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PAGES news

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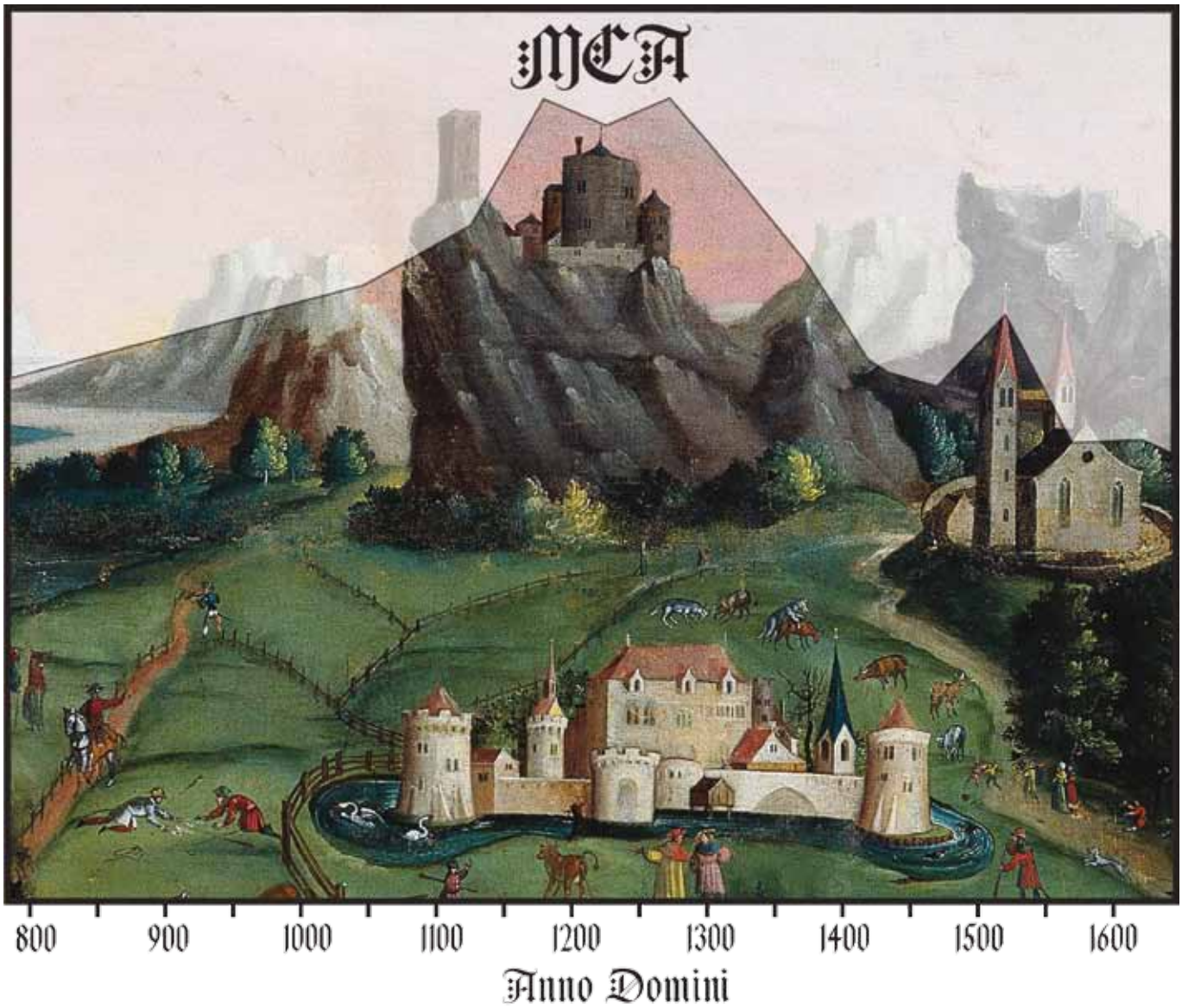
Medieval Climate Anomaly

Editors:

Elena Xoplaki, Dominik Fleitmann, Henry Diaz, Lucien von Gunten and Thorsten Kiefer



Whether the medieval time was indeed a "warm period", merely a "climate anomaly", or something different altogether may be a matter of location, scale, resolution, and method. This newsletter provides perspectives from different angles on this fascinating climatic period. In 1965, Hubert Lamb had published a pioneering temperature reconstruction for Europe from historical documents. His curve is underlying this cover picture. It would suggest that the medieval scene painted by Jörg Breu the Elder with green pasture land and people enjoying good weather, was common in the Middle Ages. The research done since then, however, has provided us with a more detailed and nuanced picture.

Inside PAGES

New PAGES website

PAGES has launched a new version of the website in keeping with the latest trends in website design. During this transition period some web pages and databases may be temporarily unavailable or outdated. We apologize for any inconvenience caused. The new website provides a "My PAGES" section, which is designed to serve as a "one-stop shop" to access PAGES offerings and get involved in PAGES activities.

Staff update

The PAGES Office has seen a lot of staff movement lately due to back-to-back good news; Louise gave birth to a son and Michelle is expecting a child in the coming days! Lucien von Gunten replaces Louise Newman as PAGES Science Officer for the duration of her maternity leave until May 2011. Lucien, a paleoclimatologist working on South American lake sediments, is taking care of the 2k Working Groups and newsletter editing. Christoph Kull, a glaciologist and former PAGES Science Officer, has been roped in to bolster production of newsletters. For the time of her maternity leave, Michelle Kaufmann, the PAGES Finance and Officer Manager, has been replaced by Therese Jost. We congratulate Louise on the birth of her son and welcome Lucien, Christoph and Therese to the PAGES office. We also look forward to welcoming another PAGES baby soon!

PAGES OSM/YSM 2013: an update

In 2010, PAGES invited applications from groups interested in hosting the 4th PAGES Open Science Meeting (OSM) and 2 Young Scientists Meeting (YSM) in 2013. We received 10 exciting bids from 5 different continents and are delighted with this exuberant interest in hosting the events. Bids from Australia, India and Germany have been shortlisted and await a final decision after additional scrutiny.

New PAGES committee members

Heinz Wanner, former Scientific Steering Committee (SSC) co-chair, rotated off the committee after six years of dedicated service but shall continue his association with PAGES as coordinator of the Regional 2k Network.

Two new members have joined the PAGES SSC in 2011:

Hubertus Fischer, Professor of Experimental Climate Physics at the University of Bern, Switzerland is the new SSC Swiss co-chair alongside the US co-chair Bette Otto-Bliesner. Hubertus is an ice core scientist with broad interests in Quaternary changes in climate and biogeochemical cycles. He is active in the PAGES Working Groups Antarctica2k and ADOM.

Claudio Latorre is an Associate Professor in the Department of Ecology at the Pontificial Catholic University of Chile in Santiago. His research interests include paleoecology and paleoclimatology of arid regions. For over a decade, he has been using rodent middens from the Atacama Desert to learn about the desert's hydrological cycle over the last 40-50 ka. Claudio Latorre also specializes in plant macrofossil analyses and the applications of stable isotopes in these environments. His appointment to the SSC will strengthen and stimulate PAGES Focus 4.

Nominations for the PAGES SSC

PAGES invites nominations for new SSC members for 2012. Bette Otto-Bliesner (USA), Cathy Whitlock (USA) and Mohammed Umer (Ethiopia) will be rotating off the SSC at the end of 2011. The SSC provides overall guidance for PAGES and oversees major scientific activities. Members are chosen on the basis of their scientific excellence and their potential to promote PAGES science and activities. PAGES particularly encourages the nomination of women and scientists from underrepresented regions. The nomination deadline is 30 June 2011. A list of current SSC members and nomination details can be found on the PAGES website (My PAGES>Get involved).

PAGES support for meetings

PAGES Executive Committee (EXCOM) discussed the workshop proposals submitted to the second call in 2010. A total of 13 meetings were awarded financial support. PAGES Working Groups that were allocated workshop support include PALSEA (Sea-Level), LUCIFS (Fluvial Systems), NICOPP (Marine Nitrogen Cycle), Varves, PAGES-CLIVAR Intersection, and the Australasian, Antarctic and North American groups of the Regional 2k Network, as well as a workshop for the entire 2k Network.

In addition, three proposals for general workshops relevant to PAGES science were approved. These include an interdisciplinary workshop on constraining estimates of future climate variability from geological records, a workshop on Greenland Ice Sheet reconstruction, and a regional paleoscience workshop focused on the Balkan and Carpathian region and community. An educational workshop on marine diatoms was also supported.

More information on funded workshops is available on the PAGES website (Meetings>PAGES supported). The next deadline for proposals is 15 June 2011 for evaluation by EXCOM in late July (online proposal submission under My PAGES).

Planet Under Pressure Conference 2012

An open international Planet Under Pressure conference will be held on 26-29 March 2012 in London. It will be led by the PAGES parent organization, the International Geosphere-Biosphere Programme (IGBP), and involve its sister programs of the Earth System Science Partnership (ESSP). The conference is a unique opportunity to bring together global-change scientists with decision-makers in policy, development, resource management, industry and other non-government organizations. It aims to provide scientific leadership towards the 2012 UN Conference on Sustainable Development - Rio+20. (www.planetunderpressure2012.net)

New PAGES publications

A special issue on the timing and geographic extent of extreme arid and humid events during the Holocene, captured in lake sediment records from hydrologically sensitive regions was published recently (*Quaternary International*, 229: 1-148). The special issue is comprised of 18 selected papers from the 3rd PAGES LIMPACS (Human Impacts on Lake Ecosystems) Conference held in Chandigarh, India in March 2009.

Additionally, the PAGES special issue "Retrospective views on our planet's

future – PAGES Open Science Meeting 2009" is now complete with all 10 articles now published open access in *Climate of the Past*.

Next newsletter issues

The next issue of *PAGES news* will highlight the PAGES Focus 4 Theme of "Regional integration of past records for management of modern resources and landscapes". This issue stems from the Regional Integration workshop held in Southampton in September 2010.

The 3rd *PAGES news* issue for 2010 will highlight the complementary science of PAGES and the other IGBP projects. Paired topical articles will provide different temporal perspectives on global change questions. Please contact the IPO if you would like to contribute to this issue.

You are also invited to submit Science Highlights, Program News and Workshop Reports for the open section of PAGES news. The next deadline for such contributions is 30 June 2011. Guidelines for authors can be found on the PAGES website (Products>Contribute a product)

PAGES Calendar 2011

2nd Australasia 2k workshop
27 - 29 April 2011 - Perth, Australia

2nd North America 2k workshop
8 - 9 May 2011 - Arizona, USA

Climate change in the Carpathian-Balkan during the Late Pleistocene and Holocene
9 - 12 June 2011 - Suceava, Romania

Polar marine diatom taxonomy and ecology workshop
4 - 8 July 2011 - Sydney, Australia

2nd NICOPP (Nitrogen Cycle in the Ocean, Past and Present) workshop
8 - 10 July 2011 - Halifax, Canada

1st Antarctica 2k workshop
18 - 19 July 2011 - Bern, Switzerland

18th INQUA Congress
20 - 27 July 2011 - Bern, Switzerland

Sediment and carbon fluxes under human impact and climate change
28 - 30 July 2011 - Bern, Switzerland

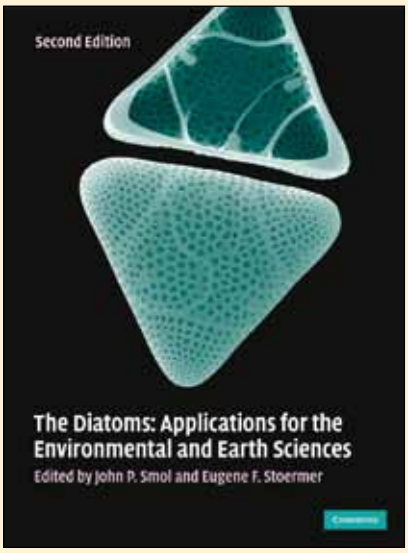
New on the PAGES Bookshelf

The Diatoms: Applications for the Environmental and Earth Sciences, 2nd Edition

Editors: John P. Smol and Eugene F. Stoermer

Cambridge University Press, 2010: ISBN 9780521509961
686 pages, 175 illustrations, 16 tables

This revised and expanded edition provides a comprehensive summary of the many uses of diatoms in the environmental and earth sciences. The 36 chapters of this book were written by 77 specialists and are organized into four main sections. The first three sections cover indicators in different aquatic environments and the final section explores the use of diatoms in other disciplines, such as forensics or archeology.



Summary of contents:

Part I: Introduction
Part II: Diatoms as indicators of environmental change in flowing waters and lakes
Part III: Diatoms as indicators in Arctic, Antarctic and alpine lacustrine environments
Part IV: Diatoms as indicators in marine and estuarine environments
Part V: Other applications
Part VI: Conclusions

Ordering information: http://post.queensu.ca/~pearl/textbook2.htm

Editorial: Medieval Climate Anomaly

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Research on the climate of the Middle Ages began in the 1960s. Motivated by historical accounts Hubert H. Lamb documented the increase in relative frequency of warm episodes, primarily around the North Atlantic and increased cool season precipitation across Britain during medieval times (Lamb, 1965). Lamb wrote first of a "Medieval Warm Epoch" and later of a "Medieval Warm Period" ending at approximately AD 1300. Lamb recognized that the available evidence implied that due to a "… shift in the upper westerlies, the depression tracks should have had an average position north of the modern normal (AD 1900–1939) position — a displacement that probably implies less sea ice …" (Lamb, 1965; 1969). He thus emphasized the relationship between changes in circulation and surface climate, and the idea of modest but persistent shifts in winter circulation over the North Atlantic and Europe during medieval times (see also Graham et al., 2010). Later, LaMarche (1974) used multi-elevation tree-ring and other data to infer late Holocene climate changes in the White Mountains of California. His analyses indicated that conditions were predominantly warmer and drier from AD 1000–1300, and cooler and wetter from AD 1400–1800. He showed that such changes could be explained by a northward-to-southward shift of the storm track over the region. LaMarche pointed out that the transition from the Medieval Warm Period to the subsequent Little Ice Age (LIA) over the western US was synchronous with the one inferred by Lamb (1965) for the North Atlantic and Western Europe, possibly indicating a shift in global circulation patterns, as already surmised by Lamb (1969; see also Graham et al., 2010).

Interestingly, within this period various important cultural events took place. From AD 800-1000 Iron Age Scandinavians colonized the North Atlantic islands and eastern North America. Iceland was settled around AD 874, Greenland ca. AD 985, and the short lived Vinland colony survived a few years around AD 1000 in Newfoundland (Arneborg, 2000; Wallace, 2000). By their arrival to Iceland, Scandinavian settlers encountered a mid–Atlantic island with favorable climatic and environmental conditions similar to those prevailing in Scandinavia (McGovern et al., 2007). In North America, the Vinland colony of the Vikings was abandoned by the mid–eleventh century. At that time drift ice had already started its appearance along the vital trade routes to Greenland (Lamb, 1995), increasing the threat of ice for seafarers. Climate change and human environmental effects on the island ecosystems played an important role in the unhappy ending to the "Norse Atlantic Saga" (Amorosi et al., 1997; Dugmore et al., 2004; Ogilvie and McGovern, 2000) combined with changes in politics and market forces in Europe (Ladurie, 1983; Jones, 1986).

A large number of studies on the temporal and regional expression of the Medieval Warm Period for different parts of the world have followed since the pioneering works of Lamb and LaMarche. A comprehensive review of those studies can be found in Hughes and Diaz (1994), Graham et al. (2010) and Diaz et al. (2011). The time frame is nowadays more commonly referred to as the Medieval Climate Anomaly (MCA). This term was coined originally by Stine (1994), who sought an explanation for the results of a wide-ranging geomorphic investigation of century-long low stands of lakes in the sub-tropical latitudes of western North and South America. The subsequent adoption of this term reflects the availability of much more information on the climate during medieval times since Lamb's pioneering studies. Since then, new proxy paleoclimate records, temporally and spatially highly resolved reconstructions, and detailed modeling studies allow for a more accurate and detailed study of the climate since the MCA (Mann et al., 2009; Cook et al., 2010; Graham et al., 2010; Diaz et al., 2011 and references therein).

Bradley et al. (2003) questioned the statement "Climate in Medieval time is often said to have been as warm as, or warmer than, it is today. Still, many aspects of the climate during the MCA require careful examination and further investigations. Among areas of ongoing research are the onset and termination as well as the positioning of the MCA in the Holocene climatic context, the climate characteristics of the period, the nature of the transition to the subsequent LIA, the spatial extent and local expression as well as the impacts on societies, associated forcing factors, and most prominently its magnitude compared to the instrumental temperature records and the magnitude and pace of the twentieth century warming.

These aspects are the focus of this PAGES Newsletter. The special section compiles latest information on climate and impacts during the MCA on global and regional scales. Historical documents, proxy records and climate models provide new insights into the temporal and spatial climatic pattern and related dynamics and forcings during medieval times.

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For full references please consult:
http://www.pages-igbp.org/products/newsletters/ref2011_1.html

Solar activity – the past 1200 years

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Solar activity highs and lows coincide with the Medieval Climate Anomaly and the Little Ice Age, respectively.

The Sun is a variable star and the most important source of energy for the Earth. This raises the question whether the Sun affects the Earth's climate. Several solar activity records show that the Sun has short- and long-term variability. An example is the well-known sunspot record (inset curve in Figure 1a), which reaches back to the year 1610 AD, when people started to use the telescope for astrophysical purposes such as observing the Sun. From the sunspot record it is known that solar activity was lower during the 17th and 18th century than today. In particular, the period from 1645 to 1715 AD named the Maunder Minimum (Eddy, 1976) is characterized by a nearly complete absence of sunspots. The sunspot record "only" goes back to 1610 AD and before this time other proxies of solar activity must be used. Presently the only proxies capable of extending the record of solar activity beyond 1610 AD are cosmogenic radionuclides, such as ^{14}C and ^{10}Be. The term "cosmogenic" points to the origin of the radionuclides — cosmogenic radionuclides are produced by nuclear reactions between cosmic ray particles and the gases of the Earth's atmosphere. Thus, cosmogenic radionuclides record the intensity of the cosmic ray intensity at Earth.

Link to the Sun

Why do cosmogenic radionuclides record the solar activity? The link between ^{10}Be and solar activity is illustrated in Figure 2. Cosmic ray particles are accelerated to high energies in the vicinity of supernova explosions in our galaxy. To reach the Earth they have to propagate through the heliosphere, which is formed by the solar wind carrying the solar magnetic field. Cosmic ray particles are charged and therefore get deflected by the solar magnetic field. The larger the strength of the solar magnetic field, the stronger is the deflection of cosmic ray particles and the lower the cosmic ray intensity at Earth. The solar magnetic field is directly related to solar activity, i.e., when solar activity is weak the strength of the solar magnetic field is weak. To summarize, the radionuclide production rate is high during a grand solar minimum like the Maunder Minimum and low during periods of high solar activity. Thus the radionuclide signal principally allows reconstructing solar activity.

In addition to the solar magnetic field, the geomagnetic field also modulates the cosmic ray intensity. From archeointensity data it is known that the geomagnetic field has varied in time (e.g., Knudsen et al., 2008) and therefore a part of the variation found in cosmogenic radionuclides is of geomagnetic origin. Hence, variations of the geomagnetic field must first be removed from the radionuclide record before solar activity can be calculated. The physics-based dependencies between radionuclide production, solar activity and geomagnetic field strength have been determined using the Monte Carlo technique (Masarik and Beer, 2009). These calculations provide the dependence of the radionuclide production on solar activity and geomagnetic field strength. Based on this dependence and the known paleogeomagnetic field, the solar activity can be derived from the radionuclide signal.

After their production in the Earth's atmosphere, the radionuclides are transported and distributed within the environment and partly stored in natural archives. The best-suited archives are tree rings (^{14}C) and polar ice (^{10}Be) and both have recorded the solar activity signal with high temporal resolution over many millennia. Tree rings and polar ice can both be dated very accurately, which is a prerequisite for high temporal resolution reconstructions. Some existing records have annual resolution for the past ca. 600 years (Berggren et al., 2009), and resolutions of a few years to decades for the Holocene (e.g., Muscheler et al., 2007; Usoskin et al., 2007; Steinhilber et al., 2008). Note that cosmogenic radionuclides are also found in other archives (e.g., alpine glaciers, lake sediments, ocean sediments) but generally the chronologies are less accurate.

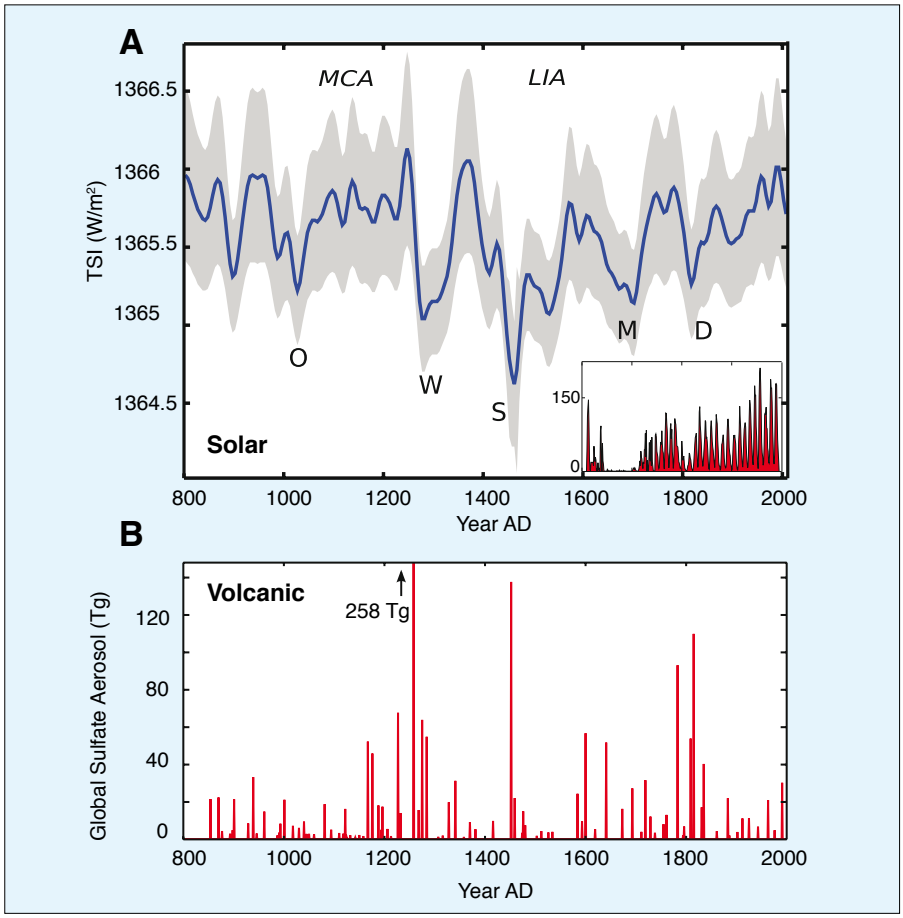

*Figure 1: **A**) Zoom-in of the 9300-year long total solar irradiance (TSI) reconstruction (Steinhilber et al., 2009) for the past 1200 years. The gray band is the 1σ uncertainty. Inset shows the group sunspot number. MCA: Medieval climate anomaly; LIA: Little Ice Age. Capital letters mark grand solar minima: O=Oort, W=Wolf, S=Spörer, M=Maunder, D=Dalton. **B**) Total global stratospheric volcanic sulfate aerosol injection in teragram (Tg) (Gao et al., 2008).*

The radionuclide signal not only reflects the cosmic ray variation due to solar and geomagnetic activity, it is also influenced by "system effects". System effects are variations induced by the transport from the atmosphere where the radionuclides are produced to the ground where they are archived. In addition to the system effects, the cosmic ray signal has uncertainty due to uncertainty in the timescale and in the radionuclide measurements.

Solar activity during the past 1200 years

Recently, total solar irradiance (TSI) has been reconstructed from a composite of several ^{10}Be records measured in polar ice for the past 9300 years (Steinhilber et al., 2008, 2009). The composite is mainly based on the ^{10}Be record from the GRIP ice core, Greenland. As system effects mostly influence the signal on short timescales, 40-year averages have been built from the ^{10}Be records.

A part of the Holocene TSI reconstruction is shown for the past 1200 years in Figure 1a. Five distinct grand solar minima can be identified known as the Oort (1040-1080 AD), Wolf (1280-1350 AD), Spörer (1460-1550 AD), Maunder (1645-1715 AD), and Dalton (1790-1820 AD) Minima. The last four grand solar minima: Wolf, Spörer, Maunder and Dalton, occurred in a cluster. This cluster coincides with the Little Ice Age (LIA), a period of cold climate conditions from about 1350 to 1850 AD. Between the Oort and the Wolf Minimum a period of high solar activity of approximately 200 years is evident. This period coincides with the Medieval Climate Anomaly (MCA), which is generally characterized by warmer and drier climate conditions. The simultaneous occurrences of the LIA with a cluster of grand solar minima and of the MCA with a long-lasting period of high solar activity, points to an influence of the Sun on the Earth's climate during these periods. In addition to solar activity, volcanic eruptions played an important role (Fig. 1b; Gao et al., 2008). During the LIA, several strong volcanic eruptions occurred at the time of grand solar minima, which had a further cooling effect. An inverse pattern is found for the MCA when only weak volcanic eruptions are identified and solar activity was high. With the beginning of industrialization in the 18th century, the importance of solar and volcanic forcing decreased while the influence of the anthropogenic greenhouse effect due to fossil fuel burning began to increase and is currently playing the dominant role (Hegerl et al., 2007).

