

ARMS 37

RECORD TYPE: FEDERAL (NOTES MAIL)

CREATOR:Robert C. McNally (CN=Robert C. McNally/OU=OPD/O=EOP [OPD])

CREATION DATE/TIME:11-APR-2003 15:19:56.00

SUBJECT:: Re: Press Release Re: 20th Century Climate Not So Hot

TO:Phil Cooney (CN=Phil Cooney/OU=CEQ/O=EOP@EOP [CEQ])

READ:UNKNOWN

TEXT:

----- Forwarded by Robert C. McNally/OPD/EOP on 04/11/2003 03:18 PM -----

David Halpern
04/11/2003 12:46:15 PM
Record Type: Record

To: Robert C. McNally/OPD/EOP@EOP
cc: Kathie L. Olsen/OSTP/EOP@EOP, Richard M. Russell/OSTP/EOP@EOP,
Clifford J. Gabriel/OSTP/EOP@EOP, David Halpern/OSTP/EOP@EOP
Subject: Re: Press Release Re: 20th Century Climate Not So Hot

Robert,

Attached are the two papers referenced in the Press Release.

Please let me know if you would like additional information.

David Halpern

Richard M. Russell
04/10/2003 05:19:51 PM

Record Type: Record

To: Robert C. McNally/OPD/EOP@EOP
cc: David Halpern/OSTP/EOP@EOP, Kathie L. Olsen/OSTP/EOP@EOP
bcc:
Subject: Re: Fwd: Cfa: 20th CENTURY CLIMATE NOT SO HOT

Our Science division is tracking it down. They will get it if it can be gotten. Dr. David Halpern will be sending it to you directly. He will also be able to answer any question you have about the study.

Robert C. McNally
04/10/2003 05:11:58 PM
Record Type: Record

To: Richard M. Russell/OSTP/EOP@EOP
cc:
bcc:
Subject: Re: Fwd: CfA: 20th CENTURY CLIMATE NOT SO HOT

If this is funded by NASA, can we get an advance copy?

Richard M. Russell
04/10/2003 05:08:41 PM

Record Type: Record

To: Robert C. McNally/OPD/EOP@EOP
cc:
Subject: Fwd: CfA: 20th CENTURY CLIMATE NOT SO HOT

Bob -- if you din't already have, this is the study the President was talking about.

----- Forwarded by Richard M. Russell/OSTP/EOP on
04/10/2003 05:07 PM -----

Kathie L. Olsen
04/10/2003 04:49:32 PM
Record Type: Record

To: John H. Marburger/OSTP/EOP@EOP, Richard M. Russell/OSTP/EOP@EOP
cc:
Subject: Fwd: CfA: 20th CENTURY CLIMATE NOT SO HOT

This is the article I forwarded to Phil.

>
>THE FOLLOWING RELEASE WAS RECEIVED FROM THE HARVARD-SMITHSONIAN
>CENTER FOR ASTROPHYSICS, IN CAMBRIDGE, MASSACHUSETTS, AND IS
>FORWARDED FOR YOUR INFORMATION. (FORWARDING DOES NOT IMPLY
>ENDORSEMENT BY THE AMERICAN ASTRONOMICAL SOCIETY.) Steve Maran,
>American Astronomical Society

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>
>Release No: 03-10
>For Immediate Release

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04/10/2003 05:11:58 PM
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Subject: Re: Fwd: Cfa: 20th CENTURY CLIMATE NOT SO HOT

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04/10/2003 05:08:41 PM

Record Type: Record

To: Robert C. McNally/OPD/EOP@EOP
cc:
Subject: Fwd: Cfa: 20th CENTURY CLIMATE NOT SO HOT

[REDACTED]
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Kathie L. Olsen
04/10/2003 04:49:32 PM
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>
>Release No: 03-10
>For Immediate Release

>
 >NOTE TO EDITORS: Photos of key climate indicators are available online at
 ><http://cfa-www.harvard.edu/press/pr0310image.html>

>
 >20th CENTURY CLIMATE NOT SO HOT

>
 >Cambridge, MA -- A review of more than 200 climate studies led by
 >researchers at the Harvard-Smithsonian Center for Astrophysics has
 >determined that the 20th century is neither the warmest century nor
 >the century with the most extreme weather of the past 1000 years. The
 >review also confirmed that the Medieval Warm Period of 800 to 1300
 >A.D. and the Little Ice Age of 1300 to 1900 A.D. were worldwide
 >phenomena not limited to the European and North American continents.
 >While 20th century temperatures are much higher than in the Little
 >Ice Age period, many parts of the world show the medieval warmth to
 >be greater than that of the 20th century.

>
 >Smithsonian astronomers Willie Soon and Sallie Baliunas, with
 >co-authors Craig Idso and Sherwood Idso (Center for the Study of
 >Carbon Dioxide and Global Change) and David Legates (Center for
 >Climatic Research, University of Delaware), compiled and examined
 >results from more than 240 research papers published by thousands of
 >researchers over the past four decades. Their report, covering a
 >multitude of geophysical and biological climate indicators, provides
 >a detailed look at climate changes that occurred in different regions
 >around the world over the last 1000 years.

>
 >"Many true research advances in reconstructing ancient climates have
 >occurred over the past two decades," Soon says, "so we felt it was
 >time to pull together a large sample of recent studies from the last
 >5-10 years and look for patterns of variability and change. In fact,
 >clear patterns did emerge showing that regions worldwide experienced
 >the highs of the Medieval Warm Period and lows of the Little Ice Age,
 >and that 20th century temperatures are generally cooler than during
 >the medieval warmth."

>
 >Soon and his colleagues concluded that the 20th century is neither
 >the warmest century over the last 1000 years, nor is it the most
 >extreme. Their findings about the pattern of historical climate
 >variations will help make computer climate models simulate both
 >natural and man-made changes more accurately, and lead to better
 >climate forecasts especially on local and regional levels. This is
 >especially true in simulations on timescales ranging from several
 >decades to a century.

>
 >--Historical Cold, Warm Periods Verified--

>
 >Studying climate change is challenging for a number of reasons, not
 >the least of which is the bewildering variety of climate indicators -
 >all sensitive to different climatic variables, and each operating on
 >slightly overlapping yet distinct scales of space and time. For
 >example, tree ring studies can yield yearly records of temperature
 >and precipitation trends, while glacier ice cores record those
 >variables over longer time scales of several decades to a century.

>
 >Soon, Baliunas and colleagues analyzed numerous climate indicators
 >including: borehole data; cultural data; glacier advances or
 >retreats; geomorphology; isotopic analysis from lake sediments or ice
 >cores, tree or peat celluloses (carbohydrates), corals, stalagmite or
 >biological fossils; net ice accumulation rate, including dust or

>chemical counts; lake fossils and sediments; river sediments; melt
>layers in ice cores; phenological (recurring natural phenomena in
>relation to climate) and paleontological fossils; pollen; seafloor
>sediments; luminescent analysis; tree ring growth, including either
>ring width or maximum late-wood density; and shifting tree line
>positions plus tree stumps in lakes, marshes and streams.

>
>"Like forensic detectives, we assembled these series of clues in
>order to answer a specific question about local and regional climate
>change: Is there evidence for notable climatic anomalies during
>particular time periods over the past 1000 years?" Soon says. "The
>cumulative evidence showed that such anomalies did exist."

>
>The worldwide range of climate records confirmed two significant
>climate periods in the last thousand years, the Little Ice Age and
>the Medieval Warm Period. The climatic notion of a Little Ice Age
>interval from 1300 to 1900 A.D. and a Medieval Warm Period from 800 to
>1300 A.D. appears to be rather well-confirmed and wide-spread,
>despite some differences from one region to another as measured by
>other climatic variables like precipitation, drought cycles, or
>glacier advances and retreats.

>
>"For a long time, researchers have possessed anecdotal evidence
>supporting the existence of these climate extremes," Baliunas says.
>"For example, the Vikings established colonies in Greenland at the
>beginning of the second millennium that died out several hundred
>years later when the climate turned colder. And in England, vineyards
>had flourished during the medieval warmth. Now, we have an
>accumulation of objective data to back up these cultural indicators."

>
>The different indicators provided clear evidence for a warm period in
>the Middle Ages. Tree ring summer temperatures showed a warm interval
>from 950 A.D. to 1100 A.D. in the northern high latitude zones, which
>corresponds to the "Medieval Warm Period." Another database of tree
>growth from 14 different locations over 30-70 degrees north latitude
>showed a similar early warm period. Many parts of the world show the
>medieval warmth to be greater than that of the 20th century.

>
>The study -- funded by NASA, the Air Force Office of Scientific
>Research, the National Oceanic and Atmospheric Administration, and
>the American Petroleum Institute -- will be published in the Energy
>and Environment journal. A shorter paper by Soon and Baliunas
>appeared in the January 31, 2003 issue of the Climate Research
>journal.

>
>Headquartered in Cambridge, Massachusetts, the Harvard-Smithsonian
>Center for Astrophysics (CfA) is a joint collaboration between the
>Smithsonian Astrophysical Observatory and the Harvard College
>Observatory. CfA scientists organized into six research divisions
>study the origin, evolution, and ultimate fate of the universe.

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>should be sent to the same address.

--
Anne L. Kinney

Proxy climatic and environmental changes of the past 1000 years

Willie Soon^{1,2,*}, Sallie Baliunas^{1,2}

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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^a' 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
NH mid-latitude	–	–	T	Esper et al. (2002)	Yes	Yes	No
Worldwide	–	–	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	–
Americas	–	–	Ts+Gm+Mp	Stine (1998)	–	Yes	–
N. Atlantic (Iceland)	63–66° N	14–24° W	Mp	Ogilvie et al. (2000)	–	–	–
				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	Aristarain 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	Karlóf 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	Lamoureux & 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
Cariaco 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 (Nilgris)	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 & Lindesay (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 Dunde ice cap, Thompson et al. (1989) noted that, according to the δ¹⁸O 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

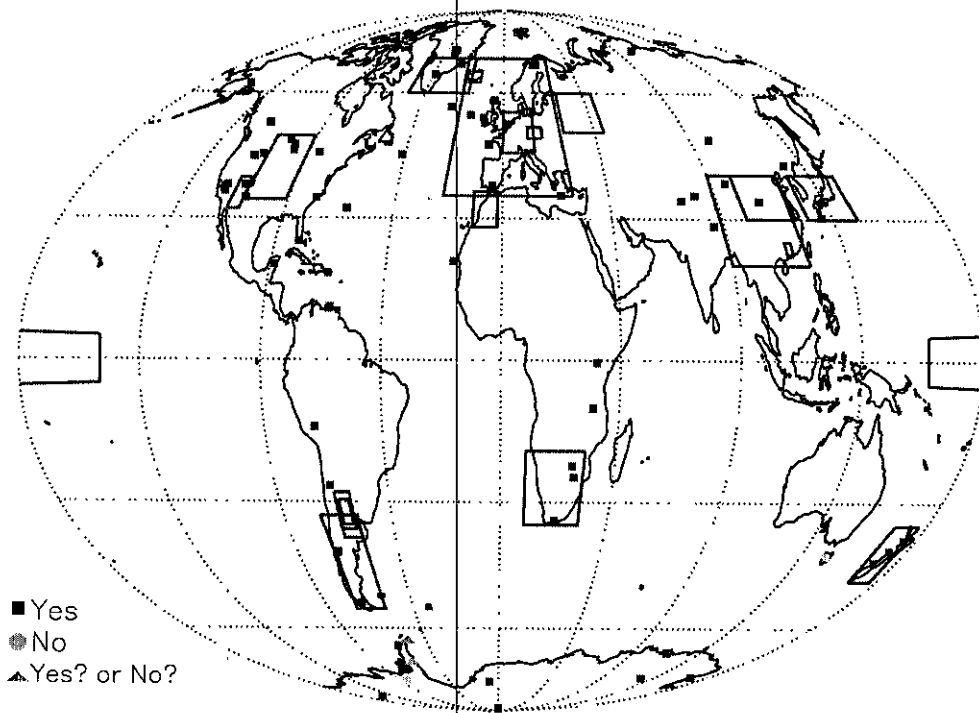


Fig. 1. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Little Ice Age interval (A.D. 1300-1900) in this proxy record? 'Yes' is indicated by red filled squares or unfilled boxes, 'No' is indicated by green filled circles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

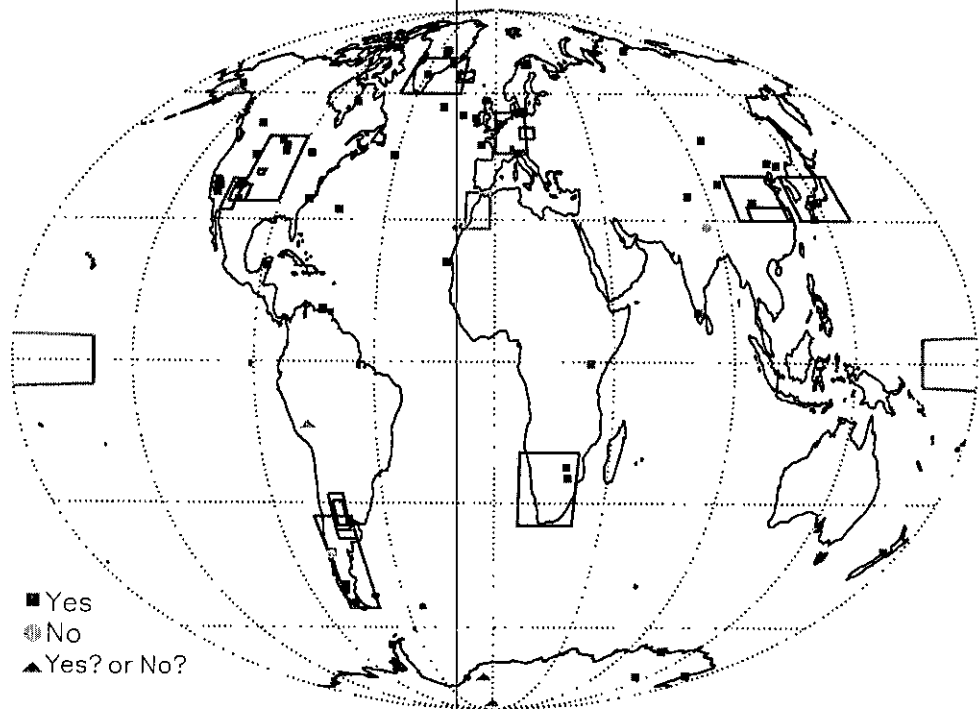


Fig. 2. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Medieval Warm Period (A.D. 800-1300) in this proxy record? 'Yes' is indicated by red filled squares or unfilled boxes, 'No' is indicated by green filled circles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

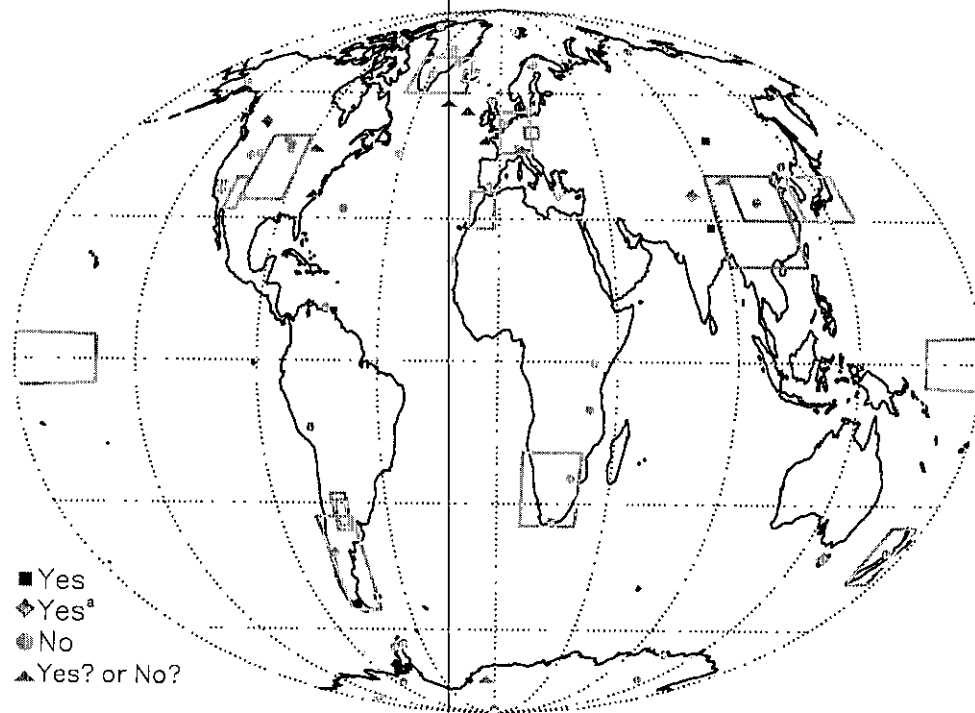


Fig. 3. Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly within the 20th century that is the most extreme (the warmest, if such information is available) period in the record? 'Yes' is indicated by red filled squares, 'No' is indicated 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 & Schwab (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 become 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.

