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Reconstructing Climatic and Environmental Changes of the Past 1000 Years: A Reappraisal

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ABSTRACT

The 1000-year climatic and environmental history of the Earth contained in various proxy records is examined. As indicators, the proxies duly represent or record aspects of local climate. Questions on the relevance and validity of the locality paradigm for climatological research become sharper as studies of climatic changes on timescales of 50-100 years or longer are pursued. This is because thermal and dynamical constraints imposed by local geography become increasingly important as the air-sea-land interaction and coupling timescales increase. Because the nature of the various proxy climate indicators are so different, the results cannot be combined into a simple hemispheric or global quantitative composite. However, considered as an ensemble of individual observations, an assemblage of the local representations of climate establishes the reality of both the Little Ice Age and the Medieval Warm Period as climatic anomalies with world-wide imprints, extending earlier results by Bryson et al. (1963), Lamb (1965), and numerous other research efforts. Furthermore, these individual proxies are used to determine whether the 20th century is the warmest century of the 2nd Millennium at a variety of globally dispersed locations. Many records reveal that the 20th century is likely *not* the warmest nor a uniquely extreme climatic period of the last millennium, although it is clear that human activity has significantly impacted some local environments.

KEY WORDS: Paleoclimate proxies • Climate change • Environmental change • Little Ice Age • Medieval Warm Period

1. Introduction

Are the Little Ice Age and Medieval Warm Period widespread climatic anomalies? Nearly four decades ago, H. H. Lamb (1965, pp. 14-15) wrote, "[M]ultifarious evidence of a meteorological nature from historical records, as well as archaeological, botanical and glaciological evidence in various parts of the world from the Arctic to New Zealand $\cdots$ has been found to suggest a warmer epoch lasting several centuries between about A.D. 900 or 1000 and about 1200 or 1300. $\cdots$ Both the "Little Optimum" in the early Middle Ages and the cold epochs [i.e., "Little Ice Age"], now known to have reached its culminating stages between 1550 and 1700, can today be substantiated by enough data to repay meteorological investigation. $\cdots$ It is high time therefore to marshal the climatic evidence and attempt a quantitative evidence." In response to Lamb's call to action, research on large-scale patterns of climate change continued with vigor.

Thirty-three years later, however, Jones et al. (1998) tentatively concluded that "[w]hile the 'Little Ice Age' cooling (with the seventeenth century being more severe over Eurasia and the nineteenth century more severe over North America) is clearly evident $\cdots$ we can only concur $\cdots$ that there is little evidence for the 'Medieval Warm Period' $\cdots$ although the fact that we have only four series before 1400 and the timescale limitations described earlier [i.e., not resolving timescales of multidecades to century with tree ring proxies used in their study] caution against dismissing the feature."

Overpeck et al. (1997) had previously commented that "[t]he annually dated record of Arctic climate variability encompassing the last 1000 years has less spatial coverage than does the multiproxy record of the last 400 years. Sediment, ice core, historical, and tree ring data for this earlier period indicate that although Arctic summers of the 20th century were generally the warmest of the last 400 years, they may not be the warmest of the last millennium[[1]] $\cdots$ The few time series of climate change spanning the last millennium also suggest that the Arctic was not anomalously warm throughout the so-called Medieval Warm Period of the 9th to 14th centuries." Nevertheless, the updated composite tree-ring summer temperature curve in Figure 1 of Briffa (2000) shows clear evidence of an anomalously warm interval from about 950 to 1100 A.D. in the northern high-latitude zone, which coincides with the Medieval Warm Period discussed here. Also, an early warm period

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[1] When considering the possible link of early 20th century warming to the rise in atmospheric CO_2 concentration, it should be noted that the Arctic-wide temperatures of Overpeck et al. began rising in the mid-19th century and peaked around 1940-1960, when the increase in the air's CO_2 content was less than 20-30% of the cumulative CO_2 increase to date; see Etheridge et al. (1996) for the preindustrial level of CO_2.

appears prominently in the averaged tree ring chronologies carefully selected and processed from 14 sites spread over 30-70°N latitude (Esper et al. 2002a).

These results are but a few of the many that have become available since Lamb's pioneering analysis. Given advancements in retrieval of information from climate proxies, as well as their extensive surface coverage, we review the accumulated evidence on climatic anomalies over the last 1000 years. We also recommend the study of Ogilvie and Jónsson (2001), which provides the most authoritative, up-to-date discussion of the historical development of the long-standing debates over the climatic nature of the Medieval Warm Period and Little Ice Age, especially in the regions surrounding the North Atlantic, including Iceland.

2. Working definitions

First, working definitions of the Medieval Warm Period and Little Ice Age must be established in order to assess the various climate proxy records. For example, Grove (2001a) captures the difficulty in deciphering the nature of the Medieval Warm Period and Little Ice Age: "The term "Little Ice Age" does not refer directly to climate but to the most recent period during which glaciers extended globally and remained enlarged, while their fronts fluctuated about more forward positions. ⋯ The term Medieval Warm Period has been the subject of considerable controversy. Its nature and even its existence has been queried, ⋯ as has that of the Little Ice Age ⋯ They were not periods of unbroken cold and warmth respectively. Climate varied on small scales both spatially and temporally, as it has also in the twentieth century. Nevertheless, climatic conditions were such during the Little Ice Age that mass balances were sufficiently predominant for the glaciers to remain enlarged, although their fronts oscillated. Similarly during the Medieval Warm Period climatic conditions caused mass balances to be negative, and volumes of glaciers to be reduced, so that they retracted substantially, though their fronts no doubt fluctuated, as they have been observed to do during the warming of the twentieth century."

Lamb (1982, 1997a), also mindful of the complex nature of weather and climate, noted that: "within the last thousand years, the development of what has been reasonably called the Little Ice Age seems to have affected the whole Earth, as has the twentieth-century recovery from it; but when the ice on the Arctic seas extended farthest south, particularly in the Atlantic sector, all the climatic zones seem to have shifted south, including the storm activity of the Southern Ocean and the Antarctic fringe. This apparently broke up much of Antarctic sea ice, enabling Captain Cook in the 1770s and Weddell in 1823 to sail further south than ships have usually been able to reach in this century.[2] The southward extension of open water would presumably result in some mildening of the regime not only over the ocean but some way into the interior of Antarctica, and this just when the world in general north of 40°S was experiencing a notably cold regime. Amongst the evidence which builds up this picture, at that time the winter rains failed to reach so far north over Chile. And radiocarbon dating of abandoned penguin rookeries on the Antarctic coast near 77.5°S, in the southernmost part of the Ross Sea, suggests that there were periods of milder climate there about AD 1250-1450 and 1670-1840. These periods include the sharpest phases of development of the Little Ice Age climate in the northern hemisphere." (page 39 of Lamb 1997a)

What are the regional and global patterns of climatic change over the last 1000 years? Accurate answers to these questions are important, both as benchmarks for the 20th century global average warming exhibited by surface thermometer records and as physical constraints for theories or mechanisms of climate change on timescales of decades to centuries.

To make progress towards this understanding, we address three questions of many individual climate proxies that differ too widely to be quantitatively averaged or compared:
(1) Is there an objectively discernible climatic anomaly occurring during the Little Ice Age, defined as 1300-1900 A.D.? This broad period in our definition derives from historical sea-ice, glaciological and geomorphological studies synthesized in Grove (2001a, 2001b) and Ogilvie and Jónsson (2001).
(2) Is there an objectively discernible climatic anomaly occurring during the Medieval Warm Period, defined as 800-1300 A.D.? This definition is motivated by Pfister et al. (1998) and Broecker (2001) and is slightly modified from Lamb's original study (1965).
(3) Is there an objectively discernible climatic anomaly occurring within the 20th century that may validly be considered the most extreme (i.e., the warmest) period in the record? An important consideration in answering this question is to distinguish the case in which the 20th century warming began early in the century versus after the 1970s, as recorded by surface thermometers. This criterion is necessary in order to judge the influence of 20th century warming by anthropogenic forcing inputs such as increased atmospheric carbon dioxide content.

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[2] See e.g., the evidence (Hendy et al. 2002) for relative warmth in the reconstructed coral-isotopic sea surface temperature throughout most of the 18th and 19th centuries at the central Great Barrier Reef, Australia. It should be noted, however, that this single proxy result does not imply uniform warmth throughout the whole south Pacific, south Atlantic and Indian Oceans. For historical accounts of sea ice conditions and harsh weather extremes during Cook's second voyage, see e.g., Forster (2000).

Anomaly, in our context, is simply defined as a period of 50 or more years of sustained warmth, wetness, or dryness within the Medieval Warm Period, or a 50-year or longer period of cold, dryness, or wetness during the Little Ice Age. Definition of the 20th century anomaly is more difficult to establish. The 20th century surface instrumental temperature record contains three distinct, multidecadal trends: early-century warming, mid-century cooling and late-century warming. But that knowledge comes from instrumental thermometry with its high time resolution and other biases that preclude a direct comparison with the proxies (proxies have their own biases). Hence, a further aspect of our research goal is to compare the 20th century objectively with more extended temperature and precipitation histories than are available from instrumental records. Given the biases of each proxy, question 3 was answered by asking if, within each proxy record, there were an earlier (pre-20th century) 50-year interval warmer (or more extreme, in the case of precipitation) than any 50-year average within the 20th century.

The third question differs from the first two. Question 3 seeks a 50-year anomaly within the 20th century compared to any other anomaly throughout the period of a proxy record while Questions 1 and 2 search for 50-year anomalies within the previously suggested 500-year and 600-year intervals of the Medieval Warm Period and Little Ice Age, respectively. But note that in the case of the third question, we treat the definition of a 50-year or more period of sustained anomaly in the 20th century no differently from that of any prior century. Thus, if a sustained warm anomaly were identified during the Medieval Warm Period and appeared warmer than an anomaly found in the 20th century, then we would assign ‘No’ to question 3. Similarly, a proxy record may show, for example, both that the 20th century anomaly is the most extreme (warmest) and that the Medieval Warm Period exists. In answering the third question, the existence of the Medieval Warm Period or Little Ice Age is not considered as they are assessed independently in answering the first two questions.

We begin with the framework of past researchers; namely, the suggested existence of the Medieval Warm Period and Little Ice Age. Our goal is thus to deduce the geographical nature of climatic and environmental conditions during these periods. Distinguishing the 20th century as a separate period is a result of the interest in the role of human activity on Earth’s climate and environment.

Another important consideration is that temporary regional cooling may have occurred on decadal, but not on multidecadal, timescales during the Medieval Warm Period, and that occasional, short-lived regional warming may have occurred during the Little Ice Age, as indicated by J. Grove (2001a, 2001b). Use of the terms Medieval Warm Period and Little Ice Age should suggest persistent, but not necessarily constant, warming or cooling, respectively, over broad areas (see Stine 1998, Grove 2001a, 2001b, Luckman 2000, Ogilvie and Jónsson 2001; Esper et al. 2002a). As suggested by Stine (1998), therefore, more appropriate terms may be the 'Little Ice-Age Climatic Anomaly' and the 'Medieval Climatic Anomaly'. Also note that the definitions of discernible, persistent climate anomalies for the Little Ice Age and Medieval Warm Period include not only distinct changes in the climatic mean but also changes in multidecadal variations (Ogilvie and Jónsson 2001). In the context of daily and regional spatial scale variability, it is important to recognize that the relationship between multidecadal mean temperature and its daily variability may undergo significant non-stationary changes (see Knappenberger et al. 2001, who document those specific time-dependent changes in temperature variability across the United States). Also, from a combination of field evidence and modeling based on an understanding derived from synoptic climatology, Bryson and Bryson (1997) demonstrated how local and regional factors (for horizontal spatial distances as small as 100 km) have produced significantly different precipitation histories for two Near East stations (e.g., Jerusalem and Kameshli, Syria) and for two stations in the Cascade Range of Oregon (e.g., mountainous versus coastal-like microclimate locations).

Our classification of a widespread anomaly based on multidecadal persistence at many locales rests on good precedent. For example, the modern globally averaged surface warming inferred from thermometer readings includes large-scale cooling trends over both the Greenland/Labrador Sea area and the eastern region of the United States (e.g., 30-45°N; 80-110°W; see Hansen et al. 1999, Robinson et al. 2002) or the Antarctic continent (e.g., Doran et al. 2002) in the last 30-50 years. Another example is the relative warmth during the Little Ice Age and relative coolness during the Medieval Warm Period seen in the borehole record of reconstructed temperature at Taylor Dome, Antarctica (77.8°S, 158.72°E, elevation 2374 meters), as compared to results from Greenland's borehole (see Clow and Waddington 1999), which do not show those features.

Assessing and confirming the global extent of the Little Ice Age and the Medieval Warm Period is premature because proxy data are geographically sparse and either one or both phenomena could be multi-phased events acting under distinct local and regional constraints and modes. Bradley and Jones (1993) and Hughes and Diaz (1994) initiated and championed the position for a non-global concomitance of the phenomena (but consider pp. 51-54 of Grove 1996 for an important clarification regarding this discourse, in light of the evidence for the Little Ice Age from glacial geology). However, in the traditionally data-rich areas of Western Europe and the Northern Atlantic, including Iceland and Greenland, both the Little Ice Age and Medieval Warm Period were distinct climate anomalies (see e.g., Pfister et al. 1998; Grove 2001a; Ogilvie and Jónsson 2001) and no objective proof discredits the existence of those phenomena in other regions. Thus, consistent with other researchers (e.g., Lamb 1965; Porter 1986; Grove 1996; Kreutz et al. 1997), we assume that both the Little Ice Age and the Medieval Warm Period may be globally distributed and teleconnected events that need not necessarily imply an extended period of global cooling or warming that persisted uniformly throughout the defined durations. The terms Medieval Warm Period and Little Ice Age still appear practical and viable, especially when considering their extension to past and future climatic events that are 'similar or equivalent' in physical scope (e.g., Bond et al. 1997, 1999; Khim et al. 2002; Stott 2002; Stott et al. 2002).[3]

Even with limited knowledge of the diverse range of local climatic behavior, the Medieval Warm Period and the Little Ice Age are not expected to be spatially homogeneous or temporally synchronous. The beginning and end dates of these climate anomalies require a better understanding (e.g., for the Little Ice Age see Porter 1981, 1986; Kreutz et al. 1997; Kaser 1999; Grove 2001a, 2001b; Luckman 2000; Schuster et al. 2000; Winkler 2000; Ogilvie and Jónsson 2001; Hendy et al. 2002; Mayewski and White 2002; Qian and Zhu 2002; Paulsen et al. 2003). Also, the imprecision of the timing of both events contributes, in part, to confusion about the phenomena. For example, Ogilvie and Farmer (1997) commented that Lamb's suggestion of a Medieval Warm Period may not be supported by documentary data even for England, because Ogilvie and Farmer's extensive and careful research using an historical dataset showed that England suffered relatively cold winters from 1260 to 1360 A.D. However, that period is near our transition between the Medieval Warm Period and Little Ice Age, so this fact does not strongly challenge our working definition and research. Collected evidence, especially that based on glacier activity, points to both a diffuse beginning and end of the Medieval Warm Period, while the Little Ice Age interval seems to have had a diffuse beginning but a more abrupt end. Based on Na^+ concentration records from annually dated ice cores from central Greenland and Siple Dome, West Antarctica, Kreutz et al. (1997) showed that the onset of Little Ice Age conditions around both poles seems to be abrupt and near-synchronous, starting about 1400 A.D. Although the notion of a Medieval Warm Period or a Little Ice Age with sharply defined transitions may be a convenient one, it is probably a non-physical construct, because regional differences in the timing of both phenomena could be quite large. As hinted by Grove (2001a), a similarly inhomogeneous climate pattern also can be identified in the 20th century warm interval.

We offer an overview of a multitude of research results within our idealized framework

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[3] Note that we refer to distinct cold and warm phases together with corresponding expressions of glacial changes but without the acceptance or refutation of the important "sharp spectral line" controversy related to climate system variability on millennial timescale discussed between Wunsch (2000, 2001) and Meeker et al. (2001).

to address our three questions about the existence of climate anomalies at individual locations. Climate indicators considered include information obtained from documentary and cultural sources, ice cores, glaciers, boreholes, speleothems, tree-growth limits, lake fossils, mammalian fauna, coral and tree-ring growth, peat cellulose, pollen, phenological data, and seafloor sediments. In its own way, each proxy provides a unique view of climate variability in terms of its relative sensitivity to the planet's thermal and hydrological fields, as well as nonclimatic factors. We rely on individual researchers for their best judgements in identifying the most significant climatic signals in their studies. Thus, our three questions are addressed within the context of local or regional sensitivity of the proxies to relevant climatic variables, including air temperature, sea surface temperature, precipitation and any combination of large-scale patterns of pressure, wind and oceanic circulation.