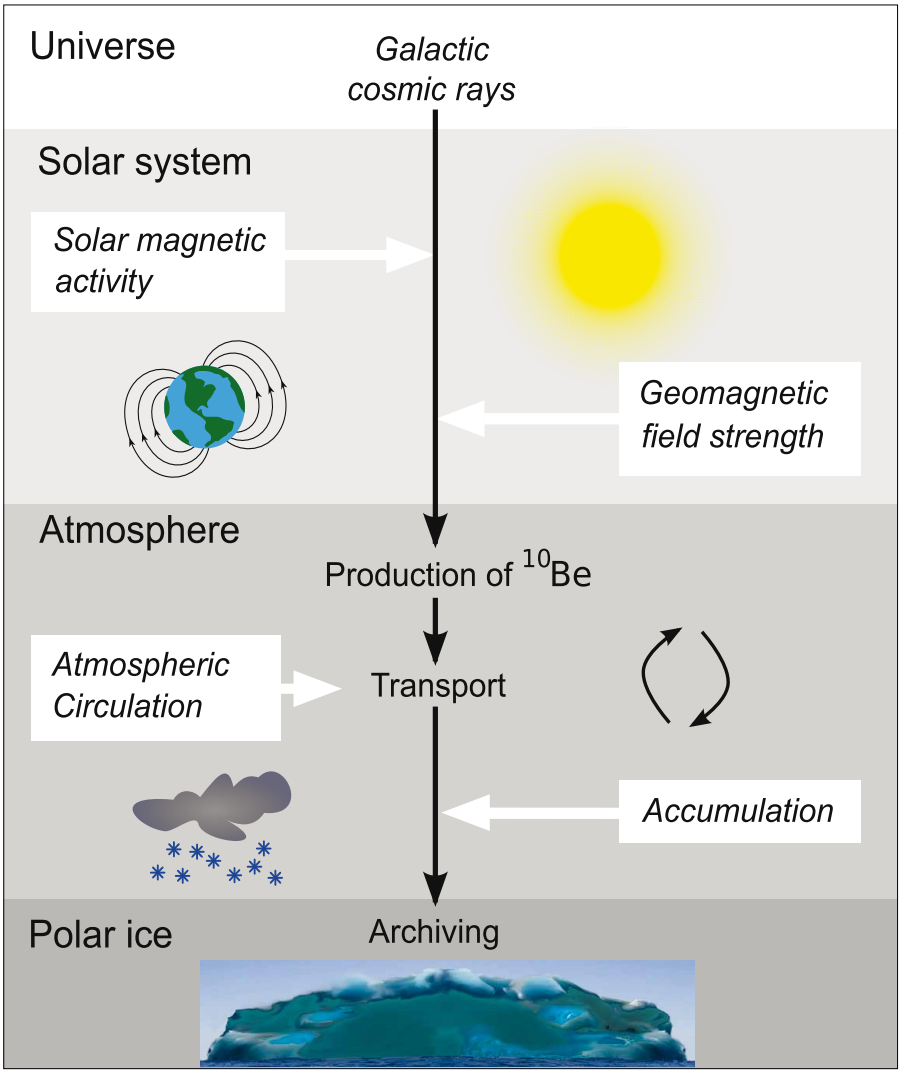

Figure 2: Illustration of the ^{10}Be system and its relationship to solar activity.

Future solar activity

An interesting question is what role the Sun is going to play in the near future. The 9300-year long composite of solar activity (Steinhilber et al., 2008) shows that during the past six decades the Sun has been in a state of high solar activity compared to the entire period of 9300 years. The statistics of the occurrence of periods of high activity suggests that the current period of high activity will come to an end in the next decades (Abreu et al., 2008). Furthermore, the distribution of grand solar minima in the past 9300 years shows that it is likely that a Maunder Minimum-like period would occur around 2100 AD (Abreu et al., 2010). Such a period of low solar activity would probably lead to a temporary reduction in Earth's temperature rise due to the anthropogenic greenhouse effect. However, the 9300-year long record shows that in the past a grand maximum has always been followed by a period of high activity, with the very likely assumption that the Sun's future behavior will be similar to that of the past, it is clear that the Sun will not permanently compensate for human-made global warming.

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For full references please consult:

http://www.pages-igbp.org/products/newsletters/ref2011_1.html

Medieval Climate Anomaly to Little Ice Age transition as simulated by current climate models

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Inter-model differences and model/reconstruction comparisons suggest that simulations of the Medieval Climate Anomaly either fail to reproduce the mechanisms of climate response to changes in external forcing, or that anomalies during this period are largely influenced by internal variability.

Comparing model simulations with proxy-based climate reconstructions offers the possibility to explain mechanisms of climate variability during key periods, such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). Discrepancies between both sources of information may also help to identify possible deficiencies in our understanding of past climate, its modeling or its representation by proxy records.

Information derived from proxy records suggests the following picture of the MCA in comparison to the subsequent colder period, the LIA, that involves quasi-coordinated climate shifts across different regions of the globe (e.g., Seager et al., 2007; Mann et al., 2009; Graham et al., 2010): evidences of an increased zonal gradient in the tropical Pacific produced by La Niña-like conditions in the eastern Pacific and anomalous warmth in the western Pacific and Indian Ocean, and a broad expansion of the Hadley Cell with associated northward shift of the zonal circulation that might have led to a more positive North Atlantic Oscillation (NAO) type of signature in the North Atlantic. Graham et al. (2010) recently showed that a pattern of change consistent with such anomalies is obtained for the MCA with an Atmosphere Ocean General Circulation Model (AOGCM) if anomalously warm sea surface temperatures are induced on the Indian Ocean and western tropical Pacific.

Current AOGCM millennial forced simulations do represent an overall warmer MCA and a cooler LIA at global and hemispherical scales (e.g., González-Rouco et al., 2006; Ammann et al., 2007) as a response to long-term changes in volcanic activity and solar irradiance. The amplitude of this response is dependent on the model sensitivity and on the specific set of forcing reconstructions used to drive the simulations. Mann et al. (2009) show that in spite of agreement in simulating global and hemispheric warming, the reconstructed pattern of MCA-LIA temperature change, and specifically the La Niña-like conditions in the eastern Pacific, were not reproduced by forced simulations with the GISS-ER and the NCAR CSM1.4 climate models. In this contribution, we will examine the MCA-LIA transition in all available high complexity AOGCM transient simulations of the last millennium.

Simulation of MCA-LIA temperature difference by AOGCMs

Simulations from six different AOGCMs are considered (see original references for details): the National Center for Atmospheric Research Climate System Model 1.4 (Ammann et al., 2007; CSM1.4 hereafter); a new version of the same model, the Community Climate System Model 3 (Hofer et al., 2011; CCSM3 hereafter); the Max Planck Institute for Meteorology ECHO-G (González-Rouco et al., 2006); the Institute Pierre Simon Laplace IPSLCM4_v2 (Servonnat et al., 2010; IPSL hereafter); the Centre National de Recherches Météorologiques CNRM-CM3.3 (Swingedouw et al., 2010; CNRM hereafter); and the Max Plank Institute for Meteorology Earth System Model (Jungclaus et al., 2010; MPI-ESM hereafter). This suite of simulations has been performed by different groups and institutions and represents forcing uncertainty through somewhat different choices of external forcing. Only some comments about the forcing that are relevant for the MCA-LIA period are provided herein.

All simulations incorporate solar variability, volcanic activity (except for IPSL) and greenhouse gas concentration changes. Variations in solar irradiance for the last millennium are smaller than previously thought (see discussion in Jungclaus et al., 2010 and Schmidt et al., 2011). The majority of simulations were performed with a comparatively high solar variability scenario, except for the specific case of MPI-ESM for which two different ensembles were made including smaller (E1) and larger (E2) irradiance changes. The total solar irradiance (TSI) change in the high solar variability scenarios ranges from 0.24% (CSM1.4, CCSM3) to 0.29% (ECHO-G) from the Late Maunder Minimum (LMM) to present and from 0.17% (CCSM3) to 0.27% (MPI-ESM-E2) from the MCA to the LMM; in MPI-ESM-E1 the values of TSI change are of 0.09% (0.04%) for the transition LMM-present (MCA-LMM). Volcanic forcing was implemented differently in the suite of models, although comparable global and annual averages were retained. With regard to greenhouse gases, all models incorporate prescribed values of CO_2 concentration except for MPI-ESM, which interactively calculates them within the carbon cycle submodel. Similarly, land use changes before 1700 AD are incorporated only in the MPI-ESM simulations as variations in vegetation types due to agricultural activities.

Figure 1 shows the MCA–LIA annual temperature differences (hatched areas indicate non significance for a $p<0.05$ level) in a forced simulation from each of the six models and also in the proxy-based reconstruction from Mann et al. (2009). For the specific case of the MPI-ESM model, results are shown for four simulations, two arbitrarily selected from each ensemble to illustrate the existing differences between the members. All simulations tend to produce an almost globally warmer MCA, except for the one of CNRM, which shows a large cooling in the Southern Hemisphere. Warming tends to be higher over the continents than oceans, particularly over the sea-ice boundary at the high latitudes of both hemispheres. Regional scale cooling (not significant everywhere) is simulated around Antarctica, mid-latitudes of the Southern Hemisphere (all models), in the North Pacific (ECHO-G), in the North Atlantic (CCSM3) or in northern Asia (CNRM). However, many of these regional scale features may well be simulation-dependent and related to initial conditions and

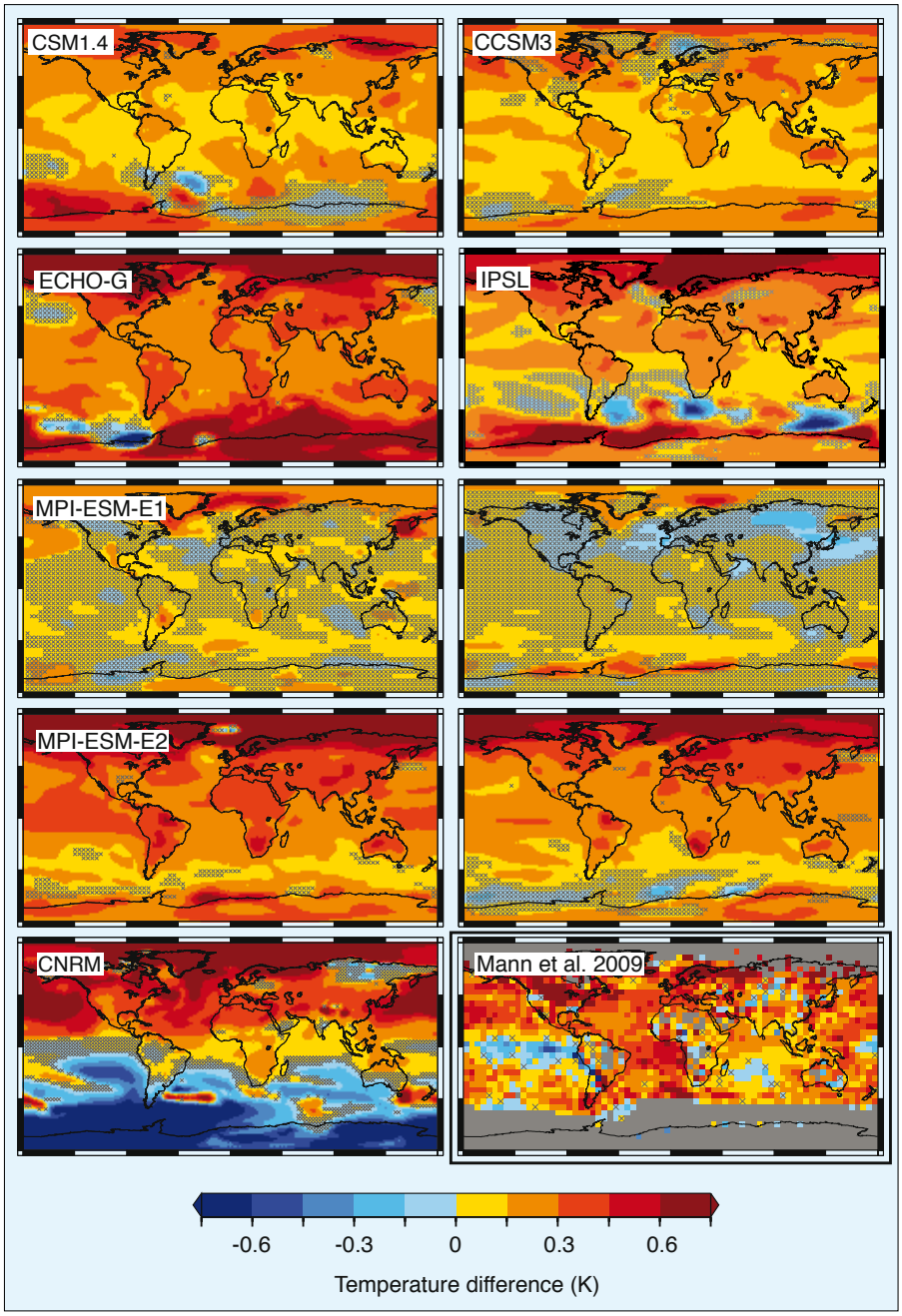

Figure 1: MCA–LIA (950-1250 AD minus 1400-1700 AD annual mean temperature difference in forced simulations produced with six different AOGCMs (see text for details on acronyms) and in the multiproxy climate field reconstruction from Mann et al. (2009). For the simulations starting in 1000 AD (CCSM3, ECHO-G, IPSL, CNRM) the period 1000 to 1250 was selected instead to define the MCA. In the case of the ECHO-G model, results are shown for the FOR2 simulation in González-Rouco et al. (2006). Hatched areas indicate non-significant differences according to a two-sided t-test ($p<0.05$).

internal variability as evidenced by the differences within the members of each MPI-ESM ensemble. Differences arise in the magnitude of warming and cooling over the North Pacific, South America or Africa in E2 or in the spread of cooling regions in the E1 members. Among the two ensembles, E1 simulates more regional/large-scale widespread cooling, a sign of the lower weight of TSI changes that allows for internal variability to become more prominent. Therefore, even if widespread warming is simulated in the MCA, the spatial pattern of temperature change is very heterogeneous and can vary considerably from model to model and even within simulations of the same model.

None of the model simulations reproduce the reconstructed pattern in Mann et al. (2009) depicting a La Niña-like state in the Pacific. Other features in the reconstructed evidence discussed by Graham et al. (2010) are also not evident in the simulated MCA–LIA temperature differences. This includes the anomalous warm pool over the western Pacific- Indian Ocean and enhanced tropical zonal temperature gradient, as well as an NAO-like temperature signature, suggestive of a northward shift of the zonal circulation. Therefore apart from the generally higher changes in continental and polar areas, the MCA–LIA change across the available model simulations is inconsistent, and shows a different response to proxy evidences.

Conclusions

The results presented here highlight major discrepancies between millennium simulations and reconstructions. If proxy-based reconstructions were considered reliable and changes in radiative forcing factors were responsible for the MCA–LIA reconstructed temperature signal, these results would have implications on our understanding of the MCA–LIA transition. These discrepancies suggest that either the MCA–LIA changes arose from internal variability only, or transient simulations with state-of-the-art AOGCMs fail to correctly reproduce some mechanisms of response to external forcing: for instance, changes in the tropics like the enhancement of the zonal gradient in the tropical Pacific is not well simulated, with implications for related teleconnections elsewhere.

Most models have used relatively high TSI variations from the MCA to the LIA and their pattern of response is typically a uniform warming in the earlier period. In spite of this, there are considerable differences among the simulations that highlight a feasible influence of initial conditions and internal variability. Furthermore, if reduced levels of past TSI are given more credit, as in the MPI-ESM-E1 ensemble, the temperature response for the MCA–LIA is less uniform in sign and visibly more influenced by internal variability. Therefore, under both high and low TSI change scenarios, it is possible that the MCA–LIA reconstructed anomalies would have been largely influenced by internal variability.

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Evidence for global climate reorganization during medieval times

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A synthesis of global climate model results and inferences from proxy records suggests an increased sea surface temperature gradient between the tropical Indian and Pacific Oceans during medieval times.

A range of in-situ proxy records indicate that tropical eastern and central Pacific sea surface temperatures (SSTs) were relatively cool during the Medieval Climate Anomaly (MCA, ca. 900-1350 AD; e.g., Cobb et al., 2003; Rein et al., 2004; Conroy et al., 2008). This idea is supported by hydroclimate changes indicated by proxy records from extra-tropical western North and South America (e.g., Swetnam et al., 1993; Stine et al., 1994; Jenny et al., 2002; Cook et al., 2004; see Fig. 1). At the same time, indications of a distinct MCA appear in proxy records distributed around the planet, many far removed from the Pacific sector (also Fig. 1). Many of the climate shifts inferred from these latter records are inconsistent in strength or character of the changes expected on the basis of a cooler tropical Pacific alone (at least as judged from observations and model results) suggesting an important role for SST changes in other tropical oceans (Seager et al., 2007; Graham et al., 2007; Graham et al., 2010). Among such "inconsistent" shifts are indications of a more "positive NAO"-like circulation pattern during boreal winter, with impacts on European climate (e.g., Lamb, 1965; Mangini et al., 2005; Trouet et al., 2009), North Atlantic SST and sea ice (e.g., Keigwin, 1996; Jensen et al., 2004; Sicre et al., 2008; Wanamaker et al., 2008; Massé et al., 2009), aridity in equatorial Africa (Verschuren et al., 2004; Russell et al., 2007; Shanahan et al., 2009) and in parts of southwest Asia (Hassan, 1981; von Rad et al., 1999; Fleitmann et al., 2003), and increased monsoon rainfall in parts of south-central and eastern Asia (Sinha et al., 2007; Tan et al., 2008; Zhang et al., 2008; Buckley et al., 2010).

Model simulations of the climate and circulation changes ensuing from the late 20th century warming of the Indian Ocean (e.g., Bader and Latif, 2003; Hurrell et al., 2004; Hoerling et al., 2004; Bader and Latif, 2005) show some of the "inconsistent" features noted above. To explore the possibility that similar warming may have occurred during the MCA, simulations were performed with a full-physics global coupled model (NCAR CCSM) in which tropical Indian, or tropical Indian and western Pacific, SSTs were increased over the range ~0.2-0.8°C. The simulated global climate and circulation shifts for boreal winter (Figs. 1 and 2; see Graham et al. (2010) for the corresponding results for boreal summer) show many of the climate changes inferred from global proxy records for the MCA, including many of those not well explained by a cooler tropical Pacific alone. These include a systematically stronger NAO during boreal winter, with associated changes in North Atlantic SSTs and sea ice, and European/North African precipitation. The simulated changes also include cooling and reduced rainfall in the equatorial eastern Pacific (boreal winter), seasonal aridity in equatorial and northeast Africa and into southwest Asia, transitioning towards relatively more moist conditions proceeding east across the Indian subcontinent, southeast Asia and into parts of China.

Overall, the findings support the general pattern of tropical SST changes seen in a recent statistical reconstruction (Mann et al., 2009), with a stronger zonal SST gradient between the Indo-Pacific Warm Pool and the eastern/central tropical Pacific during medieval times, relative to subsequent centuries.

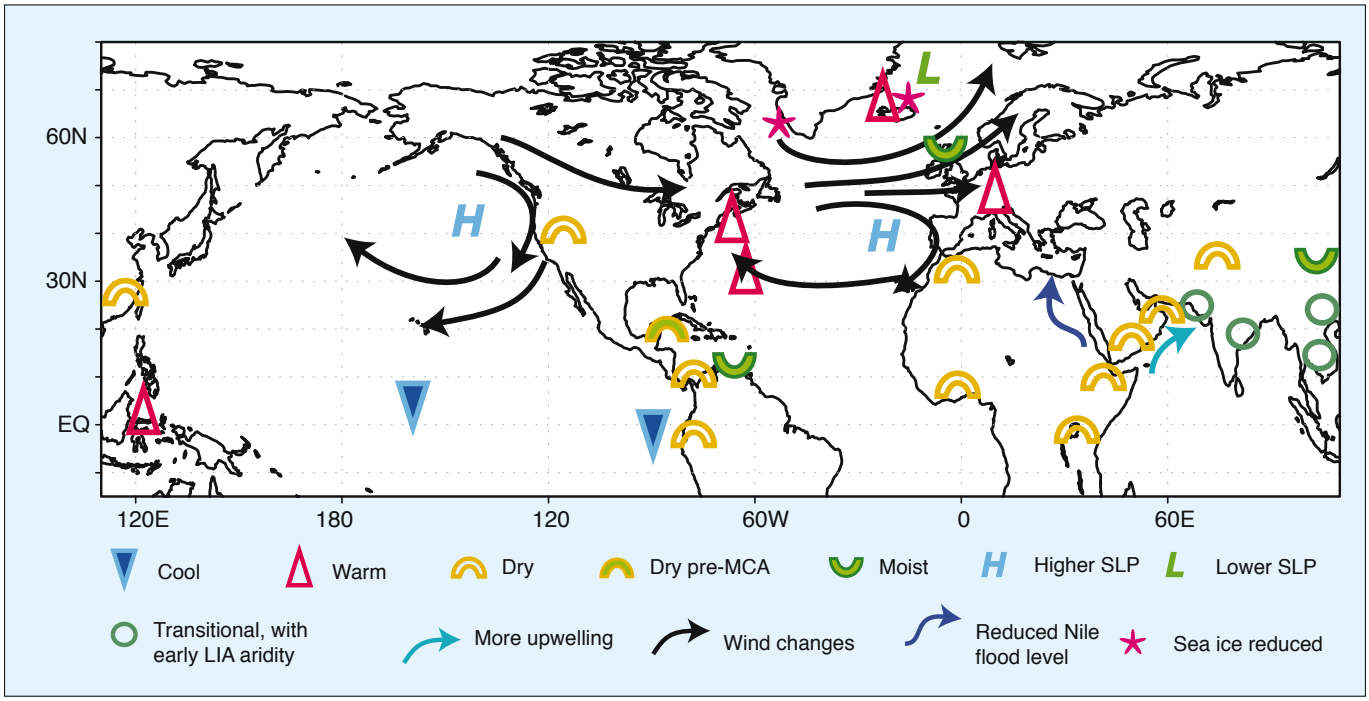

Figure 1: Schematic diagram of MCA vs LIA climate shifts as seen in a range of globally distributed proxy records

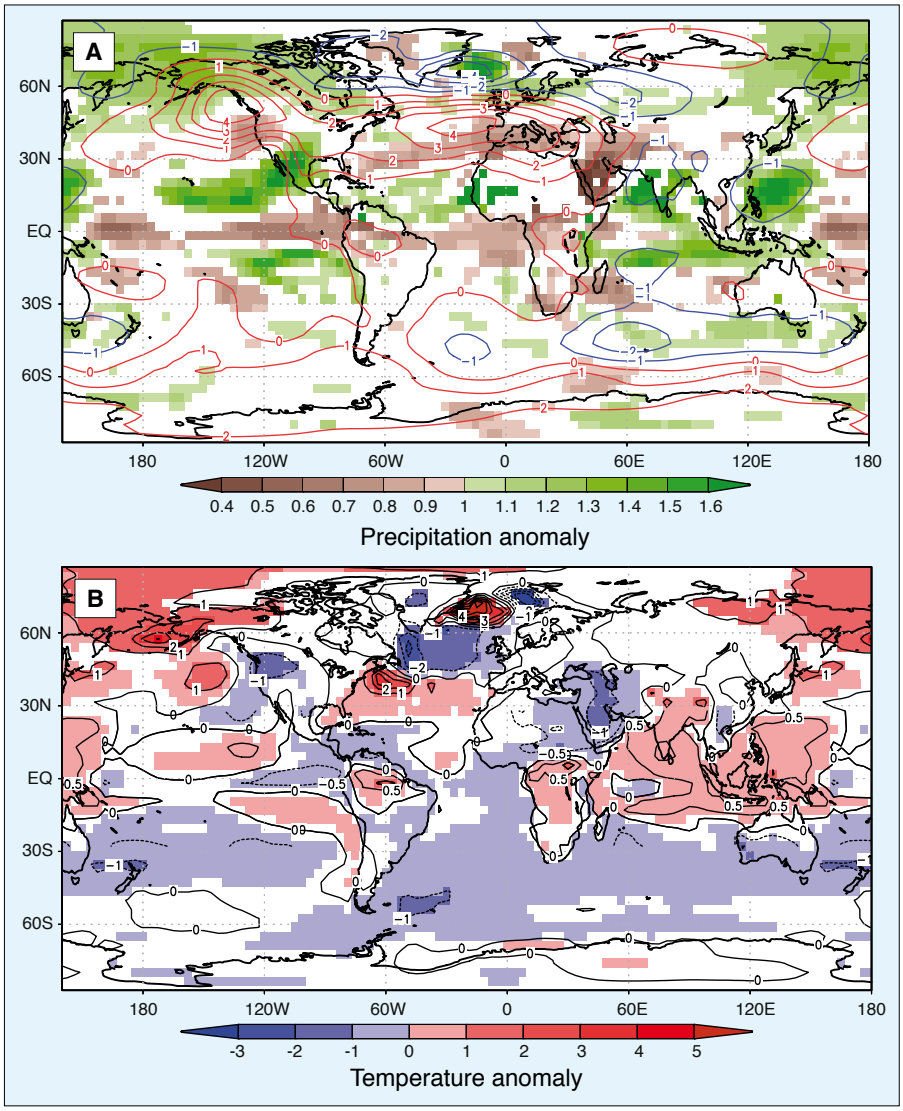

*Figure 2: **A**) Changes in December-March precipitation (fraction of control simulation climatology; color) and sea level pressure (difference with control simulation climatology; hPa, contours) for a simulation with increased tropical Indian and western Pacific SST; precipitation changes are shown only where the differences exceed the 95% confidence level. **B**) As in (A), but for December-March temperature (°C, color; values are SST over ocean and 2-meter temperature over land). Colors are shown only where temperature differences exceed the 95% confidence level. Lined contour interval is 0.5°C between 30°N and 30°S and 1°C elsewhere. Global average temperature change has been subtracted.*

Acknowledgements

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Medieval hydroclimate revisited

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Can the global pattern of Medieval hydroclimate be explained by a persistent La Niña-like state and a persistent positive North Atlantic Oscillation (NAO) and, if so, why did this happen?

