Geophysical Monograph Series

158 The Nordic Seas: An Integrated Perspective Helge Drange, Trond Dokken, Tore Furevik, Rüdiger Gerdes, and Wolfgang Berger (Eds.)

159 Inner Magnetosphere Interactions: New Perspectives From Imaging James Burch, Michael Schulz, and Harlan Spence (Eds.)

160 Earth's Deep Mantle: Structure, Composition, and Evolution Robert D. van der Hilst, Jay D. Bass, Jan Matas, and Jeannot Trampert (Eds.)

161 Circulation in the Gulf of Mexico: Observations and Models Wilton Sturges and Alexis Lugo-Fernandez (Eds.)

162 Dynamics of Fluids and Transport Through Fractured Rock Boris Faybishenko, Paul A. Witherspoon, and John Gale (Eds.)

163 Remote Sensing of Northern Hydrology: Measuring Environmental Change Claude R. Duguay and Alain Pietroniro (Eds.)

164 Archean Geodynamics and Environments Keith Benn, Jean-Claude Mareschal, and Kent C. Condie (Eds.)

165 Solar Eruptions and Energetic Particles Nachimuthukonar Gopalswamy, Richard Mewaldt, and Jarmo Torsti (Eds.)


167 Recurrent Magnetic Storms: Corotating Solar Wind Streams Bruce Tsurutani, Robert McPherron, Walter Gonzalez, Gang Lu, José H. A. Sobral, and Nachimuthukonar Gopalswamy (Eds.)

168 Earth's Deep Water Cycle Steven D. Jacobsen and Suzan van der Lee (Eds.)

169 Magnetospheric ULF Waves: Synthesis and New Directions Kazue Takahashi, Peter J. Chi, Richard E. Denton, and Robert L. Lysal (Eds.)

170 Earthquakes: Radiated Energy and the Physics of Faulting Rachel Abercrombie, Art McGarr, Hiroo Kanamori, and Giulio Di Toro (Eds.)

171 Subsurface Hydrology: Data Integration for Properties and Processes David W. Hyndman, Frederick D. Day-Lewis, and Kamini Singha (Eds.)

172 Volcanism and Subduction: The Kamchatka Region John Eichelberger, Evgenii Gordeev, Minoru Kasahara, Pavel Izbekov, and Johnathan Lees (Eds.)

173 Ocean Circulation: Mechanisms and Impacts—Past and Future Changes of Meridional Overturning Andreas Schmittner, John C. H. Chiang, and Sidney R. Hemming (Eds.)

174 Post-Perovskite: The Last Mantle Phase Transition Kei Hirose, John Brodholt, Thorne Lay, and David Yuen (Eds.)

175 A Continental Plate Boundary: Tectonics at South Island, New Zealand David Okaya, Tim Stem, and Fred Davey (Eds.)

176 Exploring Venus as a Terrestrial Planet Larry W. Esposito, Ellen R. Stofan, and Thomas E. Cravens (Eds.)

177 Ocean Modeling in an Eddying Regime Matthew Hecht and Hiroyasu Hasumi (Eds.)

178 Magma to Microbe: Modeling Hydrothermal Processes at Oceanic Spreading Centers Robert P. Lowell, Jeffrey S. Seewald, Anna Metaxas, and Michael R. Perlitt (Eds.)

179 Active Tectonics and Seismic Potential of Alaska Jeffrey T. Freymueller, Peter J. Haeussler, Robert L. Wesson, and Göran Ekström (Eds.)

180 Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications Eric T. DeWeaver, Cecilia M. Bitz, and L-Bruno Tremblay (Eds.)

181 Midlatitude Ionospheric Dynamics and Disturbances Paul M. Kintner, Jr., Anthea J. Coster, Tim Fuller-Rowell, Anthony J. Mannucci, Michael Mendillo, and Roderick Heelis (Eds.)

182 The Stromboli Volcano: An Integrated Study of the 2002–2003 Eruption Sonia Calvari, Salvatore Ingüagiatò, Giuseppe Puglisi, Maurizio Ripepe, and Mauro Rosi (Eds.)

183 Carbon Sequestration and Its Role in the Global Carbon Cycle Brian J. McPherson and Eric T. Sundquist (Eds.)

184 Carbon Cycling in Northern Peatlands Andrew J. Baird, Lisa R. Belyea, Xavier Comas, A. S. Reeve, and Lee D. Slater (Eds.)

185 Indian Ocean Biogeochemical Processes and Ecological Variability Jerry D. Wiggert, Raleigh R. Hood, S. Wajih A. Naqvi, Kenneth H. Brink, and Sharon L. Smith (Eds.)

186 Amazonia and Global Change Michael Keller, Mercedes Bustamante, John Cash, and Pedro Silva Dias (Eds.)

187 Surface Ocean–Lower Atmosphere Processes Corinne Le Quéré and Eric S. Saltzman (Eds.)

188 Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges Peter A. Rona, Colin W. Devey, Jérôme Dyment, and Bramley J. Murton (Eds.)

189 Climate Dynamics: Why Does Climate Vary? De-Zheng Sun and Frank Bryan (Eds.)


191 Rainfall: State of the Science Firan Y. Testik and Mekonnen Gebremichael (Eds.)

192 Antarctic Subglacial Aquatic Environments Martin J. Siegert, Mahlon C. Kennicutt II, and Robert A. Bindschadler (Eds.)
Abrupt Climate Change: Mechanisms, Patterns, and Impacts

Harunur Rashid
Leonid Polyak
Ellen Mosley-Thompson
Editors

American Geophysical Union
Washington, DC

Cover Image: (left) Plotted oxygen isotope data from the North Greenland Ice Core Project (black) and Mount Kilimanjaro (blue) and seawater oxygen isotope data (red) from the planktonic foraminifera Globigerinoides ruber (white) from the Andaman Sea of the northern Indian Ocean. (top middle) X-radiograph of centimeter thick sediment slice of Heinrich layer 2 from the northwest Labrador Sea (courtesy of H. Rashid). (top right) Photograph of ice cores collected from the Guliya ice field of China (courtesy of L. G. Thompson). (bottom) For the atmosphere, vectors depicting the winds in the lowest model layer and the sea level pressure. Ocean model surface temperatures are shown in blue to red colors; sea ice concentration is shown in white-gray. This coupled model consists of the National Center for Atmospheric Research Community Climate Model for the atmospheric component, the Los Alamos National Laboratory Parallel Ocean Program for the ocean component, and the Naval Postgraduate School sea ice model (courtesy of G. Strand of NCAR). (backdrop) Sea ice in the Southern Ocean during the early autumn (courtesy of NOAA).

Copyright 2011 by the American Geophysical Union 2000 Florida Avenue, N.W. Washington, DC 20009

Figures, tables and short excerpts may be reprinted in scientific books and journals if the source is properly cited.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by the American Geophysical Union for libraries and other users registered with the Copyright Clearance Center (CCC). This consent does not extend to other kinds of copying, such as copying for creating new collective works or for resale. The reproduction of multiple copies and the use of full articles or the use of extracts, including figures and tables, for commercial purposes requires permission from the American Geophysical Union. geopress is an imprint of the American Geophysical Union.

