SPATIAL AND TEMPORAL CHARACTERISTICS OF CLIMATE IN MEDIEVAL TIMES REVISITED

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The increase in high-resolution proxy records over expanding areas of the globe helps deepen understanding of the unusual climate patterns—and the forcing mechanisms responsible for them—during the years 950 to 1400.

Climate in medieval times, a period usually understood to extend from A.D. ~950 to ~1400, is of considerable interest to students of modern and future climate. This is because the period differs from recent centuries mainly by predating the Industrial Revolution with its associated changes in the composition of the atmosphere and oceans and the nature of the land surface (Hughes and Diaz 1994; Crowley and Lowery 2000; Bradley et al. 2003a,b). In this sense it represents an appealing, but imperfect "control case" for the unintended global climate experiment that has resulted from industrial and agricultural development and population growth.

In order to stimulate a synthesis of recent work on these topics, we convened a meeting of international experts to consider the following issues:

1) What were some of the key regional patterns of climatic anomalies during medieval times derived from the proxy climate records and from model simulations, and how do they compare with the twentieth-century patterns?
2) Recognizing that multiple proxy climate records are needed to constrain as much as possible the spatial and temporal variability of climate, what do recent studies using powerful statistical methods tell us about the timing and geographic coverage of the major features of climate in medieval times?
3) A number of numerical simulations using climate models of varying complexity and external forcing histories have been completed in the past few years. What do the latest model results tell us about geographic patterns and temporal characteristics of the simulated climate of this period?

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4) In what specific ways does the climate of the last several decades (approximately the last 30 years) differ from periods of comparable length in medieval times?

HISTORICAL BACKGROUND. Hubert Lamb wrote first of a "medieval warm epoch" and later of a "medieval warm period," ending in A.D. 1300, when the relative frequency of warm episodes increased, primarily around the North Atlantic [see Lamb 1965 (p. 26), 1966, 1977, 1982]. He emphasized that this took place in a context of complex climate variability, varying by season and location. He worked primarily by applying his expertise as a climatologist to the interpretation of documentary proxy evidence from western Europe (Lamb 1965). Careful reading of his papers and books shows that his interpretations are nuanced and limited, with little resemblance to sweeping statements concerning medieval climate that have appeared in popular writings and sometimes even in the scientific literature. For example, Lamb noted a longitudinal asymmetry with respect to mean temperature in the Northern Hemisphere, writing that no medieval warming was evident in some major regions of the world, notably China, Japan, and much of the Pacific Basin (Lamb 1982, 162–163). Further, in his 1965 study Lamb compared past temperatures with "modern" mean temperatures, but referred to different time periods: for example, he used 1900–50 when discussing Central England and Wales, but elsewhere "average values about 1900." Therefore, regional or continental-wide conclusions are constrained by the different baselines used, since relative to the first half of the twentieth century, annual mean temperature in Europe has warmed by >0.5°C in the last 50 years (Hegerl et al. 2007). Following Lamb, the U.S. National Academy of Sciences (NAS), recognizing the importance of climatic variability to the nation's welfare, published a landmark report (NAS 1975) and noted the following: "The early part of the last millennium (about A.D. 1100–1400 is sometimes called the Middle Ages warm epoch but was evidently not as warm as the first half of the twentieth century" (149–151).

In recent works, this time frame is more commonly referred to as the medieval climate anomaly (MCA) (Mann et al. 2009; Trouet et al. 2009; Cook et al. 2010; Graham et al. 2011). 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 subtropical latitudes of western North and South America. The subsequent adoption of this usage reflects the availability of much more information on both temperature and hydrological changes during medieval times since Lamb wrote. These newer results have cast light on interregional differences revealed by proxy climate and the variability of climate forcing factors such as explosive volcanic eruptions, solar variability, changes in land use, and greenhouse gas concentrations in the atmosphere.

At approximately the same time that Stine suggested that "medieval climate anomaly" might be a more appropriate term than "medieval warm period," Hughes and Diaz (1994) published a review as part of a special issue of the journal *Climatic Change*. The special issue focused on examining evidence available to support the notion of a wider—hemispheric or global scale—medieval warm epoch. They concluded that insufficient evidence was available then for such a large-scale warm epoch. However, high-resolution paleorecords prior to approximately the fifteenth century were (and are still) relatively sparse (compared to modern instrumental records).

Since the mid-1990s there has been a considerable growth in the availability of high-quality proxy records suitable for use in examining the climate of medieval times, especially coverage of middle and higher latitudes of the Northern Hemisphere (e.g. Mann et al. 2008; Ljungqvist 2010). On the other hand, despite recent efforts (e.g., Conroy et al. 2009; Tierney et al. 2010; Neukom et al. 2011) fewer records are available from the tropics, and the Southern Hemisphere, particularly at interannual to decadal resolution prior to about A.D. 1200 (e.g., Neukom and Gergis 2011). Furthermore, most records provide estimates for a particular season, making annual estimates and comparisons with other (seasonally different) records problematic (Bradley et al. 2003b).