Acknowledgements. This work was supported by funds from the American Petroleum Institute (01-0000-4579), the Air Force Office of Scientific Research (Grant AF49620-02-1-0194) and the National Aeronautics and Space Administration (Grant NAG5-7635). The views expressed herein are those of the authors and are independent of the sponsoring agencies. We have benefitted greatly from the true and kind spirit of research communications (including a preview of their thoughts) with the late Jean Grove (who passed away on January 18, 2001), Dave Evans, Shaopeng Huang, Jim Kennett, Yoshio Tagami and Referee #3. We thank John Daly, Diane Douglas-Dalziel, Craig and Keith Idso for their unselfish contributions to the references. We also thank the Editor, Chris de Freitas, for very helpful editorial changes that improved the manuscript. We are very grateful to Maria McEachern, Melissa Hilbert, Barbara Palmer and Will Graves for invaluable library help, and both Philip Gonzalez and Lisa Linarte for crucial all-around help.

LITERATURE CITED

- Andrén E, Andrén T, Sohlenius G (2000) The Holocene history of the southwestern Baltic Sea as reflected in sediment core from the Bornholm Basin. *Boreas* 29:233–250
- Aristarain AJ, Jouzel J, Lorius C (1990) A 400 years isotope record of the Antarctic Peninsula climate. *Geophys Res Lett* 17:2369–2372
- Arseneault D, Payette S (1997) Reconstruction of millennial forest dynamics from tree remains in a subarctic tree line peatland. *Ecology* 78:1873–1883
- Aykroyd RG, Lucy D, Pollard AM, Carter AHC, Robertson I (2001) Temporal variability in the strength of the proxy-climate correlations. *Geophys Res Lett* 28:1559–1562
- Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405:668–673
- Barclay DJ, Wiles GC, Calkin PE (1999) A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska. *Holocene* 9:79–84
- Barlow LK, Sadler JP, Ogilvie AEJ, Buckland PC and 5 others (1997) Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. *Holocene* 7:489–499
- Barnett T, Hasselmann K, Chelliah M, Delworth T and 7 others (1999) Detection and attribution of recent climate change: a status report. *Bull Am Meteor Soc* 80:2631–2659
- Baroni C, Orombelli G (1994) Holocene glacier variations in the Terra Nova Bay area (Victoria Land, Antarctica). *Antarctic Sci* 6:497–505
- Beltrami H, Taylor AE (1995) Records of climatic change in the Canadian Arctic: towards calibrating oxygen isotope data with geothermal data. *Glob Planet Change* 11:127–138
- Beltrami H, Chapman DS, Archambault S, Bergeron Y (1995) Reconstruction of high resolution ground temperature histories combining dendrochronological and geothermal data. *Earth Planet Sci Lett* 136:437–445
- Beltrami H, Wang J, Bras RL (2000) Energy balance at the Earth's surface: heat flux history in eastern Canada. *Geophys Res Lett* 27:3385–3388
- Benoist JP, Jouzel J, Lorius C, Merlivat L, Pourchet M (1982) Isotope climatic record over the last 2.5 ka from Dome C, Antarctica, ice cores. *Ann Glaciology* 3:17–22
- Bernabo JC (1981) Quantitative estimates of temperature changes over the last 2700 years in Michigan based on pollen data. *Quat Res* 15:143–159
- Bianchi GG, McCave IN (1999) Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* 397:515–517
- Biondi F, Perkins DL, Cayan DR, Hughes MK (1999) July temperature during the second millennium reconstructed from Idaho tree rings. *Geophys Res Lett* 26:1445–1448
- Black DE, Peterson LC, Overpeck JT, Kaplan A, Evans MN, Kashgarian M (1999) Eight centuries of North Atlantic Ocean atmosphere variability. *Science* 286:1709–1713
- Blackford JJ, Chambers FM (1995) Proxy climate record for the last 1000 years from Irish blanket peat and a possible link to solar variability. *Earth Planet Sci Lett* 133:145–150
- Bodri L, Cermák (1999) Climate change of the last millennium inferred from borehole temperatures: regional patterns of climatic changes in the Czech Republic. Part III. *Glob Planet Change* 21:225–235
- Bond G, Showers W, Cheseby M, Lotti R and 6 others (1997) A pervasive millennial-scale cycle in North Atlantic holocene and glacial climates. *Science* 278:1257–1266
- Bond G, Showers W, Elliot M, Evans M, Lotti R, Hajdas I, Bonani G, Johnson S (1999) The North Atlantic's 1–2 kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger cycles and the little ice age. In Clark PU, Webb RS, Keigwin LD (eds) *Mechanisms of global climate change at millennial time scales*, Vol. 112. American Geophysical Union Press, Washington DC, p 35–58
- Borisenkov YeP (1995) Documentary evidence from the U.S.S.R. In: Bradley RS, Jones PD (eds) *Climate since A.D. 1500*. Routledge, New York, p 171–183
- Bradley RS, Jones PD (1993) 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *Holocene* 3:367–376
- Bradley RS, Briffa KR, Crowley TJ, Hughes MK, Jones PD, Mann ME (2001) The scope of Medieval Warming. *Science* 292:2011–2012
- Briffa KR (2000) Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quat Sci Rev* 19:87–105
- Briffa KR, Jones PD, Bartholin TS, Eckstein D, Schweingruber FH, Karlen W, Zetterberg P, Eronen M (1992) Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Clim Dyn* 7:111–119
- Briffa KR, Schweingruber FH, Jones PD, Osborn TJ, Harris IC, Shiyatov SG, Vaganov EA, Grudd H (1998) Trees tell of past climates: but are they speaking less clearly today? *Phil Trans R Soc Lond B* 353:65–73

- Briffa KR, Osborn TJ, Schweingruber FH, Harris IC, Jones PD, Shiyatov SG, Vaganov EA (2001) Low-frequency temperature variations from a northern tree-ring density network. *J Geophys Res* 106:2929–2941
- Broecker WS (2001) Was the medieval warm period global? *Science* 291:1497–1499
- Bryson RA (1985) On climatic analogs in paleoclimatic reconstruction. *Quat Res* 23:275–286
- Bryson RA, Bryson RU (1997) High resolution simulations of regional holocene climate: North Africa and the Near East. In: Dalfes HN, Kukla G, Weiss H (eds) *Third millennium BC climate change and the Old World collapse*. NATO ASI Series, Vol. 149. Springer-Verlag, Heidelberg, p 565–593
- Bryson RA, Arakawa H, Aschmann HH, Baeris DA and 36 others (1963) NCAR Technical Note In: Bryson RA, Julian PR (eds) *Proc Conf Climate of the 11th and 16th Centuries*, Aspen CO, June 16–24 1962, National Center for Atmospheric Research Technical Notes 63-1, Boulder CO
- Bryson RA, Irving WN, Larsen JA (1965) Radiocarbon and soil evidence of former forest in the Southern Canadian Tundra. *Science* 147:46–48
- Calkin PE, Wiles GC, Barclay DJ (2001) Holocene coastal glaciation of Alaska. *Quat Sci Rev* 20:449–461
- Carignano CA (1999) Late Pleistocene to recent climatic change in Córdoba Province, Argentina: geomorphological evidence. *Quat Int* 57-58:117–134
- Chan JCL, Shi JE (2000) Frequency of typhoon landfall over Guangdong province of China during the period 1470–1931. *Int J Clim* 20:183–190
- Cioccale MA (1999) Climatic fluctuations in the central region of Argentina in the last 1000 years. *Quat Int* 62:35–47
- Clapperton CM, Sugden DE, Birnie J, Wilson MJ (1989) Late-glacial and holocene glacier fluctuations and environmental change on South Georgia, Southern Ocean. *Quat Res* 31:210–228
- Clow GD (1992) The extent of temporal smearing in surface-temperature histories derived from borehole temperature measurements. *Palaeogeogr Palaeoclim Palaeoecol* 98: 81–86
- Clow GD, Waddington ED (1999) Quantification of natural climate variability in Central Greenland and East Antarctica using borehole paleothermometry (abstract). International Union of Geodesy and Geophysics XXII General Assembly Abstract Book: B249, Birmingham UK
- Cohen AL, Tyson PD (1995) Sea-surface temperature fluctuations during the Holocene off the south coast of Africa: implications for terrestrial climate and rainfall. *Holocene* 5: 304–312
- Collins M, Osborn TJ, Tett SFB, Briffa KR, Schweingruber FH (2002) A comparison of the variability of a climate model with paleotemperature estimates from a network of tree-ring indices. *J Clim* 15:1497–1515
- Cook ER, Buckley BM, D'Arrigo RD, Peterson MJ (2000) Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies. *Clim Dyn* 16: 79–91
- Cowling SA, Skyes MT (1999) Physiological significance of low atmospheric CO₂ for plant-climate interactions. *Quat Res* 52:237–242 (See additional research exchanges in *Quat Res* 53:402–404 and *Quat Res* 53:405–406)
- Crowley TJ, Lowery TS (2000) How warm was the medieval warm period? *Ambio* 29:51–54
- Dahl-Jensen D, Mosegaard K, Gundestrup N, Glow GD, Johnsen SJ, Hansen AW, Balling N (1998) Past temperatures directly from the Greenland ice sheet. *Science* 282:268–271
- Dansgaard W, Johnsen SJ, Reeh N, Gundestrup N, Clausen HB, Hammer CU (1975) Climatic changes, Norsemen and modern man. *Nature* 255:24–28
- D'Arrigo RD, Cook ER, Salinger J, Palmer J, Buckley BM, Krusic PJ, Villalba R (1998) Tree-ring records from New Zealand: long-term context for recent warming trend. *Clim Dyn* 14:191–199
- D'Arrigo RD, Jacoby G, Frank D, Pederson N and 5 others (2001) 1738 years of Mongolian temperature variability inferred from a tree-ring width chronology of Siberian Pine. *Geophys Res Lett* 28:543–546
- Davis OK (1994) The correlation of summer precipitation in the southwestern USA with isotopic records of solar activity during the Medieval Warm Period. *Clim Change* 26: 271–287
- Dean WE, Schwab A (2000) Holocene environmental and climatic change in the Northern Great Plains as recorded in the geochemistry of sediments in Pickerel Lake, South Dakota. *Quat Int* 67:5–20
- deMenocal P (2001) Cultural responses to climate change during the late Holocene. *Science* 292:667–673
- deMenocal P, Ortiz J, Guilderson T, Sarntheim M (2000) Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* 288:2198–2202
- Domack EW, Mayewski PA (1999) Bi-polar ocean linkages: evidence from late-holocene Antarctic marine and Greenland ice-core records. *Holocene* 9:247–251
- Domack E, Leventer A, Dunbar R, Taylor F, Brackfeld S, Sjunneskog C plus ODP Leg 178 Team (2001) Chronology of the Palmer Deep site, Antarctic Peninsula: a holocene palaeoenvironmental reference for the circum-Antarctic. *Holocene* 11:1–9
- Doran PT, Prisco JC, Lyons WB, Walsh JE and 9 others (2002) Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415:517–520 (see also exchanges between Turner et al. and Walsh, Doran et al. (2002) in Recent temperature trends in the Antarctic. *Nature* 418:291–292)
- Druffel EM (1982) Banded corals: Changes in Oceanic carbon-14 during the Little Ice Age. *Science* 218:13–19
- Dyurgerov MB, Meier MF (2000) Twentieth century climate change: evidence from small glaciers. *Proc Natl Acad Sci USA* 97:1406–1411
- Ely LL, Enzel Y, Baker VR, Cayan DR (1993) A 5000-year record of extreme floods and climate change in the southwestern United States. *Science* 262:410–412
- Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295:2250–2253
- Evans DJA (2000) Ice in a greenhouse: the impacts of global warming on world glacier cover. *Trans Inst Engineers and Shipbuilders in Scotland* 143:11–19
- Evans MN, Kaplan A, Cane MA, Villalba R (2000) Globality and optimality in climate field reconstructions from proxy data. In: Markgraf V (ed) *Inter-hemispheric climate linkages*. Academic Press, San Diego, CA p 53–72
- Evans MN, Kaplan A, Cane MA (2002) Pacific sea surface temperature field reconstruction from coral $\delta^{18}\text{O}$ data using reduced space objective analysis. *Paleocean* 17:10.1029/2000PA000590
- Feng X (1999) Trends in intrinsic water-use efficiency of natural trees for the past 100–200 years. *Geochimica et Cosmochim Acta* 63:1891–1903
- Feng X, Epstein S (1994) Climatic implications of an 8000-year hydrogen isotope time series from Bristlecone Pine trees. *Science* 265:1079–1081
- Filippi ML, Lambert P, Hunziker J, Kübler B, Bernasconi S