3. Uncertainties in inferring climate from proxies

The accuracy of climate reconstruction from proxies, including the awareness of anthropogenic interventions that could pose serious problems for a qualitative and quantitative paleoclimatology, was discussed by several researchers, including Bryson (1985) and Idso (1989). Temperature changes inferred for the Medieval Warm Period and Little Ice Age Climatic Anomalies are generally accepted to be no more than 1 to 2°C when averaged over hemispheric or global spatial scales and over decades to a century. Broecker (2001) deduced that only the results from mountain snowline and borehole thermometry are precise to within 0.5°C in revealing changes on centennial timescales. But the quantification of errors is complex, and both Bradley et al. (2001) and Esper et al. (2002a) have challenged Broecker's statement. In addition, Jones et al. (1998) have provided an excellent review on the quantitative and qualitative limitations of paleoclimatology; and Henderson (2002) provides more detailed cautions on the limitations of various climate proxies, as well as an excellent overview on potential new oceanic proxies. Others, such as Ingram et al. (1978) and Ogilvie and Farmer (1997), have cautioned about quantitative interpretations of climatic results based on historical documentation.

In our independent survey of the literature, we have observed three distinct types of warnings (see Bryson 1985; Clow 1992; Graybill and Idso 1993; Huang et al. 1996; Briffa et al. 1998; Cowling and Skyes 1999; Schleser et al. 1999; Evans et al. 2000; Schmutz et al. 2000; Aykroyd et al. 2001; Ogilvie and Jónsson 2001): (i) lack of time-scale resolution for the longest-term component of climate signals; for example, in tree ring and coral records, or the loss of short-term climate information in borehole temperature reconstructions; (ii) nonlinearities (i.e., related to age, threshold, discontinuous or insufficient sampling, saturated response, limited dynamic range of proxy, etc.) of biological, chemical and physical transfer functions necessary for temperature reconstruction; and (iii) time dependence or nonstationarity of the climate-proxy calibration relations.

Estimates of ground temperature trends from borehole data can be complicated by non-climatic factors associated with changes in patterns of land-use and land cover over time (Lewis and Wang 1998; Skinner and Majorowicz 1999). In general, climate proxies from floral and faunal fossils in lake and bog sediments are only sensitive enough to resolve change to within ± 1.3°-1.8°C (e.g., Lotter et al. 2000). Isotope-coral proxies lack the climate-sensitivity resolution and the continuous length of coral growth to address millennial climatic change. Jones et al. (1998) demonstrated that both coral- and ice-core based reconstructions performed more poorly than tree-ring records when calibrated against thermometer data since 1880 A.D. In contrast, the tree ring proxy that has the best annual time-resolution is limited by the loss of information on centennial components of climate change (see further discussion in section 5.1).

Amplitudes of large-scale surface temperature change derived from tree-ring proxies can be substantially underestimated — by a factor of two to three as compared to results from borehole thermometry (Huang et al. 2000; Harris and Chapman 2001; Huang and Pollack 2002). It seems surprising that the amplitude of climate variability broadly resolved by borehole reconstruction on timescales of at least 50 to 100 years is larger than the high time resolution results from tree-ring proxies, rather than lower, because short-term climate fluctuations are smoothed out by the geothermal heat-flow that acts as a low-pass filter.[4] Differing amplitudes resulting from borehole and tree ring climate proxies suggest that longer time scale (multidecadal and century) variability is more faithfully captured by borehole results, while the same information can be irretrievably lost in tree ring records (e.g., Cook et al. 1995; Briffa et al. 2001; Collins et al. 2002; Esper et al. 2002a) because of the standardization procedure (to remove nonclimatic biases related to changing tree size, age and tree-stand dynamics).[5] This is why Jones et al. (1998) commented that although

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[4] There are exceptions in careful tree-ring studies like those of Esper et al. (2002a), which employ new databases and strategies that are optimized to capture longer timescale variability; see further discussion in section 5.1.

[5] Cook et al. (1995) cautioned that such standard detrending methodology, typically done by fitting the biology-related trend with a modified negative exponential curve or line of zero or negative slope (for the purpose of tree-ring dating, a high-pass filter is typically used), implicitly ignored the fact that a climatic signal could involve timescales exceeding the length of any individual segments of the full tree-ring chronology and even the maximum lifespans of tree species studied. In essence, the standardization process would indiscriminately remove both the biological trends and the variabilities driven by any slow changes in climate. There is thus a maximum climatic timescale that is resolvable by tree-ring proxy which in turn is related

one may be confident of comparing year-to-year and decade-to-decade (limited to periods shorter than 20-30 years) variability, which should be more sensitively imprinted in tree ring records, it requires "considerable faith" to compare, for example, the climate of the twelfth and twentieth centuries from tree ring proxies. To date, the goal of combining information from borehole and tree-ring proxies, or even between borehole and thermometer data, to arrive at a true proxy that simultaneously resolves timescales of years to centuries, has not been realized.

Despite complicating factors such as the mismatch of climate sensitivities among proxies, Beltrami et al. (1995) and Harris and Chapman (2001) have begun to address the issue. Beltrami and Taylor (1995) also have successfully calibrated a 2000-year oxygen isotope record from an ice core near Agassiz with the help of borehole temperature-depth data near Neil for the Canadian Arctic. Their procedure avoids reliance on the circular approach of tuning a composite record from two different efforts to forcibly agree with each other (as illustrated in Figure 3 of Mann 2001a). Careful research such as that of Beltrami, Harris, Chapman and their colleagues may solve the difficulty of interpreting climate signals that degrade with borehole depth or time, which has led to the false impression that reconstructed temperatures contain a significantly smaller variability in the distant past than at present.

As long as no testable climate theory capably incorporates all relevant thermal, hydrological, geological, chemical, biological and other environmental responses during the Little Ice Age and Medieval Warm Period, local climatic proxies remain the most powerful benchmarks or measures of reality. Adopting the simplest classification that provides an objective answer to each of the three questions posed yields three advantages:
(a) the classification relies on local representations of climatic change, which are prerequisites for the construction of regional and global patterns of climate signals.
(b) the current application of mathematical decomposition techniques, such as empirical orthogonal functions (EOFs), to the world-wide reconstruction of a 1000-year temperature history is strongly limited by both the inhomogeneous spatio-temporal sampling gaps in proxy records (e.g., Evans et al. 2002; Schneider 2001) and the very short length of surface thermometer record available for calibration-verification purposes (discussed further in sections 5.1 and 5.4). The classification of proxies in this study is complementary to the mathematical decomposition processes but avoids some of their difficulties (albeit at the expense of quantitative results).
(c) the different sensitivities of proxies to climate variables and the time-dependence of the

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to the lengths of the individual tree-ring series. Such a general problem in the development of millenia-long tree-ring chronology has been labeled the 'segment length curse' by Cook et al. (1995).

proxy-climate correlation (e.g., Briffa et al. 1998; Shabalova and Weber 1998; Schmutz et al. 2000; Aykroyd et al. 2001) require careful calibration and verification on a location by location basis; the classification's emphasis on local results avoids the difficulty of intercomparing disparate proxies. In other words, we are avoiding the over-emphasis on quantitative synthesis while keeping in mind that even for the same location, different proxies may yield different climate expressions simply because of their different sensitivities to local climatic variables (e.g., Fritz et al. 2000; Betancourt et al. 2002).

The combination of these three advantages suggests that a compact mathematical representation of individual proxy variations, without full understanding of proxy-climate calibration relations, may yield overconfident results. For example, Ambaum et al. (2001) and Dommenget and Latif (2002) studied the physical nature of the North Atlantic Oscillation (NAO) air pressure pattern derived from local one-point correlation analysis, in contrast to the pattern derived from an EOF analysis. A direct association to local centers of action in the Euro-Atlantic region, which establishes the phenomenon of NAO, could not be found in the EOF representation. Dommenget and Latif (2002) showed more examples of mismatches in the dominant modes of variability deduced from EOF and one-point correlation analyses over the tropical Atlantic and tropical Indian Ocean (see the illuminating synthetic example shown in that paper). Tomita et al. (2001) cautioned that the family of EOF analyses may artificially over-emphasize standing or propagating features over a region with large variance. They specifically pointed out that EOF analysis tends "to extract a widespread variability over the tropics $\cdots$ and may fail to identify smaller but equally significant signals of DSV [Decadal Scale Variability] in coastal regions and/or the extratropical oceanic frontal zones." In other words, EOFs may be convenient measures for characterizing (and then deducing information for data-poor regions back to 1000 A.D., e.g., Mann et al. 1998, 1999, 2000a) dominant spatial-temporal components of climate variability, but they do not guarantee physical meaning and, hence, physical reality.

Our study has the disadvantage of being non-quantitative and very 'low-tech'. Thus, our assessment falls short of Lamb's (1965) original call for quantitative answers. In addition, by enforcing our simple rule of employing a local or regional perspective, we avoid difficult questions about the spatio-temporal coupling of observed changes over various regions, as well as questions about specific large-scale patterns that may be responsible for those climatic anomalies (see e.g., a particular framework/viewpoint, with the emphasis on the primary role of the "Mobile Polar Highs" which "organize migratory units of circulation in the troposphere low levels" in Leroux 1993 and further insights on the role played by stratospheric polar vortex in D. Thompson et al. 2002). An early effort to study the interlinkage of widely separated proxies, for example, between marine sediments at Palmer Deep, Antarctica and atmospheric signals in Greenland ice cores, was reported by Domack and Mayewski (1999). However, many chronologies produced by radiocarbon dating have an accuracy that is too limited to allow for a reliable discussion on the timing of events from different areas (see Stine 1998; Domack and Mayewski 1999; Khim et al. 2002). The difficult effort of areal weighting of different proxy records was attempted, for example, for the Arctic region by Overpeck et al. (1997), the Northern Hemisphere extratropics by Esper et al. (2002a), and both the Northern Hemisphere and global domains by Mann et al. (1998, 1999, 2000a). However, Briffa et al. (2001) criticized the lack of discussion of uncertainties in most (except in Mann et al. and Esper et al.) of these reconstruction efforts. For example, the composite series in the Overpeck et al. (1997) reconstruction is not even calibrated directly to instrumental data.

Our different approach to climate proxies may help to clarify the existing confusion concerning the non-local EOF-based reconstruction of global temperature by Mann et al., which often seems to differ from many local temperature proxy indicators (e.g., Bradley et al. 2000; but see also the reply to that commentary by Barnett and Jones 2000). We differ from Bradley et al.'s (2000) conclusion in that we believe that the spatial and temporal sampling of the available proxy network is not adequate for a robust capturing of the spatial pattern of changes on timescales greater than several decades (see discussion in section 5.1).

4. Results

Table 1 lists the world-wide proxy climate records we have collected and studied. In order to reduce the number of entries, the list is restricted to records that contain either direct information about the three specific questions posed earlier or that provide a continuous time series for at least 400-500 years. In addition, information was excluded from research in progress (e.g., the record of sea surface conditions around the Santa Barbara Basin with 25-year data resolution by J. Kennett, private communication 2001), as well as early results that may need other independent reexamination (e.g., Pisias's [1978] analysis of marine microfossils, *Radiolaria*, from varve sediments of the Santa Barbara basin). For the majority of cases, we strictly followed the individual researchers' statement about their paleoclimatic reconstruction efforts; but a few cases exist where our own judgements were imposed, based on requirements of consistency.

Table 1 and Figures 1-3 summarize the answers to the three questions we posed. For questions 1 and 2, we find the answer to be 'Yes' when the proxy record shows a period of 50 years or longer of cooling, dryness or wetness during the Little Ice Age and a period of 50 years or longer of warming, wetness or dryness during the Medieval Warm Period. A dash indicates that either the expert opinion or its logical extension is inconclusive, provides no information, or does not cover the period in question. A 'Yes?' or 'No?' answer means that the original expert opinion made a claim that does not match our criteria. For example, the interval of warmth during the Medieval Warm Period may be too short by our definition to be a 'Yes' and so we provide a 'Yes?' Finally, in several cases in the 20th century, a 'Yes*' designation was assigned for the answer to question 3 when the 20th century warming in the proxy records first occurred early in the century (ca. 1920-1950), when the air's anthropogenic CO_2 content was still cumulatively small. Our choice for the lower limit of 50 years for the recognition of a climatic anomaly is not entirely arbitrary as it grossly represents the longer periods unresolved by Mann et al.'s (1998, 1999, 2000a) multiregression analyses.

Our figures show the results of Table 1 for the Little Ice Age (Figure 1), Medieval Warm Period (Figure 2) and the nature of 20th-century's change (Figure 3). These figures graphically emphasize the general lack of climatic information extending back to the Medieval Warm Period for at least seven geographical zones: the Australian and Indian continents, South East Asian archipelago, large parts of Eastern Europe/Russia, the Middle Eastern deserts, the tropical African and South American lowlands (although the large number of available borehole-heat flow measurements in Australia seems adequate for the reconstruction of ground temperatures back to Medieval times; e.g., Huang et al. 2000). Therefore, our conclusions are provisional.

Figure 1 indicates the Little Ice Age exists as a distinguishable climatic anomaly in all regions of the world that have been assessed. Only two records –tree-ring growth from western Tasmania and isotopic measurements from ice cores at Siple Dome, Antarctica– do not exhibit any persistent or unusual climatic change over this period (although the western Tasmanian reconstruction contains an exceptionally cold decade centered around 1900 A.D.; Cook et al. 2000).[6]

Figure 2 shows the Medieval Warm Period with only two unambiguous negative results. The Himalayan ice core result of Thompson et al. (2000) seems unambiguous, but the tree-ring proxy data from Lenca, Southern Chile (Lara and Villalba 1993) is countered by nearby evidence of the Medieval Warm Period (Villalba 1990; Villalba 1994).

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[6] Cook et al. (2000) attempted to show that the warm-season climate retrieved from their Mount Read-Lake Johnston Huon pine tree-ring data is associated with the inter-decadal (>10-year) component of sea surface temperature in the southern Indian Ocean and southwestern sector of the Pacific ocean. However, it may not be appropriate to calibrate ring-growth occurring in the heavy rainfall region of the Western Tasmanian climatic zone by using the three meteorological stations—Hobart, Launceston, and Low Head Lighthouse—that are situated in the warmer and drier Eastern Tasmanian climatic zone (see also Cook et al. 1991, as communicated by John L. Daly of Tasmania).

Figure 3 shows that most of the proxy records do not suggest the 20th century to be the warmest or the most extreme in its local representations, which seems surprising until one realizes the more limited and contrary view was drawn primarily from familiar instrumental thermometer records that yield no information on centennial-scale climate variability. There are only three unambiguous findings favoring the 20th century as the warmest of the last 1000 years—the records from the Dyer Plateau, Antarctica, the Himalayas and Mongolia (Thompson et al. 1994; Thompson et al. 2000; D'Arrigo et al 2001). An important feature of Figure 3 is the large number of uncertain answers compared to the two prior questions. This feature is not easily explained, but it could be related to inaccurate calibration between proxy and instrumental data. Another interesting feature of the result is that the warmest or most extreme climatic anomalies in the proxy indicators often occurred in the early-to-mid 20th century, rather than throughout the century.

4.1. Glaciers—Worldwide

Broadly, glaciers retreated all over the world during the Medieval Warm Period, with a notable but minor re-advance between 1050 and 1150 A.D. (Grove and Switsur 1994). Large portions of the world's glaciers, both in the Northern and Southern Hemispheres, advanced during the 1300-1900 A.D. period (Grove 2001b; see also Winkler 2000). The world's small glaciers and tropical glaciers have simultaneously retreated since the 19th century, but some glaciers have advanced (Kaser 1999; Dyurgerov and Meier 2000; D. Evans 2000). Kaser (1999) has reemphasized the key role played by atmospheric humidity in controlling the net accumulation and ablation of glaciers by modulating the sublimation and long-wave radiative forcing-feedback budgets in both dry and humid areas. So far, the proposition of 20th century warming being a natural recovery from the Little Ice Age, together with a possible amplification by anthropogenic CO_2, is plausible but not definitive (e.g., Bradley and Jones 1993; Kreutz et al. 1997; Kaser 1999; Beltrami et al. 2000; Dyurgerov and Meier 2000). By contrast, D. Evans (2000) discussed the possibility of recent widespread recession of glaciers as a glacioclimatic response to the termination of the Little Ice Age and commented that significant warming phases, especially those accompanied by relatively warm winters and cool summers, during interglacials may lead to the onset of another global glaciation.

Additional proxy records used here reveal that the climatic anomaly patterns known as the Medieval Warm Period (circa 800-1300 A.D.) and the Little Ice Age (1300-1900 A.D.) occurred across the world. The next two subsections describe detailed local changes over both the Northern and Southern Hemispheres.

4.2. Northern Hemisphere

A composite reconstruction of summer temperature (assuming a simple, uniform weighting of proxy records; see additional discussion in section 5.3) by Bradley and Jones (1993) showed that the 1530-1730 interval was the coldest period for the whole Northern Hemisphere and that the 19th century was the second coldest interval in the last 500 years.