The increased number of paleoclimate reconstructions and more detailed recent modeling studies of the MCA provide powerful tools to explore climate variability at long time scales and additional capability for elucidating key mechanisms governing the climate system, such as the North Atlantic Oscillation (NAO) (Trouet et al. 2009) and El Niño–Southern Oscillation (ENSO) (Cobb et al. 2003; Graham et al. 2007; Conroy et al. 2009). Therefore, in the last years there has been an increasing interest in describing climatic patterns during medieval times (e.g. Goosse et al. 2006; Ammann et al. 2007; Mann et al. 2009; Trouet et al. 2009). A better understanding of the role of natural (externally forced and internal) climate variability in the last millennium should help in detection and attribution studies of climate change in the context of anthropogenic global warming (Bradley et al. 2003a; Alverson et al. 2003; Jansen et al. 2007).

A PERSPECTIVE ON RECENT FINDINGS.

Temperature records. The revival of interest in the subject of climate in medieval time spans approximately the last 25 years. More recent papers have also looked at the MCA focusing on establishing the nature of the transition to the subsequent Little Ice Age (LIA) epoch (Mann et al. 2009; Graham et al. 2011), or from the perspective of a longer time frame—for example, the last 2,000 years (Graham et al. 2007; Sicre et al. 2008; Kaufman et al. 2009; Ge et al. 2010; Ljungqvist 2010; Luterbacher et al. 2011; Verleyen et al. 2011; Neukom and Gergis 2011)—to compare the MCA to other reconstructed warm periods during the Holocene, such as the Holocene thermal maximum (peak warmth occurred at different times in different places ~6,000–10,000 years before present; see, e.g., Battarbee and Binney 2008; Kaufman et al. 2004; Viau and Gajewski 2009; Wanner et al. 2008).

The recent symposium on the climate of the medieval period provided multiple pieces of evidence to support the following preliminary conclusions:

1) Consistent with the vast majority of evidence from a variety of paleorecords, the MCA period was generally warmer than during the subsequent Little Ice Age (A.D. ~1400 to ~1900) over much of the middle and high latitudes of the Northern Hemisphere. Most of the data summarized in the Solomon et al. (2007) report and in subsequent publications (e.g., Mann et al. 2008, 2009; Ljungqvist 2010) support this interpretation of the paleoclimate record (see also Juckes et al. 2007).
2) An abrupt rise in hemispheric and global temperature occurred in the twentieth century and continues through the first decade of the twenty-first century. This temperature rise is reflected in both instrumental data and in many proxy records and is well reproduced by global climate models forced by anthropogenic increases in greenhouse gases (Solomon et al. 2007).
3) Proxy records from mid and high latitudes of the Northern Hemisphere indicate that some 100-yr-long periods of the MCA might be as warm as much of the twentieth century in some regions (Guiot et al. 2010; Ljungqvist 2010). This is consistent with time averages taken over different periods during the MCA on hemispheric-to-global spatial domains, which generally show that the MCA was (within estimation uncertainty) close to the values obtained from instrumental records for the first half of the twentieth century (Jansen et al. 2007). The articles by Mann et al. (2008, 2009) provide additional context of MCA temperatures in comparison with the most recent decades.
4) Portions of the Arctic and sub-Arctic experienced warm periods during medieval times comparable to any subsequent period, with the exception of the most recent decades (Sicre et al. 2008; Kobashi et al. 2010; Vinther et al. 2010; Spielhagen et al. 2011). Proxy records of sea ice extent in the North Atlantic also suggest less coverage during medieval times than in later centuries during the LIA (Jensen et al. 2004; Massé et al. 2008; see also Ogilvie 1984). A recent study of East Antarctic shallow marine geological records does not show clear evidence of an MCA-like warm phase and only circumstantial local evidence for a cool event comparable to the LIA (Verleyen et al. 2011) in contrast to the Arctic (Kaufman et al. 2009).
5) Parts of the tropics such as the equatorial eastern Pacific may have been cooler than recent decades, indicating a La Niña–like state during some periods of the MCA (Cobb et al. 2003; see also Graham et al. 2007; Mann et al. 2009).
6) Paleodata from the Southern Hemisphere are generally too sparse to draw reliable conclusions about overall temperatures in medieval time (Jones et al. 2009). A recently published reconstruction of air temperature for southern South America indicates the presence of a prolonged (decades long) period of elevated summer temperature occurring in the thirteenth and early fourteenth centuries (Neukom et al. 2011). Keeping in mind that this reconstruction has large uncertainty prior to A.D. ~1400, some decadal means would have been comparable to decadal averages in the late twentieth century.

While there is evidence of medieval warmth, its spatial extent does not appear to be as geographically uniform as the warming seen during recent decades (Figs. 1 and 2). Based on the most recent MCA reconstruction (Fig. 2 in Mann et al. 2009), relative to a modern reference period (1961–90), the MCA was found to be warmer than the late twentieth century over ~1/3 of the equivalent global area in the reconstruction, but colder than the late twentieth century (post-1950s) over ~2/3 of the globe. Relative to an early twentieth-century 50-yr baseline (1900–49), the MCA was reconstructed to be warmer than that baseline for ~2/3 of the globe and colder than ~1/3. Therefore, the balance of evidence does not point to a high medieval period (A.D. ~1000–1300) in the Northern Hemisphere or the globe as a whole that was as warm as or warmer than the post-1970 period.