Printed in the United States of America.
CONTENTS

Preface
Harunur Rashid, Leonid Polyak, and Ellen Mosley-Thompson .......................................................... vii

Abrupt Climate Change Revisited
Harunur Rashid, Leonid Polyak, and Ellen Mosley-Thompson .......................................................... 1

A Review of Abrupt Climate Change Events in the Northeast Atlantic Ocean (Iberian Margin):
Latitudinal, Longitudinal, and Vertical Gradients
Antje H. L. Voelker and Lucia de Abreu ............................................................................................. 15

Laurentide Ice Sheet Meltwater and the Atlantic Meridional Overturning Circulation
During the Last Glacial Cycle: A View From the Gulf of Mexico
B. P. Flower, C. Williams, H. W. Hill, and D. W. Hastings ................................................................ 39

Modeling Abrupt Climate Change as the Interaction Between Sea Ice Extent and Mean Ocean Temperature
Under Orbital Insolation Forcing
J. A. Rial and R. Saha .......................................................................................................................... 57

Simulated Two-Stage Recovery of Atlantic Meridional Overturning Circulation During the Last Deglaciation
Jun Cheng, Zhengyu Liu, Feng He, Bette L. Otto-Bliesner, Esther C. Brady, and Mark Wehrenberg .......... 75

The Role of Hudson Strait Outlet in Younger Dryas Sedimentation in the Labrador Sea
Harunur Rashid, David J. W. Piper, and Benjamin P. Flower ............................................................... 93

Challenges in the Use of Cosmogenic Exposure Dating of Moraine Boulders to Trace the Geographic Extents
of Abrupt Climate Changes: The Younger Dryas Example
Patrick J. Applegate and Richard B. Alley ............................................................................................ 111

Hypothesized Link Between Glacial/Interglacial Atmospheric CO₂ Cycles and Storage/Release
of CO₂-Rich Fluids From Deep-Sea Sediments
Lowell Stott and Axel Timmermann ..................................................................................................... 123

The Impact of the Final Lake Agassiz Flood Recorded in Northeast Newfoundland and Northern Scotian
Shelves Based on Century-Scale Palynological Data
Elisabeth Levac, C. F. M. Lewis, and A. A. L. Miller ............................................................................. 139

The 1500 Year Quasiperiodicity During the Holocene
A. Ruzmaikin and J. Feynman ............................................................................................................. 161

Abrupt Climate Changes During the Holocene Across North America From Pollen
and Paleolimnological Records
Konrad Cajewski and Andre E. Viau ...................................................................................................... 173

Abrupt Holocene Climatic Change in Northwestern India: Disappearance of the Sarasvati River
and the End of Vedic Civilization
B. S. Paliwal ........................................................................................................................................ 185
Evidence for Climate Teleconnections Between Greenland and the Sierra Nevada of California During the Holocene, Including the 8200 and 5200 Climate Events
Stephen F. Wathen ............................................................................................................................... 195

Abrupt Climate Change: A Paleoclimate Perspective From the World’s Highest Mountains
Lonnie G. Thompson .............................................................................................................................. 215

AGU Category Index ................................................................................................................................... 235

Index ........................................................................................................................................................... 237
When the first book on abrupt climate change was published in 1987, the idea of millennial climatic oscillations now known as the Dansgaard-Oeschger events, named after seminal researchers Willi Dansgaard and Hans Oeschger, was slowly taking shape, while periodic collapse and rebuilding of the Northern Hemisphere ice sheets at millennial timescales, recognized as the Heinrich (named for Hartmut Heinrich) iceberg-rafting events, were not yet known. Using marine sediment data from the northeast Atlantic deep-sea cores, Gerard Bond and Wallace Broecker, and colleagues in 1992 and 1993 placed Heinrich’s work into a wider climate context; climatologists began to consider mechanisms of reorganization of the global ocean-atmospheric system at millennial and finer timescales. Several collections of papers and reports published since that time reflect an impressive development in our understanding of the history and mechanisms of abrupt climate events: Abrupt Climatic Change: Evidence and Implications (NATO-ASI series published in 1987); the 1999 AGU Geophysical Monograph Mechanisms of Global Climate Change at Millennial Scale Time Scales; Abrupt Climate Change: Inevitable Surprises, published by the National Academy Press in 2002; and “Abrupt Climate Change,” a 2008 report by the U.S. Climate Change Science Program and Subcommittee on Global Change Research.

This volume arises from contributions to the 2009 American Geophysical Union Chapman Conference on Abrupt Climate Change that addressed the progress made in understanding the mechanisms of abrupt climate events in the decade following the previous Chapman Conference on this topic (Mechanisms of Global Climate Change at Millennial Scale Time Scales and Abrupt Climate Change: Inevitable Surprises). The 2009 conference was held at the Byrd Polar Research Center of the Ohio State University, Columbus, Ohio, on 15–19 June 2009. A total of 105 scientists from 24 countries working in disciplines ranging from paleoclimatology, paleoceanography, and atmospheric and marine chemistry to paleoclimate model-data comparison to archaeology attended and presented their cutting-edge research at the weeklong conference. The basic purpose of the 2009 conference was to understand the spatiotemporal extent of abrupt climate change and the relevant forcings. This monograph covers a breadth of global paleoclimate research discussed at the conference and provides a list of critical topics that need to be resolved to better understand abrupt climate changes and thus advance our knowledge and the tools required to project future climate.

We would like to express our deep appreciation to participants and presenters for their cutting-edge research both at the conference and in this monograph. The conference was sponsored by the Office of Research and the Climate, Water and Carbon Program (CWC) of the Ohio State University, the Consortium for Ocean Leadership, and the National Science Foundation (OCE-0928601). As a result, we were able to provide travel support to all of the participating graduate students, postdoctoral researchers, and a few young investigators and most of the invited speakers. We acknowledge numerous reviewers for their critical assessment of the papers and help in streamlining the manuscripts. We would also like to acknowledge invaluable assistance provided by the staff of the American Geophysical Union.

Harunur Rashid
Byrd Polar Research Center, Ohio State University

Leonid Polyak
Byrd Polar Research Center, Ohio State University

Ellen Mosley-Thompson
Byrd Polar Research Center, Ohio State University
Department of Geography, Ohio State University

Abrupt Climate Change: Mechanisms, Patterns, and Impacts
Geophysical Monograph Series 193
Copyright 2011 by the American Geophysical Union.
10.1029/2011GM001138
Abrupt Climate Change Revisited
Harunur Rashid and Leonid Polyak

Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA

Ellen Mosley-Thompson

Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA
Department of Geography, Ohio State University, Columbus, Ohio, USA

This geophysical monograph volume contains a collection of papers presented at the 2009 AGU Chapman Conference on Abrupt Climate Change. Paleoclimate records derived from ice cores, lakes, and marine sedimentary archives illustrate rapid changes in the atmosphere-cryosphere-ocean system. Several proxy records and two data-model comparison studies simulate Atlantic meridional overturning circulation during the last deglaciation and millennial-scale temperature oscillations during the last glacial cycle and thereby provide new perspectives on the mechanisms controlling abrupt climate changes. Two hypotheses are presented to explain deep Southern Ocean carbon storage, the rapid increase of the atmospheric carbon dioxide, and retreat of sea ice in the Antarctic Ocean during the last deglaciation. A synthesis of two Holocene climate events at approximately 5.2 ka and 4.2 ka highlights the potential of a rapid response to climate forcing in tropical systems through the hydrological cycle. Both events appear contemporaneous with the collapse of ancient civilizations in low-latitude regions where roughly half of Earth’s population lives today.