4.2.1. Western Europe

Cold winters and wet summers prevailed during the Little Ice Age in Switzerland, where the most detailed and reliable information is available (Pfister 1995). A careful comparison of the Swiss and Central England (from Manley 1974) temperature records from 1659-1960 A.D. shows a general correspondence of climatic conditions between the two regions. In the Andalusia region of Southern Spain, rainfall appears to have alternated between wet and dry century-long spells (wet periods 1590-1649 and 1776-1937 A.D.; dry periods 1501-1589 and 1650-1775 A.D.) throughout the Little Ice Age, with no significant difference from the modern dry period of 1938-1997 (Rodrigo et al. 2000). Enhanced fluvial activity was documented in river basins of north, west and central Europe between 1250 and 1550 A.D. and again between 1750 and 1900 A.D. (A. T. Grove 2001). Over western Europe, Pfister et al. (1998) concluded that severe winters were less frequent and less extreme during 900-1300 A.D. than during 1300-1900 A.D. The mild-winter condition was hypothesized by Pfister et al. (1998) to have caused the northward migration of Mediterranean subtropical plants described by St. Albertus Magnus, who noted the abundance of pomegranates and fig trees in the 13th century around Cologne and parts of the Rhine valley. Olive trees, which, like fig trees, are also sensitive to prolonged periods of freezing, must have grown in Italy (Po valley), France and Germany, because a chronicler documented the damage to olive trees from the bitter frost in January 1234 A.D. Also, Lamb (1965) noted generally wet winters but drier summers for the lowlands in England, Ireland, Netherlands, Denmark, Sweden and northwest Germany from about 1200 to 1400 A.D. Those conditions are supported by documentary records that describe frequent flooding and storms around those regions during this transitional period between the Medieval Warm Period and Little Ice Age.

Was the warmth of the 1980s in western Europe exceptional or unusual? Lamb (1997a, page 386) observed that "even the great warmth of the years 1989/1991, hailed in some quarters as proof of the reality of the predicted global warming due to the enhancement of the greenhouse effect by increasing carbon dioxide and other effluents, requires the usual adjustments [i.e., from the expectation based solely on global warming model predictions]. ··· it may also have a surprising analogy in the past to the remarkable warmth —well attested in Europe— of the year 1540, shortly before the sharpest onset of the so-called Little Ice Age. Pfister records that for several decades before 1564 the climate in Switzerland — and this seems to be in line with the implications of other European chronicles — was on average about 0.4°C warmer, and slightly drier than today. The summers in the 1530s were at least as warm as in the warmest ten years of the present century, between 1943 and 1952. And the year 1540 outdid the warm dry year 1947 appreciably. From February till mid-December rain fell in Basle on only ten days. And young people were still bathing in the Rhine on the Swiss-German border at Schaffhausen in the first week of January 1541 after a ten-months-long bathing season. The warm anomaly of 1540 is the more remarkable because the weather then became severely wintry, and spring came late in 1541. Moreover, only twenty-four years later the 1564-5 winter was one of the longest and severest in the whole millennium in most parts of Europe and marked the arrival of the most notable cold climate period of the Little Ice Age, with ten to twenty historic winters, very late springs and cool summers and advancing glaciers."

Updated weather reconstruction results for the Low Countries (the present-day Benelux region) suggest that a meaningful answer to the question of whether the 20th century has the warmest extremes may be quite elusive until the seasonal dependence and resolution of a proxy-climate relation can be affirmed. For example, van Engelen et al. (2001) demonstrated that when the historical reconstructed proxy series from about 800-2000 A.D. was calibrated to instrumental temperature records at De Bilt, 20th century winter temperatures may have been slightly higher[7] than the high winter temperatures of 1000-1100 A.D.; but the 20th century summer temperatures are neither unusual nor extra-ordinarily warm when compared to natural summer temperature variabilities during other times of the second millennium (see Figures 1 and 2 of van Engelen et al. 2001).

4.2.2. North Atlantic and other oceans

During the Little Ice Age, extensive areas around Mediterranean Europe and the North Atlantic, including western and northern Europe, Greenland and Iceland, experienced unusually cold and wet conditions, as well as many extreme weather events, including deluges, landslides and avalanches (Grove 1996; Ogilvie et al. 2000; A. T. Grove 2001). From various proxies, the climate over Iceland was mild from 870 to 1170 A.D., with cold

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[7] About 0.5°C—but such warming was also clearly initiated earlier in the 19th century and the quantitative information of the 20th century warmth is certainly within the margin of uncertainty of this careful reconstruction effort.

periods setting in after 1200 A.D. Instead of being a period of unrelenting cold, however, Ogilvie (1984) emphasized that the most notable aspect of climate over Iceland during the 17th to 19th centuries, with its very cold decades during the 1690s, 1780s, 1810s and 1830s, was its large year-to-year variability (see also Ogilvie and Jónsson 2001). The colonization of Greenland's coastal area by the Vikings starting in 986 A.D. is well documented; and the generally mild and benign climatic conditions from about 800-1200 A.D. that helped to sustain the settlement are also well supported by ice core and borehole proxy information (Dansgaard et al. 1975; Dahl-Jensen et al. 1998). The Norsemen's 'Western Settlement' (around the Godthab district) was mysteriously abandoned sometime between 1341 and 1362 A.D., while the 'Eastern Settlement' (actually near the southernmost tip of west Greenland, around the Narssaq and Julianehab districts) died out between 1450 and 1500 A.D. (Grove 1996; Ogilvie et al. 2000).[8] The timing of the abandonment of the settlements coincided with a general cooling over Greenland, as established by both ice-core isotopic and borehole thermometry (Dansgaard et al. 1975; Stuiver et al. 1995; Dahl-Jensen et al. 1998). From sediment cores near Nansen Fjord, East Greenland, Jennings and Weiner (1996) confirmed an initial cooling between 1270 and 1370 A.D., together with the most severe and variable climatic conditions around the East Greenland region from 1630-1900 A.D. The results of Ogilvie et al. (2000) and Ogilvie and Jónsson (2001) suggest that the overall climatic conditions in the North Atlantic (50-80°N; 0-60°W), especially near Iceland during the 20th century, including the 1970s-1990s, were neither unusual nor extreme.

In the Mediterranean basin, the island of Crete experienced many severe winters and prolonged droughts during the winter and spring seasons between 1548 and 1648 A.D. (Grove and Conterio 1995). In Morocco, the climate during the 16th, 17th and 18th centuries was generally more variable, with frequently drier conditions, than in the early to mid-20th century (Till and Guiot 1990). But no distinctive precipitation anomaly was observed for Morocco during the Medieval Warm Period, although just like conditions during the Little Ice Age, an episode of notable drought occurred from 1186-1234 A.D. Thus, precipitation anomalies for the Little Ice Age and Medieval Warm Period are not distinct from each other. For this reason, we designated the occurrence of a distinct climatic anomaly associated with the Medieval Warm Period for Morocco in Figure 2 as uncertain or 'Yes?'.

Distinctly cooler conditions prevailed over the oceans — in the Carribean Sea by about 2-3°C (Winter et al. 2000) and in the Sargasso Sea by about 1°C (Keigwin 1996), especially during the 17th and 18th centuries relative to the present. Likewise, deMenocal

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[8] Barlow et al. (1997) emphasized that both cultural and political factors combined to make the Norse Greenlanders at the 'Western Settlement' more vulnerable to the harsh climatic conditions.

et al. (2000) found that the subtropical North Atlantic's sea surface temperature off Cap Blanc of Mauritania also was cooler by 3-4°C between 1300-1850 A.D. than at present. Similarly, during the Medieval Warm Period, the Sargasso sea surface temperature was about 1°C warmer than it is currently, while the sea surface temperature off the coast of Mauritania (west Africa) was only marginally warmer than at present. Based on Mg/Ca paleothermometry of the calcitic shells of microfossils, Cronin et al. (2003) found large (about 2 to 4°C warming or cooling) and rapid (< 100 years) shifts of spring water temperature of the Chesapeake Bay at 2100, 1600, 950 (1050 A.D.), 650 (1350 A.D.), 400 (1600 A.D.) and 150 (1850 A.D.) years before present. This Chesapeake Bay proxy temperature record of Cronin et al. (2003) recognizes five distinct climatic periods: the 20th century warm period,[9] the early Medieval Warm Period (from 450-900 A.D.), the conventional Medieval Warm Period (from 1000-1300 A.D), the early Little Ice Age (from 1450-1530 A.D.) and the late Little Ice Age (1720-1850 A.D.). High-resolution coral skeletal δ^{18}O and Sr/Ca ratio records from Bermuda indicated sea-surface temperature standard deviations of about ±0.5°C on interannual and ±0.3°C on decadal timescales during the 16th century, the ranges of variability are comparable to estimates from modern 20th century instrumental data (Kuhnert et al. 2002). However, these sub-annual resolution coral proxy data also show that although there may be large-scale climate signals like the North Atlantic Oscillation detectable at Bermuda, no correlation can be found with other Northern-Hemispheric-wide proxy reconstructions (i.e., in Kuhnert et al.'s case, they compared with Mann et al. 1998's temperature series) because of large spatial differences in climate variability. From sedimentary concentrations of titanium and iron, Haug et al. (2001) inferred a very dry climate for the Cariaco Basin during the Little Ice Age and relatively wetter conditions during the Medieval Warm Period.

Over the equatorial Central Pacific, around the NINO3.4 (5N-5°S; 160°E-150°W) region, Evans et al. (2000), in their skillful reconstruction of the ENSO-like decadal variability of the NINO3.4 sea surface temperature (SST), found an apparent sustained cool phase of the proxy NINO3.4 SST variability from about 1550 A.D. to approximately 1895 A.D., thereby extending the geographical area covered by the Little Ice Age Climate Anomaly. Evans et al. (2000) also added that the reconstructed NINO3.4 decadal-scale SST variability prior to the 17th century is similar to that of the 20th century, thus

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[9] Although Cronin et al. (2003) suggested that "recent decadal climate variability in the North Atlantic [with similar suggestion for their Chesapeake Bay record] region is extreme relative to long-term patterns may be in part anthropogenic in origin", we noted that these authors admitted to the possible bias from greater sampling resolution in the last two centuries and "rapid regional warming ~ 1800 AD [at Chesapeake Bay] was accompanied by accelerated sea level rise at the end of the Little Ice Age, about 1750-1850 AD, thus preceding large-scale fossil fuel burning". Thus we assigned 'Yes?' as answer to Question 3 in Table 1.

suggesting that recent 20th century Pacific ocean decadal changes are neither unusual nor unprecedented.

From the analysis of δ^{18}O (for proxy of sea surface salinity) and Mg/Ca (for proxy of sea surface temperature) compositions of planktonic foraminefera *Globigerinoides ruber*[10] from cores retrieved from deep ocean near the eastern edge of the Indonesian archipelago, Stott (2002) and Stott et al. (2002) confirms that sea surface temperature and salinity around this area of Western Pacific Warm Pool were significantly anomalous around the Medieval Warm Period and the Little Ice Age. During the peak of the Medieval Warm Period from about 900 to 1100 AD, the sea surface temperatures were estimated to reach as high as 30°C, although Stott (2002) emphasizes that the primary signal of the climatic fingerprint in this deep sea core is manifested through the sea surface salinity rather than sea surface temperature. Stott (2002) further suggests that the warm and more saline sea surface condition during the Medieval Warm Period and the cooler and less saline sea surface condition during the Little Ice Age are not unique throughout the Holocene but instead represent a pattern of millennial climate variability in the Western Pacific Warm Pool region.

4.2.3. Asia and Eastern Europe

From 49 radiocarbon-dated subfossil wood samples, Hiller et al. (2001) determined that the alpine tree-limit on the Khibiny low mountains of the Kola Peninsula was located at least 100-140 meters above the current tree-limit elevation during the relatively warmer time between 1000 A.D. and 1300 A.D. The summer temperatures corresponding to the tree-line shift during this warm time are estimated to have been at least 0.8°C warmer than today. Based mostly on documentary evidence, Borisenkov (1995) noted that Little Ice Age conditions began as early as the 13th century in Russia, with the characteristic of frequent climate extremes both in terms of severe winters, rainy and cool summers, and sustained droughts (up to a decade long). Middle Russia (around 50-60°N and 30-50°E) seems to have experienced its coolest winters around 1620-1680 A.D., its coolest summers and springs around 1860-1900 A.D., and distinctively warm conditions during the first half of the 16th century, similar to conditions for western Europe described above. In addition, ground surface temperature histories deduced from boreholes around the Czech republic suggest

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[10] This surface-dwelling species is abundant under warm summer surface waters of the Western tropical Pacific while the species *Globigerinoides sacculifer* is noted by Stott et al. (2002) to be present in smaller amount because it cannot form shells at temperature higher than 27°C—thus was analyzed to deduce sea surface temperatures during the cooler winter months for the Warm Pool region.

that winters during 1600-1700 A.D. were the most severe since at least 1100 A.D. (Bodri and Čermák 1999). The temperature-depth borehole records also yield a clear signature of an anomalously warm period for central Bohemia, especially around 1100-1300 A.D.

Yadav and Singh (2002) note that climate over the Himalaya region tends to vary greatly over short distances because of forcing by topography. However, temperature variations may have a better spatial coherence when compared to precipitation changes over these high-elevation areas. Based on a network of twelve tree-ring width chronologies from the western Himalaya region of India, Yadav and Singh (2002) found that the warmest spring temperatures of the 20th century around 1945-1974 A.D. were not the warmest of the last four centuries in their tree-ring proxy temperature record, nor was the character of 20th century warming found to be unusual. Esper et al. (2002b), in a study based on more than 200,000 ring-width measurements from 384 trees over 20 individual sites extending over the Northwest Karakorum of Pakistan and the Southern Tien Shan of Kirghizia, compiled a 1300-year long record of proxy temperature data that resolved decadal-scale variations. This record shows that the warmest decades since 618 A.D. in Western Central Asia occurred between 800 and 1000 A.D., while the coldest periods occurred between 1500 and 1700 A.D.

In China, Bradley and Jones (1993) found that the mid-17th century was the coldest period of the last millenium. New China-wide composite temperature averages recompiled by Yang et al. (2002) confirm this fact about the coolest period during the Little Ice Age in China. Yang et al.'s (2002) records further suggest the warm period in China from 800-1400 A.D., which roughly corresponds to the Medieval Warm Period defined in this paper. Yang et al. (2002) also note that large regional temperature variations are found for the warm period in China—in Eastern China and in the northeastern Tibetan Plateau, the warm conditions prevailed from 800-1100 A.D., while in Southern Tibetan Plateau, the warmest period occurred in 1150-1380 A.D. In contrast, Yang et al. (2002) found that the cool conditions during the Little Ice Age are more homogeneous and consistent among various climate proxies. Although not an emphasis in their work, Yang et al. (2002) further noted, from their "weighted" reconstruction curve, that the warmest period in China of the last two millenia occurred in 100-240 A.D. surpassing even the warming of the 20th century.

In northeastern China, frequent occurrences of extremely dry conditions prevailed during the 16th and 17th centuries (Song 2000). The dry conditions returned again in the 20th century and now cover a wider area (with indications of an increasing number of days with no discharge from the Yellow River; but these 20th century events are likely to be confused with other man-made factors). Based on a combination of subdecadal (< 10 years) and longer-term (> 50 years) isotopic records from stalagmites retrieved from Buddha Cave

(80 km south of Xian, central China), Paulsen et al. (2003) showed that although there were general cool and warm period during the Little Ice Age interval and Medieval Warm Period, respectively, the patterns of precipitation around the area were considerably more variable. For example, the region around Buddha Cave were generally dry from ca. 1640-1825 AD but the interval 1475-1640 AD were a relatively wetter period. Based on a homogeneous set of typhoon records from 1470-1931 A.D., Chan and Shi (2000) documented the notably larger number of land-falling typhoons over Guandong Province in the early-to-mid 19th century. Using a δ^{18}O proxy record from peat cellulose with 20-year resolution and various Chinese historical records, Hong et al. (2000) showed the general cooling trend in surface air temperature during the Little Ice Age interval in northeastern China. Hong et al. found three of the coolest minima in the record centered around 1550, 1650 and 1750 A.D. An obvious warm period peaked around 1100 to 1200 A.D., coinciding with the Medieval Warm Period. The study of documented cultivation of *Citrus reticulata Blanco* (a citrus tree) and *Boehmeria nivea* (a perennial herb), both subtropical and temperature-sensitive plants, during the last 1300 years showed that northern boundaries for these plants had shifted and expanded; their northernmost location was reached around 1264 A.D. (Zhang 1994). Zhang then deduced that temperature conditions in the 13th century around central China must have been about 1°C warmer than at present. Ren (1998) found further evidence from a fossil pollen record at Maili Bog, northeast China, that summer monsoon rainfall from 950-1270 A.D. must have been generally more vigorous in order to explain the high deposition of several pollen taxa, which are (otherwise) unexplainable by human activity at those times.

Based on less precise climate proxies like cherry-blossom-viewing dates, lake freezing dates and historical documentation of climate hazards and unusual weather, Tagami (1993, 1996) found that a warm period prevailed between the 10th and 14th centuries, and a cold period between the late 15th and 19th centuries, over large parts of southern Japan. From a study of the number of days with snowfall relative to days with rainfall, Tagami (1996) concluded that the 11th and 12th centuries were unusually warm. During the Little Ice Age, Japanese summers were relatively cool from the 1730s to 1750s, in the 1780s, from the 1830s to 1840s, and in the 1860s, while winters were cold from the 1680s to 1690s and in the 1730s and 1810s. From the tree-cellulose δ^{13}C record of a giant Japanese cedar (*Cryptomeria japonica*) grown on Yakushima Island of southern Japan, Kitagawa and Matsumoto (1995) inferred a temperature of 2°C below average from A.D. 1600 to 1700 and a warm period of about 1°C above average between A.D. 800 and 1200.