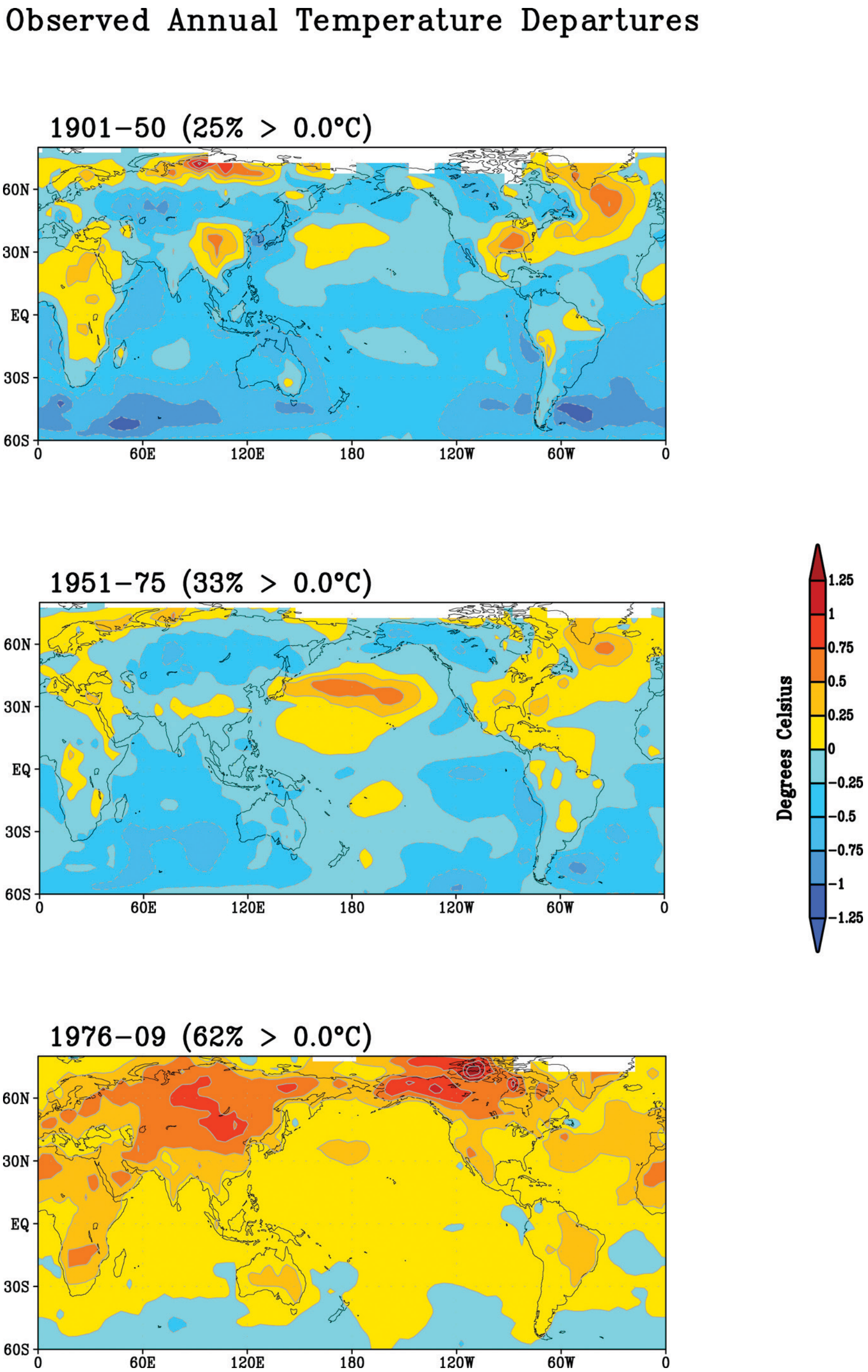

Fig. 1. Spatial distribution of surface temperature anomalies (°C) with respect to a 1901–2009 reference mean. Data source: National Oceanic and Atmospheric Administration (NOAA) merged (land/sea) data set with 5° × 5° resolution.

Hydrologic impacts. Focusing exclusively on surface temperature changes during medieval time overlooks the occurrence of widespread hydrological anomalies from the tenth to fourteenth centuries (Graham et al. 2011). In Fig. 3 we provide a qualitative sketch of regional hydroclimatic anomalies for land areas during the centuries spanning the MCA, as reported in several studies, a representative sample of which is listed in Table 1. The analysis of updated proxy records analyzed during the symposium confirms the occurrence of exceptional hydroclimatic anomalies during medieval times. In particular, the paleoclimate record supports the following:

1) Prolonged and severe droughts affected many parts of the western United States and northern Mexico (Hughes and Funkhouser 1998; Graham and Hughes 2007; Woodhouse et al. 2009; Cook et al. 2010; Graham et al. 2011). Tree ring–based studies indicate that significant and prolonged drought periods also affected other parts of the continental United States during medieval time (Cook et al. 2010), as well as Mexico (Stahle et al. 2011).
2) European proxy records show major hydrologic anomalies with drier conditions present in southern Europe and wetter conditions in northwestern Europe (Proctor et al. 2000; Esper et al. 2007) and wetter conditions in southeastern Europe and the Middle East during

