

NATURAL CLIMATE VARIABILITY AND GLOBAL WARMING

A Holocene Perspective

Edited by
**BATTARBEE
AND BINNEY**

A growing body of scientific evidence suggests that greenhouse-gas pollution is largely responsible for global warming. Yet, it is also true that the climate system varies quite naturally on different time-scales. Accurately predicting the course of future climate change requires an understanding of the natural variability of the climate system, as well as the effects of human-induced change.

This ground-breaking book addresses predictable modification in the climate system in the context of global warming. Ideal for researchers and advanced students, it explores current thinking on natural climate change, the use of models to simulate past climate variability, and the role of past climate variability in explaining current changes to ecosystems and society over the later part of the Holocene.

The volume provides the groundwork for making critical decisions about the Earth's future, and contributes substantially to the ongoing debate over global warming and climate change.

RICHARD W. BATTARBEE is Professor of Environmental Change and Director of the Environmental Change Research Centre at University College London. He is a Fellow of the Royal Society and a Foreign Member of the Norwegian Academy of Science and Letters and was the Chair of the European Science Foundation program "HOLIVAR."

HEATHER A. BINNEY is a Research Fellow in the Environmental Change Research Centre, University College London. She is a palynologist with a special interest in pollen-vegetation relationships and long term vegetation change.

Cover image:
Change in annual mean surface temperature induced by switching from today's orbital forcing to that of 6000 years ago as simulated by Paleoclimate Modeling Intercomparison Project (PMIP) models. Data were supplied by Jean-Yves Peterschmitt and extracted from the PMIP II database in Saclay, France. It is based on a figure shown in chapter 4 by Michel Crucifix but mapped on Mollweide projection which has slightly altered the contouring.

Cover design by Design Deluxe

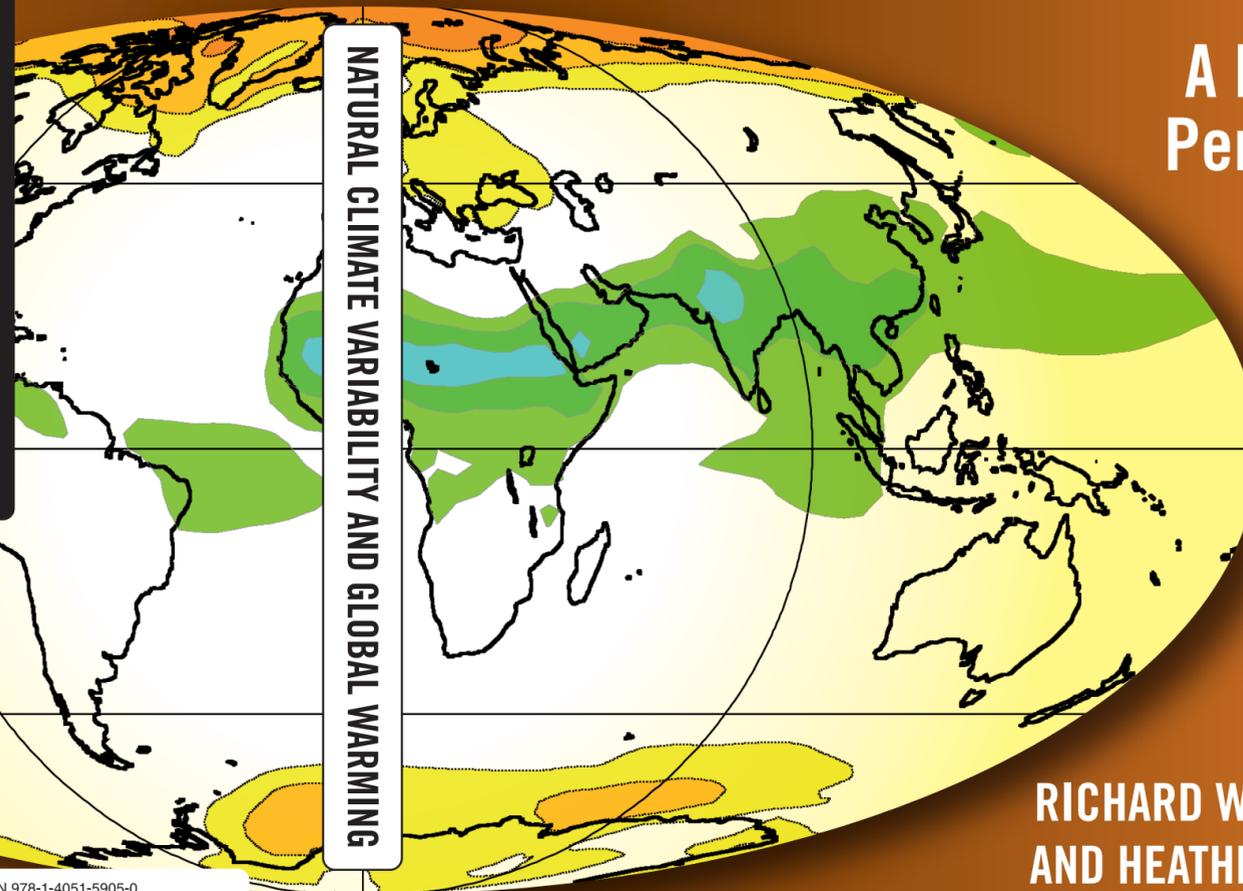
For information, news, and content about Blackwell books and journals in Earth Sciences please visit www.earth-pages.com

 **WILEY-BLACKWELL**
www.wiley.com/wiley-blackwell




WILEY-BLACKWELL

 **WILEY-BLACKWELL**



NATURAL CLIMATE VARIABILITY AND GLOBAL WARMING

NATURAL CLIMATE VARIABILITY AND GLOBAL WARMING: A HOLOCENE PERSPECTIVE

EDITED BY
RICHARD W. BATTARBEE
AND
HEATHER A. BINNEY

ENVIRONMENTAL CHANGE RESEARCH CENTRE,
UNIVERSITY COLLEGE LONDON

 **WILEY-BLACKWELL**

A John Wiley & Sons, Ltd., Publication

This edition first published 2008, © 2008 by Blackwell Publishing Ltd

Blackwell Publishing was acquired by John Wiley & Sons in February 2007. Blackwell's publishing program has been merged with Wiley's global Scientific, Technical and Medical business to form Wiley-Blackwell.

