Rapid climate change: lessons from the recent geological past

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A B S T R A C T
Rapid, or abrupt, climate change is regarded as a change in the climate system to a new state following the crossing of a threshold. It generally occurs at a rate exceeding that of the change in the underlying cause. Episodes of rapid climate change abound in the recent geological past (defined here as the interval between the last glacial maximum, dated to approximately 20,000 years ago, and the present). Rapid climate changes are known to have occurred over time periods equal to or even less than a human lifespan: moreover, their effects on the global system are sufficiently large to have had significant societal impacts. The potential for similar events to occur in the future provides an important impetus for investigating the nature and causes of rapid climate change. This paper provides a brief overview of rapid climate change and an introduction to this special issue, which presents results generated by the palaeoclimatic component of the UK Natural Environment Research Council’s rapid climate change programme, called RAPID. The papers in the special issue employ palaeoclimatic proxy data-sets obtained from marine, ice core and terrestrial archives to reconstruct rapid climate change during the last glacial cycle, its subsequent termination and the ensuing Holocene interglacial; some papers also report new attempts to match the palaeoclimatic data to hypothesised causes through numerical modelling. The results confirm the importance of freshwater forcing in triggering changes in Atlantic meridional overturning circulation (MOC) and the close links between MOC and rapid climate change. While advancing our understanding of these linkages, the RAPID research has highlighted the need for further research in order to elucidate more specific details of the mechanisms involved.

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1. Introduction
Rapid, or abrupt, climate change may be described as change that occurs when the climate system is forced across a threshold to a new state and where the rate of change is faster than the underlying cause; moreover, the amplitude of change within the climate system may often be much greater than that in the forcing (Committee on Abrupt Climate Change, National Research Council, 2002). The rate at which rapid change may occur depends on the timescale under investigation, but over the recent geological past (e.g. the last glacial-interglacial cycle, ~110,000–0 yr BP) significant changes have occurred over decades and paced at approximately millennial scale. Scientifically, past rapid climate change events are intriguing, if challenging, subjects for research. Understanding how small triggers might initiate a dramatic climatic response can help gauge the importance of so-called ‘tipping points’ within Earth systems (e.g. Lenton et al., 2008) and the capacity of the system to respond abruptly to long-term (e.g. orbital) forcing.

Rapid climate change can also have major societal impacts. Unlike the relatively slow changes that unfold over orbital (105 years) or tectonic (≥106 years) time periods, dramatic climatic shifts are possible within less than a human lifespan. Palaeoclimatic and archaeological evidence points to sudden climate shifts as a possible contributor to the demise of certain ancient centres of human occupation. Well-known examples include the drought-driven destruction of some nodes of classical Mayan civilization in Central America (e.g. Hodell et al., 1995) and of the Akkadian civilization of Mesopotamia (e.g. Weiss et al., 1993), while rapid climatic cooling is considered one of the contributory factors to the abandonment of ancient Norse settlements (e.g. Orlove, 2005). Conversely, there is also concern that human impacts on climate may increase the risk of rapid climate changes occurring in the future (e.g. Williams, 2009), as discussed in more detail below. In short, rapid climate change is a topic of immense societal relevance.