North American megadroughts

The hydroclimate of the Medieval period (here loosely defined as the period from about the 9th Century to the end of the 15th Century) features some dramatic anomalies with respect to the modern climate. Perhaps the most remarkable are the series of multidecadal "megadroughts" that struck vast areas of Southwest North America which combined to create a generally more arid climate in the region that lasted centuries. These are well documented from tree-ring records (Herweijer et al., 2007; Cook et al., 2007, 2010). In addition, there is evidence for a strong Asian monsoon during the Medieval period, wet conditions over much of tropical South America, dry conditions in equatorial East Africa, wet in South Africa, a dry western Mediterranean region and wet northwest Europe (see compilation of proxy data in Seager et al., 2007, Burgman et al., 2010 and Figure 1). What could have caused such a global reorganization of hydroclimate for such a long period of time? The North American megadroughts immediately suggest a link to tropical ocean sea surface temperatures (SSTs). Climate modeling has clarified that the historical droughts of the 19th and 20th centuries were forced by small variations in tropical SSTs. All were forced, wholly or in part, by a cold, La Niña-like tropical Pacific Ocean. In addition, a warm subtropical North Atlantic Ocean played a role in forcing the 1930s and 1950s droughts. The tree-ring data clarified that the spa-

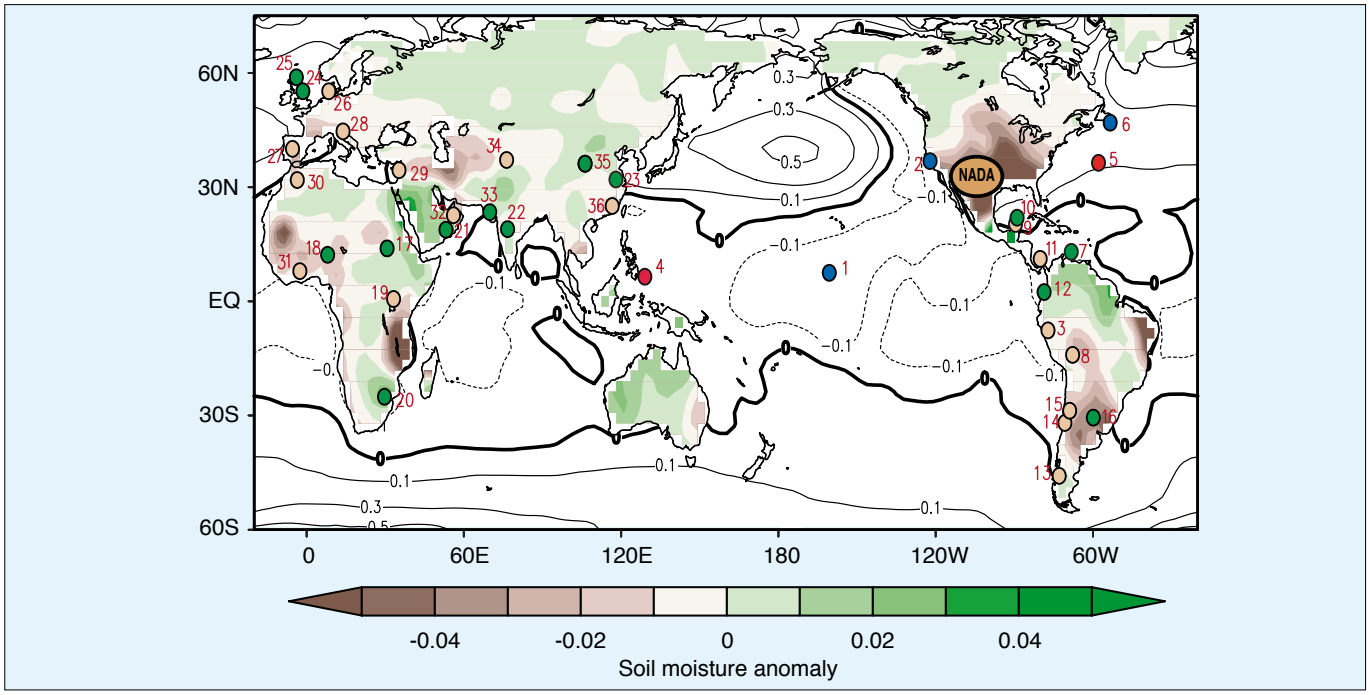

Figure 1: Global hydroclimate information from model simulations and proxy data. Brown and green dots indicate proxy records that show the 1320-1462 AD period to be drier or wetter than the subsequent Little Ice Age and modern periods. NADA (North American Drought Atlas, Cook et al., 2007) refers to dry conditions over North America. The colors over land show the soil moisture difference (soil water volume per soil volume) between the ensemble means of simulations forced by coral-reconstructed tropical Pacific SSTs for 1320-1462 AD and a simulation forced by modern observed SSTs. Contours over the ocean are the specified SST in the tropical Pacific and calculated (with an ocean mixed layer model) SSTs elsewhere. Blue and red dots over the ocean indicate proxy evidence of relatively cold and warm SSTs for this period. See Seager et al. (2008a) and Burgman et al. (2010) and supplementary material for more details including plots of the proxy data.

tial patterns of the modern and Medieval droughts were essentially the same extending from Mexico up to Oregon and from the Pacific coast into the Great Plains and sometimes as far as the Atlantic coast of the eastern USA. Persistent, multi-year La Niñas force modern droughts. Likewise, past shifts of the tropical Pacific to a more La Niña-like state for multiple decades at a time could, conceivably, have forced changes in atmospheric circulation that created the megadroughts.

Modeling of tropical Pacific Ocean forcing of North American megadroughts

Marine proxy data are quite sparse for the Medieval period. However Cobb et al. (2003, and updates at the Lisbon symposium, September 2010; http://mw-plisbon2010.fc.ul.pt/) used coral oxygen isotope data from Palmyra in the central equatorial Pacific Ocean and showed that SSTs were quite likely reduced throughout most of the Medieval period they were able to sample. However more work is needed to be certain since the coral oxygen isotopic composition could also be influenced by changes in salinity. Graham et al. (2007) examined other marine proxies from the Pacific and showed that they were consistent with a Medieval La Niña-like state. The Cobb et al. (2003) record has been used to create tropical Pacific SST fields for 1320-1462 AD that were imposed as forcing for an ensemble of 16 atmosphere GCM simulations (Seager et al., 2008a). The coral-reconstructed tropical Pacific SSTs were sufficiently cool and persistent to create multidecadal megadroughts over North America that had comparable spatial pattern and amplitude to the tree-ring reconstructed megadroughts during this 1320-1462 AD period. However, the model did not track the year-to-year evolution of the reconstructed North American hydroclimate very well.

Possible tropical Atlantic Ocean role on North American Medieval hydroclimate

In the last few years, climate modeling has shown that North American drought is also influenced by tropical North Atlantic SST variations, either via an indirect influence that involves the Pacific in winter or directly by forced stationary Rossby waves in summer (Kushnir et al., 2010; Seager et al., 2008b). Hence part of the model vs. tree-ring reconstruction discrepancy for 1320-1462 AD could be attributed to the neglect of the influence of Atlantic SST variations. Indeed Feng et al. (2008) have argued that the North Atlantic was warm during the Medieval period (in a pattern resembling the Atlantic Multidecadal Oscillation) and that this, in combination with the cold tropical Pacific, forced the North American megadroughts (see Oglesby et al., this issue). It is highly likely that the decade-to-decade and century-to-century evolution of North American hydroclimate during the Medieval period (including the succession of megadroughts interrupted briefly by wetter periods more akin to the current climate) was forced by the evolution of tropical Pacific and Atlantic SSTs acting in concert at some time and in opposition at other times. The extent to which the Pacific and the Atlantic Oceans themselves interacted is not known but it has been speculated that the two oceans can vary in a coordinated manner with possibilities for each to force and respond to the other.

Explaining the global pattern of Medieval hydroclimate: La Niña and a positive NAO

Turning to Medieval hydroclimate beyond North America, Herweijer et al. (2007), Seager et al. (2007) and Burgman et al. (2010) found around 30 proxy records from various types of archive (tree rings, speleothems, sediment cores, etc.) that showed evidence of a well defined Medieval hydroclimate anomaly (extending into the 14th and 15th centuries) relative to the subsequent Little Ice Age and modern periods. These were simply characterized as wet or dry following the interpretation of the original authors. These were then plotted together with the 1320-1462 AD time-averaged soil moisture anomalies from the ensemble mean of the model simulations forced with the tropical Pacific coral-reconstructed SST. Figure 1 presents an update of that figure.

There is general agreement on the dry conditions in the extratropical Americas and wet in the tropical Americas, typical

of a La Niña-state. The model also agrees with proxy evidence for dry conditions in equatorial East Africa and wet conditions in southern Africa. There is some indication of a stronger monsoon. The model also produces a dry Mediterranean region in agreement with some proxies. However, the model does not capture the wet conditions that proxy data indicate for northwest Europe. Data presented at the Lisbon symposium supported the dry western Mediterranean-wet northwest Europe dipole. This would not be expected from La Niña-forcing and is more likely to have been caused by a persistently positive North Atlantic Oscillation (NAO; Trouet et al., 2009). With the exception of Europe and perhaps North Africa, much of the global pattern of Medieval hydroclimate can be explained as a response to a Medieval La Niña-like state.

What caused Medieval La Niña and positive NAO states?

Why might a persistent Medieval La Niña and positive NAO have occurred? One argument is that relatively high solar irradiance and weak volcanism could have forced the tropical Pacific into a more La Niña-like state (Emile-Geay et al., 2007) with a positive NAO then being forced as a teleconnected response. Other arguments have been made that high irradiance could directly force a positive NAO (e.g., Rind et al., 2008). Recently Marchitto et al. (2010) have presented sedimentary evidence from the Soledad Basin off Baja California that La Niña-like states have coincided with increased solar irradiance throughout the Holocene, with the Medieval period being the most recent of these events. Should Medieval hydroclimate be externally forced, it would raise two important issues. The presumed amplitude of the external forcing is very small and the Medieval response would indicate a surprisingly high regional climate sensitivity. That regional climate sensitivity comes from a strong projection of forcing onto the patterns of the ENSO and NAO modes of climate variability. On the other hand, it is possible that these atmosphere-ocean states could arise from internal variability of the climate system on timescales longer than generally considered possible and potentially including as yet unknown interbasin couplings that act to persist certain preferred states. Either way, global Medieval hydroclimate is a fascinating and important challenge to our understanding of climate variability and change.

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The Medieval Climate Anomaly in Europe in simulations with data assimilation

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Data assimilation improves our understanding of the origins of climate changes during the past millennium in Europe.

Model data-comparison in the presence of large internal variability

The analyses of past climate changes are based on two main sources of information. First, proxy records provide qualitative and quantitative estimates of the changes. Second, the knowledge of the physical processes governing climate allows us to propose interpretations of the observed signals and possible explanations of their origin. This understanding of the system is generally formalized in models, ranging from conceptual models to sophisticated general circulation models. A successful study needs to stand on those two pillars and thus requires an efficient way to compare model results with proxy records.

However, such a comparison is not straightforward, in particular for the past millennium for several reasons. First, as for any paleoclimate study whatever the timescale is, proxy records covering the last millennium and model outputs do not represent the same quantity. Proxies include non-climatic signals and are generally influenced by local climate, while models simulate physical, and sometimes biogeochemical quantities averaged over thousands of square kilometers. Forward proxy models (where the variable recorded in the archive is directly estimated from the model output instead of using a calibration of the proxy in terms of simple physical variables like annual mean temperature) and regionalization techniques will certainly contribute to reduce the uncertainties associated with those issues in the near future (Hughes et al., 2010).

A second problem for the last millennium is the large role of the internal variability of the system during this period, in particular at continental and regional scales (Goosse et al., 2005). If a signal recorded in proxies is related to a known forcing such as a change in the insolation in summer or a decrease in greenhouse gas concentration, then a model that includes the adequate physics and is driven by this forcing should ideally reproduce the observed signal at the right time. However, even a perfect model cannot simulate at the right moment an event that has its origin internally in the non-linear dynamics of the climate system. Instead, a similar event may occur in the simulations earlier or later in time but never with identical temporal and spatial structure. Therefore, any difference between model results and observations can be due to model deficiencies but also simply due to a different realization of internal variability. This strongly reduces the constraints that model-data comparison could put on the realism of models. Furthermore, using a model to interpret an observed signal is nearly impossible if the model does not sim-

ulate the main characteristics of this signal at the right time.

Combining model results and proxy data through data assimilation

Data assimilation provides a way to partly bypass this latter problem. The goal of this technique is to optimally combine data with model results in order to obtain a state of the system that is compatible with both, taking into account the uncertainties on all the elements (for a recent review of applications of data assimilation devoted to the last millennium, see Widmann et al., 2010). As the obtained model state reproduces the observed signal, it is then possible to describe the origin of this signal by analyzing all the model variables.

However, data assimilation should be used in conjunction with simulations without data assimilation. In simulations with data assimilation, it is not possible to determine if a simulated event is related to a particular forcing or just to the internal variability of the system. By contrast, the average of an ensemble of simulations without data assimilation can be used to estimate the response of the system to the forcing. It is then tempting to consider that the differences between the simulations with and without data assimilation are related to the internal variability of the system. Nevertheless, this step should be made with caution since it assumes that the contributions of forced and internal variability linearly add to each other without any interactions between them and that the forced response estimated from models is perfect. This is of course only a first order approximation and data assimilation also compensates for uncertainties in the estimates of forcing reconstructions, as well as for errors in the model response to this forcing to an extent that is usually difficult to estimate.

The data assimilation technique that has been selected in our studies is a particle filter (Sequential Monte Carlo method, e.g., van Leeuwen, 2009) because it is relatively intuitive to use and because it is well adapted to strongly non-linear systems. Starting from an ensemble of initial conditions (96 in our case) obtained for instance from simulations without data assimilation, simulations are performed for one year using the climate model LOVECLIM (Goosse et al., 2010). The likelihood of each model state is then estimated from a comparison with proxy-based reconstructions. The simulations that show the largest disagreement with the proxies are stopped while the ones that are in better agreement are maintained. In order to keep the same number of particles (i.e., of members in the ensemble of simulations), the simulations that display the highest likelihood are duplicated, the number of copies being proportional to the likelihood, and then a small perturbation to the model state is added. The procedure is then prolonged for an additional year until the end of the period of interest. This technique guides the model results to follow the signal recorded in proxies. One of the limitations of the particle filter is that it requires a large number of members to reproduce the development of the system. Consequently, it is generally necessary to focus on a particular region or, when interested in a larger scale, to apply a spatial filter to remove high frequency spatial variations and to reduce the number of degrees of freedom of the system.

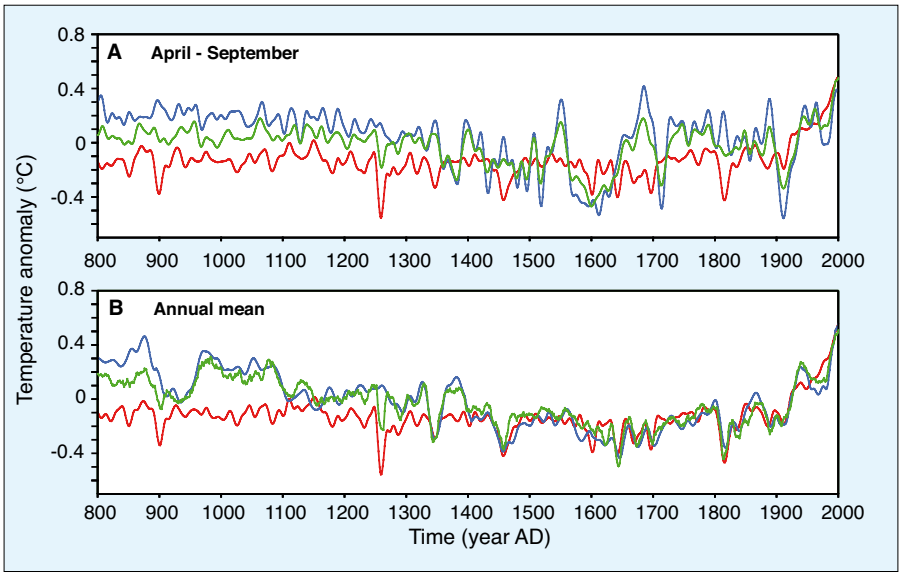

*Figure 1: **A**) Anomaly of growing season temperature (April to September) averaged over Europe (25°-65°N, 0-70°E) in the reconstruction of Guiot et al. (2010, blue), in simulations with the climate model LOVECLIM without data assimilation (red), and in simulations with LOVECLIM with data assimilation constrained by the Guiot et al. (2010) reconstruction (green). The reference period is 1900-1995. The time series has been filtered using an 11-year running mean. **B**) Same as (A) for annual mean except that the reconstruction is now the one of Mann et al. (2009) (blue) and the simulation with data assimilation is driven by this reconstruction (green).*

Application to the study of the MCA in Europe

Using this technique, it is possible to directly constrain the model to follow the relatively large number of proxy records available for the past millennium (e.g., Jones et al., 2009), eventually using forward proxy models and regionalization techniques. However, as a first step, we found it easier to use spatial reconstructions either of annual mean temperature over a large part of the world (Mann et al., 2009) or of summer temperature over Europe (Guiot et al., 2010) since they provide fields that are easy to compare with model results (Fig. 1).

In summer and winter, both reconstructions and simulations with data assimilation show a clear warm period in Europe between 900 and 1050 AD during the Medieval Climate Anomaly (MCA). This contrasts with the ensemble mean of the simulations without data assimilation (i.e., the forced response of the model), which shows only a small decrease between the early part of the millennium and the 16th-18th century (often referred to as the Little Ice Age). This weak forced response has also been found in other models driven by similar forcing as the one used here (Jungclaus et al., 2010). The analyses of the origin of the larger warming in the simulation with data assimilation shows that, in the simulation constrained by the Mann et al. (2009) reconstruction, the atmospheric circulation displays stronger westerly winds bringing warm air to northern Europe during the MCA, mainly in winter. In the simulation driven by the Guiot et al. (2010) reconstruction, westerlies are weaker in summer and a northward flow transports air from Africa to the central Mediterranean Sea and southern Europe during the MCA, contributing to the simulated warming.

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European tree-ring data and the Medieval Climate Anomaly

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European tree-ring chronologies reveal that temperatures during the Medieval Climate Anomaly (MCA) were likely as warm as during the 20th century, that earlier hydroclimatic changes have at times exceeded recent variations, and that evidence for a clear spatiotemporal pattern of the MCA remains puzzling.

Europe possesses a dense network of long instrumental station measurements, and with Scandinavia and the Alps, harbors at least two of the world's hotspots of dendroclimatic research that provide an exceptional pool of archeological wood material. Annually resolved millennium-long tree-ring chronologies that enhance our understanding of the Medieval Climate Anomaly (MCA, ca. 900-1400 AD), exist for different parts of Europe and northern Africa. Individual records that combine an adequate number of recent and historical samples can reflect high- to low-frequency variations in either warm season temperature or precipitation.

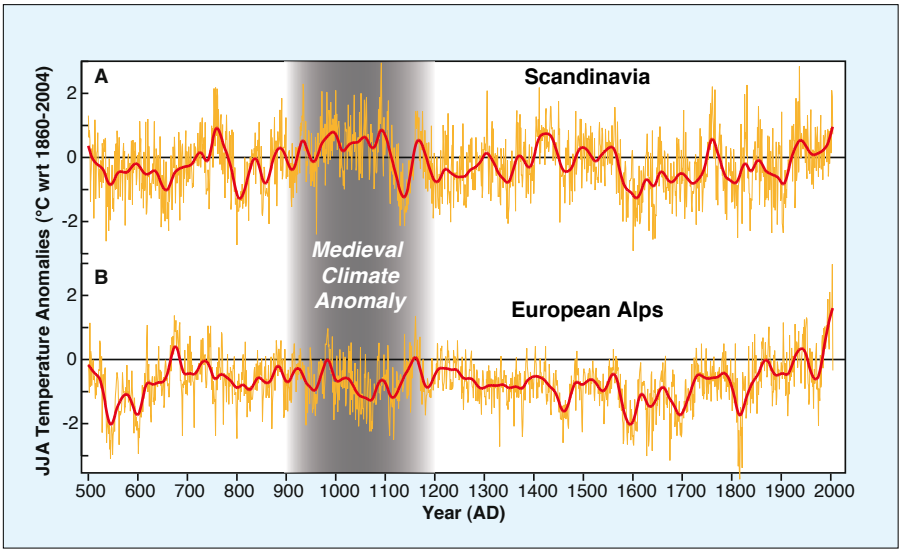

*Figure 1: Annually resolved and 40-year low-pass filtered temperature reconstructions averaged over (**A**) Scandinavia and (**B**) the Alps. Five tree ring-based warm season temperature reconstructions from Scandinavia (Briffa et al., 1992; Gouirand et al., 2008; Grudd et al., 2002; Grudd, 2008; Helama et al., 2009b) were re-scaled against June-August (JJA) temperatures (1860-2004 AD), averaged and smoothed. Their individual start and end dates range from 500-802 and from 1970-2004, respectively. Four tree ring-based warm season temperature reconstructions from the Alps (Büntgen et al., 2006, 2009, 2011; Corona et al., 2010) were re-scaled against JJA temperatures (1860-2004 AD), averaged and smoothed. Their individual start and end dates range from 500-1000 and from 2000-2004, respectively. Note that the initial reconstructions are not independent in terms of the data used and methods applied.*

Reconstructions

Millennium-long tree ring-based temperature reconstructions exist in northern Scandinavia (e.g., Briffa et al., 1992; Grudd et al., 2002; Grudd, 2008; Gouirand et al., 2008; Helama et al., 2009b) and the Alpine arc (e.g., Büntgen et al., 2005, 2006, 2009; Corona et al., 2010; Nicolussi et al., 2009). The Scandinavian composite records are based on living conifers, which grew during the past few centuries, and utilize dry-dead and sub-fossil material further back in time (see Linderholm et al., 2010 for a review). The Alpine temperature reconstructions are mainly based on high-elevation living conifers and historical construction timber. Slightly shorter temperature reconstructions that reach back into the 12th and 13th centuries are available from the Romanian Carpathians (Popa and Kern, 2009) and the Spanish Pyrenees (Büntgen et al., 2008). Both records show distinct summer temperature variations that are comparable to those obtained from the Alps. Dendrochronological studies in southern France (Serre, 1978), Albania (Seim et al., 2010) and Bulgaria (Panayotov et al., 2010) also revealed millennium-long ring width chronologies, but they only contain a mixed and overall lower climate signal (e.g., Büntgen et al., 2010a).

Northern and central European sites may reflect different patterns of temperature change (Büntgen et al., 2010b). Scandinavian summer temperatures were roughly below the 1860-2004 AD average from ca. 800-900, 1100-1400, 1570-1750, and from 1780-1920 AD (Fig. 1a). Summer warmth centered on the 760s, between ca. 980 and 1100 AD, and again in the 1410-1420s was comparable to, or even higher than, conditions during the 1930s and after ca. 1980. The timing of Scandinavian medieval warmth may have coincided with the establishment of Norse colonies in the cold and harsh environments of Iceland and Greenland (Patterson et al., 2010). In contrast, Alpine summer temperature depressions were estimated during the Little Ice Age (LIA) from the mid 15th century to ca. 1820 AD and coinciding with the Oort Solar Minima ca. 1050-1120 AD. Alpine summer temperatures during the late 20th century were unprecedented over the past 1500 years (Fig. 1b). Earlier warm periods occurred in the 990s and between ca. 1150-1250 AD and may have coincided with a rapid demographic and economic, as well as cultural and political rise of medieval Europe (McCormick, 2001).

While a few evenly distributed and highly replicated composite tree-ring chronologies (of distinct temperature sensitivity) are sufficient to capture the spatial character of European summer temperature variability (Büntgen et al., 2010b), many more records are necessary to provide a comparable meaningful picture of the continent's hydroclimatic variability. It should also be noted that most of the local-to-regional-scale hydroclimatic records best reflect drought conditions, such as soil moisture availability (Büntgen et al., 2010b), whose sensitivity is generally restricted to the early vegetation period of intense cell formation. Millennium-long ring width-based reconstructions from southern Finland (Helama et al., 2009a), south-central England (Wilson et al., unpublished data), central Europe (Büntgen et al., 2011), and the southern Mediterranean Maghreb (Esper et al., 2007; Touchan et al., 2010) preserve high- to low-frequency precipitation/drought variability (Fig. 2). Data also contain a pronounced level of synoptic-scale coherency amongst the same latitudinal belts. The two northernmost records agree well and show a drier

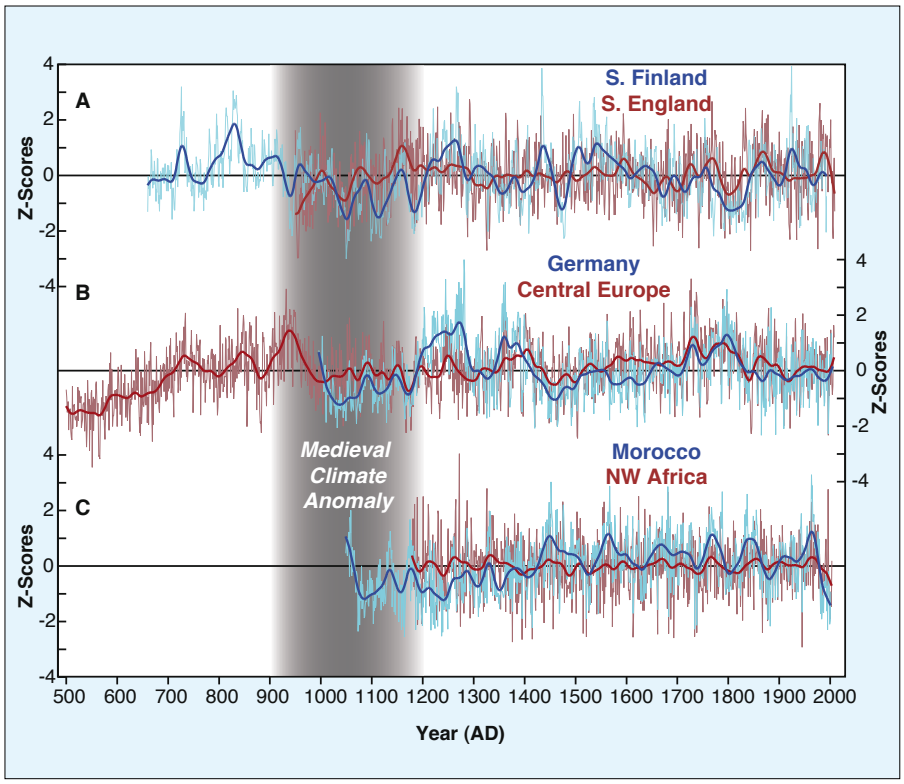

*Figure 2: Annually resolved and 40-year low-pass filtered regional-scale hydroclimatic reconstructions from (**A**) southern Finland (blue; Helama et al., 2009a) and south-central England (red; Wilson et al., unpublished data), (**B**) central Germany (blue; Büntgen et al., 2010) and central Europe (red; Büntgen et al., 2011), and (**C**) Morocco (blue; Esper et al., 2007) and northwest Africa (red; Touchan et al., 2010). Data were normalized over their individual length.*

MCA, a wetter LIA and average 20th century conditions compared to the individual record length (Fig. 2a). The central European records illustrate a similar picture with slightly higher amplitude between a drier MCA and a wetter LIA (Fig. 2b). The two records from the southern Mediterranean show decadal-scale hydroclimatic variations (Fig. 2c), but convincing indication for a longer-term contrast between an overall dry MCA, a wet LIA and an abrupt recent drought is largely derived from the study by Esper et al. (2007). It must be noted that the reconstructed northwest African drought fluctuations are based on a compilation of 39 site chronologies (Touchan et al., 2010), which are somewhat restricted in potentially preserving lower frequency information, and therefore partly deviate from the low-frequency signal displayed by Esper et al. (2007).

Evidence for a generally drier climate from ca. 1000-1200 AD is expressed in all compilations. Overall, wetter summers are found during the 13th and 14th centuries, in parallel to the global onset of the LIA, and may have added to the widespread famine in northern/central Europe in that period (e.g., Kershaw, 1973). Additionally, they may have also played a contributing role in the second plague pandemic, the Black Death (Büntgen et al., 2010c, 2011; Kausrud et al., 2010). Furthermore, the 14th century is associated with the abrupt abandonment of Greenland settlements (Patterson et al., 2010). Caution is however advised, as socio-cultural and epidemiological stressors must be carefully considered when linking climate variability to human history (de Menocal, 2001; O'Sullivan, 2008).

Perspective

The above paleoclimatic evidence emphasizes the need to better understand the timing and amplitude of the European MCA, as well as the associated spatial characteristic. Placing the MCA in a longer-term context and increasing the number of high-resolution proxy records will thus gain in importance. In this regard, it appears interesting that several multi-millennial-long chronologies of annually resolved ring width measurements have been developed for different parts of Europe. These compilations represent a unique dating tool, not only for archeological artefacts and historical construction wood, but also for antique artwork, instruments and furniture (see Haneca et al., 2009 for a review). Continuous chronologies of the past millennium are available for most countries of central and northern Europe. Oak composites of 2000 years exist for different sub-regions in England, Ireland, Denmark, Germany, Poland and France. Additional deciduous species including beech, ash and alder, as well as conifers (i.e., fir, spruce and pine) yield millennium-long chronologies for Germany, Austria, Switzerland, France and the Czech Republic. Their sample size comprises hundreds and thousands of series in Roman, Medieval, and Modern times, but dramatically drops during the so-called transition periods of increasing and continuing political turmoil. The paleoclimatic value of such compilations was recently demonstrated by introducing a random sampling strategy to update archeological chronologies into the 21st century while avoiding statistical over-fitting during the calibration (Tegel et al., 2010).