Registered office: John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloguing-in-Publication Data

Natural climate variability and global warming : a Holocene perspective / edited by R.W. Battarbee and H.A. Binney.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-4051-5905-0 (hardcover : alk. paper)

1. Paleoclimatology—Holocene. 2. Climatic changes—Research.
3. Global warming—Research. I. Battarbee, R.W. II. Binney, H.A. (Heather A.)

QC884.2.C5N38 2008

551.609'01—dc22

2007038976

ISBN: 978-1-4051-5905-0

A catalogue record for this book is available from the British Library.

Set in 10/12.5pt Minion
by Graphicraft Limited, Hong Kong
Printed and bound in Singapore
by Fabulous Printers Pte Ltd

1 2008

Contents

Contributors	vi
Abbreviations, acronyms, and terminology	viii
1 Holocene climate variability and global warming <i>Richard W. Battarbee</i>	1
2 Holocene climate research – progress, paradigms, and problems <i>H. John B. Birks</i>	7
3 The role of people in the Holocene <i>Frank Oldfield</i>	58
4 Modeling the climate of the Holocene <i>Michel Crucifix</i>	98
5 The early to mid-Holocene thermal optimum in the North Atlantic <i>Eystein Jansen, Carin Andersson, Matthias Moros, Kerim H. Nisancioglu, Birgitte F. Nyland, and Richard J. Telford</i>	123
6 Holocene climate change and the evidence for solar and other forcings <i>Jürg Beer and Bas van Geel</i>	138
7 Climate of the past millennium: combining proxy data and model simulations <i>Hugues Goosse, Michael E. Mann, and Hans Renssen</i>	163
8 Latitudinal linkages in late Holocene moisture-balance variation <i>Dirk Verschuren and Dan J. Charman</i>	189
9 Holocene rapid land-cover changes – evidence and theory <i>Martin Claussen</i>	232
10 Holocene perspectives on future climate change <i>Raymond S. Bradley</i>	254
Index	269

10

Holocene perspectives on future climate change

Raymond S. Bradley

Keywords

ENSO (or El Niño), monsoon (or Asian monsoon), climate forcing, drought

Introduction

Whatever anthropogenic climate changes occur in the future, they will be superimposed on, and interact with, underlying natural variability. Therefore, to anticipate future changes, we must understand how and why climates varied in the past. This requires well-dated records of forcing factors, as well as paleoclimate; both are available from a variety of natural archives. Relying on instrumental data to understand the spectrum of climate variability is completely inadequate; the record of large-scale (hemispheric or global) temperature extends back only ca. 150 years and the same can be said for most of the major modes of climate variability (Table 10.1). Even the longest instrumental records barely cover 300 years, and for most of the world such records are rarely longer than 120 years. This means that our understanding of climate system variability is largely limited to the interannual to decadal scale. To examine longer term (centennial to millennial-scale) variability requires much longer datasets. The Holocene provides a particularly relevant period for such an endeavor, as large-scale boundary conditions (continental ice extent, topography, sea-level) have remained very close to modern conditions for much of the Holocene, and low frequency (orbital) forcing is well understood for this period. Thus, Holocene paleoclimate data are able to resolve the full spectrum of climate variability and to place the limited instrumental records in a long-term perspective. This is particularly germane to the issue of anthropogenic climate change, as it provides a context for recent changes. Mann *et al.* (1999) argued that, for the Northern Hemisphere, the mean annual temperature of the past few decades of the 20th century was the highest for at least 1000 years, and this hypothesis has been supported by several later studies (National Research Council 2006). Moreover, Osborn and Briffa (2006) showed that both the magnitude and spatial

Table 10.1 Examples of some key climatic time series, based on instrumental records (Sources: <http://www.cru.uea.ac.uk/cru/data/> and <http://www.jisao.washington.edu/data.html>)

Instrumental data	Starts	Indices	Starts
Central England temperature	1659	Southern Oscillation Index (Tahiti–Darwin pressure)	1866
Global and hemispheric temperatures	1850	Global SST ENSO index	1845
England and Wales precipitation	1766	Multi-variate ENSO	1950
		NAO	1821
		AMO	1860
		Northern Annular Mode/Arctic Oscillation	1899
		PDO	1900
		Southern Annular Mode/Antarctic Oscillation	1948
		Indian Monsoon	1844

extent of recent warming was unprecedented in the past millennium. Such studies provide a check on energy balance and general circulation models that seek to simulate temperature changes over multi-centennial periods in order to examine the role of natural versus anthropogenic forcing (e.g. Crowley 2000; Ammann *et al.* 2003; Goosse *et al.* 2005). All of these studies conclude that the rise in temperature during the 20th century (particularly the late 20th century) is unprecedented, and the spatial pattern of warming cannot be explained by natural forcing alone; greenhouse gases provide the necessary additional forcing to account for the recent changes in temperature. Thus, paleoclimate data contribute to both detection and attribution studies related to anthropogenic climate change.

Paleoclimate data are also important for the broader debate about the role of greenhouse gases in recent climate change. Those who seek to dismiss concerns over greenhouse gases frequently point to episodes in the past when temperatures were higher (even though these episodes were commonly just in a limited geographic region and/or in a particular season). For example, critics sometimes point to the early Holocene (a time when many Northern Hemisphere alpine glaciers disappeared and Arctic sea-ice was of limited extent) as “evidence” that human-induced climate change is a fiction and recent changes are merely a manifestation of underlying natural variability. Paleoclimatic research, however, clearly shows that orbital forcing (largely due to changes in precession) was responsible for the pattern of early Holocene warming. Furthermore, the early Holocene was a time of summer warmth mainly in the Northern Hemisphere; in that hemisphere, insolation receipts steadily declined during the Holocene. In Northern Hemisphere

winters, and in the southern hemisphere summer and autumn (from December to June), insolation receipts in the early Holocene were below modern values, but increased through the Holocene. The rapid warming of the late 20th century is unrelated to this forcing; rather, the rate, seasonal pattern, and geographic extent of recent changes all point to greenhouse gases as the primary cause. Paleoclimate research can thus help to differentiate the cause and effect of climate changes, thereby elevating the discussion of strategies needed to deal with current environmental problems above the noisy distractions of those more interested in diverting attention from the issues at hand.