The NERC RAPID research programme was set up to investigate and better understand the causes and impacts of abrupt climate change. The geographical focus of the programme was mainly, but not exclusively, on the North Atlantic basin with particular emphasis on...
the role of thermohaline circulation (THC) as a cause of abrupt climatic events. In the North Atlantic the THC is driven by differences in heating and cooling between low and high latitudes, and the subsequent sinking of cold and salty water to form North Atlantic Deep Water (NADW) in the Nordic and Labrador Seas. This leads to a maximum northward heat transport at 24°N of 1.2 ± 0.3 PW (Clark et al., 2002). This heat transport is largely responsible for the current broad-scale climatic regime over landmasses bordering the North Atlantic. Recent studies have shown that this circulation can be disrupted by relatively small inputs of freshwater at critical localities in the North Atlantic Ocean by suppressing the formation of NADW, with consequent severe climatic impacts in the North Atlantic region and beyond (see, for example, Vellinga and Wood, 2002). Although the precise mechanisms remain unclear, links between slowdown of the circulation and marked climatic variations have been detected in instrumentally-based time-series data spanning the past century (e.g. Street-Perrott and Perrott, 1990 and references therein) and reflected in palaeoclimatic records covering the last glacial-interglacial cycle (e.g. Broecker, 2000) (see later discussion). Concerns that THC may be vulnerable to change through increased, anthropogenically-induced CO2 emissions provide further impetus for strategic research on this subject. To that end, studies funded within the NERC RAPID initiative initially suggested a 30% weakening of North Atlantic meridional overturning circulation (MOC) at 25°N over the past few decades (Bryden et al., 2005), although such magnitude of change was subsequently found to be within the range of seasonal variability in MOC strength (Cunningham et al., 2007). For the moment, this leaves open the question of whether the MOC has or has not weakened in recent decades (cf. Balmaseda et al., 2007; Willis, 2010). Whatever the likely trend in MOC strength over the next decade or so, it nevertheless seems clear that Northern Hemisphere climate is governed by North Atlantic Ocean circulation to a significant degree (see IPCC, 2007).

The inclusion of a palaeoclimatic dimension to the NERC RAPID research programme stemmed from an acknowledgement that ‘palaeo-data’ (environmental time-series data-sets for past intervals derived from proxies for climate within so-called ‘natural archives’) make important contributions to our evaluation and understanding of the mechanisms of abrupt climate change. There are many examples of rapid climatic events that are reflected in time-series data based on instrumental records: these include, for example, abrupt episodes of drought in the American Midwest (1930s) and the West African Sahel (1960s to 1980s; Alley et al., 2003), warming of global surface temperature during the early 20th century (Delworth and Knutson, 2000), increased storminess in the NE Atlantic during the last 45 years (Alexander et al., 2005) and integrated precipitation records for the greater Alpine region covering the period 1800 to 2002 (Auer et al., 2005). Moreover, numerical modellers have turned their attention to the simulation of abrupt climatic events during the recent period (e.g. Crowley, 2000; Delworth and Knutson, 2000; Knutson et al., 2008) and more distant past (e.g. Clark et al., 2002; Sima et al., 2004; Wiersma and Renssen, 2006). However, instrumental records are too short to encompass the full amplitude of rapid climate change events reflected in geological records of the recent past. The largest abrupt climatic events during the Holocene warm stage exceeded the amplitude of those seen in modern observations, while climatic oscillations during the last glacial stage were even more pronounced. Furthermore, modelling efforts have met with mixed success (Held, 2005; Kiehl, 2007) and in any case their outputs need to be validated. Proxy records enable past climatic oscillations and their possible driving mechanisms to be viewed within the longer-term context, while providing a possible basis for validating model simulations (e.g. Hargreaves and Annan, 2009). Partly for these reasons, the very pronounced, millennial-scale, events of the last glacial cycle have become a major focus of palaeoclimatic research in recent decades. Yet the lower-amplitude changes that have characterised the Holocene are equally vital subjects for attention, not least because they occurred during a warm stage, the climate state in which humans currently live; they may therefore provide the most relevant analogues for gauging the likely amplitude and impacts of future abrupt climatic events.

The purpose of this special issue is to present some of the results of palaeoclimatic research undertaken within RAPID and in RAPID-related projects. In addition to the presentation of individual palaeoclimatic records, the papers address problems of comparison and synchronisation between multiple archives, the use of modern observational data to help constrain interpretations of the palaeo-data, and data–model comparisons, as expanded later.

