

Proxy climatic and environmental changes of the past 1000 years

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ABSTRACT: The 1000 yr climatic and environmental history of the Earth contained in various proxy records is reviewed. As indicators, the proxies duly represent local climate. Because each is of a different nature, the results from the proxy indicators cannot be combined into a hemispheric or global quantitative composite. However, considered as an ensemble of individual expert opinions, the assemblage of local representations of climate establishes both the Little Ice Age and Medieval Warm Period as climatic anomalies with worldwide imprints, extending earlier results by Bryson et al. (1963), Lamb (1965), and numerous intervening research efforts. Furthermore, the individual proxies can be used to address the question of whether the 20th century is the warmest of the 2nd millennium locally. Across the world, many records reveal that the 20th century is probably not the warmest nor a uniquely extreme climatic period of the last millennium.

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

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1. INTRODUCTION

Are the Little Ice Age and Medieval Warm Period widespread climatic anomalies? Lamb (1965) 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 . . . has been found to suggest a warmer epoch lasting several centuries between about A.D. 900 or 1000 and about 1200 or 1300. . . . 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. . . . It is high time therefore to marshal the climatic evidence and attempt a quantitative evidence' (p. 14-15). Research on large-scale patterns of climate change continued with vigor.

Jones et al. (1998) tentatively concluded that while a Little Ice Age cooling existed, little evidence could

be found to support or reject a medieval warming. But the updated composite tree-ring summer temperature curve in Fig. 1 of Briffa (2000) shows evidence for an anomalously warm interval from about 950 to 1100 in the northern high-latitude zone, which coincides with Lamb's Medieval Warm Period. Also, a similar early warm period appears prominently in the averaged tree ring chronologies carefully selected and processed from 14 sites spreading over 30 to 70° N (Esper et al. 2002).

Those results are but a few of many that have become available since Lamb's analysis. Given advancements in retrieval of information from and extension of surface coverage for the proxies, we review the accumulated evidence on regional climatic anomalies over the last 1000 yr. We also recommend Ogilvie & Jónsson (2001), who recently provided the most authoritative discussion on the historical development of the long-standing debates on the climatic nature of the Medieval Warm Period and Little Ice Age, especially concerning the North Atlantic, including Iceland.

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2. WORKING DEFINITIONS

What are the regional patterns of climatic change over the last 1000 yr? Accurate results could serve as benchmarks for 20th century global average warming seen in the surface thermometer records and as physical constraints for theories or mechanisms of climate change on timescales of decades to centuries.

The proxies used to study climatic change over the last 1000 yr are addressed individually and therefore locally because they differ in nature too greatly to be quantitatively averaged or compared. To make progress, we consider 3 questions of many individual climate proxies:

(1) Is there an objectively discernible climatic anomaly during the Little Ice Age interval, defined as 1300–1900? This broad period in our definition derives from historical sea-ice, glaciological and geomorphological studies synthesized in Grove (2001a,b) and Ogilvie & Jónsson (2001).

(2) Is there an objectively discernible climatic anomaly during the Medieval Warm Period, defined as 800–1300? This definition is motivated by e.g. Pfister et al. (1998) and Broecker (2001), and is a slight modification of Lamb's original study (1965).

(3) Is there an objectively discernible climatic anomaly within the 20th century that is the most extreme (the warmest, if such information is retrievable) period in the record? An important consideration in answering this question is to distinguish the cases for which the 20th century warming began early in the century versus after the 1970s, as recorded by surface thermometers. This is necessary if temperature changes are to be related to anthropogenic forcing inputs like increased atmospheric carbon dioxide content.

Anomaly is simply defined as a period of more than 50 yr of sustained warmth, wetness or dryness, within the stipulated interval of the Medieval Warm Period, or a 50 yr or longer period of cold, dryness or wetness within the stipulated Little Ice Age. We define anomaly in the 20th century within each proxy in the same way. The surface instrumental record of the 20th century contains 3 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, which preclude a direct comparison to the proxies (which have their own biases). Our goal here is to compare the 20th century objectively with more extended past changes than is available from thermometry. Given the biases of each proxy, Question (3) was answered by asking if, within each proxy record, there was an earlier (pre-20th century) 50 yr interval warmer (or more extreme, in the case of precipitation) than any 50 yr average within the 20th century.

Question (3) differs from Questions (1) and (2). Question (3) looks for a 50 yr anomaly within the 20th century compared to any other anomaly throughout the period of a proxy record. Questions (1) and (2) look for a 50 yr anomaly within the previously suggested 500 and 600 yr intervals of the Medieval Warm Period and Little Ice Age, respectively. Note that in the case of Question (3), we treat the definition of a 50 yr or more period of sustained anomaly in the 20th century no different from that of any prior century. Thus, if a sustained warm anomaly were identified and happened to reside in 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 both that the 20th century anomaly is the most extreme (warmest) and that the Medieval Warm Period exists. In answering Question (3), the existence of the Medieval Warm Period or Little Ice Age is not considered, because they are assessed independently, in Questions (1) and (2).

We started with the framework of past researchers, namely, the suggested existence of the Medieval Warm Period and Little Ice Age. The goal of the study is to deduce the geographical nature of climatic and environmental conditions during these periods. Distinguishing the 20th century as a separate period is largely a practical bias because of the interest in the role of human activity on Earth's climate and environment.

Another important consideration is that temporary regional cooling (or shift between wet and dry condition) may occur on decadal, but not multidecadal, timescales during the Medieval Warm Period, and similarly, occasional, short-lived regional warming (or shift between wet and dry condition) may occur during the Little Ice Age, as indicated by Grove (2001a,b). Thus the terms Medieval Warm Period and Little Ice Age should indicate persistent but not necessarily constant warming or cooling, respectively, over broad areas (see also Stine 1998, Luckman 2000, Grove 2001a,b, Ogilvie & Jónsson 2001, Esper et al. 2002). Stine (1998) suggests that more appropriate terms may be 'Little Ice-Age Climatic Anomaly' and 'Medieval Climatic Anomaly'. It is also noteworthy that the definitions of discernible, persistent climate anomalies for the Little Ice Age and Medieval Warm Period may include not only distinct changes in the mean but also changes in the multidecadal variance (Ogilvie & Jónsson 2001). Through the microscope of daily and regional spatial scale variability, it is important to recognize that even the relation between multidecadal mean temperature and its daily variability may undergo significant non-stationary changes (e.g. Knappenberger et al. 2001, who document those time-dependent changes in temperature variability across the United States).

Also, from a combination of field evidence and modeling based on the understanding from synoptic climatology, Bryson & Bryson (1997) demonstrated how local and regional factors (for horizontal spatial distances as small as 100 km) can produce significantly different precipitation histories for 2 Near East stations (Jerusalem and Kameshli, Syria) and for 2 stations in the Cascade Range of Oregon (mountainous versus coastal-like microclimate sites).

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 (30 to 45° N; 80 to 110° W; see Hansen et al. 1999, Robinson et al. 2001) or the Antarctic continent (e.g. Doran et al. 2002) in the last 30 to 50 yr. Another example is relative warmth during the Little Ice Age and relative cool 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 m), compared to results from Greenland's borehole (see Clow & Waddington 1999), which do not show those features. These variations are of short duration compared to the anomaly, and of limited regional extent.

3. APPROACH

Table 1 and Figs. 1 to 3 summarize the answers to the questions posed here about local climatic anomalies. For Questions (1) and (2), we answered 'Yes' if the proxy record showed a period longer than 50 yr of cooling, wetness or dryness during the Little Ice Age, and similarly for a period of 50 yr or longer for warming, wetness or dryness during the Medieval Warm Period. A dash indicates that either there is no expert opinion, or that the proxy record does not cover the period in question. A 'Yes?' or 'No?' answer means that the original expert opinion was Yes or No, but that it does not match our criteria; for example, if the interval of warmth during the Medieval Warm Period were too short by our definition to be 'Yes', it would merit 'Yes?'. In several cases in the 20th century, a 'Yes?' designation was assigned for the answer to Question (3) in order to highlight the fact that the 20th century warming first occurred early in the century, ca. 1920–1950, when the air's content of anthropogenic CO₂ was still cumulatively small.