Although there has been an understandable emphasis on global (or hemispheric) temperature reconstructions, regional hydrologic variability is likely to be of most concern in the future, and so paleoclimatic reconstructions must pay particular attention to documenting past changes in precipitation and/or regional-scale water balance (as discussed by Verschuren and Charman, this volume). The Holocene record of climate variability is replete with examples of (largely unexplained) hydrologic instability. Multi-decadal- to multi-century-length droughts often started abruptly, were unprecedented (in the experience of societies at the time), and thus were highly disruptive to their agricultural, economic, and social foundations (AUP episodes: abrupt, unprecedented [in magnitude/duration], and persistent). One of the best documented examples is from Quintana Roo (Yucatan Peninsula), Mexico where there were a series of AUP droughts between ca. AD 800 and AD 1000. These were accompanied by severe economic and social disruption, leading to the “Classic Maya” collapse (Hodell *et al.* 1995, 2005). Future changes, that involve both natural and unprecedented anthropogenic forcing, may be just as disruptive if not more so. Furthermore, these changes will affect a world population that is expected to increase from ca. 6 billion people today to ca. 9–10 billion by 2070. In spite of technological advances, most of these people will continue to be subsistence or small-scale market agriculturalists, and will be just as vulnerable to climatic fluctuations as late prehistoric/early historic societies were. In an increasingly crowded world, moving on to greener pastures is not an option, making conflicts more likely (Campbell *et al.* 2007). Paleoclimatologists have a responsibility to ensure that the public, and politicians they elect, fully understand these issues so that they can better appreciate the consequences of inaction over controlling greenhouse gas emissions.

Holocene temperature changes

Long-term Holocene temperature changes largely reflect the dominant orbital forcing, with high northern latitudes receiving positive summer insolation anomalies of ca. 8–10 percent (outside the atmosphere) at the beginning of the Holocene (see Beer and van Geel, this volume). This led to warming that was especially pronounced in northern continental interiors, but there was also an increase in sea-surface temperatures in the North Atlantic, especially in the Norwegian Sea (Anderson *et al.* 2004) in the early Holocene. Orbital effects are clearly revealed,

both in paleoclimate archives and in general circulation model simulations (see Crucifix, this volume). In the tropics, the changes in orbital forcing were manifested in large-scale circulation changes involving monsoon systems (as discussed further below) and these resulted in dramatic hydrologic changes with important consequences for regional hydrology and societies living in the regions (see Verschuren and Charman, this volume; Oldfield, this volume). In the Southern Hemisphere, the effect of an increase in summer insolation over the course of the Holocene was minimized by the strong buffering effect of the oceans and the limited land area in that hemisphere.

As summer temperatures declined in the Northern Hemisphere over the course of the Holocene, high mountain regions began to experience positive mass balance conditions; this led to an increase in ice extent in most glacierized areas, and the redevelopment of glaciers in many areas where ice had disappeared. The timing of this resurgence of glacial activity (neoglaciation) varies from region to region (perhaps related to winter balance conditions, and the height of mountain ranges, etc.) but in general glaciers across the Northern Hemisphere had a new lease of life by ca. 4500 years BP, and ice shelves re-formed along the northern coast of Ellesmere Island (Nunavut, Canada) (Bradley 1990). Many detailed studies of late Holocene glacier variations have been carried out (see Grove (2004), Birks, this volume, and Verschuren and Charman, this volume) and these show that the most recent advance of glaciers was the most extensive in almost all areas. Again, the exact timing of maximum ice advances varies from one region to another, but the period between AD 1250 and 1850 (ca. 150–750 years BP) brackets this interval, known as the Little Ice Age (LIA). Given that LIA ice extent in many mountainous areas was the most extensive since the Younger Dryas (that is, the first moraines encountered upslope from the Younger Dryas moraines commonly date from the LIA) it is clear that this latest neoglacial episode was the coldest of the Holocene. Since it was quite recent, we have abundant evidence of climatic conditions during this period, including documentary records, paintings, and even photographs from the mid-19th century. Many Dutch painters of the 17th century lived their entire lives during the height of LIA conditions and so, not surprisingly, their landscape paintings reflect the snow-covered hills, frozen lakes, and icy canals that were simply normal conditions in those days. By contrast, temperatures in the interval prior to the LIA were relatively warm in many areas, particularly in north-western Europe in High Medieval time (ca. AD 1100–1200) (Bradley *et al.* 2003a). Evidence for earlier warm intervals is also found (within the generally cool neoglacial period), but with limited geographic coverage it is not possible to assess the global nature of such episodes. Even for the most recent warm period, the global extent and magnitude of temperature anomalies remains unresolved (cf. Broecker 2001; Bradley *et al.* 2003b). One approach to a better understanding of past conditions is to use paleoclimate model simulations that reproduce known patterns of temperature anomalies as a tool to estimate larger scale (hemispheric or global) temperature changes (see Goosse *et al.*, this volume). Several multi-proxy temperature reconstructions extend back into Medieval time (e.g. Mann *et al.* 1999; Moberg *et al.* 2006; Osborn and Briffa 2006). All show a sharp increase in temperatures

after the LIA, to levels at the end of the 20th century that were unprecedented in the previous millennium (National Research Council 2006). Consequently, in the brief interval of less than two centuries, the Northern Hemisphere (at least) has experienced the warmest and the coldest extremes of the late Holocene (Bradley 2000).

