The Last Millennium Climatic Record off Iberia

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The Iberian Peninsula location, at mid-latitude and at the western extreme of the European continent, turns it into a key point for climate reconstructions. Besides being at the latitude of the southern anticyclone of the North Atlantic Oscillation dipole, responsible for the Northern Hemisphere climatic conditions, the Tagus River path marks the division line between the areas of direct Atlantic and Mediterranean climate influence.

This paper will report on a compilation of data obtained from a series of shallow-water and high-sedimentation sites recovered from the South and West coasts of the Iberian Peninsula. Previous work for the region (38.33ºN, 9.21ºW, 96 m and 41.4ºN and 8.9ºW, 80 m) has proved shallow-water sites as good climate archives for the Holocene and the last millennium in particular. By means of high-resolution multi-proxy studies the Little Ice Age (LIA) climatic conditions have been explained as mainly due to negative NAO conditions, while the Medieval Warm Period (MWP), or Medieval Climate Anomaly (MCA) has been suggested to be driven by extremely continuous positive NAO conditions. Moreover, the most extreme precipitation and temperature conditions were observed at the beginning of both the MWP and the LIA.

With the compilation of the existing quantitative data and the new data gathered from a southern margin position (36.88ºN, 8.07ºW, 99 m) and a location further north (41.92ºN, 9.07ºW, 119 m), we hope to better understand the forcing behind the regional spatial distribution of the basic climatic properties during the last millennium and their relation to the global climate.

Northern Hemisphere blocking activity during the last millennium as simulated by the ECHO-G model

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A novel blocking index is proposed reconciling two traditional approaches. Blocks are considered from a two-folded complementary perspective as a signature in the anomalous height field capable of reversing the meridional jet-based height gradient in the total flow. The new index accounts for the duration, intensity, extension, propagation, and spatial structure of a blocking event. The method succeeds in identifying 2-D persistent anomalies associated to a weather regime in the total flow with blockage of the westerlies, being applicable to observations and model simulations of different resolutions, temporal lengths and time variant basic states.

The characteristics of blocking for 40 years of reanalysis (1950-1989) over the Northern Hemisphere are first compared to present-day (1950-1989) simulations of the ECHO-G model. The model shows an overall underestimation of blocking activity over the Euro-Atlantic sector and a southward shift of Eurasian blocks, which are mainly due to a model bias consisting of excessive zonal winds over the Euro-Atlantic sector and a southward shift of synoptic activity at the exit zone of the jet stream, respectively. Albeit these deficiencies, the main blocking features (location, annual cycle and persistence) as well as some of their associated impacts are captured with reasonable realism, especially over the Pacific and Atlantic sectors.

Results from two forced simulations of the ECHO-G model for the 1000-1989 period are also described. The model reproduces typical signatures obtained in temperature reconstructions such as a Little Ice Age and a Medieval Warm Period, although with different amplitudes to those derived from other AOGCMs. The observational-based hypothesis that blocking may have played a significant role in the excessively cold conditions recorded in Europe during the Maunder Minimum is tested, as is whether blocking may have partially accounted for warm temperatures over specific sectors during the Medieval Warm Period simulated by the model.

Old and new proxies to resolve temperature changes in Medieval time

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To get a better understanding of the nature of temperature changes in Medieval time requires a much broader coverage of proxy data than that which currently exists. We know very little about what temperature changes were like in the Tropics or in the southern hemisphere during this period. This limits our ability to fully constrain possible mechanisms of climate forcing during this interesting period. We need new paleotemperature proxies that can be applied in a wide range of settings, and we may need to reassess some proxies that have limitations for seasonal paleotemperature reconstruction on decadal timescales. I review these issues, with a particular focus on ice core records, and new biomarker proxies from lake sediments.

Coral records of central tropical Pacific temperature and hydrology during the Medieval Climate Anomaly

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Proxy records from around the world document profound changes in atmospheric circulation and precipitation patterns during the Medieval Climate Anomaly (MCA), yet the role of changes in sea-surface temperature (SST) in determining the structure of these changes remains uncertain. Nowhere is this more apparent than in the tropical Pacific, which is inferred to have been significantly cooler during the MCA, largely based on hydrological responses in regions sensitive to El Nino-Southern Oscillation phenomenon. However, precious few direct estimates of tropical Pacific SST exist. Tentative support for the cool-tropical Pacific MCA paradigm comes from fossil coral oxygen isotopic records, whose relatively heavy values indicate a shift towards cooler and/or drier conditions during the MCA (Cobb et al., 2003). Here we present new coral Sr/Ca records from an expanded set of MCA-dated fossil corals, enabling the separate quantification of temperature and hydrological changes in the central tropical Pacific during the MCA. We compare estimates from "bulk" coral Sr/Ca alongside micro-scale measurements of coral Sr/Ca (via Secondary Ion Mass Spectrometry) to assess the impact of diagenesis on the resulting coral Sr/Ca-based SST reconstructions, and assign quantitative error bars to the SST reconstructions based on coral-to-coral reproducibility studies. While we find tentative support for a cooler MCA, prominent decadal-scale variability during the MCA (most notably during the late 13th century) is the most robust finding to emerge from the new coral reconstructions. The inferred large decadal-scale variations in central tropical Pacific SST, if accurate, should be linked to paleo-hydrological changes recorded in teleconnected regions during the MCA—a possibility we investigate through comparisons to existing proxy records from the circum-Pacific. We find no evidence that solar or volcanic radiative forcing played a role in shaping central tropical Pacific climate during the last millennium.

Was the NAO persistently positive during the Medieval Climate Anomaly?