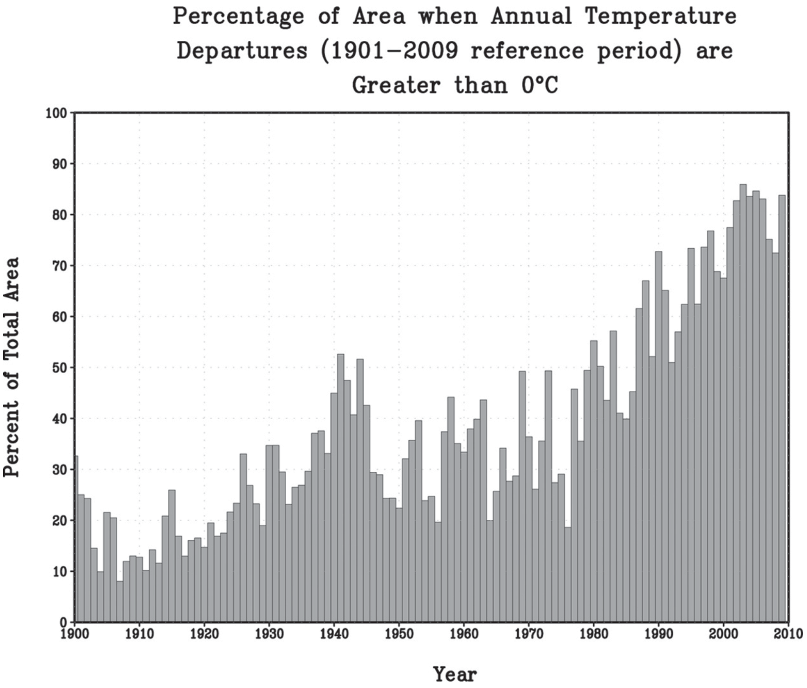

Fig. 2. Time series of the percentage area with positive mean annual surface temperature departures. Based on mapped data shown in Fig. 1.

the MCA, as compared to the LIA (Trouet et al. 2009; Luterbacher et al. 2011 and references therein).

3) Proxy records suggest that the South Asian monsoon was more drought-prone during the LIA than during the MCA (Shen et al. 2009; Berkelhammer et al. 2010), with a tendency to relatively wet conditions during the MCA in some regions (e.g. Sinha et al. 2007; Zhang et al. 2008), although there does not seem to be a clear and well-organized anomaly pattern during the MCA (Graham et al. 2011). The work by Buckley et al. (2010) using tree-ring records from Southeast Asia in concert with other proxy records in the region indicated drier conditions in the decades preceding the onset of the LIA in the fourteenth century, with a suggestion for wetter conditions in the thirteenth century.
4) Other parts of the world also experienced persistent hydrological anomalies (e.g., Verschuren et al. 2000; Chu et al. 2002; Seager et al. 2007). Evidence comes from tropical African lakes near equatorial Africa indicating that exceptionally long-lived droughts occurred during periods of the MCA. Evidence of substantial hydroclimatic anomalies during the MCA from the tropical Pacific is sparser. Evidence pointing to lower sea surface temperatures (SSTs) comes from discontinuous coral records from the central equatorial Pacific (Cobb et al. 2003), and this inference has been used to model plausible climate scenarios during medieval times that are in agreement with many of the reconstructed climate patterns from that epoch (Graham et al. 2007, 2011; Seager et al. 2007; Burgman et al. 2010). Figure 4 illustrates a possible anomaly pattern for SST and soil moisture anomalies averaged for the period A.D. 1320–1462 relative to the averages from A.D. 1856–2005 (after Burgman et al. 2010; Seager and Burgman 2011).

The widespread hydroclimatic anomalies are a major reason why the term MCA has been proposed by a number of researchers (Stine 1994; Bradley et al. 2003b; Graham et al. 2007, 2011; Seager et al. 2007; Burgman et al. 2010), since the impacts of extreme

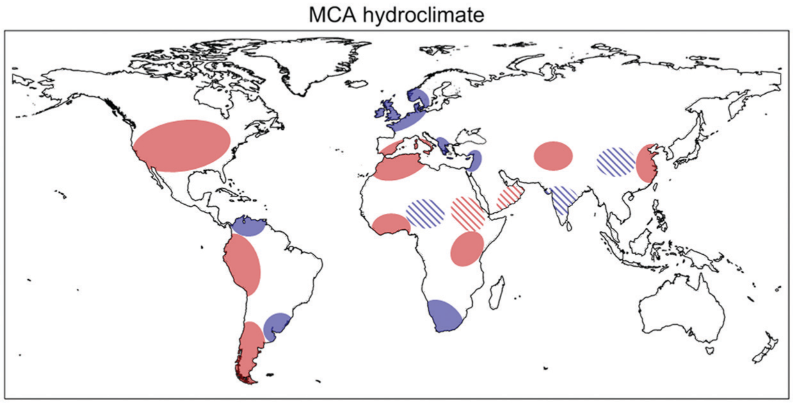

Fig. 3. Schematic map of inferred and reconstructed hydroclimate anomalies during the nominal MCA period (approximately A.D. 950–1400). Blue (red) ovals indicate predominant wetter (drier) conditions relative to twentieth-century averages. Hatched areas indicate some uncertainty exists due to differences in reconstructed values or in dating of source material. Representative reference sources are listed in Table 1.