A global association for the Little Ice Age or Medieval Warm Period is premature because proxy data are geographically sparse and either or both phe-

nomena could be multi-phased events acting under distinct local and regional constraints and modes. Bradley & Jones (1993) and Hughes & Diaz (1994) initiated and strongly held the view that the phenomena were not global, but Grove (1996; see especially p. 51 to 54) disagrees. However, in the traditionally data-rich areas of Western Europe or the Northern Atlantic including Iceland and Greenland, both the Little Ice Age and Medieval Warm Period do exist as distinct climate anomalies (Pfister et al. 1998, Grove 2001a, Ogilvie & Jónsson 2001). No objective proof discredits the existence of those phenomena in other regions. Thus, like other researchers (Lamb 1965, Porter 1986, Grove 1996, Kreutz et al. 1997), we start with previously indicated periods of Little Ice Age and Medieval Warm Period, and ask whether they are widespread, teleconnected events that need not necessarily last throughout the defined periods. The terms Medieval Warm Period and Little Ice Age remain practical and viable, especially considering the potential extension of the concept to past and future climatic events that are 'similar or equivalent' in physical scope (e.g. Bond et al. 1997, 1999).

Current knowledge on the diverse range of local climatic behavior suggests that the Medieval Warm Period and the Little Ice Age are not expected to be homogeneous and sustained. To define the beginning and end dates of these climate anomalies requires better understanding (for the Little Ice Age see Porter 1981, 1986, Kaser 1999, Grove 2001a,b, Luckman 2000, Schuster et al. 2000, Winkler 2000, Ogilvie & Jónsson 2001, Hendy et al. 2002). Imprecise data on the beginning and end of both events contributes in part to confusion about the phenomena. For example, Ogilvie & Farmer (1997) have commented that Lamb's suggestion of a Medieval Warm Period may not be supported by documentary data even for England because their extensive studies based on a historical dataset showed that England suffered relatively cold winters from 1260 to 1360. However, as that period is near the transition between the Medieval Warm Period and Little Ice Age defined in this study, this fact does not strongly contradict our results. Evidence based primarily on glacier activity points to both a poorly defined beginning and end of the Medieval Warm Period, while the Little Ice Age interval seems to have had a gradual beginning but more abrupt end. Although the notion of the Medieval Warm Period or Little Ice Age with sharply defined transitions may be a convenient one, it is probably a non-physical construct because of large regional differences in the timing of both phenomena. As suggested by Grove (2001a), an inhomogeneous climate pattern (though not necessarily an analog) can already be identified in the 20th century warm intervals as defined by instrumental records.

Table 1. A full list of paleoclimatic proxies that have sufficient length of continuous records to entertain the 3 specific questions: (1) Is there an objectively discernible climatic anomaly during the Little Ice Age interval (A.D. 1300–1900) in this proxy record? (2) Is there an objectively discernible climatic anomaly during the Medieval Warm Period (A.D. 800–1300) in this proxy record? (3) Is there an objectively discernible climatic anomaly within the 20th century that is the most extreme (the warmest, if such information is available) period in the record? A question mark after an answer indicates uncertainty or indecision. Symbols for the type of climate proxy used include 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 (any combination of proxies listed 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

Location	Latitude	Longitude	Type	Source	Answer		
					(1)	(2)	(3)
Worldwide	-	-	Mp	Mann et al. (1999)	Yes	No	Yes ^a
Arctic wide	-	-	Mp	Overpeck et al. (1997)	Yes	-	Yes ^a
Worldwide	-	-	Mp	Crowley & Lowery (2000)	Yes	No	Yes ^a
Worldwide	-	-	Mp	Jones et al. (1998)	Yes	No	Yes ^a
Worldwide	-	-	T	Briffa (2000)	Yes	No	Yes ^a
Worldwide	-	-	T	Briffa et al. (2001)	Yes	-	Yes ^a
Worldwide	-	-	T	Jones et al. (2001)	Yes	-	Yes ^a
Worldwide	-	-	T	Esper et al. (2002)	Yes	Yes	No
NH mid-latitude	-	-	Mp	Lamb (1977, 1982)	Yes	Yes	-
Worldwide	-	-	G + Is	Porter (1986)	Yes	Yes	-
Worldwide	-	-	G	Grove & Switsur (1994)	-	Yes	-
Worldwide	-	-	T+G+D	Hughes & Diaz (1994)	Yes	No? ^b	No? ^b
Worldwide	-	-	Mp	Grove (1996)	-	Yes	-
Worldwide	-	-	B	Huang et al. (1997)	Yes	Yes	No
Worldwide	-	-	D	Perry & Hsu (2000 ^c)	Yes	Yes	No
Worldwide	-	-	D	deMenocal (2001)	Yes	Yes	-
Worldwide	-	-	Ts+Gm+Mp	Stine (1998)	-	Yes	-
Americas							
N. Atlantic (Iceland)	63–66° N	14–24° W	Mp	Ogilvie et al. (2000)	Yes	Yes	No
				Ogilvie & Jónsson (2001)	Yes	Yes	No
N. Atlantic (S. Greenland)	60–70° N	20–55° W	Mp	Ogilvie et al. (2000)	Yes	Yes	No
W. Europe	45–54° N	0–15° E	Mp	Pfister et al. (1998)	Yes	Yes	No
N. Atlantic (Europe)	35–70° N	25° W–30° E	In+D	Luterbacher et al. (2000)	Yes	-	-
Central England	52° N	2° E	In+D	Lamb 65, Manley (1974)	Yes	Yes	No
S. Spain	37.30° N	4.30° W	In+D	Rodrigo et al. (2000)	Yes	-	No
Crete Is.	35.15° N	25.00° E	D	Grove & Conterio (1995)	Yes	-	No
Mid-Russia	50–60° N	30–50° E	In+D	Borisenkov (1995)	Yes	-	-
Czech Republic	48.5–51.2° N	12–19° E	In+B	Bodri & Cermák (1999)	Yes	Yes	Yes?
S. USA	37–38° N	107.5–109.5° W	Pf+Cl+D	Petersen (1994)	Yes	Yes	-
E. China (Guang Dong Prov.)	22–25° N	112–114.3° E	D	Chan & Shi (2000)	Yes	-	-
E. China-wide	20–40° N	90–120° E	D	Song (2000)	Yes	-	No?
Japan	30–40° N	125–145° E	D	Tagami (1993, 1996)	Yes	Yes	No
S. Africa	22.2° S	28.38° E	Cl	Huffman (1996)	Yes	Yes	-
E. Greenland (Nansen Fjord)	68.3° N	29.7° W	Is	Jennings & Weiner (1996)	Yes	Yes	No
C. Greenland (Crête)	71.12° N	37.32° W	Is	Dansgaard et al. (1975)	Yes	Yes	No
C. Greenland (GRIP)	72.6° N	37.6° W	B	Dahl-Jensen et al. (1998)	Yes	Yes	No
S. Greenland (Dye 3)	65.2° N	43.8° W	B	Dahl-Jensen et al. (1998)	Yes	Yes	No
C. Greenland (GISP2)	72.58° N	38.5° W	Ic+Ml	Meese et al. (1994)	Yes	Yes	No
C. Greenland (GISP2)	72.58° N	38.5° W	Is	Stuiver et al. (1995)	Yes	Yes	No
Svalbard	79° N	15° E	Ml	Tarussov (1995)	Yes	Yes	No
Devon Island	75° N	87° W	Ml	Koerner (1977)	Yes	-	Yes ^a
Ellesmere Island	80.7° N	73.1° W	Ml	Koerner & Fisher (1990)	Yes	Yes	No
Ellesmere Island	80.7° N	73.1° W	B+Is	Beltrami & Taylor (1995)	Yes	Yes	No
Gulf of Alaska	60–61° N	149° W	G+T	Calkin et al. (2001)	Yes	Yes	-
Swiss Alps (Gorner Glacier)	45.8–46.5° N	7.75–8.16° E	G+Gm	Holzhauser (1997)	Yes	Yes	No
(Grosser Aletsch Glacier)	45.8–46.5° N	7.75–8.16° E	Is+T	Holzhauser (1997)	Yes	Yes	No
South Georgia Island	54–55° S	36–38° W	G+Gm	Clapperton et al. (1989)	Yes	Yes	-
Southern Alps (Mueller Glacier)	43.44° S	170.06° E	G+Gm	Winkler (2000)	Yes	-	-
Antarctica (James Ross Island)	64.22° S	57.68° W	Is	Anstearain et al. (1990)	Yes?	-	No
Antarctica (Law Dome)	66.73° S	112.83° E	Is	Morgan (1985)	Yes	Yes	No
Antarctica (Victoria Land)	74.33° S	165.13° E	G+Gm+Is	Baroni & Orombelli (1994)	Yes	Yes	-