2. The NERC RAPID programme

In 2001 the UK Natural Environment Research Council (NERC) funded the RAPID (Rapid Climate Change) programme to investigate and understand the causes of rapid climate change, with a main (but not exclusive) focus on the role of the Atlantic Ocean’s thermohaline circulation (THC). In this context, rapid change was considered to be that occurring over periods of the order of 10–20 years. Using present-day observations, palaeo-data and a hierarchy of numerical models, RAPID was intended to improve understanding of the roles of the THC and other processes in rapid climate change, and of the global and regional impacts of such change (Srokosz, 2003). The motivation for the programme was drawn from a growing realization that future human-induced climate change could lead to a slowdown of the THC (Broecker, 1997; IPCC, 2001), with a significant impact on north-west European climate, and that palaeo-records showed evidence of such slowdowns and even shutdowns of the THC in the past (Broecker, 2000; Committee on Abrupt Climatic Change, National Research Council, 2002). RAPID ran from 2001 to 2008, with the majority of projects carrying out studies during the period 2003 to 2008. The programme had strong international scientific and programmatic links with Germany (Max Planck Institute), the Netherlands (Netherlands Organisation for Scientific Research), Norway (Research Council of Norway) and the USA (National Science Foundation and National Oceanic and Atmospheric Administration), including joint review and funding of projects. A summary and an overview of the programme were published in 2008 (NERC, 2008).

A key element of the programme was to establish an observing system for the THC (more correctly, for the MOC) in the North Atlantic – a challenging task. Ship-based trans-Atlantic measurements, which had been carried out sporadically (5 times in 50 years), had suggested that the MOC might be slowing (Bryden et al., 2005), but the uncertainty on such estimates was thought to be large due to the (then unknown) natural variability of the MOC. The observing system and initial results from it are described in a pair of papers (Cunningham et al., 2007; Kanzow et al., 2007) and these show that the natural variability of the MOC is large and suggest that decadal scale measurements are required to detect changes of the type predicted by IPCC class climate models (IPCC, 2001, 2007).

When RAPID started, there were very few observations of the contemporary workings of the THC. A palaeo-component was therefore considered important for providing additional insight into how the climate system had both affected, and responded to changes in, THC activity in the past. RAPID set the following goals for the palaeo studies:

1. To construct well-calibrated and time-resolved palaeo-data records of past climate change, including error estimates, with
a particular emphasis on the quantification of the timing and magnitude of rapid change at annual to centennial timescales; 
(2) to understand, using model experimentation and data (palaeo and contemporary), the atmosphere’s response to large changes in Atlantic northward heat transport, in particular changes in storm tracks, storm frequency, storm strengths, and energy and moisture transports; and
(3) to use both instrumental and palaeo-data for the quantitative testing of the capability of numerical models to reproduce climate variability and rapid changes on annual to centennial timescales, and to explore the extent to which the data might yield direct information about the THC and other possible rapid changes in the climate system, as well as their impacts.

From the palaeo studies, RAPID aimed to deliver:

(1) improved palaeoclimatic data-sets with associated error estimates and sufficient temporal resolution to identify variability and rapid change on annual to centennial timescales; 
(2) improved quantitative methods for using palaeoclimatic data to test numerical climate models; and
(3) an assessment of the ability of climate models to simulate rapid change and the role of THC variability in such change.

Of the 38 projects funded under RAPID, 14 were palaeoclimatic studies or had a significant palaeoclimatic component (see NERC, 2008). Although not the sole focus of these research projects, a major common theme for a number of them was the so-called 8.2 ka event (Alley et al., 1997), selected for special study because it is the youngest common theme for a number of them was the so-called 8.2 ka event (Dansgaard

More focused on cooling events rather than warmings. The effects of

by more gradual cooling; we note however that RAPID as a whole was manifest in some parts of the globe in a way that can indeed be used here. However, within the last glacial period, there was also a 5 ka) in relation to the overall record, they are not rapid in the sense of the last interglacial, the persistence of DO cycles in previous glacial has been inferred from analogous patterns of methane concentration and Antarctic temperature variability observed in records spanning those periods.

The transition from the last glacial to the warm Holocene period is also punctuated by a DO cycle (in the Northern Hemisphere this comprises the Bolling–Allerød warm period, the Younger Dyras cold period, and the rapid final warming into the Holocene – see Rasmussen et al., 2006), and indeed it seems likely that the mechanisms behind millennial-scale climate variability during the glacial also played a significant role in inducing terminations of the glacial stages (Wolff et al., 2009; Denton et al., 2010).