TABLE 1. Representative list of published peer-reviewed articles documenting hydroclimatic anomalies during the medieval climate anomaly period (A.D. ~950–1400). Some of the articles in the list may only contain a summary of other relevant work, but they provide a spatial scale reconstruction or higher-resolution versions of the original time series.

Reference article	Proxy record type	Paleoclimate signal	Geographic location
Buckley et al. (2010)	Tree rings, speleothems	Effective moisture, drought/wetness	Southeast Asia
Cook et al. (2007, 2010)	Tree rings	Drought/wetness	North America
Graham et al. (2007, 2011)	Multiproxy	Spatially distributed indicators of drought/wetness	Largely Northern Hemisphere (to about 10°S)
Hassan (2007)	Historically measured levels of streamflow	High variability, extended periods of high and low Lower Nile River floods	Nile River Basin
Jenny et al. (2002)	Lacustrine sediments	Effective moisture, precipitation	Central Chile
Seager et al. (2007)	Multiproxy	Spatially distributed indicators of drought/wetness	Hemispheric-to-global scale
Shen et al. (2009); Zheng et al. (2008)	Historical documentary	Drought/wetness index	China
Stine (1994)	Relict tree stumps in lakes, marshes, and streams	Long-term aridity/hydrologic changes	Western United States, Patagonia, South America
Trouet et al. (2009)	Tree rings, speleothems	Predominant drought in Mediterranean Europe and North Africa; anomalous wetness in northern Europe	Europe and North Africa
Vershuren et al. (2000); Vershuren (2004); Shanahan et al. (2009)	Lake level and salinity fluctuations	Effective moisture, precipitation	Tropical East Africa
Villalba (1994)	Tree rings, lake sediments	Drier conditions in central Chile	Midlatitude South American Andes

drought or pluvials have had an impact on human societies at the time equal to or greater than changes in mean air temperature (e.g., Büntgen et al. 2011).

POSSIBLE MECHANISMS OF CENTENNIAL-SCALE CLIMATIC VARIABILITY. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4; Jansen et al. 2007) has provided a useful overview and assessment of paleoclimate data spanning different time periods, and a presentation of possible causal mechanisms. There are three sets of mechanisms that have been proposed to account for preindustrial multidecadal- to multicentury-scale climatic variability: (i) external forcing by, for example, changes in solar irradiance, volcanism, and atmospheric turbidity; (ii) internal variability of the coupled ocean–atmosphere system; and (iii) some combination thereof.

We highlight a pattern of natural climatic variability in Fig. 5, reproduced from Mann et al. (2009), which shows the reconstructed difference in mean surface temperature for the period A.D. 950–1250 minus the period A.D. 1400–1700 (i.e., a nominal MCA minus LIA mean temperature difference). A cool tropical Pacific signature is evident during the MCA, whereas regional anomalies over Eurasia show some resemblance to positive NAO phases. Several studies support a conclusion that changes in the frequency or persistence of climate modes (such as ENSO) may account for some of the thermal and hydrologic features during the MCA (Burgman et al. 2010; Graham et al. 2007, 2011; Mann et al. 2005, 2009; Seager et al. 2007, 2008), with preferred La Niña–like states likely dominating the MCA (Cobb et al. 2003).

Changes in SST may have led to warm conditions in northern and western Europe through SST-forced changes in large-scale circulation patterns, namely positive phases of the NAO (Mann et al. 2009; Trouet et al. 2009; Graham et al. 2011), and to severe and persistent drought conditions in many parts of the world (Graham et al. 2011; Seager et al. 2007;

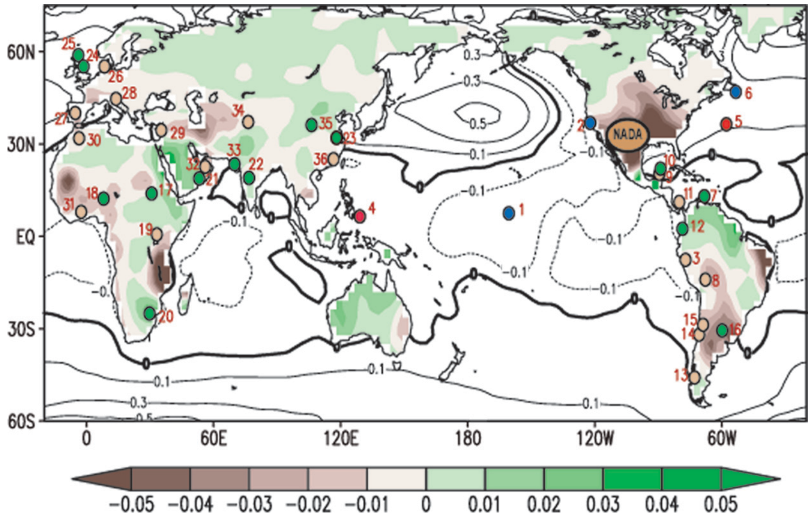

Fig. 4. Brown and green dots indicate terrestrial proxy records that show the A.D.1320–1462 period to be drier or wetter than the subsequent Little Ice Age and modern periods. NADA refers to dry conditions over North America from the North American Drought Atlas (Cook et al. 2004). The colors over land 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 A.D. 1320–1462 and another forced by modern observed SSTs. Contours over 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 cold and warm SSTs for this period. See Seager et al. (2008) and Burgman et al. (2010) and supplementary material for more details and the details of the proxy data plotted. Map kindly provided by R. Seager.