Table 1 (continued)

Location	Latitude	Longitude	Type	Source	Answer		
					(1)	(2)	(3)
Antarctica (Dome C)	74.65° S	124.17° E	Is	Benoist et al. (1982)	Yes	Yes	No
Prince William Sound, Alaska	60° N	149° W	T+G	Barclay et al. (1999)	Yes	Yes?	-
Alberta, Canada							
Columbia Icefield	52.2° N	117.8° W	T+In+G	Luckman et al. (1997)	Yes	Yes	Yes ^a
N. Québec	57.73° N	76.17° W	T	Arseneault & Payette (1997)	-	Yes	-
Central US	33-49° N	91-109° W	T+Mp	Woodhouse & Overpeck (1998)	Yes	Yes	Yes ^a
E. Idaho	44.1° N	114° W	T	Biondi et al. (1999)	Yes	-	No
N. Carolina	34.5° N	78.3° W	T	Stahle et al. (1988)	Yes	Yes	No?
California (SN)	36.5-37.5° N	118.5-120.5° W	T	Graumlich (1993)	Yes	Yes	No
California (SN)	36.5-37.5° N	118.5-120.5° W	T	Scuderi (1993)	Yes	Yes	No
California (SN)	36-38° N	118-120° W	T	Swetnam (1993)	Yes	Yes	No
New Mexico	34.5° N	108° W	T	Grissino-Mayer (1996)	Yes	Yes	No
Central Eq. Pacific (NINO 3.4)	5° N-5° S	160° E-150° W	T+In	Evans et al. (2000)	Yes	Yes?	No
C. Siberia (Taymir + Putoran)	72.47° N	102° E	T	Naurzbaev & Vaganov (2000)	Yes	Yes	No
Kola Peninsula	67-68° N	33-34° E	T+Is	Hiller et al. (2001)	-	Yes	-
N. Fennoscandia	68° N	22° E	T	Briffa et al. (1992)	Yes	Yes	No
NE. Italy	45° N	10° E	T	Serre-Bachet (1994)	Yes	Yes	No?
Morocco	28-36° N	2-12° W	T	Till & Guiot (1990)	Yes	Yes?	No
Mongolia (Tarvagatay Mts.)	48.3° N	98.93° E	T	Jacoby et al. (1996)	Yes	-	Yes
Mongolia (Tarvagatay Mts.)	48.3° N	98.93° E	T+D	D'Arrigo et al. (2001)	Yes	Yes	Yes
N. Patagonia (Rio Alerce, Argentina)	41.17° S	71.77° W	T	Villalba (1990)	Yes	Yes	No
S. Chile (Lenca)	41.55° S	72.6° W	T	Lara & Villalba (1993)	Yes	No	No
S. South America	33-55° S	60-75° W	T+G	Villalba (1994)	Yes	Yes	No
W. Tasmania	42° S	146.5° E	T	Cook et al. (2000)	No	Yes	Yes?
New Zealand	35-48° S	167-177° E	T	D'Arrigo et al. (1998)	Yes	-	No
N. Scandinavia	68° N	20° E	T+G	Karlén (1998)	Yes	Yes	No
California (SN)	38° N	110° W	Ts	Stine (1994)	-	Yes	No
California (SN)	37.5° N	119.45° W	Ts	Stine (1994)	-	Yes	No
California (SN)	38.38° N	119.45° W	Ts	Stine (1994)	-	Yes	No
California (SN)	38.85° N	120.47° W	Ts	Stine (1994)	-	Yes	No
Patagonia	48.95° S	71.43° W	Ts	Stine (1994)	-	Yes	-
Patagonia	50.47° S	72.97° W	Ts	Stine (1994)	-	Yes	-
NW Michigan (L. Marion)	45° N	85° W	Po	Bernabo (1981)	Yes	Yes	Yes?
Qinghai-Tibetan Plat. (Dunde Ice Cap)	38.1° N	96.4° E	Po	Liu et al. (1998)	Yes	Yes	Yes? ^{a,d}
NE China (Maili)	42.87° N	122.87° E	Po	Ren (1998)	-	Yes	-
NE China (Hangzhou)	30-33° N	105-122° E	Pf	Zhang (1994)	-	Yes	-
China (Taibai Mt.)	33.97° N	107.73° E	Pf+Po	Tong et al. (1996)	Yes	Yes	No
Himalaya	28.38° N	85.72° E	Is	Thompson et al. (2000)	Yes	No	Yes
Himalaya (Dasuopu Glacier)	28.38° N	85.72° E	Ic	Thompson et al. (2000)	Yes	-	Yes
Guliya Ice Cap	35.2° N	81.5° E	Ic+Is	Thompson et al. (1995)	Yes	Yes	No
E. China	30-40° N	100-120° E	Ic+D	Shi et al. (1999)	Yes	Yes	Yes?
W. China (Guliya Cap)	35.2° N	81.5° E	Ic+D	Shi et al. (1999)	Yes	Yes	Yes?
Quelccaya Ice Cap	13.93° S	70.83° W	Is+Ic	Thompson et al. (1986)	Yes	Yes?	No
Antarctica (Siple Station)	75.92° S	84.25° W	Ic+Is	Mosley-Thompson (1995)	No	-	No
Antarctica (Dyer Plateau)	70.67° S	64.88° W	Ic+Is	Thompson et al. (1994)	Yes?	-	Yes
Antarctica (Dronning Maud Land)	76° S	8.05° W	Ic+Is	Karlöf et al. (2000)	Yes	Yes?	No?
South Pole	90° S	-	Ic	Mosley-Thompson & Thompson (1982)	Yes	Yes?	No
N. Atlantic	54.27° N	16.78° W	Sd	Bond et al. (1997)	Yes	Yes	No?
N. Atlantic	44.5° N	46.33° W	Sd	Bond et al. (1999)	Yes	Yes	No
N. Atlantic	56.37° N	27.81° W	Sd	Bianchi & McCave (1999)	Yes	Yes	No?
N. Ellesmere Island	81° N	80° W	Sd+Lf	Lamoureaux & Bradley (1996)	Yes	Yes	-
SW Baltic Sea (Bornholm Basin)	55.38° N	15.4° E	Sd+Is	Andrén et al. (2000)	Yes	Yes	No
N. Fennoscandia (L. Tsuolbmajavri)	68.68° N	22.08° E	Lf	Korhola et al. (2000)	Yes	Yes	No

Table 1 (continued)

