfaucon (1655–1741), author of *Bibliotheca bibliothecarum manuscriptorum nova*, is considered one of the founders of this field.

Arabic historiography

The manuscripts discussed here are examples of a long and noble tradition of historiographical writing by the Arab people that mostly characterizes urban life (e.g. Ibn Khaldun 1378). They are also a mirror of the golden era of literature in the Arabic world that spanned nearly a century, starting from 753 CE (al-Jābirī 2009). The study of such manuscripts is only one of the approaches for analyzing the cultural transformations of past Arab societies, but alone, this is not sufficient; it is also crucial to place Arab historiography in its physical, historical, and geographical context, as was done by al-Munajjid (1960), Pedersen (1984), Sayyid (1997), Sāmarrā'ī (2001), Binebine (2004), Gacek (2009), and others. The editing process of Arabic manuscripts entails the collection of as many available copies of a specific manuscript as possible in order to compare and re-edit them in an orderly manner using legible and clear writing. Moreover, indexations and further contextualization of works within the fields of codicology and paleography are a part of the editing process. The final product can be read by non-specialists in Arabic literature, such as paleoclimatologists who aim to identify the relevant climatic information. Despite the various efforts made, however, the field of Arab manuscript research is still in a rather embryonic state with hundreds of thousands, if not several millions, of manuscripts to explore.

Figure 1: A facsimile of two pages of the manuscript of *al-Bayān*. In the section between line eight on the first page and line four on the second, different events dating from the years 331 AH (942 CE) and 333 AH (944 CE) are described that occurred in Cordoba, highlighting the temporal and spatial accuracy of the narrated events. See translation provided in the main text (Ibn Idhāri 1295).

Weather descriptions in Arabic historiography

Arabic historiography, which is primarily a narration of human actions, might be subject to personal, political, religious, and/or otherwise biased interpretations, but this usually does not interfere with the descriptions of weather and natural conditions. Regarding weather conditions, accurate recording of heavy rains, extreme cold, or solar eclipses are available in Arabic historiographic texts. These are examples of the types of observations that are most likely to be of use in reconstructing paleoclimatic timeseries. Moreover, extreme natural events and sudden disasters, famines, and epidemics are also mentioned in the manuscripts, due to their severe impact on human societies.

Examples of weather descriptions

One of the pioneers of general concepts of geography in the Maghreb region was al-Idrīsī (d. 1165), born in Ceuta, which was then subordinate to the Almoravid State in Morocco. He was a scientist, writer, geographer, and cartographer who lived in Palermo, Sicily, in the kingdom of Roger II. Apart from his geographical and cartographical work, al-Idrīsī is best known for his *Nuzhat al-mushtāq fī ikhtirāq al-āfāq* (نزهة المشتاق في اختراق الآفاق), or in Latin *Tabula Rogeriana*, which translates into "the map of Roger" – a book that is organized into seven climate zones of the Earth. He analyzed the succession of seasons and meteorological conditions according to the latitude and longitude. In the introduction of his work, al-Idrīsī writes: "*The Earth is divided into two parts, between them the equator which is the longest line in the sphere. The circularity of the Earth at the equator position is three hundred and sixty degrees, and the degree is twenty-five parasangs… However, sixty-four degrees from the equator there are no building in the Earth due to the severity of the cold, the majority of living creatures are in the northern quarter of the Earth, and the southern quarter, which is above the equator is uninhabited due to its heat …*" Ibn Khaldun (d. 1406), a social scientist and historian born in Tunis, included a passage about the regional variation of the climate and its impact on the human character in his book *al-Muqaddimah* (1378) (المقدمة). In his view, the inhabitants of temperate zones are temperate in their physical appearance and character and in their ways of life. They have all the natural conditions necessary for a "civilized" life, such as a means of making a living, dwellings, crafts, political leadership, and royal authority. They thus have religious groups, dynasties, sciences, countries, cities, buildings, horticulture, splendid crafts, and everything else that was considered "temperate".

Moreover, other Maghrebian historians developed a detailed style for ordering historical events, including descriptions of weather events at the time, which can be found in many precious manuscripts, such as *Kitāb al-Istiqsā li-akhbār duwal al-Maghrib al-Aqsā* (كتاب الاستقصا لأخبار دول المغرب الأقصى) authored by al-Nāṣirī (d. 1897). Al-Nāṣirī is considered to be the main historian of the 19th century in Morocco, as he compiled the entire history of Morocco in several volumes, as well as that of the Islamic West starting with the Islamic conquest by Oqba Ibn Nāfi at the beginning of the 8th century until the end of the 19th century. These volumes include numerous records of climatic information, which indicate, for instance, the wind speed: "*In 919 CE, the strong winds uprooted trees and demolished houses in Fez (Morocco) and people stayed in the mosques*." The same work mentions – apart from weather conditions and natural disasters – weather-related agricultural and economic events and processes, even with some details of the weight of fallen hailstones: "*In 1324 CE, there was famine in Morocco and prices rose in all parts of the country. Wheat and other vegetables became very expensive in Fez, and this lasted until the middle of the following year... on Tuesday, 30 September of the same year, the sky outside the city of Fez was covered with a dark and thick cloud, stormy winds arose and heavy hail fell, a ball weighed at least a quarter of a pound and it rained heavily. The torrents came with silt, and carried people and animals, and destroyed in the mountain of Zalegh all the vineyards, the olives and the rest of the trees.*"

Another significant work from this region is the book *Kitāb al-bayān al-mughrib fī akhbār mulūk al-Andalus wa'l-Maghrib* written by Ibn Idhāri al-Marrākushī (d. 1296). This book is one of the most important and comprehensive examples of medieval Arabic history of the Maghreb and Iberia, generally known by its shorter title *al-Bayān al-Mughrib* (البيان المغرب), or simply as *al-Bayān*, reviewed and reedited by Colin and Lévi-Provençal (1984). It is valued by modern researchers as a unique resource, and for its preservation of excerpts from lost works. Furthermore, Ibn Idhāri followed a specific method in writing the book that drew on his broad knowledge of the contemporary literature and his access to many oriental and Moroccan writings, in addition to a long list of references that he included in the introduction to his book. Therefore, he was familiar with historical schools and writing styles that existed before his time, especially historical writing in the form of annals (historiographical literature). This method arranges historical events and lists them according to the succession of years and months and is very useful in pinpointing the timing of climatic events, especially when the writer narrates the time of their occurrence with high accuracy.

Figure 2: Collection of manuscripts in a private library belonging to the heirs of Abdelkader Meklach in Tétouan, Morocco.

In his *al-Bayān* manuscript (Fig. 1), Ibn Idhāri mentions several important events that occurred in Cordoba, Spain, during the year of 331 AH (Year of the Hijra, roughly equivalent to 942 CE), such as: "*In 942 CE, … the great flood of the Cordoba river …*" In 333 AH (944 CE), he mentions events with extraordinary temporal and spatial precision, sometimes specifying the exact timing: "*This year, a major earthquake occurred in Cordoba on the night of Monday, 3 Dhū al-Qaʿdah (3 July), after the night prayer* [on 3 July, the night prayer took place at 22:12], *nothing like which had ever been seen or heard before, and it lasted an hour. The next day, the strong winds uprooted olive and fig trees as well as palms and took off roof tiles of the houses, then, torrential rains occurred with precipitation of massive hail and the killing of a lot of animals, birds, cattle and damaging crops.*"

Further potential

Historical climatology research demonstrates the great potential of the archives of societies of the Maghreb region for the reconstruction of past climate of the Mediterranean and beyond. This documentary data is characterized by high precision and a general accuracy of the descriptions of events. To date, texts from Arab historiography are hardly exploited in historical climatology. Furthermore, it must be emphasized that private and public libraries around the world still contain important collections of unused manuscripts (Fig. 2), which may provide relevant data for the reconstruction of past climates in the western Mediterranean.

AFFILIATION

Department of Biology, University Abdelmalek Essaâdi, Tétouan, Morocco

CONTACT

Yassin Meklach: yassin.mclach@gmail.com

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The potential of written sources for a historical climatology of the Middle East during the Mamluk era

Undine Ott

The Mamluk era (1250–1517 CE) was a period with phases of climate instability in the eastern Mediterranean. A trove of written sources has survived from this period but still awaits evaluation for climate history reconstruction in the Middle East.

The climate of the Middle East is more varied than the stereotypical image of barren deserts might suggest. The region encompasses Mediterranean-climate, semi-arid, and arid zones. Winter tends to bring more precipitation, while summers tend to be dry. During the medieval period, agriculture constituted by far the most important economic sector. Regardless of whether farmers practiced techniques of dry farming or relied on irrigation, agriculture depended largely on winter rains, and fluctuations in precipitation during this season could heavily affect the year's production (Frenkel 2014; Kaniewski et al. 2012).

A plethora of sources

A large number of written sources have been preserved from the Mamluk Sultanate that existed in Egypt and the Levant. The bulk of the sources is in Arabic. Arabic chronicles and annals are particularly informative about weather events and climate conditions. These works far outnumber what is extant from this period from most other parts of the world, including Europe. Mamluk-era diaries, travelogs, poems, biographies of rulers, encyclopedias, and anthologies occasionally provide useful information for historical climatology as well (Tucker 1999).

The majority of the Mamluk-era material falls into the genre of narrative sources. Documentary sources such as charters, letters, registers, or protocols, by contrast, are rare (Hirschler 2016). Furthermore, they hardly ever contain information on weather and climate. The same applies to inscriptions on buildings, tombstones, or objects. As a result, serial data on temperatures or harvest dates, for instance, cannot be compiled for medieval Egypt and the Levant.

The surviving narrative sources provide eyewitness accounts or, at least, contemporary testimony to the climate history of the Middle East. The authors were scholars or high dignitaries of the Mamluk Sultanate and focused on the urban centers and their surroundings. Rural areas are less well covered. The works generally report extreme weather events; only rarely do they remark upon normal weather conditions. The annual Nile flood is an exception: given its crucial importance for agriculture in Egypt, the flood was monitored by the sultan's court in Cairo. Cairo's canals were opened the day the river reached the level deemed sufficient to inundate the farmland of the city and its surroundings (Fig. 1). Both the elite class of the sultanate and the general population celebrated this day (in Arabic: *Wafāʾ al-Nīl*), the date of which varied from year to year. As an event, it is regularly mentioned in the aforementioned written sources even for years with average Nile floods (Hassan 2007).