The annual-precise felling dates of historical wood can provide additional insight into socio-economic dynamics of past civilizations when carefully analyzing the dendrochronological records and utilizing dates of timber harvest as a surrogate for construction activity.

Acknowledgements

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Was there a common hydrological pattern in the Iberian Peninsula region during the Medieval Climate Anomaly?

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Climate variability reconstructions for the last millennium from several Iberian lake and marine records shed light on the spatial and temporal hydroclimate and associated climate mechanisms during the Medieval Climate Anomaly.

In order to understand the causes and spatial extent of the Medieval Climate Anomaly (MCA; ca. 900-1350 AD) and the Little Ice Age (LIA; ca. 1350-1850 AD), a better characterization of temperature and precipitation changes in a larger number of sites around the globe is required. Understanding the dynamics of MCA in the climatically-vulnerable Mediterranean region is particularly interesting since it encompasses a comparison between the hydrological response to a generally accepted warm period (the MCA) and to the present global warming. To tackle the question of how the MCA and the present global warming compare, the most pertinent approach is to study highly resolved records that are mostly driven by moisture changes. Sediments from small lakes that experience considerable fluctuations in terms of lake level and chemistry and biological proxies record such information on effective moisture variability. Coastal and marine sediments also provide evidence of changes in sea surface temperature (SST), river sediment delivery, and wind patterns related to climate.

Figure 1: Satellite image of the Iberian Peninsula region with the location of lake records (stars) and marine sites (dots) discussed in the text. Image from: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.

The Iberian MCA signal: Marine and terrestrial records

Their relative small size, direct connection to surface aquifers, and rapid response to precipitation make Iberian karstic lakes particularly sensitive to moisture changes. Detailed sedimentological and geochemical analyses, complemented with the study of biological proxies (chironomids, diatoms and pollen), have been performed on long sedimentary records retrieved in 2004 from several Spanish lakes. In Figure 1 we show the location of the lakes where the MCA signal is recorded, together with some marine cores discussed below.

Most of the studied lakes (e.g., Estanya, Taravilla, Zoñar, Arreo and Montcortés) record relatively shallower lake levels and more arid conditions during the MCA. This is indicated by higher chemical concentrations in the water, and the predominance of *sclerophyllous* Mediterranean vegetation, heliophytes and more evergreen trees in the catchment. In Figure 2, the most representative Iberian records are compared with global reconstructions, such as the number of sunspots (Vaquero et al., 2002). The fact that each lake is unique and responds differently to climate variability according to its geological, hydrological, and limnological characteristics makes it necessary to use case-specific proxies and apply local individualized interpretations. The reconstruction of lake level in Lake Estanya in the Pre-Pyrenees, mostly based on sedimentary facies and elemental and isotopic geochemistry (Morellón et al., in press), clearly shows a lake level increase from the end of the MCA to the LIA (Fig. 2). Similarly, the presence of gypsum-rich laminated facies in Arreo Lake (northern Ebro Basin, Fig. 1) suggests generally lower lake levels during the MCA (Corella et al., unpublished), while a thermophilous plant association recorded in the Montcortés Lake sedimentary sequence (Rull et al., in press) points towards warmer climate in the central Pre-Pyrenees. A comparable paleohydrological signal is recorded in Lake Taravilla, located in the Iberian Range. In this lake, coarser grain-size layers with higher siliciclastic content reflect paleoflood events during periods of increased run-off triggered by intense rainfall (Moreno et al., 2008). These layers are more frequent during the LIA and almost absent during the MCA (Fig. 2). Rb/Al ratios and Si concentration, used as proxies for run-off in Lakes Zoñar and Basa de la Mora, further indicate that a drier climate extended across the Iberian Peninsula during the MCA, compared to the following centuries (Martín-Puertas et al., 2010; Pérez et al., unpublished data). Despite local differences and some dating uncertainties, the MCA stands out as a relatively dry period, which was characterized by decreased lake water balance in the eastern and, likely, the southern part of the Iberian Peninsula.

The western Iberian Peninsula lacks high-resolution lake records of the MCA, but marine sediment cores provide some paleohydrological information. Several studies conducted offshore of Lisbon indicate that the MCA was a dry interval as inferred from reduced run-off (Abrantes et al., 2005; Lebreiro et al., 2006). On the Mediterranean side, the percentage of coarse particles in

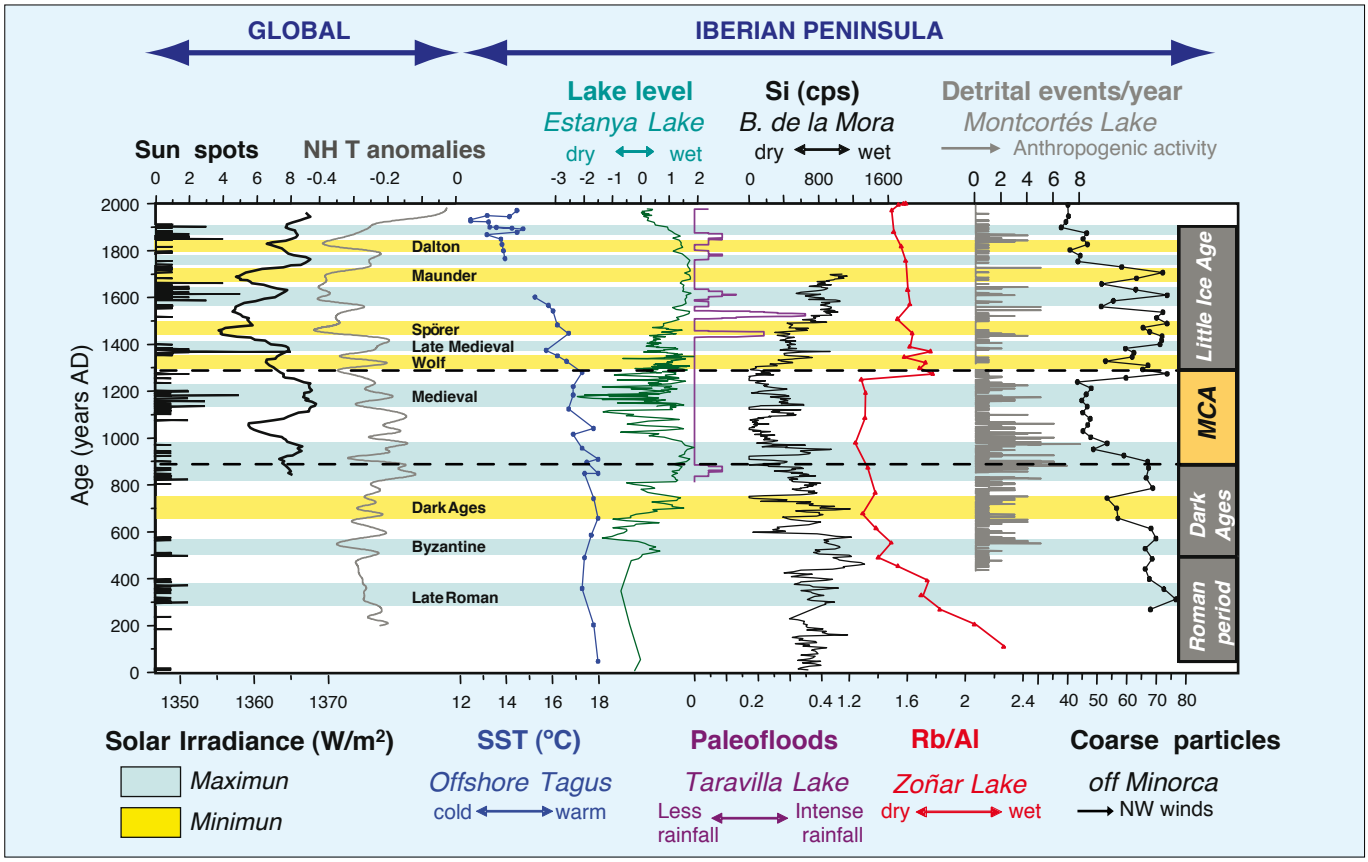

Figure 2: Compilation of global and Iberian climate reconstructions over the last 2000 years. Global records include sun spot numbers (Vaquero et al., 2002), solar irradiance (Bard et al., 2000) and temperature anomalies for the Northern Hemisphere (Jones and Mann, 2004). Iberian Peninsula records are aligned from west to east (see Fig. 1 for location) and include SST from marine cores offshore Tagus River (Rodrigues et al., 2009), lake level of Estanya Lake (Morellón et al., in press), number of floods observed in Taravilla Lake (Moreno et al., 2008), Rb/Al ratio from Zoñar Lake record (Martín-Puertas et al., 2010), number of detrital events per year recorded in Montcortés Lake (Corella et al., in press) and coarse detrital grain fraction from off Minorca (Frigola, unpublished data).

a sediment core from north of Minorca, located in a contourite drift, highlights an episode of weaker deep-water formation after 1300 AD, corresponding to the LIA (Fig. 2). At that location, particle grain-size is directly related to the intensity of deep-water currents that are formed in the nearby Gulf of Lions (Frigola et al., 2007). This result points to weaker westerlies during the MCA, which is consistent with a positive North Atlantic Oscillation (NAO) index at this latitude.

Climatic versus anthropogenic forcings

The areas surrounding some of the studied Iberian lakes were well populated during medieval times. This raises the need to discriminate climatically forced signals from anthropogenic effects on the lake dynamics (Rull et al., in press). For instance, in both Montcortés and Arreo lakes, sedimentation rates increased during the MCA (Fig. 2). However, discerning whether the higher sediment delivery was the result of climatic factors (increase in high-intensity storm events, relatively lower lake levels due to higher temperatures, more intense evaporation and decreased precipitation or more development of littoral environments) or produced by changes in land use practices (deforestation, farming and intensification of cultivation) is not an easy task. Most likely, human impact and climate variability had a joint effect on Iberian lakes during historical times. Fortunately, an integrated multiproxy approach provides some clues to detangle both factors. In Taravilla Lake, peak contents of Cerealia and other "anthropogenic" taxa associated with crops and ruderal plants occur at the base of the sequence when terrigenous paleoflood layers are scarce (Fig. 2). Thus significant removal of vegetation by human attributed fires or deforestation practices cannot be considered the main forcing for the increase in terrigenous layers (Moreno et al., 2008). In the same period, pollen reconstructions from Estanya (Morellón et al., in press), and Montcortés (Rull et al., in press) reflect warmer and drier conditions in a landscape dominated by junipers, Mediterranean elements (evergreen *Quercus*, *Olea*, *Phillyrea*, *Buxus*, *Thymelaea* and *Rosmarinus*), a relatively low presence of mesophylic woody taxa, heliophytes, some cultivated plants and a poorly developed aquatic component.

A global context for the Iberian aridity during the MCA

The Iberian records clearly documenting warmer conditions during the MCA are consistent with global paleoclimate reconstructions (e.g., Mann et al., 2009). Climate variability during the last millennium has been related to solar irradiance fluctuations and tropical volcanic eruptions (e.g., Shindell et al., 2001; Wanner et al., 2008). Recently, a persistent positive mode of the NAO during the MCA has been suggested (Trouet et al., 2009). This would lead to warmer and more arid climate in the western Mediterranean region. The Iberian Peninsula serves as a laboratory to explore the long-term pattern of the NAO index because of its location at the southern edge of the storm tracks associated with mid-latitude westerlies. Thus, a dry climate during the MCA is coherent with a dominant positive phase of the NAO, characterized by lower river discharge offshore Lisbon (Lebreiro et al., 2006; Alt-Epping et al., 2009), lower lake levels in northeast (Morellón et al., in press) and southwest Iberia (Martín-Puertas et al., 2010), fewer flood events in the Tagus River Basin (Benito et al., 2004; Moreno et al., 2008), and less intense westerly winds offshore Minorca Island (Frigola et al., unpublished data). Recent model simulations for temperature and precipitation in the Iberian Peninsula during the last millennium support the role of the NAO in creating a dry anomaly during medieval times (Gómez-Navarro et al., 2010). More analyses in progress and improved chronologies will facilitate a more detailed comparison of records to clarify the internal structure and spatial coherence of the main phases of environmental change during the MCA in the Iberian Peninsula.

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Medieval drought in North America: The role of the Atlantic Multidecadal Oscillation

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The sea surface temperature anomalies associated with the Atlantic Multidecadal Oscillation may have been a major factor contributing to widespread drought in North America during Medieval times.

The role of the Atlantic Multidecadal Oscillation

Medieval times (900-1330 AD; hereafter referred to as MT) in central and western North America were, according to proxy data reconstructions, generally warm, and especially dry (Fig. 1), with numerous decadal or longer "megadroughts" that were the worst of the past 2000 years (Woodhouse and Overpeck, 2000). Considerable attention has been paid to the role of sea surface temperature (SST) anomalies in forcing these prolonged periods of drought, especially that of the La Niña-like condition in the eastern tropical Pacific (e.g., Graham et al., 2007; Seager et al., 2007). Compelling recent evidence suggests that North Atlantic SST, through the Atlantic Multidecadal Oscillation (AMO), may also have a strong effect on persistent summertime drought in North America (Fig. 1b). At present, the AMO expresses a 60-80 year cycle between relatively warm (warm phase) and cool (cold phase) SST (Kerr, 2000; Enfield et al., 2001).

We investigated the role of the AMO in MT drought in North America using modern (present-day) observations, proxy paleo-data, and simulations from multiple climate models (Feng et al., 2010). Considering present-day relationships, for which instrumental observations can be used, the results show that persistent summertime droughts in the U.S. Great Plains and southwest North America are closely related to multidecadal variations of North Atlantic SST (AMO). During the AMO warm (cold) phases, most of North America is dry (wet).

Next, the influence of North Atlantic SST on modern North American drought was examined using simulations made by five global climate models (Feng et al., 2010). When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America despite some regional differences. Specifically, all the models simulate dry summers in the Great Plains and southwestern North America. The response of precipitation to a cold North Atlantic is much weaker, with greater disagreement among the models. Overall, the ensemble of the five models reproduced the statistical relationships between dry/wet fluctuations in North Amer-

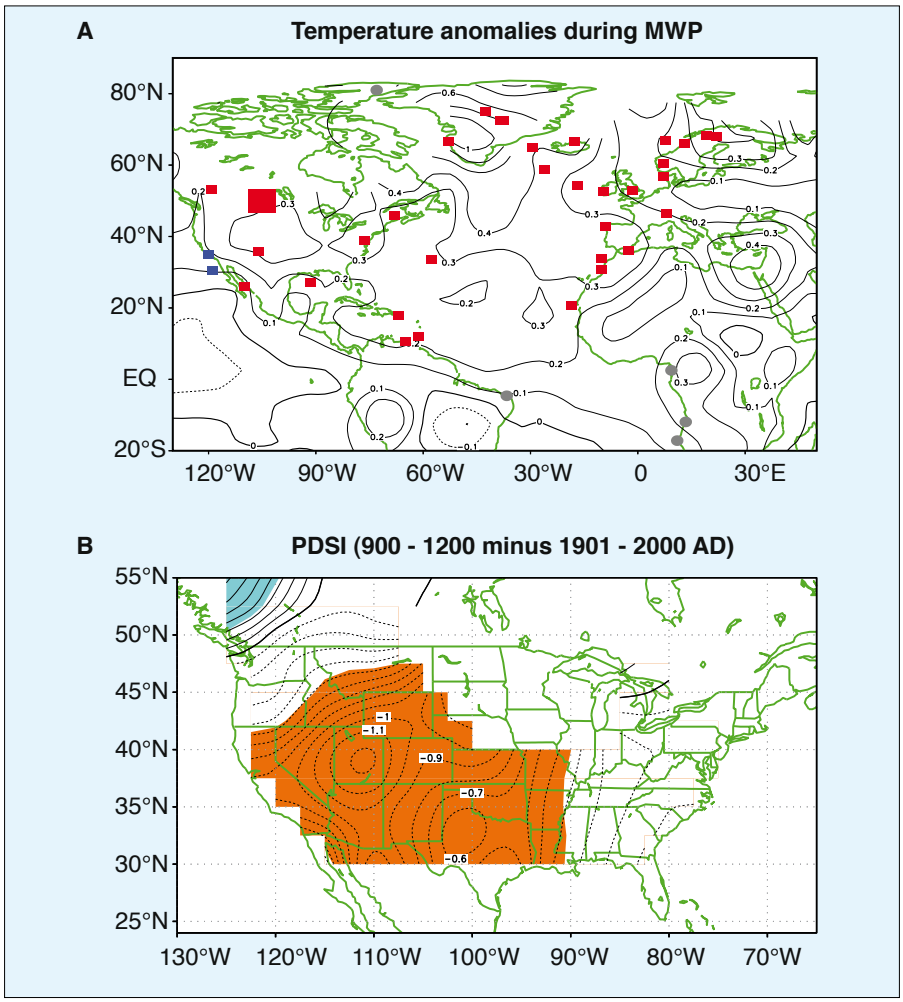

*Figure 1: **A**) Spatial distribution of the proxy data of temperature changes during MT. Blue squares, gray dots and red squares indicate cooling, no changes and warming during Medieval Times, respectively. The contour lines are the observed temperature anomalies associated with AMO warm phases for the period 1901-2006 AD. The contour interval is 0.1°C. Details of the proxy data can be found in Feng et al. (2009). **B**) Difference in tree ring reconstructed Palmer Drought Severity Index (PDSI) for 900-1200 minus 1901-2000 AD. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test. The figure is adapted from Feng et al. (2010).*

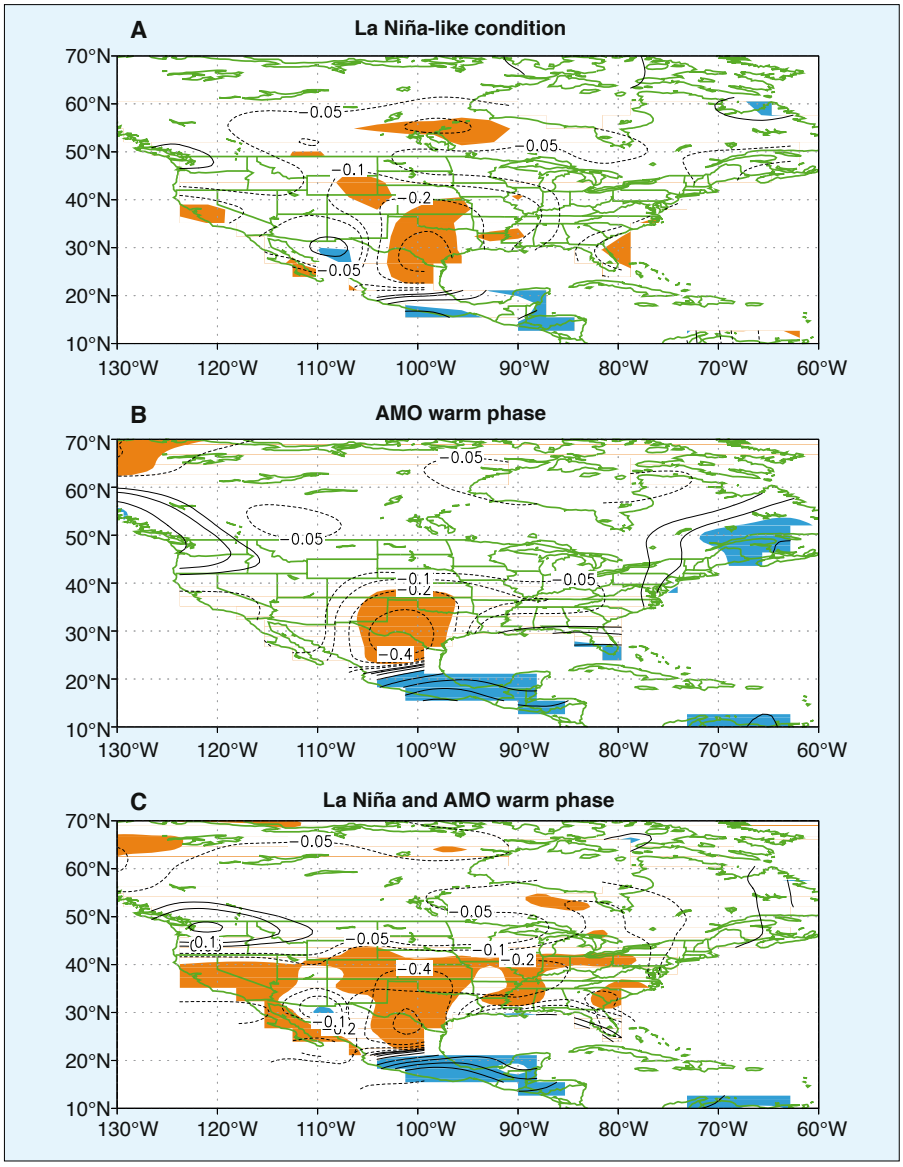

*Figure 2: Influences of (**A**) La Niña-like conditions in the eastern tropical Pacific Ocean, (**B**) AMO warm phase SST in the North Atlantic and (**C**) both La Niña-like SST in the tropical Pacific and AMO warm phase SST in the North Atlantic on the annual averaged daily precipitation (mm/day; solid lines are positive and dotted lines are negative anomalies with respect to the control run). Shadings indicate the anomalies are significant at the 95% confidence level based on a two-tailed student-test. Figure adapted from Feng et al. (2008).*

ica, and North Atlantic SST anomalies (Feng et al., 2010) quite well.

The AMO during Medieval times

Investigations of proxy SST records in both the tropical Pacific and North Atlantic (Feng et al., 2008, 2009) found a consistent basin-wide warming in the North Atlantic Ocean during MT (Fig. 1), supporting previous studies that there were generally warm periods in the North Atlantic realm (Lamb, 1977). The proxy records from the Pacific Ocean, however, yielded opposite results about SST changes in the eastern tropical Pacific during MT, with some suggesting La Niña-like conditions, while others suggest neutral or even El Niño-like conditions (Feng et al., 2008).

Using one particular model, the NCAR Community Atmosphere Model (CAM3), we further demonstrated that warm North Atlantic SST anomalies might have played a major role in the MT drought over much of North America (Feng et al., 2008). The MT drought could be simulated either by perpetual La Niña-like conditions in the eastern Pacific or by the warm phase of the AMO in the North Atlantic. La Niña conditions alone resulted in the best simulation of the intensity of MT drought (Fig. 2a), while simulation with a warm phase AMO alone reproduced well its areal extent (Fig. 2b). The two together can explain both the severity and longevity of the droughts (Feng et al., 2008) as shown in Figure 2c.

The AMO throughout the Holocene

To provide a longer-term perspective, we analyzed SST variations in the North Atlantic Ocean for the last 10 ka using empirical orthogonal functions (EOF). The first spatial mode (EOF1) accounts for 52.5% of the variance of the Holocene SST and demonstrates a basin-wide structure in the North Atlantic that clearly resembles the AMO pattern recorded during the recent instrumental period (Feng et al., 2009). The first principal component (PC1) associated with EOF1 is thus a good index that represents the temporal variations of the AMO-like SST pattern during the Holocene. The proxy record indicates that the MT drought is just one of many previous droughts on centennial timescales that impacted North America. We further demonstrated that these centennial droughts appear closely related to the AMO-like SST variations in the North Atlantic (Feng et al., 2010).

How does the AMO affect North American drought?

Clearly, the AMO or AMO-like SST had the capacity to strongly modulate precipitation and drought over North America throughout the Holocene. But the evidence presented above is all essentially statistical in nature, i.e., over a variety of timescales the AMO appears highly correlated with precipitation (and drought) over North America. The question arises: through what physical processes and mechanisms do the SST patterns reflected by AMO affect North American precipitation? Preliminary analyses from a suite of long model simulations made with the CAM3 suggest some intriguing and even surprising results (Hu et al., unpublished). A primary connection is through the influence of the AMO on the subtropical high-pressure zone in the North Atlantic (Wang et al., 2007). In summer, the poleward flow on the western side of this high-pressure system funnels moisture into the central and western US, providing a source for most of the summertime precipitation in those regions. During the warm phase of AMO, the subtropical high is displaced north and east of its mean location, reducing moisture transport into the US except along the mid-Atlantic coast. During the cool phase, the subtropical high strengthens and pushes westward, allowing for more moisture transport into the central and western US. Similar mechanisms appear to be at play during MT (Feng et al., 2008).

Future directions

The above results are intriguing, but still very preliminary. Proxy reconstructions and modern observations suggest that the AMO is associated with drought in North America. Understanding the physical mechanisms by which the AMO affects this drought remains, however, less clear. Furthermore, the AMO acts along with other phenomena, especially El Niño Southern Oscillation and the Pacific Decadal Oscillation. A much deeper understanding is

required of how these various phenomena act together, over a variety of timescales.

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Reconstructed and simulated Medieval Climate Anomaly in southern South America

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An austral summer temperature reconstruction for southern South America for the last millennium is compared to paleoclimate simulations provided by two Atmosphere-Ocean General Circulation Models with special emphasis on the Medieval Climate Anomaly.

The understanding of the current and future processes, and dynamics of the climate system can greatly benefit from the knowledge of past spatial patterns, trends, amplitudes, and frequencies of climatic variations (Jones et al., 2009, and references therein). Until recently, the rather low number and uneven spatial distribution of temporally highly resolved proxies from the Southern Hemisphere did not allow reliable continental scale reconstructions at interannual-to-interdecadal timescales (Neukom et al., 2010). Given the importance of the potential seesaw mechanism between the Northern and Southern Hemisphere (NH and SH) and the driving role of the SH oceans in regulating global climate variability, South America is a key region for the study of climate processes and dynamics. Climate in South America is influenced by a variety of oceanic and atmospheric patterns, such as the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM; Garreaud et al., 2009). Thus, SH climate reconstructions covering the past centuries to millennia can provide insights into the underlying mechanisms of climate variability and forcing imprints. Such reconstructions are essential for data/climate model comparisons. Here, we present results from a new multiproxy-based austral summer (DJF) temperature reconstruction that covers the last 1000 years in southern South America (SSA) (Neukom et al., 2010). Special emphasis is given to the temperature difference between the periods 1001-1350 ("Medieval Climate Anomaly", MCA) and 1400-1700 ("Little Ice Age", LIA). Furthermore, austral summer temperature reconstructions are also compared with two coupled atmosphere-ocean general circulation models (AOGCMs): The two ECHO-G simulations Erik1 and Erik2 using identical external forcings, but different initial conditions (i.e., the initial conditions used in year 1000 AD in Erik2 where cooler than in Erik1; González-Rouco et al., 2006), and one simulation with CCSM3 (Hofer et al., 2010). The models use slightly different anthropogenic and natural forcings, including different levels of atmospheric concentrations of carbon dioxide, methane, and nitrous oxide, of solar activity, and of volcanic aerosols. We also provide austral summer temperature difference patterns (MCA minus LIA; 1001-1350 minus 1400-1700 AD) for both the multiproxy reconstruction with their associated uncertainties and the corresponding simulations from the three model simulations.