Location	Latitude	Longitude	Type	Source	Answer		
					(1)	(2)	(3)
Switzerland (L. Neuchâtel)	47° N	6.55° W	Lf+Is	Filippi et al. (1999)	Yes	Yes	Yes?
NW Scotland (Assynt)	58.11° N	5.06° W	Sp	Proctor et al. (2000)	Yes	Yes	No
W. Ireland	53.53° N	9.93° W	Is	Blackford & Chambers (1995)	Yes	Yes	-
SW Ireland	52.5° N	9.25° W	Sp	McDermott et al. (2001)	Yes	Yes	-
Bermuda Rise	32.17° N	64.5° W	Is	Keigwin (1996)	Yes	Yes	No
Chesapeake Bay	37–38.4° N	76.1° W	Sd	Verardo et al. (1998)	Yes	Yes	-
NW Alaska (Farewell L.)	62.55° N	153.63° W	Lf+Is	Hu et al. (2001)	Yes	Yes	No
S. Dakota (Pickerel L.)	45.51° N	97.27° W	Lf	Dean & Schwalb (2000)	Yes	Yes	No
N. Dakota (Moon L.)	46.85° N	98.16° W	Lf	Laird et al. (1996)	Yes	Yes	No
N. Dakota (Rice L.)	48.01° N	101.53° W	Lf	Yu & Ito (1999)	Yes	Yes	No
Yellowstone P. (Lamar Cave)	44.56° N	110.24° W	Pf+Is	Hadly (1996)	Yes	Yes	No
Colorado Plateau (L. Canyon)	37.42° N	110.67° W	Lf+Gm+Is	Pederson (2000)	Yes	Yes	-
NE Colorado	40–41° N	102–105° W	Gm+Is+D	Madole (1994)	-	Yes	No
SW US (Colorado + Arizona)	34–37.5° N	105–112° W	Lf+Is	Davis (1994)	-	Yes	No?
SW US	32–39° N	109–114° W	Lf+Gm	Ely et al. (1993)	Yes	Yes	No
California (White Mts.)	37.43° N	118.17° W	Is	Feng & Epstein (1994)	Yes	Yes	-
California (L. Owen)	36° N	118.17° W	Is	Li et al. (2000)	Yes	Yes	No
Yucatan Peninsula (L. Chichancanab)	20° N	88.4° W	Lf+Is	Hodell et al. (2001)	Yes	Yes	-
Cariaco Basin	11° N	65° W	Sd	Black et al. (1999)	Yes	Yes	No
Canaco Basin	10.71° N	65.17° W	Sd+Is	Haug et al. (2001)	Yes	Yes	-
S. Florida	24.95° N	80.55° W	Is	Druffel (1982)	Yes	-	-
SW Puerto Rico	18.12° N	67.09° W	Is	Winter et al. (2000)	Yes	-	-
NE China (Jinchuan)	42.3° N	126.37° E	Is	Hong et al. (2000)	Yes	Yes	No
S. Japan (Yakushima Is.)	30.33° N	130.5° E	Is	Kitagawa & Matsumoto (1995)	Yes	Yes	No
N. India (Pahalgam)	34.02° N	75.20° E	Is	Ramesh (1993)	Yes	-	-
S. India (Nilgiris)	10–10.5° N	77° E	Is	Ramesh (1993)	-	Yes	-
E. Africa (L. Malawi)	10° S	35° E	Lf	Johnson et al. (2001)	Yes	-	No
E. Africa (L. Naivasha)	0.46° S	36.21° E	Lf	Verschuren et al. (2000)	Yes	Yes	No
W. Africa (Cap Blanc)	20.75° N	18.58° W	Is	deMenocal et al. (2000)	Yes	Yes	No
S. Africa	19–35° S	10–33° E	Mp	Tyson & Lindsay (1992)	Yes	Yes	No
S. Africa (Nelson Bay Cave)	34° S	23° E	Is	Cohen & Tyson (1995)	Yes	-	No
S. Africa (Makapansgat)	24.54° S	29.25° E	Sp	Tyson et al. (2000)	Yes	Yes	No
N. New Zealand (Waitomo)	38.27° S	175° E	Sp	Williams et al. (1999)	Yes	-	-
S. New Zealand (Nelson)	40.67° S	172.43° E	Sp	Wilson et al. (1979)	Yes	Yes	No
S. America (several regions)	33–38° S	59.3–67° W	Mp	Inondo (1999)	Yes	Yes	-
C. Argentina	29.5–35° S	61.75–65.75° W	Gm+D	Carignano (1999)	Yes	Yes	No
C. Argentina	28–36° S	61–67° W	G+Mp	Cioccale (1999)	Yes	Yes	No
NW Argentina	26.5° S	68.09° W	Sd+Is	Valero-Garcés et al. (2000)	Yes	-	-
W. Antarctica (Palmer Deep)	64.86° S	64.21° W	Sd	Domack et al. (2001)	Yes	Yes	No
W. Antarctica (Siple Dome)	81.65° S	148.81° W	Is	Kreutz et al. (1997)	Yes	-	No

^aWarming or extreme excursion peaked around 1920–1950 before any significant anthropogenic CO₂ release to air

^bHughes & Diaz concluded that '[our] 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 extent 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.' The main conclusion of Hughes & Diaz (1994) may be in actual agreement with the qualitative classification in our paper

^cOnly documentary, historical and archaeological research results, rather than the solar-output model results, of this paper were referred to

^dFor the Dundee ice cap, Thompson et al. (1989) noted that, according to the $\delta^{18}\text{O}$ climate proxy, the 1940s, 1950s and 1980s are at least as warm as the Holocene maximum 6000 to 8000 BP. To confirm Thompson et al. (1989) cf. Fig. 6 in Thompson (2000), because the claim that 1930s–1980s are the warmest of the last 6000–8000 yr is not clear from any figure in Thompson et al. (1989). But the main warming of the 1940s–1950s occurred before a significant rise of anthropogenic CO₂ in the air

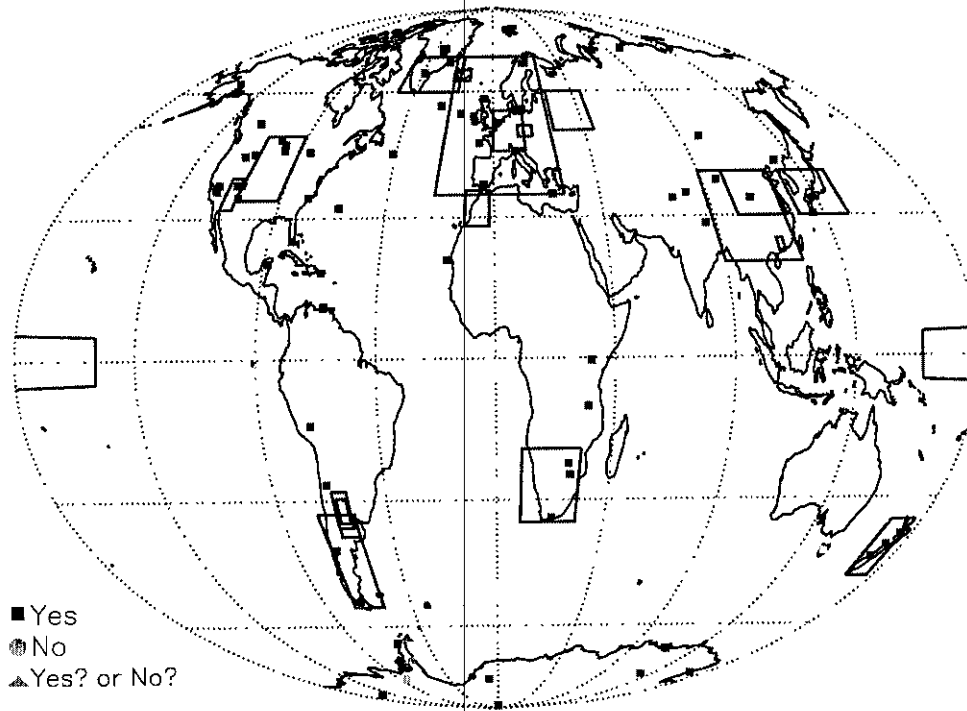


Fig. 1. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Little Ice Age interval (A.D. 1300-1900) in this proxy record? 'Yes' is indicated by red filled squares or unfilled boxes, 'No' is indicated by green filled circles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