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The North Atlantic Oscillation (NAO) is the dominant synoptic mode of cold season annual to multidecadal climate variability in the North Atlantic region. The persistently positive NAO seen in recent decades raises the question of whether it was forced by anthropogenic greenhouse warming, and whether a comparable pattern may have occurred in previous, more natural warm intervals. Millennial reconstructions from the NAO's centers of action suggest a persistently positive NAO during the Medieval Climate Anomaly (MCA), the most recent major warm interval prior to the modern era. This raises the question of whether similar findings can be found in other millennial records for the North Atlantic basin and vicinity. A millennial tree-ring chronology from West Virginian red cedar (*Juniperus virginiana*) ring widths is sensitive to the cold-season NAO, due to the tendency for warmer, wetter conditions to occur in the eastern USA during the NAO's positive phase. More positive NAO values are inferred for the period between 1000 and 1300 A.D., with a transition to relatively more negative values that persist through much of the Little Ice Age. Ensemble reconstructed values for the Medieval epoch are similar to the 20th century mean. The most positive values during the MCA are associated with RCS-standardized chronologies, which pseudoproxy tests reveal may be biased artificially positive.

Bringing the Canadian Arctic Ice Melt Records up to the surface shows the recent melt exceeds that of any period over the last 2 millennia

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Melt layer records from the Agassiz Ice Cap (Ellesmere Island) and the Devon Ice Cap have been used extensively as robust measures of past temperature. These records stopped in the 1960s or 1970s. More recent ice cores from the Penny Ice Cap (Baffin Island) provided melt up to the early 1990s. All these records span at least 2000 years and the Agassiz record spans 11000 years. The records have been brought up to the surface by taking 20m hand drilled cores and measuring detailed density and visual stratigraphy. For all cores the most recent 25 years has the highest melt of the last 2000 years, Figure 1. In the case of the one long record from Agassiz, one has to go back 4000 years to match the most recent 25 years. The calibration curve relating melt to temperature for these cores is also presented.

The Agassiz melt record is presented on the new compatible GIC005 time scale and compared to the Canada/Greenland Holocene Record based on stable isotopes (Vinther et al., 2009).

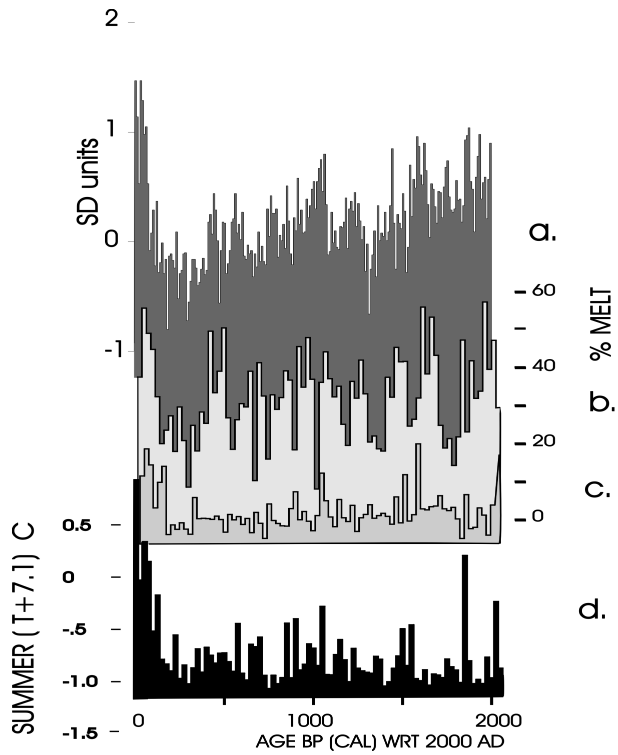

Figure 1. a) The Kaufman et al. (2009) 23 site reconstruction for the last 2000 years; b) Melt layer percent for the Penny Ice Cap , Baffin Island drilled in 1995 AD; c) Melt layer record from Devon ice core drilled in 1999; d) Agassiz Ice Cap melt record (converted to summer temperature) brought up to 2008.

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Expression of the Medieval Climate Anomaly in Speleothems

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Speleothems, such as stalagmites, stalactites and flowstones, are a rich archive of terrestrial paleoclimate information. A particular strength of speleothem records is their potential for constructing long and high-resolution records, whereas only few published records provide detailed information on the climate during Medieval times. With the exception of a few speleothem-based climate reconstructions, most of the time series reflect changes in precipitation rather than temperature. I will provide an overview of the existing speleothem-based time series covering the Medieval period, whereas special emphasis is given to climatic fluctuations recorded in stalagmites from Europe, the Mediterranean and the Indian-Asian monsoon domain.

Last millennium as represented by a suite of GCM forced simulations and reconstructions

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Forced simulations of the last millennium from several high complexity general circulation models (ECHO-G, HadCM3, CCSM, COSMOS, IPSLCM4, CNRM-CM3) are analyzed and compared with some paleoclimatic reconstructions. Different natural and anthropogenic external forcing conditions as the solar activity, the atmospheric concentrations of carbon dioxide and methane or the volcanic aerosols, are considered in the suite of forced simulations.

The analysis addresses the temperature and circulation response in the various model simulations, with attention to the influence of the internal variability and the response to external forcing. The temperature is studied in a global and hemispheric context, comparing the control and the different forced runs during the last millennium. The circulation response is focused on different known dynamical patterns, as the annular modes: the Arctic Oscillation (AO) in the Northern Hemisphere and the Antarctic Oscillation (AAO) in the Southern Hemisphere. At regional scales, the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO), or the Pacific Decadal Oscillation (PDO) are also analyzed in the pool of models. Implications for the understanding of the MWP will be discussed.