1. INTRODUCTION

Remarkable, well-dated evidence of high-magnitude, abrupt climate changes occurring during the last glacial period between ~80 and 10 ka have been documented in Greenland ice cores and marine and terrestrial records in the Northern Hemisphere. These climate perturbations are known as the Dansgaard-Oeschger (D-O) warming and cooling cycles of 2–3 kyr duration. These are bundled into Bond cycles of 5–10 kyr and are terminated by Heinrich events consisting of massive iceberg rafting from the late Pleistocene Laurentide Ice Sheet (LIS). Since the discovery of the D-O cycles in ice cores and their counterparts in marine sediments of the North Atlantic, the search for abrupt, millennial- or finer-scale events has intensified across the globe (see Voelker et al. [2002] and Clement and Peterson [2008] for an overview). In recent years, an increasing number of paleoclimatic records, mostly in the Northern Hemisphere show teleconnections with the D-O cycles recorded in Greenland. The most commonly inferred link between these rapid climate events is related to the release of cold fresh water by iceberg melting. The introduction of this fresh water is assumed to slow or shut down the formation of the North Atlantic Deep Water (NADW), thus preventing the penetration of the North Atlantic Drift (the northern branch of the Gulf Stream) into high latitudes. The climatic importance of the Gulf Stream stems from the enormous quantity of heat it transports to northwestern Europe and its facilitation of the exchange of moisture between the ocean and atmosphere.
Marine and terrestrial paleoclimate records from the Southern Hemisphere (SH) are sparse and lack sufficient temporal resolution to characterize the timescales relevant for high-frequency climate variability. Although the evidence for abrupt climate change in the SH is not clear, a one-to-one correlation has been established between the new Eastern Dronning Maud Land (EDML) Antarctic ice core record and that from Greenland [EPICA Community Members et al., 2006]. The EDML ice core was recovered from a location facing the South Atlantic and is assumed to record climate changes in the Atlantic. Paleoclimatic records from the northern tropics and subtropics mainly show changes concordant with those in the North Atlantic, while asynchronous or even anticorrelated events are exhibited in records from the southern tropics and high latitudes of the SH. For example, the Indian and East Asian monsoon histories seem to correlate with the North Atlantic climate, whereas South American monsoon records are anticorrelated with the Greenland records [Wang et al., 2006]. Furthermore, paleoclimatic proxy records from the equatorial Pacific are characterized by a complex pattern of abrupt climate change that borrows elements from both the Northern Hemisphere and Southern Hemisphere end members, suggesting that the tropical Pacific may have played a significant role in mediating climate teleconnections between the hemispheres [Clement et al., 2004; Li et al., 2010].

The Chapman Conference on Abrupt Climate Change (ACC) held at the Ohio State University in June 2009 brought together a diverse group of researchers dealing with various paleoclimatic proxy records (such as ice cores, corals, marine sediments, lakes, and speleothems) and coupled ocean-atmosphere climate models to discuss advances in understanding the ACC history and mechanisms. Special attention was given to the three most commonly invoked ACC mechanisms: (1) freshwater forcing, in which meltwater from the circum–North Atlantic ice sheets may have disrupted the meridional overturning circulation (MOC) by preventing or slowing down the formation of NADW in the Labrador and Nordic Seas; (2) changes in sea ice extent, which affect the ocean-atmosphere heat exchange, moisture supply, and salt content; and (3) tropical forcing that calls for a combination of Earth’s orbital configuration, El Niño–Southern Oscillation, and sea surface temperature conditions. Several contributions dealing with various aspects of these topics are presented in this volume.

2. KEY QUESTIONS FOR THE ACC CONFERENCE

Without providing an exhaustive list of topics raised at the conference, we list a number of pressing scientific questions that were discussed:

1. Do paleoproxies suggest a one-to-one proxy-based relationship between circumpolar–North Atlantic freshwater pulses and the strength of the MOC, as well as the determination of meltwater sources?

2. Are kinematic and nutrient proxies for the strength of the MOC (Pa/Th, Cd/Ca, and $^{13}$C) congruent across abrupt climate changes that occurred during the Younger Dryas (YD) or Heinrich events? How do these proxies differ between periods of stable and transient climate?

3. Do current general circulation models capture abrupt strengthening and gradual weakening of thermohaline circulation, consistent with the rapid warming and gradual cooling of D-O events? If not, what other factors must be considered?

4. Is there robust evidence for sea ice in the North Atlantic during the last glacial cycle? How much has sea ice extent fluctuated on millennial timescales? How have the fluctuations influenced the surface salinity and thus water mass stratification?

5. With the exception of the tropical Atlantic, most tropical paleorecords show a clear lack of D-O cooling events. Does this indicate that various parts of the tropics respond differently to the North Atlantic freshwater forcing because of local hydrological and temperature variability?

6. Given the dramatic changes in Arctic sea ice and circulation, how did the Arctic freshwater budget affect the MOC in the North Atlantic?

7. Why do Antarctic temperatures show more gradual and less pronounced warmings and coolings compared to the D-O events in Greenland? Does this suggest that the deep ocean circulation is modulating the abrupt climate change?

8. In light of the current concern about instabilities of the West Antarctic and Greenland ice sheets, how can paleocenographic records be used to decipher past ice sheet dynamics?

9. What is the link between sea ice extent and ice sheet dynamics? How does ocean heat transport influence the ice sheet margin? Might coastal ice shelves be slaves to ocean currents?

10. Was there a relationship between the demise of past civilizations and climatic deterioration? What are the climate tipping points that have driven past civilizations to collapse?

One of the important points raised at the conference is that a close examination of paleoclimatic data and modeling results does not show adequate support for many of the widely accepted explanations for abrupt climate change. For example, it is almost taken for granted that fresh water released from circum–North Atlantic ice sheets during Heinrich events perturbed the Atlantic meridional overturning circulation (AMOC), which caused abrupt changes recorded around the globe. However, with the exception of the Younger Dryas, there is no paleoprobe evidence from deep waters...
that would indicate a shutdown or slowdown of the AMOC during Heinrich events [Lynch-Stieglitz et al., 2007]. This situation does not necessarily mean that changes in paleo-bottom water composition did not occur but simply shows that adequate supporting data are lacking. Even less certainty can be applied to paleorecords older than the last glacial cycle, when these abrupt climate changes were a recurrent phenomenon. Whether such recurrent events occurred during previous glacial cycles is not well documented because of the scarcity of long paleoclimatic records with the requisite spatial and temporal resolution.

Several new areas of inquiry were discussed during the meeting including (1) development of a new chronostratigraphy for Antarctic ice cores based on local insolation and independent from bias-prone orbital tuning [Kawamura et al., 2007; Laepple et al., 2011], (2) phasing between the deep ocean and surface water warming during terminations as derived from oxygen isotope records on benthic and planktonic foraminifers [Rashid et al., 2009], (3) indication of monsoon failure from atmospheric oxygen isotopes and deep ocean temperature change from inert gases [Severinghaus et al., 2009], (4) timing of elevated subantarctic opal fluxes and deep ocean carbon dioxide release to the atmosphere and phasing between these features and the position of the western ACC [Anderson et al., 2009], (5) use of dynamic circulation proxies (Pa/Th, Nd isotopes, etc.) and models of freshwater forcing in assessing the strength of MOC, and (6) role of the Antarctic Intermediate Water in distributing heat and transporting old carbon around the ocean [Marchitto et al., 2007; Basak et al., 2010].

Members of the paleoclimate modeling community stressed the need to improve the temporal resolution and age constraints on paleoclimatic records. In addition, it was suggested to further explore “the meaning of proxies,” resolve the leads and lags in important paleorecords, and provide benchmark tests for climate sensitivity analysis. For example, oxygen isotopes in speleothems could indicate the amount of precipitation, changes in seasonality, or changes in source region of moisture. More research is needed to clarify the relationship of oxygen isotopes with these variables. Modelers also asked questions regarding the sources of carbon dioxide increase during the Antarctic isotope maximum (AIM) warming events and factors that could be attributed to the deep ocean warming during Heinrich events.

