Towards integrated historical climate research: the example of ACRE (Atmospheric Circulation Reconstructions over the Earth)

Rob Allan[1], Georgina Endfield[2], Vinita Damodaran[3], George Adamson[4], Matthew Hannaford[5], Fiona Carroll[1], Neil Macdonald[6], Nick Groom[7], Julie Jones[5], Fiona Williamson[8], Erica Hendy[9], Paul Holper[10], J. Pablo Arroyo-Mora[11], Lorna Hughes[12], Robert Bickers[13], Ana-Maria Bliuc[14]

[1]. Met Office Hadley Centre. Exeter, UK
[2]. School of Geography, University of Nottingham, UK
[3]. Centre for World Environmental History, University of Sussex, UK
[4]. Department of Geography, Kings College London, UK
[5]. Department of Geography, University of Sheffield, UK
[6]. School of Environmental Sciences, University of Liverpool, UK
[7]. Department of English, University of Exeter, UK
[8]. National University of Malaysia, Malaysia
[9]. School of Earth Sciences, University of Bristol, UK
[10]. Paul Holper and Associates, Melbourne, Victoria, Australia
[11]. Department of Geography, McGill University, Canada
[12]. School of Advanced Study, University of London, UK
[13]. Department of History, Bristol University, UK
[14]. School of Social Sciences, Monash University, Australia

ABSTRACT

Climate change has become a key environmental narrative of the 21st century. However, emphasis on the science of climate change has overshadowed studies focusing on human interpretations of climate history, of adaptation and resilience, and of explorations of the institutions and cultural coping strategies that may have helped people adapt to climate changes in the past. Moreover, although the idea of climate change has been subject to considerable scrutiny by the physical sciences, recent climate scholarship has highlighted the need for a re-examination of the cultural and spatial dimensions of climate, with contributions from the interpretive humanities and social sciences. Establishing a multidisciplinary dialogue and approach to climate research past, present and future has arguably never been more important. This paper outlines developments in historical climatology research and highlights examples of integrated multidisciplinary approaches to climate, climatic variability and climate change research, conducted across the physical sciences, social sciences, humanities and the arts. We highlight the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative as one example of such an integrated approach. Initially, ACRE began as a response from climate science to the needs of the agricultural sector in Queensland, Australia for a longer, more spatially and temporally-complete database of the weather. ACRE has now evolved to embrace an international group of researchers working together across disciplines to integrate their efforts into a four-dimensional (4D) dynamical global historical climate-quality reanalysis (reconstruction).

THE CASE FOR INTEGRATED CLIMATE RESEARCH

Debates over anthropogenic global warming, and the potentially "*looming and apocalyptic changes in future climate*"[1] (p. 6), represent one of the dominant environmental narratives of the 21st century. However, this narrative has not widely incorporated research on the societal understanding of climatic variability and climate change, nor the implications of such fluctuations and changes for human vulnerability and/ or resilience. Instead, it has tended to marginalise explorations of the institutions and cultural coping strategies that may have helped people adapt in the past. It has been argued that this may be a function of an overemphasis on climate science and modelling, and a lack of engagement with cultural climate history.[2] Determining both the likely future climates and how different communities might be affected by and respond to climate change, however, has become an issue of global and political importance. Establishing a multidisciplinary dialogue and approach to climate research past, present and future, which can also feed into climate risk management, is therefore vital[3]. Developing a true capacity for multidisciplinary research, however, is extremely challenging, while sustaining such an endeavour is a significant task, logistically and financially.[4-5]

The separation of the physical sciences as discrete from the social sciences, humanities and arts, and emphasis on scientific evidence overlooks the cultural and social context of its production. Moreover, there are contrasting categories of research questions, different modes of academic debate, and different approaches to the presentation of research between disciplines.[4-5] In facilitating the development of multidisciplinary research in climatic variability and climate change, understanding these challenges is critical. Similar challenges stem from differences in ways of thinking and processing knowledge that underpin the language of, and research training in, different disciplines.[6]

During the 1980s and 1990s, the primary focus of the climate science community was to develop model-based climate change scenarios extending out 50-100 years.[7-9] More recently, major efforts have been made to link seamlessly the various models and research approaches used in forecasting to those investigating climate change[10] – with a more equal focus on disentangling climatic variability and climate change signals and drivers, improving seasonal forecasting, and the use of all of this material for climate services (see http://gfcs.wmo.int/).[11] The climate science community has also focused on the collection and refinement of observational evidence for climate change through historical global temperature records extending back to the mid-19th century. However, there is now a growing realisation that improvements in the quantity, quality and resolution of instrumental and documentary historical observations and proxy/palaeo climate data, and developments in both reconstruction methodologies and dynamical historical reanalyses, can provide new baselines of global weather and climate. The latter can be employed to test climate models for climate change detection, and provide an essential historical framework within which to develop an understanding of potential changes in weather and climate impacts, risks and extremes. However, embracing wider collaborations with, or inputs from, the social sciences, humanities and the arts, seems to remain beyond the current thinking or capacity of the mainstream climate science community.[12]

One area that has witnessed rapid growth over the last decade in particular is research focusing on the construction of regionally specific climatic histories and historical extreme weather events, and investigations of social responses to these events. These are central to understanding the nature of the changes that might take place in the future and their impacts.[3,13] This area of research is undergoing something of a re-emergence. There was of course much interest in this latter topic in the late nineteenth and early twentieth century – for example in the work of Ellsworth Huntington, who was broadly concerned with the impacts of climate and climate changes over centuries and millennia on the development and location of civilisation and the influence of weather types on human efficiency. This "simple determinism" faced considerable criticism, not least because of the way these arguments were interpreted and applied in racist dogmas in the early twentieth century.[14] By the middle to latter parts of the twentieth century, however, Hubert Lamb and Emmanuel Le Roy Ladurie played key roles in establishing more nuanced studies of historical climate-society relationships[15] using a mix of historical documentary and instrumental data and indices.[16-17]