The Mamluk-era chronicles and annals provide information related to precipitation, temperature, and volcanic activity. They report on hail and sandstorms as well as floods and landslides, periods of severe cold, snowfall, low river levels, droughts, and eruptions of volcanic fields. Other disastrous events like earthquakes, tsunamis, city fires, epidemics, famines, or locust infestations are mentioned as well. The main extensive body of evidence concerns precipitation; water was a crucial resource in the Middle East, and too little rainfall could have severe consequences. The same was true for too much precipitation: torrential rains could overstrain canals and wash away streets. The economic and social infrastructure of rural, urban, and nomadic communities was highly vulnerable to precipitation anomalies.

Current state of research

The historical climatology of the medieval Middle East is still in its infancy. Ronnie Ellenblum (2012) attempted to reconstruct the climate history of the pre-Mamluk Middle East from written sources, and detected a series of climate disasters in the 10th and 11th centuries – the era that has been termed, with regard to Europe, the "Medieval Climate Optimum". Kate Raphael (2013) studied droughts, famines, earthquakes, and infestations of locusts, mice, and rats which affected the Middle East between the 12th and 14th centuries. Kristine Chalyan-Daffner (2013) analyzed reports from Mamluk-era sources of disastrous floods, droughts, and earthquakes in Egypt.

Recently, a group of geographers from the University of Freiburg created a dataset based on weather reports in written sources that the Middle East historian Heinz Grotzfeld had collected in the 1980s and 1990s. They published the list of entries accompanied by metadata (Vogt et al. 2016) and also entered the reports into the Tambora online database (www.tambora.org). This constituted the first attempt to systematically collect information on the climate history of the Middle East. Unfortunately, it often cites scholarly editions of sources incorrectly, and the paraphrases given of reports in Arabic sources do not, in all cases, seem reliable (see for example Glaser et al. 2016, p. 7, which provides an imprecise and incomplete translation of a passage from an Arabic source). Furthermore, a number of the editions of sources Grotzfeld had used

Figure 1: Bridge over the former Abū l-Munajja Canal which regulated the irrigation of the eastern Nile Delta, Cairo, 1260s. (Photo: K. A. C. Creswell, 1916–21, © Victoria and Albert Museum, London.)

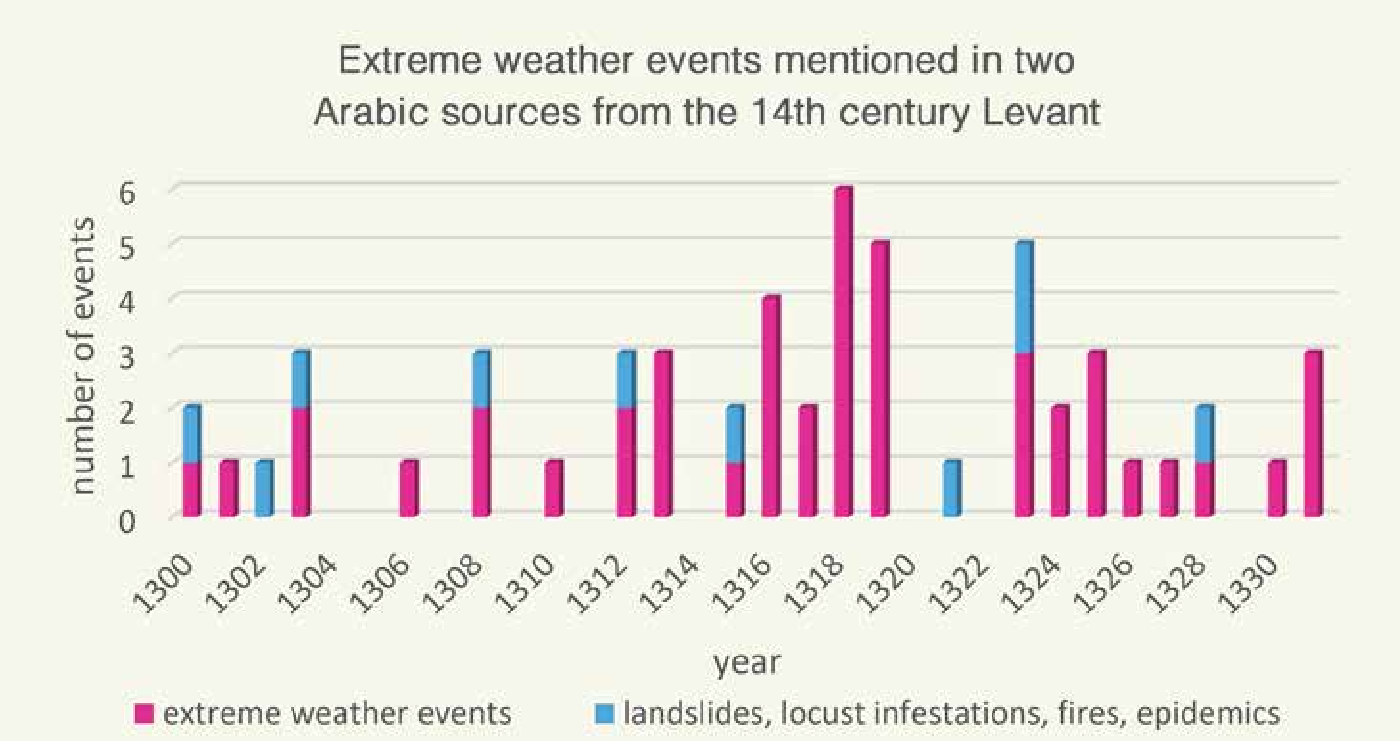

Figure 2: Extreme weather events and disasters mentioned in Abū l-Fidā''s *al-Mukhtaṣar* (completed ca. 1330) and Ibn Kathīr's *al-Bidāya wa-l-nihāya* (ca. 1370) for the period 1300–1331 CE.

have been surpassed by newer, improved editions. Besides, the dataset created fails to take into account a large number of extant Arabic sources.

Potential pathways of future research

Apart from the Grotzfeld dataset, there is, to date, no systematic collection of Middle Eastern historical material for any period between 500 and 1500 CE despite the unique abundance of sources. Instead, studies like Raphael (2013) have, in part, relied on single anecdotes found in the extant sources, or have utilized works written centuries after weather events had supposedly occurred. More source-critical studies are needed to assess the potentials as well as the pitfalls of working with the extant Arabic material.

A systematic collection of information on medieval weather events would help to illuminate medium to long-term developments in the climate history of the Middle East. A searchable online database would enable comparative studies and greatly facilitate interdisciplinary cooperation. The use of digital tools might generate new questions and propose new answers. In order to present climate-related information from written sources in a meaningful way, ordinal-scale indices for precipitation or temperature have proved useful with regard to other regions of the globe (Nash et al. in review). Indices help to quantify information from narrative sources, but no index tables have been thus far compiled for past Middle Eastern climate conditions.

Besides medium and long-term developments, single cases of extreme weather events and natural disasters might be studied (Schenk 2017). Our understanding of Mamluk politics, society and economy has significantly improved in recent years. The growing scholarship provides an ideal base for case studies on the human response to climate instability: how were disasters and climate change perceived in Mamluk-era Egypt and the Levant, how were they managed, and what impact did they have on society?

The pioneering book by Ellenblum (2012) on the climate history of the Middle East does not incorporate much data from natural archives (Preiser-Kappeler 2015), though recent studies of speleothem archives, tree-ring data, pollen records, corals, and lake sediments have provided new insights into medieval climate conditions in the eastern Mediterranean. Historical climatology needs to incorporate these findings (Telelis 2008). The Mamluk era covers the phase of transition from the Medieval Climate Anomaly to the Little Ice Age. The written record at times provides more detailed and more precisely dated information than paleoclimatic data. A first preliminary survey of weather-related reports in Arabic annalistic works suggests, for instance, that the 1310s witnessed an extraordinary series of extreme weather events (Fig. 2). This period has, with regard to Europe, been termed the "Dantean Anomaly" (Brown 2001, pp. 251-254). The Freigeist Dantean Anomaly Project (dantean.hypotheses.org), hosted by the Leibniz Institute for the History and Culture of Eastern Europe in Leipzig, aims to compare medieval climate conditions in the Middle East and several regions of Europe. Comparative projects like this might contribute to answering the question whether phases of climate instability during the Middle Ages were limited to certain regions or constituted rather global phenomena (Bauch et al. 2020; Roberts et al. 2012).

AFFILIATION

Leibniz Institute for the History and Culture of Eastern Europe, Leipzig, Germany

CONTACT

Undine Ott: undine.ott@leibniz-gwzo.de

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A preliminary global inventory of historical documentary evidence related to climate since the 14th century

Angela-Maria Burgdorf

The first global inventory of documentary evidence related to climate extending back to the Late Medieval Period lays the foundation for incorporating historical documentary evidence into climate reconstructions on a global scale, complementing early instrumental measurements as well as natural climate proxies.

Climatic variations have impacted societies since the very beginning of human history. To track these changes over time, humans have thus often closely monitored the weather as well as natural phenomena influencing everyday life. Resulting documentary evidence from archives of society gives invaluable insights into the past climate beyond the timescale of instrumental and early instrumental measurements. This information complements other proxies from the archives of nature (such as tree rings) in climate reconstructions, as documentary evidence often also covers seasons and regions that are not well represented with natural proxies. Tree-ring proxies, for example, are restricted to annual signals of temperature or precipitation during the growing season. Documentary evidence relating to ice freeze-up and break-up dates can provide complementary temperature signals for winter and spring.

While a mature body of research on detecting climate signals from historical documents exists, the large majority of studies are confined to a local or regional scale and thus lack a global perspective. Here, I attempt to compile the first systematic global inventory of documentary evidence related to climate extending back to the Late Medieval Period. It combines information on past climate from all around the world, retrieved from many studies of historical documentary sources.

Existing documentary evidence related to climate

Sources containing historical documentary evidence related to climate range from chronicles, administrative/clerical documents, personal diaries, and travel reports, to ship logbooks, scientific writings, and newspaper articles.