Burgman et al. 2010). Persistent positive phases of the Atlantic Multidecadal Oscillation (AMO) may have further amplified the recurrence and/or severity of widespread droughts in North America (e.g., Feng et al. 2010; see also Trouet et al. 2009). Remote and regionally forced responses of the atmosphere to changes in SST may also explain why some regions are more frequently inferred to be relatively warm in medieval times, whereas others are not. Several results presented during the symposium based on diverse proxies from different regions (e.g., Pacific corals, speleothems from cave records in subtropical and extratropical areas of the Northern Hemisphere, eastern U.S. tree rings, etc.) supported the global pattern of Mann et al. (2009) and the dominance of La Niña and positive phases of the NAO and AMO during the MCA. While there is growing evidence that recurrent states of these modes of variability were at least partially responsible for the regional signatures of the MCA, the causes for the long persistence of these circulation anomalies (whether externally forced or purely internal) remain uncertain and are one of the most intriguing questions in the current debate.

One possible mechanism for the persistence of these anomalies relates to dynamical responses to natural radiative forcing by explosive volcanism and solar irradiance changes (e.g. Mann et al. 2005; Meehl et al. 2009). Solar activity has long been suspected as having played a major role in forcing climatic variability in the last millennium, particularly in establishing the contrast between the MCA and LIA periods (Ammann et al. 2007; Lean 2010), although the contention regarding solar irradiance changes for the past millennium remains unresolved. Support for the solar forcing hypothesis can be found in Jansen et al. (2007) wherein a number of climate model simulations of the last millennium forced

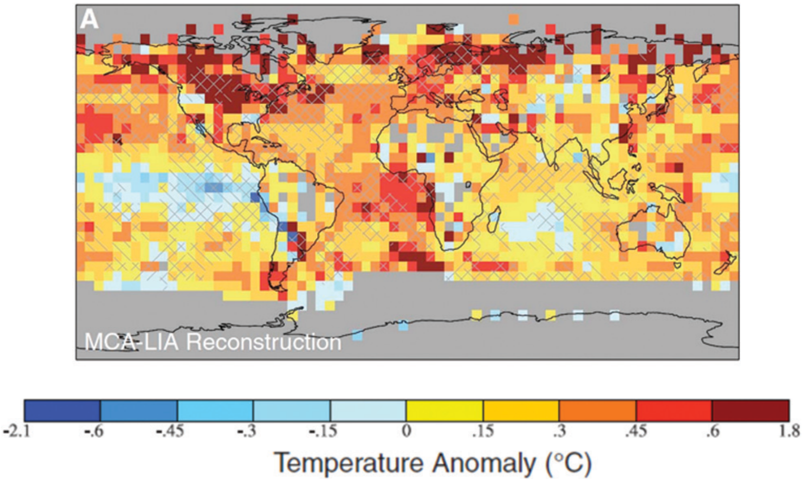

Fig. 5. Map of the reconstructed difference in mean surface temperature (°C) for the period A.D. 950–1250 minus the period A.D. 1400–1700 (i.e., a nominal MCA minus LIA mean temperature difference). Figure reproduced from Mann et al. (2009) with permission.

with estimated natural forcings produced warmer temperatures from about A.D. 1000–1400 relative to A.D. 1500–1899. It should be noted that a number of modeling studies during the last decade also have shown that increased solar irradiance does not cause surface warming in all locations (Ammann et al. 2007; Goosse et al. 2006; Graham et al. 2011; Meehl et al. 2009; Shindell et al. 2003; see also Meehl and Hu 2006). In general, the patterns of surface temperature response to solar forcing, as reproduced by models, exhibit maximum response over the higher-latitude continents because of snow and ice albedo feedbacks. This pattern shows some resemblance to the leading mode of temperature variability in the preindustrial period (Zorita et al. 2005).

More recently, efforts to reproduce major paleoclimate features for the last 1,000 years as a means to validate global climate models have been undertaken (Hofer et al. 2011; Mann et al. 2009; Servonnat et al. 2010; Swingedouw et al. 2010). Most of these global climate models reproduce some aspects of the spatial pattern of temperature change emphasized by computing the difference between a nominal average for the MCA minus the LIA. The average temperature differences between these periods are assumed to result from changes in the external forcing, but regional differences are also presumed to be a result of internal climate variability and/or model-to-model differences. We note, however, that a recent climate model intercomparison of MCA minus LIA surface temperature patterns simulated by six models finds substantial discrepancies with proxy-based reconstructions, suggesting a pure internal origin of the MCA–LIA changes, or that state-of-the-art models do not adequately reproduce some response mechanisms to external forcing. These modeled differences between averaged MCA minus LIA surface temperature can be gleaned from a contribution by González-Rouco et al. (2011) published in a recent issue of the Past Global Changes (PAGES) newsletter.