The temperature spectrum of Holocene temperature change is dominated at the low-frequency end by orbital forcing. At higher frequencies, there is evidence that solar forcing may have played a role, not necessarily by direct radiative forcing, but probably via stratospheric changes (related to the absorption of ultraviolet radiation) with subsequent effects on tropospheric circulation (Bradley 2003). Solar irradiance changes may also affect modes of climate variability (ENSO, NAO) with large-scale anomaly patterns as a result (discussed further, below). Consequently, solar effects seem to vary geographically, and since the forcing is small the response signal is easily lost within the ongoing variability of the climate system, a fact that has made detection of solar forcing a contentious issue. Moreover, explosive volcanic eruptions have also had radiative effects at various times, further confusing the picture. Both solar forcing and volcanic forcing appear to have played important roles at different times during the Holocene (see further discussion in Beer and van Geel, this volume). Thus the higher frequency part of the Holocene temperature spectrum is dominated by these two factors. Most recently, within the past ca. 50 years, these underlying natural forcings have become increasingly overwhelmed by anthropogenic forcing due to greenhouse gases. If these gases continue to increase as currently envisaged, model simulations indicate that orbitally modulated glaciations that might have been expected in the millennia ahead may not occur (as discussed further in Crucifix, this volume). To what extent anthropogenic land-use and land-cover changes might have affected global temperature prior to the past century (Ruddiman 2005) remains an intriguing open question, and an area of very active research involving both modeling and paleovegetation reconstructions (see Claussen, this volume; Birks, this volume; Oldfield, this volume).

Precipitation and hydrologic variability

Because of the importance of assessing the global effects of greenhouse gas increases, there has been much emphasis on reconstructing global or hemispheric mean temperature change, in order to place recent variations in a long-term perspective. Global warming now appears to be inevitable for the foreseeable future, but what is often overlooked are the associated changes in precipitation and hydrologic conditions that will certainly be associated with the rise in global temperature. Placing such changes in context is more difficult than reconstructing paleotemperatures because the correlation field for precipitation is much smaller (more geographically restricted) than for temperature. Consequently, precipitation and associated hydrologic variability must be considered on a regional scale.

This perspective reveals that there were extremely large regional precipitation variations, exposing the fallacy of describing the Holocene as having experienced very little change in climate. That unfortunate mantra emanates from studies of isotopic variations in ice cores from Greenland, where indeed Holocene changes were small. From a tropical perspective, however, the Holocene has been a time of profound hydrologic and ecologic change, with critical consequences for societies in many areas (see chapters by Claussen, this volume; Oldfield, this volume; Verschuren and Charman, this volume). Here, two examples of regional hydrologic variability are considered, to illustrate the value of a Holocene perspective on past precipitation changes in what are now some of the most densely populated areas of the globe.

A Holocene perspective on the El Niño-Southern Oscillation

The full range of variations in the El Niño-Southern Oscillation (ENSO) is poorly documented when the temporal perspective is limited to the instrumental period. Variations in ENSO (and associated teleconnections via the atmosphere) affect hundreds of millions of people, with economic impacts involving billions of dollars. Prediction of future ENSO variability rests on a thorough understanding of past variability, on a wide range of time-scales. When viewed over the Holocene as a whole, a number of proxy records indicate that ENSO, as we understand it today, changed in character over the course of the Holocene, largely in response to orbital forcing. Precessional changes brought about a shift in seasonality, with perihelion in the early Holocene close to the middle of Northern Hemisphere summer, compared with today when it is in January. Model simulations suggest that this resulted in a steady increase in the amplitude of ENSO through the Holocene (Clement *et al.* 2000). Early Holocene El Niños, although present, were less frequent and of smaller magnitude (i.e. sea-surface temperature anomalies were smaller). This is confirmed by various proxy records from Australia, New Zealand, and elsewhere that reflect ENSO variability (McGlone *et al.* 1992). In addition, isolated coral records (which provide a “snapshot” of conditions for ca. 6500 ¹⁴C years BP) indicate that interannual variability in this area was greatly reduced compared with modern values (e.g. Tudhope *et al.* 2001; Brown *et al.* 2006). Other evidence suggests that the intensification of El Niños crossed a critical threshold around 5500 ¹⁴C years BP, leading to heavy rainfall in south-western Ecuador (especially after ca. 3500 years BP), as documented in lake sediments from Laguna Pallcacocha (Rodbell *et al.* 1999; Moy *et al.* 2002). In fact, the greatest variability of the ENSO system may have been ca. 1000–1500 years BP, with somewhat cooler El Niño events since then (cf. Clement *et al.* 2000; Moy *et al.* 2002).

On shorter time-scales, both solar and volcanic forcing appears to have important influences on conditions in the tropical and equatorial Pacific. Although the relationship between solar irradiance and solar activity is not clearly understood (Y.-M. Wang *et al.* 2005), the correlation between solar activity changes in recent centuries and surface temperature varies geographically across the Pacific (Waple

et al. 2001). Specifically, the western tropical Pacific warms more than the eastern tropical Pacific (analogous to La Niña-like conditions) when solar activity is high; this may be the result of a direct radiative effect, since cloudiness is lower over the western Pacific warm pool. This relationship alone is not a very strong basis for a hypothesis that links solar forcing to an ENSO response, but it is somewhat supported by a similar pattern (albeit reversed in sign) associated with explosive volcanic eruptions. These reduce incoming solar radiation and lead to greater cooling (in response to the radiative perturbation) in the western tropical Pacific than in the eastern tropical Pacific, as seen in both model simulations and empirical data (Adams *et al.* 2003; Mann *et al.* 2005). In effect, explosive volcanism is associated (statistically) with El Niño events, as first pointed out by Handler (1984). Because ENSO has atmospheric teleconnections across the globe (Diaz and Kiladis 1992), the El Niño response to such forcing is likely to have consequences in many other parts of the world. For example, several paleoclimatic studies reveal a strong relationship between prolonged and geographically extensive droughts in the south-western USA (“megadroughts”; Stahle *et al.* 2000) and cold La Niña-like conditions in the eastern Equatorial Pacific (Cole *et al.* 2002). These episodes are of particular interest because they were far more persistent than any drought experienced in the instrumental period, lasting at least a decade (and sometimes extending over several decades within a particular century). The Mexican megadrought of the mid- to late 16th century led to crop failures and social disruption, exacerbated by a fatal hemorrhagic fever (known to the Mayans as *cocolitzli*) spread by foraging rats that invaded houses in search of food. This led to the deaths of as many as 15 million people (Acuña-Soto *et al.* 2002). No drought of this severity and duration has occurred in the past 150 years. Interestingly, historical records from eastern China also record unprecedented climatic variability in the late 16th century, with extensive droughts from 1585 to 1590 (Zhang 2005). This was the most persistent and severe drought for at least 500 years, with many lakes, rivers, and wells drying up across eastern China. A few decades later (1637–1643) another devastating drought occurred, first in the north of China, then extending across the south. From historical documentary records, it is clear that these two episodes were the most extensive droughts of the past millennium in China (Figure 10.1), and it may be no coincidence that the latter coincided with the end of the Ming dynasty. Certainly, social disruption resulting from the 1637–1643 drought contributed to the turmoil that led to the Qing assuming power in AD 1644. It is likely that all of these severe and persistent anomalies, on both sides of the Pacific, reflect ocean–atmosphere teleconnections associated with unusual ENSO conditions in the late 16th and early 17th centuries, the like of which have not been experienced in the period of instrumental records. This may have involved persistently cool conditions in the eastern and/or central Equatorial Pacific, the cause of which is unknown.