Documentary evidence can be divided into direct observations and indirect (proxy) data. Direct observations include narrative reports on daily weather, climate anomalies, weather-induced hazards, and non-weather-related events such as famines and epidemics. Indirect data are principally organic (plant phenology, information related to crop harvest) or non-organic (ice-snow phenology, information on water levels) in nature, but this category also includes cultural evidence (rogation ceremonies; Pfister et al. 1999). When using historical data, it is important to note that direct observations are not necessarily more accurate than indirect proxy data: a record of someone noting a "cold winter" can be much more vague than, for example, records of late flowering of cherry blossoms or delayed dates of ice break-up in a harbor. About half the documentary evidence included in this inventory is based on direct observations, 20% on indirect proxy data, and 15% on a combination thereof. A small number of series are multi-proxy reconstructions, combining documentary evidence with instrumental measurements and natural proxies.

While some documentary series extend further into the past beyond the Late Medieval Period, the focus here is on more recent evidence. About a third of all data series included in the inventory are available for the 15th century, 54% for the 16th century, 65% for the 17th century, 90% for the 18th century, and 100% after 1800.

Documentary evidence is unevenly distributed in space. While many series are available for Europe (43%) and Asia (31%), much less evidence stems from other continents: 10% from Africa, 8% from North America, 6% from South America, and only 2% from Australia (Fig. 1). For Europe and Asia, especially China, documentary series exist for both temperature and precipitation. For Africa and South America, on the other hand, all the available data provide information on precipitation but not temperature. The majority of data series in the inventory are proxies for precipitation (50%) and temperature (36%); very few data are available for other proxies such as wind and cryosphere parameters (e.g. data on glacier movements) (14%).

Case-study: Temperature anomalies after volcanic eruptions

To point out the value of documentary evidence for climate reconstructions, temperature anomalies after the strong volcanic eruption of Mount Serua (Indonesia) in 1693 (Arfeuille et al. 2014) and a further unknown eruption in 1695 (Sigl et al. 2015) are analyzed. These two eruptions resulted in a noteworthy cooling over the Northern Hemisphere (NH), especially in the summer months of the following years (Sigl et al. 2015). If this cooling is captured by natural proxies such as ice cores, one can assume that it must also have been documented in archives of society. Especially relevant in this context are records related to harvest, which would have been impacted by cooling during the growing season.

To investigate a potential cooling signal in the NH following the 1693 and 1695 volcanic eruptions, temperature signals from 22 available documentary series covering this timespan are analyzed. The temperature

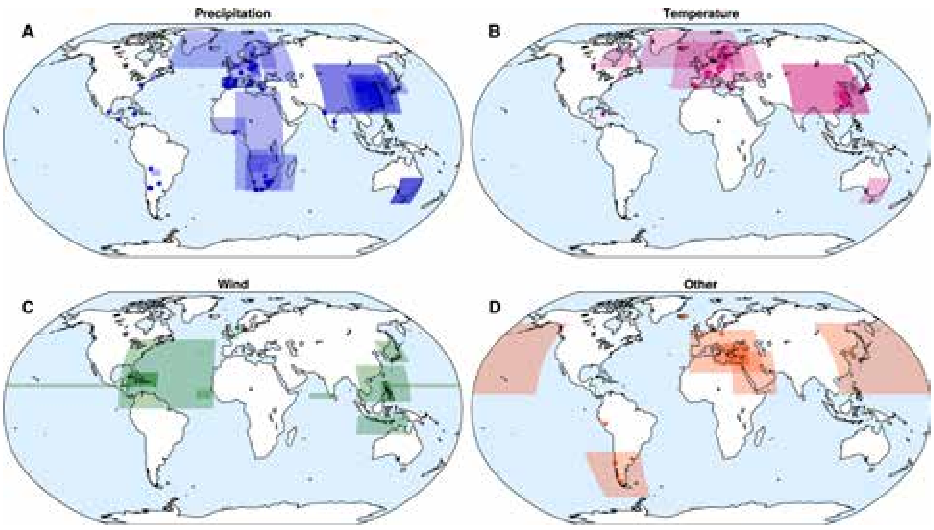

Figure 1: Spatial distribution of available documentary series on climate from the global inventory for **(A)** precipitation, **(B)** temperature, **(C)** wind, and **(D)** other. Circles indicate evidence assigned to a specific location; rectangles mark relevant areas for which climate information is found by a source.

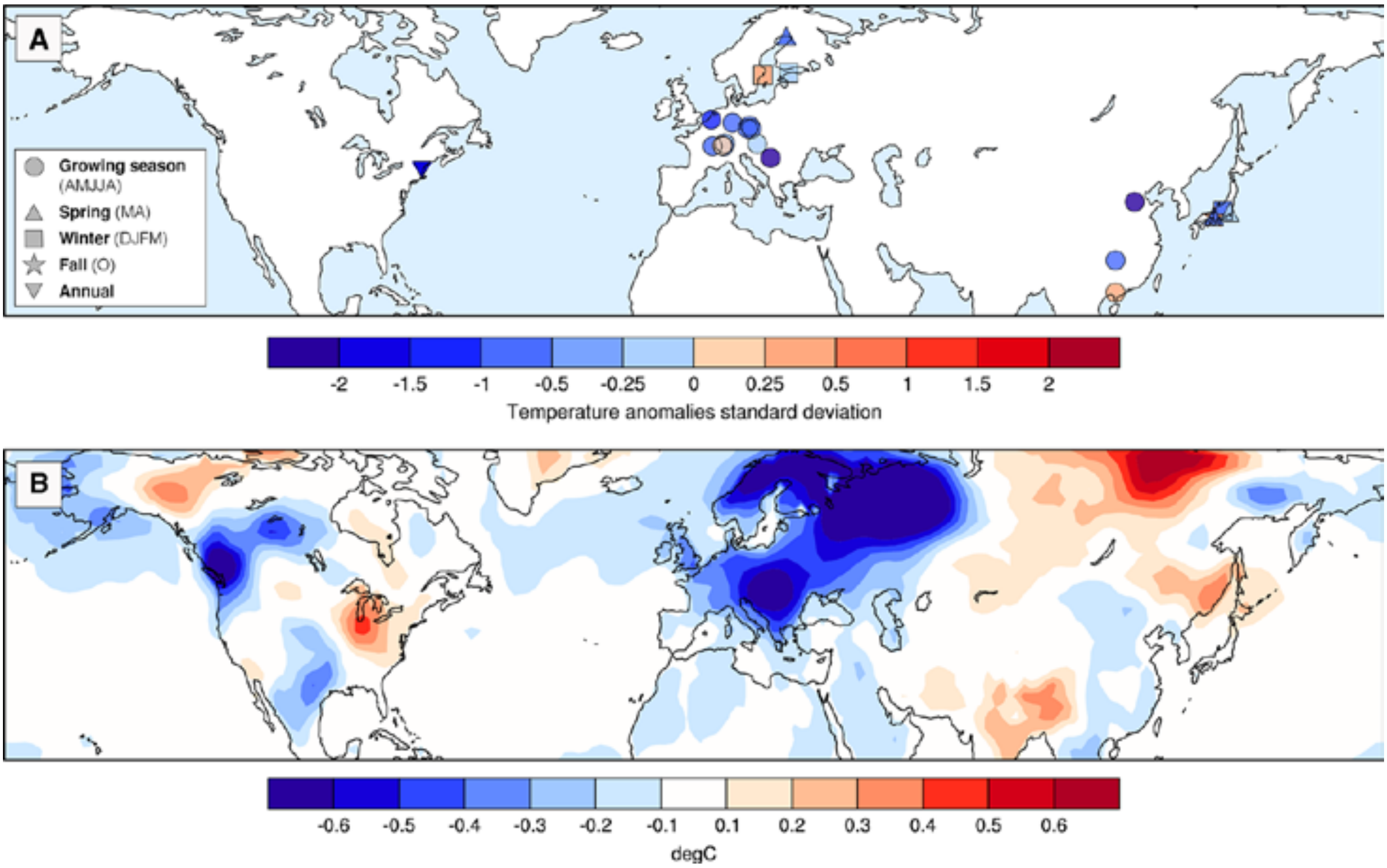

Figure 2: (A) Temperature composites from documentary series for the 1693 and 1695 volcanic eruptions. Proxy series are categorized into seasonal groups. **(B)** Composites of surface air temperature during the growing season (April–August) from the EKF400v2.0 reconstruction.

during the anomalous period 1693–1697 (five years) was expressed relative to the combined average of the 10 years prior (1683–1692) and 10 years after (1698–1707). Each documentary series represents a temperature signal for a particular season or month. To compare these temperature composites, they are grouped into signals for spring (March–April), growing season (April–August), fall (October), winter (December–March), as well as an annual signal.

As shown in Figure 2a, 16 of the 22 documentary series show negative temperature anomalies for the years after the volcanic eruptions in 1693 and 1695. The signal is especially homogenous over Europe where the growing season during 1693–1697 was notably cooler than during the reference period. All but one of the European growing season proxies exhibit negative anomalies. They consist of temperature proxies based on various phenological parameters, e.g. grape and grain harvest dates, freezing of water bodies, duration of snow cover, as well as direct observations of the weather such as reports on temperature-related features such as extreme frost periods. The most prominent anomaly can be seen over the Carpathian Basin, a proxy based on documentary evidence from Hungarian sources (Bartholy et al. 2004). Also, spring proxies in Europe (ice break-up on the Torne River; Loader et al. 2011) and Japan (dates of the cherry blossom; Aono and Kazui 2008; Aono 2014) indicate cooler-than-normal conditions. For winter and fall, less evidence is available, and no clear signal emerges.

The sole source for North America shows a strong negative anomaly based on the annual proxy in New England (Baron 1995). This potentially indicates that colder-than-average temperatures following the volcanic eruptions might not be restricted to the warm seasons but were rather a multi-annual event. The historical evidence relating to summer temperatures for China is based on the REACHES Climate Database (Wang et al. 2018) and contains regional variations.

These findings based on documentary evidence correspond with the temperature composite from the EKF400v2.0 reconstruction (Franke et al. 2017) for the growing season (April–August; Fig. 2b). The global reconstruction shows very strong negative anomalies over Europe and indicates that the post-volcanic cooling after the 1693 and 1695 eruptions was especially strong over Europe. The temperature signal over Asia and North America is more ambiguous. This is in good agreement with the signal shown in the documentary evidence (Fig. 2a).