4.2.4. North America

Overall, the composite summer temperature anomaly of Bradley and Jones (1993) shows that, over North America, mean temperature of the 15th-17th centuries was 1°C cooler than the average of the reference period 1860-1959.

Over the southern Sierra Nevada, California, Graumlich (1993) found that the coolest 50-year interval in her 1000-year tree-ring proxy record occurred around 1595-1644 A.D., while the wettest 50-year period was 1712-1761 A.D. Those occurrences are consistent with our definition of a discernible climatic anomaly associated with the Little Ice Age interval of 1300-1900 A.D. Ely et al. (1993) noted from river records in Arizona and Utah that the most extreme flooding events occurred during transitions from cool to warm climate conditions, especially during the late 1800s to early 1900s. For the Central U.S.A. (33-49°N and 91-109°W), drought episodes were noted for the 13th-16th centuries (from data compiled by Woodhouse and Overpeck 1998). These droughts were of longer duration and greater spatial extent than the 1930s-1950s drought (i.e., the 'Dust Bowl' drought). Additionally, both Yu and Ito (1999) and Dean and Schwalb (2000) identified cycles of aridity lasting about 400 years from lake records of the Northern Great Plains, where the last dry condition peaked around 1550-1700 A.D. Based on the tree ring proxy of hydroclimatic conditions in Southern Manitoba, George and Nielsen (2002) found that the Red River basin had experienced extremely dry conditions between 1670 and 1775 AD. These authors also concluded that the multidecades-scale change of the hydroclimate across the northeastern Great Plains during the last 600 years had been remarkably coherent upon comparing their tree-ring results with the limnological records from North Dakota and Minnesota.

From an extensive collection of multiproxy evidence, Stine (1998) concluded that during the Medieval Warm Period prolonged intervals of extreme drought affected California, the northwestern Great Basin, and the northern Rocky Mountains/Great Plains, while markedly wetter regimes persisted over the Upper Midwest/sub-arctic Canada and Southern Alaska/British Columbia regions. There was also a significant but brief interval around 1110-1140 A.D. when moisture conditions changed from dry to wet in California, the northwestern Great Basin, the northern Rocky Mountains/Great Plains, and from wet to dry in the Upper Midwest/sub-arctic Canada and Southern Alaska/British Columbia. The most likely explanation for this rapid and dramatic switch from wet to dry conditions around the Upper Midwestern U.S. around 1100 A.D. is the contraction and subsequent expansion of the circumpolar vortex. Summer polar fronts shifted significantly southward, stopping the penetration of moisture-laden air from the Gulf of Mexico (based on early ideas of Bryson et al. 1965). Stine (1998) added the requirement of a concomitant jet-stream change, from zonal to azonal, in order to explain the distinct observed differences of the moisture patterns between the Upper Midwest and Southern Alaska/British Columbia. Graumlich's (1993) reconstruction of summer temperature and winter precipitation from trees in the Sierra Nevada confirmed the overall warm and dry conditions for California during Medieval times, when two of the warmest and driest 50-year intervals occurred — at 1118-1167, 1245-1294 A.D. and 1250-1299, 1315-1364 A.D., respectively.

Hu et al. (2001), based on their high-resolution (multidecadal) geochemical analysis of sediments from Farewell Lake by the northwestern foothills of the Alaska Range, also found pronounced signatures of the Medieval Warm Period around 850-1200 A.D. During the Little Ice Age, the surface water temperature of Farewell Lake fell to a low in 1700 A.D. that was estimated to be about 1.75°C cooler than at present. They also noted that colder periods were in general wetter (in contrast to drier conditions during the Little Ice Age in the Central United States region described above) than the warm periods in this part of Northwest Alaska. On the Yucatan Peninsula, prolonged drought episodes recur approximately every 200 years, with the two most significant recent peaks centered around 800 and 1020 A.D. (Hodell et al. 2001). Timings of these severe droughts also seem to fit several known discontinuities in the evolution of the Mayan culture.

4.3. Southern Hemisphere

Figures 1, 2 and 3 highlight the scarceness of Southern Hemisphere coverage by proxy climatic information through the second millennium A.D.

4.3.1. New Zealand

In New Zealand, the δ^{18}O concentration in a stalagmite record from a cave in northwest Nelson shows the coldest times during the Little Ice Age to be around 1600-1700 A.D., while exceptionally warm temperatures occurred around 1200-1400 A.D., in association with the general phenomenology of the Medieval Warm Period (Wilson et al. 1979). The cooling anomaly around 1600-1700 A.D., apparent in the δ^{18}O stalagmite record, coincides with the smallest growth rings (i.e., the coolest period) for silver pine (*Lagarostrobus colensoi*) from Mangawhero of North Island. However, at Ahaura, South Island, the smallest ring width index of the 600-year record occurred about 1500-1550 A.D. (D'Arrigo et al. 1998). Williams et al. (1999) issued important cautions concerning the interpretation of stable isotope data from New Zealand, especially the correctional functional relations among temperature, precipitation and δ^{18}O data (which are strongly influenced by oceans surrounding New Zealand) from Waitomo, North Island speleothems. The mean annual temperatures at Waitomo from 1430-1670 A.D. were deduced, based on the analysis of δ^{18}O data from Max's cave stalagmite, to be about 0.8°C cooler than at present.

4.3.2. South Africa

Tyson et al. (2000) showed, through isotopic measurements of a stalagmite, that the interior region of South Africa, near the Makapansgat Valley (eastern part of South Africa), had a maximum cooling of about 1°C around 1700 A.D compared to the present. This cooling corresponds well with the maximum cooling signal contained in a coral record from southwestern Madagascar (Tyson et al. 2000). Tyson and Lindesay (1992) demonstrated that the Little Ice Age in South Africa exhibited two major cooling phases, around 1300-1500 A.D. and 1675-1850 A.D., with a sudden warming interval occurring between 1500 and 1675 A.D. In addition, Tyson and Lindesay suggested a weakening of the tropical easterlies that increased the incidence of drought during the Little Ice Age in South Africa—with a relatively drier condition for the summer rainfall region in the northeast, but a wetter condition for the winter rainfall region near the coastal Mediterranean zone in the southwest. At Makapansgat Valley, the Medieval Warm Period peaked with a temperature about 3-4°C warmer than at present around 1200-1300 A.D. (Tyson et al. 2000). The multiproxy review by Tyson and Lindesay (1992) showed evidence for a wetter South Africa after 1000 A.D., when forest and wetland become more extensive, including the development of a riverine forest in the northern Namib desert along the Hoanib river during the 11th-13th centuries.

4.3.3. South America

Over southern South America's Patagonia, the Little Ice Age's climatic anomalies, as deduced from tree ring records, were manifest as cold and moist summers with the most notable, persistent century-long wet intervals centered around 1340 and 1610 A.D. (Villalba 1994). From a multiproxy study of lacustrine sediments at Lake Aculeo (about 34°S; 50 km southeast of Santiago, Chile), Jenny et al. (2002) found a period of greatly increased flood events centered around 1400-1600 A.D. (and in three other intervals: 200-400, 500-700 and 1850-1998 A.D.), which could be interpreted as increased winter rains from enhanced mid-latitude westerlies that usher in more frontal system activities. In contrast, during the Medieval Warm Period, the southern Patagonia region at latitudes between 47-51°S became abnormally dry for several centuries before 1130 A.D. when water levels in several lakes (Lake Argentino, Lake Cardiel and Lake Ghio) around the area dropped significantly. Also, trees like the southern beech, *Nothofagus sp.*, grew as old as 100 years in the basin of these lakes before being killed by reflooding of the lakes (Stine 1994).

Slightly north toward the Central region of Argentina (around the Córdoba Province), Carignano (1999), Cioccale (1999) and Iriondo (1999) noted the prevailing conditions for the advancement of the Andean glaciers during the Little Ice Age, with two distinct cold and dry intervals around the 15th to 16th, and the 18th to the early-19th centuries. The significant climate aridification and deterioration in central Argentina (in contrast to the more humid conditions and increased flood frequency in central Chile near Lake Aculeo) during the Little Ice Age interval is supported by the formation of large, parabolic sand dunes 150-200 meters long, 60-80 meters wide, and 2-3 meters high in the Salinas Grandes basin (Carignano 1999). Meanwhile, the Mar Chiquita Lake was transformed into a swamp surrounded by dunes in the 18th century. Today, Mar Chiquita is the largest lake in Argentina, covering a surface area of 6000 km^2 to a depth of 13 meters (Iriondo 1999). The climatic conditions during the Medieval Warm Period around Central Argentina were generally warmer and more humid than at other times in the second millennium A.D., when the dune fields were conquered by lakes and the Mar Chiquita Lake expanded beyond its present dimensions. Precipitation exceeded current levels, and the mean local temperature may have been about 2.5°C warmer, perhaps because of the southward shift of the tropical climate belt into this area (Iriondo 1999). The northern part of Córdoba Province was invaded by the eastern boundary of the Chaco Forest, which is located hundreds of kilometers to the northwest today (Carignano 1999). Cioccale (1999) further noted evidence for human cultivation of hillside areas in Central Andes, Peru, at places as high as 4300 meters above sea level around 1000 A.D.

4.3.4. Antarctica

The last important source of geographical information for conditions during the Medieval Warm Period and the Little Ice Age in the Southern Hemisphere is obtained from glaciers, ice cores and sea sediments on and around Antarctica. Although many notable physical, biological and environmental changes have recently occurred there, especially around the Antarctic Peninsula during the last 50 years (e.g., Mercer 1978; Thomas et al. 1979; Rott et al. 1996; Vaughan and Doake 1996; Smith et al. 1999; Doran et al. 2002; Marshall et al. 2002), most of the 20th century changes contained in the proxy records discussed here cannot be considered extreme or unusual (see Figure 3, also Vaughan and

Doake 1996; D. Evans 2000). For example, Vaughan and Doake (1996) deduced that a further warming of 10°C would be required to destabilize the Filchner-Ronne and Ross ice shelves that support the West Antarctic Ice Sheet. Under an even more extreme parametric study using a coupled thermo-mechanical ice sheet and climate model, Huybrechts and de Wolde (1999) concluded that their results do not support a catastrophic collapse or even strongly unstable behavior of the marine-based ice sheet on West Antarctica. Extended studies based on geological proxy evidence appear to support the very-long-term stability of the Antarctic Ice Sheets (e.g., Kennett and Hodell 1995; Sugden 1996).

For the Little Ice Age, advances of glaciers on South Georgia Island (which is half-covered by glaciers[11]) began after the late 13th century, with a peak advancement around the 18th-20th centuries (Clapperton et al. 1989). Glacier retreats occurred after about 1000 A.D., which corresponds to the timing for the Medieval Warm Period. Baroni and Orombelli (1994) noted a similar scenario for glacier advances and retreats during the Little Ice Age and Medieval Warm Period for the Edmonson Point glacier at the Terra Nova Bay area of Victoria Land on the Antarctic continent (East Antarctica). The Edmonson Point glacier retreated in two distinct phases, around 920-1020 A.D. and 1270-1400 A.D., and then advanced at least 150 meters after the 15th century. Isotopic thermometry from ice cores at Dome C (74.65°S; 124.17°E; elevation 3240 meters) and Law Dome (66.73°S; 112.83°E; elevation 1390 meters) both indicate cooler and warmer anomalies for the Little Ice Age and Medieval Warm Period, respectively (Benoist et al. 1982; Morgan 1985). High-resolution records of magnetic susceptibility from deep sea cores (Domack and Mayewski 1999; Domack et al. 2001) drilled near the Palmer Deep site (64.86°S; 64.21°W) off the Antarctic Peninsula also show a marked increased in bio-productivity and corresponding decrease in magnetic susceptibility because of dilution of the magnetite, with a peak centered around 1000-1100 years BP. This observation probably implies warm temperatures and minimal sea-ice conditions, coinciding with the Medieval Warm Period. In the same record, Domack and colleagues found a decrease in bio-productivity and a corresponding increase in magnetic susceptibility owing to less dilution of the magnetic minerals by biogenic materials, from about 700 to 100 years BP. This time period corresponds to the Little Ice Age of the 14th to 19th century and is likely to have been accompanied by cool and windy conditions. A similar interpretation of low magnetic susceptibilty and high bio-productivity and, high magnetic susceptibilty and low bio-productivity for the warmer and cooler climates during the Medieval Warm Period and Little Ice Age interval, respectively, by Khim et al. (2002) based on their analyses of the

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[11] Based on Clapperton et al. (1989) with updates from an October 8, 2002's email testimony of Mr. Gordon M. Liddle, Operations Manager, Government of South Georgia and the South Sandwich Islands.

deep sea core A9-EB2 (455 cm long) recovered from the Eastern Bransfield oceanic basin (61.98°S; 55.95°W). Abundance analyses of Na^+ sea salt in the ice core from Siple Dome (81.65°S; 148.81°W) also confirms the Little Ice Age anomaly characterized by substantial variability in the strength of meridional circulation between 1400 and 1900 A.D. (Kreutz et al. 1997).

However, there also are indications for significant regional differences in climatic anomalies associated with the two phenomena in Antarctica. The temperature at Siple Station (75.92°S; 84.25°W; elevation 1054 meters) was relatively warm from the 15th to early 19th century (although there were also noticeable decade-long cooling dips centered around 1525 A.D., 1600 A.D. and 1750 A.D.; see Figure 29.7 of Mosley-Thompson 1995). The 400-year isotopic temperature inferred from a core at Dalinger Dome (64.22°S; 57.68°W; elevation 1640 meters) on James Ross Island off the Antarctic Peninsula also showed 1750-1850 A.D. to be the warmest interval, followed by a cooling of about 2°C since 1850 and continuing to 1980 (Aristarain et al. 1990). A recent borehole temperature reconstruction from Taylor Dome, East Antarctica (77.8°S, 158.72°E, elevation 2374 meters) reported the same inverted temperature anomalies, during which the Little Ice Age interval was about 2°C warmer, while the coldest temperature of the past four thousand years was reached around 1000 A.D. (Clow and Waddington 1999; note that we omitted these discussions from Table 1 and Figures 1-3 since their results are only preliminary and presented in a conference abstract).

Stenni et al. (2002) found that the Little Ice Age did not appear in their new Talos Dome ice core results as a long-lasting cold period. They noted a more persistent cold period from 1680 to 1820 A.D. but emphasized the centennial scale of warmer and cooler spells punctuating the Talos Dome record. In terms of the 20th century warming noted in other proxy records from the Southern Hemisphere, Stenni et al. (2002) remarked that the Talos Dome record showed no clear signature and that the warming in their record occurs before 1930 and another warming pulse seems to begin just after 1970. Stenni et al. also concluded that, when comparing their Talos Dome results with three other East Antarctica isotope records, there is little temporal synchronicity for the strongest Little Ice Age cooling phase around East Antarctica because of the influence of the local geography. But even at a single location, different proxies may give different climatic expressions as a result of differences in either the proxies' spatial and temporal sensitivities or genuine microclimatic phenomena (see further discussion in Stenni et al. 2002 for East Antartica). From all proxy records assembled here, we note there is no simple way to classify the contrasting warm/cold climatic anomalies in terms of a convenient division between East and West Antarctica, as has been hinted in some previous studies. Thus, the climatic anomaly patterns of the Little Ice Age and Medieval Warm Period around Antarctica remain to be fully revealed.

5. Discussion

The widespread, but not truly global, geographical evidence assembled here argues for the reality of both the Little Ice Age and the Medieval Warm Period, and should serve as a useful validation target for any reconstruction of global climate history over the last 1000 years. Our results suggest a different interpretation of multiproxy climate data than argued by Mann et al. (1998, 1999, 2000a). Since calibration of proxy indicators to instrumental data is still a matter of open investigation, it is premature to select a year or decade as the warmest or coldest of the past millennium. However, we now present a scientific examination on the quality of the Mann et al. (1998, 1999, 2000a) reconstruction, focusing on its limitations, especially because[12] these results are prominently featured and promoted in the Third Assessment Report of the Intergovernmental Panel on Climate Change (Albritton et al. 2001).

5.1. An examination of Mann et al.'s analyses and results

Mann, Bradley and Hughes (1998, 1999) and Mann et al. (2000a) conducted one of the most ambitious attempts to reconstruct global temperature variability and its pattern over the past millennium. Based on many long proxy records and their match with five leading spatial-temporal EOFs from modern surface thermometer records, Mann and colleagues developed a quantitative temperature history of the Northern Hemisphere dating as far back as 1000 A.D.