Reconstructing climate changes over medieval times using climate model simulations with data assimilation

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Three simulations with data assimilation have been performed using the LOVECLIM climate model constrained to follow the temperature histories obtained from a compilation of 56 well-calibrated surface temperature proxy records and 2 spatial reconstructions (one global and one for summer temperature in Europe). We show first how this new data assimilation technique, based on a particle filter, improves the results compared to the simpler one applied previously. Secondly, we demonstrate that the data assimilation is providing an efficient and robust constraint on the simulated climate variability over the past centuries. At the hemispheric and continental scales, the model reconstructions using data assimilation are in good agreement with both the instrumental record of the past 150 years and with reconstructions of climate in past centuries derived from the application of traditional statistical approaches to networks of proxy data. Using those simulations with data assimilation and independent proxies, we analyze the changes in the Atlantic Ocean and in the atmospheric circulation in the North-Atlantic-European Sector during the so-called Medieval Warm Period and their influence on European temperatures.

Evidence for Global Climate Reorganization During Medieval Times

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Coupled climate model simulations using increased tropical warm pool SSTs agree well with globally distributed marine and terrestrial proxy records, supporting the idea that changes in the tropical SSTs were an important driving mechanism for the Medieval Climate Anomaly (MCA). In the model, the altered tropical SSTs induce zonal and meridional shifts in tropical and extra-tropical circulation patterns giving rise to the many of the MCA hydroclimate and temperature signals seen in many proxy records. It is likely not coincidental that the tropical SST pattern that produces this apparently realistic model response is remarkably similar to a recent climate field reconstruction of MCA-LIA temperature differences. We describe regional tropical and extra-tropical signatures of the MCA climate seen in the model results and proxy data, and note multi-proxy evidence for a sharply bounded episode of climate change within general time frame of the MCA, considering both proxy sensitivities and proposed dynamical mechanisms.

A robust reconstruction of the April to September temperature in Europe during the Medieval Period

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We obtained a gridded reconstruction of spring-summer temperatures in Europe during the last 1400 years based on tree-ring, documentary, pollen, and ice core sources. We decomposed the frequency spectra of each series into three bands and we did a separate reconstruction in each band using an analogue technique. Each proxy was then used in the frequency bands where it is robust. We proved that the method preserves the long-term variations and the variability of the temperature. We find that (1) according to the long-term variations shown in this reconstruction, conditions during the last decade have exceeded all those known during the Medieval period; (2) based on an analysis of the distribution of extreme temperatures, the maximum event of the Medieval Period (1.1°C higher than the 1960-1990 reference period) had a return period of more than 1000 years, but this recently fell to less than 26 years; (3) all decades before AD 1350 were warm on average but relatively heterogeneous, while the last decade was homogeneously warmer. The new result is that this anthropogenic change is characterised by spatial homogeneity, with similar changes in both average temperatures and in the distribution of extreme events, while natural climate forcings induce warm periods with heterogeneous spatial patterns and less frequent extreme events.

Was there a Medieval Climate Anomaly, and if so, Where and When?

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We meant the title of our 1994 review "Was there a Medieval Warm Period, and if so Where and When?" (Hughes and Diaz, 1994) to be read in two ways. Firstly, it was to be read quite literally. Secondly, it was meant to be ironic. The literal reading was rewarded by an attempt to identify and synthesize records thought to be appropriate to this task. Irony was used to imply that, since a clear and simple answer was not forthcoming from the review, it might be useful to reformulate the question. Please read the title of this abstract in the light of this explanation of the 1994 title.

The trajectories of these two concepts ("Medieval Warm Period" and "Medieval Climate Anomaly ") will be traced. A case will be made for the abandonment of both of them, on the grounds that they are inappropriate, uninformative, and that they very probably divert attention from more revealing ways of thinking about the Earth's climate over the past two millennia.

It is clear from many recent publications, especially many of the abstracts submitted for this meeting, that high-resolution paleoclimatology has moved firmly from the mode of descriptive climatology to that of physical climatology. As a result, there is little utility in picking over definitions of the geographic and temporal extent of putative epochs, especially in the Late Holocene. The pressing questions concern the dynamics of the climate system, and the relative roles of free and forced variations, whether the forcings are anthropogenic or not.

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On the dating and the geographical extent of the Medieval Warm Period (MWP)

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Since the MWP was vaguely defined in the 1960s, its definition and reality has become more and more diffuse over the last 40 years. This is principally down to the lack of an accepted, and a universally used, date for the period. This is despite there being a number of important papers that have given specific intervals that could be easily and justifiably classed as the MWP. The problem with an accepted date stems from too many scientists stating that the warmest part of their reconstruction, at approximately the right time, is their MWP. Similar issues exist with the Little Ice Age.

Naming periods in the instrumental period (e.g. the early and late 20th century warming periods) is generally based on looking at the global average temperature series or at time series of forcing histories. These principles should be used for defining the MWP. The first possibility is to consider the poorly known forcing histories for the last 1500 years and defining the MWP (and the LIA) accordingly. This can be considered circular, as it would be difficult to objectively compare the forcing histories with a large-scale reconstruction. The second and more promising approach is to objectively define a period based on a thorough examination of all the proxy reconstructions available that extend over the last 1200-1500 years. This approach needs to consider reconstructions over as much of the NH as possible (and include the few from the SH) and not just those from the eastern North America, North Atlantic and European region. Definition should not be based on single proxies.