Outlook

As demonstrated in the example of the volcanic eruptions of 1693 and 1695, documentary evidence has great potential to aid in accurately reconstructing past temperature. Although there is relatively little documentary evidence available compared to natural proxies or instrumental measurements, the historical information is of high precision and thus of great value. In addition to temperature proxies, there are many sources available that may help reconstruct precipitation through dry-wet indices. These sources might be particularly relevant in arid subtropical regions in the Mediterranean, China, and Africa, for example, where other sources of information are sparse.

This global documentary inventory on climate compiles a set of essential documentary evidence and thus lays the foundation for incorporating historical documentary evidence into climate reconstructions on a global scale. These sources are invaluable in complementing early instrumental measurements as well as natural climate proxies to realistically reconstruct the past climate.

AFFILIATIONS

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

CONTACT

Angela-Maria Burgdorf: angela-maria.burgdorf@giub.unibe.ch

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SISAL achievements and future initiatives

Nikita Kaushal[1], F. Lechleitner[2] and L. Comas-Bru[3]

Phase 1: Achievements

Speleothems are important paleoclimate archives because of their global distribution and exceptional age control. During Phase 1 (2017–2020), the PAGES working group Speleothem Isotopes Synthesis and Analysis (SISAL; pastglobalchanges.org/sisal) built a global network of speleothem researchers and created a global database of speleothem oxygen and carbon isotopes. Led mainly by early-career researchers, the group has published three database versions (SISAL_v1: Atsawawaranunt et al. 2018a, 2018b; SISAL_v1b: Atsawawaranunt et al. 2019; Comas-Bru et al. 2019; SISAL_v2: Comas-Bru et al. 2020a, 2020b). SISAL_v2 contains nearly 700 speleothem records with standardized age models and incorporates most of the speleothem records published so far (see Fig. 1).

The first version was supported by a paper summarizing our experiences with building SISAL_v1 (Comas-Bru and Harrison 2019), and a special issue comprising regional reviews of speleothem-based climate reconstructions (pastglobalchanges.org/products/12764). SISAL also published a protocol to use the database for isotope-enabled model evaluation (Comas-Bru et al. 2019). Since then, the database has been used to address long-standing fundamental issues, such as the relationship between the oxygen isotopic composition of speleothems, drip water, and meteoric precipitation (Baker et al. 2019); data-model comparisons examining the impact of convective activity on precipitation oxygen isotopes (Hu et al. 2018); data-model comparisons on interpreting oxygen isotopes from monsoon regions on orbital time-scales (Parker et al. 2020); and model reconstruction of the mid-Holocene to examine insolation forcing of climate (Cauquoin et al. 2019). An additional paper used the SISAL database to look at routinely measured and rarely interpreted speleothem carbon isotopes (Fohlmeister et al. 2020).

Long-term data stewardship

In the last three years, SISAL has fostered community discussions on data quality and sharing, and provided proof of aligned academic incentives resulting from such activities. This has been achieved through a team of regional coordinators supported by the group's Steering Group. During Phase 2, we are exploring the next step of providing long-term data stewardship in larger community-curated database sites. This will ensure that quality-checked, up-to-date speleothem data will be available beyond the working group's timeline. Further, this will ensure that public archiving of speleothem data is supported by a community that is actively engaging with issues such as data standardization and interoperability.

Phase 2: Future initiatives

During Phase 1, we created a database of speleothem isotopic data, the most commonly measured speleothem proxy. However, many factors influence the isotopic composition of speleothems and robust interpretations remain a key gap. During Phase 2, we will use (1) cave monitoring data and process-based models to establish more robust baselines for the modern period, and (2) contiguous speleothem measurements, such as trace element records, to facilitate interpretations of the recorded regional climate and environmental changes.

We are liaising with the cave monitoring community via the Innsbruck Quaternary Research group (cave-monitoring.org) to gather data from individual researchers. Currently, the webpage consists of cave locations, lists of measured cave monitoring parameters, and contact information (Fig. 1). Phase 2 aims to build a database of cave-monitoring data as required for proxy-system and process-based modeling. We will also examine over 50 recent publications on the application of trace element proxies from speleothems, to understand how trace elements can strengthen climatic interpretations of speleothem isotopic data in addition to providing independent paleoclimatic and paleoenvironmental information. These two research avenues should ultimately provide us with a new set of tools for robust interpretations of the speleothem records for use in PMIP isotope- and non-isotope enabled climate model evaluations.

As we begin our work on Phase 2, we encourage interested researchers from all career stages and backgrounds to join the group. Contact a member of the Steering Group (pastglobalchanges.org/science/wg/sisal/people), subscribe to the SISAL mailing list (listserv.unibe.ch/mailman/listinfo/sisal.pages), or follow us on Twitter (@SISAL_wg).

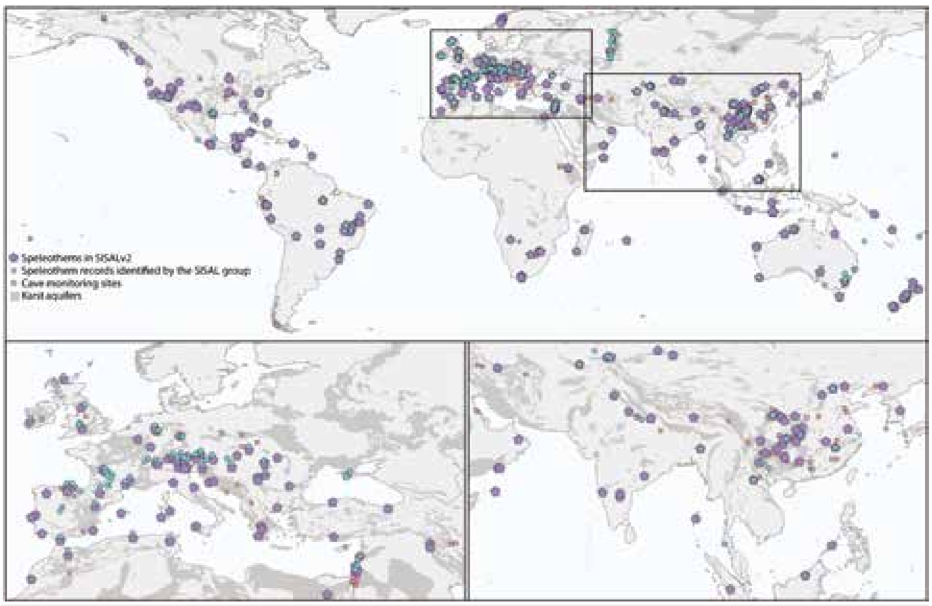

Figure 1: Cave monitoring sites available in the cave-monitoring.org database and speleothem records available in SISAL_v2 database are plotted on a karst aquifer map of the world. European and Asian sites have been expanded in the panels below.

AFFILIATIONS

[1]Asian School of the Environment, Nanyang Technological University, Singapore

[2]Department of Chemistry and Biochemistry, University of Bern, Switzerland

[3]School of Archaeology, Geography and Environmental Science, University of Reading, UK

CONTACT

Nikita Kaushal: nikitageologist@gmail.com

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Climate Variability Across Scales (CVAS): Phase Two

Raphaël Hébert, M. Casado and T. Laepple

Climate variability occurs at all timescales, encompassing periodic oscillations such as daily and annual cycles at short timescales and the Milankovitch periodicities at longer timescales, as well as the scaling continuum of climate variability which contains continuously increasing variance with timescale. The climatic signal of the recent instrumental period, when direct measurements are available, contains both natural and anthropogenic signatures. This makes attribution and detection of climate change complicated, particularly at the regional scale where forced variability plays a relatively smaller role.

To demodulate the internal variability from the response to external forcing, which is necessary to improve future climate projections, it is thus needed to go beyond the instrumental record. For instance, it remains uncertain whether the internal variability is dependent on the background state, and thus whether we should expect a warmer world to be more stable, or more variable with increasing occurrence and magnitude of extreme events.

In this context, paleoclimate records are a unique tool to extend our observation of climate variability to longer timescales, to be able to study not only the climate system without the impacts of human activity, but also different background states characterized by various combinations of orbital parameters, greenhouse gas concentrations, climatic conditions, and geological configurations.

Challenges remain, however, in the interpretation of paleoclimate proxies, as many archival processes are involved, each of which may affect the recorded signal. For instance, precipitation intermittency creates aliasing in ice-core records, and then diffusion acts as a low-pass filter (Casado et al. 2020). Similarly, aliasing is created in sediment cores by seasonality and the sampling scheme, while bioturbation and sediment mixing also act as low-pass filters (Dolman et al. 2020). Those non-climatic processes lead to timescale-dependent biases and errors (Kunz et al. 2020) which may completely dominate the climatic signal over particular timescale bands (Fig. 1).

Proxy system modeling (PSM) is crucial in order to recognize and quantify proxy-specific biases, and allow for a formal characterization and interpretation of the transfer function from the climate input to the recorded signal. The further development of PSM is thus an important topic of paleoclimate research and at the heart of CVAS' (pastglobalchanges.org/cvas) research goals, building on the legacy and integrating

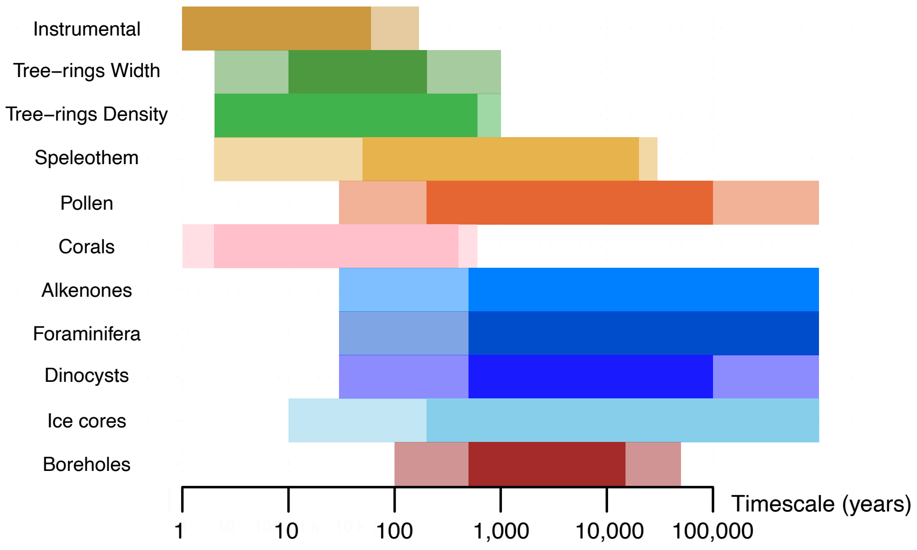

Figure 1: Shown are the timescales approximately spanned by different climate sensitive proxies. The solid part indicates the most reliable range, whereas the shaded part generally requires proxy system modeling to be interpreted due to effects such as diffusion, bioturbation, biological smoothing, detrending, limited length and availability, lack of modern analogs, changing climatic interpretation, and others.

the former Paleoclimate Reanalyses, Data Assimilation and Proxy System modeling (DAPS; pastglobalchanges.org/daps) group.