In the western USA, some of the most extensive and persistent droughts of the past millennium occurred during a period that has been characterized elsewhere as a “Medieval Warm Period” (Bradley *et al.* 2003b; Cook *et al.* 2004; Graham *et al.* 2007). Although there is evidence for warm episodes in Europe during High

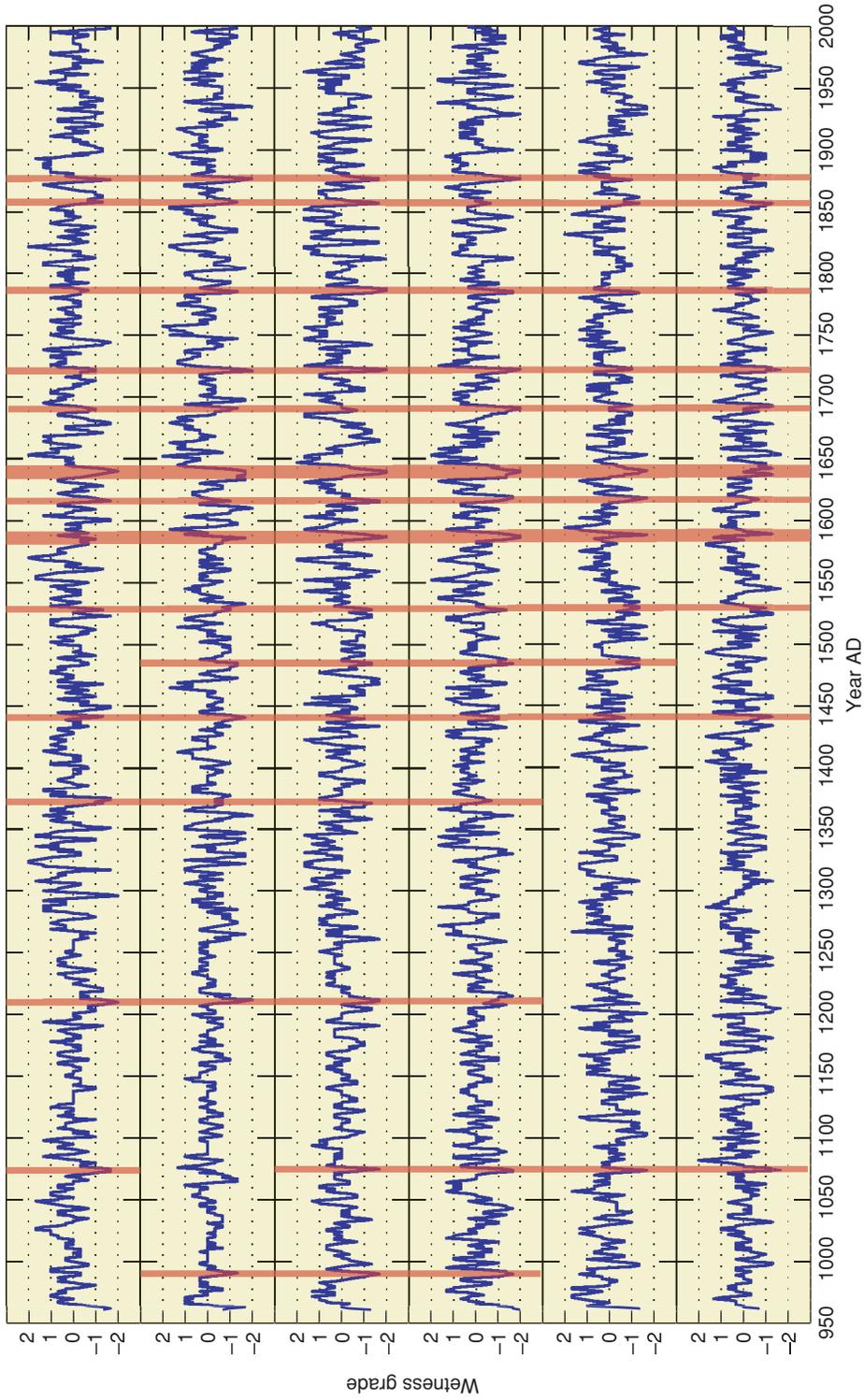


Figure 10.1 Three-year running means of annual wetness grades (derived from documentary records) for six regions of China (top to bottom, north-eastern China to the mouth of the Yangtze, ca. 41°N to ca. 29°N, and 110° to ca. 122°E). Dry episodes are rated with negative values; periods of extensive drought are highlighted by vertical bars. (From Zhang 2005.)