The medieval period within a 2000-year-long proxy temperature reconstruction for the Arctic

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Spatial-temporal trends in average Arctic summer temperature during the medieval period were investigated using a recently published 2000-year-long reconstruction (Kaufman et al., 2009, *Science* 325:1236). The synthesis includes all available proxy temperature records that extend back to at least 1000 AD and are resolved at annual to sub-decadal scale from north of 60° latitude. A composite including 12 records from lake sediment, seven from glacier ice, and four from tree rings (23 total records) was averaged and calibrated to decadal mean summer temperature for the instrumental period. During much of the first half of the first millennium AD, temperatures appear to have been similar to or higher than the warmest interval of the middle ages, probably because of precessional forcing, which was most pronounced at high latitude. Following the 6^{th} century and prior to the 20^{th}, the average warmest interval occurred between 940 and 970 AD. Only some sites registered peak pre-industrial temperatures during this interval, however.

The high average temperature is dominated by sites in the northwestern North Atlantic sector (Greenland and Canadian High Arctic), especially isotope records from glacier ice. Six of the eight records with the highest temperature are from ice sheets and ice caps, and one is from a lake on Greenland. This might reflect a regional temperature pattern, or the sensitivity of the isotopes to changes in seasonality of precipitation and location of the moisture source, which are affected by storm-track trajectories and sea-ice cover. The four proxy records from trees indicate the maximum warmth of the medieval period occurred immediately following the warmest interval registered in glacier ice, from 970-1010 AD. Three of the four tree-ring records are from Eurasia, which might indicate a regional pattern. Proxy records from lakes are more widely distributed than the other two types and they most closely track the overall mean. They indicate three intervals of relative warmth during the medieval period: 980-1010, 1040-1080, and 1190-1250 AD. The warmth during the later period is reinforced by isotope-based proxy records from glacier ice, which show a secondary warm period from 1210-1230 AD. Because the number of sites is limited, and because records from glacier ice and trees are clustered geographically (NW North Atlantic and Eurasia, respectively), distinguishing regional patterns in temperature from seasonal or hydrological biases is not currently possible.

Evidence from 180 proxy records of widespread Northern Hemisphere warmth in the 9th to 11th centuries

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The amplitude and geographical coherency of the late-Holocene pre-industrial temperature variability has been much discussed and the occurrence of a distinct Medieval Warm Period (c. AD 800–1300) and a Little Ice Age (c. AD 1300–1900), on a global or hemispheric scale, has been repeatedly questioned. In order to assess the geographical coherency of pre-industrial, climate changes we have mapped the spatial-temporal pattern of centennial temperature variability in the Northern hemisphere between the 9th and 20th century using all available millennial length, palaeotemperature proxy records. Our database comprises a total 180 proxy records from a wide range of archives including, but not limited to, ice-cores, marine sediments, lake sediments, tree-ring chronologies and reconstructions, speleothems and historical data.

The temporal resolution of the proxy records used ranges from annual to centennial. Our analysis is undertaken using centennial means. By accepting such low-resolution records, we can use substantially more records to competently extend our reconstruction back to the medieval period. The geographical pattern of normalized temperature anomalies and their probabilities are gridded onto a 2°x2° polar projection using near-neighbor estimation.

We find evidence of a widespread medieval warming culminating in the 10–11th centuries, followed by a gradual cooling into the 17th century, succeeded by a dramatic warming from the 18th century that accelerated into the 20th century. Our result also indicates that the warmth in the 10th and 11th centuries was as uniform as is the current 20th century warming. However, with a resolution of only 100 years, it is not possible to assess whether any decade in the past was as warm as any in the late 20th or early 21st centuries.

Multiproxy summer surface air temperature field reconstructions for southern South America back to AD 900.

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We present the first regional-scale summer temperature field reconstruction for southern South America (SSA) back to AD 900 using 22 proxies from natural and human archives. The reconstructed mean summer temperatures between 900 and 1350 are mostly above the 1901–1995 climatology. After 1350, we reconstruct a sharp transition to colder conditions, which last until approximately 1700. The summers in the eighteenth century are relatively warm with a subsequent cold relapse peaking around 1850. In the twentieth century, summer temperatures reach conditions similar to earlier warm periods. In the early part of the reconstruction (900-1450), reconstruction uncertainties are larger due to the limited number of proxy records available (5 records). However, the warm phase before 1350 as well as the 14th century cooling are robust to changes in predictor network and reconstruction methodology.

We find regional differences in the characteristics of medieval temperatures: In subtropical SSA, the warmest anomalies are reconstructed in the 11th century, whereas in higher latitudes, medieval maxima are found in the 13th and 14th centuries. This corroborates evidence from other regions, suggesting that the Medieval Climate Anomaly was a temporally and spatially heterogeneous phenomenon in contrast to the globally consistent warming of the recent decades.

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Potential Dynamical Mechanisms Underlying the Pattern of the 'Medieval Climate Anomaly'

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I will review recent work aimed at establishing the nature of, and factors underlying, patterns of large-scale climate variability in past centuries. Evidence is compared from (1) recent proxy-based reconstructions of climate indices and spatial patterns of past surface temperature variability, (2) ensemble experiments in which proxy evidence is assimilated into coupled ocean-atmosphere model simulations to constrain the observed realization of internal variability, and (3) ensemble coupled model simulations of the response to changes in natural external radiative forcing.

Implications for the roles of internal variability, external forcing, and specific climate modes such as ENSO and the NAO will be discussed. Implications for long-term variations in Atlantic tropical cyclone activity will also be discussed.