That non-local view and representation of climate variability is also echoed by Bradley et al. (2000). But the mathematics of EOFs introduces a potential and significant bias, as mentioned above. More importantly the non-local view of climate change has limited application to interannual variability. Yet, even for interannual variation, careful studies like Lau and Nath (2001) have shown that changes in heat anomalies at an open, maritime site in the Central Pacific are more likely responses to local variations in wind dissipation, while balances of energetics in a coastal region like the Gulf of Alaska are more dependent on non-local atmospheric advection of temperature and heat anomalies. As the interaction timescale increases, crucial but currently unresolved questions on the thermal and dynamical constraints of local geography and the nature of air-sea coupling will become more important (see Häkkinen 2000; Seager et al. 2000; Marshall et al. 2001 for updated discussions on the nature of air-sea-ice coupling for generating interannual, decadal and

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[12] This rationalization was suggested and recommended by an anonymous referee.

multidecadal climate variability over the North Atlantic). Questions on the validity of the locality paradigm will come into sharper focus as climatic changes on timescales on the order of about 50-100 years are pursued.

Several facts regarding Mann et al.'s reconstruction methodologies and their limitations are germane to these issues. First, Mann et al. (1998) stated the most fundamental assumption in their multi-proxy reconstruction effort is that all spatial patterns of climate variation over the last 1000 years precisely follow the observed global pattern of change in near-surface air temperature of the last 80-90 years or so.[13] Second, Mann et al. (1998) emphasized that their results find little skill in reconstructing the first eigenvectors prior to 1400 A.D., because no data exist for useful resolution of hemispheric-scale variability. Third, although 12 additional proxies were added to allow Mann et al. (1999) to reconstruct back to 1000 A.D., as opposed to 1400 A.D. in Mann et al. (1998), the positive calibration/variance scores are carried *solely* by the first principal component (PC #1), which consists of high-elevation tree growth proxy records from Western North America (Mann et al. 1999). This fact has led Mann et al. (1999) to report that the spatial variance explained by the distribution of their proxy "networks" in the calibration and verification process is only 5%, and that it is the time component, not the spatial detail, that is "most meaningful" for their millennial reconstruction results. (It is then easy to see that Mann et al's 1000-year reconstructed 'Northern-Hemispheric mean temperature' is dominated by relative changes in the western North America time series—compare Figures 2a and 2b in Mann 2001b). Mann et al. (1999) also specifically emphasized that their calibration/verification procedure fails if they remove the one crucial Western North American composite tree ring series from the list of 12 proxies.

In light of these limitations, the retrodiction of hemispheric-scale temperature changes from 1400 A.D. to 1000 A.D. is not robust, and no scientifically confident statements can be made about global temperature changes for the last 1000 years. Nevertheless, Mann et al.'s (1998, 1999, 2000a) key conclusions are that:
(a) the 20th century is 'nominally the warmest' of the past millennium, valid at least over the Northern Hemisphere.
(b) the decade of the 1990s was the warmest decade and 1998 the warmest year of the last millennium at 'moderately high levels of confidence.'[14]

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[13] Mann (2002) subsequently cautioned that the "calibrated relation is determined from the 20th-century period, during which anthropogenic forcing played a prominent role. The approach could therefore yield a biased reconstruction of the past if the fundamental patterns of past temperature variation differ from those recorded in modern surface temperatures." (page 1481).

[14] This claim was made by Mann et al. (1999) without comment on the likely association of 1998's global

(c) the notion of the Little Ice Age as a globally synchronous cold period can be dismissed.
(d) the notion of the Medieval Warm Epoch, according to Lamb (1965), applies mainly to western Europe and was not a global phenomenon (see our perspectives in section 6).

In contrast to the first claim above are the earlier borehole-heatflow temperature results of Huang et al. (1997), who utilized more than 6000 heatflow-depth measurements distributed worldwide to deduce a composite ground temperature record over the last 20,000 years. Over the last 1000 years, Huang et al. found that the composite ground temperature 500-1000 years ago was warmer by 0.1-0.5°C than the present.[15] After the early warmth, the temperature cooled to a minimum of 0.2-0.7°C below today's level about 200 years ago. Unlike tree-ring proxy climate results, borehole temperature reconstructions lose high frequency climate information, thus making the direct calibration and comparison with surface thermometer results difficult (see, however, an inter-calibration attempt by Harris and Chapman 2001).

Post-Mann et al. (1998, 1999) tree-ring reconstruction (re)analyses, like Briffa (2000) and Esper et al. (2002a), have also clearly shown evidence for a Medieval Warm Period that is at least as warm as the 20th century, for at least up to 1990. This is why many authors, including Broecker (2001), cautioned against any definitive conclusion on the nature of true climatic change from proxy records or from EOF mathematical reconstructions.

Three existing criticisms of, and significant challenges to, the conclusions of Mann and colleagues by several other researchers are:
(1) The majority of the tree-ring records used by Mann et al. (1999) have been standardized (see footnote 5). That process removes nonclimatic tree growth factors; and as a result, most of the climate variability information on timescales longer than about thirty years is lost (see Briffa and Osborn 1999; Briffa et al. 2001 and our deduction of the upper limit below). Briffa and Osborn also emphasized the significance of the lack of good time-resolution paleo-records in contrast to Mann et al.'s claim of a large number of independent datasets

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warmth to the well-noted 1997/98 El Nino event in that paper.

[15] Our own private communications with SP. Huang and between M. MacCracken and H. N. Pollack, and in turn kindly shared with us by M. MacCraken on June 7, 2001, confirm that the warm feature during the Medieval Warm Period derived using this relatively "lower-quality" heatflow data, rather than direct borehole temperature profilings, is robust. In fact, H. N. Pollack carefully explained that "We do have a paper in *Geophysical Research Letters* (v. 24, n. 15, pp. 1947-1950, 1997) that uses lower-quality geothermal data (note carefully: this does not mean borehole temperature profiles!) from some 6000 sites, and this analysis does show a MWP when analyzed as a global dataset. When analyzed as separate high latitude (>45 degrees) and low latitude (<45 degrees), the amplitude is greater at high latitudes and smaller at low latitudes, but [the Medieval Warm Period feature is] still present."

that can be used for multi-proxy reconstruction.[16]
(2) Strong evidence has been accumulating that tree growth has been disturbed in many Northern Hemisphere regions in recent decades (Graybill and Idso 1993; Jacoby and D'Arrigo 1995; Briffa et al. 1998; Feng 1999; Barber et al. 2000; Jacoby et al. 2000; Knapp et al. 2001) so that after 1960-1970 or so, the usual, strong positive correlation between the tree ring width or tree ring maximum latewood density indices and summer temperatures have weakened (referred to as "anomalous reduction in growth performance" by Esper et al. 2002a). The calibration period of Mann et al. (1998, 1999, 2000a) ended at 1980, while 20 more years of climate data post-1980 (compared to the 80 years length of their calibration interval, 1902-1980) exist. If the failure of inter-calibration of instrumental and tree growth records over last two to three decades suggests evidence for anthropogenic influences (i.e., from CO_2, nitrogen fertilization or land-use and land-cover changes or through changes in the length of growing seasons and changes in water and nutrient utilization efficiencies and so on), then no reliable quantitative inter-calibration can connect the past to the future (Idso 1989). Briffa and Osborn (1999) have also criticized the impact of unusual tree growth on the calibration procedure of tree-ring climate proxies (see additional discussions in Jacoby and D'Arrigo 1995; Briffa et al. 1998; Barber et al. 2000; Briffa 2000; Jacoby et al. 2000). This matter has largely been unresolved, which means that global or Northern Hemisphere-averaged thermometer records of surface temperature cannot be simply attached to reconstructed temperature records of Mann et al, based mainly on tree-ring width, which cannot yet be reliably calibrated, to the latter half of the 20th century.
(3) Broecker (2001) tentatively concluded that the Medieval Warm Period was a global-scale event, although the hypothesized climate responses may be[17] anti-phased between the northern and southern high-latitude or polar regions. In terms of Broecker's hypothesis, the strength of the Atlantic ocean's thermohaline circulation oscillates naturally on a timescale of about 1500 years, based on the original findings of Bond et al. (1997, 1999) and its bipolar seasaw imprints on climate (see also the quote from Lamb [1982, 1997a] in section 2).

The 1902-1980 period of surface thermometer records adopted by Mann et al. (1999) as the calibration interval at best samples two to four *repeatable* or characteristic

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[16] But see updated attempts by Briffa et al. (2001) and Esper et al. (2002a) to retrieve longer timescale climatic information from tree-ring data that are fundamentally limited by actual segment lengths of individual tree-ring series, dead or living, concatenated to produce the composite tree-ring chronology. In Esper et al.'s case, the segment lengths of their individual tree-ring series are about 200 to 400 years.

[17] The tentativeness arises because we do not know the precise mechanism of change Broecker proposed: it can be either thermohaline circulation mediated type of change or tropical ocean-induced changes with large amplification and northern-southern hemisphere synchronization effects through the water vapor feedback.

"multi-decadal" (say, 20-to-30-year) events. Therefore, the base spatial pattern adopted by Mann et al. (1998, 1999, 2000a) does not account for any relevant climate changes that may recur over 40-year and longer, e.g., centennial timescales. There may be skill in resolving > 40-year changes for limited regions like the North Atlantic for as far back as 1700 A.D. (e.g., as studied in Baliunas et al. 1997; Delworth and Mann 2000; Cullen et al. 2001), but a similar conclusion cannot be reached for global-scale changes spanning the last millennium. A direct comparison of > 40-year temperature variability by Esper et al. (2002a) confirmed that Mann et al's Northern Hemispheric mean reconstruction has significantly underestimated the multidecadal and centennial scale changes[18] (see Figure 3 of Esper et al. 2002a). Another reason we do not accept the conclusions of the two most recent studies by Mann and colleagues in claiming that both GCM and proxy reconstructions have skill for the study of multidecadal climatic changes (see also contradictions of claims by Mann and colleagues in Collins et al. 2002) is the fact that various proxy-based reconstructions of the North Atlantic Oscillation (NAO) index back to 1675 demonstrated little verification skill, especially around the late 18th- to mid-19th-century as compared to NAO results based on available instrumental records (Schmutz et al. 2000). Evans et al. (2002) demonstrateded similar problems in inter-calibration skill when comparing various paleo-reconstructions of ENSO-mode variability over the 19th century; and, hence, they

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[18] There is an internal inconsistency in the claim by Mann and Hughes (2002) that the differences between their results (Mann et al. 1998, 1999, 2000) and Esper et al. (2002a) may be partly explained by the fact that "[h]alf of the surface area of the NH temperature record estimated by Mann et al. lies at latitudes below 30°N, where as the Esper et al. estimate is based entirely on latitude above 30°N." Figure 9 of Mann et al. (2000) clearly show that the reconstruction record of Mann et al. yields similar amplitude and time variability for both the NH-wide and NH extratropical (30-70°N) averaged temperatures. Huang and Pollack (2002), by comparing their borehole temperature results with the synthetic subsurface temperatures generated by both Mann et al. and Esper et al. reconstructions, argued that it would require "an extraordinary contrast between the tropics and the extra-tropical continents at the hemispheric scale to account for the subtantial difference between the negative transient predicted by the MBH [Mann et al.] reconstruction and the positive transients predicted by the ECS [Esper et al.] reconstruction and observed in boreholes." By further studying both the instrumental and reconstructed temperature dataset of Mann et al. (2000) [results of this independent checking are available from `wsoon@cfa.harvard.edu`], we find neither verification nor independent support for the claims by Mann (2002) and Mann et al. (2003) that "[n]early all of the proxy reconstructions are seen ... to be internally consistent (i.e., well within the uncertainties of the Mann et al. reconstruction). [sic.]" The argument by Mann and colleagues is that concensus to the wide variety of proxy results can be reached by "simply" re-scaling all proxy datasets according to their sensitivities to different: (1) spatial sampling patterns, (2) seasons and (3) latitude bands. By contrast, we suggest that the large differences in the results from different proxy reconstruction efforts (i.e., Esper et al. [2002] versus Mann et al. [1999] and Huang et al. [2000] versus Mann et al. [1999]) are real, owing to the differences in the long-term variance captured by the different proxies or internal biases of each proxy (with respect to their climatic information contents) or both.

cautioned about over-confidence in all proxy reconstructed versions of ground-truth.

Ogilvie and Jónsson (2001) have further noted that all current calibrations of proxies to large-scale instrumental measurements have been mainly valid over phases of rising temperature. The concern is that a different calibration response arises when the procedure is extended to an untested climate regime associated with a persistent cooling phase. Evans et al. (2002) worried about the reality of spurious frequency evolution that may contaminate a multiproxy reconstruction in which the type of proxy data changes over time and no sufficient overlap of proxy data exists for a proper inter-proxy calibration/validation procedure. In other words, each proxy may have its distinct frequency response function, which could confuse the interpretation of climate variability. Finally, another concern is the lack of understanding of the air-sea relationship at the multidecadal time scale, even in the reasonably well observed region of the North Atlantic (Häkkinen 2000; Seager et al. 2000; Marshall et al. 2001; Slonosky and Yiou 2001; JS. von Storch et al. 2001).

Taking all the physical criticisms and technical problems together, we conclude that the answers proposed for several key questions on climate behavior of the past millennium in Mann et al. (1998, 1999, 2000a) are uncertain because of the unverifiable assumptions implicit in the mathematical extrapolation of the observed pattern of climatic changes —valid in the sampling of the 20-30 year scale of variability at most— to the full historical changes of the last 1000 years.

The Mann et al. (1998, 1999, 2000a) large-scale proxy temperature reconstruction is not capable of resolving the three specific questions we pose in this paper about the local reality of the Little Ice Age, Medieval Warm Period and 20th century warming (e.g., the mismatches between the local sea-surface temperature reconstruction from Bermuda and Mann et al. Northern-hemispheric proxy temperature shown in Figure 7 and additional comparative studies discussed on page 167 of Kuhnert et al. 2002). We have found that although the Mann et al. (1998, 1999, 2000a) reconstructed temperature seems to be well-calibrated for the annual-mean Northern-hemisphere-wide (or globally averaged) instrumental temperatures, but we were not able to find any satifactory calibrations for seasonal averages and/or for smaller regional averages (see also footnote 18). Thus, the composite time series of Mann et al. cannot yet be considered a realistic constraint for both timing and amplitude for global- or hemisphere-scale climatic changes of the past millennium, as further applied by, for example, Crowley (2000) to deduce *causes* of those changes in proxy-based reconstructions.

Briffa (2000, page 87) concluded that dendroclimatological records in general support "the notion that the last 100 years have been unusually warm, at least within the context of the last two millennia, [h]owever, this evidence should not be considered [un]equivocal [NB:

our correction to Briffa's statement]." Later, Briffa et al. (2001), by adopting a new analysis procedure that seeks to preserve greater, long timescale variability (which shows a notable increase in variance at the 24-37 year time scale compared with a previous standardization procedure) in their tree ring density data than previously possible, stated that the 20th century is the globally warmest century of the last 600 years. This conclusion is consistent with the borehole reconstruction results of Huang et al. (2000). (Both Briffa et al. [2001] and Huang et al.'s [2000] new reconstruction did not extend back to 1000 A.D.) However, longer and more carefully-reconstructed tree-ring chronologies from Esper et al. (2002a) show that the Medieval Warm Period is indeed as warm as, or possibly even warmer than, the 20th century for at least a region covering the Northern Hemisphere extratropics from about 30°N to 70°N.

An important aspect of both the Briffa et al. (2001) and Esper et al. (2002a) studies is the new derivation of formal, time-dependent standard errors for their temperature reconstructions, amounting to about ± 0.1 to 0.3°C from 1000 through 1960 (see also Jones et al. 1999; Jones et al. 2001). This assignment of standard errors contrasts with those assigned in Mann et al.'s (1999) annually-resolved series, where the uncertainties were assigned only for pre-instrumental data points in their original publication (their assumption of 'error-free' instrumental thermometer data is incorrect—see Jones et al. 1999, Folland et al. 2001 and the discussion of systematic adjustments and issues of surface temperature measurements in section 5.4). Over the full second millennium, Esper et al. (2002a) deduced a slightly larger range in their confidence limits after 1950 (compared to the pre-1950 interval extending back to 800 A.D.) and attributed those higher uncertainties to the anomalous modern ring-growth problem.

The accumulation of wide-spread proxies and the need to augment results like those from EOFs require a systematic re-examination of the qualitative results from many climate proxy indicators. The conservative view about standard errors (Briffa et al. 2001; Esper et al. 2002a) is adopted as a guide for a lower bound of errors (i.e., an error as large as 0.6-1.0°C for a confidence level of three standard deviations) in our analysis. This approach is guided by Jones et al. (2001), who emphasize the poor quality of paleoclimatic information over the Southern Hemisphere and say "it is dangerous to place too much reliance on these curves [NB: referring to the multiproxy summer temperatures for the Southern Hemisphere], because the associated errors are likely greater than those for the NH [Northern Hemisphere]." In addition, we ignore all systematic errors.

5.2. On links between hemispheric-scale climate and tropical Pacific ENSO

The observed global warming of the 1990s as a decade, or even 1998 as a single year (which has been claimed to be the warmest of the Second Millennium), may be tied to strong El Nino-related events. Yet there is no clear sign that recent El Nino events are deterministically unusual compared to those of the last 350-400 years (Wunsch 1999; Cane 2001; Evans et al. 2002; or see Figure 14 in Mann et al. 2000a or Figures 17 and 18 in Mann et al. 2000b). To compare the physical extent of recent to past El Nino events, consider, for example, the historical results on the severity and wide-ranging impacts of the 1789-1793 ENSO by R. H. Grove (1998).[19] Kiladis and Diaz (1986) concluded, based on careful studies of historical and instrumental data, that the very-strong El Nino of 1982/83 was really not so exceptional in terms of its climatic anomalies when compared to the 1877/78 El Nino event.