Austral summer temperature reconstructions back to the MCA and comparison with two AOGCMs

Figure 1 shows the austral summer (DJF) land-surface air temperature anomalies (with respect to the 1001-1700 AD reference period) for SSA (south of 20°S) both for the principal component-multiple regression based reconstructions (Neukom et al., 2010) and the three model simulations spanning the period 1001-1990 AD. The reconstruction generally points to warmer conditions during the MCA. A strong decrease in temperature is visible in the second half of the 14th century. The climate reconstruction for this period mainly relies on tree-ring information from the Andes, lake sediments from Central Chile and an ice core from the tropical Andes (Neukom et al., 2010; see Fig. 1 bottom left). Cooler conditions prevail throughout the late 17th century (LIA). The difference in mean austral summer temperature between the two periods (1001-1350 minus 1400-1700 AD) is approximately 0.39°C in the reconstruction, 0.14°C and 0.49°C in CCSM3 and Erik1, respectively. A possible explanation for the rather small difference in the CCSM3 simulation compared to the Erik1 simulation is the lower equilibrium climate sensitivity of CCSM3. The associated ±2 Standard Error (SE) uncertainties of this difference (based on the uncalibrated variance in the 20th century calibration period; see Neukom et al., 2010, for more details) for the MCA and the LIA are of the order of ± 0.3°C (shaded parts in Fig. 1 top panel). The interpretation for the sudden drop in the mean temperature during the "MCA-LIA" transition is not known yet.

The reconstructions (Neukom et al., 2010) point to positive temperature anomalies in the 18th century, followed by a cooling phase that starts in the early 19th century. Since approximately the 1850s, SSA has experienced a long-term warming trend with superimposed shorter cooling periods. The multiproxy-based reconstruction and the AOGCMs generally agree on the centennial-scale warm and cold phases and their amplitude. However, there are differences between the reconstruction and the models in the timing of the MCA-LIA transition, which appears around 60 years later in the models. Additionally, the simulated transition is a two step process: a first step is initiated with

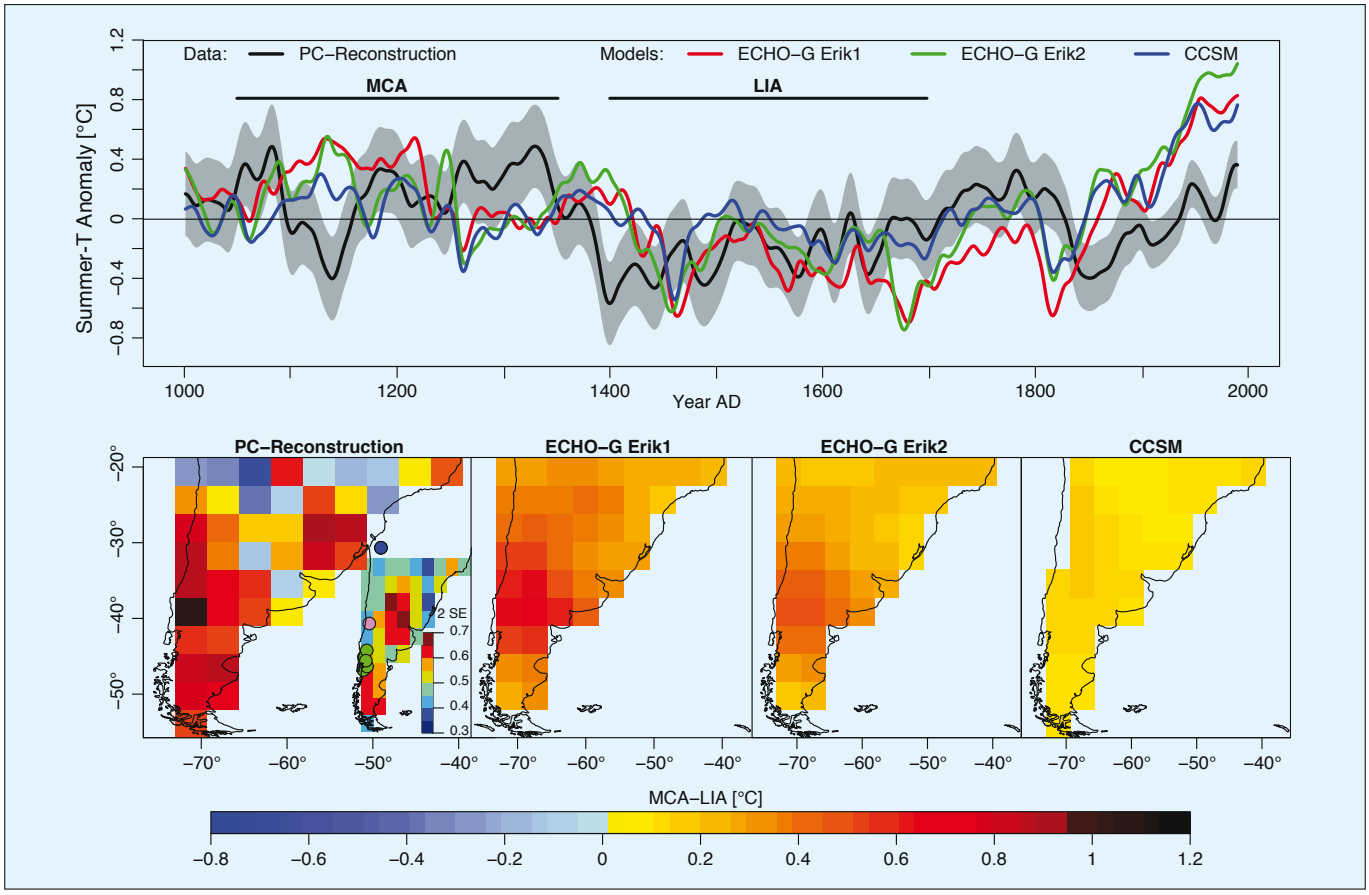

Figure 1: ***Top****: Austral summer (DJF) surface air temperature for southern South America (south of 20°S) for the period 1001-1990 AD (Neukom et al., 2010), expressed as 30-year Gaussian filtered anomalies with respect to the 1001-1700 AD climatology. Black: principal component-multiple regression based reconstructions and associated filtered ±2 SE uncertainty bands (shaded); red: ECHO-G Erik1, green: ECHO-G Erik2, blue: CCSM3 AOGCM simulations.* ***Bottom****: Spatial austral summer (DJF) surface air temperature difference patterns (MCA minus LIA; 1001-1350 minus 1400-1700 AD) for the multiproxy reconstruction (left; interpolated to the 3.75°x3.75° grid of the AOGCMs) and the AOGCMs simulations . The inset in the left panel represents the available proxy time series in the pre-1700 period (green: tree ring series; purple: lake sediment record; blue: ice core) and the 2 SE derived from the 20th century calibration period, averaged over the period 1001-1700 AD (Neukom et al., 2010).*

the strongest volcanic eruption of the last millennium around 1258 AD and a second step coincides with the Spörer solar Minimum (ca. 1460-1550 AD) . Thus the model simulations seem to be more sensitive to external forcings than the multiproxy reconstruction would suggest. This leads to larger model temperature amplitudes on decadal timescales, in particular for the ECHO-G simulations. The models overestimate the warming in industrial time with respect to the proxies, most likely because of aerosol forcing and land use changes which are not considered in the simulations.

Figure 1 (bottom panels) shows the austral summer surface air temperature difference patterns (MCA minus LIA; 1001-1350 minus 1400-1700 AD) for the multiproxy reconstruction (left) and the three simulations. The inset in Figure 1 (bottom left) represents the available proxy records as well as the distribution of the ±2 SE over the period 1001-1700 AD. In the reconstructions, the MCA was up to 1.1°C (1.6°C in the non interpolated 0.5°×0.5° resolved version of Neukom et al., 2010) warmer compared to the LIA, which is apparent in the west and south and partly in the east of SSA. The reconstructions in those areas can be considered as reliable, as reflected by the low SE (Fig. 1, bottom inset). Less reliable are regions in the centre of SSA and parts of Patagonia. This is mainly due to the lack of proxy data in these regions and some quality issues in the instrumental calibration data. The reconstructed MCA conditions in the northwestern- and northeasternmost parts were slightly colder compared to the LIA.

ECHO-G simulations (Erik1 and 2) and to some extent also the CCSM3 simulation are generally in good agreement with the overall anomaly pattern of the reconstruction and both models show the anomalous warm conditions during the MCA period compared to the LIA with strongest anomalies in the southwest. The negative values in the northeast are not reproduced by the two models considered herein.

Conclusions

The paucity of high-resolution proxy data covering the early part of the last millennium results in uncertain multiproxy reconstructions for the medieval period. Though not homogeneous in time, this early period until approximately the mid 14th century is, on average, warmer than the subsequent period until around 1700 AD. There is a rather good agreement between the reconstruction and the two AOGCMs both in terms of mean conditions as well as the general spatial anomaly pattern. Future work based on more high-resolution proxy records, including detection and attribution studies, will help to refine these patterns, as well as the timing and causes of the MCA-LIA transition.

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Blocking circulation anomalies in the Tasman Sea region during the Medieval Climate Anomaly

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Contrasting Australasian and Antarctic proxy archive signals are being exploited to reconstruct regional- and Southern Hemisphere-scale atmospheric circulation patterns, which indicate that the frequency of blocking events across the southwest Pacific increased during the Medieval Climate Anomaly.

A recent focus on the land-sparse and data-sparse Southern Hemisphere (SH) has begun to fill critical gaps in our observational record of past climates identified by the paleoclimate research community (Jansen et al., 2007). This thrust is providing balance to Northern Hemisphere (NH) reconstructions, and is facilitating linkages between archives from the tropics through to Antarctica. Underscoring the usefulness of Australasian mid-latitude climate reconstructions are newly emerging perspectives about past extremes and mean climate state changes for the region. These new views are supplementing the general understanding of natural climate variability ranges prior to land-based instrumental records (typically less than 150 years coverage), and are expanding knowledge about tropically-based climate phenomena (El Niño-Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), Indian Ocean Dipole, the Madden-Julian Oscillation, Australasian monsoon and the South Pacific Convergence Zone (SPCZ)) and other key extra-tropical components of the global climate system (e.g., the Antarctic Circumpolar Current (AAC), the Southern Annular Mode (SAM), and the mid-latitude westerlies).

Regional paleoclimate reconstructions in Australasia are being undertaken to increase natural climate variability understanding, leading to more robust validation of global climate models and improved model selection for future scenario-building. This approach is feeding into improved formulation of scenarios that are guiding mitigation and climate change adaptation strategies for Australia, New Zealand, and the small island nations of the Southwest Pacific. Observed patterns in multi-proxy paleoclimate syntheses are currently being compared to broad-scale circulation outputs from paleoclimate models (i.e., Paleoclimate Modelling Intercomparison Project (PMIP)), which will verify how well some climate models perform for the Australasian region. A key time span includes the last 2000 years, which contains the Medieval Climate Anomaly (MCA). The MCA expression in Australasia is particularly relevant to study because this period is considered as a key analogue to a future warmer-than-present world.

Approaches to integrating proxies

For New Zealand, a paleoclimate proxy integration approach called Regional Climate Regime Classification (RCRC) is being used to link paleoclimate time slices to modern circulation analogues (Lorrey et al., 2007, 2008). Uniquely, inferences about past atmospheric pressure patterns made from RCRC time slices provide a qualitative "upscaling" that can complement limited downscaled paleoclimate model information. This approach has been a boon for directly comparing proxies that are sensitive to atmospheric circulation changes and paleoclimate model outputs that lack sufficient locally downscaled precipitation or temperature results (e.g., PMIP), opening a new avenue for climate model testing and validation.

An alternative approach is employing pressure gradient and threshold detection algorithms to identify hemispheric circulation patterns associated with regional paleoclimate anomalies (Goodwin et al., 2010). The approach links modern synoptic type sets to unique climate responses at each proxy site.

With the exception of annually-resolved proxies used in the aforementioned synoptic paleoclimatology approaches, there is some uncertainty in the alignment of the archive signals that cover the MCA because of chronological uncertainties and sampling resolutions. In addition, some proxies are more susceptible to distortion than others due to geophysical and anthropogenic activity (Lorrey et al., 2010). However, careful interpretations of the records within a regionally-comprehensive network have meant multi-centennial approximations of past circulation patterns are possible using the two aforementioned approaches.

Regional synoptic circulation reconstructions for the MCA

The example RCRC time slice shown for ca. 750 to 925 AD (Fig. 1a) covering New Zealand is analogous to what occurs in a typical La Niña year, when northern and eastern regions tend to receive normal or above normal rainfall, and southern and western regions are often drier than normal. Overall the pattern is analogous to a blocking regime (Kidson, 2000), typified by more frequent northerly and easterly circulation synoptic types that block the prevailing west-to-east progression of anticyclones and troughs that characterize New Zealand's daily weather variability. Blocking patterns are generally more frequent during the warm season in La Niña years when the sub-tropical high pressure belt moves southward, conspiring with the SAM (often in a positive mode during Austral summer; L'Heureux and Thompson, 2006) to increase anticyclone presence over southern New Zealand. This pattern also has a spatially similar signature to the penultimate IPO-negative phase between 1944-1976 AD.

Time slices produced for New Zealand suggest an MCA that can be broken into at least three phases; an early (ca. 750-1075 AD), middle (ca. 1100-1300 AD), and late (ca. 1350-1550 AD) phase (Lorrey et al., 2010). Weaker precipitation anomalies in the northern and eastern regions of New Zealand in the late MCA phase indicate a slackening of the blocking strength. The middle phase is characterized by oscillations back and forth between more frequent northerly and easterly circulation (blocking) and periods of more frequent southwesterly flow (zonal regimes). The oscillatory nature of the mid-MCA phase is also suggested by at least three surface exposure age- and radiocarbon-dated glacier advances in the Southern Alps (Schaefer et al., 2009) and periods of cooler summer temperatures reconstructed from tree rings in western South Island (Cook et al., 2002).

Variability and drivers during the Polynesian Warm Period

The early 2nd millennium AD heralded the arrival and permanent occupation of New Zealand by Maori (Wilmshurst et al., 2008), and it has been suggested that this

interval could be termed "the Polynesian Warm Period" (PWP; Williams et al., 2009). The PWP corresponds to the mid- to late-MCA phases described above, which saw significant Polynesian voyaging episodes and cultural shifts in the southwest Pacific (Anderson et al., 2006; Allen, 2006). The "La Niña-like" blocking patterns that are strongly indicated for New Zealand prior to and during the PWP support evidence from other paleoclimate reconstructions that suggest the SH westerly wind belt and ACC shifted northward between ca. 650-1250 AD with Antarctic cooling that affected the mid-latitudes. It is proposed that high latitude changes in this interval helped set up a positive high-latitude/tropical feedback that initiated a more "La Niña-like" climate state in the equatorial Pacific (Mohtadi et al., 2007), consistent with reconstructions of a "cool" ENSO signature in the central-eastern Equatorial Pacific, expansion of the Hadley circulation, and ridging in the NH mid-latitudes (Graham et al., 2010). Under a blocking regime, there would have been enhanced anticyclonic activity in the SH mid-latitudes, including the Tasman sector. However, significant zonal regime episodes during the mid- to late-MCA/PWP suggest that blocking regimes were not exclusive at the time, but rather there were sustained, strong periods of bi-modal circulation operation. This raises the likelihood that the regional variability associated with both ENSO (and IPO) phases (including droughts, storms, SPCZ shifts, local changes in tropical cyclone incidence, prevailing wind change, and SST anomalies) were probably as significant during the MCA/PWP to Australasian and Pacific Island populations as they are at present.

The atmospheric circulation anomalies reconstructed for New Zealand during the early MCA are nested within a larger SH pattern that blankets the Australasian and southwest Pacific sectors (Fig. 1b), indicated by a multi-proxy-based pressure gradient reconstruction using Eastern Australian coastal behavior and wave climate, Southern Australian mega-lake hydrology, coral-based subtropical sea-surface temperatures, East and West Antarctic ice core glaciochemistry, and Antarctic lake hydrological balance and katabatic wind records (Goodwin et al., 2010). Composites of the conjoint archive signals for the Southern Hemisphere during the early MCA alludes to the basic structure of the Tasman region circulation anomaly suggested by the New Zealand RCRC reconstruction. More important, the synoptic reconstructions produced from the New Zealand and wider spatial approaches have been done independently, but thus far have yielded some similar results for the characteristic patterns and also timing of circulation changes during the MCA. Both reconstructions suggest predominance of Tasman Sea region blocking during the early MCA, and easing of the anomaly pattern between ca. 1350-1550 AD (Goodwin et al., 2010; Lorrey et al., 2010).

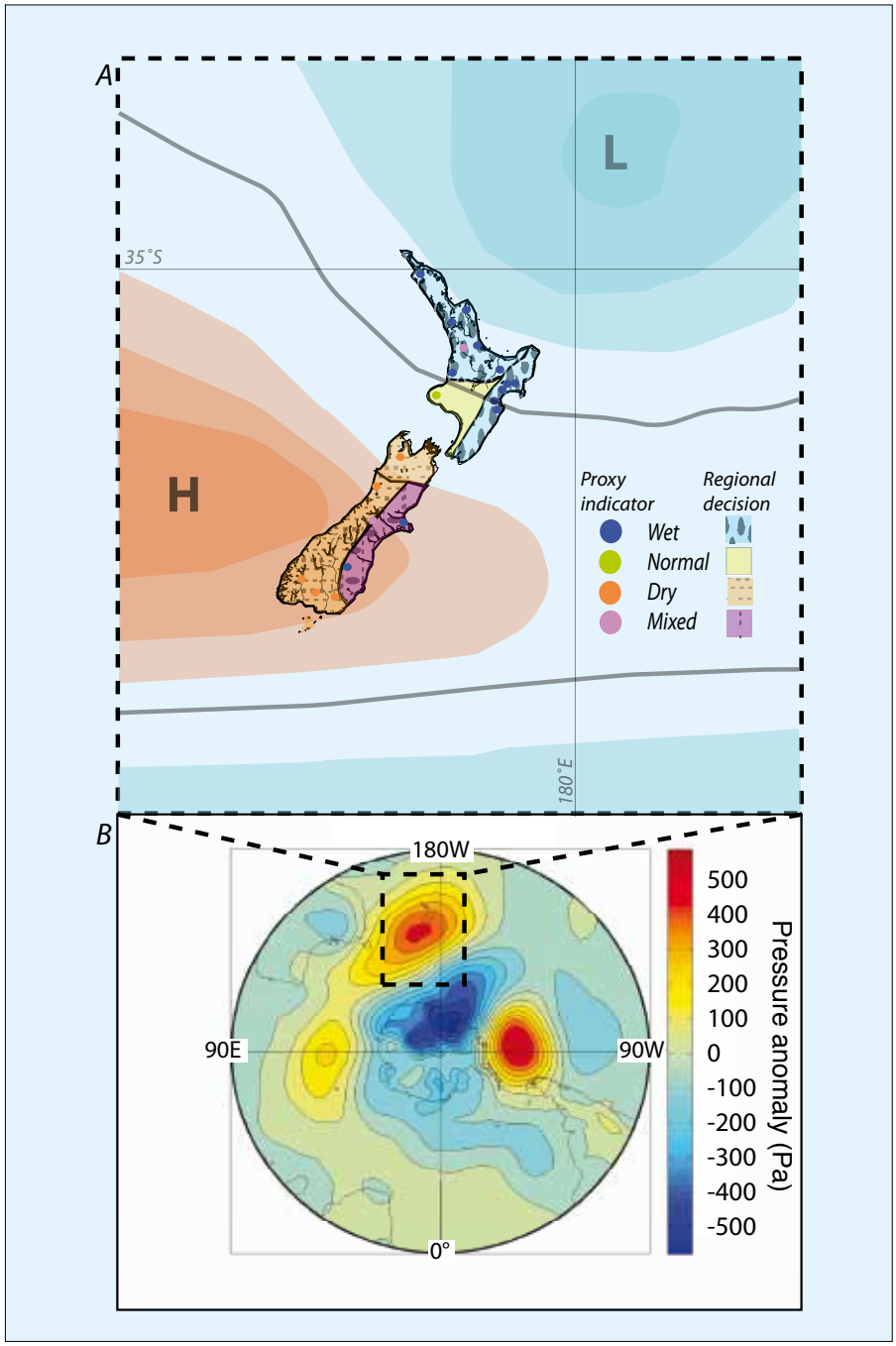

*Figure 1: **A**) RCRC paleoclimate time slice for New Zealand covering ca. 750-925 AD. Proxy sites and interpretation of paleo-precipitation signals are indicated with filled circles. The proxies used for this time slice included pollen, coastal accretion deposits, lake and alluvial sediments, and speleothems. The regional shading indicates how each of six homogenous climate districts (after Kidson, 2000) were qualified, based on a subjective assessment of the available proxy evidence in each district. The regional divisions coarsely correspond to the main axial ranges of New Zealand, which intersect the prevailing flow. The national paleoclimate anomaly pattern was compared to modern reference regimes (Kidson, 2000) to support inferences about the synoptic types that would have characterized past circulation anomalies. Synoptic types proposed for the paleoclimate time slice were then used to generate a conceptual pressure anomaly map, indicated by regions of high (H) and low (L) pressure, suggesting more frequent northerly and easterly flow. **B**) Distal and local proxy data used in pressure gradient / threshold detection analysis (Goodwin et al., 2010) are included, such as Law Dome (Antarctica) ice core data, Lake Frome (AUS) lake level reconstructions, and the East Coast of Australia wave climate reconstructions. These proxies were used to produce a SH pressure anomaly signature, indicating how the New Zealand regional anomalies fit within a hemispheric pattern.*

Future direction

Comparison of different paleo-integration approaches (qualitative and quantitative) based on multi-proxy data assemblages that are aligned to reconstructing atmospheric pressure patterns are adding confidence to past change interpretations for

Australasia, and are providing a synoptic/dynamical basis for interpreting and understanding past climates. In essence, the synoptic patterns reconstructed for New Zealand, Australia, and other locations in the SH should fit together like jigsaw puzzle pieces, and the reconstructions that result commonly (but not always) appear analogous to distinct hemispheric circulation modes that are temporally fractal (self-similar). We suggest the large-scale patterns that generate distinct atmospheric pressure anomalies across the SH mid-latitudes are important to recognize for paleoclimate science, and provide a mechanism for rectifying contrasting archive signals. The patterns also provide a means to link proxies spaced by large distances, and for surmounting difficulties that arise where local climatic effects guided by orographic influences are strong. The addition of new high resolution proxy reconstructions from speleothems, lakes, tree rings, coastal and glacial deposits on land, as well as corals and other biogenic archives (like corals, shells and otoliths) are expected to enrich the chronology of changes that are emerging from the Australasian region.

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Climate during the Medieval Climate Anomaly in China

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Various climate archives reveal a heterogeneous occurrence of the Medieval Climate Anomaly in China in terms of timing, amplitude and duration. Uncertainty analyses indicate that it is difficult to assess whether the medieval warmth exceeded that of the late 20th century.

During the past few decades, the Medieval Climate Anomaly (MCA), a supposed interval of elevated temperatures between approximately AD 900 and 1300, has generated considerable interest due to its potential value as a "natural" analogue of 20th century "greenhouse" warming. Recently published National Research Council (2006) and IPCC (2007) reports have placed a high priority on identifying the confidence level in regional to hemispherical temperature changes during the past 2000 years, including the putative MCA.

China is one of the few regions in the world with almost all types of climate archives that could provide high-resolution proxy data, including the world's longest continuous written historical records. Temperature time series of the last 500 to 2000 years have been reconstructed based on historical documents and natural archives (e.g., tree rings, ice cores, stalagmites, lake sediments) from China. In this paper, the results of regional proxy-based reconstructions are reviewed and the associated reconstruction uncertainty is assessed.

Regional reconstructions

Five climate regions of China have been selected (Northeast, Northwest, Central East, Tibet, and Southeast) to conduct the uncertainty assessment of the regional reconstructions (Ge et al., 2010). However, the Southeast has been excluded from the regional reconstructions assessment because the time series from that region are too short to cover the MCA. Examples of regional reconstructions from the climate zones are shown in Figure 1.

For the Northeast region temperature proxy data from lake sediments, peats and stalagmites cover the last 2000 years. The MCA is heterogeneously expressed in all three series in terms of timing, amplitude and variation patterns. The annually resolved 2650-year warm season (May, June, July and August: MJJA) temperature series reconstructed by a stalagmite layer thickness record from the Shihua Cave (115°56'E, 39°47'N), Beijing, indicates a pronounced warmth occurring from the 9th to 13th centuries (Fig. 1e) (Tan et al., 2003). The $\delta^{18}O$ proxy record from peat cellulose with a 20-year resolution from the Jinchuan peat (126°22'E, 42°20'N), Jilin Province, reveals a pronounced warm period at around AD 1100-1200 (Hong et al., 2000). However, the MCA is not visible in the quantitatively reconstructed mean July temperature from the Daihai Lake sediment (Xu et al., 2003).

The Tibet region has four reconstructed temperature series covering more than 950 years. One is a composite of the ice cores Dasuopu, Dunde, Guliya and Puruogangri (Fig. 1c), one is based on tree rings and two are individual lake sedimentary records. The MCA is discernable in form of a $\delta^{18}O$ maximum in Dunde and Guliya ice records, invisible in Puruogangri ice record, and shows a negative trend in the Dasupu record (Thompson et al., 2006a). When the four ice cores are composed as one series, the MCA is not discernable (Thompson et al., 2006b) (Fig. 1c). The temperature reconstruction based on tree-ring widths of *Qilian juniper* from Wulan (Fig. 1b), Qinghai Province, indicates a moderate warming around AD 1144-1264 (Zhu et al., 2008). A lower resolution Total Organic Carbon (TOC) record form Qinhai Lake sediment in the Qinghai Province reveals warm and dry conditions from AD 1160-1290 (Shen et al., 2001); while the sediment record of Sugan lake in the same province shows a pronounced warm period from AD 500-1200 (Qiang et al., 2005).