The precise physical mechanisms responsible for the sun–climate links working at the different time scales are still incompletely understood, despite the progress made in recent years, particularly in what concerns the 11-yr solar cycle (e.g. Baldwin and Dunkerton 2005; Shibata and Kodera 2005; Gray et al. 2010). According to these studies, enhanced solar irradiance during the 11-yr solar cycle leads to increased ultraviolet absorption by ozone and warming in the stratosphere; this warming then alters the circulation patterns in the atmosphere below. Consistently, recent works have detected a sizeable 11-yr solar signal in stratospheric (Labitzke 2005) and extratropical tropospheric circulation patterns (Kodera 2002; Baldwin and Dunkerton 2005; Woollings et al. 2010), including the location and strength of blocking episodes (Barriopedro et al. 2008) and NAO centers of action (Kodera 2002; Ogi et al. 2003).

This "top-down" mechanism that also suggests that equatorial anomalies resembling La Niña–like conditions at solar maximum (Shindell et al. 2003, 2006) might add a "bottom-up" mechanism working in tandem—a solar heating of the sea surface and dynamically coupled air–sea interactions (Meehl et al. 2009). Although the effects of the 11-yr solar cycle are relatively small at the surface, centennial solar variations may be amplified through the above noted mechanisms, and by persisting over relatively long intervals (effect of small perturbations accumulated over long time periods; Gray et al. 2010). In this regard, the response of patterns of sea surface temperatures and ocean currents to small changes in solar variability might be important because of the large heat content of the ocean, which can integrate them in time and provide a subsequent feedback to the atmosphere.

Regardless, given the large uncertainties in the magnitude of the solar forcing, resulting from the lack of compelling evidence for substantially higher solar activity during the MCA compared to recent periods (Solanki et al. 2004; Usoskin et al. 2007; Steinhilber et al. 2009; Gray et al. 2010; Shapiro et al. 2011), the difficulty of reconciling the temporal evolution of proxy anomalies with solar forcing in any simple way, and the incomplete understanding (and model simulation) of the atmospheric circulation responses, it has not yet been established whether or not solar forcing is a viable mechanism for explaining the reconstructed pattern of climatic anomalies during the MCA. It is quite plausible that internal variability changes could amplify relatively small solar irradiance changes, as has been suggested by Meehl et al. (2008, 2009; see also a review of this issue by Gray et al. 2010). Satellite measurements of total solar irradiance changes associated with the 11-yr sunspot cycle indicate differences of about 0.2 W m^{-2} (Gray et al. 2010), and a recent study by Tung and Camp (2008) documented a solar cycle signal in surface temperature based on analysis of two atmospheric reanalysis datasets. This topic will continue to be an area of active research.

Explosive volcanism also appears to play a significant role in modulating large-scale climate patterns and can account for a significant fraction of the temporal evolution of hemispheric and regional temperature changes for the last 1,000 years (Bradley 1988; Bradley et al. 2003a,b; Crowley 2000; Crowley and Lowery 2000; Crowley et al. 2003; Mann et al. 2005; Fischer et al. 2007; Jungclaus et al. 2010; Shindell et al. 2004). Both modeling studies and extensive climate observations over the past few centuries indicate that secular variations in the frequency and intensity of explosive volcanism, particularly when the eruptions arise from the tropics, can have long-lasting impacts on climate that are reflected in decadal and longer climatic changes.

Regional expressions of the MCA (e.g., summer warming in Europe) may also be due to some extent to the long-term cooling induced by changes in land use (Goosse et al. 2006). Concerning the end of the MCA, there is some evidence of rapid shifts in temperature and precipitation patterns leading into the LIA interval that may have been associated with large snow and sea ice anomalies (Massé et al. 2008). The development of colder conditions during the LIA may also have been influenced by very large volcanic eruptions or sequences thereof (Anderson et al. 2008; Briffa et al. 1998; Robock 2000; Zielinski 1995).

