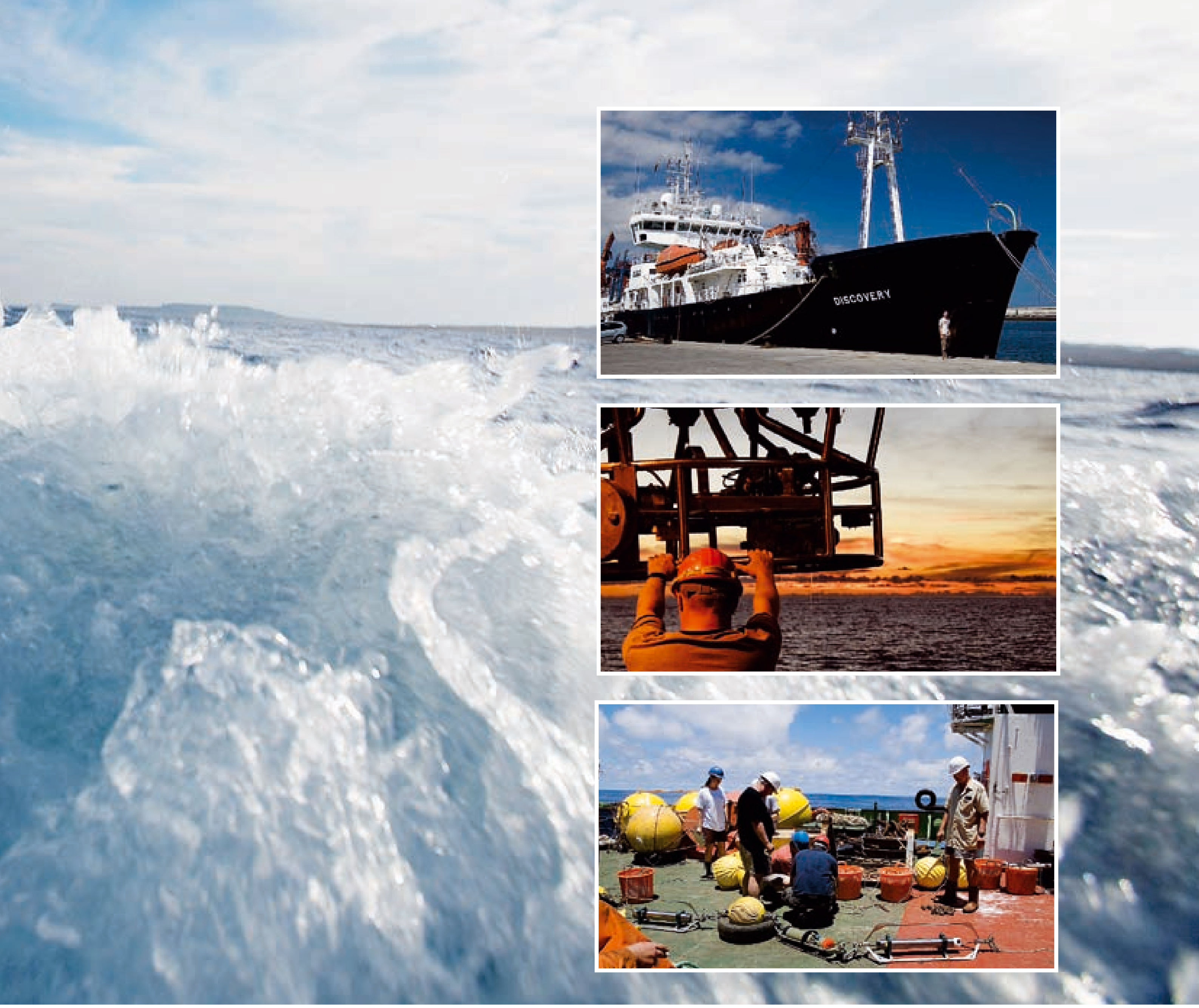
NATURAL ENVIRONMENT RESEARCH COUNCIL

RAPID CLIMATE CHANGE

The Rapid Climate Change programme

Contents

RAPID CLIMATE CHANGE



PAST PRESENT FUTURE

Executive summary

In 2001, the Natural Environment Research Council set up the £20 million Rapid Climate Change programme to investigate the fundamental processes that cause climate to change abruptly.

Scientists and engineers from the Rapid Climate Change programme deploying the array of scientific instruments across the Atlantic Ocean at latitude 26.5°North.