The Medieval climate of Europe: results of the Millennium Project

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Within the EU-funded 'Millennium' project, new multi-proxy palaeoclimate data covering at least the last one thousand years have been collected from the North Icelandic Shelf, the northern Boreal zone and the Alpine and Mediterranean regions. The offshore evidence suggests relative warmth prior to a rather abrupt decline around AD 1300. In the northern Boreal zone, tree growth indicators (ring width, maximum density, annual height increment, minimum blue reflectance) suggest that growth during the 11th Century was almost as high as, and statistically indistinguishable from, tree growth during the 20th Century. Stable carbon isotope ratios from tree rings record changes in the internal concentration of carbon dioxide and, in the northern Boreal zone, are regarded as a proxy for photosynthetic rate, and therefore summer sunshine. Low values during the 11th Century suggest that it was warm but cloudy, in contrast to the Little Ice Age, centred on the 17th Century, which was cool but sunny. Preliminary results of oxygen isotope analysis of tree rings suggests anomalously low values during the 11th Century, perhaps indicating large-scale changes in circulation. In the first half of the 12th Century there is a marked growth decline across northern Fennoscandia. This is the only major growth decline in the last Millennium that is not associated with known volcanic forcing. Data on the Mediaeval climate of other parts of Europe are still being collated.

Refining the timing and magnitude of medieval warmth in the NW North Atlantic

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A new time series derived from 89 high-precision ^{14}C dates on *in situ* dead vegetation exposed by retreating cold-based ice caps across Baffin Island (uncertainty <15 years) and a new 2 ka annually resolved (uncertainty <5 years) multiproxy glacier-dominated lacustrine record from Iceland, supported by a second, decadally resolved nonglacial, Icelandic lacustrine record, provide the most precise paleoclimate reconstructions for the Common Era around the NW North Atlantic region yet available. Both regions show significant ice-cap growth and cold summers beginning between 550 and 750 AD and continuing until 950 AD, when climate proxies indicate the onset of a period of relative summer warmth. In Iceland, Medieval Period warmth appears stable for nearly 200 years, with a modest perturbation after 1150 AD. But conditions return to those of the preceding two centuries by ~1200 AD. On Baffin Island no ice caps form between 950 and 1250 AD. Termination of medieval warmth is recognized on Baffin Island by the inception of a large number of ice caps between 1250 and 1300 AD that remain intact until the 21st Century, although ice cap shrinkage is underway by 1900 AD. A second pulse of ice cap inception occurs about 1450 AD, after which virtually all ice caps are in an expanded state and remain that way until the 20th Century. Maximum ice-cap extent on Baffin Island is attained in the second half of the 19th Century. A similar pattern is reflected in both Icelandic lakes. All Icelandic proxies reflect an irreversible shift toward expanded ice caps and decreasing summer temperatures beginning 1250 AD, and intensifying about 1450 AD. Peak summer cold is achieved in the first half of the 19th Century.

In both Iceland and the Eastern Canadian Arctic medieval summer warmth extends from 950 to 1250 AD, and is bracketed by glacial activity for the preceding 200 to 400 years and by renewed ice-cap growth and landscape destabilization commencing about 1250 AD, after which conditions never return to similar centennial warmth until after 1900 AD. Based on the many ice caps that have melted in the early 21st Century, but that failed to melt during medieval time, it is possible to conclude with virtually no uncertainty that there was no century during medieval time with sustained warmth as high as during the past 100 years. But in neither region were medieval summers as warm as during the Holocene Thermal Maximum.

New Perspectives on the Role of the AMO in MWP Drought: Results from Proxy Data and Climate Model Analyses

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We investigated relationships between North Atlantic sea surface temperatures (SST) and persistent drought in North America using modern observations, proxy paleo-data, and simulations from multiple climate models. The observational results show that persistent droughts in the U.S. Great Plains and southwest North America are closely related to multidecadal variations of North Atlantic SST (Atlantic Multidecadal Oscillation, AMO). During the AMO warm (cold) phases, most of North America is dry (wet). We further demonstrate that warm North Atlantic SST anomalies played a major role in the MWP drought over much of North America. We next analyzed SST variations in the North Atlantic Ocean for the last 10ka using empirical orthogonal function (EOF) analysis. The first spatial mode (EOF01) of the Holocene SST demonstrates a basin-wide structure in the North Atlantic that clearly resembles the AMO pattern recorded during the recent instrumental period. The first principal component (PC01) associated with EOF01 is thus a good index that represents the temporal variations of the AMO-like SST pattern during the Holocene. The MWP drought is just one of numerous droughts on centennial timescales that the proxy record indicates impacted North America. We further demonstrate that these centennial droughts are closely related to the AMO-like SST variations in the North Atlantic. Finally, the influence of North Atlantic SST on North American drought is examined using simulations made by 5 global climate models. When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America, despite some regional differences. Specifically, dry summers in the Great Plains and the North American Southwest are simulated by all models. The precipitation response to a cold North Atlantic is much weaker and contains greater disagreement among the models. Overall, the ensemble of the 5 models could well reproduce the statistical relationship between the dry/wet fluctuations in the North America and North Atlantic SST anomalies. Clearly, the AMO or AMO-like SST has had the capacity to strongly modulate precipitation and drought over North America throughout the Holocene.