The mechanism generally considered to be at play in these events involves changes in the thermohaline circulation driven by adjustments in the amount and rate of freshwater input to the North Atlantic. In short the “bipolar seesaw” mechanism (Stocker and Johns, 2003) requires input of freshwater from icebergs or lake drainage around the ice sheet margins; this changes the density structure in crucial sinking regions such that the MOC weakens or shallows, reducing THC flux. Less heat is therefore transported to high northern latitudes (driving the northern temperature and atmospheric circulation response), while the Southern Ocean warms (the Antarctic response). After some period the circulation resumes its strong mode, and a rapid northern warming occurs, allowing the Southern Ocean to cool. Direct evidence about the past strength of the MOC is difficult to obtain (e.g. Lynch-Stieglitz et al., 2007) although it does appear to have weakened at least during the cooler phases of millennial variability during the last termination (Gherardi et al., 2005).

A major difficulty with the interpretation of palaeo-data records as far as RAPID’s stated aims are concerned is that of synchronising the records and reconstructing past events with an adequate temporal resolution. Annual layering in the Greenland ice sheets allows these ice-core records to be analyzed at an annual resolution. Counting the layers from the surface downwards entails cumulative analytical errors that increase with depth (age), because layers thin with depth and become less distinct; the counting errors are of the order of 100 years at 12.0 ka and 500 years at ca. 21 ka BP (Lowe et al., 2008). However, the errors are much smaller for estimates of the durations of short intervals represented in the ice cores, which is why the durations of DO and other abrupt climatic events can be estimated with a decadal to sub-decadal resolution (Vinther et al., 2006).

Most geological archives cannot be dated with this degree of precision, which limits their potential for reconstructing palaeoenvironmental
event at timescales of use to climate modellers, and for making
precise comparisons with ice-core records. There are approaches that
can reduce the uncertainties in palaeo-reconstructions, although
these have been under-exploited hitherto. These include the study of
annually-laminated and marine sediments (varves), annual
growth lines in fossil trees and cave calcite (speleothem), improved
calibration procedures for radiocarbon-based chronologies, and
synchronisation of records using isochronous markers, such as
volcanic ash layers. Several of the papers in this volume show how
some of this potential can be realised, enabling more confident
conclusions to be drawn concerning the rate and regional synchronicy
of past events.

Some of the research funded by the RAPID programme and
reported in this volume that addressed the rapid events of the last
termination has delivered important information regarding the
sensitivity of ocean circulation and the wider impacts of circulation
changes. However, an obvious contextual issue is that glacial and
termination events occurred when very large ice masses occupied the
northern continents, when the Earth experienced a glacial baseline
climate state. While concern about possible future rapid climatic
responses to variations in MOC strength is clearly bolstered by the
knowledge that such changes have already occurred, the baseline
climate state is now very different. Hence the mechanisms that may
drive future climate changes will have to be induced by other means,
perhaps through changes in temperature, precipitation and more
subtle meltwater inputs. For this reason, the greatest interest in RAPID
was in rapid climate changes during the Holocene, when an
interglacial baseline state prevailed. The prominent 8.2 ka event was a
particular focus, and is discussed elsewhere in the volume. While
still apparently triggered by a freshwater input from a retreating ice
sheet, it nevertheless serves as a template and modelling target for
climate changes induced by MOC change within a climate similar to
that of today. The collection of quantitative data relating to this event,
combined with the use of models to simulate it, was therefore a strong
priority. Smaller and less abrupt climate changes seen elsewhere in
the Holocene are of uncertain origin: the possibility exists that
changes in THC were involved, and some of these were also
considered in RAPID.

4. Discussion

Like the NERC RAPID programme itself, the papers in this special
issue focus particularly, although not exclusively, on the North
Atlantic region. Collectively, they employ a range of palaeoclimatic
proxy data types from marine and terrestrial archives as well as
numerical modelling, to investigate rapid climate change including
the temporal structure of specific events, the geographical distribu-
tion of the climatic impacts, and the potential causes. They address
timescales from the last glacial cycle through the glacial–interglacial
transition (last termination) to the late Holocene.