In Central East China, Ge et al. (2003) reconstructed winter (October to April) temperatures at a 10- to 30-year resolution from phenological observations recorded in Chinese historical documents

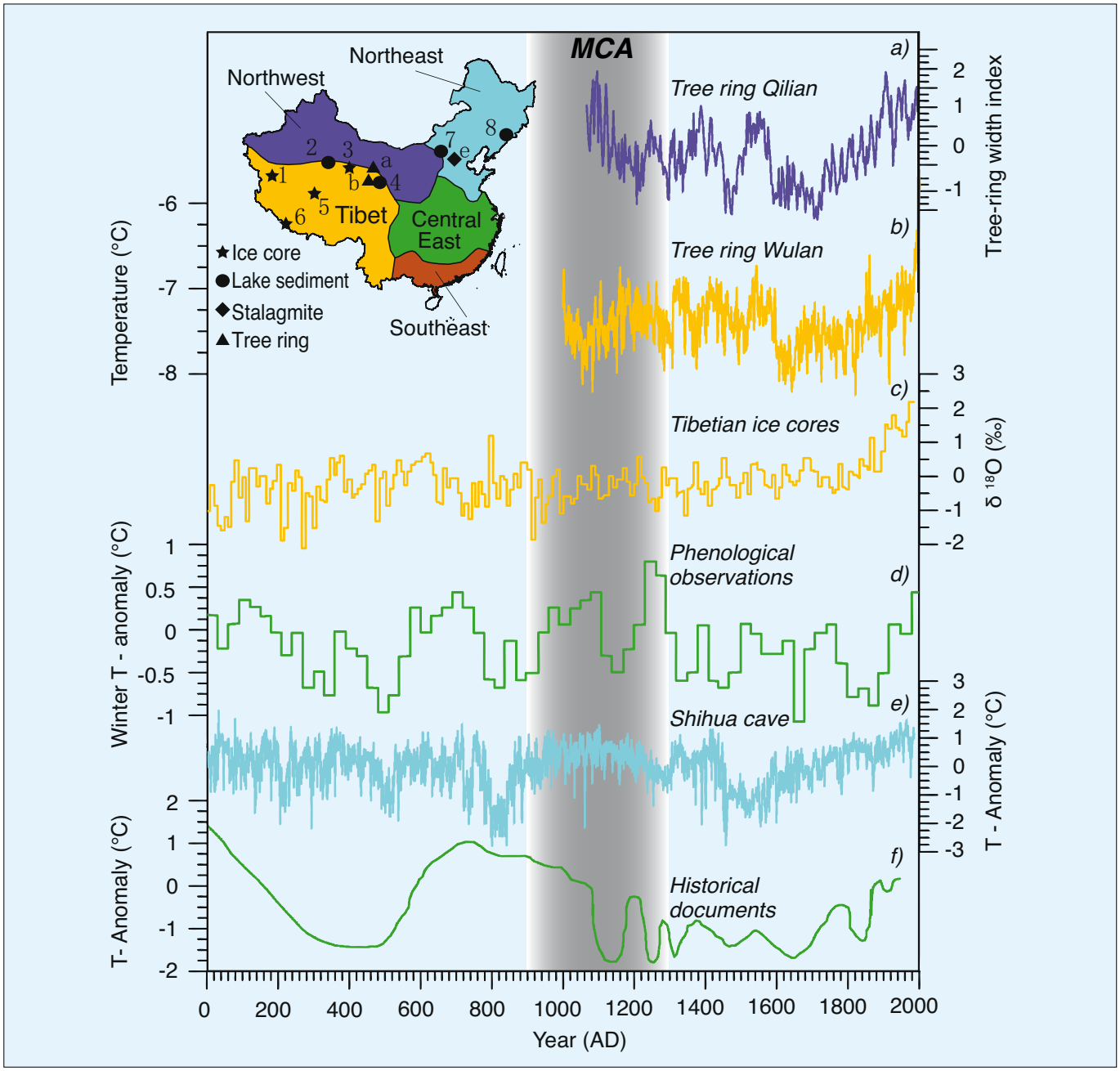

*Figure 1: Locations of proxy temperature series and the five defined climate regions (**inset**), and examples of the longest temperature series from four climate zones: **a**) Ring-width index developed for* Qilian juniper *in middle Qilian Mountains (Northwest) (Liu et al., 2007); **b**) Reconstructed mean temperature from September to April for the Wulan area (Tibet) (Zhu et al., 2008); **c**) Tibetan Plateau δ¹⁸O composite (Tibet) (Thompson et al., 2006b); **d**) Winter half-year (Oct-Apr) temperature anomaly (Central East) (Ge et al., 2003); **e**) Shihua temperatures from July to August (Northeast) (Tan et al., 2003); **f**) Annual mean temperature variations (Central East) (Chu, 1973). The locations of the archives a, b and e are depicted in the inset. Not shown are c, d and f which are regional composites or represent regional temperature conditions. Other natural archives decribed in the text but not shown in the main panel are: **1**. Guliya ice core; **2**. Sugan lake sediments; **3**. Dunde ice core; **4**. Qinghai lake sediments; **5**. Puruogangri ice core; **6**. Dasupu ice core; **7**. Daihai lake sediments; **8**. Jinchuan peat sediments.*

for the past 2000 years (Fig. 1d). According to this reconstruction, the winter temperatures from AD 930-1310 in central eastern China were 0.2°C higher than those of the 1950s-1970s, with a maximum warming of 0.9°C occurring during the AD 1230-1250 period. This pronounced warm anomaly was once disregarded by Chu (1973), one of the most famous Chinese climatologists who initiated the study of climatic changes by historical documents. He found that the climate turned cold at the beginning of the 11th century. Although it warmed at the 13th century, the mean amplitude during this period was lower than the average conditions during the past 2000 years. So he suggested that as a whole the Song periods (AD 960-1279) were generally characterized by a cold period (Fig. 1f). However, later studies pointed out that Chu's reconstruction were based on an incorrect calendar conversion applied to dates of spring snowfall in Hangzhou, the capital of the Southern Song Dynasty (AD 1127-1279) (Zhang, 1994). Subsequent studies suggested the existence of an MCA in Central East China by using multiple independent subjective phenological evidences, which include the distribution and the north cultivation boundaries of winter wheat, sugarcane, tea plant, citrus and ramie, the safety date for full heading time of rice in Kaifeng, the capital of the Northern Song Dynasty, and plant phenological evidence in Hangzhou (Zhang, 1994; Man, 1996).

In the Northwest, the only highly resolved temperature reconstruction is a tree-ring record form the middle Qilian Mountain covering the last millennium, which reveals that a discernable warm period occurred AD 1050-1150 (Liu et al., 2007) (Fig. 1a).

Seen from a regional perspective, all four studied regions experienced warm periods within the 10th to 14th centuries. However, the timing, duration and magnitudes of these warm periods vary substantially in each region and between regions. The maximal temperature in

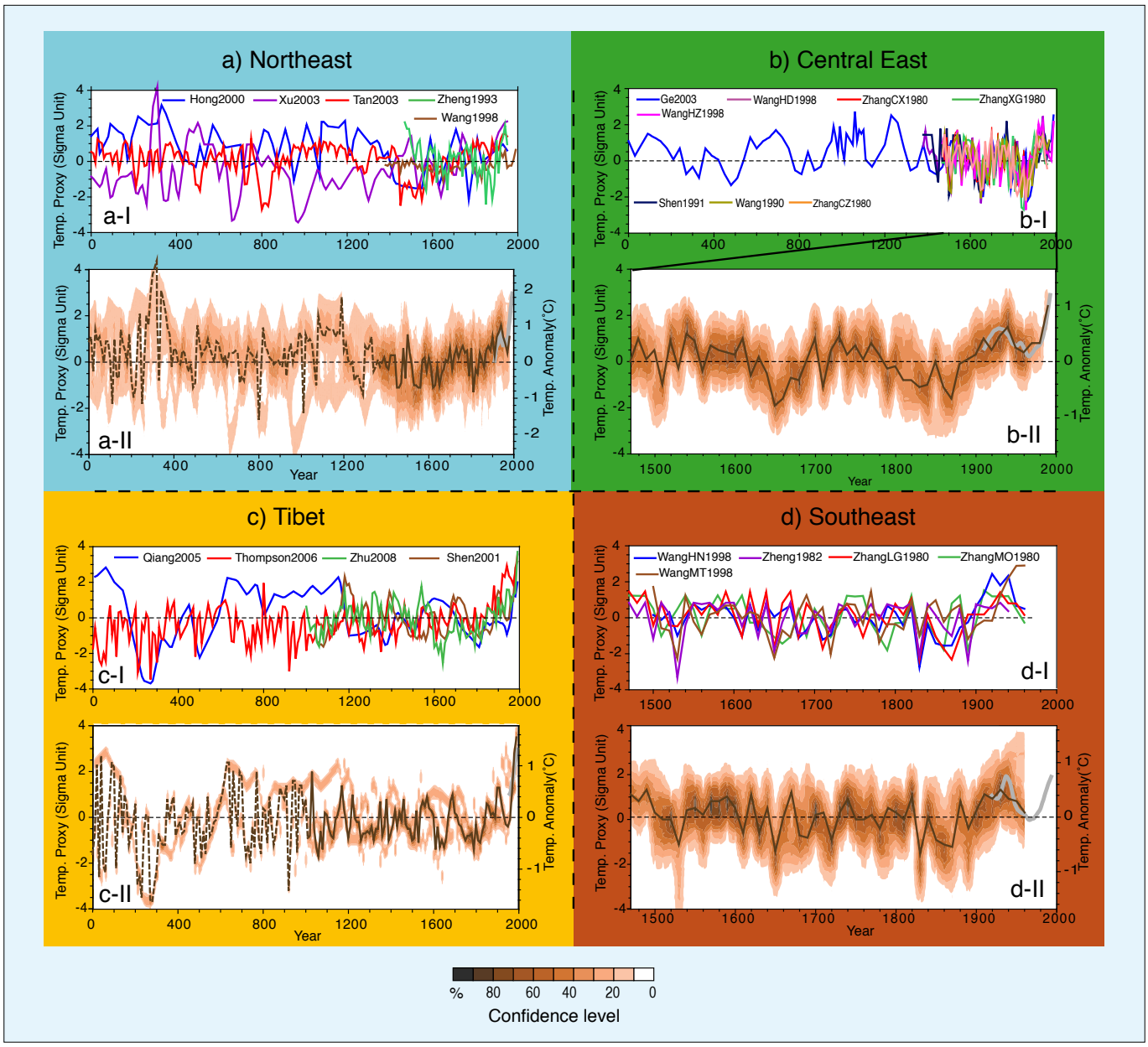

*Figure 2: Upper panels (I): Proxy mean annual temperatures with decadal resolution and their uncertainty range in (**a**) Northeast, (**b**) Central East, (**c**) Tibet and (**d**) Southeast climate zones (see inset Figure 1). Lower panels (II): The bold-brown curve is the regional temperature coherent series, the part with fewer series is marked with a dashed bold brown curve, and the bold gray curve is the 10-year smoothed instrumental temperature. The right axes represent the temperature anomaly with respect to the different period and different regions. Figure after Ge et al. (2010).*

Central East China in the AD 1240s is ~0.8°C above the AD 1901-1950 average (due to the various regions from where reconstructions are available and the variable instrumental data availability, the period AD 1901-1950 has been selected as the common reference period for all areas). The maximal temperatures are 0.4°C warmer in the 1190s for the Northeast and 0.2°C in the 1000s for the Tibet region. In the Northwest, the highest temperatures were reached in the 1100s. Finally, in the Northeast and Central East regions, the warm peaks during AD 900-1300 are higher than temperatures of the late 20th century (Ge et al., 2010) (Fig. 2).

Uncertainty analysis

The proxy-based reconstructions are subject to uncertainties mainly due to dating, proxy interpretation to climatic parameters, spatial representation, calibration of proxy data during the reconstruction procedure, and available sample sizes. Recently, Ge et al. (2010) conducted an assessment in the uncertainty of the regional reconstructions by adopting the envelope assessment method used in the fourth assessment report of IPCC.

The results (Fig. 2) indicate that the proxies have a high level of confidence in the Northeast, Central East and Southeast for the last 500 years, but large uncertainties exist prior to the 16th century. On multidecadal to centennial timescales, several reconstructions show warming peaks that occurred during the period AD 900-1300, whereas their low confidence levels do not allow to assess whether the MCA has been warmer than the late 20th century.

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The Medieval Climate Anomaly in Greenland ice core data

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Temperature signals in ice core data

Greenland ice core data can be used to derive information on past climatic conditions in the Greenland area. Recently, Vinther et al. (2010) demonstrated a high correlation between $\delta^{18}O$ data and Greenland coastal temperature observations even on seasonal timescales, reaffirming the ability of ice core $\delta^{18}O$ to capture local temperatures, first proposed by Dansgaard (1954).

The Vinther et al. (2010) analysis of the seasonal ice core $\delta^{18}O$ data showed that the winter $\delta^{18}O$ contains the strongest temperature signal, and that even annual average Greenland temperatures are more accurately captured in the winter $\delta^{18}O$ rather than annual average $\delta^{18}O$ data. This surprising fact is partly explained by the observation that Greenland winter temperatures are much more variable than summer temperatures and thus dominate the annual average variability (Vinther et al., 2010). Past Greenland climatic conditions can also be derived directly from Greenland ice core borehole temperature observations, by solving the equation of heat conduction in moving ice and firn (Dahl-Jensen et al., 1998). Using a Monte Carlo inversion technique, Dahl-Jensen et al. (1998) derived temperature histories from both southern and central Greenland from high precision borehole temperature measurements obtained at the DYE-3 and GRIP ice core drill sites. A third way of estimating past Greenland temperature conditions is to measure isotopes on nitrogen and argon trapped in air-bubbles within the ice (Severinghaus et al., 1998). These gases undergo a temperature dependent mass fractionation in the snow column before the air-bubbles are formed in the ice, thus retaining a retrievable temperature signal.

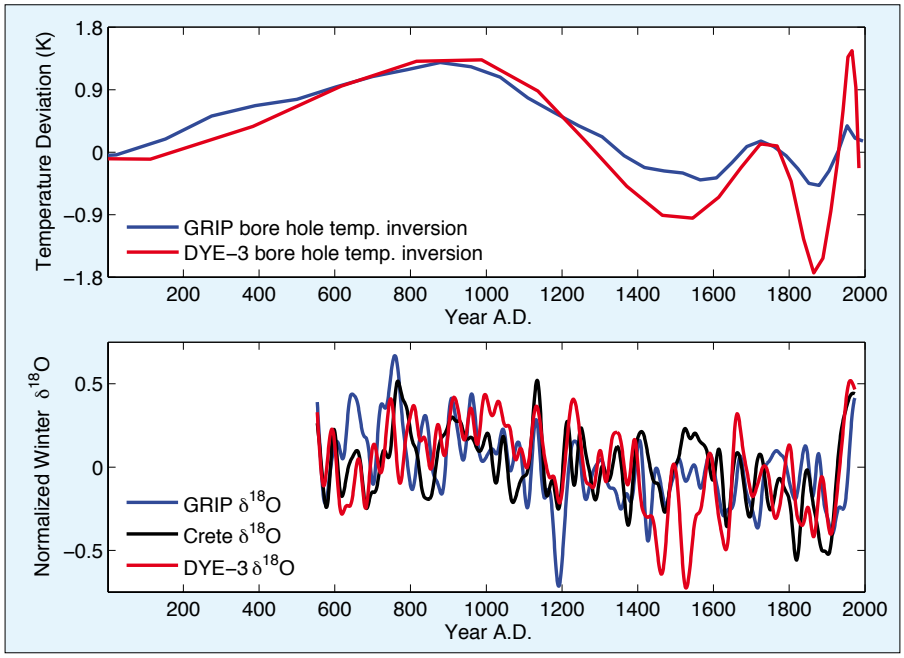

Figure 1: Two Greenland ice core temperature proxies. ***Top****: Bore hole temperature inversions from central (GRIP) and southern (DYE-3) Greenland (from Dahl-Jensen et al., 1998). Temperature deviations are given with respect to the period 1881-1980 AD.* ***Bottom****: Normalized winter $\delta^{18}O$ from central (Crete, GRIP) and southern (DYE-3) Greenland smoothed with a Gaussian filter with a 50-year half-width (from Vinther et al., 2010).*

Greenland temperature conditions during the past two millennia

The Dahl-Jensen et al. (1998) inversions of two Greenland ice core borehole temperature profiles are shown in the top panel of Figure 1. Looking at the inversions it is important to remember that temperature signals in the ice sheet diffuse with time, meaning that the inversions will lose more and more high frequency information as we move back in time. Even so, it is clear from both the DYE-3 and the GRIP borehole temperature inversions that a warm Medieval Climate Anomaly (MCA) can be observed with peak temperatures from 800 to 1000 AD being some 1.3K warmer than the 1881-1980 AD reference period. From 1000-1400 AD a general cooling is observed at both drill sites, followed by two cold periods culminating around 1500 and 1860 AD, respectively. A recent warming culminating in the 1950s is also seen in both records. One noteworthy difference between the DYE-3 and GRIP temperature inversions is the amplitude of the most recent temperature oscillations. While some of the difference is probably climatic, it is also possible that the much higher accumulation rate at the DYE-3 drill site allowed for a better preservation of the recent temperature signals in the DYE-3 borehole, thus contributing to the higher amplitudes in the DYE-3 inversion.

In the bottom panel of Figure 1, winter $\delta^{18}O$ records from three Greenland ice cores all spanning the past 1450 years are presented (Vinther et al., 2010). To ease comparison with the borehole inversions, the records have all been smoothed with a Gaussian filter (tuned to have 50% damping of a signal with a 50-year cycle). The MCA warmth is also seen in the winter $\delta^{18}O$ data and it seems to coincide with the warmth observed in the borehole inversions. The first cold spells around 1500 AD are only clearly identifiable in the DYE-3 winter $\delta^{18}O$ data, while the 1860 AD cold period and the warming culminating in the 1950s are seen in all three winter $\delta^{18}O$ records.

It is noteworthy that the winter $\delta^{18}O$ records and the DYE-3 borehole temperature inversion all suggest that the warming culmination in the 1950s resulted in Greenland temperatures comparable to or only slightly cooler than peak MCA warmth. This observation is supported by a recent study spanning the last millennium by Kobashi et al. (2010). Using the gas fractionation technique on ice cores, they found that peak Greenland temperature conditions in the in the 12th century were just 0.3K warmer than those observed during the 1950s. The GRIP borehole inversion is therefore the only data set suggesting significantly higher temperatures during the MCA than during the 1950s, lending further support to the speculation that the quite low accumulation rate at the GRIP drill site did hamper the inversion of this recent short-lived climatic warming.

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Assessing the Medieval Climate Anomaly in the Middle East: The potential of Arabic documentary sources

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New evidence from documentary sources provides detailed climatic information to fill the Middle East gap in Medieval Climate Anomaly reconstructions.

The Middle East region harbors a wealth of documentary and natural archives that contain detailed information on climate conditions and events. To date, however, only a few proxy-based climate reconstructions are available from the area for the assessment of thermal and hydroclimatic characteristics of the Medieval Climate Anomaly (MCA). Existing chronologies and reconstructions mostly provide information for specific seasons and hydroclimatic parameters (commonly precipitation and droughts). The reconstructions are based on natural proxies such as tree rings (e.g., Touchan et al., 2007), pollen records (Kaniewski et al., 2010), speleothems (e.g., Bar Matthews et al., 1997; Frumkin et al., 1991; Fleitmann et al., 2004), lake sedimentary records (e.g., Kuzucuoğlu et al., 2011), Dead Sea sedimentary records (e.g., Enzel et al., 2003; Migowski et al., 2006) or Red Sea corals (e.g., Felis and Nimbur, 2010). For compilations of available data from natural and documentary archives the reader is referred to Luterbacher et al. (2006, 2011) and references therein. Most of this data is hampered by a high degree of spatial and temporal variability and/or insufficient spatio-temporal resolution to assess in detail the MCA climate. Therefore its spatial and temporal extent in the Middle East requires further investigations.

Historical climatology studies have shown that documentary archives are a valuable source for climate reconstructions during the last centuries (Brázdil et al., 2005, 2010; Glaser and Riemann, 2009; Glaser, 2008; Pfister et al., 1998, 1999). The large body of written historical sources from Islamic Medieval times shows great potential and perspective for climate reconstructions in the Middle East during the MCA. Apart from a few preliminary studies, e.g., by Grotzfeld (1991, 1995) and Oliver (1991), these sources have not yet been adequately explored from a climatological perspective (Jones et al., 2009). The recently funded German Science Foundation project "Historical Climatology of the Middle East based on Arabic sources since AD 800" aims at using Arabic sources to reconstruct past climate, including hydrological variations and extremes in the Middle East and northeastern Africa back to 800 AD.

Figure 1: A facsimile of a page from the diary of Ibn Tawq, a Damascene notary. The entry dated Shawwāl 9, 885 AH (12.12.1480 AD) describes among other things the end of autumn and the beginning of the winter season (see Ibn-Tawq, 2000).

Arabic historical documents as sources for climate reconstruction

In contrast to Europe, archives with regular and continuous records from Arabic medieval administrations have almost all either been completely destroyed or are barely accessible. Consequently, the source types for climate information for the period from 800 to 1500 AD are mainly restricted to the akhbār genre (historiographical literature) including universal and town chronicles, accounts of journeys, and occasional diaries. A basic principle in the analysis of these sources is the focus on reported events by contemporary authors.

Here we present preliminary results based on a survey of around 50 medieval Arabic historiographical literature sources. We include well known, edited works that have in some cases also been translated into English, German and French, such as al-Tabarī's "History of Prophets and Kings" (al-Tabarī, 1960-1969 AD, 1985-2002 AD) but also less known chronicles and diaries from manuscripts (for an example see Figure 1). From some diaries, weather tables can be derived, e.g., for the period from 1480-1500 AD from the diary of the Damascene notary Ibn Tawq. In total, more than 3000 excerpts amounting to 5000 references on climate related information, have been extracted from these sources.

The peak in the amount of available data for MCA occurred in the 13th century in the Arabic regions; this is much earlier than in Europe where such sources were mainly produced after ca. 1500 AD (Glaser and Riemann, 2009; Brázdil et al., 2010; Pfister et

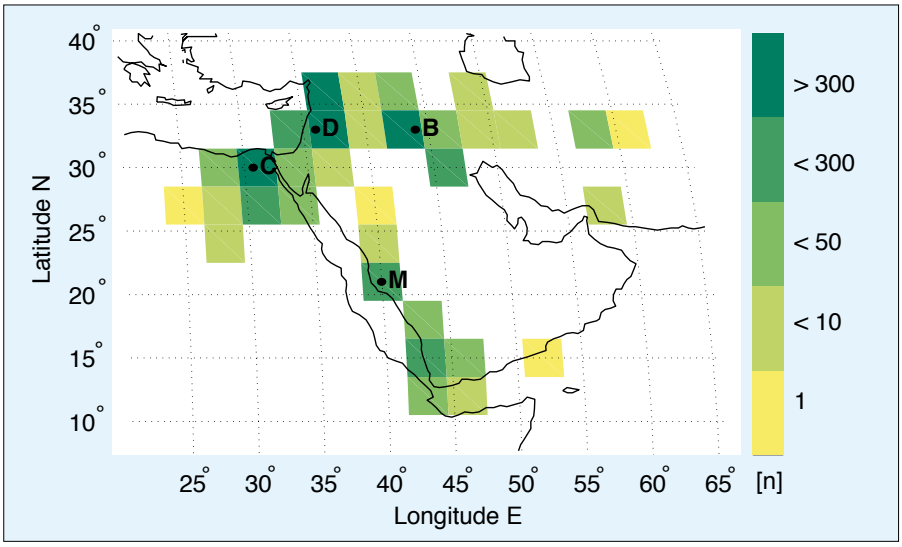

Figure 2: Spatial distribution of available information for the time period from 800 to 1500 AD. Squares show the location of reported events, the color indicates absolute number of reports. Note the concentration to the main cultural centers Baghdad (B) for the Abbassid period, Palestine and Syria with Damascus (D) for the Ayyubid period, Cairo (C) for the Fatimid and Mamluk period, and Hejaz with Mecca (M) and Medina.

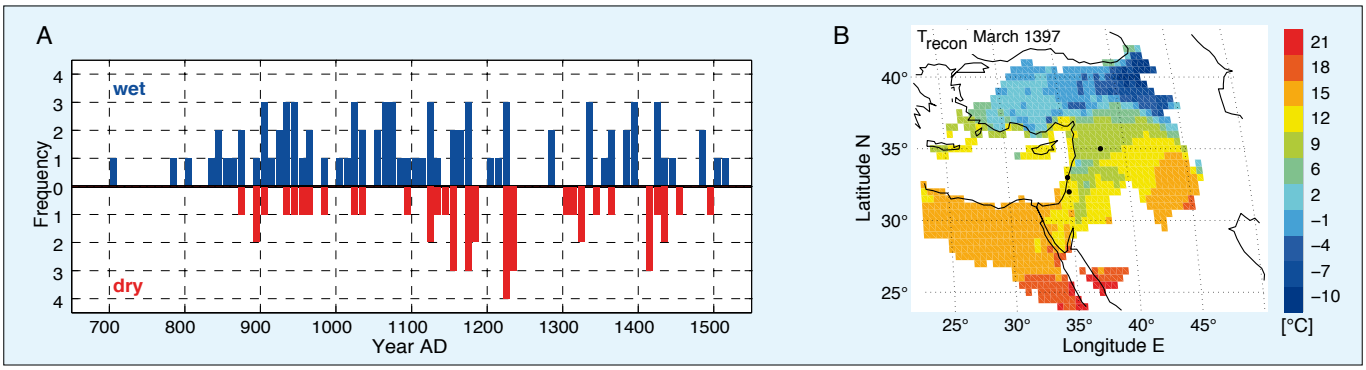

*Figure 3: **A**) Example of a time series for hydroclimatic conditions for Iraq showing the number of wet (blue bars) and dry (red bars) winters per decade (modified after Grotzfeld, 1991). **B**) Example of large scale absolute temperature field reconstruction based on historical sources for March AD 1397. Black dots indicate locations of historical information used for this reconstruction. Temperatures are calculated for areas with correlation values >0.8 with location of historical information. For details on reconstruction methodology see Riemann (2011).*

al., 1998). The decrease in available records after the 13th century could be related to a shift in the writing style and focus of the Arabic chronicles from accounts of events to biographical data and anecdotes at the turn of the 16th century (Grotzfeld, 1995).

Figure 2 shows the spatial distribution of information held in our database to date for the time period from 800 to 1500 AD. The geographical coverage includes Iraq, Egypt, Syria and Palestine as well as the Hejaz and Yemen. In the course of time from the 9th to 15th century the spatial focus of the reports is moving from the Abbasid centers of power and science in Iraq to the Ayyubid centers in Syria and Palestine and finally to Fatimid and Mamluk Egypt reflecting the political and cultural changes in the area.

Winter rain and almond blossom instead of summer drought and tasty wine

In terms of climate-related information, the Arabic and European sources are in many respects similar. The authors usually report on events in their hometown and vicinity. Sometimes comparisons with remote or historical events are also made. The climatic information within a source is more or less sporadic, describing single events, especially natural hazards such as floods, droughts, and exceptionally cold or dry winters. In addition, the impacts of such events, their effects on harvest yields, food supply, economic and social crises are described. Reported events focus mainly on hydroclimatic and less on thermal conditions. The onset of the winter rainy season is one of the most frequently reported features due to its crucial role for agricultural production. Also, closely related to food supply are reports on droughts. For some cities like Baghdad, there exists the potential to establish continuous flood chronologies (Weintritt, 2009). An often-reported specific type of extreme event in the Middle East is sand storms, which are often connected to a specific circulation pattern (lower level Red-Sea Troughs, Saaroni et al., 1998). Cloud coverage is typically reported in connection with observations of the lunar crescent. Phenological information is linked to regional agricultural products such as dates or almonds. However, this kind of information is too sparse for the reconstruction of continuous time series.