Why medieval climate matters to southwestern North America: Sharpening our paleoclimatic focus on the future

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Perhaps no other part of the paleoclimatic record is more relevant to ensuring sustainability of the Southwest region than the last 2000 years, and particularly the medieval period. Multi-decadal droughts ("megadroughts") occurred multiple times during this period and had large impacts on the flow of the Colorado River and on the humans who lived nearby. There are two reasons why understanding these megadroughts and the likelihood that they could occur in the future needs to be a first-order priority in establishing "no-regrets" adaptation options for the region. First, comparison of instrumental and proxy hydrologic data with simulations made with CMIP3 coupled atmosphere-ocean climate models indicates that these models may significantly underestimate the probability of future megadrought. For example, a simulated 1 in 10 chance of an AD 1150's style megadrought should really be a 2 in 10, or even 3 in 10 chance. Further multi-proxy paleoclimatic work would refine these estimates. Second, even if climate change is limited by successful mitigation strategies, we know megadroughts can arise due to natural causes alone, and until we can preclude these causes from happening in the future, we must be prepared to deal with megadrought of at least the scale indicated by the paleoclimatic record.

What are the full dimensions of the southwestern medieval megadroughts? Paleoclimate data are providing increased knowledge on several fronts. First, we know when the droughts occurred, and we also have evidence that timing of the meteorological megadrought was not always coincident with start and end of the hydrological (e.g., snowpack or Colorado River flow) megadrought. Reductions in streamflow associated with megadroughts may have been worsened by reductions in snowpack. Second, a new dendroclimatic reconstruction of Colorado River flow, consistent with a more uniform scaling of climatic variance across time scales, indicates that medieval megadroughts were substantially (i.e., 25%) more severe (drier) than previously estimated. This has major implications for developing management decisions, as water managers turn increasingly to paleoclimatic data to complement model-based estimates of future flow. Third, limited evidence indicates that anomalously high temperatures may have exacerbated portions of some medieval megadroughts (e.g., through spring snowpack reductions). Although current estimates of medieval warm temperature anomalies indicate that they were significantly below 20th and 21st century anomalies, independent proxy data such as (or from) lake sediments (i.e., geochemical and faunal) are needed to obtain robust conclusions regarding the influence of temperature anomalies on medieval megadrought. Fourth, our published preliminary data suggest that atmospheric dust loading was not a significant positive feedback on drought during medieval times, but a network of high-resolution dust records is needed to confirm this hypothesis. Lastly, the seasonal nature of precipitation deficits during medieval megadroughts is quite uncertain, particularly with respect to the potential role of summer monsoon rainfall. A research program designed to illuminate the full dimensions of the medieval megadroughts in southwest North America using tree-ring, lake and speleothem data is currently underway, as are efforts aimed at methods for enhanced data-model comparison and improved articulation of how changes in the tropical Pacific may have influenced megadrought in the Southwest.

Global Medieval Hydroclimate: What we do, do not, and need to know

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The Medieval period—the centuries up until the mid-15th Century—contained some truly impressive hydroclimate anomalies. Perhaps most impressive of these were the sequence of multidecadal droughts—megadroughts—in western North America that added up to creating a more arid climate in the region for essentially the entire MCA. Other impressive hydroclimate features of the MCA appear to include a good run of Nile floods, wet in northern South America as inferred from the Cariaco basin, a strong Indian monsoon, dry in the Mediterranean region and wet in northwest Europe. It is argued that these fit into a spatial pattern familiar from modern day interannual to decadal variability. A persistent La Niña-like state in the tropical Pacific Ocean would explain the North American anomalies the monsoon and the Nile, but other records in Europe and Asia would be easier to explain if at the same time there was a persistent positive state of the North Atlantic Oscillation and, perhaps, of the Atlantic Multidecadal Oscillation. While there is limited marine evidence of La Niña conditions during the MCA, and modeling studies support its prominent role in driving Medieval hydroclimate, the lack of marine proxies in general for the period makes it hard to prove that this atmosphere-ocean configuration held. But if it did, it raises the interesting question of whether such a co-ordinated atmosphere-ocean state arose from internal variability, including inter-basin coupling, or as a nonlinear response to radiative forcing. If it is the latter then it is quite unlike model responses to expected rises in greenhouse gases.

Results from ensemble simulations of the last millennium

Drew Shindell
NASA/GISS

I will discuss some of our recent research in modeling of historical climate change and fire during the past millennium. These results will concentrate on the climate response to solar variability and the impact of climate change on fire occurrence, both in comparison with paleoclimate data. I will present changes between the MWP and LIA, and how the spread across ensemble members compares with the magnitude of differences seen in proxy reconstructions. I will also discuss the temporal relationship between forcing and response in these coupled ocean-atmosphere climate model runs, and how the ocean's lagged response causes divergence between the peaks in forcing and the times of greatest temperature and precipitation responses.

Solar Activity during the Medieval Climate Anomaly

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Solar activity has been long recognized to be one of the most important external forcing mechanisms influencing the climate of our planet. This contribution aims to review the current state of knowledge on the solar activity during the MCA (Medieval Climate Anomaly) spanning approximately between the years 900 and 1300 CE. We discuss the advantages and caveats of different proxies of solar activity that have been used to characterize this period. While doing so we try to address the longer-term picture, i.e. to put the MCA period in perspective of the last several millennia.

In recent decades significant attention has been given to low-resolution solar proxies based on the production of isotopes allowing studying the long-term evolution of solar activity. In this respect we describe the so-called "solar medieval maximum", showing that it can hardly be considered as a true grand-maximum of solar activity. Then we describe two grand-minima of solar activity taking place within the MCA period, namely Oort Minimum (1010-1070) and Wolf Minimum (1270-1340). Finally we evaluate the MCA period using high-resolution solar proxies (based on historical observations of sunspots and aurorae) allowing the study of specific space climate events. We show "Worcester's storms" (1128-1129) as an example of the use of solar proxies of high resolution.