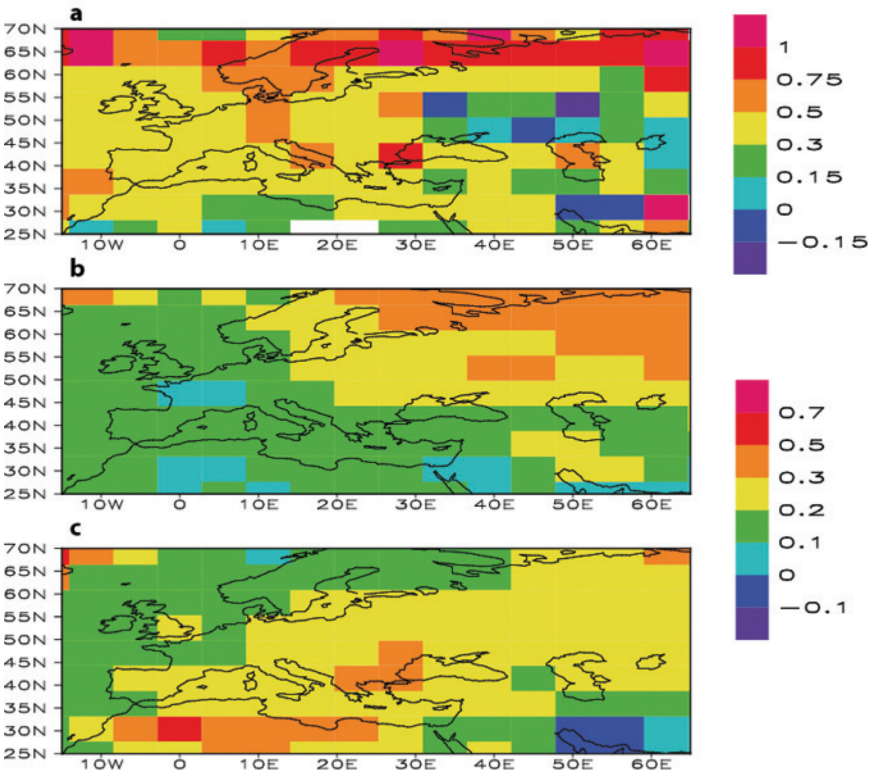

Fig. 6. Difference in annual mean surface temperature (°C) between key periods of the MCA (A.D. 900–1050) and the LIA (A.D. 1500–1650) (a) in the reconstruction of Mann et al. (2008), (b) in the simulation using data assimilation nudged to the Mann et al. target, and (c) in the simulation using data assimilation nudged to the Guiot et al. (2010) reconstruction target. Figure courtesy of H. Goosse.

While modeling studies have elucidated some potential mechanisms associated with regional- to hemispheric-scale patterns of climate anomalies inferred from the various climate reconstructions, the ultimate causes for the development of the MCA are not yet known. More recent studies combining model results with proxies through data assimilation show that the spatial patterns of temperature variability observed during the last millennium could have been produced largely by internal variability of the climate system without imposing any change in external forcing (Widmann et al. 2010; Goosse et al. 2011a,b). Figure 6, taken from Goosse et al. (2011a), illustrates the idea that internal variability of the climate system could "explain" the relatively large climatic changes that are inferred from the proxy record for the MCA. In the case illustrated in Fig. 6 for annual mean temperature changes in Europe, the model simulations—nudged at regular iterations to match a target proxy field—reproduce most of the large-scale surface temperature differences between the MCA and LIA periods. This hypothesis has large implications for future climate, as it would mean a much stronger internal variability of the climate system at centennial time scales than that expected from the instrumental record. Huybers and Curry (2006) also provide evidence to indicate a possible change in the power spectrum continuum of surface temperature in the neighborhood of the centennial time scale, so enhanced low-frequency variability (at time scales longer than ~100 years) may indicate that climatic variance is more energetic at lower frequencies, a feature that climate models have yet to reproduce.

The question of internally forced variability as a proximate cause for multidecadal to multicentury swings in hemispheric and global climate remains very much a plausible explanation for MCA–LIA-type century-scale climatic anomalies. Palmer (1999) offers an elegant exposition for the possibility that preferred states of the climate system arising from nonlinear interactions possibly interacting with weak external forcing could change the frequency distribution of the leading modes of variability of the general atmospheric circulation (e.g., the Pacific–North American mode), which could lead to multiple states of the system. Therefore, a combination of internal variability with small changes in external forcing also seems reasonable to explain the temporal persistence of patterns of internal multidecadal variability. Swingedouw et al. (2010) also suggest that low-frequency variations in the NAO and in the thermohaline circulation (see also Hofer et al. 2011) may have amplified in the North Atlantic sector the changes due to total solar irradiance variations.

SUMMATION. We have highlighted the trajectory of the terms "medieval warm period" and "medieval climate anomaly" through the early work of Hubert Lamb in the 1950s–80s, and the cautious mention of the possibility of such an epoch in a U.S. National Academy of Sciences report in 1975. The origin of the term "medieval climate anomaly" was traced to the work of Stine (1994) as he sought a more appropriate climatic context for his observations. He had developed records of extreme and sustained lake and river low stands between A.D. 850 and 1350 in the midlatitudes of both North and South America, and sought explanations based on large-scale shifts of the atmospheric circulation. This led him to suggest that "*to avoid prejudicing future palaeoclimatic analyses, reference to a 'Mediaeval Warm Period' or a 'Little Optimum', except when applied locally, should be replaced with some other phrase, such as 'Neo-Atlantic' or 'Mediaeval Climatic Anomaly' that avoids precise characterization of conditions*" (Stine 1994, p. 549).

Given the state of knowledge in 1994, Stine's suggestion was entirely reasonable and appropriate. It is now clear that climate in medieval times had much more interesting and informative characteristics than simply being warmer or colder than some reference period. Substantial evidence exists for elevated frequency, spatial extent, and persistence of severe droughts over large parts of the global midlatitudes in medieval times compared to the several centuries that followed. This in turn has raised intriguing questions concerning possible mechanistic bases of these anomalous climates in medieval times. The current effort to answer these questions of physical climatology is an excellent example of the transformation of high-resolution paleoclimatology from a descriptive to an analytical mode of investigation. When using the terms "medieval warm period" and "medieval climate anomaly," researchers need to be aware of some of the ambiguities and recognize the inherent limitations of using this terminology on the grounds that it may be imprecise, uninformative, or generally inappropriate; they also very probably divert attention from more revealing ways of thinking about Earth's climate over the past two millennia. It is clear from many recent publications, and from many of the presentations at the Symposium on Medieval Climate in Lisbon, Portugal, 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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