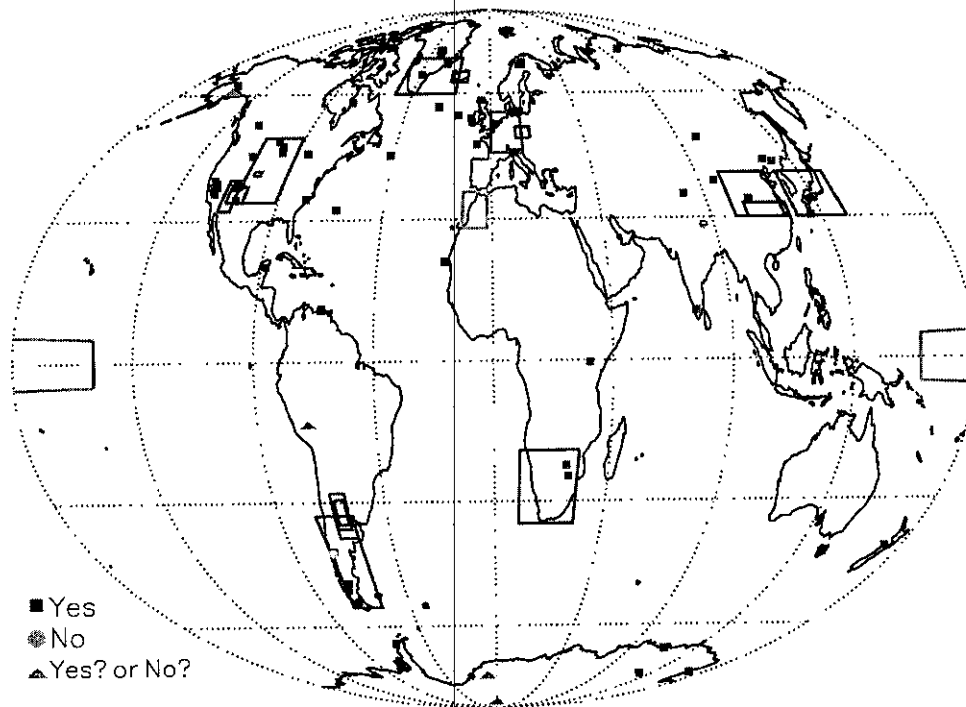


Fig. 2. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Medieval Warm Period (A.D. 800-1300) in this proxy record? 'Yes' is indicated by red filled squares or unfilled boxes, 'No' is indicated by green filled circles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

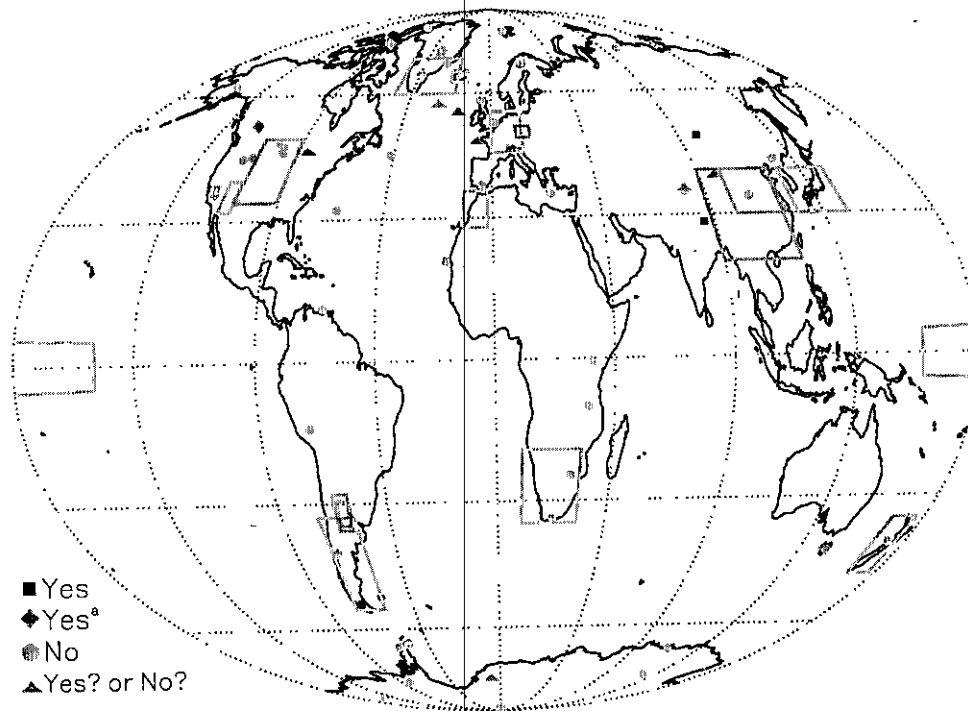


Fig. 3. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly within the 20th century that is the most extreme (the warmest, if such information is available) period in the record? 'Yes' is indicated by red filled squares, 'No' is indicated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

The climate indicators considered here include information from documentary and cultural sources, ice cores, glaciers, boreholes, speleothems, tree-growth limits, lake fossils, mammalian fauna, coral and tree-ring growth, peat cellulose, and pollen, phenological and seafloor sediments. In a rather inhomogeneous way, each proxy is influenced by both climatic and non-climatic factors. We rely on individual researchers for their best judgments in interpreting climatic signals. The 3 questions are addressed in 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.

4. 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, has been discussed by Bryson (1985), Idso (1989) and others. The tempera-

ture changes inferred for the Medieval Warm 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 scale 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 a centennial timescale. But the quantification of errors is complex, and both Bradley et al. (2001) and Esper et al. (2002) have challenged Broecker's statement. Earlier, Jones et al. (1998) provided an enlightening review of the quantitative and qualitative limitations of paleoclimatology. Others like Ingram et al. (1978) and Ogilvie & Farmer (1997) had cautioned against the use of quantitative interpretations of climatic results that are based on historical documentation.

In our survey of the literature we have observed 3 distinct types of warnings (Bryson 1985, Clow 1992, Graybill & Idso 1993, Huang et al. 1996, Briffa et al. 1998, Cowling & Skyes 1999, Schleser et al. 1999, Evans et al. 2000, Schmutz et al. 2000, Aykroyd et al. 2001, Ogilvie & Jónsson 2001):

(1) the lack of timescale resolution for the longest-term component of climate signals, e.g. in tree ring and

coral records, or the loss of short-term climate information in borehole temperature reconstructions;

(2) the nonlinearities (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;

(3) the 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 pattern of land use and land cover over time (Lewis & Wang 1998, Skinner & 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 to 1.8°C (e.g. Lotter et al. 2000). Isotope-coral proxies lack the climate-sensitivity resolution and the continuous length of record to address millennial climatic change. Jones et al. (1998) showed that both coral- and ice-core-based reconstructions performed more poorly than tree-ring records when calibrated against thermometer data since A.D. 1880. On the other hand, tree ring proxies, which usually have annual time resolution, suffer from the loss of information on multi-decadal to centennial and longer components of climate change.

The amplitude of large-scale surface temperature change derived from tree-ring proxies can be substantially underestimated—by a factor of 2 to 3 compared to results from borehole thermometry (Huang et al. 2000, Harris & Chapman 2001). It is surprising that the amplitude of climate variability broadly resolved by borehole reconstruction on timescales of at least 50 to 100 yr is larger, rather than smaller, than the high time resolution results from tree-ring proxies, because short-term climate fluctuations are smoothed out by the geothermal heat-flow that acts as a low-pass filter.¹ The different amplitudes found from borehole and tree-ring climate proxies suggest that longer timescale (multi-decades and century) variability is more faithfully captured by borehole results, while the same information can be irretrievably lost from tree-ring records (see e.g. Collins et al. 2002) because of the standardization procedure (to remove bias due to aging of trees). This is why Jones et al. (1998) commented that although one may be confident of inter-comparing year-to-year and decade-to-decade (limited to periods shorter than 20 to 30 yr) variability, which should be more sensitively imprinted in tree-ring

records, it requires 'considerable faith' to compare, for example, the climate of the 12th and 20th centuries from tree-ring proxies. To date, the practical goal of combining information from borehole and tree-ring proxies, or even comparing borehole and thermometer data, to yield an accurate proxy record that simultaneously resolves timescales of years to centuries, remains unfulfilled.