The direct link between tropical ENSO events and global or hemispheric-scale climate parameters like temperature and rainfall is drawn from reasonably well-observed air and sea conditions and their hemisphere-wide teleconnection influences seen for the very-strong El Nino events of 1982/83 and 1997/98 (e.g., Harrison and Larkin 1998; Bell et al. 1999; Krishnamurti et al. 2000; Ueda and Matsumoto 2000; Hsu and Moura 2001; Kumar et al. 2001; Lau and Weng 2001). In that respect, it is noteworthy to contrast the *a posteriori* reasoning of Mann et al. (2000b) to achieve an internal consistency of their claim of the 1990s having been the warmest decade and 1998 the warmest single year of the past millennium (claimed by Mann et al. 1999) from the paleo-reconstructed Northern Hemispheric temperature with their Nino-3 (5°N-5°S; 90-150°W) sea surface temperature reconstruction, which showed no unusual ranking of those two events to mean that ENSO variability is very weakly coupled to global or hemispheric mean temperatures. That interpretation of Mann and colleagues is not internally consistent with what is known about robust teleconnection effects by ENSO during the 1980s and 1990s. A likely resolution might simply be that their paleo-reconstruction efforts are only calibrated by instrumental data up to 1980.

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[19] Historical evidence related to the 1789-1793 ENSO points to severe drought conditions around south India, Australia, Mexico, Southern Africa and regions around St. Helena (South Atlantic) and Montserrat (Carribean). But there is scarcely any indication of anything unusual in the 1791 global temperature anomaly pattern reconstructed by the multiproxy regression method of Mann et al. (2000b, Figure 25a) in those areas. On the other hand, the reconstruction of the rainfall anomaly field for the past 1000 years could be an entirely different problem altogether (Mann et al.'s effort focused solely on temperature reconstruction). For a careful discussion of recent observational evidence in terms of the 'trigger' and 'mature-enhancing' phases in the coupling between El Nino and the equatorial Indian Ocean, see for example Ueda and Matsumoto (2000).

5.3. On criticisms of the Crowley and Lowery (2000) composite proxy curve

Although our approach and results are not directly comparable to those of Mann et al. (1998, 1999, 2000a), they can be compared with the results of Crowley and Lowery (2000). We have decided against a superposition of these diverse indicators of climate proxies because their individual sensitivities to temperature and other climatic variabilities are not well defined. Thus, the calibration steps of using a renormalization and an arbitrary arithmetic mean, and then calibration with instrumental data for *only selective time-intervals* (see below), as adopted by Crowley and Lowery (2000) to produce a composite curve, are simply biased correlation exercises. A selective set of proxy records, each with unequal spatial-temporal resolution and differing in climate sensitivity cannot be combined to produce a composite curve as readily as Crowley and Lowery (2000) assume.

The composite curve of Crowley and Lowery (2000) yields results inconsistent with its underlying proxies as well as those discussed here. The authors conclude that "[d]espite clear evidence for Medieval warmth greater than present in some individual records, the new hemispheric composite supports the principal conclusion of earlier hemispheric reconstructions and, furthermore, indicates that maximum Medieval warmth was restricted to two-three 20-30 year intervals [identified by the authors as 1010-1040, 1070-1105, and 1155-1190 A.D.], with composite values during these times being only comparable to the mid-20th century warm time interval."

Crowley and Lowery later proceed to recalibrate the composite, non-dimensional curve to hemispheric-mean thermometer temperatures by using selective intervals, namely 1856-1880 and 1925-1965 A.D. The interval of 1880-1920 was claimed to be contaminated by "anomalous tree-ring growth due to the 19th century rise in CO_2." In contrast, Bradley and Jones (1993) first produced their composite Northern Hemisphere temperature curve and then proceeded to improve its confidence by examining the potential problem of spatial sampling because "there are still extremely large areas for which we have no data." Bradley and Jones checked their composite results against the entire record of available instrumental summer temperature anomalies from about 1850 to 1980, as shown in Figure 7 of their paper. This approach is in sharp contrast to that of Crowley and Lowery, who calibrate their composite proxy curve based on limited areal coverage to Northern-Hemisphere-wide averaged instrumental data for only selective time-intervals and then claim the composite proxy temperature to be valid or relevant for the whole Northern Hemisphere and for the full time interval covered by the instrumental and proxy records.

The omission of the 1880-1920 period in the instrumental calibration is problematic and its explanation by Crowley and Lowery is insufficient. The anthropogenic CO_2 fertilization effect, suspected as an influence after the 1960s, could not already have been occurring between 1880 and 1920 and not afterward (see e.g., Knapp et al. 2001 for a discussion on the impact of the post-1960s CO_2 rise on western juniper growth rates under water-stressed conditions in Central Oregon[20]). More puzzling, Crowley and Lowery claim that only five (from the White Mountains of the Sierra Nevada, central Colorado, Ural Mountains of western Siberia, Qilian Shan of western China, as well as a 'phenological' record from East China) out of 15 of their proxy series were affected by this CO_2 fertilization effect, while four other tree ring proxy records (those from Jasper, Alberta; northern Sweden; the Alps of southern France; and the Black Forest in Germany) utilized in their composite curve were unaffected (see, however, the notable examples of late-20th-century reduced tree growth in the forests of interior central Alaska and western Canada by Jacoby and D'Arrigo 1995; Barber et al. 2000)

A more promising explanation for a non-climatic growth response may be related to land-use, landscape and soil nutrient changes, rather than a direct and too early CO_2 aerial fertilization effect in the late 19- and early 20th century. Even more likely, the problem of the mismatch between instrumental data and Crowley and Lowery's composite curve around 1880-1920 could simply be a *real* difference between individual local proxy change and Northern-Hemisphere-averaged temperature variation that cannot be remedied by the *ad hoc* re-justification scheme proposed in Crowley and Lowery (2000).

The composite curve of Crowley and Lowery was calibrated against Northern Hemisphere-mean instrumental temperature anomalies and that calibration suggests a Northern Hemisphere temperature reconstruction. But equally well, the composite curve could be calibrated against global temperature to produce a similar claim of statistical association. After all, the correlation between the Northern Hemisphere-mean and the global-mean annual temperatures over 1866-2000 is about 0.94. However, such a process may shed no new information because modern thermometer data, when averaged over hemispheric scales, are relatively insensitive to regional details. Thus, the information from the largest-scale of change has, ultimately, very limited value for the practical problem of understanding local- and regional-scale changes. (Both Briffa et al. 2001 and Esper et al. 2002a provide a similar discussion on the difficulty of distinguishing among large-scale spatial averages when calibrating regional proxy data).

As a result, the composite curve presented by Crowley and Lowery (2000) contains little physical information, especially for objective tests relative to the nature of the Little Ice Age, the Medieval Warm Period and the 20th century warm period.

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[20] The evidence for anthropogenic CO_2-fertilization seems to be much weaker in Tasmania and New Zealand (see e.g., D'Arrigo et al. 1998).

5.4. On problems of calibrating proxy indices to instrumental data

Thus far, we have avoided discussion of attribution of suspected climatic factors to observed changes over the last 1000 years; there remain several barriers in the way of achieving this goal. Barnett et al. (1999) made an important point; namely, that it is *impossible* to use available instrumental records to provide estimates of multi-decadal and century-long natural climatic variations. Thus, paleo-proxies remain our only hope for assessing the amplitude and pattern of climatic and environmental change in the pre-human era. We argue with Barnett et al. (1999) that each proxy should be studied in terms of local change before several records can be combined for regional and larger spatial-scale analyses and interpretations. Our conclusion derives mainly from: (1) the real possibility of non-stationarity in the proxy-climate calibration to instrumental records, (2) the lack of adequate superposition rules, given the existence of variability in each type of proxy, and (3) the lack of a clear physical understanding of the multidecadal climate variability from theoretical or empirical studies.

Although instrumental temperature records are believed to have passed quality-control tests (Jones et al. 1999; Folland et al. 2001; Jones and Moberg 2003), most of the ship-based measurements of bulk sea surface temperature exhibit large systematic adjustments. These adjustments range from 0.1°C to 0.45°C between 1856 and 1941 in hemispheric-scale averages, owing to the attempt to homogenize old water bucket-based measurements with modern ship engine intake measurements (see Figures 6 and 7 and the discussion on pp. 570-576 of Parker et al. 1995; Folland et al. 2001). Thus, difficulty seems unavoidable when merging measurements using instruments of different sensitivities and responses, and warrants a warning added to the phrase "calibration and independent cross-validation using instrumental data" in any reconstruction efforts (e.g., Mann et al. 1998, 1999, 2000a). The corrupted part of the early records is likely to set the ultimate constraint on the limited use of the verification procedure — for example, over the 1854-1901 interval in Mann et al. (1998, 1999, 2000a). Furthermore, Hurrell and Trenberth (1999) have shown significant differences among four sea surface temperature datasets,[21] even for climatologies as late as 1961-1990. Those differences not only have important consequences for the

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[21] Emery et al. (2001a, 2001b) elaborated on the distinction between bulk sea surface temperature measured at depths from 0.5 m to 5.0 m below sea surface from buoys and ships and "skin" sea surface temperature inferred from infrared satellite measurements that sample only the top 10 μm of the oceanic layer. Overall, bulk minus skin sea surface temperature differences have mean values of about 0.3°C with an rms variability of up to 0.4°C, but the distinction is not a matter of constant adjustment to account for the cooler skin temperatures. The skin temperature has the important distinction of pertaining to the molecular layer that controls the air-sea exchanges of heat, momentum and gases.

proxy-calibration process, but also for the interpretation of atmospheric circulation, moist convection, and precipitation fields over the tropics. In addition, Christy et al. (2001) found a significant relative warming of the decadal trend in bulk sea surface temperature compared to nighttime marine air (sampled on ship decks at a few meters height) and lower tropospheric temperature over the tropics (20°N to 20°S). Any calibration of paleo-proxy indicators to a "surface temperature" that does not distinguish between the air and the sea includes such differences as unquantifiable uncertainties.

Another significant problem is the indication that an anthropogenic influence may have already left its fingerprint on the recent growth of trees across the Northern Hemisphere. If this anthropogenic effect were present in tree ring data, then the calibration and verification procedure designed for extended paleoclimatic reconstructions would be significantly corrupted by further uncertainties (Idso 1989). Even with the convincing calibration of the proxy and instrumental data within their overlap interval, the calibration failure in the last 2 to 3 decades obscures climatic information from the proxy recorders. Another major concern is the inherently very long delay, including stases, between climatic forcing anomalies and responses. For example, in the biological and glaciological proxies a long temporal inertia exists in the forcing-feedback system (e.g., Bryson 1985; Cole 1985; Calkin et al. 2001; Hormes et al. 2001 for vegetational and glacial changes and their physical delays). The suggested time lags are as long as a few thousand years!

Enormous difficulties remain before an adequate sampling of historical changes can be amassed for conclusions on the largest spatial scales. Also, the assumption of global coherence is likely incorrect (and that assumption can be shown to be incorrect even for the anthropogenic CO_2-influenced 20th century). This is why the core result of Mann et al., based mostly on the 600-1000 yr long tree-ring proxy records, through the EOF-calibrated pattern of temperature change over the 1902-1980 interval (or the later procedure using the 1902-1993 interval), does not address important questions about the context of the recent 20th century change relative to the variability of the last millennium. Refocusing on local changes from multiple proxy records can yield important information on the scope of 20th century changes relative to changes of past centuries.

Finally, a reiteration of the charge of Ogilvie and Jónsson (2001) is in order: "climate researchers should continue to seek to chart the climate of the past thousand years with a fresh approach rather than attempting to fit their findings into the convenient straightjacket of those hackneyed labels, the 'Medieval Warm Period' and the 'Little Ice Age'." In fact, Kreutz et al. (1997) and the follow-up effort by Mayewski and White (2002), based mainly on mismatches of the nature of 20th century climatic change between various proxy indicators (i.e., from their polar ice core analyses while citing sea surface records from the

Sargasso Sea and Santa Barbara basin) and instrumental thermometers, suggest that *the Little Ice Age has not yet ended.* These authors argue it is possible that many components of the climate system, besides temperature, are still responding to perturbations from the Little Ice Age. Adopting this unique perspective, Mayewski and White remark that "When the recent rise in temperature seen in the Mann record [see our discussion in section 5.1 for details] is compared with our ice core-generated records of atmospheric circulation, a curious conclusion arises: Atmospheric circulation patterns appear to be within the range of variability of the LIA [Little Ice Age], but temperatures over the last few decades are markedly higher than anything during the LIA $\cdots$ We are forced to conclude that the LIA is not yet over and therefore human-induced controls on temperature are at play. While natural climate remains the baseline, human factors [the authors, Mayewski and White, are referring mainly to anthropogenic emissions of greenhouse gases and sulfur] may now be overpowering the trends that natural climate would follow if left undisturbed." But such an interpretation of the 20th century surface thermometer warming is similarly contentious. Karlén (2001), for example, notes that according to the Vostok ice core record of atmospheric carbon dioxide, the present concentration of atmospheric CO_2 is about 100 ppmv higher than it was during any previous interglacial during the last 400,000 years. Thus, if climate were to respond sensitively to carbon dioxide, global temperatures, or at least Vostok temperature, today ought to be considerably higher than previous interglacials. Yet evidence exists to suggest that the "present interglacial [at least for conditions around Vostok][22] has been about 2°C cooler than the previous one and the climate is now, in spite of the recent warming, cooler than it was at the beginning of this interglacial" (Karlén 2001).

6. Conclusions

This paper presents a survey of site-specific paleoclimatic reconstructions, then considers whether they indicate that the Medieval Warm Period and the Little Ice Age were observed on broad area of the globe. We conclude that the Medieval Warm Period and Little Ice Age are widespread climatic anomalies, although we emphasize the complex nature of translating the proxy changes into convenient measures like temperature and

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[22] Other paleoclimatic reconstructions, e.g., of tropical sea surface temperatures during the last and present interglacials, using the Mg/Ca ratios of foraminiferal shells from sediment near the Indo-Pacific Warm Pool region (around the Makassar strait, Indonesia), led to a similar conclusion about the relative warmth (about 1°C warmer) of the previous interglacial, ca. 120-124 kyr BP (Visser et al. 2003).

precipitation as well as confirming their spatio-temporal representation and resolution.[23]

The procedures and emphases of our study contrast with those of Mann et al. (1998, 1999, 2000a), whose results are mainly a mathematical construct. Also in contrast to them, our assessment maintains the wide view of including many local climatic and environmental changes over the last 1000 years rather than relying on a mathematical filter to sieve only temperature changes. The wider views may be more appropriate when one seeks a broader perspective on the nature of climatic and environmental changes of the past millennium (e.g., Bryson 1985).

Mann et al. (1999) suggest that there has been a misleading speculation: "that temperatures were warmer [than current 20th century global warming] even further back, ∼1000 years ago–a period described by Lamb (1965) as the Medieval Warm Epoch (though Lamb, examining evidence mostly from western Europe *never* [emphasis added] suggested this was a global phenomenon)." A similar statement has also been made by Bradley (2000).

We correct those claims that misrepresent Lamb's statements—the restatement by Mann, Bradley and colleagues is contrary to Lamb's original statements and published ideas (in several of H. H. Lamb's popular and semi-technical books; e.g., Lamb 1977; Lamb 1982; Lamb 1997b). (A useful verification of this rhetorical confusion about whether Lamb utilizes any evidence from outside of western Europe may be found in Lamb [1963], a preamble to Lamb's [1965] more well-cited paper, where Lamb discussed evidence for climatic anomalies from all over the world. See also the first quote in the Introduction to this paper.) However, criticism on the actual quality of data at Lamb's time is quite another matter; see, for example, updated comments in Pfister et al. (1998).

Unfortunately, current knowledge of Earth's climate system does not yield quantitative and conclusive answers on many straightforward questions regarding the geographical nature and physical causes of surface temperature or precipitation changes over the last 1000 years. Note also that the adopted period of 1000 years is strictly a convenience that merits little scientific meaning.

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[23] In this sense, we are forced to reject the temptation to come up with a "best-guess" depiction of the large-scale or hemispheric-scale averages of the temperature anomalies. A practical reason is the potentially large sampling errors introduced by various kinds of inhomogeneity. One useful quantitative estimate by Sakamoto and Masuda (2002) showed that when there is no *a priori* choice to the selection of the spatial distribution of the proxy data points across the globe, the difference between a 100-point average *surface* temperature (with actual accounting of the elevation at each of the 100 irregularly-distributed points given the current topography and climatology) and a 100-point average *sea-level* temperature can be more than 2°C.