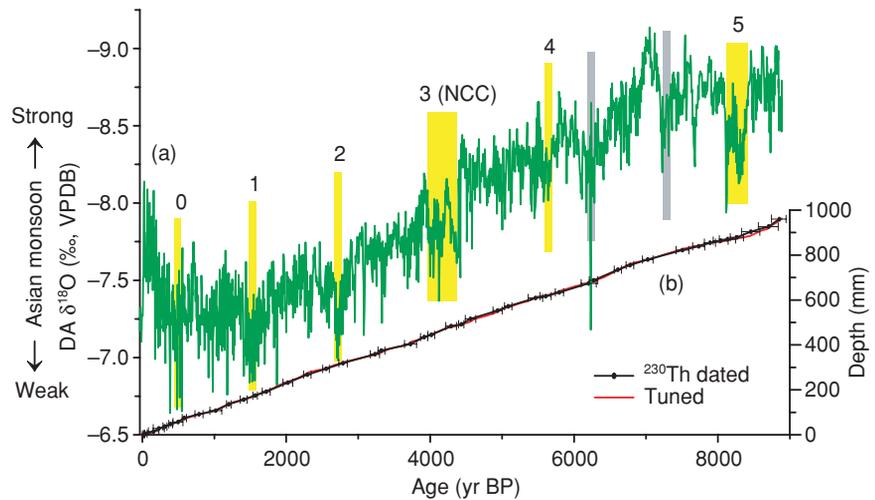
Medieval time (especially in the late 12th century; e.g. Pfister *et al.* 1998), in the central Equatorial Pacific, at least, coral isotopic records show that this interval could equally be termed a “Medieval Cold Period” (Cobb *et al.* 2003). This highlights the importance of documenting regional climate variations over as wide a geographic area as possible, in order to ensure that evidence from one region is not simply extrapolated to the global scale.

There are two other important points that relate to a La Niña–south-western USA drought connection. The first is that the most significant climate variability in the past may have involved **regional** hydrologic variability, related to **regional** temperature anomalies. Such anomalies may not be at all apparent on a globally averaged basis. Secondly, if the former megadroughts were indeed related to prolonged La Niña episodes, it begs the question as to what caused such episodes to persist; there are no comparable examples of such long-lasting La Niñas in the period of instrumental records. Furthermore, if there was indeed a globally extensive Medieval Warm Period (cf. Broecker 2001), is it likely that future warm conditions will lead to a repetition of regional anomalies like those recorded by proxy records from the past? The droughts of the south-western USA that occurred during High Medieval time affected an area that is now the fastest growing region in the USA, where there is a burgeoning demand for water. If such persistent droughts were to recur in this region, it would have severe economic and social consequences. Given the stakes involved, improving our understanding of past ENSO variability on all time-scales is of critical importance. Accounting for this full spectrum of variability must be considered when constructing models of future ENSO dynamics.

A Holocene perspective on the Asian Monsoon

Billions of people in East and South Asia rely on the seasonal regularity of rainfall from the monsoons. Instrumental rainfall records in the region, however, rarely extend back more than ca. 150 years, so long-term variability of the monsoon systems is poorly understood. Paleoclimatic records have greatly expanded our perspective. A Holocene record of monsoon rainfall is provided by oxygen isotopes in a stalagmite from Dongge Cave, China (Figure 10.2; Y.J. Wang *et al.* 2005); isotopic values reflect fractionation associated with monsoon rainfall, with lower values indicating more rainfall (a “stronger monsoon”). This extremely well-dated record clearly exhibits variability on a wide range of time-scales, from the millennial scale down to just a few years (the minimum sampling interval is ca. 4.5 years). Long-term changes related to orbitally induced insolation anomalies dominate the overall series, with isotopically lighter rainfall signifying a stronger monsoon in the early Holocene, when summer insolation was higher in the Northern Hemisphere. Superimposed on the low-frequency, orbitally forced changes are multi-decadal to centennial-scale variations that may be related to solar activity, and embedded in these are even higher frequency changes (on the time-scale of a few years) that may have been forced by major volcanic eruptions (e.g. ca. 6200–6250 cal. years BP; cf.

Figure 10.2 (a) The oxygen isotope record from a stalagmite from Dongge Cave, southern China (25°17'N, 108°5'E) (green line). Thermal ionization mass spectrometry dates are shown along the bottom, with age–depth model given by the solid line (b). The overall enrichment in $\delta^{18}\text{O}$ reflects a weakening monsoon rainfall regime over the course of the Holocene due to orbital forcing (higher summer insolation in the early Holocene). Superimposed on this low-frequency trend are short dry episodes (highlighted, yellow bars) that appear to correlate with ice-rafting (“Bond”) events in the North Atlantic. The gray bars represent two other notable weak Asian Monsoon events that can be correlated to ice-rafted debris events. The complex drier interval around 4000–4200 years BP corresponds to the collapse of Neolithic cultures in China (NCC). (From Y.J. Wang *et al.* (2005). Reprinted with permission from AAAS.)



Castellano *et al.* 2005), or simply random events that inevitably occur when long intervals of time are being considered. There is also evidence that the East Asian monsoon has strengthened over the past few hundred years (Figure 10.2), but whether this signal is related to anthropogenic forcing is not clear.

The Dongge Cave stalagmite record does not have annual resolution, but other proxies from the region can be used to extend our understanding of monsoon variability to the interannual scale. For example, an ice core from a high-elevation glacier in the Himalayas (Dasuopu, China: 28°23'N, 85°43'E, 7200 m above sea-level) provides a multi-proxy record of Indian monsoon precipitation for the past millennium. The dust record in this core has a strong inverse correlation with summer rainfall in north-west India, but these records only extend back to the mid-19th century (Thompson *et al.* 2000). The much longer ice-core record reveals larger variations in monsoon rainfall than anything recorded in the past ca. 150 years. Of particular note is the period from ca. 1790–1796, which was exceptionally dry, as shown by large anomalies of dust, chloride ions, and oxygen isotopes (relatively enriched in the heavy isotope ^{18}O , which is characteristic of times of low rainfall) (Thompson *et al.* 2000). Historical records from India, although sparse, confirm that this was indeed an exceptionally dry period, with very low monsoon rainfall, leading to crop failures and starvation, with at least 600 000 deaths as a result; in the northern Madras Presidency, half the population died (Grove 1998). Furthermore, Grove notes that there were very unusual climatic conditions in many other parts of the world at this time. We do not have a clear understanding of what caused this sequence of monsoon failures in the late 18th century, but it was probably related to strong and persistent El Niño conditions (which lasted throughout the 1790s, according to historical records; Ortlieb 2000), perhaps with the strongest SST anomalies in the central Pacific rather than in the eastern Equatorial Pacific (cf. Kumar *et al.* 2006). Unfortunately, we do not yet have any coral records from the Central Pacific that span this unusual period of time.