Despite complicating factors such as the mismatch of climate sensitivities among proxies, a first step has been taken by Beltrami et al. (1995) and Harris & Chapman (2001). Also, Beltrami & Taylor (1995) successfully calibrated a 2000 yr oxygen isotope record from an ice core (near Agassiz) with the help of borehole temperature-depth data (near Neil) for the Canadian Arctic region. Such careful research may help resolve the difficulty of interpreting climate signals that degrade with borehole depth or time. This depth-dependent, increasing degradation has led to the false impression that reconstructed temperatures from geothermal heat flows contained a significantly smaller variability in the distant past than at present.

The approach used here relies on local representations of climate change, which is an advantage because understanding local proxies is the prerequisite for constructing regional and global patterns of change. Another advantage is that by working with a local or regional perspective, we avoid the difficult questions concerning the spatio-temporal coupling of observed changes among various regions and any specific large-scale pattern responsible for those climatic anomalies. Our study has the disadvantage of being non-quantitative. Thus, our assessment falls short of Lamb's (1965) original call for quantitative answers.

An early attempt to study the interlinkage of geographically separated and different proxies, e.g. between marine sediments at Palmer Deep, Antarctica, and atmospheric signals in Greenland ice cores, has been reported by Domack & Mayewski (1999). But many chronologies depend on radiocarbon dating and are too limited in accuracy to allow for reliable interpretation of the timing of events from different areas (e.g. Stine 1998, Domack & Mayewski 1999). The difficult task of areal weighting of different proxy records has been attempted; for the Arctic region by Overpeck et al. (1997), the Northern Hemisphere by Crowley & Lowery (2000), Northern Hemisphere extratropics by Esper et al. (2002) and both Northern Hemisphere and global domains by Mann et al. (1998, 1999, 2000). However, Briffa et al. (2001) criticized the lack of consideration of uncertainties in some of these reconstructions. For example, the composite series in Overpeck et al.'s (1997) reconstruction is not even calibrated with instrumental data.

¹There are exceptions in careful tree-ring results like those of Esper et al. (2002) that are optimized to capture longer timescale variability

5. RESULTS

Table 1 lists the worldwide proxy climate records we have collected and studied. We restricted the list to records that contain either direct information about the 3 specific questions we posed or at least a continuous time series for 400 to 500 yr. For the majority of cases we followed what individual researchers stated according to their paleoclimatic reconstructions. In a few cases we elaborated on their results in order to remain consistent to our framework.

The figures show the results from Table 1 for the Little Ice Age (Fig. 1), Medieval Warm Period (Fig. 2) and the nature of the 20th century's change (Fig. 3). The figures graphically emphasize the shortage of climatic information extending back to the Medieval Warm Period for at least 7 geographical zones: the Australian and Indian continents, the SE 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; see Huang et al. 2000). Therefore, our conclusions are provisional.

Fig. 1 indicates that Little Ice Age exists as a distinguishable climate anomaly from all regions of the world that have been assessed. Only 2 records—tree ring growth from western Tasmania and isotopic measurements from ice cores at Siple Dome, Antarctica—do not exhibit any persistent climatic change over this period (although the western Tasmania reconstruction contains an exceptionally cold decade centered around 1900; Cook et al. 2000).

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

Fig. 3 shows that most of the proxy records do not suggest the 20th century to be the warmest or the most extreme in their local representations. There are only 3 unambiguous findings favoring the 20th century as the warmest anomaly of the last 1000 yr—the records from the Dyer Plateau, Antarctica, the Himalayas and Mongolia (Thompson et al. 1994, 2000, D'Arrigo et al. 2001). An important, seemingly counter-intuitive, feature of Fig. 3 is the large number of uncertain answers compared to the 2 prior questions, perhaps partly owing to inaccurate calibration between proxy and instrumental data. Also, another feature of the result is the many cases in which the

warmest or most extreme climatic anomalies in the proxy indicators occurred in the early to mid-20th century ('Yes^a'), rather than sustaining throughout the century.

5.1. Glaciers

Broadly, glaciers retreated all over the world during the Medieval Warm Period, with a notable, but minor, re-advance between 1050 and 1150 (Grove & Switsur 1994). Large portions of the world's glaciers, both in the Northern and Southern Hemispheres, advanced during the 1300 to 1900s (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 & Meier 2000, D. Evans 2000). Kaser (1999) 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 the 20th century warming as a natural recovery since the Little Ice Age, together with an amplification by anthropogenic CO₂, is plausible but not definitive (Bradley & Jones 1993, Kreutz et al. 1997, Kaser 1999, Beltrami et al. 2000, Dyurgerov & Meier 2000). On the other hand, 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 during interglacials, especially those accompanied by relatively warm winters and cool summers, 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 (ca. A.D. 800–1300) as well as the Little Ice Age interval (A.D. 1300–1900) occurred across the world. The next 2 subsections describe detailed local changes in the Northern and Southern Hemispheres.

5.2. Northern Hemisphere

A composite reconstruction of summer temperature anomaly assuming a simple, uniform weighting of proxy records by Bradley & Jones (1993) showed that the 1530–1730 interval was the coldest period for the Northern Hemisphere, and the 19th century was the second coldest interval in the last 500 yr.

5.2.1. Western Europe

Cold winters and wet summers prevailed during the Little Ice Age in Switzerland, a location with detailed

and reliable information (Pfister 1995). A careful comparison of the Swiss and central England temperature records (Manley 1974) from 1659–1960 reveals a general correspondence of climatic conditions between the 2 regions. In the Andalusia region of southern Spain, rainfall appears to have alternated between dry and wet century-long spells (wet periods persisted 1590–1649 and 1776–1937; dry periods 1501–1589 and 1650–1775) throughout the Little Ice Age, and with no significant difference to the modern dry period of 1938–1997 (Rodrigo et al. 2000). Enhanced fluvial activity was documented in river basins of North, Western and Central Europe for 1250–1550 and 1750–1900 (A. T. Grove 2001). Over Western Europe, Pfister et al. (1998) concluded that severe winters were less frequent and less extreme during 900–1300 than those during 1300–1900. The mild-winter condition was hypothesized by Pfister et al. (1998) to have caused the northward migration of Mediterranean subtropical plants, where St. Albertus Magnus 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 air temperature below freezing, must have grown in Italy (Po valley), France and Germany because a chronicler documented the damage to the olive trees by the bitter frost in January 1234. Lamb (1965) noted generally wet winters but drier summers for the lowlands in England, Ireland, the Netherlands, Denmark, Sweden and NW Germany from about 1200 to 1400. Those conditions are supported by documentary records that describe frequent flooding and storms around those regions during the transitional period between Medieval Warm Period and Little Ice Age.

Is the warmth of the 20th century for western Europe exceptional or unusual? Weather reconstruction results for the Low Countries, the present-day Benelux region, suggest that in order to compare the 20th century to previous centuries, seasonal information in a proxy-climate relation will be required (van Engelen et al. 2001). For example, van Engelen et al. (2001) showed that when the historical reconstructed series from about 800 to 2000 were calibrated to the instrumental temperature records at De Bilt, the 20th century winter temperatures may have been slightly higher (about 0.5°C—the quantitative information on the 20th century warmth is certainly within the margin of uncertainties) than the high winter temperatures of 1000–1100 but that recent warming began in the 19th century. In contrast, the 20th century summer temperatures are neither unusual nor extraordinarily warm when compared to summer temperature variabilities during other times of the 2nd millennium (see Figs. 1 & 2 of van Engelen et al. 2001).

5.2.2. 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, were experiencing 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). Climate over Iceland was found, based on various proxies, to be mild from 870 to 1170, with cold periods setting in after 1200. Instead of being a period of unrelenting cold, 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 & Jónsson 2001).