A new breed of scholars working at this interface, especially geographers and historians, have been at the forefront of a new form of historical climatology and climate history research, with its focus on both climate reconstruction and explorations of the societal impacts of, and responses to, past climate change at a range of scales (see, for example [15, 18-30], among many others). Such pioneering work is not only providing detailed regional climate histories but, perhaps most significantly, is offering important insights into how societies have coped with and have responded to climatic variability and anomalous weather events in the past.[a] The environmental history community is also now engaged in work that explores how society has conceptualised, apprehended and responded to climate changes in different contexts and at different points in time, a point acknowledged by Culver.[31] Moreover, there is an imperative to do so, given that it is "*increasingly acknowledged that the [climate change] agenda needs to include consideration of the strategies for human adjustment to future changes*" and to address the factors that influence human perceptions and behaviour all of which may contribute to relative vulnerability or resilience.[32]

Yet such studies have often remained isolated from climate modelling endeavours and have been embedded within individual disciplines, leading to the problems of communication and integration listed above. New initiatives are seeking to address this problem. The emergence of the resilience paradigm[33], for example, has generated a new role for history in climate research. Driven by IHOPE (Integrated History and future of People on Earth), this approach develops Holling's theories[34] of ecological systems with multiple stable states into integrated social-environment systems.[35-36] Here, historical and archaeological data provides the temporal dimension unveiling the processes that have governed system dynamics, in order to identify interventions towards sustainability.[37-41] With a focus on agent-based models, this approach has been more closely aligned with policy-driving organisations such as the IPCC (Intergovernmental Panel on Climate Change) and Future Earth than historical climatology approaches. However, it has been criticised as downplaying the role of human agency in the past, and for failing to recognise that an individual's vulnerability is as much a function of their dynamic worldviews and beliefs as their assets and capabilities, to the extent that this cannot be replicated within a model.[42-45]

Although the current availability of digital climate data (particularly daily series, which enable extremes to be assessed) is often restricted to the second half of the 20th century over many parts of the world, there have emerged in recent years a number of integrated climate initiatives that build on historical climatology approaches.[46] The most recent include the University of Freiburg-led Tambora.org project[47], which offers a collaborative research environment with access to large data collections on climatic parameters such as temperature, precipitation, storms, floods, etc. with different regional and thematic foci derived from historical sources. Significantly, this provides a database for original text quotations together with bibliographic references and the extracted places, dates and searchable information on climate and environment. A further example is the University of Bern-led Euro-Climhist database [48], which represents a comprehensive tool for managing, analysing and displaying climatic (high-resolution) proxy evidence from 1.2 million natural and documentary archives, including data detailing the Late Maunder Minimum and its societal implications across Europe based on a range of historical and proxy data sources. These efforts highlight the need for the careful documentation of historical sources, rather than to just provide their interpretation as fact, made without sufficient consideration of the cultural and societal background shaping them.

There are also a number of very significant data rescue initiatives underway, recently discussed in the literature.[3,46,49]. These include The Mediterranean Data Rescue (MEDARE) initiative – a cooperative effort aimed

---

[a] See, for example, Christian Pfister, Rudolf Brázdil , Rudiger Glaser , Mariano Barriendos, Dario Camuffo, Matias Deutsch , Petr Dobrovolny, Silvia Enzi, Emanuela Guidoboni, Oldrich Kotyza, Stefan Militzer S, Lajos Racz, Fernando S Rodrigo.. "Documentary evidence on climate in sixteenth-century Europe". Climatic Change 43 **(1999)**: 55–110; Christian Pfister "The vulnerability of past societies to climatic variation: a new focus for historical climatology in the twenty-first century". *Climatic Change* **100**(**1**) (2010):25–31; David J Nash and Georgina H. Endfield" 'Splendid rains have fallen': links between El Niño and rainfall variability in the Kalahari, 1840–1900". *Climatic Change* **86**(**3-4**) (2008): 257-290; Mariano Barriendos "Climatic variations in the Iberian peninsula during the Late Maunder Minimum (AD 1675-1715). "An Analysis of data from rogation ceremonies". *Holocene* **7** (1997):105-111; Rudolf Brazdil Hubert Valasek and Katarina Chroma "Documentary evidence of an economic character as a source for the study of meteorological and hydrological extremes and their impacts on human activities". Geogfiska Ann 88 **(2006)**: 79–86; Georgina H. Endfield and David J. Nash; "Drought, desiccation and discourse: missionary correspondence and nineteenth-century climate change in central southern Africa". *Geographical Journal*, **168**(**1**) (2002): 33-47; Phil D. Jones, P.D and Keith R. Briffa, "Unusual climate in northwest Europe during the period 1730-1745 based on instrumental and documentary data". *Climatic Change* **79** (2006): 361-379; Neil Macdonald, Cerys A. Jones, Sarah J. Davies and Cathryn Charnell-White "Historical weather accounts from Wales: an assessment of their potential for reconstructing climate". *Weather* **65** (2010): 72-81

at enhancing surface climate data availability over the Greater Mediterranean Region. MEDARE's purpose is to "*develop, consolidate and improve surface climate data and metadata rescue activities across the [Greater Mediterranean Region] GMR*". The long-term goal is to work towards the development and provision of comprehensive high-quality, high-resolution time series of instrumental climate data for the region[46] (p. 35). Another key example of an international consortium-led initiative with a major focus on data rescue is the Atmospheric Circulation Reconstructions over the Earth (ACRE). This initiative, with a strong multidisciplinary focus, melding together climate science with the social sciences, humanities and the arts around global outputs from historical reanalyses based on archival records, is the focus of the next section.