Another important aspect of the second phase of CVAS is the development and improvement of statistical tools for the analysis of timeseries and spatial distributions. These will be made available to other PAGES working groups to further space-time analysis in the broader geoscience community.

Both the PSM and statistical tools developed will contribute essential elements to the overarching aim of CVAS: a comprehensive synthesis of the spatio-temporal structure of climate variability, or "the CLIMAP of temperature variability". This implies a particular focus on decadal- to millennial-scale variability, where the greatest knowledge gap lies. Beyond the rather complete picture provided by instrumental data up to decadal timescales, the very long timescales (>10 kyr) are also relatively well quantified since there are few effective spatial degrees of freedom remaining, i.e. a few high-quality timeseries effectively represent the global behavior. The PAGES 2k Network (pastglobalchanges.org/2k) and Speleothem Isotopes Synthesis and AnaLysis (SISAL; pastglobalchanges.org/sisal) working groups will therefore provide very valuable information, which will be at the core of our investigation.

CVAS will subsequently explore the implications of the results for future reconstruction and assimilation efforts, and also for constraining future climate evolution. While climate models have demonstrated their ability to produce realistic forced climate variability, important modeling challenges remain to accurately capture internal feedbacks and processes necessary to close the variance gap with regional climate reconstructions at longer than multidecadal scales (Laepple and Huybers 2014).

The environment, biodiversity, and human society are all linked to the stability of the Earth system and its sensitivity to external forcing, as well as the statistics of extremes. These are thus central topics in PAGES' holistic Earth system science approach, and CVAS has accordingly adopted an interdisciplinary approach based on statistical and spectral analysis. The application of CVAS concepts beyond climate variability will also be explored. Particularly through potential collaboration with the Resistance, Recovery and Resilience in Long-term Ecological Systems (EcoRe3; pastglobalchanges.org/ecore3) and PalEOclimate and the PeopLing of the Earth (PEOPLE 3000; pastglobalchanges.org/people3000) groups, we will investigate possible linkages and interactions between physics and life on timescales longer than centuries.

AFFILIATION

Alfred-Wegener-Institut for Polar and Marine Research, Potsdam, Germany

CONTACT

Raphaël Hébert: raphael.hebert@awi.de

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The International Paleofire Network (IPN)

Carole Adolf[1], O. Blarquez[2], D. Colombaroli[3], E. Dietze[4], K. Marcisz[5] and B. Vannière[6]

Fire plays an essential role in Earth's ecosystems in terms of ecology, carbon cycling, and radiative forcing, as well as having been extensively used for agro-pastoral purposes for millennia. However, each of the last few years has been an exceptional wildfire year, creating exorbitant damage to human and animal life, ecosystems, and infrastructure. As climate continues to warm, extreme wildfire events like the ones seen in the Western United States, Siberia, Australia, Indonesia, the Amazon, and the Brazilian Pantanal, among others, are projected to increase in frequency across all biogeographic regions (IPCC 2018).

In light of these events, it is clear that we need an even more in-depth understanding of wildfire dynamics, as well as cross-disciplinary approaches to develop effective ecosystem-specific fire management practices. It is especially challenging to address the uncertainties related to changes in fire regimes due to climate change in an increasingly urbanized world. Long-term records of fire provide crucial information regarding the interplay between fire, vegetation, climate, and human land use. In combination with traditional fire knowledge, climate models and urban planning approaches, powerful and effective insights can be gained for the development of effective and sustainable fire policies.

Hence, the aim of the International Paleofire Network (IPN; www.paleofire.org) is to provide a platform to develop, catalog, and enable wildfire knowledge exchange across temporal and spatial scales, as well as across research disciplines and stakeholder communities. The IPN especially wants to increase the amount of paleofire research that can directly inform regional- to global-scale fire modeling and fire policy, by supporting paleofire research projects written in close collaboration with stakeholders. The aim is to increase the amount of actionable wildfire insights that address pressing issues faced by fire managers today, while accounting for climate change in the future. To reach this goal, the IPN will locate and connect wildfire expertise around the world; provide tools, training, and expertise to analyze paleofire data; and host wildfire discussion forums, webinars, and workshops. Additionally, the IPN wants to support early-career researchers to improve their employability by connecting them to a wide stakeholder community.

The work of the IPN originates from the PAGES Global Paleofire Working Group (pastglobalchanges.org/gpwg2), which ran in two phases from 2008 until 2019. The focus has been on identifying long-term regional and global fire trends, calibration methods, and the inclusion of different knowledge bases to inform fire policy.

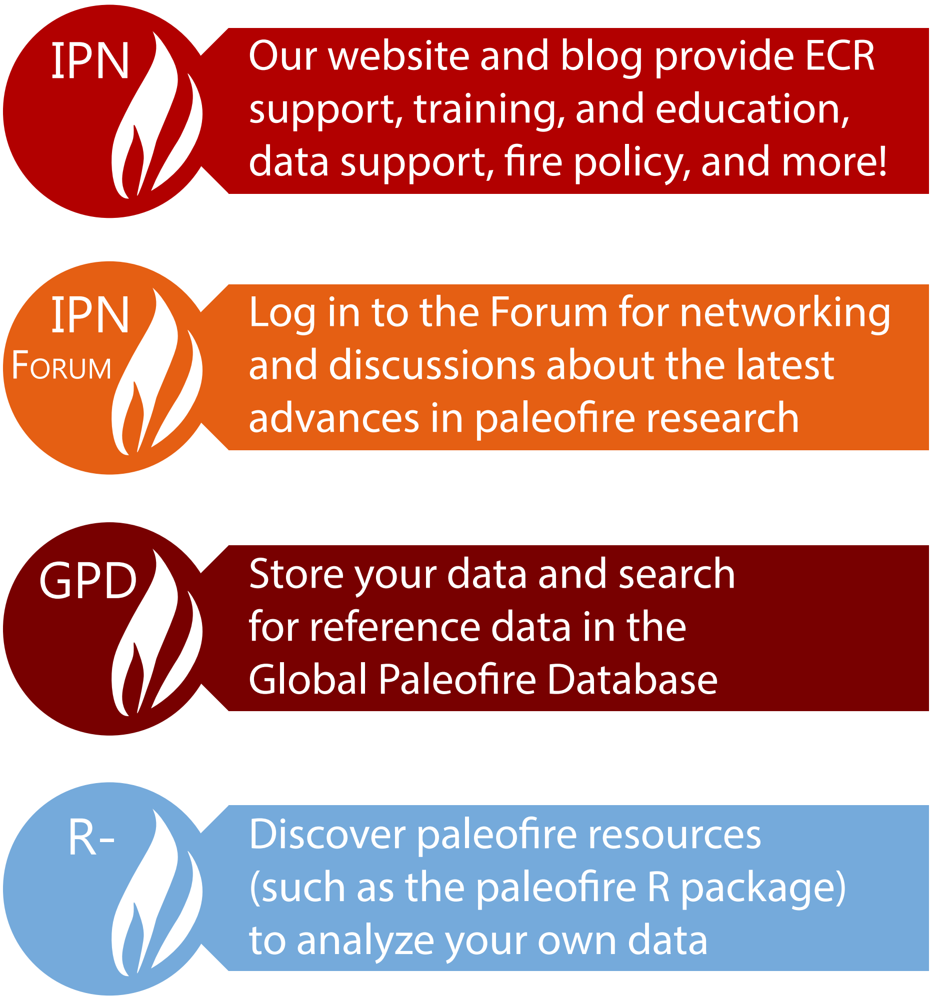

Figure 1: Structure and description of the different components of the IPN.

The IPN will continue to maintain the Global Paleofire Database (GPD) and its associated paleofire R package, and will provide a platform for highlighting further method developments. The GPD, which is a public-access database, is of central importance to enable regional syntheses and to identify geographical gaps in paleofire records. Alongside the GPD, the IPN hosts a paleofire discussion forum (https://discourse.paleofire.org), where a collection of resources and information regarding literature, events, and discussion topics is available. Interested colleagues are encouraged to actively engage with the IPN and to provide further feedback regarding the IPN and its activities via contact@paleofire.org and/or using the following questionnaire: https://forms.gle/a4jwjJvygoxtUqxL7

AFFILIATIONS

[1]Long-Term Ecology, Department of Zoology, University of Oxford, UK
[2]Geography Department, University of Montreal, Canada
[3]Geography Department, Royal Holloway University of London, UK
[4]Polar Terrestrial Environmental Systems, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
[5]Climate Change Ecology Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznan, Poland
[6]Centre National de la Recherche Scientifique (CNRS), MSHE, Chrono-environnement, Besançon, France

CONTACT

IPN Executive Committee: contact@paleofire.org

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The DEEPICE research and training network

Emilie Capron[1] and Amaelle Landais[2]

Exciting challenges lie ahead for the European ice-core community! A new continuous deep ice core will soon be drilled down to the bedrock in East Antarctica, as part of the Beyond EPICA Oldest Ice core (BE-OI) project to potentially recover ice from 1.5 million years (Myr) ago. This new deep ice core should enable us to address major scientific questions regarding the role of ice-sheet size and greenhouse gas concentrations on the dynamics of past climate changes. In particular, a key challenge is to understand why the periodicity of glacial to interglacial cycles changed from 41 to 100 thousand years during the Mid-Pleistocene Transition, between 0.8 and 1.2 Myr before present, while at the same time the orbital forcing given by astronomical parameters keeps the same periodicity (Fig. 1).