3. DISCUSSION OF MAJOR FINDINGS

3.1. Last Glacial-Interglacial Climate Cycle

After four decades of intense research, there are not that many high-resolution (millennial to submillennial scale) paleoceanographic records available from the North Atlantic, the critical area for understanding changes in the MOC. Voelker and de Abreu [this volume] provide an overview of the last four glacial cycles from high-accumulation-rate sites on the Iberian margin based mostly on data from Martarat et al. [2007], Voelker et al. [2009], and Salgueiro et al. [2010]. Latitudinal (43.20° to 35.89°N) and longitudinal (10.39° to 7.53°W) gradients in sea surface temperature and density are reconstructed in this chapter using a foraminiferal assemblage–based transfer function (SIMMAX [Pflaumann et al., 1996]) and δ18O from 11 sediment cores from the northeastern Atlantic. In addition to sea surface conditions, δ18O and δ13C compositions in various planktonic foraminifers covering the depth range of 50 to 400 m indicate changes in calcification depth during glacial intervals. Voelker and de Abreu also evaluated changes in seasonality based on the difference in δ18O between Globigerina bulloides and Globorotalia inflata [Ganssen and Kroon, 2000]. As a result, migration of subpolar and subtropical boundaries and hydrographic fronts during abrupt climate events were identified. Voelker and de Abreu suggest that nutrient levels and thus ventilation of the upper 400 m of the water column were not driven by millennial-scale events. In contrast, millennial-scale oscillations in ventilation were recorded in the intermediate to bottom waters, indicating the status of the overturning circulation either in the North Atlantic or in the Mediterranean Sea that admixed deep flowing Mediterranean Overflow Water to the Glacial North Atlantic Intermediate Water. One of the important aspects of Voelker and de Abreu’s contribution is the detailed documentation of the upper water structure during the penultimate glacial (marine isotope stage (MIS) 6) that has been characterized by only scarce data thus far.

Flower et al. [this volume] review planktonic Mg/Ca-δ18O evidence from the Gulf of Mexico (GOM) to investigate the role of meltwater input from the LIS in abrupt climate change during MIS 3 and the last deglaciation. The chapter provides an important summary of the current understanding of the ACC in the GOM by synthesizing data mostly presented by Flower et al. [2004], Hill et al. [2006], and Williams et al. [2010]. These data show that the ice volume–corrected seawater δ18O in the GOM matches the East Antarctic ice core δ18O [EPICA Community Members et al., 2006]. Flower et al. [this volume] conclude that (1) LIS meltwater pulses started during Heinrich stadials and lasted through the subsequent D-O events; (2) LIS meltwater pulses appear to coincide with the major AIM events; and (3) LIS meltwater discharge is associated with distinct changes in deep ocean circulation in the North Atlantic during H events. These observations lead the authors to propose a direct link between GOM meltwater events and the weakening of the
AMOC as modulated by the Antarctic climate. Furthermore, Flower et al. hypothesize that LIS melting is linked to the Antarctic climate, so that it was the AMOC reduction (via the bipolar seesaw and Antarctic warming) that drove increased LIS meltwater input to the GOM and not vice versa. This causality, however, may have been limited as LIS meltwater input to the GOM continued throughout D-O 8 and Bølling/Allerød events despite a lack of evidence for AMOC reduction during these intervals [Rahmstorf, 2002].

Since the D-O cycles were first discovered in Greenland ice cores and then later confirmed in deep-sea sediments of the Atlantic, a large number of modeling efforts were directed toward understanding the origin and significance of these paleoclimatic events. Rial and Saha [this volume] simulate the D-O cycles using a conceptual model, based on simple stochastic differential equations, termed the sea ice oscillator (SIO), which borrowed elements from the Saltzman et al. [1981] concept. Simulation results show that sea ice extent and mean ocean temperature can be driven by changes in orbital insolation, which play a dominant role in controlling atmospheric temperature variability. The SIO model has two internal parameters controlling the abruptness of temperature change: the free frequency of the oscillator and the intensity of positive feedbacks. The model best reproduces the D-O cycles if the free oscillation period is set around 1.5 kyr, as originally proposed by Bond et al. [1997]. The performance of the SIO model is tested against two of the best resolved paleoclimate records: the Greenland ice core $\delta^{18}$O [North Greenland Ice Core Project members, 2004] and planktonic and benthic foraminiferal $\delta^{18}$O records of sea surface and deep-sea temperature from the Portuguese margin (core MD95-2042 [Shackleton et al., 2000]). Shackleton et al. [2000] have shown that the $\delta^{18}$O of planktonic foraminifer exhibits changes similar to those in the Greenland ice core, whereas the $\delta^{18}$O record of benthic foraminifer (water depth below 2200 m) varies in a manner similar to the Antarctic air temperature. At any rate, Rial and Saha conclude that the time integral of the surface ocean proxy history is proportional to that of the deep ocean temperature, and the latter is shifted by $\pi/2$ with respect to sea ice extent. Surprisingly, a similar relationship was found between methane-synchronized temperature proxies from Greenland and East Antarctic ice core records [Blunier and Brook, 2001]. Rial and Saha’s model output is reproduced using ECBilt-Clio, another well regarded model [Goosse et al., 2002].

To summarize up-to-date results on abrupt climate events of the last glacial cycle, Figures 1 and 2 show records representative of the global climate during this period. These records were selected based on the geographic location and temporal resolution adequate to assess millennial- or finescale climate events. Regardless of the nature of climate archives, the climatic expression of the D-O cycles is evident from the southwest Pacific Ocean to northeastern Siberia.

### 3.2. Deglaciation Period

One of the most studied periods of the last glacial cycle is the time between 10 and 25 ka, commonly known as the last deglaciation. This period contains four very well studied abrupt climate events: the Younger Dryas (also known as H0 event, 11.6–12.9 ka); Bølling-Allerød (B-A) (14.6 ka); the so-called “Mystery Interval” (14.5–17.5 ka); and the last glacial maximum (LGM) (19–26.5 ka). The rationales behind focusing on the last deglaciation interval include the availability of paleoclimate records with high temporal resolution and a robust age control constrained by $^{14}$C accelerator mass spectrometry and U-Th dating. It is not surprising that 5 out of 14 chapters in this volume focus on climate events from this interval. In addition, we outline several new hypotheses (relative to the deglaciation events) that have emerged since the 2009 conference.