MULTIDISCIPLINARY CLIMATE / WEATHER RECONSTRUCTIONS: ACRE AS AN EXAMPLE

ACRE and historical reanalysis

The international ACRE initiative (http://www.met-acre.org) [50] undertakes and facilitates historical global surface terrestrial and marine weather data recovery, imaging and digitisation. Under ACRE's international umbrella, there are various regional data foci and collection partners, each taking responsibility for finding, digitising, and making accessible historical weather data from their region (see Figure 1). All of these data are fed into several existing international repositories, including the International Comprehensive Ocean Atmosphere Data Set (ICOADS), International Surface Temperature Initiative (ISTI), Global Precipitation Climatology Centre (GPCC) and the International Surface Pressure Databank (ISPD).

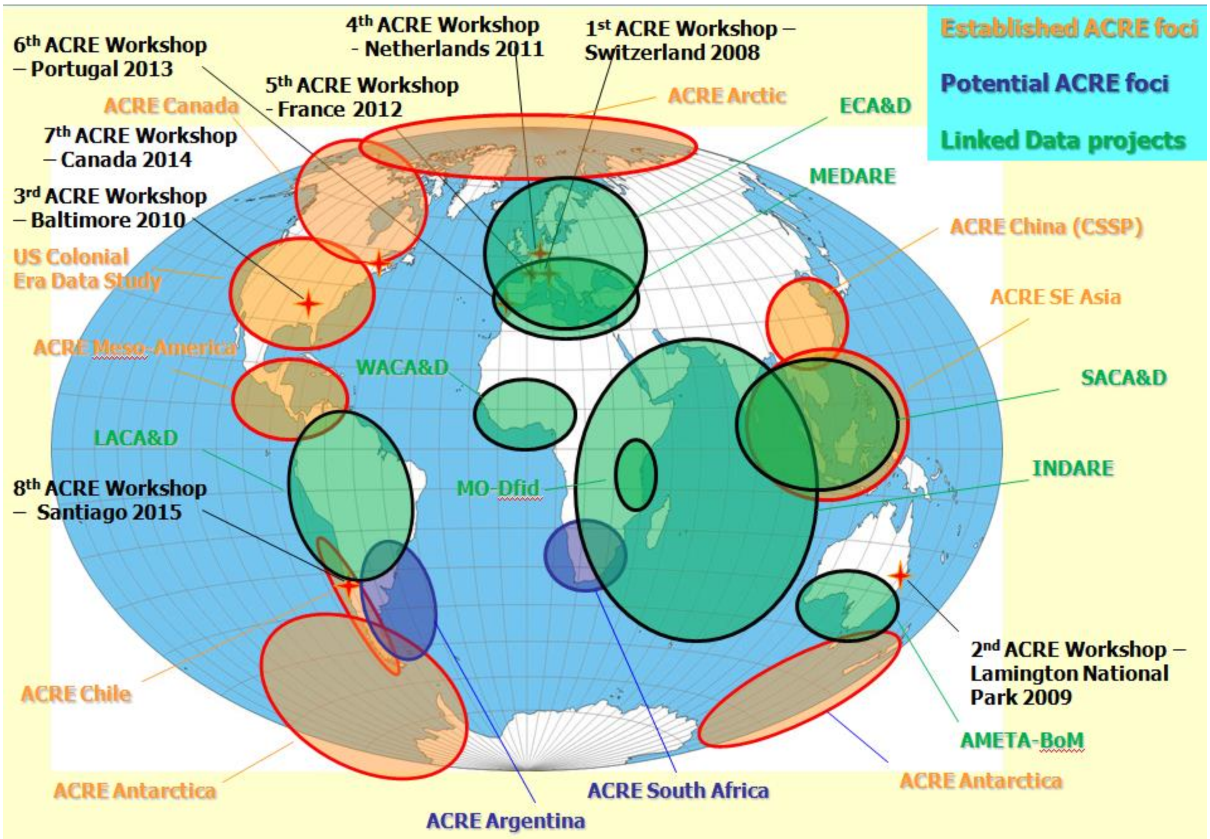

Figure 1: ACRE Regional foci and associated data rescue projects: see top right hand side key for details (ECA&D, SACA&D, WACA&D and LACA&D - http://www.ecad.eu/icad.php; INDARE - http://www.wmo.int/pages/prog/wcp/wcdmp/INDARE.php; MEDARE - http://www.omm.urv.cat/MEDARE/; CSSP - http://www.metoffice.gov.uk/research/collaboration/cssp-china; MO-Dfid (see Page 4 last Tanzanian entry) - http://www.gfcs-climate.org/sites/default/files/Information%20Matrix%20on%20Ongoing%20and%20Planned%20Initiatives%20Final%20221014.docx; AMETA-BoM - http://en.wikipedia.org/wiki/Todd_Weather_Folios Also shown in black type are the locations and dates the annual ACRE Workshops since the initiative began.

ACRE works with the above repositories to provide the best quality and quantity of surface weather observations for assimilation into all reanalyses[b], especially the ACRE-facilitated 20th Century Reanalysis Project (20CR) (http://www.esrl.noaa.gov/psd/data/20thC_Rean/).[51] The current version extends from 1850 to near-present, with various experiments ('scout runs') looking to push 20CR back into the early 19th Century.