With these Holocene perspectives on monsoon rainfall in South and East Asia, it is clear that the overall record of monsoon variability results from multiple forcing factors acting on the climate system, producing a nested set of responses. With an instrumental perspective of less than ca. 150 years, there is no way that a complete understanding of monsoon variability can be acquired, and this may limit predictions of future monsoon variability since anthropogenic effects will strongly modulate natural variability. To develop a comprehensive model of monsoon variability, the full range of conditions experienced in the Holocene must be recognized.

Perspectives: past and future

People do not experience global mean conditions; they live in communities that are subject to regional climate variability. Even modest changes in global climate can lead to large changes in a particular region, and these changes may be much larger than the global mean change. In particular, precipitation patterns will be greatly affected as the atmospheric circulation adjusts to whatever new state emerges. We can gain insight into the nature and magnitude of past regional anomalies (and their human impacts) by examining the Holocene paleoclimate record, and evaluating how those changes developed in relation to past forcing. Gaining an understanding of unusual regional conditions is crucial in an increasingly crowded world. With such a perspective, we can document past anomalies that may not have been experienced in the recent period of instrumental records, yet are part of the full spectrum of climate variability that will inevitably underlie any future anthropogenic effects. Hydrologic changes are especially important, given that many models now used for future climate simulations do not accurately portray modern precipitation regimes. Demonstrating an ability to reconstruct precipitation and hydrologic conditions in the past provides a critical test of models, in order to provide more reliable forecasts of future changes. Deciphering the past, however, also requires a better understanding of how anthropogenic influences may have affected the very records we seek to interpret for paleoclimatic purposes. Until quite recently, such anthropogenic effects were thought to be fairly local and limited in their impacts, but an increasing body of literature raises questions about whether humans had a more global impact on atmospheric composition and (through land-use changes) on the surface energy balance across large areas. These are critical challenges ahead for research on both natural archives of Holocene environmental change, and for modeling studies that seek to simulate past (and ultimately, future) climatic conditions.

References

Acuña-Soto R., Stahle D.W., Cleaveland M.K. & Therrell M.D. (2002) Megadrought and megadeath in 16th century Mexico. *Emerging Infectious Diseases*, 8, 360–362.

- Adams J.B., Mann M.E. & Ammann C.M. (2003) Proxy evidence for an El Niño-like response to volcanic forcing. *Nature*, **426**, 274–278.
- Ammann C.M., Meehl G.A., Washington W.M. & Zender C.S. (2003) A monthly and latitudinally varying volcanic forcing dataset in simulations of 20th century climate. *Geophysical Research Letters*, **30**, 1657, doi:10.1029/2003GL016875.
- Anderson C., Koç N., Jennings A. & Andrews J.T. (2004) Nonuniform response of the major surface currents in the Nordic Seas to insolation forcing: implications for the Holocene climate variability. *Paleoceanography*, **19**, doi:10.1029/2002PA000873.
- Beer J. & van Geel B. (this volume) Holocene climate change and the evidence for solar and other forcings. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 138–162. Blackwell, Oxford.
- Birks J. (this volume) Holocene climate research – progress, paradigms, and problems. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 7–57. Blackwell, Oxford.
- Bradley R.S. (1990) Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian High Arctic. *Quaternary Science Reviews*, **9**, 365–384.
- Bradley R.S. (2000) Past global changes and their significance for the future. *Quaternary Science Reviews*, **19**, 391–402.
- Bradley R.S. (2003) Climate forcing during the Holocene. In: *Global Change in the Holocene* (Eds A.W. Mackay, R.W. Battarbee, H.J.B. Birks, & F. Oldfield), pp. 10–19. Arnold, London.
- Bradley R.S., Briffa K.R., Cole J., Hughes M.K. & Osborn T.J. (2003a) The climate of the last millennium. In: *Paleoclimate, Global Change and the Future* (Eds K. Alverson, R.S. Bradley & T.F. Pedersen), pp. 105–141. Springer-Verlag, Berlin.
- Bradley R.S., Hughes M.K. & Diaz H.F. (2003b) Climate in Medieval time. *Science*, **302**, 404–405.
- Broecker W.S. (2001) Was the Medieval Warm Period global? *Science*, **291**, 1497–1499.
- Brown J., Collins M. & Tudhope A. (2006) Coupled model simulations of mid-Holocene ENSO and comparisons with coral isotope records. *Advances in Geosciences*, **6**, 29–33.
- Campbell K.M., Gullette J., McNeill J.R., *et al.* (2007) *The Age of Consequences: The Foreign and National Security Implications of Global Climate Change*. Center for Strategic and International Studies, Washington, DC, 119 pp.
- Castellano E., Becagli S., Hansson M., *et al.* (2005) Holocene volcanic history as recorded in the sulphate stratigraphy of the European Project for Ice Coring in Antarctica Dome C (EDC96) ice core. *Journal of Geophysical Research*, **110**, D06114, doi:10.1029/2004JB005259.
- Claussen M. (this volume) Holocene rapid land-cover changes – evidence and theory. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 232–253. Blackwell, Oxford.
- Clement A.C., Seager R. & Cane M.A. (2000) Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit. *Paleoceanography*, **15**, 731–736.