In addition to the logistical challenges associated with the drilling of a ~3 km-long ice core in extreme climatic conditions, large technological and scientific challenges need to be tackled in order to exploit the precious archive in the field and back in the laboratory. The new records between 0.8 and 1.5 Myr before present will be located at the bottom of the ice core and, hence, the ice will be extremely thinned: 1 m of ice is expected to contain 10,000 years of climate and environmental history. Retrieving the best scientific outputs from this precious ice requires the development of new techniques to be able to precisely analyze very small quantities of ice. The proxies measured in the ice should then be translated into climate or environment parameters, which requires the determination of the associated transfer functions. Finally, the results related to atmospheric greenhouse gas concentrations, ice-sheet dynamics, and climate changes will have to be compared with climate and ice-sheet model simulations, in order to set the ice-core-based interpretations in a global context with the ultimate aim to better understand the climate dynamics of the Mid-Pleistocene Transition.

The H2020-MSCA Deep icE corE Proxies to Infer past antarctiC climatE dynamics (DEEPICE; pastglobalchanges.org/deepice) Innovative Training Network (2021–2025), with its team encompassing 12 research institutes and seven non-academic partners from 11 countries, capitalizes on this unique European scientific endeavor. It will provide an educational and training program to 15 PhD students, benefiting from the momentum created by the BE-OI drilling project and its societal impact by complementing it with a program of basic and applied science questions to prepare for the BE-OI ice-core analysis that will start in the coming years. Moreover, the DEEPICE network will offer unique links with non-academic partners that will provide the students with the extended skill set required for pursuing either academic or non-academic careers.

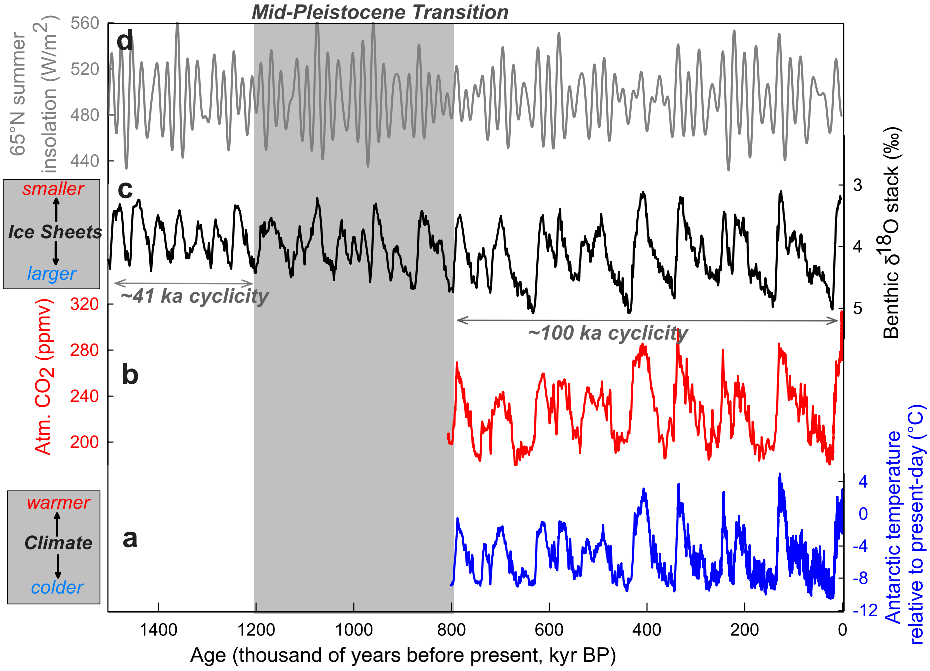

Figure 1: Key paleoclimatic records over the past 1.5 Myr. **(A)** Antarctic climate (Jouzel et al. 2007) and **(B)** atmospheric CO_2 concentration measured on Antarctic ice cores (Bereiter et al. 2015); **(C)** Marine benthic foraminifera $\delta^{18}O$ indicative of ice-sheet volume changes (Lisiecki and Raymo 2005); **(D)** 65°N summer insolation (Laskar et al. 2004).

The DEEPICE science goals

The overall objective of DEEPICE is to equip the 15 early-career researchers (ECRs) with a solid background in ice-core-related climate science, with a particular focus on Antarctica, technical and communication expertise, and access to a large collaborative network within the academic and non-academic worlds. The DEEPICE specific science goals are to:

- develop novel techniques required for the analyses of the precious ice samples of the BE-OI ice core to obtain the highest possible resolution records of climate and environment;
- document surface climate parameters in the East Antarctic plateau, where weather data are rare and instrumentation deployment is difficult;
- quantify potential effects that may affect the quality of climate records in the deepest ice;
- document past ice-sheet dynamics and flow in East Antarctica in relation to climate change;
- study and document the past climate dynamics in Antarctica on short and long timescales, with the ultimate aim to improve predictions on future climate and the state of the Antarctic ice sheet;
- communicate state-of-the-art research on climate change with a focus on the role of Antarctica in the climate system.

The DEEPICE training program

Through a number of networking events, three training schools, and collaborative efforts between host institutions including the opportunity for the ECRs to receive training at multiple institutions, the DEEPICE training program will provide the ECRs with experience in the following fields:

- Development of novel, state-of-the-art specialized instrumentation;
- Climate and ice-sheet modeling;
- Statistical analysis of signal processing;
- Mediation, education;
- Interdisciplinary and cross-sectoral research.

Calls for DEEPICE PhD applications will start in January 2021. Please spread the word to students who are interested in experimental, statistical, or modeling approaches applied to past climate questions!

AFFILIATIONS

[1]Université Grenoble Alpes, CNRS, IRD, IGE, Grenoble, France

[2]Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France

CONTACT

Emilie Capron: emilie.capron@univ-grenoble-alpes.fr

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Early-career researchers' perceptions of PAGES working groups

Deirdre D. Ryan[1], S.J. Alexandroff[2], F.A. Lechleitner[3], N. Schafstall[4], T. Trofimova[5] and H. Detlef[6]

In January 2020, a survey was sent to PAGES early-career researchers (ECRs) to assess their understanding of PAGES' structure, awareness of support offered by the PAGES Early-Career Network (ECN; pastglobalchanges.org/ecn), and the involvement of ECRs in working groups (WGs). The latter assessment serves as an important baseline metric for active efforts by PAGES to improve ECR involvement in WGs.

The survey was developed by this article's authors and spearheaded by Dr. Henrieka Detlef. PAGES members who identified as ECR on their member profiles and those subscribed to the ECN mailing list were emailed survey requests. Recognizing there may be some overlap, this totalled 653 PAGES members. We received 123 responses (~19%); however, eight of the survey participants had no awareness of WGs, so the results presented here are based upon the responses of the remaining 115 individuals (Fig. 1). The survey results are not considered representative of all PAGES ECRs.

Half of the respondents (51%, 59 of 115) are subscribed to at least one WG mailing list, but only 26% (30) consider themselves to be an active or contributing member to at least one WG. Most active members (98%) consider WG involvement beneficial to their career. The majority of active members are either postdoctoral researchers or PhD students located in Europe or North America, followed by South America and Australia/Oceania, and then Africa and Asia. Involvement in WGs is most commonly initiated through attendance at a WG workshop and/or through a supervisor. We were unable to assess the representation of ECRs within WGs as records of membership are not maintained by WGs.

The survey helped to identify hurdles for ECR involvement in WGs. A large percentage (71%) of respondents, who were aware of WGs and/or subscribed to a WG mailing list, have never approached a WG regarding membership. Barriers to ECR involvement in WGs included not knowing how to join a working group, the impression that they have nothing to offer or that they may not be welcome to join a WG, and a lack of any WG that fits their research. Four survey participants who did approach WGs for membership were unsuccessful due to a lack of positive response from the WG.

Survey participants were also asked to provide suggestions on how to facilitate the inclusion and involvement of ECRs in WGs. The most repeated suggestion was more funding to cover travel costs. Other responses were:

- An annual open call by WGs for new membership;
- Active efforts by WG members to invite ECRs and involve ECRs in new projects;
- Virtual options for all WG meetings and workshops;
- A mentoring program with senior scientists who are willing to provide support to ECRs from disadvantaged backgrounds or whose supervisors are not active within PAGES.

Other efforts to enhance ECR involvement are already underway. Since 2018, every WG has been required to appoint an ECR as liaison to the PAGES ECN. New WGs are encouraged to include ECRs in the steering group and highlight their participation in the proposal. Workshop funding is primarily reserved for the support of participating ECRs. In addition, the PAGES ECN has started a science cluster which aims to connect ECRs who want to start new WGs or collaborate on other scientific projects. Finally, a webinar series is slated to begin before the end of 2020 that will focus on how ECRs can engage in existing WGs. Announcements will be made on the PAGES ECN website and in the PAGES e-news as these activities develop.

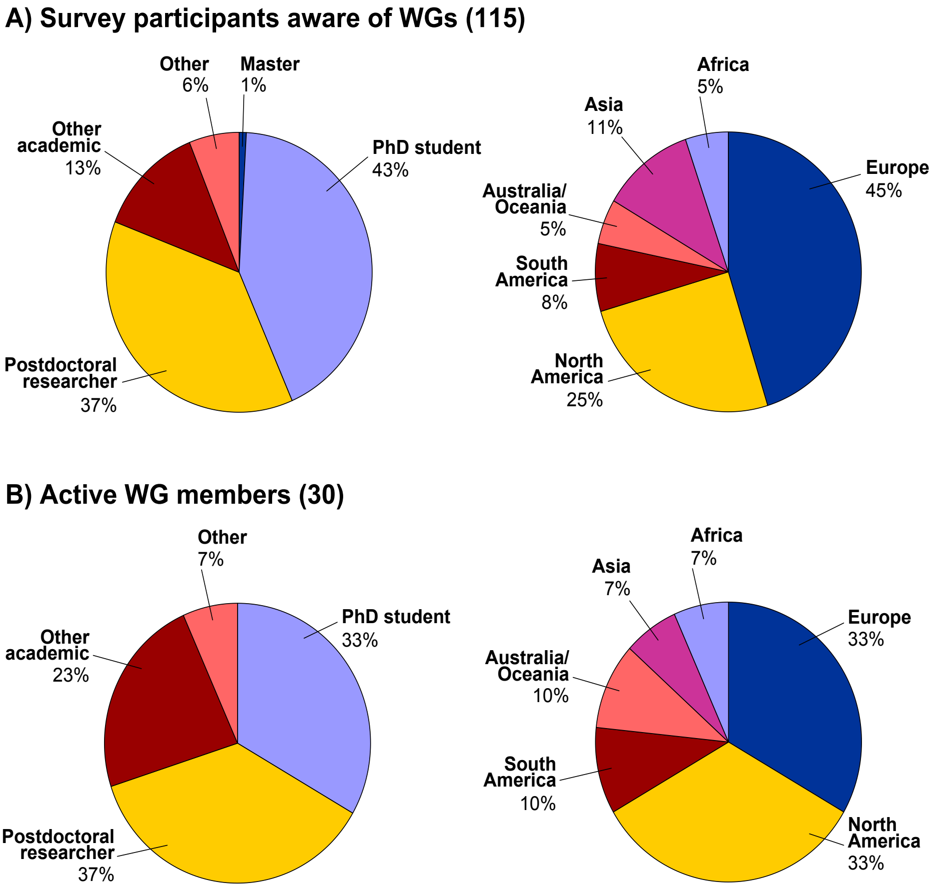

Figure 1: Career stage and continent of residence of **(A)** participants who are aware of WGs and **(B)** participants who are active within a WG. Career stages in the survey, summarized here as "Other academic" included Research Associate, Lecturer, Instructor; Senior Lecturer; Associate Professor, Reader; or Professor (non-tenured). The "Other" designation includes those working outside academia or actively looking for academic employment.