The 20CR is an ongoing international project led by the National Oceanic and Atmospheric Administration (NOAA) and Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado. It generates 4 dimensional (4D) global reanalysis datasets for climate applications extending back to the 19th Century using an Ensemble Kalman Filter and only surface synoptic pressure observations.[51] Monthly sea ice boundary conditions from the COBE-SST2 data set plus new pentad Simple Ocean Data Assimilation with sparse input (SODAsi.2) sea surface temperature fields[52] provide boundary conditions for the latest release, 20CRv2c. Dynamical downscaling by the Met Office regional climate modelling system - Providing REgional Climates for Impacts Studies (PRECIS) (http://www.metoffice.gov.uk/precis) - is being used to 'take' 20CR output down to finer resolution (25 km to 100 m). This will enhance the value of this output for the climate science community, wide ranging climate applications and services, policy makers, planners, environmental managers, educational and public sectors (https://docs.google.com/viewer?a=v&pid=sites&srcid=bWV0LWFjcmUub3JnfGFjcmV8Z3g6MWEwMTRjMzI0ZmE0ZTEwNg). Both the data and 20CR outputs are freely available.

Multidisciplinary Background

Over the past five years, ACRE has been working with climate-linked projects and networks led by colleagues in the UK social sciences, humanities and arts communities, funded by bodies such as the Arts and Humanities Research Council (AHRC) and the Joint Information Systems Committee (JISC) (Figure 1). ACRE is also part of the Indian Ocean World Centre (IOWC) initiative based at McGill University in Canada (http://indianoceanworldcentre.com/), and is contributing, along with the University of Sussex, to their focus on *The Indian Ocean World: The Making of the First Global Economy in the Context of Human-Environment Interaction* (http://indianoceanworldcentre.com/Team_7). The challenge now, is to engage with the wider international social sciences, humanities and arts communities. Already, ACRE's data collecting activities embrace many of the archives of the old European empires, an invaluable source for the Global South (the nations of Africa, Central and Latin America, and most of Asia) where data can be sparse and difficult to locate. In support of this, the initiative is working to develop a formal collaboration with the International Council on Archives (http://www.ica.org/3/homepage/home.html).

---

[b] In reanalyses, observations and a numerical model that simulates one or more aspects of the Earth system are combined objectively to generate a synthesized estimate of the state of the system. A reanalysis typically extends over several decades or longer, and covers the entire globe from the Earth's surface to well into the stratosphere.

Figure 2: ACRE collaborations with Citizen Science, Social Sciences, Humanities and Arts projects

These collaborations (Figure 2), have led ACRE, and its wider community, to begin to go further, and to look at integrating historical 20CR reanalysis output with broader social, historical, cultural, environmental research from the social sciences, humanities and arts communities. Here, we briefly review the nature of some of these collaborations.

Citizen science and maritime logbooks

One of the largest and yet underused sources of historical meteorological and environmental data are archive collections of ships logbooks. These logs contain detailed weather observations - air and sea temperatures, air pressure, wind and clouds etc - and qualitative descriptions of sea-ice. There are millions of handwritten pages, and ACRE and its partners have been working to mine them -- photographing hundreds of thousands of pages from UK and US ship voyages dating back into the late 18th - early 19th Century. Rescuing the observations is an enormous task, requiring the reading of millions of handwritten entries, and the transcription of weather and ice records within the entries. This work builds on previous projects such as the EU funded Climatological Database for the World's Oceans (CLIWOC) project, and on pioneering work on the potential and reliability of ships logbooks as a historical source. [53] Through a combination of serendipity and necessity, ACRE has been integral to the development of 'citizen science' data rescue projects, such as *Old Weather* (http://old.oldweather.org/), *Old Weather 2* (http://www.oldweather.org/) (initially funded by JISC, Figure 2.) and *Weather Detective* (http://www.weatherdetective.net.au/) (funded by the Australian Broadcasting Commission as the winner of their 2014 National Science Week Citizen Science project). By providing scanned ship logbook weather observations via dedicated web sites, these projects enable volunteers to contribute to the data rescue and digitisation task. So far, around 20,000 volunteers have read well over 1 million pages of paper records and contributed millions of recovered weather observations to international climate datasets – such as the ICOADS, ISTI, GPCC and the ISPD. This initiative improves the quality and quantity of material in such repositories, increasing the pool of global historical surface weather observations assimilated by all reanalyses, especially 20CR.

Documentary reconstructions of extreme weather events in the UK, past, present and future

There is rising concern over the impacts of 'extreme' weather events such as droughts, floods, storms and unusually high or low temperatures. While social and economic systems have generally evolved to accommodate some deviations from "normal" weather conditions, extremes can overwhelm them. Such events, therefore, can have significant impact.[54] The reconstruction of regionally specific historical extreme weather events, and investigations of the social responses to these events, are of crucial significance to assess how different communities in different contexts might be affected by, and respond to, future events and to understand the nature of the events that might take place in the future. Such studies could provide a guide to where the critical human sensitivities to future events may lie. One such study is the three-year AHRC-funded research project, supported under the AHRC's *Care for the Future: thinking forward through the Past* theme and led by the University of Nottingham, with colleagues at Aberystwyth, Glasgow and Liverpool Universities and in partnership with ACRE (Figure 2), The Royal Geographical Society (with the Institute of British Geographers) and Historic England. This team is recovering and integrating historical documentary evidence of past extreme weather events in a series of case studies across the UK - in Southwest, Central and Eastern England, central and coastal Wales and Northwest Scotland. The research, which draws on a wide varierty of materials from farmers' diaries and estate correspondence through to school records and qualitative and instrumental weather diaries, is providing the evidence needed to construct a comprehensive history of extreme weather events and their societal implications across the UK over recent centuries (http://www.nottingham.ac.uk/research/groups/weather-extremes/index.aspx).