- (1999) Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchâtel, Switzerland, during the last two millennia. *J Paleolimnol* 21:19–34
- Folland CK, Rayner NA, Brown SJ, Smith TM and 7 others (2001) Global temperature change and its uncertainties since 1861. *Geophys Res Lett* 28:2621–2624
- Graumlich LJ (1993) A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quat Res* 39:249–255
- Graybill DA, Idso SB (1993) Detecting the aerial fertilization effect of atmospheric CO₂ enrichment in tree-ring chronologies. *Glob Biogeochem Cycles* 7:81–95
- Grissino-Mayer HD (1996) A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. In Dean JS, Meko DM, Swetnam TW (eds) *Tree rings, environment and humanity*, Radiocarbon (U Arizona Press), Tucson, p 191–204
- Grove AT (2001) The 'Little Ice Age' and its geomorphological consequences in Mediterranean Europe. *Clim Change* 48:121–136
- Grove JM (1996) The century time-scale. In: Driver TS, Chapman GP (eds) *Time-scales and environmental change*. Routledge, London p 39–87
- Grove JM (2001a) The initiation of the Little Ice Age in regions round the North Atlantic. *Clim Change* 48:53–82
- Grove JM (2001b) The onset of the Little Ice Age. In: Jones PD, Ogilvie AEJ, Davies TD, Briffa KR (eds) *History and climate—memories of the future?* Kluwer Academic Publishers, New York p 153–185
- Grove JM, Conterio A (1995) The climate of Crete in the sixteenth and seventeenth centuries. *Clim Change* 30:223–247
- Grove JM, Switsur R (1994) Glacial geological evidence for the medieval warm period. *Clim Change* 26:143–169
- Hadly EA (1996) Influence of late-Holocene climate on Northern Rocky Mountain mammals. *Quat Res* 46:289–310
- Häkkinen S (2000) Decadal air-sea interaction in the North Atlantic based on observations and modeling results. *J Clim* 13:1195–1219
- Hansen J, Ruedy R, Glascoe J, Sato M (1999) GISS analysis of surface temperature change. *J Geophys Res* 104:30997–31022
- Harris RN, Chapman DS (2001) Mid-latitude (30° to 60°N) climatic warming inferred by combining borehole temperatures with surface air temperatures. *Geophys Res Lett* 28:747–750
- Haug GH, Hughen KA, Sigman DM, Peterson LC, Röhlk U (2001) Southward migration of the intertropical convergence zone through the holocene. *Science* 293:1304–1308
- Hendy EJ, Gagan MK, Alibert CA, McCulloch MT, Lough JM, Idsall PJ (2002) Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* 295:1511–1514
- Hiller A, Boettger T, Kremenetski C (2001) Mediaeval climatic warming recorded by radiocarbon date alpine tree-line shift on the Kola Peninsula, Russia. *Holocene* 11:491–497
- Hodell DA, Brenner M, Curtis JH, Guilderson T (2001) Solar forcing of drought frequency in the Maya lowlands. *Science* 292:1367–1370
- Holzhauser H (1997) Fluctuations of the Grosser Aletsch Glacier and the Groner Glacier during the last 3200 years: New results. In Frenzel B, Boulton GS, Glaser B, Huckriede U (eds) *Glacier fluctuations during the Holocene*, Akademie der Wissenschaften und der Literatur, p 35–58
- Hong YT, Jiang HB, Liu TS, Zhou LP and 5 others (2000) Response of climate to solar forcing recorded in a 6000-year $\delta^{18}\text{O}$ time-series of Chinese peat cellulose. *Holocene* 10:1–7
- Hu FS, Ito E, Brown TA, Curry BB, Engstrom DR (2001) Pronounced climatic variations in Alaska during the last two millennia. *Proc Natl Acad Sci USA* 98:10552–10556
- Huang S, Shen PY, Pollack HN (1996) Deriving century-long trends of surface temperature change from borehole temperatures. *Geophys Res Lett* 23:257–260
- Huang S, Pollack HN, Shen PY (1997) Late Quaternary temperature changes seen in the world-wide continental heat flow measurements. *Geophys Res Lett* 24:1947–1950
- Huang S, Pollack HN, Shen PY (2000) Temperature trends over the past five centuries reconstructed from borehole temperatures. *Nature* 403:756–758
- Huffman TN (1996) Archaeological evidence for climatic change during the last 2000 years in Southern Africa. *Quat Int* 33:55–60
- Hughes MK, Diaz HF (1994) Was there a 'Medieval Warm Period', if so, where and when? *Clim Change* 26:109–142
- Idso SB (1989) Letter to the editor—a problem for paleoclimatology? *Quat Res* 31:433–434
- Ingram MJ, Underhill DJ, Wigley TML (1978) Historical climatology. *Nature* 276:329–334
- Iriondo M (1999) Climatic changes in the South American plains: records of a continent-scale oscillation. *Quat Int* 57:58:93–112
- Jacoby GC, D'Arrigo RD (1995) Tree-ring width and density evidence for climatic and potential forest change in Alaska. *Glob Biogeochem Cycles* 9:227–234
- Jacoby GC, D'Arrigo RD, Davaajamts T (1996) Mongolian tree rings and 20th-century warming. *Science* 273:771–773
- Jacoby GC, Lovelius NV, Shumilov OI, Raspopov OM, Karbainov JM, Frank DC (2000) Long-term temperature trends and tree growth in the Taymir region of northern Siberia. *Quat Res* 53:312–318
- Jennings AE, Weiner NJ (1996) Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. *Holocene* 6:171–191
- Jenny B, Valero-Garces B, Urrutia R, Kelts K, Veit H, Appleby PG, Geyh M (2002) Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during the last 2000 years: the Laguna Aculeo record (33°–50°S). *Quat Int* 87:3–18
- Johnson TC, Barry S, Chan Y, Wilkinson P (2001) Decadal record of climate variability spanning the past 700 yr in the Southern tropics of East Africa. *Geology* 29:83–86
- Jones PD, Briffa KR, Barnett TP, Tett SFB (1998) High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *Holocene* 8:455–471
- Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperatures and its changes over the past 150 years. *Rev Geophys* 37:173–199
- Jones PD, Osborn TJ, Briffa KR (2001) The evolution of climate over the last millennium. *Science* 292:662–667
- Karlén W (1998) Climate variations and the enhanced greenhouse effect. *Ambio* 27: 270–274
- Karlöf L, Winther JG, Isaksson E, Kohler JF and 10 others (2000) A 1500 year record of accumulation at Amundsenisen western Dronning Maud Land, Antarctica, derived from electrical and radioactive measurements on a 120 m ice core. *J Geophys Res* 105: 12471–12483
- Kaser G (1999) A review of the modern fluctuations of tropical glaciers. *Glob Planet Change* 22:93–103

- Keigwin LD (1996) The little ice age and medieval warm period in the Sargasso Sea. *Science* 274:1504–1508
- Kitagawa H, Matsumoto E (1995) Climatic implications of $\delta^{13}\text{C}$ variations in a Japanese cedar *Cryptomeria japonica* during the last two millennia. *Geophys Res Lett* 22:2155–2158
- Knapp PA, Soulé PT, Grissino-Mayer HD (2001) Post-drought growth responses of western juniper (*Juniperus occidentalis* var. *occidentalis*) in central Oregon. *Geophys Res Lett* 28:2657–2660
- Knappenberger PC, Michaels PJ, Davis RE (2001) Nature of observed temperature changes across the United States during the 20th century. *Clim Res* 17:45–53
- Koerner RM (1977) Devon Island ice cap: core stratigraphy and paleoclimate. *Science* 196:15–18
- Koerner RM, Fisher DA (1990) A record of Holocene summer climate from a Canadian high-Arctic ice core. *Nature* 343: 630–631
- Korhola A, Weckström J, Holmström L, Erästo P (2000) A quantitative Holocene climatic record from diatoms in Northern Fennoscandia. *Quat Res* 54:284–294
- Kreutz KJ, Mayewski PA, Meeker LD, Twickler MS, Whitlow SI, Pittalwala II (1997) Bipolar changes in atmospheric circulation during the Little Ice Age. *Science* 277: 1294–1296
- Kuhnert H, Pätzold J, Schnetger B, Wefer G (2002) Sea-surface temperature variability in the 16th century at Bermuda inferred from coral records. *Palaeogeogr Palaeoclim Palaeoecol* 179:159–171
- Laird KR, Fritz SC, Maasch KA, Cumming BF (1996) Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature* 384:552–554
- Lamb HH (1965) The early medieval warm epoch and its sequel. *Palaeogeogr Palaeoclim Palaeoecol* 1:13–37
- Lamb HH (1977) *Climate—Past, Present and Future* Vol. 2 Climatic History and Future, Methuen
- Lamb HH (1982) *Climate history and the modern world*, Methuen
- Lamoureux SF, Bradley RS (1996) A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *J Paleolim* 16:239–255
- Lara A, Villalba R (1993) A 3260-year temperature record from *Fitzroya cupressoides* tree rings in southern South America. *Science* 260:1104–1106
- Lawton RO, Nair US, Pielke RA Sr, Welch RM (2001) Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* 294:584–587
- Lewis TJ, Wang K (1998) Geothermal evidence for deforestation induced warming: implications for the climatic impact of land development. *Geophys Res Lett* 25:535–538
- Li HC, Bischoff JL, Ku TL, Lund SP, Stot LD (2000) Climate variability in East-Central California during the past 1000 years reflected by high-resolution geochemical and isotopic records from Owens Lake sediments. *Quat Res* 54: 189–197
- Liu K, Yao Z, Thompson LG (1998) A pollen record of Holocene climatic changes from Dunde ice cap, Qinghai-Tibetan Plateau. *Geology* 26:135–138
- Lotter AF, Birks HJB, Eicher V, Hofmann W, Schwander J, Wick L (2000) Younger Dryas Allerød summer temperatures at Gerzensee (Switzerland) inferred from fossil pollen and cladoceran assemblages. *Palaeogeogr Palaeoclim Palaeoecol* 159:349–361
- Luckman BH (2000) The Little Ice Age in the Canadian Rockies. *Geomorph* 32:357–384
- Luckman BH, Briffa KR, Jones PD, Schweingruber FH (1997) Tree-ring based reconstruction of summer temperatures at Columbia Icefield, Alberta, Canada, AD 1073–1983. *Holocene* 7:375–389
- Luterbacher J, Rickli R, Tinguely C, Xoplaki E and 30 others (2000) Monthly mean pressure reconstruction for the late Maunder Minimum period (AD 1675–1715). *Int J Clim* 20:1049–1066
- Madole RF (1994) Stratigraphic evidence of desertification in the west-central Great Plains within the past 1000 yr. *Geology* 22:483–486
- Manley G (1974) Central England temperatures: monthly means 1659 to 1973. *Quart J Roy Meteorol Soc* 100: 389–405
- Mann ME, Bradley RS, Hughes MK (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392:779–787
- Mann ME, Bradley RS, Hughes MK (1999) Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophys Res Lett* 26:759–762
- Mann ME, Grille E, Bradley RS, Hughes MK, Overpeck J, Keimig FT, Gross W (2000) Global temperature patterns in past centuries: an interactive presentation. *Earth Interact* 4:1–29 [available online <http://Earthinteraction.org>]
- Marshall GJ, Lagun V, Lachlan-Cope TA (2002) Changes in Antarctic Peninsula tropospheric temperatures from 1956 to 1999: a synthesis of observations and reanalysis data. *Int J Clim* 22:291–310
- Marshall J, Johnson H, Goodman J (2001) A study of the interaction of the North Atlantic Oscillation with ocean circulation. *J Clim* 14:1399–1421
- McDermott F, Mattey DP, Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* 294:1328–1331
- Meese DA, Gow AJ, Grootes P, Mayewski PA and 5 others (1994) The accumulation record from the GISP2 core as an indicator of the climate change throughout the Holocene. *Science* 266: 1680–1682
- Mercer JH (1978) West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. *Nature* 271:321–325
- Morgan VI (1985) An oxygen isotope climate record from the Law Dome, Antarctica. *Clim Change* 7:415–426
- Mosley-Thompson E (1995) Paleoenvironmental conditions in Antarctica since A.D. 1500: ice core evidence. In: Bradley RS, Jones PD (eds) *Climate since A.D. 1500*, Routledge, New York, p 572–591
- Mosley-Thompson E, Thompson LG (1982) Nine centuries of microparticles deposition at the South Pole. *Quat Res* 17:1–13
- Naurzbaev MM, Vaganov EA (2000) Variation of early summer and annual temperature in east Taymir and Putorian (Siberia) over the last two millennia. *J Geophys Res* 105: 7317–7326
- Ogilvie AEJ (1984) The past climate and sea-ice record from Iceland. Part 1. Data to A.D. 1780. *Clim Change* 6:131–152
- Ogilvie A, Farmer G (1997) Documenting the medieval climate. In: Hulme M, Barrow E (eds) *Climate of the British Isles—present, past and future*. Routledge, London, p 112–133
- Ogilvie AEJ, Jónsson T (2001) 'Little Ice Age' research: a perspective from Iceland. *Clim Change* 48:9–52
- Ogilvie AEJ, Barlow LK, Jennings AE (2000) North Atlantic climate c. A.D. 1000: millennial reflections on the Viking discoveries of Iceland, Greenland and North America. *Weather* 55:34–45
- Overpeck J, Hughen K, Hardy D, Bradley R 14 others (1997) Arctic environmental change of the last four centuries. *Science* 278:1251–1256
- Pederson JL (2000) Holocene paleolakes of Lake Canyon,