- Cobb K.M., Charles C.D., Cheng H. & Edwards R.L. (2003) El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, **424**, 271–276.
- Cole J.E., Overpeck J.T. & Cook E.R. (2002) Multi-year El Niño events and persistent drought in the contiguous United States. *Geophysical Research Letters*, **29**(13), 1647, doi:10.1029/2001GL013561.
- Cook E.R., Woodhouse C.A., Eakin C.M., Meko D.M. & Stahle D.W. (2004) Long-term aridity changes in the western United States. *Science*, **306**, 1015–1018.
- Crowley T.J. (2000) Causes of climate change over the past 1000 years. *Science*, **289**, 270–277.
- Crucifix M. (this volume) Modelling the climate of the Holocene. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 98–122. Blackwell, Oxford.
- Diaz H.F. & Kiladis G. (1992) Atmospheric teleconnections associated with the extreme phase of the Southern Oscillation. In: *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation* (Eds H.F. Diaz & V. Markgraf), pp. 7–28. Cambridge University Press, Cambridge.
- Goosse H., Renssen H., Timmermann A. & Bradley R.S. (2005) Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. *Quaternary Science Reviews*, **24**, 1345–1360.
- Goosse H., Mann M.E. & Renssen H. (this volume) Climate of the past millennium: combining proxy data and model simulations. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 163–188. Blackwell, Oxford.
- Graham N.E., Hughes M.K., Ammann C.M. *et al.* (2007) Tropical Pacific–mid-latitude teleconnections in Medieval times. *Climatic Change*, **83**, 241–285.
- Grove J.M. (2004) *Little Ice Ages: Ancient and Modern*. Routledge, Abingdon, 760 pp.
- Grove R.H. (1998) Global impact of the 1789–93 El Niño. *Nature*, **393**, 318.
- Handler P. (1984) Possible association of stratospheric aerosols and El Niño type events. *Geophysical Research Letters*, **11**, 1121–1124.
- Hodell D.A., Curtis J.H. & Brenner M. (1995) Possible role of climate in the collapse of Classic Maya civilization. *Nature*, **375**, 391–395.
- Hodell D.A., Brenner M. & Curtis J.H. (2005) Terminal Classic drought in the northern Mayan lowlands inferred from multiple sediment cores in Lake Chichancanab, Mexico. *Quaternary Science Reviews*, **24**, 1413–1427.
- Kumar K.K., Rajagopalan B., Hoerling M., Bates G. & Cane M. (2006) Unraveling the mystery of Indian monsoon failure during El Niño. *Science*, **314**, 115–118.
- Mann M.E., Bradley R.S. & Hughes M.K. (1999) Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters*, **26**, 759–762.
- Mann M.E., Cane M.A., Zebiak S.E. & Clement A. (2005) Volcanic and solar forcing of the Tropical Pacific over the past 1000 years. *Journal of Climate*, **18**, 447–456.

- McGlone M.S., Kershaw A.P. & Markgraf V. (1992) El Niño/Southern Oscillation climatic variability in Australasian and South American paleoenvironmental records. In: *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation* (Eds H.F. Diaz & V. Markgraf), pp. 435–462. Cambridge University Press, Cambridge.
- Moberg A., Sonechkin D.M., Holmgren K., Datsenko N.M. & Karlén W. (2005) Highly variable northern hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature*, **433**, 613–617.
- Moy C.M., Seltzer G.O., Rodbell D.T. & Anderson D.M. (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, **420**, 162–165.
- National Research Council (2006) *Surface Temperature Reconstructions for the Last 2000 Years*. National Academies Press, Washington, DC, 141 pp.
- Oldfield F. (this volume) The role of people in the Holocene. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 58–97. Blackwell, Oxford.
- Ortlieb L. (2000) The documented historical record of El Niño events in Peru: an update of the Quinn record (sixteenth through nineteenth centuries). In: *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts* (Eds H.F. Diaz & V. Markgraf), pp. 207–295. Cambridge University Press, Cambridge.
- Osborn T.J. & Briffa K.R. (2006) The spatial extent of 20th century warmth in the context of the past 1200 years. *Science*, **311**, 841–844.
- Pfister C., Schwarz-Zanetti G., Wegmann M. & Luterbacher J. (1998) Winter air temperature variations in western Europe during the Early and High Middle Ages (AD 750–1300). *The Holocene*, **8**, 535–552.
- Rodbell D.T., Seltzer G.O., Anderson D.M., Abbott M.B., Enfield D.B. & Newman J.H. (1999) A ~15 000-year record of El Niño-driven alluviation in southwestern Ecuador. *Science*, **283**, 516–520.
- Ruddiman W.F. (2005) *Plows, Plagues and Petroleum*. Princeton University Press, Princeton, 202 pp.
- Stahle D.W., Cook E.R., Cleaveland M.K., *et al.* (2000) Tree-ring data document 16th century megadrought over North America. *Eos (Transactions of the American Geophysical Union)*, **81**, 121 and 125.
- Thompson L.D., Yao T., Mosley-Thompson E., Davis M.E., Henderson K.E. & Lin P.-N. (2000) A high resolution millennial record of the South Asian monsoon from Himalayan ice cores. *Science*, **289**, 1916–1919.
- Tudhope A.W., Chilcott C.P., McCulloch M.T., *et al.* (2001) Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. *Science*, **291**, 1511–1517.
- Verschuren D. & Charman D. (this volume) Latitudinal linkages in late Holocene moisture-balance variation. In: *Global Warming and Natural Climate Variability: a Holocene Perspective* (Eds R.W. Battarbee & H.A. Binney), pp. 189–231. Blackwell, Oxford.

- Wang Y.J., Cheng H., Edwards R.L., *et al.* (2005) The Holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science* **308**, 854–857.
- Wang Y.-M., Lean J.L. & Sheeley Jr. N.R. (2005) Modeling the Sun's magnetic field and irradiance since A.D. 1713. *The Astrophysical Journal*, **625**, 522–538.
- Waple A.M., Mann M.E. & Bradley R.S. (2001) Long-term patterns of solar irradiance forcing in model experiments and proxy-based surface temperature reconstructions. *Climate Dynamics*, **18**, 563–578.
- Zhang D. (2005) Severe drought events as revealed in the climate records of China and their temperature situations over the last 1000 years. *Acta Meteorologica Sinica*, **19**, 485–491.