The Snows of Yesteryear'/'Eira Ddoe

In a related project, *The Snows of Yesteryear/'Eira Ddoe'* (http://eira.llgc.org.uk/), funded by the AHRC's Landscape and Environment Programme, a research team based at the National Library of Wales and the University of Wales examined archival sources from the early modern period for descriptions of extreme weather events. Information came from diaries, letters and ballads. The team also engaged the community to understand how extreme weather is processed as memory. The project team discussed these representations of climate data as a series of keywords with climate scientists, and began a narrative about using archives from the pre-instrument period for the end result of the research - a source for understanding historic weather events. These data were also the basis – in an allegorical sense – for a performance by Eddie Ladd, Dawns Ysbrydion/Ghost Dance, subsequently commissioned by the National Theatre of Wales. This showed the importance of understanding community vulnerability and resilience to extreme weather, historically and in contemporary society. The project also was a good example of the ways that digital humanities and information management in the humanities have much to add to the study of climate change, especially in the requirements for an underlying digital infrastructure to support this collaborative work, integrating research questions with content, tools, methods, and community involvement where appropriate.

The Chinese Maritime Customs project (CMCS)

The value of interactions between disciplinary initiatives can be seen in the relationship between the History of the Chinese Maritime Customs Service (CMCS) project (http://www.bristol.ac.uk/history/customs/), and ACRE (Figure 2). The CMCS was a foreign-staffed agency of the Chinese central state operating between 1854 and 1950. It undertook a wide range of infrastructural and technology transfer initiatives to service China's foreign trade and the country's incorporation into globalising networks and systems, including lighthouse construction, river and harbour conservancy, hydrography and meteorology. The central archives of the CMCS, held in China, became available to researchers in 2000 for the first time. The service played a central role in the generation and dissemination of climate data in China from c.1880-1940s. The project team began to collaborate with ACRE, identified the current location of the historic data records, and secured AHRC knowledge exchange funding[55] to try to secure access to this, and to provide details of the history of the CMCS meteorological system, its development, standards and equipment.[56]

FACILITATING ACCESS

Support for a baseline of high-resolution, high-quality digital images of archival records containing weather, climate, environmental, cultural and societal information to support integrated historical climate research is essential. In order to facilitate access to such material, there is a need for a generic digital research infrastructure that can support the management of data gathered remotely, especially historic weather primary source materials including logbooks and other weather diaries; provide a transcription platform where necessary, open provide access to the primary sources and the data they contain, and provide the ability to integrate reanalyses products. There should also be a means of oversight of transcription, data management support, and support for use of reanalyses tools, especially access to the complex range of multidisciplinary information required to work with these data. With ACRE, it would allow future use and re-use by processing tools for reanalysis that do not yet exist. Given that these data and reanalyses outputs must ultimately be multilingual, and multi-disciplinary, this is an enormous task. Nonetheless, what is required is an archive that can be accessed by anyone undertaking digitisation of archival records that relate to historic weather and the reanalyses generated from them (the current efforts in climate are still very climate science focused http://www.idare-portal.org/). There are relevant international standards, developed by organisations including the Digital Curation Coalition (http://www.dcc.ac.uk). Integration of existing data archives, through the use of linked data approaches, may be suitable. Critically, the technical solutions require sustained support and intervention.

Educational structures and digital resources

It is equally important to advertise the "*endeavours and successes in data recovery*".[57] For example, ACRE must look to develop the tools and structures that will allow it to engage with a wider audience, especially in the educational sphere, through the provision of a new dynamical global 4D historical database of the weather vastly enhanced via integration with layers of multidisciplinary content. Reaching out in this manner is important for many reasons: First, in many developed countries there is a marked decline in the number of secondary school students pursuing maths and science subjects.[58-59] In the USA, for example, from the mid-1970s to the early-2000s, there has been no substantive change in the proportion of high school graduates who go on to complete or enrol in a STEM field of study.[60] Second, associated with the decline in students pursuing science at secondary and tertiary level are concerns about shortages of teachers, especially in primary schools, with science and mathematics qualifications (http://www.cpre.org/images/stories/cpre_pdfs/math%20science%20shortage%20paper%20march%202009%20final.pdf and https://royalsociety.org/~/media/education/policy/vision/reports/ev-7-vision-research-report-20140624.pdf). Third, the past decade has seen a rise in scepticism about the reality of human-induced climate change. The US National Research Council[61] (p. 35) reports a "*deliberate and organised effort to misdirect the public discussion and distort the public's understanding of climate change*", while in 2013 it was reported that 91 US climate change counter-movement organisations had a total income of more than US$7 billion during 2003–2010.[62]

The challenge now is to produce an international resource for students and the public, presenting weather/climate, climatic variability and climate change in its fuller context. Such a digital resource could be as large as funding permits and would bring to the global audience the vast resources of ACRE and its wider community extending into the social sciences, humanities and the arts. Users would be able to access historic dynamical 4D global reanalysis fields and the weather data and other relevant information used to generate them. Such material would be embellished by access to layers of social, historical, cultural and environmental information provided by the social sciences, humanities and the arts. With such a resource, it would be possible to track local weather historically over centuries, either from direct observations or historical reanalyses and/or their downscaled products. There would also be the potential to link climatic and environmental changes with key historic events.