Comprehensive data set to reconstruct climate for medieval times

Preliminary results show that the methodology of historical climatology, which has been mainly developed on the basis of European documentary sources, can be applied to this body of data as well. The hermeneutic approach, including critical source analysis and interpretation using information beyond the source texts, as well as classification and derivation of (semi-quantitative) indices can be adopted, but specific adaptations are required. These include methodological aspects of the analysis of Arabic sources, for instance the evaluation of isnad (chain of narrators) when assessing the reliability of relevant accounts in secondary sources. The dating is given in the Hijra calendar system based on lunar months. Its conversion into the Gregorian calendar is typically possible with a precision of one day. Arabic documentary data can be used to establish time series of hydroclimatic information with at least decadal resolution for most of the time span from 800 to 1500 AD. However, for some sub-periods much higher resolution can be achieved, e.g., daily resolution for periods in the 13th and 15th century where we can rely on information from diaries. The spatial distribution of the data for some periods further allows the reconstruction of large-scale temperature and precipitation fields (Fig. 3b, for details on methodology see Riemann, 2011). Future work also includes the reconstruction of more or less continuous temperature and precipitation series at a seasonal time scale. Figure 3a presents a preliminary time series of hydroclimatic winter conditions for Iraq. This time series is not fully homogenous yet, with major data gaps between 1200 and 1400 AD and therefore it does not allow an interpretation of the climate in the area for the whole period. However, in the currently available data, for instance for the periods 900-950 and 1020-1070 AD, a higher frequency of particularly wet winters can be observed.

The results will be further refined and compared with independent climate evidence from natural archives. Furthermore, links with North Atlantic/European and subtropical/tropical climate will be analyzed. Paleo-model output will be used to understand climate variations from the MCA over the Little Ice Age onwards to current conditions in the Middle East.

Acknowledgements

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Nile flood discharge during the Medieval Climate Anomaly

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Records of Nile flood discharge from AD 930 to 1450 reveal pronounced variability in the frequency of extreme floods due to differential influence of global climatic forcing mechanisms on the two main catchment areas of the Nile tributaries, namely Equatorial Africa and the Ethiopian Highlands.

A record of variations in Nile flood discharge dating back to the 7th century AD (Hassan, 1981) provides a basis for analyzing the relationship between Nile floods, climate change, and famines in Egypt during the Medieval Climate Anomaly (MCA). The volume of Nile flood discharge, as well as its seasonality, is primarily governed by the impact of climate on rainfall over the Nile catchment areas in Ethiopia and Equatorial Africa. Throughout Egyptian history, Nile floods influenced food production, which depended on Nile water for irrigation and the amount of silt annually deposited on the floodplain. Correction and calibration of the primary historical annual records of Nile minimal and maximal flood levels, followed by an analysis of the calibrated data reveal that Nile floods discharge during the MCA interval from AD 930 to 1350 were not constant. Instead, this period is characterized by multi-decadal long episodes of major low Nile flood levels from AD 930 to 1070, and from AD 1180 to 1350, as well as periods of major high Nile flood levels from AD 1070 to 1180 and from AD 1350 to 1470 (Fig. 1). In addition, examination of the frequency of periods of anomalously extreme Nile floods (i.e., annual floods with unusually high or low levels) with known historical crises (Hassan, 2007) reveals that the onset of the MCA was marked by a dramatic increase of extreme low floods. The percentage climbs from 0-3% to 20% during the period from AD 930 to 1070 and to 14% from AD 1070 to 1180, in spite of an overall increase of the volume of flood discharge during that latter period. Subsequently, from AD 1180 to 1350, the number of extremely high floods increased at the expense of extremely low floods (Fig. 1). This period, characterized in general by a decrease in Nile flood discharge, coincides with the epic droughts that occurred from AD 1209 to 1350 in Californian mountain ranges as documented by tree stumps (Stine, 1994), suggesting a global climatic teleconnection. These droughts, according to Knox (1993), were apparently associated with changes in mean global annual temperature of 1-2°C. Nevertheless, apparently slight climatic changes in mean global temperature from the 9th to the 15th century were associated with pronounced hydrological responses. This is confirmed by the simulation of the hydrology of the Nile in response to different climate change scenarios (Conway and Hulme, 1996): precipitation anomalies were found to produce larger changes in runoff of about threefold magnitude. The high sensitivity of Nile flood discharge to changes in precipitation is further confirmed by recent historical changes with a 20th century (AD 1900-1984) average of 85 billion cubic metres compared to 110 billion cubic meters from AD 1870 to 1899 (Said, 1993).

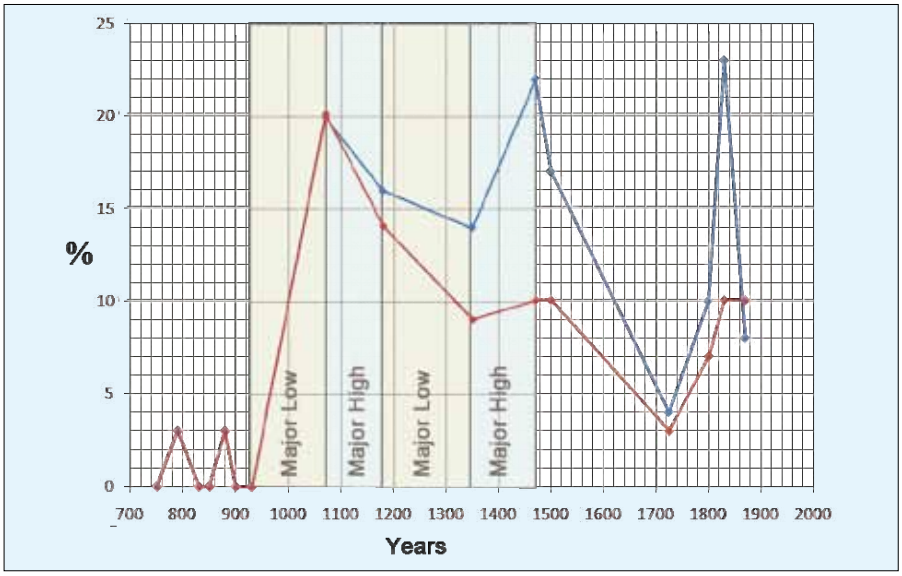

*Figure 1: Percentage of anomalously low floods (**red**) and of both extremely low and high floods (**blue**) superimposed on the major episodes of low and high Nile flood discharge.*

The impact of fluctuations in Nile flood discharge during the MCA on the geomorphology of the flood plains is attested by the dramatic changes in the area of the capital city Cairo during this period (Hassan, 1997). Until AD 942, the eastern bank of the Nile floodplain was narrow and restricted to the area currently known as Old Cairo (Misr al-Qadima). Almost all of the area now occupied by the city was created in the ensuing period from AD 942 to 1403.

Comparison of the variations in Nile flood discharge with proxies of the North Atlantic Oscillation (NAO; Jansen and Koç, 2000; Baker et al., 2000) demonstrate a remarkable coherence between the fluctuations of Nile flood discharge and variations in North Atlantic sea surface temperature (SST). In general, variations in Norwegian Sea summer SST from AD 910 to 1070, from AD 1180 to 1340, and from AD 1400 to 1500 are inversely correlated with the fluctuations in Nile flood maxima (Jansen and Koç, 2000). By contrast, the Norwegian Sea summer SST variations are positively correlated with the fluctuations in Nile flood maxima from AD 800 to 910, from AD 1070 to 1180, and from AD 1700 to 1800. This "flip-flop" relationship is also manifested when variations in summer sea surface temperatures at Vøring Plateau off central Norway (Jansen and Koç, 2000) are compared with the Nile flood discharge, albeit not synchronously (Hassan, 2007). However, from AD 930 to 1010 and again from AD 1200 to 1350, as well as from AD 1400-1500 and AD 1700-1900 the temperatures at Vøring Plateau are inversely correlated with the height of Nile flood maxima. By contrast, from AD 800 to 850, from AD 1070 to 1180, and again from AD 1350-1400 the relationship is concordant (Hassan, 2007).

Nile flood discharge was also found to be in concordance with the Indian monsoons (Zickfeld et al., 2005), co-varying positively, except for the period from ca. AD 850 to 1080, when they are inversely correlated (Hassan, 2007). This may be in part related to the effect of ENSO and the extreme El Niño events between AD 967 and 1096, which often cause a reduction in Nile flood discharge (Quinn, 1992). Indeed, Nile discharge was low from AD 930 to 1070.

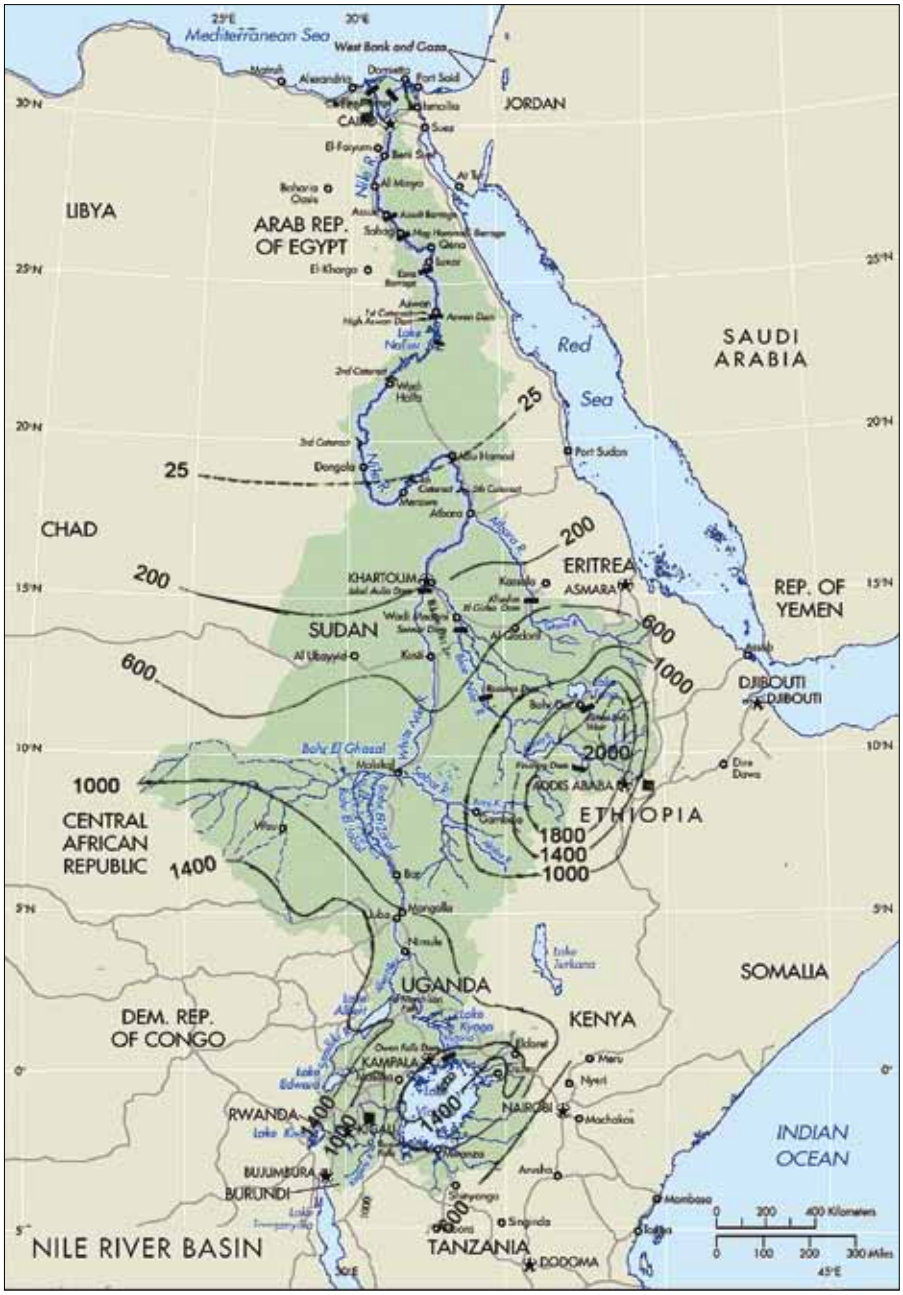

Figure 2: Nile River Basin showing mean annual rainfall in mm in the main Nile catchment areas in Ethiopia and Equatorial Africa.

An understanding of the variations in Nile flood discharge must take into consideration the various global and local climatic variables influencing rainfall in the main sources of the Nile. Correlations with proxies of climate change elsewhere are also subject to the peculiarities of the proxies, the integrity of the evidence, and their locations. In this respect, it is particularly important to realize that the main catchment areas of the Nile tributaries—the Ethiopian Highlands (10°N) and the Equatorial Plateau (equator) are more than 1000 km apart and are influenced by different climatic regimes, and that precipitation in the catchments is influenced by the proximity to oceans, highland topography, land surface moisture, lakes and swamps. East Africa, one of the main sources of the Nile, is influenced by ENSO, and the SST of nearby Indian and Atlantic oceans. Farther North, the effect of NAO is more pronounced (Dore, 2005). Zhang and Delworth (2006) concluded that multidecadal variability in the Atlantic Ocean could cause observed multidecadal variations of Sahel and Indian summer rainfall. Street-Perrott and Perrott (1990) observed that several prolonged droughts in the Sahel during the past 14 ka were associated with large injections of freshwater into the northern Atlantic Ocean.

Using proxy data from Scotland and Morocco, Trouet et al. (2009) found persistent positive NAO during the MCA, resulting in stronger than average westerlies across the mid-latitudes and to a northward migration of the Intertropical Convergence Zone, affecting rainfall both in Equatorial East Africa and Ethiopia (the main water sources of the Nile; Fig. 2). This may explain the two wet episodes from AD 1070 to 1180 and again in the transition to the Little Ice Age from AD 1350 to 1470. However, this modality was interrupted by a low discharge episode from AD 1180 to 1350.

The Nile record clearly indicates that a distinct anomaly marked by extremely low floods and an overall diminution in Nile flood discharge lasted from AD 930 to 1070 (Fig. 1). Although the frequency of total extreme floods (blue line) persisted, there was a shift to a higher percentage (ca. +10% from AD 900 to 1350) of extremely high floods relative to extremely low floods (red line). Even though a period of relatively high flood discharge lasted from AD 1070 to 1180, a return to lower flood discharge occurred from AD 1180 to 1350.

By AD 1350 and until 1470, coinciding with a transition to the Little Ice Age, the Nile flood discharge was relatively high. This was associated with an increase in water flow from Ethiopia relative to that from Equatorial Africa (Hassan, 1981). These results indicate that Nile flood discharge in the Main Nile is influenced by multiple variables associated with the differential effects of global climatic mechanisms, such as NAO and ENSO, on the catchment areas in Equatorial Africa and the Ethiopian Highlands. Throughout the period from AD 950 to 1350, famines and plagues have had an adverse effect on society. The famines were in numerous instances caused by clusters of deficient Nile flood discharge, sometimes at close intervals. The deleterious impact of the fluctuations in Nile flood discharge were compounded by the impact of extremely high and low Nile flood discharges on the geomorphology of the channel and floodplain, influencing land use. Shifts in the relative contribution from the Equatorial and Ethiopian tributaries characterized by different rainfall seasons would have also negatively influenced agricultural food production.

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For full references please consult:

http://www.pages-igbp.org/products/newsletters/ref2011_1.html

The Medieval Warm Period redux: Where and when was it warm?

Lisbon, Portugal, 22-24 September 2010

Henry F. Diaz[1], R. Trigo[2], D. Barriopedro[2], E. Xoplaki[3], M. Hughes[4] and M.E. Mann[5]

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In recent years, an increasing number of studies have been published describing elements of the Medieval Climate Anomaly (MCA). The general time frame for this epoch is generally taken to span from ca. 950-1300 AD. In order to assess the most updated and comprehensive characterization of the MCA period at regional and global scales, a symposium was organized and held in Lisbon, in September 2010. The symposium topics, within the framework of the PAGES 2k Network, are at the interface of Regional Climate Dynamics and Global Earth-System Dynamics (PAGES Foci 2 and 3), and overlap with the goals of Cross-Cutting Theme 2 (Proxy development, calibration, validation) and Cross-Cutting Theme 3 (Modeling).

The main objective of the 3-day symposium was to revisit the MCA by incorporating widespread and continuous paleoclimatic evidence in a homogeneous and consistent manner, and to scale it against the instrumental temperature record to allow a meaningful quantitative comparison in the magnitude of warming against the 20th-century pace. The déjà-vu title was chosen on purpose, as the organizers wanted to revisit the question posed already in 1994 by Hughes and Diaz in their Climatic Change review "Was there a Medieval Warm Period, and if so, where and when?", taking into account that the latest IPCC report in 2007 (WG1) emphasizes the same ambivalence: "Regionally restricted evidence by itself, … is of little practical relevance to the question of whether climate in medieval times was globally as warm or warmer than today".

The symposium, attended by 35 participants from 10 different countries including a mix of senior scientists and early career researchers, was divided in two parts: 1) Establishing the MCA Epoch as a Distinct Period, and 2) Climate Reconstruction Tools and Numerical Modeling of the MCA Climate. The first part focused on already existing and new proxies capable of resolving temperature changes in the last two millennia and covering a wide spectrum of regions (R. Bradley), including Tropical Pacific (K. Cobb), the Mediterranean basin (E. Xoplaki), western Europe (J. Guiot; D. McCarroll; A. Moreno), North America (J. Overpeck; A. Viau), the North Atlantic (G. Miller), Greenland (B. Vinther), the Arctic (D. Fisher; D. Kaufman) and South America (J. Luterbacher). Other authors provided a wider picture on the spatial and temporal extension of the MCA event (D. Fleitmann; M. Hughes; P. Jones; F. Lungqvist; M. Mann) or the underlying large-scale dynamics associated with the MCA and the LIA period (R. D'Arrigo; V. Trouet; E. Wahl; H. Wanner). The second part of the symposium was mostly devoted to the latest results obtained by the modeling community (D. Shindell; N. Graham; F. González-Rouco), emphasizing the need for better assimilation procedures (H. Goosse), capacity to reproduce major drought and wet periods (R. Seager) but also reproduction of large-scale patterns such as the AMO (R. Oglesby) and blocking (D. Barriopedro), as well as the need to improve the characterization of the solar activity variability (R. Trigo).

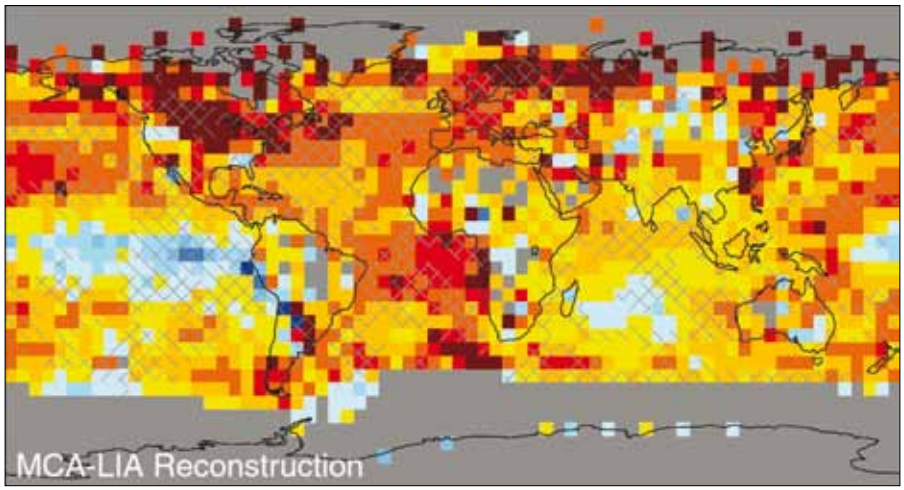

Figure 1: Reconstructed surface temperature difference (Medieval Climate Anomaly (MCA) minus Little Ice Age (LIA). Original figure from Mann et al. (2009), reprinted with permission from AAAS.

In summary, in answer to the question posed above regarding the spatial and temporal scales of the MCA, the general consensus of the participants is that in the past 15 years additional evidence has become available of a climatic anomaly occurring during the time interval ca. 900-1300 AD, albeit with important differences regarding the timing and spatial extent. The participants also stressed that a Northern Hemisphere or global mean value is of less relevance when looking at the regional spatial scales where the impacts of climatic anomalies are experienced.

A more detailed description including scientific conclusions of the symposium can be found in this issue of the PAGES Newsletter. A special issue in the journal *Global and Planetary Change* (Elsevier) has also been negotiated and the organizers are confident that a significant number of talks presented at the symposium will be published in this dedicated issue. Additionally, a review article with the current state-of-the-art consensus on the MCA epoch is currently submitted to *Bulletin of American Meteorological Society*.

Acknowledgments

The workshop was sponsored by PAGES, the National Oceanic and Atmospheric Administration (NOAA), the Portuguese Science Foundation (FCT) and the Luso-American Foundation (FLAD).

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Active Tephra 2010: International field conference on tephrochronology

Kirishima City, Japan, 9-17 May 2010

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INTAV meets in Japan

INQUA's international focus group on tephrochronology and volcanism (INTAV) met in Kirishima in southern Kyushu. A total of 76 participants (including 25 students) from 12 countries attended. Around 50 oral papers, including six invited keynote talks, were presented over three days alongside nearly 40 posters. Financial support from PAGES and the INQUA INTREPID project enabled 11 young scientists to attend the conference. Further support was provided by the Tokyo Geographical Society, Paleo, West Japan Engineering, Asahi, JAQUA, and the city of Kirishima.

Papers and Eyjafjöll session

The conference commenced with two public lectures by David Lowe (Waikato University) "Connecting with our past: using tephras and archaeology to date the Polynesian settlement of Aotearoa/New Zealand" and by Hiroshi Machida (Tokyo Metropolitan University) "Widespread tephras originating from Kagoshima occurring in northeast Asia and adjacent seas."

A highlight was a special session on the 2010 eruptions from the Icelandic Eyjafjöll volcano, which attracted local TV and newspaper coverage. This Eyjafjöll session included talks by Chris Hayward and Thor Thordarson (both Edinburgh University) and by Siwan Davies (Swansea University). It became evident that this eruption would provide an excellent opportunity to enhance knowledge on cryptotephras from Icelandic volcanoes, which are being increasingly utilized for time control in the Northern Hemisphere ice-core, marine and terrestrial records (Davies et al., 2010). An INTAV-sponsored meeting on the eruption and its implications for tephra studies will be held in Edinburgh on May 5-6, 2011 and a tephrochronology session is scheduled at the INQUA Congress in Bern in July 2011.

Further keynote presentations were given by Nick Pearce (Aberystwyth University) on developments and applications in LA-ICP mass spectrometry, Duane Froese (Alberta University) on Yukon-Alaskan Quaternary permafrost studies linked by tephras, Siwan Davies (Swansea University) on tephras in Greenland ice cores, Mitsuhiro Nakagawa (Hokkaido University) on petrology and eruption processes of Shikotsu and Aira calderas, Simon Blockley (London University) on tephra age-modeling including Bayesian studies, and Takeshi Nakagawa (Newcastle University) on recent geochronological and analytical work of the exceptional varve sequence of Lake Suigetsu.

Figure 1: Right on cue: a small eruption of Showa Crater of Sakurajima volcano on Day 1 of the intra-conference fieldtrip (12 May). Photo: Anja Moebis

Field trips

An intra-conference fieldtrip included a visit to the Uenohara Jomon-no-mori archeological centre where a village from the Jomon period (ca. 9.5 ka ago) had been preserved under tephra deposits. The group was then treated to a stunning and apt backdrop for a tephra-based meeting: the Sakurajima volcano has been active since 1955, with more than 8670 eruptions since then. Around 500 eruptions had already taken place in 2010 prior to this visit. Two small vulcanian eruptions took place in Showa crater, by a remarkable coincidence, whilst the group visited the eastern flank of the volcano at the closest point to the active crater (Fig. 1). Furthermore, participants were taken to outcrops of layers of tephras and buried soils dating back 30 ka, to the spectacular Jomon Tenjindan archeological site, and to a magnificent coastal exposure, ~20-30 m high, of the deposits of the voluminous Aira tephra formation dated at ca. 30 ka.

The conference was followed by a three day trip to the Unzen volcano where deposits from the 1990-1995 eruption series, including lava domes, block-and-ash flow deposits, and pyroclasic flow deposits, were seen. Visited sites also included the extremely impressive, ~25-km-wide, Aso caldera and associated deposits, the volcanic vents in central Kyushu, and the volcanoes of Kuij and Yufi-Tsurumi in northeastern Kyushu.

Conclusion

The conference and field trips were remarkable. As one veteran participant remarked, "tephra studies have never been so healthy". The rise of young tephrochronologists was especially prominent and augurs well for future research and leadership of the discipline. Papers from the meeting are to be published in a volume of Quaternary International that will also commemorate the career of Hiroshi Machida.

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Paleochronology building workshop

San Miguel de Allende, Mexico, 17-21 August 2010

Maarten Blaauw[1], J. Andrés Christen[2] and Workshop Participants

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Chronologies are vital for the study of past global change. The strength of conclusions based on paleoenvironmental reconstructions is often constrained by the precision and reliability of their chronologies. However, constructing paleochronologies can be a daunting task requiring a detailed knowledge of statistical techniques and/or dedicated software. For example, radiocarbon dates require calibration, ages might have to be estimated for non-dated core depths, and chronological uncertainties need to be quantified as reliably as possible.

This summer an educational workshop on paleochronology building was held in San Miguel de Allende, central Mexico. The workshop attracted 27 participants (Fig. 1) from a range of continents (North America, Europe, Asia, Australia, Africa), career stages (from early PhD students to senior faculty), and scientific backgrounds (e.g., ^{14}C dating, modeling, statistics, palynology, oceanography and peat research).

Lectures were given on the theory of radiocarbon calibration, classic and Bayesian sediment age-depth modeling and multi-site interpretations. In addition to the theoretical sessions, much time was devoted to hands-on computer sessions where participants used some of the latest age-modeling software, in particular clam (Blaauw, 2010), OxCal (Bronk Ramsey, 2008), Bchron (Haslett and Parnell, 2008), and Bacon (a recent update to Bpeat; Blaauw and Christen, 2005).

A very interesting poster session was held, with an innovative promenade guided tour by each of the poster presenters. Local cuisine was sampled and excursions were organized to the town's beautiful colonial center and to El Charco Del Ingenio (a huge botanical garden with an impressive range of cacti). Time was also set aside to discuss plans for future collaborations and papers. The workshop started by introducing the ideas and methods of calibrating radiocarbon dates, basic age-depth modeling (e.g., linear interpolation), and Bayesian statistics. This was followed by more advanced topics including models of sediment accumulation, detection and treatment of outlying dates, methods to decide which depths of a core to date next, and multiple-site synthesis methods such as tuning and Bayesian synchroneity tests. Eric Grimm (Illinois State Museum) gave an additional presentation on the Neotoma metadatabase initiative for paleo-data.