Simulating the impact of freshwater discharge into the North Atlantic during the Heinrich and other meltwater events has gained a significant momentum after the work of Stouffer et al. [2006] and Liu et al. [2009]. Numerous modeling studies, where freshwater discharge was artificially added to the North Atlantic, have shown large climate impacts associated with abrupt AMOC changes. These results highlight the need to better understand the mechanisms of the AMOC variability under the past, present, and future climate conditions. The mechanisms controlling the recovery of the AMOC are, however, difficult to investigate as they require long simulations with models that can capture very different internal variabilities. Cheng et al. [this volume] describe the AMOC recovery stages from a model simulation of the last deglaciation built on the work of Liu et al. [2009]. These authors perform a remarkably long simulation using an atmosphere-ocean general circulation model [Liu et al., 2009], which allows for a clear identification of transient states of the recovery process including the AMOC overshoot phenomenon [Renold et al., 2010]. This 5000 year simulation time covers the last deglaciation period using insolation and fresh water estimated from paleoproxies as forcings. In particular, the simulation offers an explanation for the B-A warm period by a recovery of the AMOC in less than 400 years. An in-depth analysis of the AMOC recovery suggests that the two convection sites in the North Atlantic simulated in the model do not recover at the same time: the first stage of the recovery occurred in the Labrador Sea and was then followed by convection recovery in the Greenland-Iceland-Norwegian (GIN) Seas. The study suggests that reinitiation of convection in the Labrador Sea is related to the reduction
Figure 1. Geographic distribution of paleoclimate proxy records for the last glacial cycle (stars) and the last deglaciation (circles) as shown on Figures 2 and 3.
Figure 2. Comparison of various proxy records that demonstrate abrupt climate changes during the last glacial cycle. (a) Global stack of benthic foraminiferal oxygen isotopes ($\delta^{18}O$) [Lisiecki and Raymo, 2005]. (b) The $\delta^{18}O$ in planktonic foraminifera *Globigerina bulloides* from the North Atlantic Integrated Ocean Drilling Program Site 1313 (H. Rashid, unpublished data, 2011). (c and d) Carbon isotopes ($\delta^{13}C$) in benthic foraminifera *Cibicidoides wuellerstorfi* from the South Atlantic Ocean Drilling Program Site 1089 [Charles et al., 2010] and core MD97-2120 from the SW Pacific Ocean [Pahnke and Zahn, 2005], respectively. (e and f) Alkenone ($U_{37}k$) derived sea surface temperatures from the NE Atlantic core MD01-2443 [Martarat et al., 2007; Voelker and de Abreu, this volume, Figure 5] and core MD01-2412 from the NW Pacific Ocean [Harada et al., 2008], respectively. (g) Magnetic susceptibility record from Lake El’gygytgyn, NE Siberia [Nowaczyk et al., 2007]. (h) The $\delta^{18}O$ in the Shanbao speleothems, NE China [Wang et al., 2008]. (i) Antarctic temperature reconstructed from the deuterium content ($\Delta T$ elevation corrected) in the Eastern Droning Maud Land facing the South Atlantic [Stenni et al., 2010]. (j) The $\delta^{18}O$ in the North Greenland Ice Core Project ice core with a revised chronology [Svensson et al., 2008]. (k) June insolation at 65°N [Berger and Loutre, 1991]. All records are plotted according to their independent age models. Note that the vertical grey bar indicates the duration of marine isotope stage 4 and the two vertical discontinuous lines indicate the 20 and 130 ka time horizons.
of freshwater forcing, leading to an increase in salinity. Convection in the GIN Seas is then forced by a (partial) recovery of the AMOC and associated salinity transport. Overall, Cheng et al. provide a convincing mechanism, in which both local and remote salinity feedbacks play a role in the AMOC recovery.

New data from four sediment cores in addition to the synthesis of earlier results from the Labrador margin [Rashid et al., this volume] shed light on the development of the YD event. There has been a long-standing debate about the origin of YD event [e.g., Mercer, 1969; Johnson and McClure, 1976; Ruddiman and McIntyre, 1981; Teller and Thorleifson, 1983; Teller et al., 2005; Broecker et al., 1989; Andrews et al., 1995; Lowell et al., 2005]. Most of these studies propose freshwater flooding at sites of deepwater formation in the North Atlantic; however, a freshwater signature has not been found in proxy records near these sites thus far. Rashid et al. show that a δ18O depletion in planktonic foraminifers indicates a YD freshwater signature in the Hudson Strait but not in the more distal cores despite the presence of a H0 high-carbonate bed in these cores. Rashid et al. hypothesize that if the fresh water discharged through Hudson Strait was admixed with fine-grained detrital carbonates, it would form a hyperpycnal flow transported through the deep Labrador Sea Northwest Atlantic Mid-Ocean Channel to distal sites of the NW Atlantic Ocean such as the Sohm Abyssal Plain. With the release of entrained sediment, fresh water from the hyperpycnal flow would buoyantly rise and lose its signature by mixing with the ambient sea water. This mechanism explains a lack of YD δ18O depletion in sediment cores retrieved from the NW Atlantic. Thus, the long-sought smoking gun for the signature of YD (H0) freshwater flood [e.g., Broecker et al., 1989] remains elusive.

Applegate and Alley [this volume] evaluate the potential of using cosmesogenic radionuclides (CRN) to date glacial moraine boulders to trace the geographic expression of abrupt climate change. The chapter provides a synthesis of the current state of the knowledge using CRN to determine the extent and retreat of glaciers in a terrestrial setting. Problems highlighted deal with selecting samples for exposure dating and with the calculation of exposure dates from nuclide concentrations. Failure to address these issues will yield too-young exposure dates on moraines that have lost material from their crests over time. In addition, geomorphic processes are likely to introduce errors into the calibration of nuclide production rates. The authors point to a conclusion from a recent study by Vacco et al. [2009] that the ages of true YD moraines should cluster around the end of YD, however the recent modeling study complicated this simplistic assumption. Applegate and Alley demonstrate their points using beryllium-10 exposure dates from two “not so primed” moraines of inner Titcomb Lakes (Wind River Range, Wyoming, United States) and Waiho Loop of New Zealand. The sampling strategies prescribed may help in minimizing problems with defining true age of the moraines. The chapter includes a guide for determining the minimum number of samples that must be collected to answer a particular paleoclimate question.

During the termination of the last ice age, atmospheric CO2 rapidly increased in two steps [Monnin et al., 2001], and atmospheric Δ14C (Δ14C_atm) decreased by ~190% between 17.5 and 14.5 ka [Reimer et al., 2009] (Figure 3), coined the “Mystery Interval” by Denton et al. [2006]. From two eastern Pacific sediment cores off Baja California, Marchitto et al. [2007] have documented two strong negative excursions of Δ14C, which were corroborated by another eastern Pacific record of Stott et al. [2009, this volume] and a record from the western Arabian Sea [Bryan et al., 2010]. One of those negative excursions of Δ14C corresponds to the Mystery Interval and the other to the YD. The emerging understanding is that during the LGM, there was a hydrographic divide between the upper 2 km of the water column and the deep Southern Ocean, where dense and salty deep waters hosted the depleted Δ14C [Adkins et al., 2002]. Accordingly, these depleted Δ14C waters were termed the “Mystery Reservoir.” The origin of the “Mystery Reservoir” has been linked to freshwater release into the North Atlantic during H1 and YD (H0) [Toggweiler, 2009]. It has been further inferred that the resulting AMOC weakening initiated a chain of events reaching to the tropics and Southern Hemisphere [Anderson et al., 2009]. According to this interpretation, as the northward heat flow slowed, the heat accumulated in the tropics and warmed the Southern Ocean, resulting in the reduction of sea ice extent around Antarctica. This sea ice retreat shifted the Southern Hemisphere westerlies poleward through a mechanism that remains unknown, allowing the ventilation of the deep ocean that stored CO2 and some other chemical components such as silica. As a result, a rise in atmospheric CO2, depleted Δ14C_atm, and a dramatic increase in the accumulation of siliceous sediments were observed in the Southern Ocean [Anderson et al., 2009].
signal of old radiocarbon in the atmosphere during the deglaciation. This source is inferred to be a combination of liquid and hydrate CO$_2$ in subduction zones and volcanic centers other than on mid-ocean ridges. During glacial times, CO$_2$ hydrates in the cold intermediate ocean are stable and able to trap liquid CO$_2$ bubbling up from below the seafloor. During deglaciation, a swath of these hydrates becomes unstable and releases radiocarbon-dead CO$_2$ to the ocean-atmosphere system, thus increasing atmospheric CO$_2$ and decreasing $\Delta^{14}C_{\text{atm}}$. This hypothesis is likely to stimulate wide interest in the scientific community; however, it requires vigorous testing through experiments, observations, and modeling.