Climate proxy research does yield an aggregate and broad perspective on questions regarding the reality of the Little Ice Age, the Medieval Warm Period and the 20th century surface thermometer global warming. The picture emerges from many localities that both the Little Ice Age and Medieval Warm Period are widespread and perhaps not precisely timed or synchronous phenomena, easily within the margin of viewpoints conceived by Bryson et al. (1963), Lamb (1965) and numerous other researchers like J. Grove (1996, 2001a, 2001b). Our many local answers confirm that both the Medieval Climatic Anomaly and the Little Ice Age Climatic Anomaly are worthy of their respective labels. Furthermore, thermometer warming of the 20th century across the world seems neither unusual nor unprecedented within the more extended view of the last 1000 years. Overall, the 20th century does not contain the warmest or most extreme anomaly of the past millennium in most of the proxy records.

However, it is also clear that human activity has shaped almost every aspect of past environmental and climatic changes on local and regional spatial scales (perhaps on scales as small as 10 to 1000 km^2 for precipitation and 10^4 to 10^5 km^2 for temperature). For example, palynological analyses of two cores from the Huanghe (Yellow River) delta, with evidence for a major reduction in arboreal pollen [*Quercus* (*Lepidobalamus*)] followed by sudden increases in sediment discharge, conifer [*Pinus* (*Diploxylon*)] and buckwheat pollen [*Fagopyrum*] around 4 kyr to 1.3 kyr BP, suggested significant human-induced vegetational changes through deforestation and agricultural cultivation (Yi et al. 2003). Lawton et al. (2001) showed how the deforested areas of tropical lowlands can, in combination with favorable topographical conditions and altered atmospheric air flow across the landscape, significantly raise the bases of convective and orographic clouds around the Monteverde montane cloud forests of Costa Rica during the dry season, and thus drastically impact local ecosystems. However, see A. T. Grove (2001) for a clarification on the imprecise and misleading claim of the dominant role played by human activity (deforestation, agricultural expansion and population growth) on geomorphological changes (soil erosion or rapid sedimentation in river valleys and deltas to form the 'younger fill' of the Mediterranean Europe's fluvial terraces) in Mediterranean Europe, instead of the more powerful influences from Alpine glacier advances associated with the Little Ice Age.

Yet, subjective exercises to superpose the two not-entirely-compatible instrumental temperature and proxy climate time series need a lot more attention. It might seem surprising or frustrating that paleoclimatic reconstruction research has not yet provided confident and applicable answers to the role of anthropogenic forcing on climate change. This point is particularly sharp when considering the fact that even though some proxy records (e.g., those from Overpeck et al. 1997) show unprecedented 20th century warmth with most of the increase occurring in the early to mid-decades of the 20th century, when the amount of anthropogenic CO_2 in the air was less than 20-30% of the total amount there now. Unless there are serious flaws in the timing of the early-to-middle 20th century surface thermometer warming, or unknown anthropogenic mechanisms that caused a large amplification of surface temperature of the then-small increase in anthropogenic atmospheric CO_2, then the early part of the 20th century warming must be largely dissociated from anthropogenic CO_2 emissions. Other anthropogenic factors still need to be studied on a case by case basis.

Thus, a resolution of the pattern and amplitude of natural climate variability on multidecadal and centennial timescales through a multiproxy approach remains extremely important. The results may help quantify the relative apportionment of natural versus anthropogenic factors of recent climate change (i.e., the last three decades or so). The other avenue to quantify natural and anthropogenic climate variability using sophisticated general circulation models (GCMs) still suffers from the following problems: (i) the GCMs' underestimation of climate variance on multidecadal and centennial timescales (e.g., Barnett et al. 1999; von Storch et al. 2001; Collins et al. 2002), (ii) large differences among model-generated variability on both local and regional scales (e.g., Räisänen 2001), and (iii) unrealized climate variability if based only on one or two realizations[24] of a forcing scenario (e.g., Delworth and Knutson 2000; Andronova and Schlesinger 2001) or because of the GCM's inability to account for certain biochemical and biophysical feedbacks and nondeterministic component of the earth's climate system (Idso 1998; Ou 2001; Pielke 2001). JS. von Storch et al. (2001), for example, present a critical discussion on the lack of confidence in the representation by current GCMs of low-frequency climate variability related primarily to the inability of models to resolve small-scale oceanic eddies. In addition, natural climate variations on multidecadal, centennial and millennial timescales could be highly non-stationary with complex spatio-temporal phasing (i.e., with part of such characteristics documented in the present study) that would be difficult for GCMs to emulate robustly. Such natural climatic factors likely operate in the real world together with further complications such as forcing by anthropogenic greenhouse gases and multi-component (rather then sulfate aerosol alone) aerosols. From the longer term perspective offered by paleoclimatic studies, one can at least conclude that large and rapid climatic and environmental changes have been common over the past millennium. Such natural changes impacted human society significantly, so further climate research, including adaptation strategies, rather than mitigation, seems to be pertinent (e.g., chapter 18 of

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[24] For example, Cherchi and Navarra (2003) showed that a minimum ensemble size of 16 members is needed in order to capture the observed interannual (1979-1993) variability for their focus on the nature of sea-surface-temperature-forced responses of the South Asian summer monsoon system.

Lamb 1982; Pielke 1998).

The quest in paleoclimate reconstruction efforts is to decipher and understand the physical mechanisms associated with the widest possible range of climate variabilities. That goal requires careful and systematic observation of the present-day Earth. The logistic and technical feasibility for the important objective and bias-free strategy to detect global warming due to the enhanced atmospheric concentration of carbon dioxide has been elaborated by Goody et al. (1998) and Keith and Anderson (2001).

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Table 1: A full list of paleoclimatic proxies that have sufficient length of continuous records to entertain the three specific questions:
(1) Is there an objectively discernible climatic anomaly during the Little Ice Age interval (1300-1900 A.D.) in this proxy record?
(2) Is there an objectively discernible climatic anomaly during the Medieval Warm Period (800-1300 A.D.) in this proxy record?
(3) Is there an objectively discernible climatic anomaly within the 20th century that may validly be considered the most extreme (the warmest, if such information is available) period in the record?
We list the location, type of proxies, reference and the logical answers to the three specific questions posed in this study.

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
World-wide	–	–	Mp	Mann et al. 99	yes	no	yes[*]
Arctic-wide	–	–	Mp	Overpeck et al. 97	yes	—	yes[*]
World-wide	–	–	Mp	Crowley & Lowery 00	yes	no	yes[*]
World-wide	–	–	Mp	Jones et al. 98	yes	no	yes[*]
World-wide	–	–	T	Briffa 00	yes	no	yes[*]
World-wide	–	–	T	Briffa et al. 01	yes	—	yes[*]
World-wide	–	–	T	Jones et al. 01	yes	—	yes[*]
NH Mid-Latitude	–	–	T	Esper et al. 02a	yes	yes	no
World-wide	–	–	Mp	Lamb 77, 82	yes	yes	—
World-wide	–	–	G + Is	Porter 86	yes	yes	—
World-wide	–	–	G	Grove & Switsur 94	—	yes	—
World-wide	–	–	T+G+D	Hughes & Diaz 94	yes	no?[+]	no?[+]
World-wide	–	–	Mp	Grove 96	—	yes	—
World-wide	–	–	B	Huang et al. 97	yes	yes	no
World-wide	–	–	D	Perry & Hsu 00[†]	yes	yes	no
World-wide	–	–	D	deMenocal 01	yes	yes	—
China-wide	–	–	Mp	Yang et al. 02	yes	yes	—
Americas	–	–	Ts+Gm+Mp	Stine 98	—	yes	—

[+] In reality, Hughes & Diaz concluded that "[o]ur review indicates that for some areas of the globe (for example, Scandinavia, China, the Sierra Nevada in California, the Canadian Rockies and Tasmania), temperatures, particularly in summer, appear to have been higher during some parts of this period than those that were to prevail until the most recent decades of the twentieth century. These regional episodes were not strongly synchronous. Evidence from other regions (for example, the Southeast United States, southern Europe along the Mediterranean, and parts of South America) indicates that the climate during that time was little different to that of later times, or that warming, if it occurred, was recorded at a later time than has been assumed. ··· To the extend that glacial retreat is associated with warm summers, the glacial geology evidence would be consistent with a warmer period in A.D. 900-1250 than immediately before or for most of the following seven hundred years." We simply note that the main conclusion of Hughes & Diaz (1994) may be in actual agreement with the qualitative classification in our paper.

[†] We refer only to the documentary, historical and archaeological research results, rather than the solar-output model results, of this paper.

Table 1 (continued)

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
N. Atlantic (Iceland)	63-66°N	14-24°W	Mp	Ogilvie et al. 00, Ogilvie and Jónsson 01	yes	yes	no
N. Atlantic (S. Greenland)	60-70°N	20-55°W	Mp	Ogilvie et al. 00	yes	yes	no
W. Europe	45-54°N	0-15°E	Mp	Pfister et al. 98	yes	yes	no
N. Atlantic (Europe)	35-70°N	25W-30°E	In+D	Luterbacher et al. 00	yes	—	—
Central England	52°N	2°E	In+D	Lamb 65, Manley 74	yes	yes	no
S. Spain	37.30°N	4.30°W	In+D	Rodrigo et al. 00	yes	—	no
Crete Is.	35.15°N	25.00°E	D	Grove & Conterio 95	yes	—	no
Mid-Russia	50-60°N	30-50°E	In+D	Borisenkov 95	yes	—	—
Czech Republic	48.5-51.2°N	12-19°E	In+B	Bodri & Čermák 99	yes	yes	yes?
S. USA	37-38°N	107.5-109.5°W	Pf+Cl+D	Petersen 94	yes	yes	—
E. China (GuangDong Prov.)	22-25°N	112-114.3°E	D	Chan & Shi 00	yes	—	—
E. China-wide	20-40°N	90-120°E	D	Song 00	yes	—	no?
Japan	30-40°N	125-145°E	D	Tagami 93, 96	yes	yes	no
S. Africa	22.2°S	28.38°E	Cl	Huffman 96	yes	yes	—
E. Greenland (Nansen Fjord)	68.3°N	29.7°W	Is	Jennings & Weiner 96	yes	yes	no
C. Greenland (Crête)	71.12°N	37.32°W	Is	Dansgaard et al. 75	yes	yes	no
C. Greenland (GRIP)	72.6°N	37.6°W	B	Dahl-Jensen et al. 98	yes	yes	no
S. Greenland (Dye 3)	65.2°N	43.8°W	B	Dahl-Jensen et al. 98	yes	yes	no
C. Greenland (GISP2)	72.58°N	38.5°W	Ic+Ml	Meese et al. 94	yes	yes	no
C. Greenland (GISP2)	72.58°N	38.5°W	Is	Stuiver et al. 95	yes	yes	no
Svalsbard	79°N	15°E	Ml	Tarussov 95	yes	yes	no
Devon Island	75°N	87°W	Ml	Koerner 77	yes	—	yes*
Ellesmere Island	80.7°N	73.1°W	Ml	Koerner & Fisher 90	yes	yes	no
Ellesmere Island	80.7°N	73.1°W	B+Is	Beltrami & Taylor 95	yes	yes	no
Gulf of Alaska	60-61°N	149°W	G+T	Calkin et al. 01	yes	yes	—
Swiss Alps (Gorner+ Grösser Aletsch Glacier)	45.8-46.5°N	7.75-8.16°E	G+Gm +Is+T	Holzhauser 97	yes	yes	no
South Georgia Island	54-55°S	36-38°W	G+Gm	Clapperton et al. 89	yes	yes	—
Southern Alps (Mueller Glacier)	43.44°S	170.06°E	G+Gm	Winkler 00	yes	—	—
Antarctica (James Ross Island)	64.22°S	57.68°W	Is	Aristarain et al. 90	yes?	—	no
Antarctica (Law Dome)	66.73°S	112.83°E	Is	Morgan 85	yes	yes	no
Antarctica (Victoria Land)	74.33°S	165.13°E	G+Gm+Is	Baroni & Orombelli 94	yes	yes	—
Antarctica (Dome C)	74.65°S	124.17°E	Is	Benoist et al. 82	yes	yes	no

Table 1 (continued)

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
Prince William Sound, Alaska	60°N	149°W	T+G	Barclay et al. 99	yes	yes?	—
Alberta, Canada Columbia Icefield	52.2°N	117.8°W	T+In+G	Luckman et al. 97	yes	yes	yes*
N. Québec	57.73°N	76.17°W	T	Arseneault & Payette 97	—	yes	—
S. Manitoba	49.5°N	97.17°W	T	St. George & Nielsen 02	yes	—	—
Central US	33-49°N	91-109°W	T+Mp	Woodhouse & Overpeck 98	yes	yes	yes*
E. Idaho	44.1°N	114°W	T	Biondi et al. 99	yes	—	no
N. Carolina	34.5°N	78.3°W	T	Stahle et al. 88	yes	yes	no?
California (SN)	36.5-37.5°N	118.5-120.5°W	T	Graumlich 93	yes	yes	no
California (SN)	36.5-37.5°N	118.5-120.5°W	T	Scuderi 93	yes	yes	no
California (SN)	36-38°N	118-120°W	T	Swetnam 93	yes	yes	no
New Mexico	34.5°N	108°W	T	Grissino-Mayer 96	yes	yes	no
Central Eq. Pacific (NINO3.4)	5°N-5°S	160°E-150°W	T+In	Evans et al. 00	yes	yes?	no
C. Siberia (Taymir+Putoran)	72.47°N	102°E	T	Naurzbaev & Vaganov 00	yes	yes	no
Kola Peninsula	67-68°N	33-34°E	T+Is	Hiller et al. 01	—	yes	—
N. Fennoscandia	68°N	22°E	T	Briffa et al. 92	yes	yes	no
NE. Italy	45°N	10°E	T	Serre-Bachet 94	yes	yes	no?
Morocco	28-36°N	2-12°W	T	Till & Guiot 90	yes	yes?	no
W. Central Asia	35-41°N	72-77°E	T	Esper et al. 02b	yes	yes	no
Western Himalaya	30.5-31.2°N	78.5-80°E	T	Yadav & Singh 02	yes	—	no
Mongolia (Tarvagatay Mts.)	48.3°N	98.93°E	T	Jacoby et al. 96	yes	—	yes
Mongolia (Tarvagatay Mts.)	48.3°N	98.93°E	T+D	D'Arrigo et al. 01	yes	yes	yes
N. Patagonia (Rio Alerce, Argentina)	41.17°S	71.77°W	T	Villalba 90	yes	yes	no
S. Chile (Lenca)	41.55°S	72.6°W	T	Lara & Villalba 93	yes	no	no
S. South America	33-55°S	60-75°W	T+G	Villalba 94	yes	yes	no
W. Tasmania	42°S	146.5°E	T	Cook et al. 00	no	yes	yes?
New Zealand	35-48°S	167-177°E	T	D'Arrigo et al. 98	yes	—	no
N. Scandinavia	68°N	20°E	T+G	Karlén 98	yes	yes	no
California (SN)	38°N	110°W	Ts	Stine 94	—	yes	no
California (SN)	37.5°N	119.45°W	Ts	Stine 94	—	yes	no
California (SN)	38.38°N	119.45°W	Ts	Stine 94	—	yes	no
California (SN)	38.85°N	120.47°W	Ts	Stine 94	—	yes	no
Patagonia	48.95°S	71.43°W	Ts	Stine 94	—	yes	—
Patagonia	50.47°S	72.97°W	Ts	Stine 94	—	yes	—

Table 1 (continued)

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
NW Michigan (L. Marion)	45°N	85°W	Po	Bernabo 81	yes	yes	yes?
Qinghai-Tibetan P. (Dunde Ice Cap)	38.1°N	96.4°E	Po	Liu et al. 98	yes	yes	yes*?‡
NE China (Maili)	42.87°N	122.87°E	Po	Ren 98	—	yes	—
NE China (Hangzhou)	30-33°N	105-122°E	Pf	Zhang 94	—	yes	—
China (Taibai Mt.)	33.97°N	107.73°E	Pf+Po	Tong et al. 96	yes	yes	no
Himalaya	28.38°N	85.72°E	Is	Thompson et al. 00	yes	no	yes
Himalaya (Dasuopu Glacier)	28.38°N	85.72°E	Ic	Thompson et al. 00	yes	—	yes
Guliya Ice Cap	35.2°N	81.5°E	Ic+Is	Thompson et al. 95	yes	yes	no
E. China	30-40°N	100-120°E	Ic+D	Shi et al. 99	yes	yes	yes?
W. China (Guliya Cap)	35.2°N	81.5°E	Ic+D	Shi et al. 99	yes	yes	yes?
Quelccaya Ice Cap	13.93°S	70.83°W	Is+Ic	Thompson et al. 86	yes	yes?	no
Antarctica (Siple Station)	75.92°S	84.25°W	Ic+Is	Mosley-Thompson 95	no	—	no
Antarctica (Dyer Plateau)	70.67°S	64.88°W	Ic+Is	Thompson et al. 94	yes?	—	yes
Antarctica (Dronning Maud Land)	76°S	8.05°W	Ic+Is	Karlöf et al. 00	yes	yes?	no?
South Pole	90°S	—	Ic	Mosley-Thompson & Thompson 82	yes	yes?	no

‡For the Dunde ice cap, Thompson et al. (1989) noted that, according to the δ^{18}O climate proxy, the decades of the 1940s, 1950s and 1980s are at least as warm as the Holocene maximum of 6000 to 8000 years ago. In order to confirm Thompson et al. (1989)'s original statement, please consider Figure 6 of Thompson (2000), because the claim that 1930s-1980s is the warmest of the last 6000-8000 years ago is not clear from any figure in Thompson et al. (1989). But the main warming of the 1940s-1950s occurred before significant rise of anthropogenic CO_2 in the air. This is why we added a question mark plus an asterik to this entry.