AFFILIATIONS
[1]MARUM – Center for Marine Environmental Sciences, University of Bremen, Germany
[2]College of Life and Environmental Sciences, University of Exeter, UK
[3]Department of Chemistry and Biochemistry and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[4]Czech University of Life Sciences, Faculty of Forestry and Wood Science, Department of Forest Ecology, Prague, Czech Republic
[5]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway
[6]Department of Geoscience, Aarhus University, Denmark

CONTACT
Henrieka Detlef: henrieka.detlef@geo.au.dk

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PAGES ECN develops activity clusters: A new structure to support global networking

The PAGES ECN Steering Committee*

The PAGES Early-Career Network (ECN; pastglobalchanges.org/ecn) was developed to create a permanent platform for early-career researchers (ECRs) to exchange ideas, perform outreach, engage in skill development, and find collaborations among fellow ECRs within PAGES. The PAGES ECN is an integral part of PAGES and provides a platform for all ECRs, whether or not they are directly involved with an active PAGES working group. Moreover, the ECN helps ECRs become more involved in the scientific community and within PAGES.

Originally founded by 11 ECRs following the 2017 PAGES Young Scientists Meeting in Spain, the structure of the group has evolved as membership has grown. The Steering Committee, now comprising 10 members serving fixed terms, largely oversees visioning, communication, and coordination of activities among different branches of the group.

Many initiatives and activities have recently grown into activity "clusters". Any ECN member is welcome to initiate or join a cluster, which is run relatively independently, albeit in close communication with the Steering Committee. With this new cluster structure, we aim to increase diverse and global representation within the PAGES ECN and encourage collaboration among members. We invite ECRs from various backgrounds to bring in their ideas and engage in leadership roles, whether they are directly managing ongoing activities (e.g. the blog) or single products (e.g. a local workshop). In this article, we introduce our updated structure and some exciting new initiatives.

Training and networking events are organized by the Workshop and Webinar clusters, with annual workshops and webinars on topics relevant for ECRs as well as for the wider paleoscience community. The Write Club cluster organizes online writing retreats for members to commit scheduled time to writing in a focused atmosphere. The Blog cluster organizes our peer-reviewed blog, The Early Pages (theearlypages.blogspot.com), giving ECRs the opportunity to share their research and stories and gain experience in the review process. The Science cluster is the most recent initiative to be formed, which aims to facilitate scientific collaboration and new projects among ECRs. The ECN clusters also catalyze opportunities for ECRs beyond PAGES, such as the ECR workshop "Past Socio-Environmental Systems" (PASES; pases2020.com), jointly organized with INQUA (inqua.org/ecr).

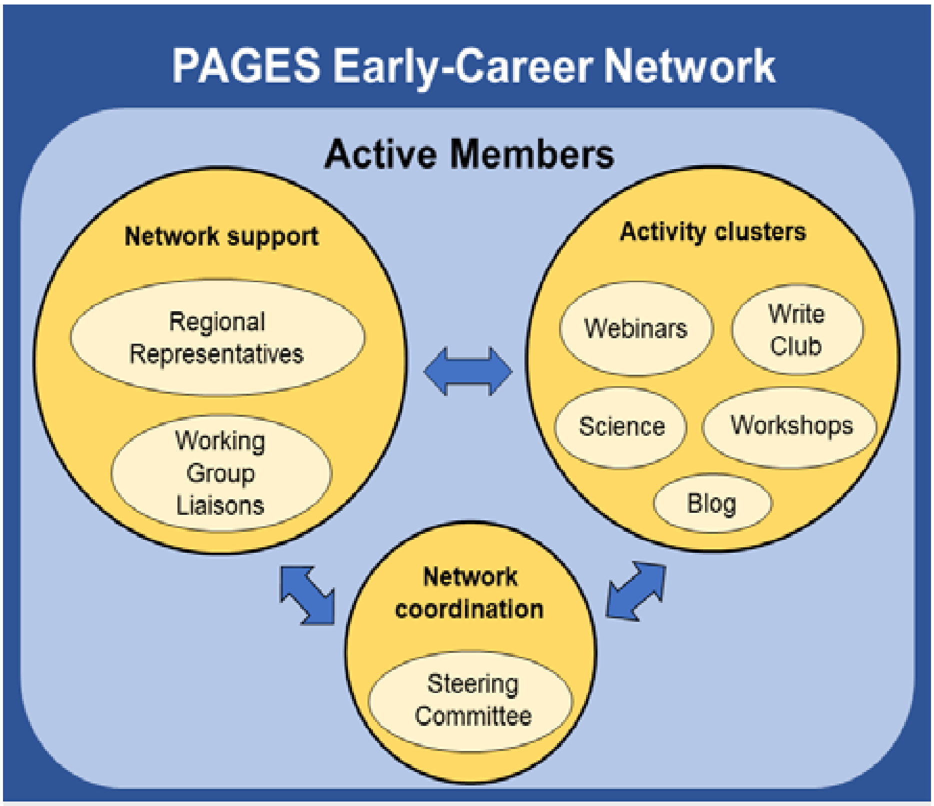

Figure 1: Structural overview of the PAGES ECN.

Each PAGES working group has at least one member serving as an ECN liaison to ensure optimal communication about opportunities for ECRs in PAGES. Regional representatives from countries worldwide work to promote the ECN and PAGES among peers in their region. Regional representatives support the ECN by sharing job, funding, and other opportunities from their region and are a point of contact for local ECRs. Many new initiatives within the ECN are driven by regional representatives, in connection with the activity clusters (Fig. 1). For example, regional representatives in Central and South America have organized several Spanish-language webinars and those in Africa are developing an interactive database to track opportunities for ECRs within their region. New ideas for workshops, outreach, and other ECN products are also being developed by the Steering Committee, regional representatives, and other active ECN members.

All interested ECRs of PAGES are welcome to join the ECN to participate in any of our activities or share ideas and contribute to our products. If you are interested in joining or leading a cluster, please send an email to the appropriate contact (an overview and contact information is found on our website: pastglobalchanges.org/ecn/clusters).

Initiatives to form new clusters are welcome as well. If you want to learn more about our activities in general, go to our website (pastglobalchanges.org/ecn) or contact your local regional representative (pastglobalchanges.org/ecn/regional-reps). You can also subscribe to the ECN mailing list (listserv.unibe.ch/mailman/listinfo/pages.ecn.pages) to receive our monthly newsletter and general announcements.

AFFILIATIONS
*S.J. Alexandroff (University of Exeter, UK); X. Benito (National Socio-Environmental Synthesis Center (SESYNC), University of Maryland, Annapolis, USA); A. Bonk (University of Gdańsk, Poland); M. Mette (US Geological Survey, St. Petersburg Coastal and Marine Science Center, FL, USA); N. Schafstall (Czech University of Life Sciences, Prague, Czech Republic); T. Trofimova (NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway)

CONTACT
PAGES ECN Steering Committee:
pages.ecn@gmail.com

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PAGES 2k Network community survey

PAGES 2k Network coordinators*

Currently in its 13th year, the PAGES 2k Network (pastglobalchanges.org/2k) entered its third phase in 2017. This phase is scheduled to sunset at the end of 2021. In order to gather feedback, the coordinators surveyed current participants and the broader 2k Network community in June 2020. We are grateful to the 49 respondents who took the time to provide thoughtful feedback, including one of the original founders of the Network (self-identified).

Responses came largely from scientists who completed their PhD more than eight years ago (76%). Many respondents have been involved in one or more of the Phase 3 projects (ARAMATE, CLIM-ARCH-DATE, CLIVASH2k, CoralHydro2k, Global T CFR, GMST reconstructions, Iso2k, MULTICHRON, PALEOLINK, PSR2k; pastglobalchanges.org/science/wg/2k-network/projects) as a project member (29%), project coordinator (8%), contributor to database compilation efforts (33%), and/or manuscript co-author (31%).

Approximately half of all respondents, including those not directly involved in the working group, had used data provided by the projects and previous 2k Network efforts (45%). While some of the projects are still gaining momentum, others are in the process of disseminating their final results or have already concluded. The collective effort has been impressive; outputs have included comprehensive datasets (Fig. 1) and data-model comparisons, and several papers have already been published (e.g. Bracegirdle et al. 2019, Neukom et al. 2019, PAGES 2k Consortium 2019, Bothe and Zorita 2020, Konecky et al. 2020).

Survey respondents gave useful suggestions for improving the PAGES 2k Network and its coordination, including communication, via circulars or online meetings, as well as by enabling interested parties to more easily become involved with the ongoing efforts. The responses also highlight the importance of facilitating networking among participants at different career stages and in different geographical regions, as the network consists of a large number of both early-career researchers and more established scientists spread around the globe.

Looking forward to the scientific challenges that the PAGES 2k Network and the broader community should work to solve over the next five to 10 years, many respondents agreed that better data coverage is necessary, both spatially and temporally, in order to resolve greater detail. There was a call to extend the focus further back in time, such as the past 5000 years or as far back as the early Holocene. On the other side of the spectrum, some respondents suggested making the connection to future climate change more prominent. Others commented on the focus on temperature reconstructions and suggested expanding this to include hydroclimate or human–climate interactions. Development of new proxies and data-model integration were also identified as potential goals. As some of the projects of the PAGES 2k Network are creating databases, there was also concern about the future maintenance of these databases once the working group eventually sunsets.