- Colorado Plateau: Paleoclimate and landscape response from sedimentology and allostratigraphy. *Geol Soc Amer Bull* 112:147-158
- Perry CA, Hsu KJ (2000) Geophysical, archaeological, and historical evidence support a solar-output model for climate change. *Proc Natl Acad Sci USA* 97:12433-12438
- Petersen KL (1994) A warm and wet little climatic optimum and a cold and dry little ice age in the Southern Rocky Mountains, USA. *Clim Change* 26:243-269
- Pfister C (1995) Monthly temperature and precipitation in central Europe 1525-1979: quantifying documentary evidence on weather and its effects. In: Bradley RS, Jones PD (eds) *Climate since A.D. 1500*. Routledge, New York, p 118-142
- Pfister C, Luterbacher J, Schwarz-Zanetti G, Wegmann M (1998) Winter air temperature variations in western Europe during the early and high Middle ages (AD 750-1300). *Holocene* 8:535-552
- Pisias NG (1978) Paleooceanography of the Santa Barbara Basin during the last 8000 years. *Quat Res* 10:366-384
- Porter SC (1981) Glaciological evidence of holocene climatic change. In: Wigley TML, Ingram MJ, Farmer G (eds) *Climate and history—studies in past climates and their impact on man*. Cambridge University Press, Cambridge, p 82-110
- Porter SC (1986) Pattern and forcing of the Northern Hemisphere glacier variations during the last millennium. *Quat Res* 26:27-48
- Proctor CJ, Baker A, Barnes WL, Gilmour MA (2000) A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Clim Dyn* 16:815-820
- Ramesh R (1993) First evidence for Little Ice Age and Medieval Warming in India (abstract). *EOS Trans AGU suppl* 74: 118
- Ren G (1998) Pollen evidence for increased summer rainfall in the Medieval Warm Period at Maili, Northeast China. *Geophys Res Lett* 25:1931-1934
- Robinson WA, Hansen J, Ruedy R (2001) Where's the heat? Insights from GCM experiments into the lack of Eastern U.S. warming. American Meteor Soc 81st Annual Meeting, Albuquerque NM, January 14-19 2001 (abstract) American Meteorological Society, Washington DC
- Rodrigo FS, Esteban-Parra MJ, Pozo-Vázquez D, Castro-Díez Y (2000) Rainfall variability in southern Spain on decadal to centennial time scales. *Int J Clim* 20:721-732
- Rott H, Skvarca P, Nagler T (1996) Rapid collapse of northern Larsen ice shelf, Antarctica. *Science* 271:788-792
- Schleser GH, Helle G, Lücke A, Vos H (1999) Isotope signals as climate proxies: the role of transfer functions in the study of terrestrial archives. *Quat Sci Rev* 18:927-943
- Schmutz C, Luterbacher J, Gyalistras D, Xoplaki E, Wanner H (2000) Can we trust proxy-based NAO index reconstructions? *Geophys Res Lett* 27:1135-1138
- Schuster PF, White DE, Naftz DL, Cecil LD (2000) Chronological refinement of an ice core record at Upper Fremont Glacier in south central North America. *J Geophys Res* 105:7317-7326
- Scuderi LA (1993) A 2000-year tree ring record of annual temperatures in the Sierra Nevada mountains. *Science* 259: 1433-1436
- Seager R, Kushnir Y, Visbeck M, Naik N, Müller J, Krahmann G, Cullen H (2000) Causes of Atlantic ocean climate variability between 1958 and 1998. *J Clim* 13:2845-2862
- Serre-Bachet F (1994) Middle ages temperature reconstructions in Europe, a focus on Northeastern Italy. *Clim Change* 26:213-240
- Shi Y, Yao T, Yang B (1999) Decadal climatic variations recorded in Guliya ice core and comparison with the historical documentary data from East China during the last 2000 years. *Sci in China Ser D (suppl)* 42:91-100
- Skinner WR, Majorowicz JA (1999) Regional climatic warming and associated twentieth century land-cover changes in north-western North America. *Clim Res* 12:39-52
- Slonosky VC, You P (2001) The North Atlantic Oscillation and its relationship with near surface temperature. *Geophys Res Lett* 28:807-810
- Smith RC, Ainley D, Baker K, Domack E and 7 others (1999) Marine ecosystem sensitivity to climate change. *Bio-science* 49:393-404
- Song J (2000) Changes in dryness/wetness in China during the last 529 years. *Int J Clim* 20:1003-1015
- Stahle DW, Cleaveland MK, Hehr JG (1988) North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985. *Science* 240: 1517-1519
- Stine S (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature* 369:546-549
- Stine S (1998) Medieval climatic anomaly in the Americas. In: Issar AS, Brown N (eds) *Water, environment and society in times of climatic change*. Kluwer Academic Press, Dordrecht, p 43-67
- Stuiver M, Grootes PM, Braziunas TF (1995) The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the Sun, ocean and volcanoes. *Quat Res* 44:341-354
- Swetnam TW (1993) Fire history and climate change in Giant Sequoia groves. *Science* 262:885-889
- Tagami Y (1993) Climate change reconstructed from historical data in Japan. In: *Proc Int Symp Global Change by IGBP March 27-29 1992, Tokyo*. International Geosphere-Biosphere Programme-IGBP, Tokyo, p 720-729
- Tagami Y (1996) Some remarks on the climate in the Medieval Warm Period of Japan. In: Mikami T, Matsumoto E, Ohta S, Sweda T (eds) *Paleoclimate and environmental variability in Austral-Asian transect during the past 2000 years (IGBP Proceedings)*. International Geosphere-Biosphere Programme-IGBP, Nagoya, p 115-119
- Tarussov A (1995) The Arctic from Svalbard to Severnaya Zemlya: climatic reconstructions from ice cores. In: Bradley RS, Jones PD (eds) *Climate Since A.D. 1500*, Routledge, New York, p 505-516
- Thomas RH, Sanderson TJO, Rose KE (1979) Effect of climatic warming on the West Antarctic ice sheet. *Nature* 277: 355-358
- Thompson LG (2000) Ice core evidence for climate change in the Tropics: implications for our future. *Quat Sci Rev* 19: 19-35
- Thompson LG, Mosley-Thompson E, Dansgaard W, Grootes PM (1986) The little ice age as recorded in the stratigraphy of the tropical Quelccaya ice cap. *Science* 234:361-364
- Thompson LG, Mosley-Thompson E, Davis ME, Bolzan JF and 6 others (1989) Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan plateau. *Science* 246:474-477
- Thompson LG, Peel DA, Mosley-Thompson E, Mulvaney R, Dai J, Lin PN, Davis ME, Raymond CF (1994) Climate since AD 1510 on Dyer Plateau, Antarctic Peninsula: evidence for recent climate change. *Ann Glaciol* 20:420-426
- Thompson LG, Mosley-Thompson E, Davis ME, Lin PN, Dai J, Bolzan JF, Yao T (1995) A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability. *Ann Glaciol* 21:175-181
- Thompson LG, Yao T, Mosley-Thompson E, Davis ME, Henderson KA, Lin PN (2000) A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science* 289:1916-1919

- Till C, Guot J (1990) Reconstruction of precipitation in Morocco since 1100 A.D. based on *Cedrus atlantica* tree-ring widths. *Quat Res* 33:337–351
- Tong G, Zhang J, Fan S, Zhao J, Wang G, Wang Y, Wang L, Cui J (1996) Environmental changes at the top of Taibai Mountain, Qinling since 1ka ago. *Mar Geol Quat Geol* 16: 95–104
- Tyson PD, Lindsay JA (1992) The climate of the last 2000 years in southern Africa. *Holocene* 2:271–278
- Tyson PD, Karlén W, Holmgren K, Heiss GA (2000) The Little Ice Age and medieval warming in South Africa. *South African J Sci* 96:121–126
- Valero-Garcés BL, Delgado-Huertas A, Ratto N, Navas A, Edwards L (2000) Paleohydrology of Andean saline lakes from sedimentological and isotopic records, Northwestern Argentina. *J Paleolimnology* 24:343–359
- van Engelen AFV, Buismann J, Ijnsen F (2001) A millennium of weather, winds and water in the low countries. In: Jones PD, Ogilvie AEJ, Davies TD, Briffa KR (eds) *History and climate—memories of the future?* Kluwer Academic Publishers, New York, p 101–124
- Vaughan DG, Doake CSM (1996) Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature* 379:328–331
- Verardo S, Cronin T, Willard D, Kerhun R (1998) Climate and environmental changes recorded by Chesapeake Bay Dinoflagellate cysts in the last millennium. *Geol Soc Amer Abs* 74: 284
- Verschuren D, Laird KR, Cumming BF (2000) Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* 403:410–414
- Villalba R (1990) Climatic fluctuations in northern Patagonia during the last 1000 years as inferred from tree-ring records. *Quat Res* 34:346–360
- Villalba R (1994) Tree-ring and glacial evidence for the medieval warm epoch and the little ice age in southern South America. *Clim Change* 26:183–197
- von Storch JS, Muller P, Bauer E (2001) Climate variability in millennium integrations with coupled atmosphere-ocean GCMs: a spectral view. *Clim Dyn* 17:375–389
- Williams PW, Marshall A, Ford DC, Jenkinson AV (1999) Palaeoclimatic interpretation of stable isotope data from holocene speleothems of the Waitomo district, North Island, New Zealand. *Holocene* 9:649–657
- Wilson AT, Hendy CH, Reynolds CP (1979) Short-term climate change and New Zealand temperatures during the last millennium. *Nature* 279:315–317
- Winkler S (2000) The 'Little Ice Age' maximum in the southern Alps, New Zealand: preliminary results at Mueller Glacier. *Holocene* 10:643–647
- Winter A, Ishioroshi H, Watanabe T, Oba T, Christy J (2000) Caribbean sea surface temperatures: two-to-three degrees cooler than present during the Little Ice Age. *Geophys Res Lett* 27:3365–3368
- Woodhouse CA, Overpeck JT (1998) 2000 years of drought variability in the central United States. *Bull Am Meteor Soc* 79:2693–2714
- Yu Z, Ito E (1999) Possible solar forcing of century-scale drought frequency in the northern Great Plains. *Geology* 27:262–266
- Zhang D (1994) Evidence for the existence of the medieval warm period in China. *Clim Change* 26:289–297

*Editorial responsibility: Chris de Freitas,
Auckland, New Zealand*

*Submitted: April 11, 2002; Accepted: August 29, 2002
Proofs received from author(s): January 3, 2003*

A Preprint for Energy & Environment (March 2003)

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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 ... 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.” 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 ... we can only concur ... that there is little evidence for the ‘Medieval Warm Period’ ... 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] ... 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

¹When considering the possible link of early 20th century warming to the rise in atmospheric CO₂ 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 CO₂ content was less than 20-30% of the cumulative CO₂ increase to date; see Etheridge et al. (1996) for the preindustrial level of CO₂.

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.

²See 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

³Note 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 $\pm 1.3^{\circ}$ - 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

⁴There 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.

⁵Cook 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

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 Dommenges 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. Dommenges 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 . . . 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., Piasis'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 CO₂ 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).

⁶Cook 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 CO₂, 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 higher⁷ 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

⁷About 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?'.⁸

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

⁸Barlow 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 $\delta^{18}\text{O}$ and Sr/Ca ratio records from Bermuda indicated 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, 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

⁹Although 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 $\delta^{18}\text{O}$ (for proxy of sea surface salinity) and Mg/Ca (for proxy of sea surface temperature) compositions of planktonic foraminifera *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

¹⁰This 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 periods 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 Guangdong Province in the early-to-mid 19th century. Using a $\delta^{18}\text{O}$ 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 $\delta^{13}\text{C}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $3\text{-}4^\circ\text{C}$ 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 $47\text{-}51^\circ\text{S}$ 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 km² 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 glaciers¹¹) 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 increase 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 susceptibility and high bio-productivity and, high magnetic susceptibility 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

¹¹Based 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 Antarctica). 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 because¹² 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

¹²This 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

¹³Mann (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).

¹⁴This 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

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

¹⁵Our own private communications with SP. Huang and between M. MacCracken and H. N. Pollack, and in turn kindly shared with us by M. MacCracken 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 CO₂, 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 be¹⁷ 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

¹⁶But 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.

¹⁷The 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 changes¹⁸ (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) demonstrated similar problems in inter-calibration skill when comparing various paleo-reconstructions of ENSO-mode variability over the 19th century; and, hence, they

¹⁸There 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, whereas 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 substantial 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 consensus 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 satisfactory 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.

¹⁹Historical 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 (Caribbean). 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 CO₂.” 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 CO₂ 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 CO₂ rise on western juniper growth rates under water-stressed conditions in Central Oregon²⁰). 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 CO₂ 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 CO₂ 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.

²⁰The evidence for anthropogenic CO₂-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

²¹Emery 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 CO₂-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 ... 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 CO₂ 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

²²Other 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.

²³In 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 km² for precipitation and 10⁴ to 10⁵ km² 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 CO₂ 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 CO₂, then the early part of the 20th century warming must be largely dissociated from anthropogenic CO₂ 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 realizations²⁴ 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 than 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

²⁴For 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).

Acknowledgments

This work was supported by funds from the Air Force Office of Scientific Research (Grant AF49620-02-1-0194), the American Petroleum Institute (Grants 01-0000-4579 and 2002-100413) the National Aeronautics and Space Administration (Grant NAG5-7635), and the National Oceanic and Atmospheric Administration (Grant NA96GP0448). The views expressed herein are those of the authors and are independent of sponsoring agencies.

We have benefited greatly from the true and kind spirit of research communications (including constructive criticisms and a preview of their thoughts) with the late Jean Grove (who passed away on January 18, 2001), Dave Evans, Shaopeng Huang, Jim Kennett, Hong-Chun Li, Lowell Stott, Yoshio Tagami and Taiping Zhang. We thank John Daly and Diane Douglas-Dalziel for their unselfish contributions of many excellent collections of references. We are also very grateful to Maria McEachern, Melissa Hilbert, Barbara Palmer and Will Graves for invaluable library help and both Philip Gonzalez and Lisa Linarte for crucial all-around help.

We thank the three anonymous referees for constructive comments.

References

- Albritton DL and 58 others (2001) Summary for Policymakers. In Houghton JT et al. (eds) *Climate Change 2001: The scientific basis*, Cambridge University Press, p. 1-20
- Ambaum MHP, Hoskins BJ, Stephenson DB (2001) Arctic oscillation or North Atlantic oscillation? *J Clim* 14: 3495-3507 [with corrigendum in *J Clim* 15: 553 (2002)]
- Andrén E, Andrén T, Sohlenius G (2000) The Holocene history of the southwestern Baltic Sea as reflected in sediment core from the Bornholm Basin. *Boreas* 29: 233-250
- Andronova NG, Schlesinger ME (2001) Objective estimation of the probability density function for climate sensitivity. *J Geophys Res* 106: 22605-22612
- Aristarain AJ, Jouzel J, Lorius C (1990) A 400 years isotope record of the Antarctic Peninsula climate. *Geophys Res Lett* 17: 2369-2372
- Arseneault D, Payette S (1997) Reconstruction of millennial forest dynamics from tree remains in a subarctic tree line peatland. *Ecology* 78: 1873-1883
- Aykroyd RG, Lucy D, Pollard AM, Carter AHC, Robertson I (2001) Temporal variability in the strength of the proxy-climate correlations. *Geophys Res Lett* 28: 1559-1562
- Baliunas S, Frick P, Sokoloff D, Soon W (1997) Time scales and trend in the Central England Temperature data (1659-1990): A wavelet analysis. *Geophys Res Lett* 24: 1351-1354
- Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405: 668-673
- Barclay DJ, Wiles GC, Calkin PE (1999) A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska. *Holocene* 9: 79-84
- Barlow LK and 8 others (1997) Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. *Holocene* 7: 489-499
- Barnett T, Jones P (2000) Reply (to Bradley et al. 2000's comments). *Bull Am Meteor Soc* 81: 2990-2992
- Barnett T and 10 others (1999) Detection and attribution of recent climate change: A status report. *Bull Am Meteor Soc* 80: 2631-2659
- Baroni C, Orombelli G (1994) Holocene glacier variations in the Terra Nova Bay area (Victoria Land, Antarctica). *Antarctic Sci* 6: 497-505