This digital resource would be managed and maintained by a well-coordinated multi-disciplinary team, including professional science communicators, web experts and researchers. However, in order to support the veracity and sustainability of such efforts, there would need to be new educational structures. It would require the development of a truly multi/cross-disciplinary curriculum at secondary to tertiary education levels which would expose students and researchers to a wider range of integrated science, social sciences, humanities and arts subjects and studies. In a very broad sense, some fledgling elements of such engagements are seen in the UK *RCUK School-University Partnerships Initiative* (http://www.rcuk.ac.uk/pe/PartnershipsInitiative/) where the University of East Anglia's component notes that "*We will also show that sciences, arts and humanities subjects do not exist in isolation, and that much can be gained by working together in a cross-disciplinary way to investigate and solve problems.*"

CONCLUSION

This paper has argued the need for climate research to incorporate investigations of societal understanding of climate variability and change, and implications for human vulnerability and resistance. It has outlined new research in historical climatology and climate history research, which explores the societal impacts of, and responses to, past climate change, but argues that this research needs closer links to climate science. The paper demonstrates that the capacity for genuine integrated historical climate research, incorporating scientific, social scientific and arts and humanities perspectives, is already in place. This alignment would have the propensity to produce new and enhanced products and perspectives which would be invaluable for policymakers involved in adaptation and management decisions across various scales. Such potentials are embodied in an enhanced international ACRE initiative integrated within historical climate research activities.

The next step for ACRE will be to build on the multidisciplinary interactions noted in this paper and to demonstrate the effectiveness of this collaborative platform. Numerous historical events, however, could provide a timely forum for the implementation of multidisciplinary collaborations. These include the eruptions of Tambora in 1815, and the subsequent 'year without a summer' in 1816, and of Krakatoa in 1883. Work by ACRE is starting to reveal important insights into the implications of different estimates of volcanic aerosols.[c] ACRE has also started to reconstruct and model the temperature and pressure data recorded through Shackleton's Imperial Trans-Antarctic Expedition (1914–17) and the loss of the *Endurance* in October 1915.[d] There is also significant scope to extend ACRE's activities to high-resolution downscaled 20CR output via the Met Office PRECIS team, with foci on key episodes in British climate history, such as the autumn 1894 floods and the following winter 1894-95 freeze.[e] There is also potential to link into other major climate research projects, such as the Oxford University led *Managing the Risks, Impacts and Uncertainties of drought and water Scarcity (MaRUIS) project* (http://www.mariusdroughtproject.org/), in which at least one member of the 20CR ensemble output will be downscaled to provide a high-resolution baseline of UK droughts from 1850-2014. Details of all of the publications that have referred to or used ACRE-facilitated 20CR output and products can be found at http://www.esrl.noaa.gov/psd/data/20thC_Rean/pubs/

[c] See https://vimeo.com/120228702 under one set of volcanic aerosol estimates; https://vimeo.com/120787915 under another set of volcanic aerosol estimates (much larger amounts but timing is late; https://vimeo.com/120792719 has no volcanic aerosols and will serve as a "control" of what can be obtained from the sparse pressure observations alone). See also ACRE's work drawing on data available for Krakatoa eruption in 1883 (https://vimeo.com/117533217)
[d] See https://vimeo.com/121803689
[e] See https://docs.google.com/viewer?a=v&pid=sites&srcid=bWV0LWFjcmUub3JnfGFjcmV8Z3g6MWEwMTRjMzI0ZmE0ZTEwNg

With the right level of support and, critically, ongoing multidisciplinary collaboration, some examples of which have been considered in this paper, such initiatives are certainly within reach. These activities are imperative if progress is to be made in our understanding of past, present and potential future climate changes and their socio-economic and cultural implications for our future.

ACKNOWLEDGEMENTS

The lead author is supported by a combination of funding from the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101), the European Union's Seventh Framework Programme (FP7) European Reanalysis of Global Climate Observations 2 (ERA-CLIM2) project and the Climate Science for Service Partnership (CSSP) China under the Newton Fund. The Nottingham based project exploring *Documentary reconstructions of extreme weather events in the UK, past, present and future*, is funded through the AHRC, Grant number: AH/K005782/1.

REFERENCES

1. Hulme, M., 2008: The conquering of climate: discourses of fear and their dissolution. *The Geographical Journal*, **174** (**1**) (2008): 5-16.

2. Carey, M., 2012: Climate and history: a critical review of historical climatology and climate change historiography. *WIREs Clim Change*, **3**, 233-249. doi: 10.1002/wcc.171 (http://onlinelibrary.wiley.com/doi/10.1002/wcc.171/pdf).

3. McGregor, G.R., 2015: Climatology in support of climate risk management: A progress report. *Progress in Physical Geography,* **39**: 536-553; DOI:10.1177/0309133315578941.

4. Pain, E., 2003: Multidisciplinary Research: Today's Hottest Buzzword? *Science Career Magazine*, June 3.

5. Pain, E., 2014: Better Recognition for Multidisciplinary Research. *Science Career Magazine,* July 17.

6. Strober, M.H., 2011: *Interdisciplinary Conversations: Challenging Habits of Thought,* Stanford University Press, 232pp.

7. Houghton, J.T., Jenkins, G.J. and Ephraums, J.J., (eds.). 1990: *Report prepared for Intergovernmental Panel on Climate Change by Working Group I.* Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia, 410 pp.

8. Houghton, J.T., Callander, B.A. and Varney, S.K., (eds.) 1992: *Report prepared for Intergovernmental Panel on Climate Change by Working Group I combined with Supporting Scientific Material*. Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Victoria, Australia, 218 pp.

9. Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., ed. *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment

Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. ISBN 0-521-56433-6.

10. Palmer, T.N., Doblas-Reyes, F.J., Weisheimer, A. and Rodwell, M.J., 2008: Toward Seamless Prediction: Calibration of Climate Change Projections Using Seasonal Forecasts. *Bull. Amer. Meteor. Soc.*, **89**, 459–470.