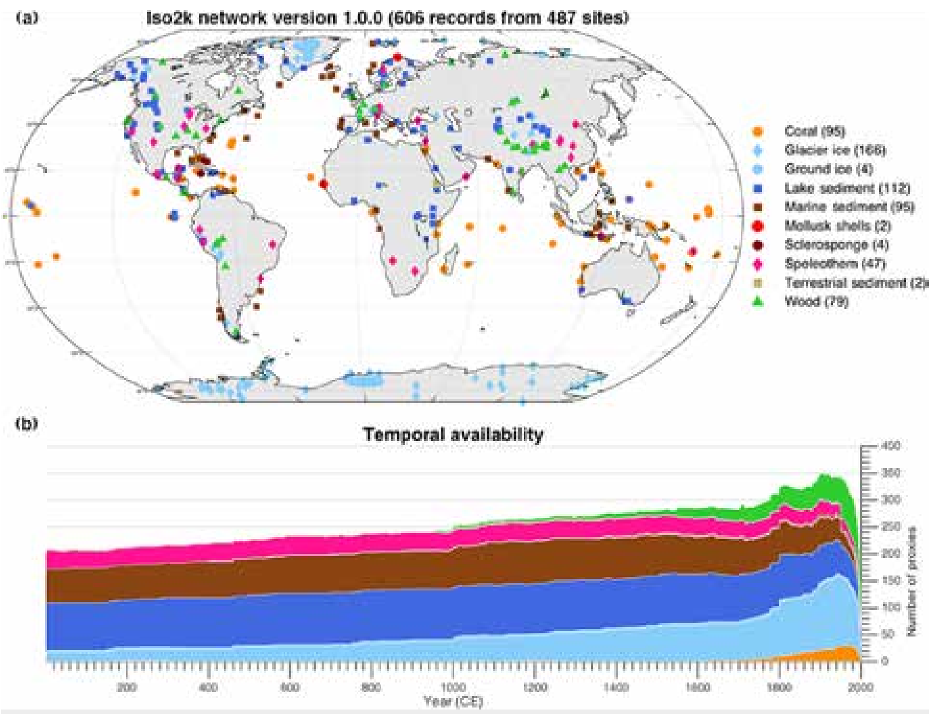

Figure 1: Example of a large community effort by Iso2k project participants during the 2k Network's third phase: a database of paleo-$\delta^{18}O$ and δ^2H records over the past 2000 years. **(A)** Spatial distribution of records in the database from different archives (see legend). **(B)** Availability of records in the Iso2k database over time during the past 2000 years. Reproduced from Konecky et al. (2020).

Approximately half of the survey respondents were enthusiastic about a subsequent fourth phase (44%), while 46% felt that it was time to wrap up the working group and transition efforts to work on the challenges identified above. While no definite plans have yet been made, the coordinators are currently considering options for online events in 2021 as well as possibilities to reach out to the wider community in person at the PAGES Open Science Meeting in Agadir, Morocco, in May 2022. We hope to use this opportunity to provide networking opportunities, workshops, and/or a celebration of the past 13 years of this working group. Updates will be available at pastglobalchanges.org/calendar/upcoming/127-pages/2065.

Phase 3 of the PAGES 2k Network built on the strong foundation established during the preceding eight years; the success of the network is largely due to the enthusiasm and energy of the many scientists at all career stages who have contributed over this period. Regardless of the future of this working group, we hope to be able to pass on the expertise that has been accumulated, particularly in online community collaboration, to the next generation of paleoscientists and PAGES working groups.

AFFILIATIONS

*N.J. Abram (The Australian National University, Canberra, Australia); O. Bothe (Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research, Geesthacht, Germany); S. Eggleston (PAGES International Project Office, Bern, Switzerland); B.L. Konecky (Washington University, St. Louis, USA); H.W. Linderholm (University of Gothenburg, Sweden); B. Martrat (Institute of Environmental Assessment and Water Research IDAEA-CSIC, Barcelona, Spain); H. McGregor (University of Wollongong, Australia); S.J. Phipps (University of Tasmania, Hobart, Australia); S. St. George (University of Minnesota, Minneapolis, USA)

CONTACT

Sarah Eggleston: sarah.eggleston@pages.unibe.ch

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Paleo sea-level science is advancing through Earth- and ice-process insights, but key questions linger

Daniel M. Gilford[1], S. Coulson[2] and V. C. Alvarez[3]

PALSEA Express virtual meeting, 15-16 September 2020

Unconventional and historic, the first-ever virtual PALeo constraints on SEA level rise (PALSEA; pastglobalchanges.org/palsea) Express workshop (pastglobalchanges.org/calendar/2020/127-pages/2043) was held in September, fostering valuable scientific exchanges among new and established community members. Eight invited speakers, 23 poster presenters, and a record number of over 200 attendees focused on improving their understanding of ice-sheet and solid-Earth processes that drive paleo sea-level change.

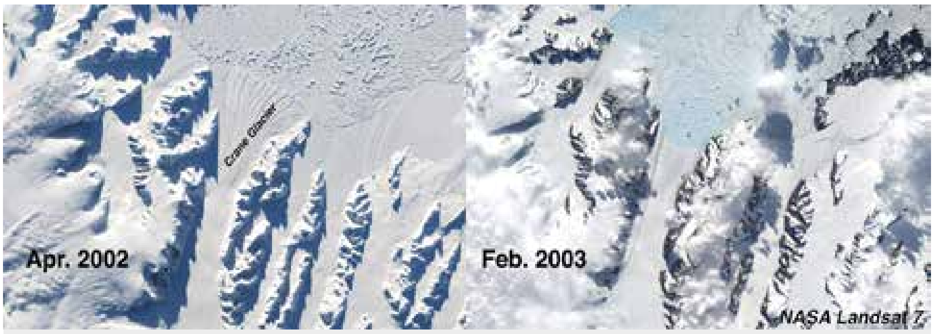

Figure 1: The stunning retreat of Crane Glacier (West Antarctica) following ice-shelf crevassing and collapse in 2002 (NASA; https://earthobservatory.nasa.gov/images/43459/retreat-of-crane-glacier-antarctic-peninsula).

A new compilation of Northern Hemisphere (NH) ice-sheet extent through the Quaternary (Batchelor et al. 2019) showed key spatial differences in ice-sheet configurations between glacial cycles, emphasizing the ongoing need to gather new field evidence and constrain past ice-sheet extents for modeling study support. Data standardization and consolidation has been a core goal of the PALSEA community over the last decade. Workshop presentations promoted open and accessible data and methods, highlighting the growing number of tools and databases available to the community, and their usefulness. One talk, for example, illustrated the importance of sea-level databases for assessing coastal environment vulnerability (Horton et al. 2019).

The uncertain fate and historical evolution of the Antarctic Ice Sheet (AIS) was an overarching theme of the meeting. The AIS is strongly coupled with the surrounding Southern Ocean, driving important ice-ocean interactions which feed back on AIS stability. Several invited talks considered the physical mechanisms controlling this stability, including brittle ice-sheet processes and feedbacks between meltwater pulses, ocean stratification, and basal AIS melt. An improved ice-sheet model capturing hydrofracturing and calving of marine-terminating ice shelves (e.g. observed Crane Glacier retreat over 2002–2003, Fig. 1) suggested more Last Interglacial (LIG) AIS retreat than previously thought, bringing LIG global mean sea-level estimates closer to (though not fully reconciling them with) those from observed sea-level indicators. A report from the WArm Climate Stability of West Antarctic ice sheet in the last INterglacial (WACSWAIN; https://www.esc.cam.ac.uk/research/research-groups/wacswain) field campaign outlined critical ongoing efforts to document LIG AIS extent with >600-m ice cores.

Coupled sea-level ice-sheet models demonstrated the considerable influence that NH ice-mass changes can have on AIS variability (Gomez et al. accepted for publication in *Nature*). Dramatic melting of NH ice sheets during the most recent deglaciation (~14,000–10,000 years ago) led to geographically variable sea-level rise around Antarctica, driving increased AIS mass losses (since flux across the grounding line is proportional to water height), and may have affected AIS stability during the Holocene and LIG. Additional insights from glacial isostatic adjustment (GIA) models and the incorporation of 3D Earth structure were central themes of the virtual poster session.

Advances by the paleo sea-level community also raised old questions. Several presentations built on John Mercer's classical paper (1968), suggesting LIG sea-level highstands could inform future sea-level rise. However, LIG peak sea level remains elusive, with recent estimates showing little change from the 6–9 m estimated by a landmark review five years ago (Dutton et al. 2015). Combining evidence from Bahamian coral terraces, GIA models, and a machine-learning technique, one speaker suggested LIG peak sea level could have been as low as 1.1 m (Dyer et al. in review in *Sci Adv*), bringing previous higher estimates into question. Other challenges discussed were the relative timing of Antarctic and Greenland ice-sheet retreat during deglacial periods, the role of spatially varying mantle viscosity in ice-sheet stability, and whether certain sea-level indicators can be considered eustatic.

The virtual nature of the workshop encouraged broader academic diversity, including participants from 34 different countries. Removing financial and travel barriers noticeably increased participation and involvement from early-career researchers. Attendees highlighted the impact of the pandemic and political and racial unrest on the paleo sea-level science community, and in particular the need to support young scientists. Discussions also emphasized the paramount importance of diversifying our community moving forward and supporting initiatives such as #BlackInGeoscienceWeek. We hope PALSEA Express 2020 was the first of many such successful virtual meetings.

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AFFILIATIONS

[1]Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers University, New Brunswick, NJ, USA

[2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA

[3]School of Earth and Environment, University of Leeds, UK

CONTACT

Daniel M. Gilford: daniel.gilford@rutgers.edu

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PAGES
PAST GLOBAL CHANGES

PAGES International Project Office
Hochschulstrasse 4
CH-3012 Bern
Switzerland

Telephone +41 31 631 56 11
Email pages@pages.unibe.ch
Website pastglobalchanges.org
Twitter @PAGES_IPO
Facebook PastGlobalChanges

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Series Editors
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Angela Wade

Layout
Sarah Eggleston

Design
sujata design

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