- Bell GD and 6 others (1999) Climate assessment for 1998. *Bull Am Meteor Soc* 80: S1-S48
- Beltrami H, Chapman DS, Archambault S, Bergeron Y (1995) Reconstruction of high resolution ground temperature histories combining dendrochronological and geothermal data. *Earth Planet Sci Lett* 136: 437-445
- Beltrami H, Taylor AE (1995) Records of climatic change in the Canadian Arctic: Towards calibrating oxygen isotope data with geothermal data. *Glob Planet Change* 11: 127-138
- Beltrami H, Wang J, Bras RL (2000) Energy balance at the Earth's surface: Heat flux history in Eastern Canada. *Geophys Res Lett* 27: 3385-3388
- Benoist JP, Jouzel J, Lorius C, Merlivat L, Pourchet M (1982) Isotope climatic record over the last 2.5 ka from Dome C, Antarctica, ice cores. *Ann Glaciology* 3: 17-22
- Bernabo JC (1981) Quantitative estimates of temperature changes over the last 2700 years in Michigan based on pollen data. *Quat Res* 15: 143-159
- Betancourt JL, Grissino-Mayer HD, Salzer MW, Swetnam TW (2002) A test of "annual resolution" in stalagmites using tree rings. *Quat Res* 58: 197-199
- Bianchi GG, McCave IN (1999) Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* 397: 515-517
- Biondi F, Perkins DL, Cayan DR, Hughes MK (1999) July temperature during the second millennium reconstructed from Idaho tree rings. *Geophys Res Lett* 26: 1445-1448
- Black DE and 5 others (1999) Eight centuries of North Atlantic Ocean atmosphere variability. *Science* 286: 1709-1713
- Blackford JJ, Chambers FM (1995) Proxy climate record for the last 1000 years from Irish blanket peat and a possible link to solar variability. *Earth Planet Sci Lett* 133: 145-150
- Bodri L, Čermák V (1999) Climate change of the last millennium inferred from borehole temperatures: Regional patterns of climatic changes in the Czech Republic—Part III. *Glob Planet Change* 21: 225-235
- Bond G and 9 others (1997) A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* 278: 1257-1266
- Bond G and 7 others (1999) The North Atlantic's 1-2 kyr climate rhythm: Relation to Heinrich events, Dansgaard/Oeschger cycles and the little ice age. In Clark PU, Webb RS, Keigwin LD (eds) *Mechanisms of global climate change at millennial time scales*, American Geophysical Union Press, vol 112, p. 35-58

- Borisenkov YeP (1995) Documentary evidence from the U.S.S.R. In Bradley RS, Jones PD (eds) *Climate Since A.D. 1500*, Routledge, p. 171-183
- Bradley RS (2000) 1000 years of climate change. *Science* 288: 1353, 1355
- Bradley RS and 5 others (2001) The scope of Medieval Warming. *Science* 292: 2011-2012
- Bradley RS, Hughes MK, Mann ME (2000) Comments on "Detection and attribution of recent climate change: A status report". *Bull Am Meteor Soc* 81: 2987-2990
- Bradley RS, Jones PD (1993) 'Little Ice Age' summer temperature variations: Their nature and relevance to recent global warming trends. *Holocene* 3: 367-376
- Briffa KR and 7 others (1992) Fennoscandian summers from AD 500: Temperature changes on short and long timescales. *Clim Dyn* 7: 111-119
- Briffa KR and 7 others (1998) Trees tell of past climates: But are they speaking less clearly today? *Phil Trans R Soc Lond B* 353: 65-73
- Briffa KR, Osborn TJ (1999) Seeing the wood from the trees. *Science* 284: 926-927
- Briffa KR (2000) Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quat Sci Rev* 19: 87-105
- Briffa KR and 6 others (2001) Low-frequency temperature variations from a northern tree-ring density network. *J Geophys Res* 106: 2929-2941
- Broecker WS (2001) Was the medieval warm period global? *Science* 291: 1497-1499
- Bryson RA (1985) On climatic analogs in paleoclimatic reconstruction. *Quat Res* 23: 275-286
- Bryson RA, Bryson RU (1997) High resolution simulations of regional Holocene climate: North Africa and the Near East. In Dalfes HN, Kukla G, Weiss H (eds) *Third Millennium BC Climate Change and the Old World Collapse*, NATO ASI Series Vol. 149, Springer-Verlag, p. 565-593
- Bryson RA and 39 others (1963) In Bryson RA, Julian PR (eds) *Proceedings of the Conference on climate of the 11th and 16th centuries*, National Center for Atmospheric Research Technical Notes 63-1, 103 pp.
- Bryson RA, Irving WN, Larsen JA (1965) Radiocarbon and soil evidence of former forest in the Southern Canadian Tundra. *Science* 147: 46-48
- Burns SJ and 5 others (2002) A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. *J Geophys Res* 107 (D20): 4434,

doi:10.1029/2001JD001281

- Calkin PE, Wiles GC, Barclay DJ (2001) Holocene coastal glaciation of Alaska. *Quat Sci Rev* 20: 449-461
- Campbell ID, Campbell C, Apps MJ, Rutter NW, Bush ABG (1998) Late Holocene ~1500 yr climatic periodicities and their implications. *Geology* 26: 471-473
- Cane MA (2001) Book review—El Nino and the Southern Oscillation: Multiscale Variability and Global and Regional Impact, Diaz HF, Markgraf V (eds), Cambridge Univ Press. *EOS* 82: 556
- Carignano CA (1999) Late Pleistocene to recent climatic change in Córdoba Province, Argentina: Geomorphological evidence. *Quat Int* 57-58: 117-134
- Chan JCL, Shi JE (2000) Frequency of typhoon landfall over Guangdong province of China during the period 1470-1931. *Int J Clim* 20: 183-190
- Cherchi A, Navarra A (2003) Reproducibility and predictability of the Asian summer monsoon in the ECHAM4-GCM. *Clim Dyn*: in press
- Christy JR and 5 others (2001) Differential trends in tropical sea surface and atmospheric temperatures since 1979. *Geophys Res Lett* 28: 183-186
- Chu G and 6 others (2002) The 'Medieval Warm Period' drought recorded in Lake Huguangyan, tropical South China. *Holocene* 12: 511-516
- Cioccale MA (1999) Climatic fluctuations in the Central region of Argentina in the last 1000 years. *Quat Int* 62: 35-47
- Clapperton CM, Sugden DE, Birnie J, Wilson MJ (1989) Late-glacial and Holocene glacier fluctuations and environmental change on South Georgia, Southern Ocean. *Quat Res* 31: 210-228
- Clow GD (1992) The extent of temporal smearing in surface-temperature histories derived from borehole temperature measurements. *Palaeogeogr Palaeoclim Palaeoecol* 98: 81-86
- Clow GD, Waddington ED (1999) Quantification of natural climate variability in Central Greenland and East Antarctica using borehole paleothermometry (abstract). *International Union of Geodesy and Geophysics XXII General Assembly Abstract Book*: B249
- Cohen AL, Tyson PD (1995) Sea-surface temperature fluctuations during the Holocene off the south coast of Africa: Implications for terrestrial climate and rainfall. *Holocene* 5: 304-312

- Cole K (1985) Past rates of change, species richness, and a model of vegetational inertia in the Grand Canyon, Arizona. *Amer Naturalist* 125: 289-303
- Collins M, Osborn TJ, Tett SFB, Briffa KR, Schweingruber FH (2002) A comparison of the variability of a climate model with paleotemperature estimates from a network of tree-ring indices. *J Clim* 15: 1497-1515
- Cook ER and 7 others (1991) Climatic change in Tasmania inferred a 1089-year tree-ring chronology of Huon pine. *Science* 253: 1266-1268
- Cook ER, Briffa KR, Meko DM, Graybill DA, Funkhouser G (1995) The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *Holocene* 5: 229-237
- Cook ER, Buckley BM, D'Arrigo RD, Peterson MJ (2000) Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies. *Clim Dyn* 16: 79-91
- Cowling SA, Skyes MT (1999) Physiological significance of low atmospheric CO₂ for plant-climate interactions. *Quat Res* 52: 237-242 (See additional research exchanges in *Quat Res* 53: 402-404 and *Quat Res* 53: 405-406)
- Cronin TM, Dwyer GS, Kamiya T, Schwede S, Willard DA (2003) Medieval warm period, little ice age and the 20th century temperature variability from Chesapeake Bay. *Glob Planet Change*: in press
- Crowley TJ (2000) Causes of climate change over the past 1000 years. *Science* 289: 270-277
- Crowley TJ, Lowery TS (2000) How warm was the medieval warm period? *Ambio* 29: 51-54
- Cullen HM, D'Arrigo RD, Cook ER, Mann ME (2001) Multiproxy reconstructions of the North Atlantic Oscillation. *Paleocean* 16: 27-39
- Dahl-Jensen D and 6 others (1998) Past temperatures directly from the Greenland ice sheet. *Science* 282: 268-271
- Dansgaard W and 5 others (1975) Climatic changes, Norsemen and modern man. *Nature* 255: 24-28
- D'Arrigo RD and 6 others (1998) Tree-ring records from New Zealand: Long-term context for recent warming trend. *Clim Dyn* 14: 191-199
- D'Arrigo RD and 8 others (2001) 1738 years of Mongolian temperature variability inferred

- from a tree-ring width chronology of Siberian Pine. *Geophys Res Lett* 28: 543-546
- Davis OK (1994) The correlation of summer precipitation in the southwestern USA with isotopic records of solar activity during the Medieval Warm Period. *Clim Change* 26: 271-287
- Dean WE, Schwalb A (2000) Holocene environmental and climatic change in the Northern Great Plains as recorded in the geochemistry of sediments in Pickerel Lake, South Dakota. *Quat Int* 67: 5-20
- Delworth TL, Knutson TR (2000) Simulation of early 20th century global warming. *Science* 287: 2246-2250
- Delworth TL, Mann ME (2000) Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim Dyn* 16: 661-676
- deMenocal P (2001) Cultural responses to climate change during the late Holocene. *Science* 292: 667-673
- deMenocal P, Ortiz J, Guilderson T, Sarnthein M (2000) Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* 288: 2198-2202
- Domack EW, Mayewski PA (1999) Bi-polar ocean linkages: Evidence from late-Holocene Antarctic marine and Greenland ice-core records. *Holocene* 9: 247-251
- Domack E and 5 others plus ODP Leg 178 Team (2001) Chronology of the Palmer Deep site, Antarctic Peninsula: A Holocene palaeoenvironmental reference for the circum-Antarctic. *Holocene* 11: 1-9
- Dommenget D, Latif M (2002) A cautionary note on the interpretation of EOFs. *J Clim* 15: 216-225
- Doran PT and 12 others (2002) Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415: 517-520; See also exchanges between Turner et al. and Walsh, Doran et al. (2002) in Recent temperature trends in the Antarctic. *Nature* 418: 291-292
- Druffel EM (1982) Banded corals: Changes in oceanic carbon-14 during the Little Ice Age. *Science* 218: 13-19
- Dyurgerov MB, Meier MF (2000) Twentieth century climate change: Evidence from small glaciers. *Proc Natl Acad Sci USA* 97: 1406-1411
- Ely LL, Enzel Y, Baker VR, Cayan DR (1993) A 5000-year record of extreme floods and climate change in the Southwestern United States. *Science* 262: 410-412

- Emery WJ, Castro S, Wick GA, Schlüssel P, Donlon G (2001a) Estimating sea surface temperature from infrared satellite and in situ temperature data. *Bull Am Meteor Soc* 82: 2773-2785
- Emery WJ, Baldwin DJ, Schlüssel P, Reynolds RW (2001b) Accuracy of in situ sea surface temperatures used to calibrate infrared satellite measurements. *J Geophys Res* 106: 2387-2405
- Esper J, Cook ER, Schweingruber FH (2002a) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295: 2250-2253
- Esper J, Schweingruber FH, Winiger M (2002b) 1300 years of climate history for Western Central Asia inferred from tree-rings. *Holocene* 12: 267-277
- Etheridge DM and 5 others (1996) Natural and anthropogenic changes in atmospheric CO₂ over the last 1000 years from air in Antarctic ice and firn. *J Geophys Res* 101: 4115-4128
- Evans DJA (2000) Ice in a greenhouse: The impacts of global warming on world glacier cover. *Trans Inst Engineers and Shipbuilders in Scotland* 143: 11-19
- Evans MN, Kaplan A, Cane MA (2002) Pacific sea surface temperature field reconstruction from coral $\delta^{18}\text{O}$ data using reduced space objective analysis. *Paleocean* 17: 10.1029/2000PA000590
- Evans MN, Kaplan A, Cane MA, Villalba R (2000) Globality and optimality in climate field reconstructions from proxy data. In Markgraf V (ed) *Inter-hemispheric Climate Linkages*, Academic Press, p. 53-72
- Feng X (1999) Trends in intrinsic water-use efficiency of natural trees for the past 100-200 years. *Geochimica et Cosmochimica Acta* 63: 1891-1903
- Feng X, Epstein S (1994) Climatic implications of an 8000-year hydrogen isotope time series from Bristlecone Pine trees. *Science* 265: 1079-1081
- Filippi ML, Lambert P, Hunziker J, Kübler B, Bernasconi S (1999) Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millenia. *J Paleolim* 21: 19-34
- Folland CK and 10 others (2001) Global temperature change and its uncertainties since 1861. *Geophys Res Lett* 28: 2621-2624
- Forster G (2000) *A Voyage Round the World*, 2 vols. edited by N. Thomas and O. Berghof, University of Hawaii Press

- Fritz SC, Ito E, Yu Z, Laird KR, Engstrom DR (2000) Hydrologic variation in the Northern Great Plains during the last two millennia. *Quat Res* 53: 175-184
- St. George S, Nielsen E (2002) Hydroclimatic change in Southern Manitoba since A.D. 1409 inferred from tree rings. *Quat Res* 58: 103-111
- Goody R, Anderson J, North G (1998) Testing climate models: An approach. *Bull Am Meteor Soc* 79: 2541-2549
- Graumlich LJ (1993) A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quat Res* 39: 249-255
- Graybill DA, Idso SB (1993) Detecting the aerial fertilization effect of atmospheric CO₂ enrichment in tree-ring chronologies. *Glob BioGeoChem Cyc* 7: 81-95
- Grissino-Mayer HD (1996) A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. In Dean JS, Meko DM, Swetnam TW (eds) *Tree rings, environment and humanity, Radiocarbon* (U Arizona Press), p. 191-204
- Grove AT (2001) The "Little Ice Age" and its geomorphological consequences in Mediterranean Europe. *Clim Change* 48: 121-136
- Grove JM (1996) The century time-scale. In Driver TS, Chapman GP (eds) *Time-scales and environmental change*, Routledge, p. 39-87
- Grove JM (2001a) The initiation of the Little Ice Age in regions round the North Atlantic. *Clim Change* 48: 53-82
- Grove JM (2001b) The onset of the Little Ice Age. In Jones PD, Ogilvie AEJ, Davies TD, Briffa KR (eds) *History and Climate—Memories of the Future?*, Kluwer, p. 153-185
- Grove JM, Conterio A (1995) The climate of Crete in the sixteenth and seventeenth centuries. *Clim Change* 30: 223-247
- Grove JM, Switsur R (1994) Glacial geological evidence for the medieval warm period. *Clim Change* 26: 143-169
- Grove RH (1998) Global impact of the 1789-93 El Nino. *Nature* 393: 318-319
- Hadly EA (1996) Influence of late-Holocene climate on Northern Rocky Mountain mammals. *Quat Res* 46: 289-310
- Häkkinen S (2000) Decadal air-sea interaction in the North Atlantic based on observations and modeling results. *J Clim* 13: 1195-1219
- Hansen J, Ruedy R, Glascoe J, Sato M (1999) GISS analysis of surface temperature change.