Figure 1: Workshop participants, with guide Mario (top row, far right) at El Charco del Ingenio ecological reserve in San Miguel de Allende. Photo by Amy Myrbo.

The following workshop days were mostly devoted to applying the discussed methods in practice. Next to producing age-models for individual sites, the chronological uncertainties of the proxies themselves were plotted as "ghost graphs" (Blaauw et al., 2007), and several methods were applied to integrate multiple proxy sites. For example, if multiple sites contain the same imprecisely dated tephra, an integrated age estimate of that tephra based on all sites will be more precise and reliable than if calculated from individual sites. Another approach was to test for the synchroneity of environmental proxy events between multiple sites, without resorting to tuning. Of course, participants were given ample time to apply the age-modeling techniques to their own sites.

Information about the workshop, including presentations and software, can be found on http://chrono.qub.ac.uk/blaauw/Workshop/ and http://www.cimat.mx/Eventos/PBW/.

Acknowledgments

The workshop organizers wish to thank PAGES and INQUA (under the tephra initiative INTREPID led by Prof. David Lowe, New Zealand) for their financial support of this meeting.

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Paleo-ocean acidification and carbon cycle perturbation events

NSF-PAGES workshop, Santa Catalina Island, USA, 25-29 August 2010

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Ocean acidification is a current area of concern for the future functioning of marine ecosystems and ocean biogeochemical cycles. The term "ocean acidification" describes the effects of the oceanic uptake of anthropogenic CO_2 including a progressive decrease of seawater-pH. While seawater is not likely to ever become acidic, a reduction in pH and associated carbonate system changes may nevertheless affect ocean biogeochemical processes, particularly biological calcification. However, modern ocean observations and laboratory experiments consider time scales that are too short to reveal the long-term potential of marine organisms to acclimatize or adapt to changing environmental conditions. Furthermore, as experiments focus on a few species or isolated strains, they provide little information on the potential for whole ecosystem changes. The U.S. National Science Foundation (NSF) and PAGES jointly sponsored this workshop to bring together an international group of carbon cycle modelers, carbonate chemistry specialists, and biological, chemical and physical (paleo-) oceanographers to discuss past carbon cycle perturbations and the long-term response of marine organisms to changing conditions, and to provide a geological perspective on future concerns.

Richard Zeebe (University of Hawaii) and Andy Ridgwell (University of Bristol) presented the boundary conditions of past marine carbonate chemistry and stressed the importance of distinguishing between extended periods of high pCO_2 with relatively slowly evolving ocean carbonate chemistry, and geologically rapid changes which reflect chemical effects more comparable to the consequence of ongoing CO_2 emissions. Acknowledging that the rate of anthropogenic CO_2 emissions is probably unparalleled in recent Earth history, Zeebe defined an "ocean acidification event" as one having a duration shorter than about 10 ka. Pleistocene glacial to interglacial transitions and early Cenozoic hyperthermals fall under this definition, but the only event that may be comparable in magnitude of CO_2 release is the Paleocene-Eocene Thermal Maximum (PETM).

Daniela Schmidt (University of Bristol), Luc Beaufort (CEREGE) and Sam Gibbs (NOC Southampton) reiterated the importance of the rate of environmental change in assessing the potential for future changes in marine ecosystems. They also focused on the complications associated with attributing biological responses to paleo-ocean acidification. Identifying stressful conditions at the sea surface, which would affect organisms' biology including calcification, is often indistinguishable from competing factors affecting preservation at the seafloor. Similarly, synergistic effects of temperature or nutrient changes cannot necessarily be separated from shifts in ocean carbonate chemistry. Independent proxy evidence is therefore of utmost importance to identify the physical and chemical boundary conditions that led to physiological and ecological shifts. In addition, the fossil record is biased towards those organisms that secrete skeletal hard parts, in particular marine calcifiers. Ecologically important phyto- and zooplankton are rarely preserved in the sediment and little is known about their fate under past ocean acidification conditions.

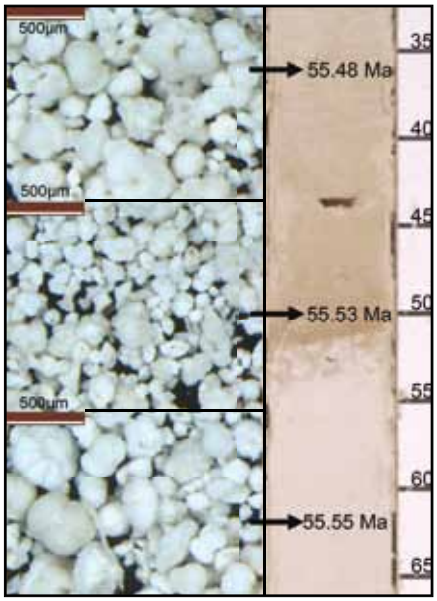

Figure 1: Core section from Shatsky Rise ODP Site 1210A, showing reduced carbonate preservation at the Paleocene-Eocene Thermal Maximum. During the PETM 30-50% of deep-sea benthic foraminifer species suffered extinction (Thomas, 1998). The scale bar on the right indicates depth of the core section in cm, which reflects on the lower sedimentation rate after the onset of the event. Picture credit: Laura Foster, University of Bristol; dates after Westerhold et al. (2008).

Proxies for ocean carbonate chemistry include the boron isotope proxy for seawater-pH, the carbon isotopic composition of alkenones for aqueous [CO_2], foraminiferal B/Ca and U/Ca ratios for bottom-water carbonate saturation and carbonate ion concentration, foraminiferal shell weights, and the depth of the carbonate compensation depth to constrain whole-ocean carbonate saturation. Gavin Foster (NOC Southampton) and Jimin Yu (LDEO) presented proxy comparisons and recent advances in paleo-pH reconstructions. They demonstrated that quantitative reconstructions beyond the Pleistocene glacial/interglacial cycles are limited by uncertainties on the elemental and isotopic composition of seawater, and the lack of estimates on a second parameter of the carbon system from the same surface or deep-ocean environment. In addition, most of the established proxies are based on marine carbonates. This is problematic for ocean acidification events in which widespread dissolution of carbonates occurs, such as during the peak of the PETM (when only clays and organic molecules were preserved in many Atlantic sediments) (e.g., Fig. 1). As a novel approach to address this issue, Appy Sluijs (University of Utrecht) presented promising findings on the carbon isotopic composition of organic dinoflagellate cysts as a candidate proxy for aqueous CO_2.

The workshop reiterated that no perfect analogue to anthropogenic ocean acidification has yet been found in Earth's geological record, but that an improved knowledge of the physicochemical boundary conditions in the surface and deep ocean, their rates and magnitudes and biological responses will nevertheless place important constraints on the consequences of current and future ocean acidification. A more comprehensive report on the rates, magnitudes and evidence for paleo-ocean acidification will be published as a peer-reviewed paper.

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Lakes, rivers and floodplains: Evolving relations

Floodplain Lakes Workshop, Fayetteville, USA, 16-19 September 2010

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The evolution of floodplain lakes systems was the theme for a workshop held in Fayetteville, in September 2010. This workshop attracted 30 participants from across the USA, but also from Australia, Russia, Canada, Brazil, and China, with case histories presented from the Murray-Darling, Yangtze, Mississippi and Missouri, Amazon, Rio Manu, Sacramento, White River, Peace-Athabasca and Cauca (Columbia) river systems.

The meeting arose from a gathering at the 3rd PAGES Open Science meeting in Corvallis, Oregon, in 2009 and was set within Focus 4 ("PHAROS") of PAGES, and particularly aligned with the Theme "Water" and the associated Working Groups Human Impacts on Lake Ecosystems (LIMPACS) and Land Use and Climate Impacts on Fluvial Systems (LUCIFS).

The presentations spanned three main themes: proxy and chronological development, regional integration and evidence of human impact. The 20 presentations and seven posters covered evidence of accelerated catchment sediment yields, lead and other metal pollutants, and the response of floodplain wetlands to connectivity to the river, regulation of flow, and alteration to water quality. Situated in the Mississippi Basin, the meeting explored in detail the evolution of meander belts in the Missouri River with climate-driven shifts between meandering and braided states, as evident from dated paleo-wetland sequences (Fig. 1).

Considerable discussion was directed towards the particular challenges that are posed by undertaking paleoenvironmental research in such dynamic systems and the need to develop links between researchers working on the history of these systems. Despite recognition of these challenges, study after study showed that sedimentary profiles provided decipherable and informative records of hydroecological changes, and participants identified that a focus on river-wetland interactions holds considerable promise for addressing scientific and management issues of high societal concern. In particular, capacity was seen to engage with those river authorities that were underpinning policies and management decisions only with short-term instrumental records. It was also noted that floodplain sites were of cultural significance as many communities live within floodplains and it is often via rivers that humanity experiences climate variability (droughts and floods).

In line with the goals of PHAROS the meeting initiated discussion on regional upscaling of data. This was exemplified by the presentation of a regional synthesis of wetland change from the Murray Darling Basin. This further stimulated the creation of a network of floodplain lake researchers across North America to roll-start the process of assembling a database of geomorphic and paleolimnological research with a view to providing evidence for regional patterns of change and for identifying regions in need of research.

The organizers received considerable interest in response to the call for papers for a special issue of the *Journal of Paleolimnology*. The participants also made plans for a biannual meeting at which point the community may be in a position to plan for a substantive review output such as an issue in the *Developments in PaleoEnvironmental Research (DPER)* series. Further, the focus of several projects on RAMSAR (convention on wetlands of international importance) sites (in Australia, Columbia, USA and Brazil) stimulated a proposal for a future activity focussed on exchanging palaeoecological evidence of change with agencies vested with the responsibility of assessing the natural ecological character of listed wetlands and setting limits of acceptable change.

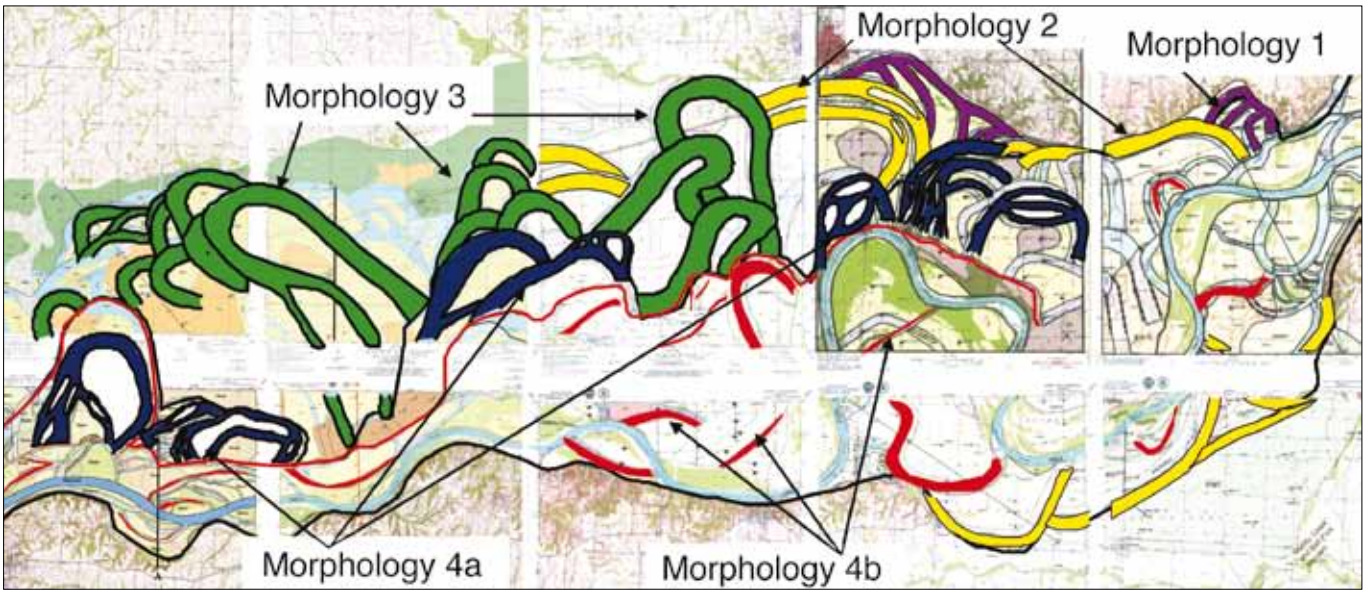

Figure 1: The evolving styles of Missouri River channels. Channel fills older than 3.5 ka BP are highly sinuous with neck cutoffs generating long oxbow lakes. An abrupt climate driven shift in channel shape induced shorter oxbows from lower sinuosity channels, interspersed with sandy islands. From 3.0 ka BP the channels adopted a more braided pattern with few substantive oxbow lakes, with braiding the prevailing state by 1.5 ka BP. The evolving pattern reflects sustained and ongoing increases in the ratio of bedload to discharge.

Holocene climate variability at high-southern latitudes: An integrated perspective (HOLOCLIP)

HOLOCLIP kick-off meeting , Université Pierre et Marie Curie, Paris, 29-30 June 2010

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Southern Hemisphere (SH) high-latitudes are challenging places to document and understand the mechanisms of natural climate variability: (1) the regional climate response involves complex and poorly documented interactions involving all the components of the climate system; (2) temperature changes are amplified compared to low latitude environments; and (3) Antarctica and its surroundings are characterized by a strong regional variability. These regional differences are obvious during the recent instrumental period, which depicts a large warming over western Antarctica during the last 50 years while no clear trends were observed for other Antarctic regions. Regional differences have also been highlighted over the course of the Holocene from geological and glacial records, supported by model experiments.

In the framework of the European Science Foundation (ESF) PolarCLIMATE program (http://www.esf.org/research-areas/polar-sciences/polarclimate.html), HOLOCLIP aims to bring together the ice core, marine sediment core and modeling communities to study the processes linking the different components of the climate system and linking the climatic response to the external forcing over the Holocene. Key areas of the Antarctic Ice Sheet and their marine surroundings have been selected (Fig. 1).

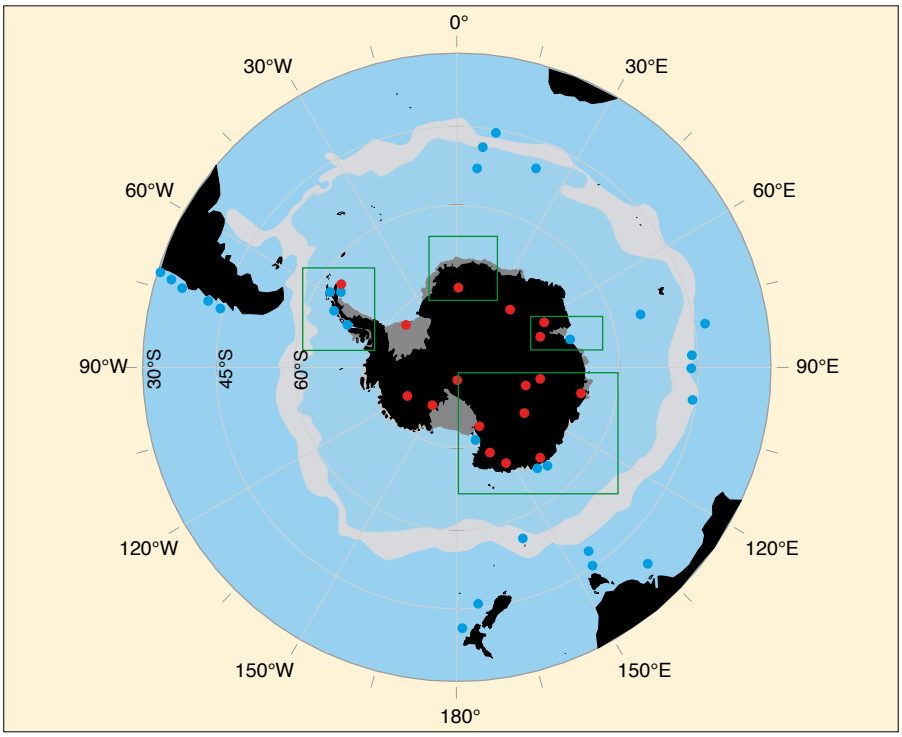

Figure 1: The investigated areas (green boxes) are reported on a map showing the ice (red dots) and marine (blue dots) core locations. The gray shaded area is the position of the modern polar front zone.

The objectives of this Joint Research Project are multiple and can be grouped as follows:

1. To validate and calibrate our proxies through investigation of the modern systems, to improve understanding of the tools that we currently use for climatic reconstructions.
2. To document changes in the different components of the Holocene climate system in terms of amplitudes, frequencies and timing, using a multi-proxy approach.
3. To document the regional heterogeneity of the different climate components over the Holocene by investigating several marine cores from the Antarctic continental margin and ice cores from the ice sheet and integrating the results in climate models via assimilation techniques.
4. To evaluate relationships between the different components / parameters, through a detailed comparison of marine and ice-core records, to better document the interactions among atmosphere-cryosphere-ocean.
5. To quantify the main forcing factors and to detect the regional climate sensitivity to these forcings.
6. To document the feedbacks between different system components.

LOCEAN (Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques) at University Pierre and Marie Curie, hosted the HOLOCLIP kick-off meeting. Nineteen scientists from the ice core, sediment core and climate modeling communities gathered to discuss available data, plan activities and coordinate the scientific teams for the next year.

Each project partner presented their main contribution to HOLOCLIP to provide an overview of the available data and the plans for new data to be obtained (Fig. 1). Climate modelers presented the model (LOVECLIM) that will be used to perform transient and snapshot simulations.

The actions to be performed before the end of the first year of the project are:

- Laboratory measurements on ice and sediment cores to produce additional high-resolution data sets.
- The compilation of a database hosted on the project website (www.holoclip.org) to facilitate a number of synthesis products.
- Data synthesis of Antarctic temperatures, sea-surface temperatures and sea ice cover at five time slices (8, 6, 4, 2, 0 ka BP). Data synthesis will serve as a ground truth for climate model evaluation and data assimilation.
- Exchange of samples among partners (both modern and fossil) to achieve the best calibration and paleo-reconstructions possible.
- Exchange of young scientists among partners for training.

ESF-HOLOCLIP is funded by national contributions from Italy, France, Germany, Spain, The Netherlands, Belgium and the United Kingdom, with Stanford University as an associated partner.

The first Asia2k regional workshop

Nagoya, Japan, 26-27 August 2010

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Asia is an important region in the PAGES 2k Network for the reconstruction of climate of the last 2000 years. Around 60% of people in the world live in Asia and major climate phenomena, such as large-scale monsoon systems, affect their livelihood regionally and the climate system globally. However, paleoclimate data of last two millennia have not been integrated well in Asia until now.

For the reconstruction of paleoclimate with annual or sub-annual time resolution, tree rings are one of the most advantageous climate archives. Many long tree-ring chronologies have been established in cold and dry Asia such as the Tibetan plateau and Gobi desert. Unlike most higher latitude regions, tree-ring studies in tropical and subtropical Asia are constrained by the additional challenge of harboring only few tree species that form annual rings. However, dendrochronologists have recently managed to overcome this limitation by systematically searching for ring-forming and climate-sensitive tree species, and have successfully developed the first tree-ring based reconstructions of past precipitation and temperature in humid and temperate Asia, including Indochina, Taiwan, and Japan.

Furthermore, historical documents, especially from China, provide exceptionally long records of past climate with a seasonal resolution that can reach back to more than two millennia. Lake and marine sediment studies have also resulted in important data sets of high-resolution climate variations in Asia. A growing number of speleothems records from China and many other countries reflect past hydroclimate on various time scales. Ice cores from the mountains and corals from coastal regions provide further unique data sets on climate dynamics from land and ocean.

The first Asia 2k Regional Workshop was designed to review the state of paleoclimate science in Asia towards the synthesis of various kinds of proxy-based Asian climate reconstructions during last two millennia.

A total of 73 scientists and students, including the 15 invited international scientists, attended this workshop with 24 oral and 26 poster presentations. Oral sessions consisted of keynotes by members of the scientific committee (E. Cook, H. Borgaonkar, B. Buckley and O. Solomina), followed by presentations on state-of-the-art proxy-based reconstructions of Asian paleoclimate using tree rings, ice cores, stalagmites, lake sediments, marine archives and historical documents together with climate modeling. Proxy, region and time range covered by all oral presentations are illustrated in Fig.1. All abstracts and presentations can be viewed on the Asia 2k website (http://www.pages-igbp.org/index.php/workinggroups/asia2k/publications).

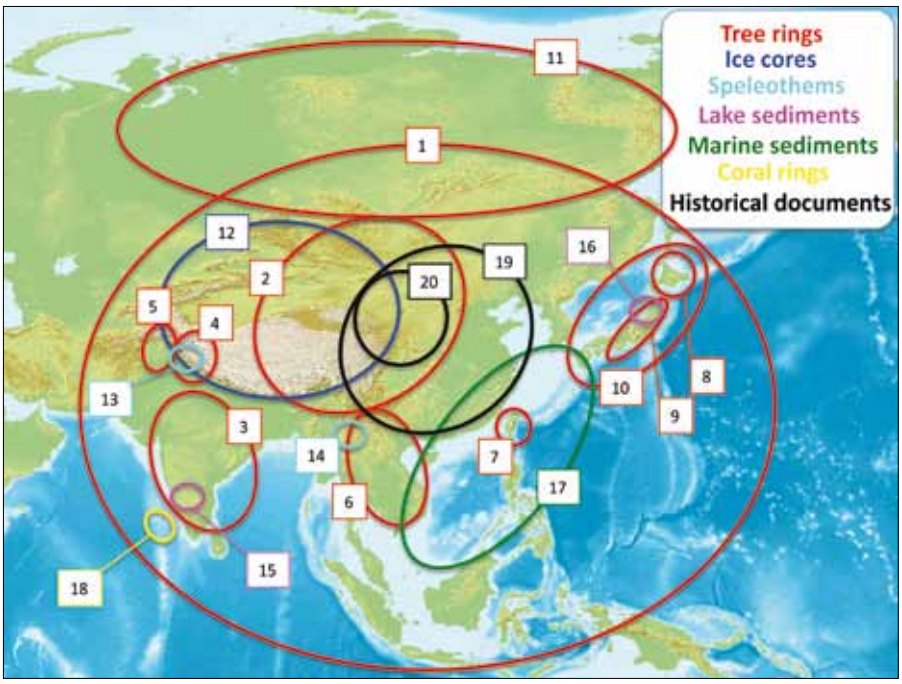

Figure 1: Covered areas and proxy types presented during the workshop. Tree rings: (1) E. Cook, 1000 yrs; (2) Y. Liu, 2500 yrs; (3) H. Borgaonkar, 500 yrs; (4) R. Yadav, 1000 yrs; (5) J. Palmer, 750 yrs; (6) B. Buckley, 1000 yrs; (7) W. Wright, 1000 yrs; (8) K. Yasue, 500 yrs; (9) Y. Hoshino, 2000 yrs; (10) T, Nakatsuka, 400 yrs; (11) O. Solomina, 2000 yrs; Ice cores: (12) K. Fujita, 2000 yrs; Speleothems: (13) V.M. Padmakumari, 2000 yrs; (14) C. Muangsong, 2000 yrs; Lake sediments: (15) R. Shankar, 2000 yrs; (16) K. Yamada, 2000 yrs; Marine sediments: (17) M-T. Chen, 2000 yrs; Coral rings: (18) S.M. Ahmad, 100 yrs; Historical documents: (19) Q. Ge, 2000 yrs; (20) T. Nagano, 300 yrs. These captions indicate the maximum time span covered by the presented data sets.

The tree-ring session started with the presentation of a gridded reconstruction of the Palmer Drought Severity Index (Monsoon Asia Drought Atlas) using a continental scale database of tree-ring width ((1) E. Cook in Fig.1, same hereafter). Tree-ring chronologies did not only reveal long climate histories in the cold and dry Asia ((2) Y. Liu, (4) R. Yadav, (5) J. Palmer, (11) O. Solomina) but they also demonstrated the value of tree rings for climate reconstructions in humid and temperate Asia ((3) H. Borgaonkar, (6) B. Buckley, (7) W. Wright, (8) K. Yasue, (9) Y. Hoshino, (10) T. Nakatsuka). After a comprehensive review of Asian mountainous ice core studies ((12) K. Fijita), new speleothem records were presented from South and Southeast Asia ((13) V. M. Padmakumari, (14) C. Muangsong). Lake and marine sediment records presented ((15) Shankar, (16) Yamada, (17) M-T. Chen) covered more than 2000 years with decadal time resolutions. Finally, various climate records were presented from Chinese historical documents ((19) Q. Ge, (20) T. Nagano).

After the workshop, the Scientific Committee and other workshop participants discussed future directions of the Asia 2k Working Group in detail and tentatively concluded that the second Asia 2k workshop should be held in the fall of 2011 in order to conduct a training course for analyses and compilation of past climate data sets towards the 2k paleoclimate synthesis in Asia.

PAGES international course: South American climatology and quantitative high-resolution climate reconstructions in Palaeoecology

Valdivia, Chile, 23-27 October 2010

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This educational course on quantitative paleoecology and South American climatology was organized as a pre-conference event prior to a major international PAGES symposium in Valdivia (see below). The objective of this course was to impart a high level of first-hand knowledge to early career researchers from Latin American countries working in paleoecology and paleoclimatology. The course topics had been selected on the basis of students' enquires that followed the "International Workshop on Methods in Quaternary Palaeoecology" held in La Serena in 2007 (Maldonado and Latorre, 2008).

A total of 27 participants from Argentina (11), Chile (8), Brazil (3), Colombia (2), Switzerland (2) and Bolivia (1) were chosen from over 70 applicants. All participants were graduate students or young post-doctoral scientists working with a variety of different paleo-proxies (pollen, diatoms, tree rings, plant macrofossils, etc.) on projects across South America (Fig. 1).

The lectures on the first three days of the course were given by Prof. John Birks (University of Bergen) on quantitative paleoecology and environmental reconstructions, including an overview of the major numerical methods such as ordination analysis, analysis of stratigraphical data, data calibration and transfer functions. The last two days, Prof. René Garreaud (University of Chile) gave a presentation on South American climatology including the basic climate dynamics, the fundamental statistical tools applied in climatology and the general concepts of South American climate. After the lectures, the participants had the opportunity to discuss their own data with the lecturers and immediately apply their newly acquired knowledge.

Given that the course topics were highly relevant to the general PAGES objectives, all participants also attended the II International Symposium "Reconstructing Climate Variations in South America and the Antarctic Peninsula over the last 2000 years" (LOTRED-SA) the following week. At the LOTRED-SA conference, they met experienced researchers working on different projects in South America and had the opportunity to exchange and discuss ideas with them.

Figure 1: Twenty-seven participants from Argentina, Chile, Brazil, Colombia, Switzerland and Bolivia attended the workshop. Their research areas and used proxies are indicated in the map above.

Initiatives like this PAGES supported educational meeting, offer emerging South American researchers the chance to gain access to the finest knowledge and expertise.

The conveners wish to thank Prof. John Birks and Prof. René Garreaud for their willingness to deliver the course and PAGES, University of La Serena, Centre for Advanced Studies in Arid Zones (CEAZA), Southern University of Chile (UACh) and Center for Scientific Studies (CECS) for financial and logistical support.

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