In a related study that takes into account the relationship between the rise in atmospheric CO$_2$ and temperature in low to high latitudes, Russell et al. [2009] reconstruct precipitation and temperature histories from southeast African Lake Tanganyika based on compound-specific hydrogen isotopes and paleotemperature biomarker index TEX$_{86}$ in terrestrial leaf waxes. It has been shown that Lake Tanganyika paleo-temperature followed the temperature rise in Antarctica at 20 ka [Minnin et al., 2001] as well as the Northern Hemisphere summer insolation at 30°N [Tierney et al., 2008]. Furthermore, temperatures in Lake Tanganyika began to increase ~3000 years before the rise of atmospheric CO$_2$ concentrations during the last ice age termination (Figure 3). This is a significant discovery that needs to be replicated from similar climate settings in other regions of the world. An extensive statistical testing is also needed to confirm whether the temperature record from Lake Tanganyika can be applied more generally throughout the tropics or whether it represents only a regional warming. If the reconstructed temperature history from Lake Tanganyika survives the scrutiny of proxy validation, it would strongly suggest that the primary driver for glacial-interglacial termination, at least for the last ice age, lies in the tropics rather than in high latitudes.

3.3. Holocene Climate

The conventional view based primarily on Greenland ice core $\delta^{18}O$ records suggests that climate in the Holocene (current interglacial) was rather uniform and remarkably stable in comparison to the preceding glacial and interstadial

![Figure 3. Paleoclimatic proxy records of the last deglaciation. (a) Biogenic opal flux in the Southern Ocean, interpreted as a proxy for changes in upwelling south of the Antarctic Polar Front [Anderson et al., 2009]. (b) Atmospheric CO$_2$ from Antarctic Dome C [Minnin et al., 2001] placed on the Greenland Ice Sheet Project 2 (GISP2) timescale. (c) Baja California intermediate water $\Delta^{14}C$ [Marchitto et al., 2007]. (d) The $^{231}Th/^{230}Th$ ratios from the Bermuda Rise (increasing values reflect reduced Atlantic overturning circulation) [McManus et al., 2004]. (e) The $e_{Nd}$ of fossil fish tooth/debris record suggesting variations of water mass at Baja California [Basak et al., 2010]. (f) Ti/Ca ratios in bulk sediment from western equatorial Atlantic, interpreted as a proxy for high Amazon River runoff [Jaeschke et al., 2007]. (g) TEX$_{86}$-derived surface temperature of Lake Tanganyika [Tierney et al., 2008]. (h) The $\delta^{18}O$ in Shanbao speleothems [Wang et al., 2008]. (i and j) GISP2 methane and oxygen isotope ratios ($\delta^{18}O$) [Stuiver and Grootes, 2000; Blunier and Brook, 2001], respectively. All records are plotted according to their independent age models.](image-url)
periods (MIS 2–3). However, as more new paleoclimatic records emerge, such as palynological and paleolimnological data from North America [Viau et al., 2006; Gajewski and Viau, this volume] and tropical climate records reconstructed from high-elevation ice cores [Thompson, this volume], it appears that Holocene climate variability may have been greater than has been assumed based on prior data sets.

In the early Holocene, large climatic fluctuations were related to freshwater pulses from the disintegrating LIS into the western North Atlantic [e.g., de Vernal et al., 2000]. Using palynological data (terrestrial palynomorphs and marine dinocysts) from the Newfoundland and northern Scotian Shelf sediment cores, Levac et al. [this volume] assess the impact of fresh water on the circulation over the Labrador margin and related climate change during the final demise of the proglacial Lake Agassiz. The authors identify a circa 8.7 ka detrital carbonate bed accompanied by two meltwater pulses that lowered sea surface salinity (SSS) in the coastal water of Newfoundland. In contrast, data from the Scotian Shelf do not show changes in the SSS at this time. The divergent impact of freshwater pulses at these two sites is explained by the absence of a diluting effect of the North Atlantic Current at the Newfoundland margin as opposed to the warmer Scotian Shelf. Keigwin et al. [2005] have documented a cooling event around 8.5 ka, likely correlated to that identified by Levac et al., as far south as Cape Hatteras, suggesting a large geographic impact of the Lake Agassiz drainage. Surprisingly, such a pronounced cooling event has not been found in the northern Labrador Sea and Baffin Bay, possibly because of a lack of high-resolution records due to the stronger winnowing conditions of the Labrador coastal current [Chapman, 2000; Rashid et al., 2011].

Ruzmaikin and Feynman [this volume] investigate a quasiperiodic 1500 year climate oscillation during the Holocene and its relation to the AMOC. They employed a simple conceptual model to simulate the forcing mechanism for this oscillation. The analysis of six paleoclimatic records from the Atlantic Ocean and sunspot numbers using wavelet and empirical mode decomposition methods allowed the authors to overcome the leaks from one mode to another, a common problem in conventional band-pass filtering. Ruzmaikin and Feynman conclude that solar forcing does not drive the 1500 year climate cycle “directly,” contrary to the inference by Bond et al. [2001]. Instead, they suggest a simple model of excitation of this oscillation in a nonlinear dynamical system with two equilibrium states. They reason that the transitions between the two states are caused by the noise, ocean, and solar variability, and the implication is that the beats between the centennial ocean variability and ~90 year solar cycles produce the 1500 year oscillation in the noisy system. This conceptual framework for the 1500 year oscillation requires more rigorous testing by more sophisticated, coupled ocean-atmosphere models.

Gajewski and Viau [this volume] suggest that the Holocene in North America can be divided into four general periods with abrupt transitions at ~8, 6, and 3 ka, generally consistent with the hypothesis of Ruzmaikin and Feynman [this volume]. Gajewski and Viau further infer that the late Holocene 5.2 ka, 4.2 ka, and Little Ice Age (circa 1300–1870 A.D.) cooling/drying events were part of a continual series of millennial-scale climatic fluctuations.

Paliwal [this volume] documents abrupt climate events during the Holocene from a series of lake records and groundwater data from the western Indian peninsula. Some of these abrupt climate events, in combination with neotectonic activity, altered the drainage pattern that caused a disappearance of the Vedic Sarasvati River and other tributaries of the Indus River. Paliwal infers that the onset of the arid climate in the Thar Desert around 3.5 ka may have caused the decline of the Indus Valley Harappan and Mohenjo-Daro civilizations. Interestingly, fossils of elephants and bamboo curtains discovered in the Quaternary gypsum deposits of Rajasthan suggest the existence of an even earlier advanced civilization (>12.82 ka). This Vedic civilization, which flourished along the banks of the Sarasvati River, is older than the Harappan and Mohenjo-Daro civilizations (5 ka) of the Indus Valley [Weiss et al., 1993; Rashid et al., 2011]. However, the lack of high-resolution radiocarbon dates prevents correlation of these terrestrial records to Indian summer monsoon records [Thompson et al., 1997; Rashid et al., 2011], which is essential to evaluate the impact of climate changes on the fate of these ancient civilizations.

From Sierra Nevada’s Coburn Lake, Wathen [this volume] reconstructed an 8500 year fire history using charcoal microparticles as a proxy. In addition to published data from the Sierra Nevada and surroundings, the author correlates his records with the long-distance fire records from Lake Francis of eastern Canada and soot records of Greenland ice cores. Wathen suggests that severe fires at Coburn Lake occurred at the beginning of severe droughts, consistent with the Greenland soot records. Furthermore, the 8.2 ka and 5.2 ka climatic events identified in the Lake Coburn charcoal record are inferred to be related to large-scale shifts in the major precipitation belts: the Intertropical Convergence Zone (ITCZ), the Subtropical Desert Zone, and the Polar Front. Wathen hypothesizes that most instances of severe fires and erosion at Coburn Lake occurred in response to stresses on vegetation that were adapted to colder and wetter conditions in response to abrupt climate events. A similar mechanism is suggested for the Coburn Lake fire history of the last 1800 years, although some major climatic
settings, such as the position of the ITCZ, were different in the late Holocene.