As discussed earlier, the last glacial cycle was characterised by
large-amplitude climatic instability. However, as Jung and Kroon
(2011-this issue) show, this instability has varied in amplitude during
the last glacial. Their benthic foraminiferal δ18O records from the
deepestwater North Atlantic and Intermediate-water Indian Ocean show
that the greatest amplitude events, characterised by what they
describe as classic ‘Dansgaard–Oeschger’ type, occurred during
intervals of intermediate climate, i.e. in marine isotope stage (MIS)
3. By comparison, the full glacial interval (MIS-2) showed millennial-
scale oscillations of reduced amplitude, Bigg et al. (2011-this issue)
undertook a data–model comparison of Heinrich Episodes, episodes of
ice-margin collapse during the last glacial stage, when ‘armadas’ of
icebergs swept across the North Atlantic, destabilizing the region (see
Hemming, 2003). In particular, they investigated the rates of change
and of post-event recovery in MOC, as well as other aspects of North
Atlantic climate change. Their work confirms the role of melting of the
Laurentide ice sheet in Heinrich events, but reveals varying meltwater
routeways and regional climatic impacts between different events.

Given the scientific interest in abrupt climate changes during the last
deglaciation, it is perhaps unsurprising that a number of papers in this
issue focus on that interval. Stanford et al. (2011a-this issue) provide
a useful overview of the modern hydrography and circulation features of
the northern North Atlantic, before reviewing the results of recent
hydrographic surveys of the sea bed in the area of the Eirik Drift, to
the south of Greenland. Their investigations reveal the complexity of the
western boundary currents that skirt Cape Farewell, but also how the
effects of past freshwater forcing can be inferred from studies of the
sediments deposited by those currents. The data collated thus far
indicate that the ocean climate system responds in a non-linear manner
to freshwater forcing. Thornalley et al. (2011-this issue) examined
changes in ocean salinity and temperature using paired isotopic and
elemental analyses of planktonic foraminifera from a site located to the
south of Iceland. Their study covers the interval spanning the last glacial
maximum (MIS-2) as well as the last deglaciation interval. Centennial-
scale cooling and ocean freshening events during this interval are also
considered to have been initiated by meltwater events from the
Laurentide ice sheet, but regulated by background shifts in climate
to over this period. Hall et al. (2011-this issue) investigated past alterations
in deep-ocean bottom-current speed, as indicated by variations in grain-
size of sediments accumulating on the floor of the western subtropical
North Atlantic. Their work shows a complex interplay between
deepestwater sourced from the Southern Ocean and that originating
from the North Atlantic during the last deglaciation. Stanford et al.
(2011b-this issue) focused in detail on sea level records of the last
deglaciation, and in particular the large-magnitude meltwater event
known as Meltwater Pulse 1a (mwp-1a), which apparently led to a
marked increase in the rate of sea-level rise during the last termination,
but which has a disputed relationship to climate variability owing to
dating uncertainties. A statistical re-evaluation of available sea-level
records suggests that it is possible to rationalise the different records,
and that the meltwater pulse was less sharply defined than has been
assumed. Their findings have important implications for our under-
standing of the relationship between meltwater pulses and MOC
strength. MacLeod et al. (2011-this issue) examine the evidence of
the Younger Dryas Stadial on land, specifically in the records of ice advance
in Scotland. It has long been known that the late glacial stadial led to the
re-advance of glaciers in upland British Isles. However, dating
uncertainties often obscure the detailed relationship between climate
glacial and glacier dynamics. Using an accurately and precisely dated
proglacial varve record, the authors show for the first time that
maximum ice advance in the Loch Lomond area occurred very late in the
stadial. The results are helping to quantify the lag time between MOC
variations and glacier response. Austin et al. (2011-this issue) present a
reconstruction of marine radiocarbon reservoir ages through the
Younger Dryas from the NE Atlantic and demonstrate that a weakening
of the North Atlantic’s overturning circulation, with which the Younger
Dryas and other intervals of abrupt climate change appear to be
associated, can significantly affect ocean–atmosphere carbon exchange.