11. Visbeck, M., 2008: From climate assessment to climate services. *Nature Geoscience,* **1,** 2-3.

12. Shaman, J., S. Solomon, R. R. Colwell and C. B. Field, 2013: Fostering Advances in Interdisciplinary Climate Science. *Proceedings of the National Academy of Sciences*, **110**, (Supplement 1), 3653-3656, doi:10.1073/pnas.1301104110.

13. Alexander, L.V., Tapper, N., Zhang, X., Fowler, H., Tebaldi, C. and Lynch, A., 2009: Editorial – “Climate extremes: progress and future directions”. *International Journal of Climatology,* **29**(**3**), 317–319;

14. Hulme, M., 2011: Reducing the Future to Climate: a Story of Climate Determinism and Reductionism. *Osiris,* **26**, 1.

15. Jones, P.D., 2008: Historical Climatology - a state of the art review. *Weather*, **63**, 181-186.

16. Le Roy Ladurie, E., 1971: *Times of Feast, Times of Famine: A History of Climate since the year 1000*. Rev. and updated. Garden City: Doubleday., 426pp.

17. Lamb, H.H., 1977: *Climate: Present, Past and Future. Vol. 2: Climatic History and the Future*. Methuen, London, 837pp.

18. Grove, R. H., 1988: *Conservation and colonial expansion: a study of the evolution of environmental attitudes and conservation policies on St Helena, Mauritius and in India, 1660–1860*. PhD thesis. University of Cambridge, Faculty of History.

19. Barriendos, M. 1997: Climatic variations in the Iberian peninsula during the late Maunder minimum (AD 1675–1715): An analysis of data from rogation ceremonies. *Holocene*, **7**, 105 – 111.

20. Barriendos, M. and Dannecker, A., 1999: La sequıa de 1812–1824 en la costa central catalana. Consideraciones climaticas e impacto social del evento. In *La Climatologıa Espanola En los Albores del Siglo XXI*, Raso J.M. and Martın Vide, J. (eds). Oikos-Tau: Barcelona, 53–62.

21. Pfister, C. 2010: The vulnerability of past societies to climatic variation: a new focus for historical climatology in the twenty-first century. *Clim. Change,* **100, (1)**, 25–31.

22. Pfister, C., Brázdil, R., Glaser,R., Barriendos, M., Camuffo, D., Deutsch,M., Dobrovolny, P., Enzi, S., Guidoboni, E., Kotyza,O., Militzer S, Racz,L., andRodrigo, F.S., 1999a:. Documentary evidence on climate in sixteenth-century Europe. *Clim. Change,* **43**, 55–110.

23. Pfister, C., Brázdil, R., and Glaser, R. (Ed.)., 1999b: Climatic Variability in Sixteenth Century Europe and its Social Dimension. *Clim. Change*, **43,** (**1**), 789–792.

24. Jones, P.D and Briffa, K.R, 2006: Unusual climate in northwest Europe during the period 1730-1745 based on instrumental and documentary data. *Clim. Change,* **79**, 361-379.

25. Jones, P.D., Osborn, T.J. and Briffa, K.R. , 2001: The Evolution of Climate Over the Last Millennium, *Science*, **292,** 662-667.

26. Brázdil, R, Pfister, C, Wanner, H., von Storch, H. and Luterbacher J. 2005: Historical climatology in Europe – the state of the art. *Clim. Change*, **70,** 363–430.

27. Brázdil, R., Valasek, H. and Chroma, K. 2006: Documentary evidence of an economic character as a source for the study of meteorological and hydrological extremes and their impacts on human activities. *Geogfiska Ann.,* **88**, 79–86.

28. Brázdil, R., Wheeler, D. and Pfister, C., 2010: European climate of the past 500 years based on documentary and instrumental data. *Clim. Change*, **101**, **1-2**, 1-6.

29. Przybylak, R., Wyszyński, P., Vízi, Z. and Jankowska, J., 2013: Atmospheric pressure changes in the Arctic from 1801 to 1920. *Int. J. Climatol*., **33**: 1730–1760. doi: 10.1002/joc.3546.

30. Zhang, D.D., Pei, Q., Lee, H.F., Zhang, J., Chang, C.Q., Li|, B., Li, J. and Zhang, X., 2015: The pulse of imperial China: a quantitative analysis of long-term geopolitical and climate cycles. *Global Ecology and Biogeography,* **24**, **1**, 87- 96. DOI: 10.1111/geb.12247.

31. Culver, L., 2014: Seeing Climate through Culture. *Environmental History*, **19**, 311-318.

32. Curtis, S.E. and Oven, K.G., 2012: Geographies of Health and Climate Change, *Progress in Human Geography* **36**, (no. 5) 654–66.

33. Berkes, F. and Folke. C., 1998: *Linking social and ecological systems: management practices and social mechanisms for building resilience.* Cambridge University Press, Cambridge, UK.

34. Holling, C.S., 1973: Resilience and stability of ecological systems. In: *Annual Review of Ecology and Systematics.* (**4**), 1-23.

35. Folke, C. 2006: Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change,* **16**, 253-267.

36. Gallopin, G.C., 2006: Linkages between vulnerability, resilience and adaptive capacity. *Journal of Global Environmental Change,* **16** (**3**), 293–303.

37. Redman, C. L. and Kinzig, A.P., 2003. Resilience of past landscapes: resilience theory, society, and the longue durée. *Conservation Ecology*, **7, 1**, 14. http://www.consecol.org/vol7/iss1/art14/

38. Dearing, J.A., 2006: Climate-human-environment interactions: resolving our past. *Climate of the Past*, **2**, (Special Issue), 187-203.