Introduction

Society is performing a giant experiment on humanity's life-support system. Pre-industrial atmospheric carbon dioxide concentrations were 270 parts per million (ppm): in 2008, they reached 385ppm. They are currently increasing by 2ppm a year. The world is approaching the 450ppm limit widely thought necessary to avoid dangerous and possibly irreversible climate change. To borrow a phrase from the US physicist Richard Feynman, tickling the dragon's tail is a dangerous game: the consequences may be rapid and irreversible. It is of the greatest importance that we improve our understanding of the planet's climate system and the likelihood of abrupt changes to it. Nations are not responding quickly to the risk of global warming but the UK research community is taking an international lead in this area.

The oceans and rapid climate change

The oceans control Earth's climate over decades to centuries, so understanding how they are changing is the key to choosing appropriate climate change mitigation and adaptation measures. Many estimates of future change are based on forecasts from climate models that predict gradual climate responses, more or less proportional to the steadily increasing greenhouse gas concentrations. However, ice and sediment core records reveal that in the past climate has changed abruptly – in as little as 10 to 20 years. This is too fast to implement prevention strategies and could make adaptation extremely expensive. Quantifying and understanding the ocean processes that cause climate to change abruptly – and how they do this – is what spurred the Natural Environment Research Council to set up the £20 million Rapid Climate Change programme.

From the start of the programme in 2001, a key focus was a better understanding of the ocean physics in the North Atlantic. Previous research has demonstrated that abrupt climate changes in the past can be linked to changes in the overturning circulation known to oceanographers as the Atlantic Meridional Overturning Circulation (AMOC), and nick-named the Atlantic Heat Conveyor because it acts as a conveyor belt transporting

heat northwards. This is part of a much larger global ocean circulation system.

Before the programme, computer models had shown that this heat conveyor produces a substantially warmer climate in western Europe than would otherwise be the case. The models also show that increasing greenhouse gases in the atmosphere may cause the circulation to slow, and according to the UN's Intergovernmental Panel on Climate Change Fourth Assessment Report (2007) it is very likely that the Atlantic conveyor will slow down in the 21st century. As a result, less heat would reach western Europe. While the increased greenhouse gas concentrations would still cause a net warming, the local, seasonal and less predictable effects of a slowdown give cause for concern. In 2006, an independent report from the consultants Pricewaterhouse Coopers which analysed the economic impact of an abrupt shutdown of the circulation, estimated that unforeseen changes in the conveyor leading to rapid and unexpected shifts in climate, could cost the world economy billions of pounds. But before the Rapid Climate Change programme, quantification and understanding of the Atlantic overturning circulation relied on sporadic measurements and theoretical results.

In 2005, an analysis published in the journal *Nature*, based on five snapshots of the circulation taken between 1957 and 2001, indicated a possible slow-down of the Atlantic conveyor by up to 30 per cent. Crucially, there were no data on daily, monthly or annual natural variability. If this information were available, it would have determined if such variability was contaminating estimates of long-term change. All this has now changed. The centre-piece of the Rapid Climate Change programme is continuous daily monitoring using a system of moorings across the entire Atlantic basin, from the west coast of Africa to Miami. The array of scientific instruments is vital for researchers to make better predictions of future climate changes and their impacts. The success of the pilot scheme (2004-2008) has ensured the future of the array until 2014.