The remaining papers deal with the Holocene warm stage.
McDermott et al. (2011-this issue) deal with oxygen-isotope values
recorded in European speleothems. Despite the abundance of previously
published speleothem research, this is the first time that spatial
gradients have been examined across Europe. The authors show that
speleothem δ18O values are closely correlated with longitude, but that
the gradient of the relationship decreased from early to mid-Holocene, a
pattern that reflects changing atmospheric circulation, which in turn
was controlled by orbitally-forced insolation. Daley et al. (2011-this
issue) summarize RAPID-funded and RAPID-related studies of isotope
records covering the 8.2 ka cooling event. Their analysis of well-dated
terrestrial sites around the North Atlantic margins revealed no clear
spatial variation in the timing of the cooling event, pointing to a
simultaneous climatic impact around the circm-North Atlantic region.

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In a parallel paper, Tindall and Valdes (2011-this issue) describe the results of modelling experiments of the 8.2 ka cooling event, undertaken using the UK Hadley centre model HadCM3. Simulations of temperature, precipitation amount and precipitation oxygen-isotope ratios are broadly consistent with the palaeoclimatic data, as discussed by the authors and in Daley et al. (2011-this issue) although concordance between them was better for the strength of the climate signal than for its duration, which was significantly shorter in the model simulations. Miller et al. (2011-this issue) and Farmer et al. (2011-this issue) provide Holocene palaeoceanographical records. The former examined diatom assemblage data obtained from a subpolar North Atlantic core located on the Gardar Drift. Diatoms are phytoplankton and so are sensitive to near-surface water mass characteristics, including temperature. The study shows that there have been significant changes in water mass properties during the Holocene, although the 8.2 ka event is characterised as part of a broad cooling trend between 9 and 7 ka rather than as an abrupt cold event. Farmer et al. (2011-this issue) present a Holocene record of variations in oxygen isotope and Mg/Ca ratios in planktonic foraminifera from the same core. Analyses of surface-dwelling and thermocline-dwelling species provide evidence for changes in the structure of the ocean water column at this location during the Holocene, and allow its relationship to abrupt cooling events to be assessed. Their results show that the surface to subsurface temperature contrast has increased during the Holocene, although abrupt cooling events are evident in both records, suggesting a common forcing throughout the water column. Finally, Baker et al. (2011-this issue) present a stable isotope record obtained from a speleothem column in a cave in the north of Scotland, which developed over the past 1000 years. They demonstrate a record of North Atlantic variability within the resulting isotopic time series.

5. Conclusions and future work

The results of the palaeo-component of RAPID have provided new information about the details of rapid climate change during both the last glacial stage and the Holocene. This new information has included details about the nature, structure and duration of individual events. These new studies have confirmed the linkages between meltwater forcing, changes in MOC and rapid climate change events. However, the results show that there are no simple cause and effect relationships between freshwater forcing and climatic response, so the details of the mechanisms leading to variations in MOC strength remain elusive. Despite improvements in the chronologies for the palaeoclimatic time series presented here, part of the problem in investigating the causes of such short-duration episodes lies in dating uncertainties. Improving age models will remain one of the challenges for the future. Comparison of model simulations and palaeo-data for abrupt events provides a challenging test of model performance. Crucially, while we can now define the strength and timing of a number of events, and hypothesise about a cause involving freshwater impacts, the evidence about changes in ocean circulation and water masses induced by such causes remains weak in most cases; this critical intermediate evidence would greatly aid confidence in modelling events and applying the results to future change. Nonetheless, data–model comparisons have provided some promising results; a greater abundance of palaeo-data would further such endeavours, although this might include re-evaluation of existing data-sets as well as further new palaeoclimatic research. The most recent IPCC report (2007) predicts that the slowdown of the MOC over the next 100 years will be between 0 and 50% over the range of IPCC models. Therefore, there is a continuing need for data – both palaeoeclimatic and present day – to test and refine models and to narrow that range of uncertainty.

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