The viking colonization of Greenland's coastal area starting in 986 is well documented, and the generally mild and benign climatic conditions from about 800 to 1200 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, while the 'Eastern Settlement', actually near the southernmost tip of west Greenland, around the Narssaq and Julianehab districts, died out between 1450 and 1500 (Grove 1996, Ogilvie et al. 2000). It also seems that both cultural and political factors contributed in making the Norse Greenlanders at the Western Settlement more vulnerable to the harsh climatic conditions (Barlow et al. 1997). The timing for the abandonment of these settlements coincided with the 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 & Weiner (1996) confirmed an initial cooling between 1270 and 1370, together with the most severe and variable climatic conditions around the East Greenland region from 1630 to 1900. The results of Ogilvie et al. (2000) and Ogilvie & 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 to 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 (Grove & 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 & 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 to 1234. Thus, precipitation anomalies for the Little Ice Age and Medieval Warm Period do not differ from each other in this region—both intervals suffered from persistent drought conditions. For this reason, we gave an uncertain designation for the occurrence of a distinct climatic anomaly associated with Medieval Warm Period for Morocco in Table 1 and Fig. 2.

Distinctly cooler conditions prevailed over the ocean surface—in the Caribbean Sea by about 2 to 3°C (Winter et al. 2000) and in the Sargasso Sea by about 1°C (Keigwin 1996), especially during the 17th and 18th centuries as opposed to the present. DeMenocal et al. (2000) showed that the subtropical North Atlantic's sea surface temperature off Cap Blanc of Mauritania (west Africa) was also cooler by 3 to 4°C between 1300 and 1850 than at present. During the Medieval Warm Period, the Sargasso sea surface temperature was about 1°C warmer than the present-day value (Keigwin 1996), while the sea surface temperature off the coast of Mauritania was only marginally warmer than at present (DeMenocal et al. 2000). High-resolution coral skeletal $\delta^{18}\text{O}$ and Sr/Ca ratio records from Bermuda indicate sea-surface temperature standard deviations of about $\pm 0.5^\circ\text{C}$ on interannual and $\pm 0.3^\circ\text{C}$ on decadal timescales during the 16th century, and those ranges of variability are comparable to estimates from modern 20th century's instrumental data (Kuhnert et al. 2002). But those sub-annually resolved 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 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 in the Medieval Warm Period. Over the equatorial Central Pacific, around the NINO3.4 (5°N–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), showed that there appeared to be a sustained cool phase of the proxy NINO3.4 SST variability from about 1550 to about 1895, hence 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 suggesting that the recent 20th century decadal-scale changes in the equatorial Pacific Ocean are neither unusual nor unprecedented.

5.2.3. Asia and Eastern Europe

From 49 radiocarbon-dated subfossil wood samples, Hiller et al. (2001) found that the alpine tree-limit on the Khibiny low mountains of the Kola Peninsula was located at least 100 to 140 m above current tree-limit elevation during the relatively warmer time between 1000 and 1300. The summer temperatures corresponding to this 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 the coolest winters around 1620–1680, the coolest summers-springs around 1860–1900, as well as distinctively warm conditions during the first half of the 16th century, similar to conditions for Western Europe described above. The ground surface temperature histories deduced from boreholes around the Czech Republic suggest that winters during 1600 and 1700 were the most severe compared to any other winters since at least 1100 (Bodri & Cermák 1999). The temperature-depth borehole records also yield a clear signature of an anomalously warm period for central Bohemia, especially around 1100–1300.

Bradley and Jones (1993) showed that the mid-17th century was the coldest in China. In NE 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 including the 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). Chan & Shi (2000) further documented the notably larger number of land-falling typhoons over Guangdong Province in the early-to-mid-19th century based on a homogeneous set of typhoon records from 1470 to 1931. Using a $\delta^{18}\text{O}$ proxy record from peat cellulose with 20 yr resolution and various Chinese historical records, Hong et al. (2000) showed the general cooling trend in the surface air temperature during the Little Ice Age interval in NE China. Hong et al. found 3 of the coolest minima in the record centered around 1550, 1650 and 1750. An obvious warm period peaked around 1100–1200, 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 yr showed that northern boundaries for these plants had

shifted and expanded; their northernmost location was reached around 1264 (Zhang 1994). Zhang then deduced that temperature conditions in the 13th century around central China must have been about 1°C warmer than present. Ren (1998) found further evidence from a fossil pollen record at Maili Bog, NE China, that summer monsoon rainfall from 950 to 1270 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 the 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 the study of number of days with snowfall relative to days with rainfall, Tagami (1996) concluded that the 11th and 12th centuries were unusually warm in Japan. During the Little Ice Age, summers were relatively cool from the 1730s to 1750s, in the 1780s, from the 1830s to the 1840s and in the 1860s, and winters were cold through the 1680s to 1690s, and in the 1730s and 1810s. From the tree-cellulose $\delta^{13}\text{C}$ record of a giant Japanese cedar *Cryptomeria japonica* grown on Yakushima Island of southern Japan, Kitagawa & Matsumoto (1995) inferred a cool temperature of 2°C below average from 1600 to 1700 and a warm period of about 1°C above average between 800 and 1200.

5.2.4. North America

Overall, the composite summer temperature anomaly from Bradley & Jones (1993) showed that over North America the temperature during the 15th to 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 yr interval in the 1000 yr tree-ring proxy record was around 1595–1644, while the wettest 50 yr period was 1712–1761. These periods are consistent with our definition of a discernible climatic anomaly associated with the Little Ice Age interval of 1300–1900. 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, 91–109° W), drought episodes were noted for the 13th to 16th centuries (Woodhouse & Overpeck 1998). These droughts were of longer duration and greater extent than the

1930s–1950s drought. Additionally, both Yu & Ito (1999) and Dean & Schwalb (2000) pointed to the cycles of aridity lasting about 400 yr from lake records of the Northern Great Plains, where the last dry condition peaked around 1550–1700.

From an extensive collection of multiproxy evidence, Stine (1998) concluded that during the Medieval Warm Period prolonged intervals of extreme drought visited California, the NW Great Basin, the northern Rocky Mountains/Great Plains, while markedly wetter regimes persisted in the upper Midwest/sub-Arctic Canada and Southern Alaska/British Columbia areas. There was also a significant but brief interval around 1110–1140 when moisture conditions switched from dry to wet in California, the NW 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 in the upper Midwestern U.S. around 1100 is the contraction and subsequent expansion of the circumpolar vortex. Summer polar fronts shifted significantly southward, and stopped the penetration of moisture-laden air from the Gulf of Mexico (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 (1993)'s 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 the 2 warmest and the 2 driest 50 yr intervals occurred, at 1118–1167, 1245–1294 and 1250–1299, 1315–1364, respectively.

Hu et al. (2001), based on their high-resolution (multidecadal) geochemical analysis of sediments from Farewell Lake by the NW foothills of the Alaska Range, also found pronounced signatures of the Medieval Warm Period around 850–1200. During the Little Ice Age the surface water temperature of Farewell Lake suffered a low in 1700 calibrated to be about 1.75°C cooler than present. They also noted that colder periods were in general wetter (in contrast to drier conditions during Little Ice Age in the Central U.S. region described above) than the warm periods in this part of NW Alaska. On the Yucatan Peninsula, prolonged drought episodes recur approximately every 208 yr, with the 2 most significant recent peaks centered around 800 and 1020 (Hodell et al. 2001). The timing of severe droughts also seems to fit several known discontinuities in the evolution of the Mayan culture.

5.3. Southern Hemisphere

Figs. 1–3 highlight the sparse coverage of the Southern Hemisphere by proxy climatic information through the 2nd millennium.

5.3.1. New Zealand

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

5.3.2. South Africa

Tyson et al. (2000) showed through isotopic measurements in speleothem 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 compared to the present. This cooling feature corresponds well with the maximum cooling signal contained in a coral record from SW Madagascar (Tyson et al. 2000). Tyson & Lindesay (1992) showed that the Little Ice Age in South Africa had 2 major cooling phases, around 1300–1500 and 1675–1850, with a sudden warming interval between 1500 and 1675. In addition, Tyson & 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 present around 1200–1300 (Tyson et al. 2000). The multiproxy review by Tyson & Lindesay (1992) showed evidence for a wetter South Africa after 1000, when forest and wetland became more extensive, including the development of a riverine forest in the northern Namib desert along the Hoanib river during the 11th–13th centuries.