J Geophys Res 104: 30997-31022

Harris RN, Chapman DS (2001) Mid-latitude (30°-60°N) climatic warming inferred by combining borehole temperatures with surface air temperatures. *Geophys Res Lett* 28: 747-750

Harrison DE, Larkin NK (1998) Seasonal U.S. temperature and precipitation anomalies associated with El Nino: Historical results and comparison with 1997-98. *Geophys Res Lett* 25: 3959-3962

Haug GH, Hughen KA, Sigman DM, Peterson LC, Röhlk U (2001) Southward migration of the intertropical convergence zone through the Holocene. *Science* 293: 1304-1308

Heikkilä M, Seppä H (2003) A 11,000 yr paleotemperature reconstruction from the southern boreal zone in Finland. *Quat Sci Rev* : in press

Henderson GM (2002) New oceanic proxies for paleoclimate. *Earth and Planetary Science Letters* 203: 1-13

Hendy EJ and 5 others (2002) Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* 295: 1511-1514

Hiller A, Boettger T, Kremenetski C (2001) Mediaeval climatic warming recorded by radiocarbon date alpine tree-line shift on the Kola Peninsula, Russia. *Holocene* 11: 491-497

Hodell DA, Brenner M, Curtis JH, Guilderson T (2001) Solar forcing of drought frequency in the Maya lowlands. *Science* 292: 1367-1370

Holzhauser H (1997) Fluctuations of the Grosser Aletsch Glacier and the Groner Glacier during the last 3200 years: New results. In Frenzel B, Boulton GS, Gläser B, Huckriede U (eds) *Glacier fluctuations during the Holocene*, Akademie der Wissenschaften und der Literatur, p. 35-58

Hong YT and 8 others (2000) Response of climate to solar forcing recorded in a 6000-year $\delta^{18}\text{O}$ time-series of Chinese peat cellulose. *Holocene* 10: 1-7

Hormes A, Müller BU, Schlichter C (2001) The Alps with little ice: Evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *Holocene* 11: 255-265

Hsu HH, Moura AD (2001) Meeting summary: Workshop on the impacts of the 1997-99 ENSO. *Bull Am Meteor Soc* 82: 305-312

Hu FS, Ito E, Brown TA, Curry BB, Engstrom DR (2001) Pronounced climatic variations in Alaska during the last two millenia. *Proc Natl Acad Sci USA* 98: 10552-10556

Huang S, Pollack HN (2002) Borehole temperature observations compared to synthetic subsurface temperatures generated by proxy climate reconstructions (abstract). EOS Trans AGU suppl 83: p. F 918

Huang S, Pollack HN, Shen PY (1997) Late Quaternary temperature changes seen in the world-wide continental heat flow measurements. Geophys Res Lett 24: 1947-1950

Huang S, Shen PY, Pollack HN (1996) Deriving century-long trends of surface temperature change from borehole temperatures. Geophys Res Lett 23: 257-260

Huang S, Pollack HN, Shen PY (2000) Temperature trends over the past five centuries reconstructed from borehole temperatures. Nature 403: 756-758

Huffman TN (1996) Archaeological evidence for climatic change during the last 2000 years in Southern Africa. Quat Int 33: 55-60

Hughes MK, Diaz HF (1994) Was there a 'Medieval Warm Period', if so, where and when? Clim Change 26: 109-142

Hurrell JW, Trenberth KE (1999) Global sea surface temperature analyses: Multiple problems and their implications for climate analysis, modeling, and reanalysis. Bull Am Meteor Soc 80: 2661-2678

Huybrechts P, de Wolde J (1999) The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming. J Clim 12: 2169-2188

Idso SB (1989) Letter to the editor—A problem for paleoclimatology? Quat Res 31: 433-434

Idso SB (1998) CO₂-induced global warming: A skeptic's view of potential climate change. Clim Res 10: 69-82

Ingram MJ, Underhill DJ, Wigley TML (1978) Historical climatology. Nature 276: 329-334

Iriondo M (1999) Climatic changes in the South American plains: Records of a continent-scale oscillation. Quat Int 57-58: 93-112

Jacoby GC, D'Arrigo RD (1995) Tree-ring width and density evidence for climatic and potential forest change in Alaska. Glob Biogeochem Cyc 9: 227-234

Jacoby GC, D'Arrigo RD, Davaajamts T (1996) Mongolian tree rings and 20th-century warming. Science 273: 771-773

Jacoby GC and 5 others (2000) Long-term temperature trends and tree growth in the Taymir region of Northern Siberia. Quat Res 53: 312-318

- Jennings AE, Weiner NJ (1996) Environmental change in eastern Greenland during the last 1300 years: Evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. *Holocene* 6: 171-191
- Jenny B and 6 others (2002) Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during the last 2000 years: The Laguna Aculeo record (33°50'S). *Quat Int* 87: 3-18
- Johnson TC, Barry S, Chan Y, Wilkinson P (2001) Decadal record of climate variability spanning the past 700 yr in the Southern tropics of East Africa. *Geology* 29: 83-86
- Jones PD, Briffa KR, Barnett TP, Tett SFB (1998) High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control-run temperatures. *Holocene* 8: 455-471
- Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J Clim* 16: 206-223
- Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperatures and its changes over the past 150 years. *Rev Geophys* 37: 173-199
- Jones PD, Osborn TJ, Briffa KR (2001) The evolution of climate over the last millennium. *Science* 292: 662-667
- Karlén W (1998) Climate variations and the enhanced greenhouse effect. *Ambio* 27: 270-274
- Karlén W (2001) Global temperature forced by solar irradiation and greenhouse gases? *Ambio* 30: 349-350
- Karlöf L and 13 others (2000) A 1500 year record of accumulation at Amundsenisen western Dronning Maud Land, Antarctica, derived from electrical and radioactive measurements on a 120 m ice core. *J Geophys Res* 105: 12471-12483
- Kaser G (1999) A review of the modern fluctuations of tropical glaciers. *Glob Planet Change* 22: 93-103
- Keigwin LD (1996) The little ice age and medieval warm period in the Sargasso Sea. *Science* 274: 1504-1508
- Keith DW, Anderson JG (2001) Accurate spectrally resolved infrared radiance observation from space: Implications for the detection of decade-to-century-scale climatic change. *J Clim* 14: 979-990

- Kennett JP, Hodell DA (1995) Stability or instability of Antarctic ice sheets during the warm climates of the Pliocene ? GSA Today 5: 1-22 (about 5 pp.)
- Khim BK, Yoon HI, Kang CY, Bahk JJ (2002) Unstable climate oscillations during the late Holocene in the Eastern Bransfield Basin, Antarctic Peninsula. Quat Res 58: 234-245
- Kiladis GN, Diaz HF (1986) An analysis of the 1877-78 ENSO episode and comparison with 1982-83. Mon Wea Rev 114: 1035-1047
- Kitagawa H, Matsumoto E (1995) Climatic implications of $\delta^{13}\text{C}$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millenia. Geophys Res Lett 22: 2155-2158
- Knapp PA, Soulé PT, Grissino-Mayer HD (2001) Post-drought growth responses of western juniper (*Juniperus occidentalis* var. *occidentalis*) in central Oregon. Geophys Res Lett 28: 2657-2660
- Knappenberger PC, Michaels PJ, Davis RE (2001) Nature of observed temperature changes across the United States during the 20th century. Clim Res 17: 45-53
- Koerner RM (1977) Devon Island ice cap: Core stratigraphy and paleoclimate. Science 196: 15-18
- Koerner RM, Fisher DA (1990) A record of Holocene summer climate from a Canadian high-Arctic ice core. Nature 343: 630-631
- Korhola A, Weckström J, Holmström L, Erästö P (2000) A quantitative Holocene climatic record from diatoms in Northern Fennoscandia. Quat Res 54: 284-294
- Kreutz KJ and 5 others (1997) Bipolar changes in atmospheric circulation during the Little Ice Age. Science 277: 1294-1296
- Krishnamurti TN and 7 others (2000) Coupled atmosphere-ocean modeling of the El Nino of 1997-98. J Clim 13: 2428-2459
- Ku TL, Li HC (1998) Speleothems as high-resolution paleoenvironment archives: Records from northeastern China. Proc Indian Acad Sci (Earth Planet Sci) 107: 321-330
- Kuhnert H, Pätzold J, Schnetger B, Wefer G (2002) Sea-surface temperature variability in the 16th century at Bermuda inferred from coral records. Palaeogeogr Palaeoclim Palaeoecol 179: 159-171
- Kumar A, Wang WQ, Hoerling MP, Leetma A, Ji M (2001) The sustained North American warming of 1997 and 1998. J Clim 14: 345-353
- Laird KR, Fritz SC, Maasch KA, Cumming BF (1996) Greater drought intensity and

- frequency before AD 1200 in the Northern Great Plains, USA. *Nature* 384: 552-554
- Lamb HH (1963) On the nature of certain climatic epochs which differed from the modern (1900-39) normal. In Proceedings of the WMO-UNESCO Symposium on Climate Change, Rome, 1961. UNESCO Arid Zone Res. 20, p. 125-150
- Lamb HH (1965) The early medieval warm epoch and its sequel. *Palaeogeogr Palaeoclim Palaeoecol* 1: 13-37
- Lamb HH (1977) *Climate — Past, Present and Future* Vol. 2 Climatic History and Future, Methuen
- Lamb HH (1982) *Climate history and the modern world*, Methuen
- Lamb HH (1997a) *Climate history and the modern world*, 2nd Edition, Routledge
- Lamb H (1997b) *Through all the changing scenes of life: A meteorologist's tale*, Taverner
- Lamoureux SF, Bradley RS (1996) A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *J Paleolim* 16: 239-255
- Lara A, Villalba R (1993) A 3260-year temperature record from *Fit roya cupressoides* tree rings in southern South America. *Science* 260: 1104-1106
- Lau NC, Nath MJ (2001) Impact of ENSO and SST variability in the North Pacific and North Atlantic: Seasonal dependence and role of extratropical sea-air coupling. *J Clim* 14: 2846-2866
- Lau KM, Weng HY (2001) Coherent modes of global SST and summer rainfall over China: An assessment of the regional impacts of the 1997-98 El Nino. *J Clim* 14: 1294-1308
- Lawton RO, Nair US, Pielke Sr. RA, Welch RM (2001) Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* 294: 584-587
- Leroux M (1993) The Mobile Polar High: A new concept explaining present mechanisms of meridional air-mass and energy exchanges and global propagation of palaeoclimatic changes. *Glob Planet Change* 7: 69-93
- Lewis TJ, Wang K (1998) Geothermal evidence for deforestation induced warming: Implications for the climatic impact of land development. *Geophys Res Lett* 25: 535-538
- Li HC, Bischoff JL, Ku TL, Lund SP, Stot LD (2000) Climate variability in East-Central California during the past 1000 years reflected by high-resolution geochemical and isotopic records from Owens Lake sediments. *Quat Res* 54: 189-197
- Li HC, Ku TL, Stot LD, Chen W (1998) Applications of interannual-resolution stable

- isotope records of speleothem: Climatic changes in Beijing and Tianjin, China during the past 500 years—the $\delta^{18}\text{O}$ record. *Sci in China (Series D)* 41: 362–368
- Liu K, Yao Z, Thompson LG (1998) A pollen record of Holocene climatic changes from Dunde ice cap, Qinghai-Tibetan Plateau. *Geology* 26: 135–138
- Lotter AF and 5 others (2000) Younger Dryas Aller d summer temperatures at Gerzensee (Switzerland) inferred from fossil pollen and cladoceran assemblages. *Palaeogeogr Palaeoclim Palaeoecol* 159: 349–361
- Luckman BH (2000) The Little Ice Age in the Canadian Rockies. *Geomorph* 32: 357–384
- Luckman BH, Briffa KR, Jones PD, Schweingruber FH (1997) Tree-ring based reconstruction of summer temperatures at Columbia Icefield, Alberta, Canada, AD 1073–1983. *Holocene* 7: 375–389
- Luterbacher J and 33 others (2000) Monthly mean pressure reconstruction for the late Maunder Minimum period (AD 1675–1715). *Int J Clim* 20: 1049–1066
- Madole RF (1994) Stratigraphic evidence of desertification in the west-central Great Plains within the past 1000 yr. *Geology* 22: 483–486
- Manley G (1974) Central England temperatures: Monthly means 1659 to 1973. *Quart J Roy Meteorol Soc* 100: 389–405
- Mann ME (2001a) Climate during the past millennium. *Weather* 56: 91–102
- Mann ME (2001b) Little Ice Age. In MacCracken MC, Perry JS (eds) *Encyclopedia of Global Environmental Change: Volume 1—The Earth System: Physical and Chemical Dimensions of Global Environmental Change*, John Wiley and Sons Ltd., p. 504–509
- Mann ME (2002) The value of multiple proxies. *Science* 297: 1481–1482
- Mann ME, Bradley RS, Hughes MK (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392: 779–787
- Mann ME, Bradley RS, Hughes MK (1999) Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys Res Lett* 26: 759–762
- Mann ME, Hughes MK (2002) Tree-ring chronologies and climate variability. *Science* 296: 848
- Mann ME and 6 others (2000a) Global temperature patterns in past centuries: An interactive presentation. *Earth Interact* 4 (Paper No. 4): 1–29 [available online <http://Earthinteraction.org>]

- Mann ME, Bradley RS, Hughes MK (2000b) Long-term variability in the El Niño Southern Oscillation and associated teleconnections. In Diaz HF, Markgraf V (eds) *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impact*, Cambridge Univ Press, p. 357-412
- Mann ME, Rutherford S, Bradley RS, Hughes MK, Keimig FT (2003) Optimal surface temperature reconstructions using terrestrial borehole data. *J Geophys Res*: in press
- Marshall GJ, Lagun V, Lachlan-Cope TA (2002) Changes in Antarctic Peninsula tropospheric temperatures from 1956 to 1999: A synthesis of observations and reanalysis data. *Int J Clim* 22: 291-310
- Marshall J, Johnson H, Goodman J (2001) A study of the interaction of the North Atlantic oscillation with ocean circulation. *J Clim* 14: 1399-1421
- Mayewski PA, White F (2002) The last thousand years of climate change. In *The Ice Chronicles*, University Press of New England, p. 131-145
- McDermott F, Matthey DP, Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* 294: 1328-1331
- Meeker LD, Mayewski PA, Grootes PM, Alley RB, Bond GC (2001) Comment on "On sharp spectral lines in the climate record and the millennial peak" by Carl Wunsch. *Paleocean* 16: 544-547
- Meese DA and 8 others (1994) The accumulation record from the GISP2 core as an indicator of the climate change throughout the Holocene. *Science* 266: 1680-1682
- Mercer JH (1978) West Antarctic ice sheet and CO_2 greenhouse effect: A threat of disaster. *Nature* 271: 321-325
- Morgan VI (1985) An oxygen isotope climate record from the Law Dome, Antarctica. *Clim Change* 7: 415-426
- Mosley-Thompson E, Thompson LG (1982) Nine centuries of microparticles deposition at the South Pole. *Quat Res* 17: 1-13
- Mosley-Thompson E (1995) Paleoenvironmental conditions in Antarctica since A.D. 1500: Ice core evidence. In Bradley RS, Jones PD (eds) *Climate Since A.D. 1500*, Routledge, p. 572-591
- Naurzbaev MM, Vaganov EA (2000) Variation of early summer and annual temperature in east Taymir and Putorian (Siberia) over the last two millennia. *J Geophys Res* 105:

7317-7326

Niggemann S, Mangini A, Richter DK, Wirth G (2003) A paleoclimate record of the last 17,600 years in stalagmites from the B7 cave, Sauerland, Germany. *Quat Sci Rev*: in press

Nyberg J, Malmgren BA, Kuijpers A, Winter A (2002) A centennial-scale variability of tropical North Atlantic surface hydrography during the late Holocene. *Palaeogeogr Palaeoclim Palaeoecol* 183: 25-41

Ogilvie AEJ (1984) The past climate and sea-ice record from Iceland, Part 1: Data to A.D. 1780. *Clim Change* 6: 131-152

Ogilvie AEJ, Barlow LK, Jennings AE (2000) North Atlantic climate c. A.D. 1000: Millennial reflections on the Viking discoveries of Iceland, Greenland and North America. *Weather* 55: 34-45

Ogilvie A, Farmer G (1997) Documenting the medieval climate. In Hulme M, Barrow E (eds) *Climate of the British Isles—Present, Past and Future*, Routledge, p. 112-133

Ogilvie AEJ, Jónsson T (2001) "Little Ice Age" research: A perspective from Iceland. *Clim Change* 48: 9-52

Ou HW (2001) Possible bounds on the Earth's surface temperature: From the perspective of a conceptual global-mean model. *J Clim* 14: 2976-2988

Overpeck J and 17 others (1997) Arctic environmental change of the last four centuries. *Science* 278: 1251-1256

Parker DE, Folland CK, Jackson M (1995) Marine surface temperature: Observed variations and data requirements. *Clim Change* 31: 559-600

Paulsen DE, Li HC, Ku TL (2003) Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records. *Quat Sci Rev*: in press

Pederson JL (2000) Holocene paleolakes of Lake Canyon, Colorado Plateau: Paleoclimate and landscape response from sedimentology and allostratigraphy. *Geol Soc Amer Bull* 112: 147-158

Perry CA, Hsu KJ (2000) Geophysical, archaeological, and historical evidence support a solar-output model for climate change. *Proc Natl Acad Sci USA* 97: 12433-12438

Petersen KL (1994) A warm and wet little climatic optimum and a cold and dry little ice age in the Southern Rocky Mountains, USA. *Clim Change* 26: 243-269

Pfister C (1995) Monthly temperature and precipitation in central Europe 1525-1979:

- Quantifying documentary evidence on weather and its effects. In Bradley RS, Jones PD (eds) *Climate Since A.D. 1500*, Routledge, p. 118-142
- Pfister C, Luterbacher J, Schwarz-Zanetti G, Wegmann M (1998) Winter air temperature variations in western Europe during the early and high Middle ages (AD 750-1300). *Holocene* 8: 535-552
- Pielke Jr RA, (1998) Rethinking the role of adaptation in climate policy. *Glob Environ Change* 8: 159-170
- Pielke Sr RA, (2001) Earth system modeling—An integrated assessment tool for environmental studies. In Matsuno T, Kida H (eds) *Present and future of modeling global environmental change: Toward integrated modeling*, TERRAPUB Tokyo, p. 311-337
- Pisias NG (1978) Paleoceanography of the Santa Barbara Basin during the last 8000 years. *Quat Res* 10: 366-384
- Porter SC (1981) Glaciological evidence of Holocene climatic change. In Wigley TML, Ingram MJ, Farmer G (eds) *Climate and History—Studies in past climates and their impact on Man*, Cambridge University Press, p. 82-110
- Porter SC (1986) Pattern and forcing of the Northern hemisphere glacier variations during the last millennium. *Quat Res* 26: 27-48
- Proctor CJ, Baker A, Barnes WL, Gilmour MA (2000) A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Clim Dyn* 16: 815-820
- Qian W, Zhu Y (2002) Little Ice Age climate near Beijing, China, inferred from historical and stalagmite records. *Quat Res* 57: 109-119
- Ramesh R (1993) First evidence for Little Ice Age and Medieval Warming in India (abstract). *EOS Trans AGU suppl* 74: 118
- Räisänen J (2001) CO₂-induced climate change in CMIP2 experiments: Quantification of agreement and role of internal variability. *J Clim* 14: 2088-2104
- Ren G (1998) Pollen evidence for increased summer rainfall in the Medieval warm period at Maili, Northeast China. *Geophys Res Lett* 25: 1931-1934
- Robinson WA, Ruedy R, Hansen J (2002) General circulation model simulations of recent cooling in the east-central United States. *J Geophys Res* 107 (D24), 4748, doi:10.1029/2001JD001577
- Rodrigo FS, Esteban-Parra MJ, Pozo-Vázquez D, Castro-Díez Y (2000) Rainfall variability

- in Southern Spain on decadal to centennial time scales. *Int J Clim* 20: 721-732
- Rott H, Skvarca P, Nagler T (1996) Rapid collapse of Northern Larsen ice shelf, Antarctica. *Science* 271: 788-792
- Sakamoto N, Masuda K (2002) Significance of the sampling errors due to changing land-sea distribution in the Phanerozoic paleo-climate reconstruction. *J Meteor Soc Japan* 80: 531-537
- Schleser GH, Helle G, Lücke A, Vos H (1999) Isotope signals as climate proxies: The role of transfer functions in the study of terrestrial archives. *Quat Sci Rev* 18: 927-943
- Schmutz C, Luterbacher J, Gyalistras D, Xoplaki E, Wanner H (2000) Can we trust proxy-based NAO index reconstructions? *Geophys Res Lett* 27: 1135-1138
- Schneider T (2001) Analysis of incomplete climate data: Estimation of mean values and covariance matrices and imputation of missing values. *J Clim* 14: 853-871
- Schuster PF, White DE, Naftz DL, Cecil LD (2000) Chronological refinement of an ice core record at Upper Fremont Glacier in south central North America. *J Geophys Res* 105: 7317-7326
- Scuderi LA (1993) A 2000-year tree ring record of annual temperatures in the Sierra Nevada mountains. *Science* 259: 1433-1436
- Seager R and 6 others (2000) Causes of Atlantic ocean climate variability between 1958 and 1998. *J Clim* 13: 2845-2862
- Seppä H, Birks HJB (2002) Holocene climate reconstructions from the Fennoscandian tree-line area based on pollen data from Toskaljavri. *Quat Res* 57: 191-199
- Serre-Bachet F (1994) Middle ages temperature reconstructions in Europe, a focus on Northeastern Italy. *Clim Change* 26: 213-240
- Shabalova MV, Weber SL (1998) Seasonality of low-frequency variability in early-instrumental European temperatures. *Geophys Res Lett* 25: 3859-3862
- Shi Y, Yao T, Yang B (1999) Decadal climatic variations recorded in Guliya ice core and comparison with the historical documentary data from East China during the last 2000 years. *Sci in China Ser D (suppl)* 42: 91-100
- Skinner WR, Majorowicz JA (1999) Regional climatic warming and associated twentieth century land-cover changes in north-western North America. *Clim Res* 12: 39-52
- Slonosky VC, Yiou P (2001) The North Atlantic Oscillation and its relationship with near

- surface temperature. *Geophys Res Lett* 28: 807-810
- Smith RC and 10 others (1999) Marine ecosystem sensitivity to climate change. *Bioscience* 49: 393-404
- Song J (2000) Changes in dryness/wetness in China during the last 529 years. *Int J Clim* 20: 1003-1015
- Stahle DW, Cleaveland MK, Hehr JG (1988) North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985. *Science* 240: 1517-1519
- Stenni B and 6 others (2002) Eight centuries of volcanic signal and climate change at Talos Dome (East Antarctica). *J Geophys Res* 107: doi:10.1029/2000JD000317
- Stine S (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature* 369: 546-549
- Stine S (1998) Medieval climatic anomaly in the Americas. In Issar AS, Brown N (eds) *Water, Environment and Society in Times of Climatic Change*, Kluwer Academic Press, p. 43-67
- Stott L (2002) SST variability in the Western Pacific Warm Pool during the past 2000 years (abstract). *EOS Trans AGU suppl* 83: p. F 915
- Stott L, Poulsen, C, Lund S, Thunell, R (2002) Super ENSO and global climate oscillations at millennial time scales. *Science* 297: 222-226 (plus erratum posted October 25, 2002)
- Stuiver M, Grootes PM, Braziunas TF (1995) The GISP2 $\delta^{18}\text{O}$ climate record of the past 16,500 years and the role of the Sun, ocean and volcanoes. *Quat Res* 44: 341-354
- Sugden DE (1996) The East Antarctic ice sheet: Unstable ice or unstable ideas? *Trans Inst Br Geogr NS* 21: 443-454
- Swetnam TW (1993) Fire history and climate change in Giant Sequoia groves. *Science* 262: 885-889
- Tagami Y (1993) Climate change reconstructed from historical data in Japan. In *Proceedings of International Symposium on Global Change by IGBP, International Geosphere-Biosphere Programme-IGBP*, p. 720-729
- Tagami Y (1996) Some remarks on the climate in the Medieval Warm Period of Japan. In Mikami T, Matsumoto E, Ohta S, Sweda T (eds) *Paleoclimate and environmental variability in Austral-Asian transect during the past 2000 years (IGBP Proceedings)*, International Geosphere-Biosphere Programme-IGBP, p. 115-119

- Tarussov A (1995) The Arctic from Svalbard to Severnaya Zemlya: Climatic reconstructions from ice cores. In Bradley RS, Jones PD (eds) *Climate Since A.D. 1500*, Routledge, p. 505-516
- Thomas RH, Sanderson TJO, Rose KE (1979) Effect of climatic warming on the West Antarctic ice sheet. *Nature* 277: 355-358
- Thompson DWJ, Baldwin MP, Wallace JM (2002) Stratospheric connection to northern hemisphere wintertime weather: Implications for prediction. *J Clim* 15: 1421-1428
- Thompson LG (2000) Ice core evidence for climate change in the Tropics: Implications for our future. *Quat Sci Rev* 19: 19-35
- Thompson LG, Mosley-Thompson E, Dansgaard W, Grootes PM (1986) The little ice age as recorded in the stratigraphy of the tropical Quelccaya ice cap. *Science* 234: 361-364
- Thompson LG and 9 others (1989) Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan plateau. *Science* 246: 474-477
- Thompson LG and 7 others (1994) Climate since AD 1510 on Dyer Plateau, Antarctic Peninsula: Evidence for recent climate change. *Ann Glaciology* 20: 420-426
- Thompson LG and 6 others (1995) A 1000 year climate ice-core record from the Guliya ice cap, China: Its relationship to global climate variability. *Ann Glaciology* 21: 175-181
- Thompson LG and 5 others (2000) A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science* 289: 1916-1919
- Till C, Guiot J (1990) Reconstruction of precipitation in Morocco since 1100 A.D. based on *Cedrus atlantica* tree-ring widths. *Quat Res* 33: 337-351
- Tomita T, Wang B, Yasunari T, Nakamura H (2001) Global patterns of decadal scale variability observed in sea surface temperature and lower-tropospheric circulation fields. *J Geophys Res* 106: 26805-26815
- Tong G and 7 others (1996) Environmental changes at the top of Taibai Mountain, Qinling since 1ka ago. *Mar Geol Quat Geol* 16: 95-104 (In Chinese but English Abstract available)
- Tyson PD, Karlén W, Holmgren K, Heiss GA (2000) The Little Ice Age and medieval warming in South Africa. *South African J Sci* 96: 121-126
- Tyson PD, Lindesay JA (1992) The climate of the last 2000 years in southern Africa. *Holocene* 2: 271-278
- Ueda H, Matsumoto J (2000) A Possible Triggering Process of East-West Asymmetric

- Anomalies over the Indian Ocean in Relation to 1997/98 El Nino. *J Meteor Soc Japan* 78: 803-818
- Valero-Garcés BL, Delgado-Huertas A, Ratto N, Navas A, Edwards L (2000) Paleohydrology of Andean saline lakes from sedimentological and isotopic records, Northwestern Argentina. *J Paleolimnology* 24: 343-359
- van Engelen AFV, Buisman J, Ijnsen F (2001) A millennium of weather, winds and water in the low countries. In Jones PD, Ogilvie AEJ, Davies TD, Briffa KR (eds) *History and Climate—Memories of the Future?*, Kluwer, p. 101-124
- Vaughan DG, Doake CSM (1996) Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature* 379: 328-331
- Verardo S, Cronin T, Willard D, Kerhin R (1998) Climate and environmental changes recorded by Chesapeake Bay Dinoflagellate cysts in the last millennium. *Geol Soc Amer Abs* 74: 284
- Verschuren D, Laird KR, Cumming BF (2000) Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* 403: 410-414
- Villalba R (1990) Climatic fluctuations in Northern Patagonia during the last 1000 years as inferred from tree-ring records. *Quat Res* 34: 346-360
- Villalba R (1994) Tree-ring and glacial evidence for the medieval warm epoch and the little ice age in southern South America. *Clim Change* 26: 183-197
- Visser K, Thunell R, Stott L (2003) Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation. *Nature* 421: 152-155
- von Storch JS, Müller P, Bauer E (2001) Climate variability in millennium integrations with coupled atmosphere-ocean GCMs: A spectral view. *Clim Dyn* 17: 375-389
- Williams PW, Marshall A, Ford DC, Jenkinson AV (1999) Palaeoclimatic interpretation of stable isotope data from Holocene speleothems of the Waitomo district, North Island, New Zealand. *Holocene* 9: 649-657
- Wilson AT, Hendy CH, Reynolds CP (1979) Short-term climate change and New Zealand temperatures during the last millennium. *Nature* 279: 315-317
- Winkler S (2000) The 'Little Ice Age' maximum in the Southern Alps, New Zealand: Preliminary results at Mueller Glacier. *Holocene* 10: 643-647
- Winter A, Ishioroshi H, Watanabe T, Oba T, Christy J (2000) Caribbean sea surface

- temperatures: Two-to-three degrees cooler than present during the Little Ice Age. *Geophys Res Lett* 27: 3365-3368
- Woodhouse CA, Overpeck JT (1998) 2000 years of drought variability in the Central United States. *Bull Am Meteor Soc* 79: 2693-2714
- Wunsch C (1999) The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bull Am Meteor Soc* 80: 245-255 (See also important research exchanges in *Bull Am Meteor Soc* 80: 2721-2728)
- Wunsch C (2000) On sharp spectral lines in the climate record and the millennial peak. *Paleocean* 15: 417-424
- Wunsch C (2001) Reply to Meeker et al. (2001). *Paleocean* 16: 548
- Yadav RR, Singh J (2002) Tree-ring-based spring temperature patterns over the past four centuries in Western Himalaya. *Quat Res* 57: 299-305
- Yang B, Braeuning A, Johnson KR, Shi Y (2002) General characteristics of temperature variation in China during the last two millenia. *Geophys Res Lett* 29: 10.1029/2001GL014485, 38-1-38-4
- Yi S, Saito Y, Oshima H, Zhou Y, Wei H (2003) Holocene environmental history inferred from pollen assemblages in the Huanghe (Yellow River) delta, China: Climatic change and human impact. *Quat Sci Rev*: in press
- Yu Z, Ito E (1999) Possible solar forcing of century-scale drought frequency in the northern Great Plains. *Geology* 27: 262-266
- Zhang D (1994) Evidence for the existence of the medieval warm period in China. *Clim Change* 26: 289-297