Accumulation of past climate records over the last decade shows that during the past 5000 years when climatic conditions were similar to recent (prior to the rise in anthropogenic greenhouse gases), Earth experienced at least two abrupt global-scale climate events (5.2 ka and 4.2 ka). Thompson [this volume] provides a detailed synthesis of these events using ice core records from the world’s highest mountains combined with other published paleoclimate histories. These events, which persisted for a few centuries, were related to profound changes in the hydrological cycle in the tropics and midlatitudes [Magny and Haas, 2004] and appear to correlate with the decline of ancient civilizations [Weiss et al., 1993; MacDonald, 2011; Rashid et al., 2011; Thompson, this volume]. However, the forcing mechanisms for these abrupt changes remain elusive thus far due in large measure to insufficient spatial coverage.

The 5.2 ka event is preserved in diverse paleoclimate archives that include ice core oxygen isotope records from Kilimanjaro in Tanzania and Huascaran in northern Peru, methane records from Antarctica and Greenland, marine sediment records from the Bay of Bengal, and deposition of Saharan dust in the South American Andes. Other ice core proxies including dust and soluble chemical species such as Cl− and SO42− also show drastic changes associated with the 5.2 ka event. Terrestrial records such as trees preserved in a standing position hundreds of feet below the surface of Lake Tahoe [Lindström, 1990], plants emerging from the retreating margins of an Andean glacier [Thompson et al., 2006], and the “Tyrolean ice man” or “Ötzi” in the Eastern Alps are other notable observations concomitant with the 5.2 ka event. There are not many deep-sea records that contain the 5.2 ka event at present. However, all of these paleoclimatic records point to a near-global low- to mid-low-latitude abrupt climate event that appears to have impacted civilizations on three continents.

The other abrupt climate event during the late Holocene is dated between 4.0 and 4.5 ka and seems to be very widespread as it is found in many tropical and extratropical paleoclimate archives. It is associated with prominent dust peaks in the Huascaran and Kilimanjaro ice cores and is thus interpreted as a major drought interval during the late Holocene [Davis and Thompson, 2006]. Sediment cores from the Gulf of Oman and Bay of Bengal, as well as lake records from the Gharwal Himalayas and northern Africa also indicate dry climatic conditions around 4.2 ka. These events are also expressed in archeological data from the Euphrates and Tigris drainage basins. Thompson [this volume] further synthesizes many North African, Middle Eastern, South Pacific, and South Asian paleoclimate records centered around the 4.2 ka event. Like the 5.2 ka event, it is also believed to have lasted at least a few centuries. If such a rapid and sustained drought as during the 4.2 ka event were to occur today, with Earth’s population rapidly approaching 7 billion, the impact would be very troubling.

4. RECOMMENDATIONS

Participants recommended several major areas in which improved approaches to understanding abrupt climate change are needed. These include the following: (1) collecting more high-accumulation-rate and high-resolution data and improving coordination of paleoclimate proxy and modeling approaches; (2) concentrating on a few key time intervals (such as 5.2 ka and 4.2 ka events) but using multiple proxies; (3) developing novel paleoclimatic proxies such as clumped isotopes, a promising tool for an independent paleotemperature record, and biomarker proxies for sea ice and temperature; (4) reconstructing a history of sea ice distribution that provides a fast and powerful feedback in polar and subpolar regions such as the North Atlantic and sub-Antarctic; and (5) facilitating deep drilling in the Indian Ocean, an under investigated ocean region that is critical to understanding the history of the Indian monsoon as well as the erosion and uplift of the Himalayas, with the recent recovery of a nearly a million yearlong climate record from the EPICA Dome C ice core raising the scientific necessity of attaining an equally long record from the southern Indian Ocean.

Many meeting participants emphasized that more paleoclimatic records with improved temporal resolution and “near-zero uncertainty” dating are required for state-of-the-art model to data comparison studies. Plans are urgently needed for the paleoclimatic community to expand the number and spatial distribution of longer high-quality proxy data sets to complement those that already exist for the last glacial cycle. Data sets that include multiple evolutions of glacial and interglacial conditions are essential for current efforts to project climate change under a warmer Earth scenario as is currently underway by the Intergovernmental Panel on Climate Change.

To contribute to climate change prediction efforts, it is especially important to understand the mechanisms driving late Holocene abrupt climate events such as those at circa 5.2 and 4.2 ka. These events are found mainly in low-latitude climate archives related to the hydrological cycle history and appear to be contemporaneous with collapses of civilizations in the Middle East, Indian subcontinent, and Mesoamerica. As more than half of the humanity lives in the tropical belt, the significance of any change in regional hydrological cycles cannot be overemphasized.
REFERENCES


Blunier, T., and E. J. Brook (2001), Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, Science, 291, 109–112.


Harada, N., M. Sato, and T. Sakamoto (2008), Freshwater impacts recorded in tetraunsaturated alkenones and alkenone sea surface temperatures from the Okhotsk Sea across millennial-


Rashid, H., S. Lodestro, J. Gruzner, A. Voelker, and B. P. Flower (2009), New assessment for the last four glacial cycles’ Northern Hemispheric ice-sheet variability from the IODP Site U1313 of the North Atlantic, paper presented at Chapman Conference on Abrupt Climate Change, AGU, Columbus, Ohio.


Russell, J. M., et al. (2009), Abrupt climate change in the southeast African tropics between 0 and 60,000 yr BP: Testing the influence of ITCZ migration on temperature and precipitation in the southern tropics, paper presented at Chapman Conference on Abrupt Climate Change, AGU, Columbus, Ohio.


Shackleton, N. J., M. A. Hall, and E. Vincent (2000), Phase relationships between millennial-scale events 64,000–24,000 years ago, Paleoceanography, 15, 565–569.


Tierney, J. E., et al. (2008), Northern Hemisphere controls on tropical southeast African climate during the last 60,000 years, Science, 322, 252–255.


E. Mosley-Thompson, L. Polyak, and H. Rashid, Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA. (rashid.29@osu.edu)
The Iberian margin is a key location to study abrupt glacial climate change, and regional variability is studied combining published and new records. Looking at the trend from marine isotope stage (MIS) 10 to 2, the planktic foraminifer data, conforming to Martrat et al. [2007], show that abrupt events, especially Heinrich events, became more frequent and their impacts stronger during the last glacial cycle. However, there were two older periods with strong impacts on the Atlantic meridional overturning circulation: the Heinrich-type event associated with termination IV and the one occurring during MIS 8 (269 to 265 ka). During Heinrich stadials, the Polar Front reached the northern Iberian margin (approximately 41°N), while the Arctic Front was located in the vicinity of 39°N. During all glacial periods, there existed a boundary at the latter latitude, either the Arctic Front during extreme cold events or the Subarctic Front during less strong coolings or warmer glacials. Along with the fronts, sea surface temperature (SST) increased southward by about 1°C per 1° latitude leading to steep SST gradients. Glacial hydrographic conditions were similar during MIS 2 and 4 but much different during MIS 6. MIS 6 was a warmer glacial with subtropical waters reaching as far north as 40.6°N. In the vertical structure, Greenland-type oscillations were recorded down to 2465 m during Heinrich stadials, i.e., deeper than in the western basin, due to the admixing of Mediterranean Outflow Water. It is evident that latitudinal, longitudinal, and

---

1Now at Camberley, UK.
vertical gradients existed along the Iberian margin, i.e., in a relatively restricted area, but sufficient paleodata now exist to validate regional climate models for abrupt climate change events.