5.3.3. 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 (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 (and in 3 other intervals: 200–400, 500–700 and 1850–1998), which could be interpreted as increased winter rains from enhanced mid-latitude westerlies that ushered in more frontal system activities. In contrast, during the Medieval Warm Period, the southern Patagonia region at latitudes between 47 and 51°S became abnormally dry for several centuries before 1130 when water levels in several lakes (Lake Argentino, Lake Cardiel and Lake Ghio) dropped significantly. Also, trees like the southern beech *Nothofagus* sp. grew as old as 100 yr 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 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 2 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 m long, 60–80 m wide, and 2–3 m 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 km² and with a depth of 13 m (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 2nd millennium, when the dune fields were conquered by lakes and the Mar Chiquita Lake expanded beyond its present dimensions. Precipitation exceeded current val-

ues, 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 kms to the northwest today (Carignano 1999). Cioccale (1999) noted evidence of human cultivation of hillside areas in Central Andes, Peru, at places as high as 4300 m above sea level around 1000.

5.3.4. 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 studies 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 yr (Mercer 1978, Thomas et al. 1979, Rott et al. 1996, Vaughan & 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 Fig. 3, also Vaughan & Doake 1996, D. Evans 2000).

For the Little Ice Age, advances of glaciers in South Georgia Island, which is currently half-covered by glaciers, 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, which corresponds to the timing for the Medieval Warm Period. Baroni & Orombelli (1994) described a similar sequence 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 2 distinct phases, around 920–1020 and 1270–1400, and then advanced at least 150 m after the 15th century. Isotopic thermometry from ice cores at Dome C (74.65°S, 124.17°E, elevation 3240 m) and Law Dome (66.73°S, 112.83°E, elevation 1390 m) 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 & Mayewski 1999, Domack et al. 2001) drilled near Palmer Deep site (64.86°S, 64.21°W) off the Antarctic Peninsula also show a marked increase, in bio-productivity, hence a decrease in magnetic susceptibility because of dilution of the magnetite, with a peak centered around 1000–1100 yr BP. This observation probably implied 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, hence an increase in magnetic susceptibility owing to less dilution of the magnetic minerals by biogenic materials, from about 700 to 100 yr BP. This time period corresponds to the Little Ice Age of ca. 14th–19th centuries and is likely to have been accompanied by cool and windy conditions. Abundance analyses of Na⁺ sea salt in the ice core from Siple Dome (81.65°S, 148.81°W) also confirm the Little Ice Age anomaly characterized by substantial variability in the strength of meridional circulation that extended between 1400 and 1900 (Kreutz et al. 1997).

But there are also indications for significant regional differences in climatic anomalies associated with the 2 phenomena at Antarctica. The temperature at Siple Station (75.92°S, 84.25°W, elevation 1054 m) was relatively warm from the 15th to early 19th centuries (although there were also noticeable decade-long cooling dips centered around 1525, 1600 and 1750; Mosley-Thompson 1995). The 400 yr isotopic temperature inferred from a core at the Dalinger Dome (64.22°S, 57.68°W, elevation 1640 m) on James Ross Island, off the Antarctic Peninsula, also showed 1750–1850 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 m), also 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 4000 yr was reached around 1000 (Clow & Waddington 1999); note that we have omitted these discussions in our Table 1 or Figs. 1 to 3 because the results are claimed as preliminary and they were only presented in a conference abstract.

6. DISCUSSION

The widespread geographical evidence assembled here supports the existence of both the Little Ice Age and the Medieval Warm Period, and should serve as useful validation targets for any reconstruction of global climate history of the last 1000 yr. Our results suggest a different interpretation of the multiproxy climates compared to recent conclusions of Mann et al. (1998, 1999, 2000). Because the calibration of proxy indicators to instrumental data is still a matter of open-ended research (with differing sensitivities not only for the same proxy at different locations but also for different proxies at the same location), it is premature to select a year or decade as the warmest or coldest in a multiproxy-based record.

Barnett et al. (1999) has pointed out that it is *impossible* to use available instrumental records to provide estimates for the multi-decadal and century-long type of *natural* climatic variations, owing to the specific period and short duration of instrumental records. Thus, paleo-proxies remain the only hope for assessing the amplitude and pattern of climatic and environmental change in the pre-anthropogenic era. We agree with Barnett et al. (1999) that each proxy should be studied first in terms of local change before several records can be combined for regional and larger spatial-scale analyses and interpretations. The conclusion derives mainly from the real possibility of non-stationarity in the proxy-climate calibration to instrumental records, the lack of adequate superposition rules given variability in each type of proxy, as well as the lack of clear physical understanding on the multidecadal climate variability from theoretical or empirical studies.

All current calibration of proxies to large-scale instrumental measurements have been mainly valid over phases of rising temperature (Ogilvie & Jónsson 2001). 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 timescale, even in the reasonably well observed region of the North Atlantic (Häkkinen 2000, Seager et al. 2000, Marshall et al. 2001, Slonosky & Yiou 2001, von Storch et al. 2001).

Briffa (2000) concluded that dendroclimatological records may support 'the notion that the last 100 years have been unusually warm, at least within the context of the last two millennia' Slightly 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 yr timescale 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 yr. This conclusion is consistent with the borehole reconstruction results of Huang et al. (2000). However, longer and more carefully reconstructed tree-ring chronologies from Esper et al. (2002) showed that the Medieval Warm Period was as warm as the 20th century for at least a region covering the Northern Hemisphere extratropics from about 30 to 70° N.

An important aspect of both the Briffa et al. (2001) and Esper et al. (2002) 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, 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 (that assumption of 'error-free' instrumental thermometer data is incorrect—see Jones et al. 1999, Folland et al. 2001). Over the full 2nd millennium, Esper et al. (2002) deduced a slightly larger range in their confidence limits after 1950 (compared to the pre-1950 interval extending back to 800) and attributed those higher uncertainties to the accounting for the anomalous modern ring-growth problem (Graybill & Idso 1993, Jacoby & D'Arrigo 1995, Briffa et al. 1998, Feng 1999, Barber et al. 2000, Jacoby et al. 2000, Knapp et al. 2001).

7. CONCLUSION

Many interesting questions on the geographical nature and physical factors of surface temperature or precipitation changes over the last 1000 yr cannot be quantitatively and conclusively answered by current knowledge. The adopted period of 1000 yr is strictly a convenience that merits little scientific weight.

Climate proxy research provides an aggregate, broad perspective on questions regarding the reality of Little Ice Age, 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 epoch are widespread and near-synchronous phenomena, as conceived by Bryson et al. (1963), Lamb (1965) and numerous researchers since. Overall, the 20th century does not contain the warmest anomaly of the past millennium in most of the proxy records, which have been sampled world-wide. Past researchers implied that unusual 20th century warming means a global human impact. However, the proxies show that the 20th century is not unusually warm or extreme.

The lack of unusual warmth in the 20th century does not argue against human impacts on local and regional scales (perhaps on scales as small as 10 to 1000 km² for precipitation and 10⁴ to 10⁵ km² for temperature). Recently, Lawton et al. (2001) demonstrated 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. It is thus clear that human activity affects local environment and climate. On the other hand, A. T. Grove (2001) advised caution when interpreting dubious claims about the dominant role played by human activity such as in deforestation, agricultural expansion and population growth on geomorphological changes in Mediterranean Europe. In particular, A. T. Grove (2001) showed that the wide spread occurrence of the medieval fluvial terrace called the 'younger fill' around Mediterranean Europe was more powerfully influenced by increased frequency of deluges during Alpine glacier advances associated with the Little Ice Age than by soil erosion and rapid sedimentation caused by deforestation.

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