Table 1 (continued)

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
N. Atlantic	54.27°N	16.78°W	Sd	Bond et al. 97	yes	yes	no?
N. Atlantic	44.5°N	46.33°W	Sd	Bond et al. 99	yes	yes	no
N. Atlantic	56.37°N	27.81°W	Sd	Bianchi & McCave 99	yes	yes	no?
N. Ellesmere Island	81°N	80°W	Sd+Lf	Lamoureux & Bradley 96	yes	yes	—
SW. Baltic Sea (Bornholm Basin)	55.38°N	15.4°E	Sd+Is	Andrén et al. 00	yes	yes	no
S. China (Huguangyan L.)	21.15°N	110.28°E	Lf+Is	Chu et al. 02	yes	yes	—
NW. Finland (L. Toskaljavri)	69.2°N	21.47°E	Lf+Po+T	Seppä & Birks 02	yes	yes	—
N. Fennoscandia (L. Tsuolbmajavri)	68.68°N	22.08°E	Lf	Korhola et al. 00	yes	yes	no
S. Finland (L. Laihalampi)	61.49°N	26.08°E	Lf+Po	Heikkilä & Seppä 03	—	no?	no
Switzerland (L. Neuchâtel)	47°N	6.55°W	Lf+Is	Filippi et al. 99	yes	yes	yes?
W. Ireland	53.53°N	9.93°W	Is	Blackford & Chambers 95	yes	yes	—
Bermuda Rise	32.17°N	64.5°W	Is	Keigwin 96	yes	yes	no
Chesapeake Bay	37-38.4°N	76.1°W	Sd	Verardo et al. 98	yes	yes	—
Chesapeake Bay	38-38.9°N	76.22-76.4°W	Sd+Is	Cronin et al. 03	yes	yes	yes?
NW Alaska (Farewell L.)	62.55°N	153.63°W	Lf+Is	Hu et al. 01	yes	yes	no
W Canada (Pine L.)	52.07°N	113.45°W	Lf	Campbell et al. 98	yes	yes	no
S. Dakota (Pickerel L.)	45.51°N	97.27°W	Lf	Dean & Schwalb 00	yes	yes	no
N. Dakota (Moon L.)	46.85°N	98.16°W	Lf	Laird et al. 96	yes	yes	no
N. Dakota (Rice L.)	48.01°N	101.53°W	Lf	Yu & Ito 99	yes	yes	no
Yellowstone P. (Lamar Cave)	44.56°N	110.24°W	Pf+Is	Hadly 96	yes	yes	no
Colorado Plateau (L. Canyon)	37.42°N	110.67°W	Lf+Gm+Is	Pederson 00	yes	yes	—
NE Colorado	40-41°N	102-105°W	Gm+Is+D	Madole 94	—	yes	no
SW US (Colorado +Arizona)	34-37.5N	105-112W	Lf+Is Is	Davis 94	—	yes	no? —
SW US	32-39°N	109-114°W	Lf+Gm	Ely et al. 93	yes	yes	no
California (White Mts.)	37.43°N	118.17°W	Is	Feng & Epstein 94	yes	yes	—
California (L. Owen)	36°N	118.17°W	Is	Li et al. 00	yes	yes	no
Yucatan Peninsula (L. Chichancanab)	20°N	88.4°W	Lf+Is	Hodell et al. 01	yes	yes	— —
Cariaco Basin	11°N	65°W	Sd	Black et al. 99	yes	yes	no
Cariaco Basin	10.71°N	65.17°W	Sd+Is	Haug et al. 01	yes	yes	—
S. Florida	24.95°N	80.55°W	Is	Druffel 82	yes	—	—
NE. Carribean	17.89°N	66.60°W	Sd+Is	Nyberg et al. 02	yes	yes	no
SW. Puerto Rico	18.12°N	67.09°W	Is	Winter et al. 00	yes	—	—

Table 1 (continued)

Location	Lat.	Long.	Type	Reference	Ans. (1)	Ans. (2)	Ans. (3)
NW Scotland (Assynt)	58.11°N	5.06°W	Sp	Proctor et al. 00	yes	yes	no
SW. Ireland	52.5°N	9.25°W	Sp	McDermott et al. 01	yes	yes	—
NW. Germany (Sauerland Mtn)	51.43°N	7.78°W	Sp+Is	Niggemann et al. 03	yes	yes	—
NE China (Jinchuan)	42.3°N	126.37°E	Is	Hong et al. 00	yes	yes	no
NE China (Shihua Cave)	39.8°N	115.9°E	Sp+Is	Li et al. 98, Ku & Li 98	yes	yes	no
C. China (Buddha Cave)	33.67°N	109.08°E	Sp+Is	Paulsen et al. 03	yes	yes	no?
S. Japan (Yakushima Is.)	30.33°N	130.5°E	Is	Kitagawa & Matsumoto 95	yes	yes	no
N. India (Pahalgam)	34.02°N	75.20°E	Is	Ramesh 93	yes	—	—
S. India (Nilgiris)	10-10.5°N	77°E	Is	Ramesh 93	—	yes	—
E. Africa (L. Malawi)	10°S	35°E	Lf	Johnson et al. 01	yes	—	no
E. Africa (L. Naivasha)	0.46°S	36.21°E	Lf	Verschuren et al. 00	yes	yes	no
W. Africa (Cap Blanc)	20.75°N	18.58°W	Is	deMenocal et al. 00	yes	yes	no
S. Africa	19-35°S	10-33°E	Mp	Tyson & Lindesay 92	yes	yes	no
S. Africa (Nelson Bay Cave)	34°S	23°E	Is	Cohen & Tyson 95	yes	—	no
S. Africa (Makapansgat)	24.54°S	29.25°E	Sp	Tyson et al. 00	yes	yes	no
S. Oman	16.93°N	54.00°E	Sp+Is	Burns et al. 02	yes	—	no
W. Pacific	6.3°N	125.83°E	Sd+Is	Stott 02, Stott et al. 02	yes	yes	no
N. New Zealand (Waitomo)	38.27°S	175°E	Sp	Williams et al. 99	yes	—	—
S. New Zealand (Nelson)	40.67°S	172.43°E	Sp	Wilson et al. 79	yes	yes	no
S. America (multiple regions)	33-38°S	59.3-67°W	Mp	Iriondo 99	yes	yes	—
C. Argentina	29.5-35°S	61.75-65.75°W	Gm+D	Carignano 99	yes	yes	no
C. Argentina	28-36°S	61-67°W	G+Mp	Cioccale 99	yes	yes	no
NW. Argentina	26.5°S	68.09°W	Sd+Is	Valero-Garcés et al. 00	yes	—	—
W. Antarctica (E. Bransfield Basin)	61.98°S	55.95°W	Sd+Is	Khim et al. 02	yes	yes	—
W. Antarctica (Palmer Deep)	64.86°S	64.21°W	Sd	Domack et al. 01	yes	yes	no
W. Antarctica (Siple Dome)	81.65°S	148.81°W	Is	Kreutz et al. 97	yes	—	no

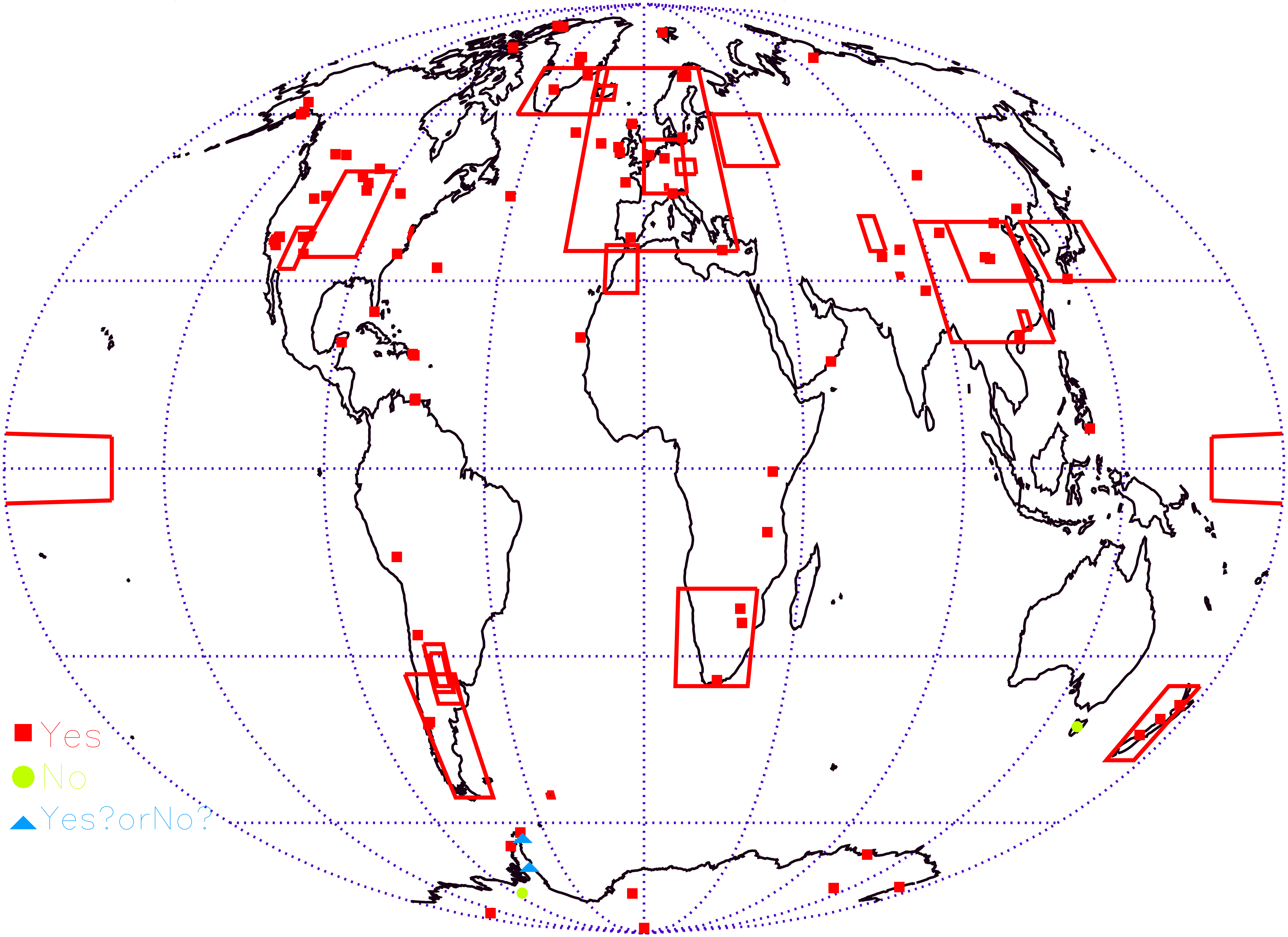
yes*: the warming or extreme excursion peaked around 1920s-1950s before any significant anthropogenic CO_2 release to air
anwers ending with a question mark (?) refers to indecision
B: Borehole
Cl: Cultural
D: Documentary
G: Glacier advance or retreat
Gm: Geomorphology
In: Instrumental
Is: Isotopic analysis from lake sedimentary or ice cores, tree or peat celluloses, corals, stalagmite or biological fossils
Ic: Net ice accumulation rate, including dust or chemical counts
Lf: Lake fossils and sediments; river sediments
Ml: Melt layers in ice cores
Mp: Multiproxy and can be any combination of the proxies list here
Pf: Phenological and Paleontological fossils
Po: Pollen
Sd: Seafloor sediments
Sp: Speleothem isotopic or luminescent analysis
T: Tree ring growth, either ring width or maximum latewood density, including shifting tree line positions
Ts: Tree stumps in lakes, marshes and streams

Fig. 1.— Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Little Ice Age interval (1300-1900 A.D.) in this proxy record? 'Yes' is indicated by red filled-squares or unfilled boxes, 'No' is indicated by green filled-circles and 'Yes? or No?' (undecided) is shown with blue filled-triangles.

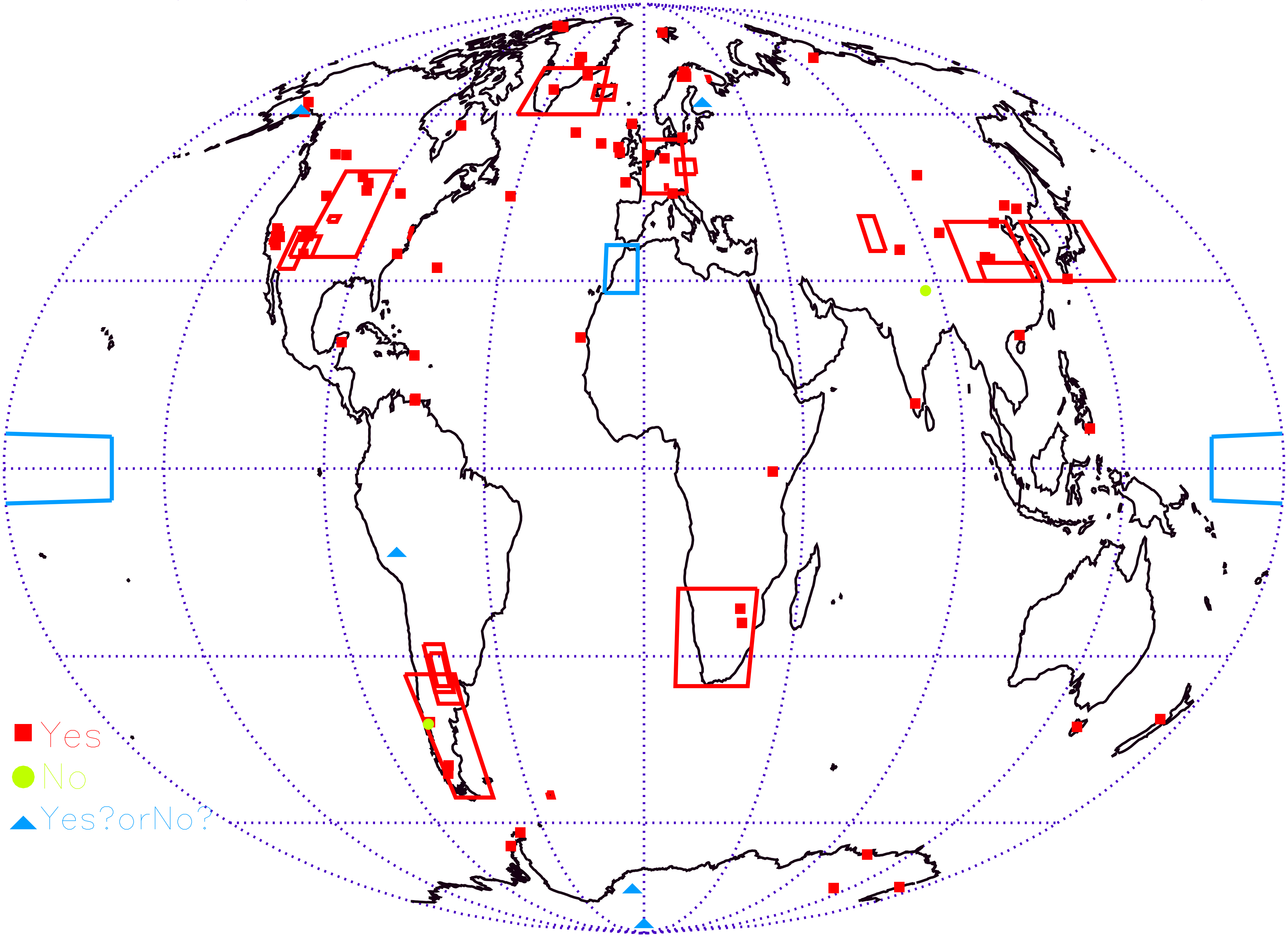
Fig. 2.— Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Medieval Warm Period (800-1300 A.D.) in this proxy record? ‘Yes’ is indicated by red filled-squares or unfilled boxes, ‘No’ is indicated by green filled-circles and ‘Yes? or No?’ (undecided) is shown with blue filled-triangles or unfilled boxes.

Fig. 3.— Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly within the 20th century that may validly be considered the most extreme (the warmest, if such information is available) period in the record? ‘Yes’ is indicated by red filled-squares, ‘No’ is indicated by green filled-circles or unfilled boxes and ‘Yes? or No?’ (undecided) is shown with blue filled-triangles or unfilled boxes. An answer of ‘Yes*’ is indicated by yellow filled-diamonds or unfilled boxes to mark an early to middle 20th century warming rather than the post-1970s warming.

(1) Is there an objectively discernible climatic anomaly during the Little Ice Age interval (1300–1900 A.D.) in this proxy record?



(2) Is there an objectively discernible climatic anomaly during the Medieval Warm Period (800–1300 A.D.) in this proxy record?



(3) Is there an objectively discernible climatic anomaly within the 20th century that is the most extreme (the warmest) period in the record?