1. INTRODUCTION

The western Iberian margin is a focal location for studying the impact and intensity of abrupt climate change variability. Sediment cores retrieved there at a depth of more than 2200 m showed that the δ18O of planktic foraminifer exhibits changes similar to those found in Greenland ice core records (e.g., δ18OIce), whereas the δ18O record of benthic foraminifer varies in a manner more reminiscent of the Antarctic temperature signal [Shackleton et al., 2000]. Thus, core sites retrieved at this margin allow studying interhemispheric linkages in the climate system. In addition, the southern edge of the North Atlantic’s ice-rafted detritus (IRD) belt [Hemming, 2004; Ruddiman, 1977] intercepted with the margin, so that melting icebergs reached the margin during Heinrich and Greenland stadials of the last glacial cycle and during ice-rafting events of preceding glacials [Baas et al., 1997; Bard et al., 2000; de Abreu et al., 2003; Moreno et al., 2002; Naughton et al., 2007; Sánchez-Góñi et al., 2008; Zahn et al., 1997]. Following the work of Sánchez-Góñi and Harrison [2010] who documented that on the Iberian margin, the duration of the related surface water cooling and the Heinrich ice-rafting event per se can differ, Greenland stadials associated with Heinrich events are referred to as Heinrich stadials. Otherwise, the Greenland stadial and Greenland interstadial nomenclature in this chapter follows the Integration of Ice-core, Marine and Terrestrial Records (INTIMATE) group [Lowe et al., 2001, 2008] and the North Greenland Ice Core Project members [2004]. Only during Heinrich stadials did the Polar Front reach the Iberian margin [Eynaud et al., 2009] associated with abrupt and intense cooling in the sea surface temperature (SST) [Bard et al., 2000; Cayre et al., 1999; de Abreu et al., 2003; Martrat et al., 2007; Naughton et al., 2009; Vautravers and Shackleton, 2006; Voelker et al., 2006]. Using the records of three core sites, Salgueiro et al. [2010] were the first to show that while cooling was recorded at all sites during Heinrich events, there existed a clear boundary between 40°N and 38°N that affected not only the SST but also productivity. They attributed this boundary to a stronger influence of subtropical surface and subsurface waters in the southern region, which is in accordance with evidence from nannofossils [Colmenero-Hidalgo et al., 2004; Incarbona et al., 2010] and planktic foraminifer stable isootope data [Rogerson et al., 2004; Voelker et al., 2009]. Voelker et al. [2009], furthermore, showed that upper water column stratification was diminished during the Heinrich events of marine isotope stage (MIS) 2, especially along the western margin.

The Heinrich and Greenland stadials left their imprints also farther down in the water column related to changes in the Atlantic meridional overturning circulation (AMOC) strength. One well-documented change was the increased influence of lesser ventilated southern sourced waters, in particular, the Antarctic Bottom Water (AABW), due to the shoaling of the interface between Glacial North Atlantic Intermediate Water (GNAIW) and AABW [Margari et al., 2010; Shackleton et al., 2000; Skinner and Elderfield, 2007; Skinner et al., 2003] when AMOC was reduced or shut off. Along with this change, ventilation of the deeper water column was reduced [Baas et al., 1998; Schönfeld et al., 2003; Skinner and Shackleton, 2004], and nutrient levels were raised [Willamowski and Zahn, 2000]. In the middepth range, another water mass is also important on the Iberian margin: the Mediterranean Outflow Water (MOW). Evidence for MOW changes mainly come from core sites in the Gulf of Cadiz, i.e., the southern margin. Voelker et al. [2006] showed that the lower MOW core reacted to abrupt climatic changes and was stronger during most parts of the Heinrich stadials and during Greenland stadials in accordance with evidence for deep convection in the Mediterranean Sea [Kuhnt et al., 2008; Schmiedl et al., 2010; Sierro et al., 2005]. Similar evidence also emerged for the upper MOW core [Llave et al., 2006; Toucanne et al., 2007], and for MIS 2, it has been shown that the MOW was not only strengthened, but settled significantly deeper, as deep as 2000 m, in the water column [Rogerson et al., 2005; Schönfeld and Zahn, 2000]. Thus, abrupt climatic changes affected all levels of the water column on the western Iberian margin.

During the last decades, many cores have been retrieved from this region and studied in high-resolution, but the records were seldom combined for a comprehensive regional reconstruction. In this review, records from several cores are being compiled to look at regional variability in the response to abrupt climate change events and to trace latitudinal, longitudinal, and vertical gradients during the last glacial cycle. All of this is important information needed for model/data comparisons to validate how well climate models reproduce past conditions [e.g., Kjellström et al., 2010] and which local phenomena might have to be included in regional models to correctly represent the past conditions. Thus, this study aims to describe how hydrographic conditions changed along with the abrupt climate events and to relate them to the potential driving mechanisms. After having identified gradients during the last cycle, their existence at the same position and with the same intensity during previous glacial cycles will be tested.
Hereby, one focus will be on the glacial upper water column structure as this will allow identifying boundaries between subpolar- and subtropical-dominated waters with implications for the position of hydrographic fronts.

2. MODERN HYDROGRAPHIC SETTING

The western Iberian margin represents the northern part of the Canary/northwest African eastern boundary upwelling system, and its upper water column hydrography is marked by seasonally variable currents and countercurrents (Figure 1a). Upwelling and its associated features (Figure 1b) dominate the hydrography generally from late May/early June to late September/early October [Haynes et al., 1993] and is driven by the northward displacement of the Azores high-pressure cell and the resulting northerly winds. Intense upwelling on the western margin is linked to topographic features like Cape Finisterre, Cape Roca, and Cape São Vicente (Figure 1b) or submarine canyons [Sousa and Bri- caud, 1992]. The Lisbon plume, linked to Cape Roca, can either extend westward as in Figure 1b or southward toward Cape Sines. During intense upwelling events, the filament off Cape São Vicente extends southward and is fed by the Portugal Coastal Current (PCC) [Fiúza, 1984]. The more persistent feature, however, is an eastward extension of the filament along the southern Portuguese shelf break and slope [Relvas and Barton, 2002] where, when westerly winds prevail, the waters merge with locally upwelled waters (Figure 1b).

The Portugal Current (PC), which branches of the North Atlantic Drift off Ireland, consists of the PC per se in the open ocean and the PCC along the slope during the upwelling season. The PC advects surface and subsurface waters slowly equatorward [Perez et al., 2001; van Aken, 2001] and is centered west of 10°W in winter (Figure 1a) [Peliz et al., 2005]. The PC’s subsurface component is the Eastern North Atlantic Central Water (ENACW) of subpolar (sp) origin, which is formed by winter cooling in the eastern North Atlantic Ocean [Brambilla et al., 2008; McCartney and Talley, 1982]. The PCC, on the other hand, is a jet-like upper slope current transporting the upwelled waters southward [Alvarez-Salgado et al., 2003; Fiúza, 1984]. At Cape São Vicente, a part of this jet turns eastward and enters the Gulf of Cadiz [Sanchez and Relvas, 2003]. In the Gulf of Cadiz, it flows along the upper slope toward the Strait of Gibraltar [Garcia-Lafuente et al., 2006], then called the Gulf of Cadiz Slope Current [Peliz et al., 2007]. This current either forms an anticyclonic meander in the eastern Gulf of Cadiz or

Figure 1. (a) Map of the western Iberian margin with core sites and surface water circulation in winter as summarized by Peliz et al. [2005]. The location of core MD95-2039 (white circle), which is mentioned in the text but for which no data are shown, is also indicated. (b) NASA Aqua MODIS satellite-derived chlorophyll a picture (http://oceancolor.gsfc.nasa.gov/FEATURE/gallery.html) for 13 September 2005 showing the regions most affected by upwelling along the Iberian margin (lighter shades) and the extensive filaments off capes Finisterre, Roca, and São Vicente. Dots mark the same core locations as in Figure 1a (except for MD95-2039).