39. Dearing, J. A., Bullock, S., Contanza, R., Dawson, T. P., Edwards, M. E., Poppy, G. M. and Smith, G., 2012: Navigating the perfect storm: research strategies for socialecological systems in a rapidly evolving world. *Environmental Management*, **49**, (**4**), 767-775. (doi:10.1007/s00267-012-9833-6).

40. Constanza, R., Graumlich, L. J. and Steffen, W., 2007: *Sustainability or Collapse? An integrated history and future of people on Earth,* Cambridge: The MIT Press, 495 pp.

41. Constanza, R., van der Leeuw, S., Hibbard, K., Aulenbach, S., Brewer, S., Burek, M., Cornell, S., Crumley, C., Dearing, J., Folke, C., Graumlich, L., Hegmon, M., Heckbert, S., Jackson, S. T., Kubiszewski, I., Scarborough, V., Sinclair, P., Sörlin, S. and Steffen, W., 2012: Developing an Integrated History and Future of People on Earth (IHOPE), *Current Opinion in Environmental Sustainability,* **4**, 106-114.

42. Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M., 2009: Adaptation to climate change in the developing world. *Earthscan Reader in Adaptation to Climate Change*, 161-185.

43. Pillat, T. 2012: From climate and society to weather and landscape. *Archaeological Dialogues*, **19**(**1**), 29-42.

44. Endfield, G., 2014: Exploring particularity: the importance of vulnerability, resilience and memory in climate change discourses: Special Forum Issue on Climate Change and Environmental History. *Environmental History,* **19** (**2**), 303-310.

45. Adamson, G.C.D., 2015: Private diaries as information sources in climate research. *WIREs Climate Change* (Accepted).

46. Brunet, M. and Jones, P., 2011: Data rescue initiatives: bringing historical climate data into the 21st century *Climate Research,* **47**:29-40.

47. Riemann, D. Glaser, R., Kahle, M. and Vogt, S., 2015: The CRE tambora.org - New Data and Tools for Collaborative Research in Climate and Environmental History. *Geoscience Data Journal* (In review).

48. Pfister, C. and Dietrich, U. (Eds.): 2006: *Euro-Climhist: A database on past weather and climate in Europe and its human dimension.* University of Bern, available at: (www.euroclimhist.ch).

49. Peterson, T.C. and Manton M. J., 2008: Monitoring changes in climate extremes. A tale of international collaboration. *Bull. Amer. Meteor. Soc.*, **89,** 1266–1271.

50. Allan, R., P. Brohan, G.P. Compo, R. Stone, J. Luterbacher, and S. Brönnimann, 2011: The International Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative. *Bull. Amer. Met. Soc.*, **92**, 1421-1425. doi:10.1175/2011BAMS3218.1.

51. Compo G P, Whitaker J S, Sardeshmukh P D, Matsui N, Allan R J, Yin X, Gleason B E, Vose R S, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel R I, Grant A N, Groisman P Y, Jones P D, Kruk M C, Kruger A C, Marshall G J, Maugeri M, Mok H Y, Nordli Ø, Ross T F, Trigo R M, Wang X L, Woodruff S D, and Worley SJ 2011: The Twentieth Century Reanalysis Project, *Quart. J. Royal Meteorol. Soc.*, **137**, 1-28, doi: 10.1002/qj.776.

52. Hirahara, S, Ishii, M. and Fukuda, Y., 2014: Centennial-Scale Sea Surface Temperature Analysis and Its Uncertainty. *J. Climate*, **27**, 57–75. http://dx.doi.org/10.1175/JCLI-D-12-00837.1

53. Wheeler, D., 2005: An examination of the accuracy and consistency of ships' logbook weather observations and records, *Clim. Change,* **73**, 97-116.

54. Berz G., Kron W., Loste, T., Rauch E., Schimtschek J., Schmieder J., Siebert A., Smolka A. and Wirtz A., 2011: World map of natural hazards – a global view of the distribution and intensity of significant exposures. *Natural Hazards*, **23**, 443-465.

55. AHRC, 2009: Leading the World: The Economic Impact of UK Arts and Humanities Research, *Report of the Impact Task Force*, Swindon: AHRC http://www.ahrc.ac.uk/About/Policy/Documents/leadingtheworld.pdf.

56. Bickers, R., 2015: 'Throwing Light on Natural Laws': Meteorology on the China coast, 1869-1912. In Bickers, R. and Jackson, I., eds. *Treaty Ports in Modern China: Law, Land and Power*. Routledge, 256pp.

57. Griffin, R.E., 2015: When are Old Data New Data? *Geo. Res. J.,* **6**, 92-97.

58. Goodrum, D., Druhan, A., and Abbs, J., 2011: The Status and Quality of Year 11 and 12 Science in Australian Schools. Canberra, ACT: Australian Academy of Science.

59. Smith, E., 2011. Staying in the science stream: patterns ot participation in A-level science subjects in the UK. *Educational Studies*, **37**(**1**), 59-71. doi: 10.1080/03055691003729161

60. Lowell, B.L., Salzman, H., Bernstein, H., and Henderson, E. (2009, November 7). Steady as She Goes? Three Generations of Students Through the Science and Engineering Pipeline. Paper presented at the *Annual Meetings of the Association for Public Policy Analysis and Management,* Washington, DC.

61. National Research Council (NRC), 2011: America's climate choices. National Academies Press, Washington.

62. Brulle, R.J., 2013: Institutionalizing delay: foundation funding and the creation of U.S. climate change countermovement organizations, *Clim. Change*, **122**, 681-694. doi: 10.1007/s10584-013-1018-7