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 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." 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	22-25°N	112-114 3°E	D	Chan & Shi 00	yes	—	—
(GuangDong Prov.)							
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	68 3°N	29.7°W	Is	Jennings & Weiner 96	yes	yes	no
(Nansen Fjord)							
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	Is	McCose et al. 94	yes	yes	no
C. Greenland (GISP2)	72.58°N	38.5°W	Is	Stuiver et al 95	yes	yes	no
Svalbard	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+	45.8-46.5°N	7.75-8.16°E	G+Gm	Holzhauser 97	yes	yes	no
Grösser Aletsch Glacier)			+Is+T				
South Georgia Island	54-55°S	36-38°W	G+Gm	Clapperton et al. 89	yes	yes	—
Southern Alps	43.44°S	170 06°E	G+Gm	Winkler 00	yes	—	—
(Mueller Glacier)							
Antarctica	64.22°S	57 68°W	Is	Aristarain et al 90	yes?	—	no
(James Ross Island)							
Antarctica	66.73°S	112.83°E	Is	Morgan 85	yes	yes	no
(Law Dome)							
Antarctica	74 33°S	165 13°E	G+Gm+Is	Baroni & Orombelli 94	yes	yes	—
(Victoria Land)							
Antarctica	74.65°S	124.17°E	Is	Benoist et al. 82	yes	yes	no
(Dome C)							

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	52.2°N	117.8°W	T+In+G	Luckman et al. 97	yes	yes	yes*
Columbia Icefield							
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	72 47°N	102°E	T	Naurzbaev & Vaganov 00	yes	yes	no
(Taymir+Putoran)							
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	Serro-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	Easper et al 02b	yes	yes	no
Western Himalaya	30 5-31 2°N	78 5-80°E	T	Yadav & Singh 02	yes	—	no
Mongolia	48 3°N	98 93°E	T	Jacoby et al 96	yes	—	yes
(Tarvagatay Mts)							
Mongolia	48 3°N	98.93°E	T+D	D'Arrigo et al 01	yes	yes	yes
(Tarvagatay Mts.)							
N. Patagonia	41.17°S	71.77°W	T	Villalba 90	yes	yes	no
(Rio Alerce, Argentina)							
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	Fo	Bernabo 81	yes	yes	yes?
Qinghai-Tibetan P (Dunde Ice Cap)	38.1°N	96.4°E	Fo	Liu et al 98	yes	yes	yes*?†
NE China (Maili)	42.87°N	122.87°E	Fo	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 $\delta^{18}\text{O}$ 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 asterisk 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. Tauolbmajavri)	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	Heikkila & 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. Carriboan	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 & Lindsey 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 CO₂ release to air
answers 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

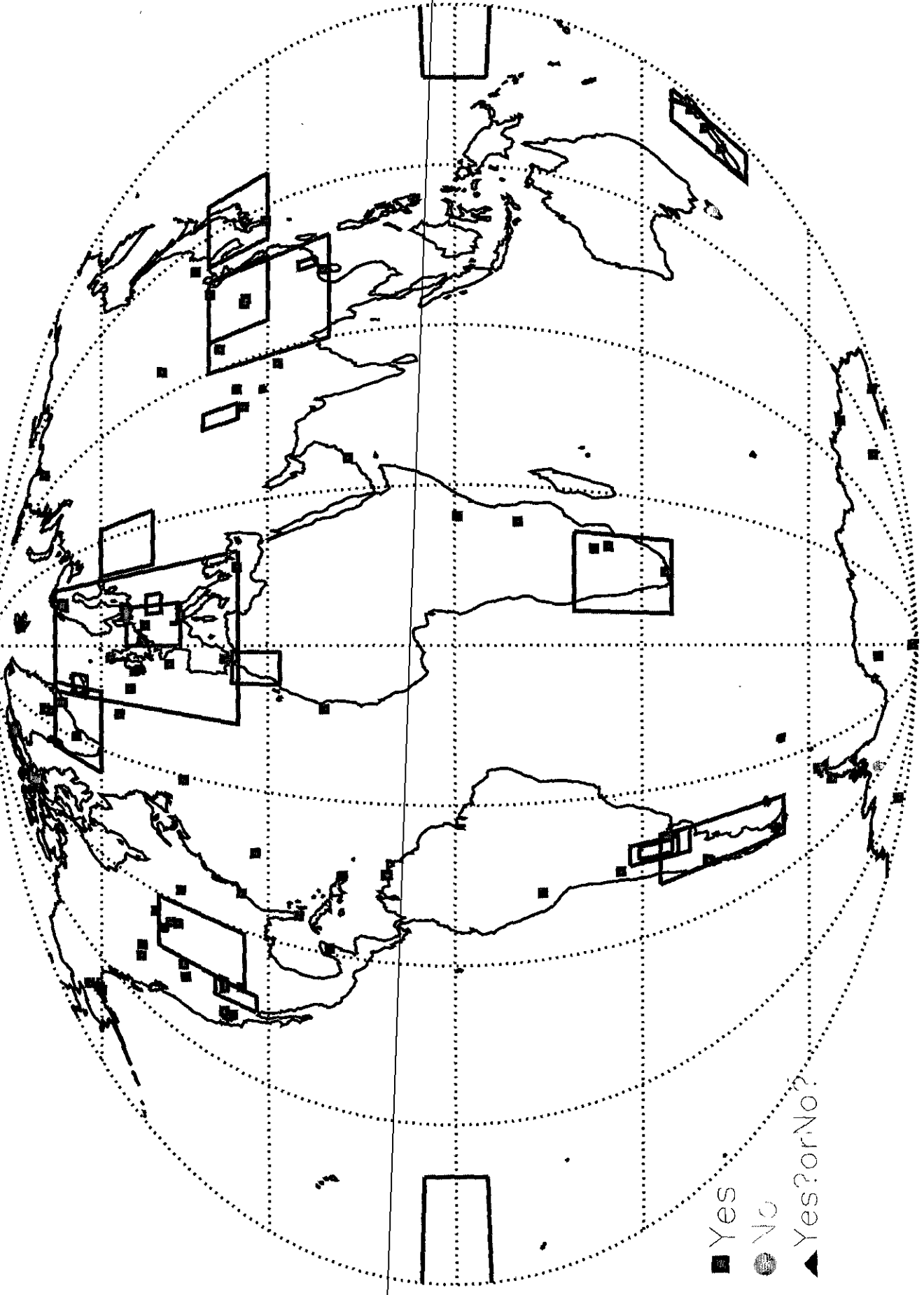
Ts: Tree stumps in lakes, marshes and streams

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.

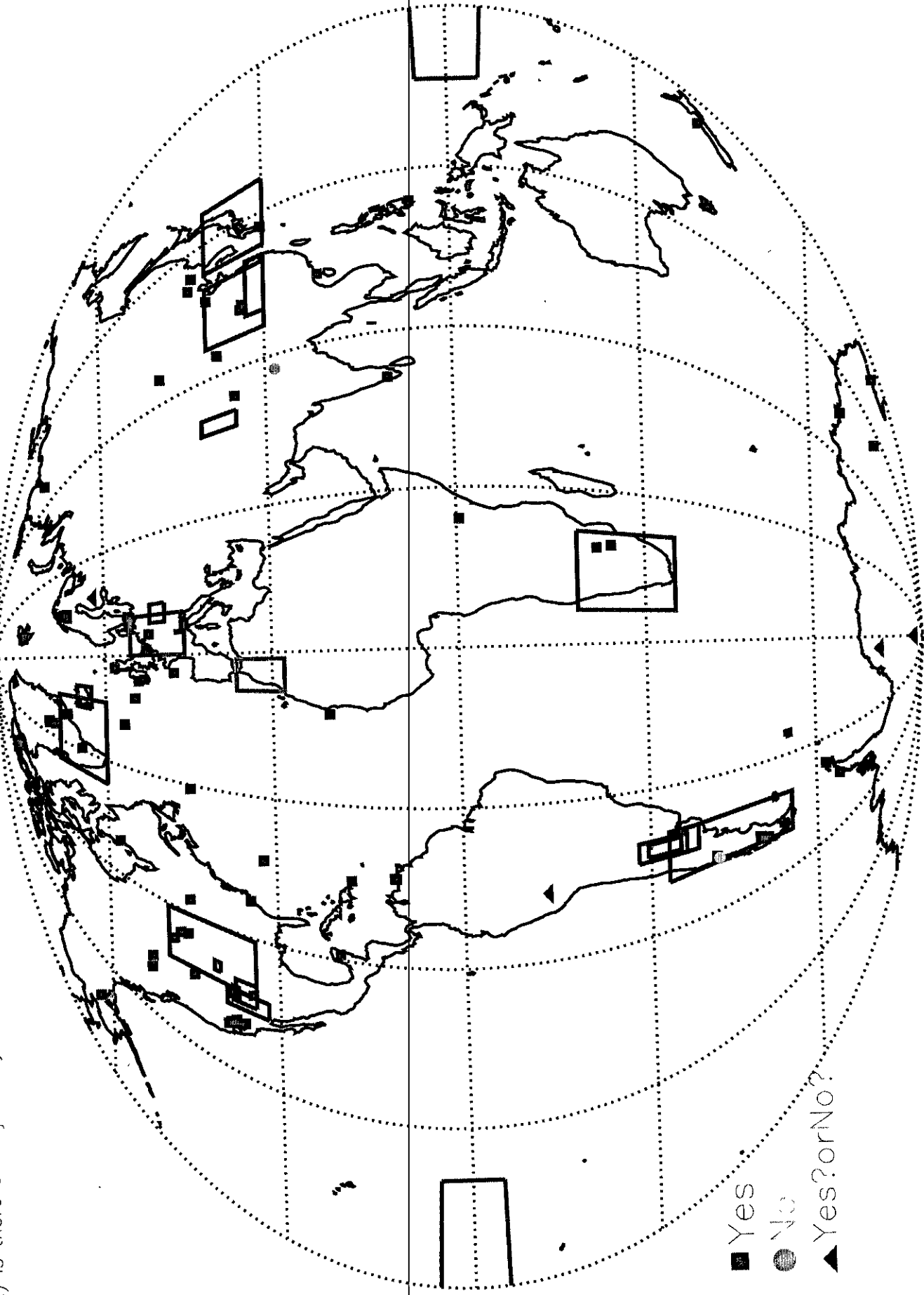
Fig. 2.— Geographical distribution of local answers to the following question: Is there an objectively discernible climatic anomaly during the Medieval Warm Period (800-1300 A.D.) in this proxy record? 'Yes' is indicated by red filled-squares or unfilled boxes, 'No' is indicated by green filled-circles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

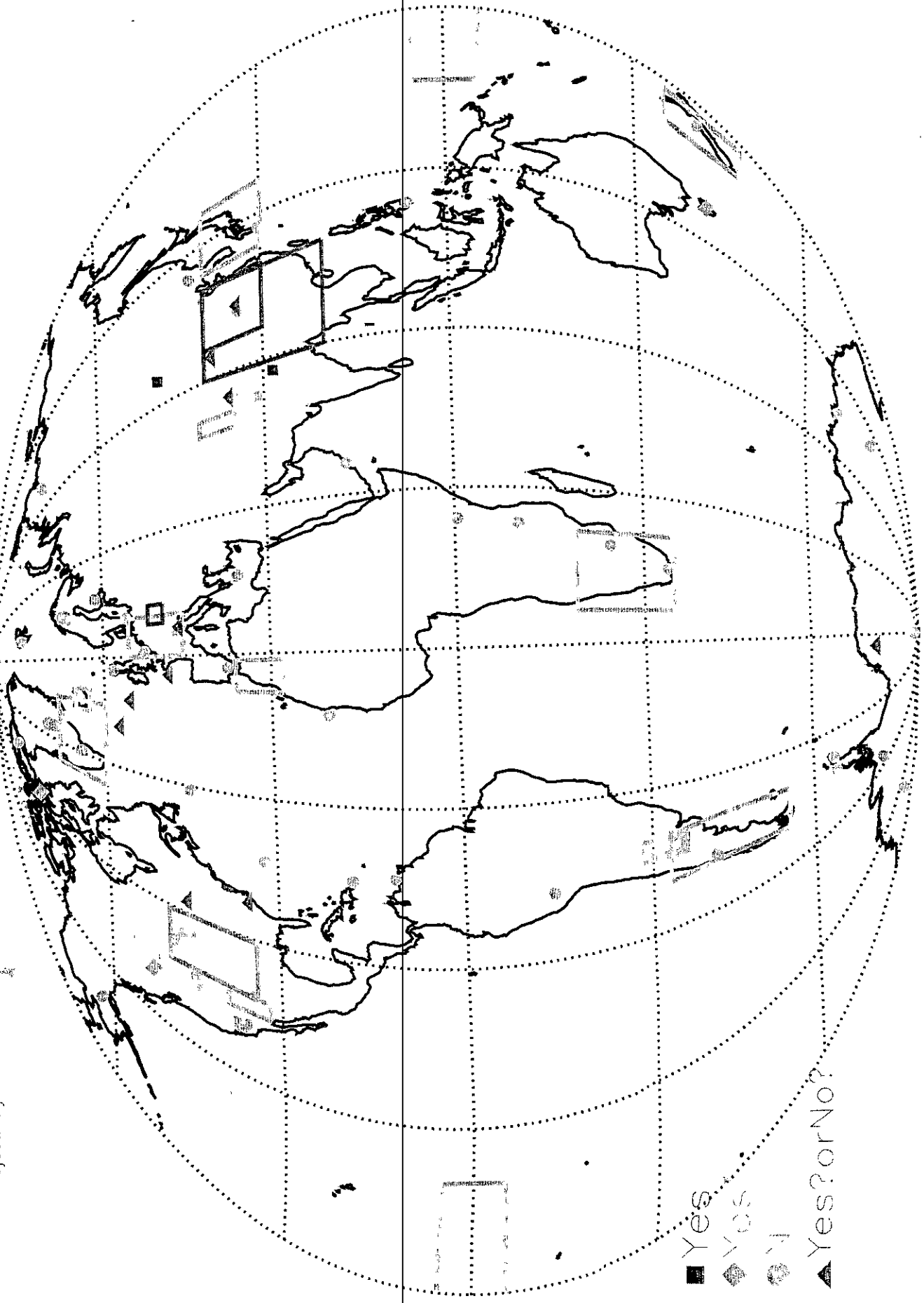


(2) Is there an objectively discernible climatic anomaly during the Medieval Warm Period (800–1300 A.D.) in this proxy record?



- Yes
- No
- ▲ Yes? or No?

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



- Yes
- ◆ Yes
- Yes
- ▲ Yes? or No?