Reconciling contradicting proxy records of MCA-LIA NAO variability

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Two millennial-length hydroclimatic proxy records from close to the centers of action of the winter North Atlantic Oscillation (NAO) indicate that the Medieval Climate Anomaly (MCA) was characterized by a pervasive positive phase of the NAO(1). Supplementary Proxy Surrogate reconstructions based on climate model results and proxy data indicate a clear shift to weaker NAO conditions into the Little Ice Age (LIA). Multidecadal NAO variability results in synoptic-scale shifts in surface pressure, wind fields, and precipitation. Globally distributed terrestrial and marine proxies suggest that this NAO shift is one aspect of a global MCA-LIA climate transition that is hypothesized to be coupled to prevailing La Niña–like conditions amplified by an intensified Atlantic meridional overturning circulation (AMOC) during the MCA.

The majority of high-resolution palaeoceanographic data that span the last millennium are consistent with the hypothesis that the MCA (Little Ice Age, LIA) was characterized by more (less) intense AMOC. These data include proxies for sea surface temperature, bottom water temperature, sea ice cover, upwelling intensity and reconstructions of ocean hydrographic variability, including Gulf Stream outflow, North Atlantic Deep Water return flow and the position of the oceanic Polar Front. There are multiple datasets, however, including the Na ion ice core proxy from the Greenland Ice Sheet (2, 3), that indicate enhanced storminess and cyclone frequency across the North Atlantic, and thus a positive rather than a negative NAO phase, during the LIA. A possible explanation of this discrepancy in proxy records has been provided by ensemble simulations of the cyclone-resolving Climate Community System Model (CCSM) coupled ocean-atmosphere general circulation model for the Maunder Minimum during the LIA (4). These simulations indicate major mid-latitude blocking anticyclones and reduced cyclone frequency constructions for the LIA, consistent with NAO negative phase. Simultaneously, however, the simulations suggest an increased intensity of cyclones when anticyclones break down during the LIA. I will here discuss the possibility that enhanced LIA storminess, as indicated by a number of paleoceanographic proxies, may be a product of more intense, rather than more frequent, LIA storms.

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Paleohydrological signatures of the Medieval Warm Period in the Iberian Peninsula reconstructed from lacustrine records

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Small lakes experience considerable lake level, water chemistry and biological fluctuations in response to changes in effective moisture, a key climatic parameter in Mediterranean areas. Iberian karstic lakes are particularly sensitive to moisture changes due to their relative small size, the direct connection to the aquifers and the hydrological features of their basins. Furthermore, their relatively high depth/area ratios favour the deposition of finely laminated sediments, suitable for high-resolution chronological reconstructions. Detailed sedimentological and geochemical analyses complemented with some biological proxies (chironomids, diatoms, pollen) were performed in several cores from a number of karstic lakes in Spain: in the Guadalquivir River Basin (Zoñar), the Pyrenees (Estanya, Montcortés), the NW Ebro Basin (Arreo) and the Iberian Range (Taravilla and El Tobar).

Age models are based on a combination of radiometric dating (^{137}Cs, ^{210}Pb, AMS ^{14}C) and, in some cases, varve counting. In most sites, relatively shallower lake levels and higher chemical water concentrations, with predominance of Mediterranean vegetation and a decrease in arboreal pollen reflect more arid conditions during the Medieval Warm Period (MWP) (9th- mid 14th century). Higher clastic input seems to be mostly controlled by anthropogenic impact due to increasing farming activities during medieval times. Fluctuating, but generally more diluted waters and higher lake levels occurred during the following centuries (Little Ice Age, 1350-1850 AD), consistently with other regional palaeoclimatic reconstructions. Despite local differences and some dating uncertainties, the MWP stands out as a relatively dry period, characterized by decreased lake water balance in the Mediterranean regions of the Iberian Peninsula. The available MWP Iberian reconstructions show an opposite pattern (more arid) compared to some eastern Mediterranean sites (wetter) suggesting a marked Western – Eastern Mediterranean regional variability during that time period.

The MWP in Greenland ice core data

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Temperature estimates for the MWP in Greenland can be obtained from various Greenland ice core data, i.e. directly from water stable isotopes, from gas diffusion, from bore hole thermometry and indirectly from water stable isotope diffusion. These temperature proxies from Greenland ice cores tend to show a MWP, but it's amplitude and duration varies in the different data sets. Differences are also observed between ice cores drilled at different locations on the Greenland ice sheet. A comparison of the different data sets, and a comparison between the present Greenland warmth, the 1930s warm period and the MWP will be discussed.

Paleoclimates of North America within the context of northern hemispheric-scale climate change of the past 2,000 years

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The debate concerning the causes of the global temperature increase of the past century results in part from the difficulty in establishing the magnitude of surface temperature change that can be attributed to natural climate variability and that caused by human impact through greenhouse gas emissions. The critical issue in attributing the relative contribution of human activity to recent increases in global temperatures remains the interactions between different time-scales of climate variability. Shorter time-scale variability is superimposed on longer time scales, and the combination determines the maximum amplitude of warming or cooling.

The Medieval Climate Anomaly (MCA) is sometimes considered as equal to or warmer than the 20th century warming. We discuss evidence using moderate resolution records from across North America that show that the MCA was part of a natural ~1,000 ±100 years quasi-cycle operating throughout the Holocene where variability in climate at this scale is estimated to be no more than ±0.2°C at the continental-scale of North America. Regional expressions of the century-scale MCA in northern Boreal Canada and eastern US illustrate the complex dynamics in temperature patterns. Considering higher-frequency changes at multi-decadal scales, we show using high-resolution reconstructions of the northern hemisphere that during the height of the MCA, century-scale rates of change were +0.11°C per decade, compared to +0.21°C per decade since 1980 further supporting a human-caused greenhouse gas forcing signal.

New pollen-based reconstructions of summer temperature in central/eastern North America and implications for differences in MCA-LIA circulation patterns

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A new version of the pollen ratio method of temperature reconstruction will be introduced. This new approach uses an optimized selection of pollen taxa in the binomial logistic form of the generalized linear model (GLM) to estimate a pollen-climate forward relationship based on modern pollen and associated climate data. This forward relationship is designed for incorporation into a Bayesian Hierarchical Model (BHM) framework for paleoclimate reconstruction, but can also be inverted to directly yield expected value (EV) reconstructions of summer temperature based on fossil pollen assemblages. Explicit modeling of reconstruction uncertainty can be done in this inverted form using a 2-way Monte Carlo framework that takes advantage of the binomial specification of the ratio model and Gaussian distributions of estimated parameters.

Validated summer temperature reconstructions for the northern Midwest of the United States (Wisconsin) have been developed using the inverted GLM ratio method from three absolutely-dated (varved) lake basins. The high explained deviance of the GLM fit provides reconstructions with 95% uncertainty ranges narrow enough to allow clear distinction of a cooler LIA in relation to earlier and later times (by ~1.5 deg, compared to a mean 95% reconstruction uncertainty range of ± ~0.45 deg). These reconstructions indicate a relatively late onset of the MCA-LIA transition, at approximately 1400-1450 CE, based on the assumption of a median 50-100 year lag in forest vegetation response to climate (cf. Williams et al., 2002). Other sites in temperate central-eastern North America are being examined, and validated results obtained will also be presented.

The reconstructed summer temperatures suggest that the transition between the polar front and warm/moist southerly flow into central temperate North America associated with the Bermuda high was shifted south and eastward in the LIA, relative to its position during the MCA and more recently. A potential modern analog for such a shift is described in Figure 1.

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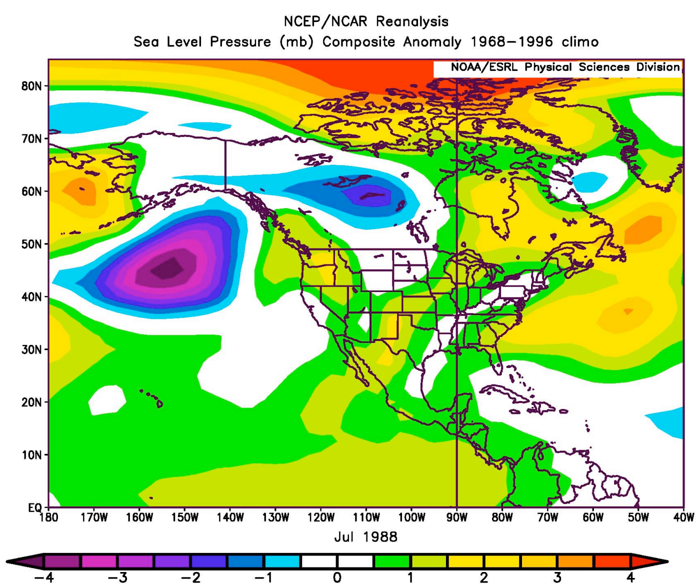

Figure 1 Surface pressure composite for July 1988. The composite SLP for this month, an unusually warm July during the later 20th century, shows a strongly enhanced Bermuda High whose influence extends well into the central and eastern interior of North America, including the region of the pollen-based reconstructions reported. As a hypothesis, this pattern could be a potential analog for MCA mid-summer, and the negative of it (a significantly weaker Bermuda High) could be a potential analog for the LIA.

Can we understand the dynamics of the MCA-LIA transition based on one single climate mode?

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The climate system is quasi-stochastic and intermittent in its behaviour. The important climate modes are the result of complex dynamics, namely the westerlies in the midlatitudes and the Hadley and Walker circulation in the tropics. In addition, memory effects and exchange processes between ocean / sea ice, land and atmosphere, including their feedbacks, contribute to the formation of important modes being responsible for climate change at different timescales from months or years to decades or even centuries. Examples are: ENSO, PNA/PDO, and NAO/AMO. These modes also influence or interact with important continental to global scale phenomena, e.g. the African, Indian or East Asian Monsoon.

The westerlies in both hemispheres fluctuate between a high index and a low index (blocking) state. Because of its larger landmass this process is more accentuated in the Northern Hemisphere. Therefore, the winter climate of this region with its high temperature and precipitation variability is determined by two to three frequent climate modes, namely the NAO/NAM/AO, the classical blocking and a more meridionally shaped mode (see Barnston and Livezey 1987, and Corti et al. 1999). Based on different examples it will be asked whether or not we should study the succession of these and other modes, including their intermittent interaction, if we want to explain the formation of century scale warm or cold periods, and the transition between them (e.g. between the MCA and the LIA).

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Evidence of the Medieval Climate Anomaly from the Mediterranean Basin

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We review the availability of temporally low and highly resolved terrestrial and marine proxies as well as paleo-environmental evidence from the Mediterranean area covering the past 2000 years. Based on the different archives, their climate interpretation and considering uncertainties, we present a preliminary report on the current knowledge concerning the spatial and temporal extent of the MCA/LIA transition period in the context of the past 2000 years in the Greater Mediterranean Region. We will address future challenges in how to incorporate the existing climate information in a statistical exercise to estimate past climate variations in the area.