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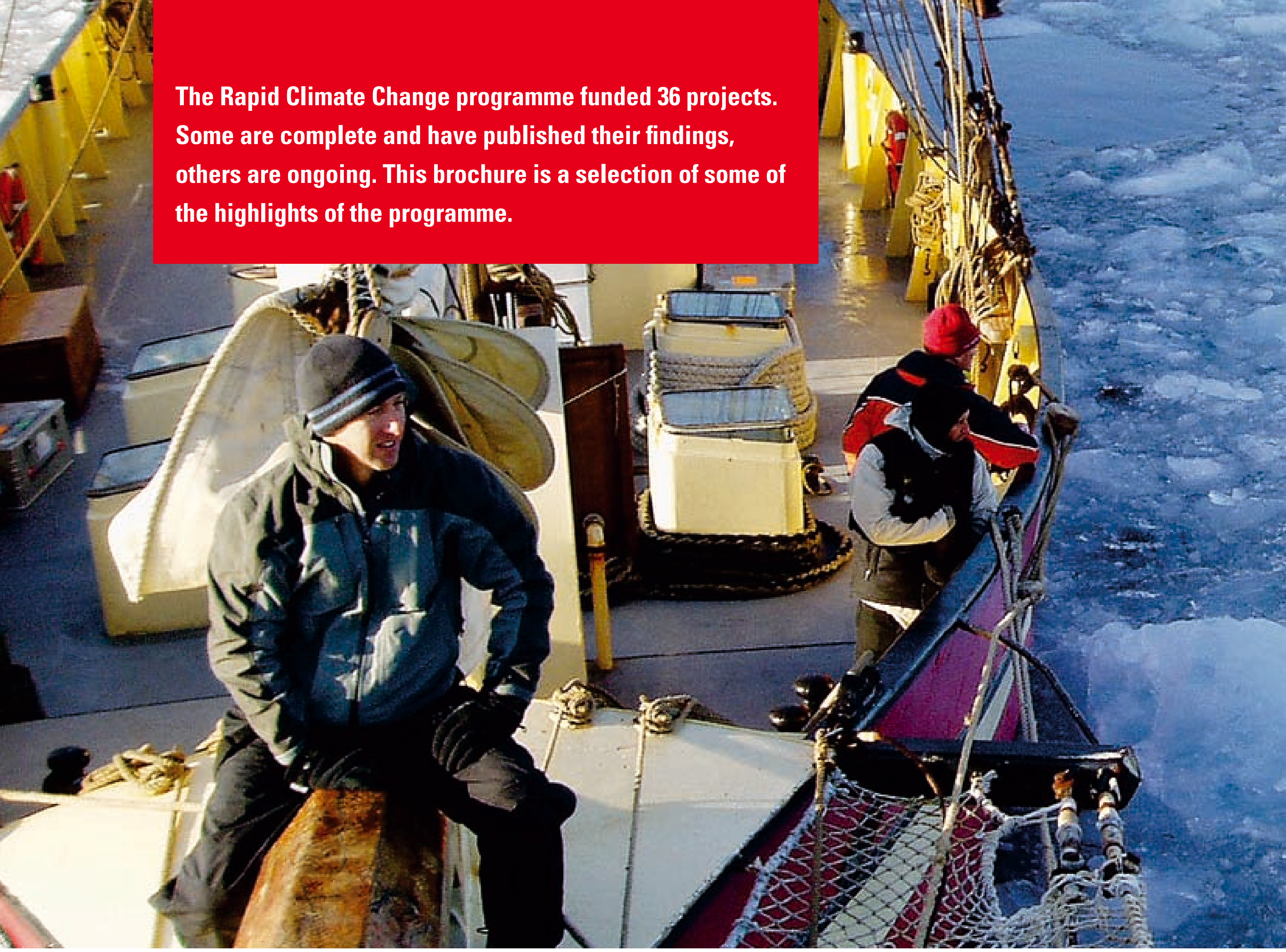
The Rapid Climate Change programme funded 36 projects. Some are complete and have published their findings, others are ongoing. This brochure is a selection of some of the highlights of the programme.



The bigger picture

For a complete understanding of how climate can change rapidly, scientists need to combine information on the past, present and likely future. Researchers on the Rapid Climate Change programme have focused on past abrupt climate changes, particularly 8200 years ago, the current state of the overturning circulation, and improving climate models based on their findings and new ways of using model results.

Outcomes

- The first continuous daily measurements of the Atlantic Meridional Overturning Circulation – the Atlantic Heat Conveyor.
- The first evidence of large sub-annual natural variability in the strength of the Atlantic conveyor.
- Significantly increased knowledge of the nature and causes of a major abrupt change in climate 8200 years ago.
- Improved modelling of rapid climate change.

From pilot scheme to decadal measuring system

One clear outcome of the Rapid Climate Change programme is the internationally acknowledged need for longer-term observations of the Atlantic conveyor, beyond the four-year pilot scheme. The Natural Environment Research Council has committed £16.1 million to ensure a further six years of continuous measurements, up to 2014. Matching funds have also been committed by the National Science Foundation and the National Oceanic and Atmospheric Administration in the United States to complete the transatlantic monitoring array. This follow-on programme is called Rapid WATCH (Will the Atlantic Thermohaline Circulation Halt?). The Rapid WATCH programme is working closely with the Met Office Hadley Centre and policy-makers to ensure the measurements are used effectively, particularly in decadal prediction systems.

Pictures courtesy Capefarewell.com

International partners

The programme has driven international cooperation and co-funding partnerships with the National Science Foundation and the National Oceanic and Atmospheric Administration in the USA, the Netherlands Organisation for Scientific Research and the Norwegian Research Council.

Science into policy

The programme has forged close relationships with a wide variety of policy-makers and stakeholders and used these links to communicate key scientific results clearly and effectively.

Inspirational outreach

With the publication of major research papers, the public profile of the Rapid Climate Change programme has been very high. The team has worked closely with writers, journalists, film-makers, poets and artists, and specifically with the Cape Farewell project, to engage with a broad audience.

PAST PRESENT FUTURE

Understanding the past

Rapid cooling 8200 years ago

Rapid climate change is something that has captured the imagination of the public and governments alike. But why are scientists worried about abrupt climate change? Quite simply because it has happened before.

Assembling the new 18-metre core barrel on board the Royal Research Ship Charles Darwin *between Scotland and Newfoundland, July 2004.*

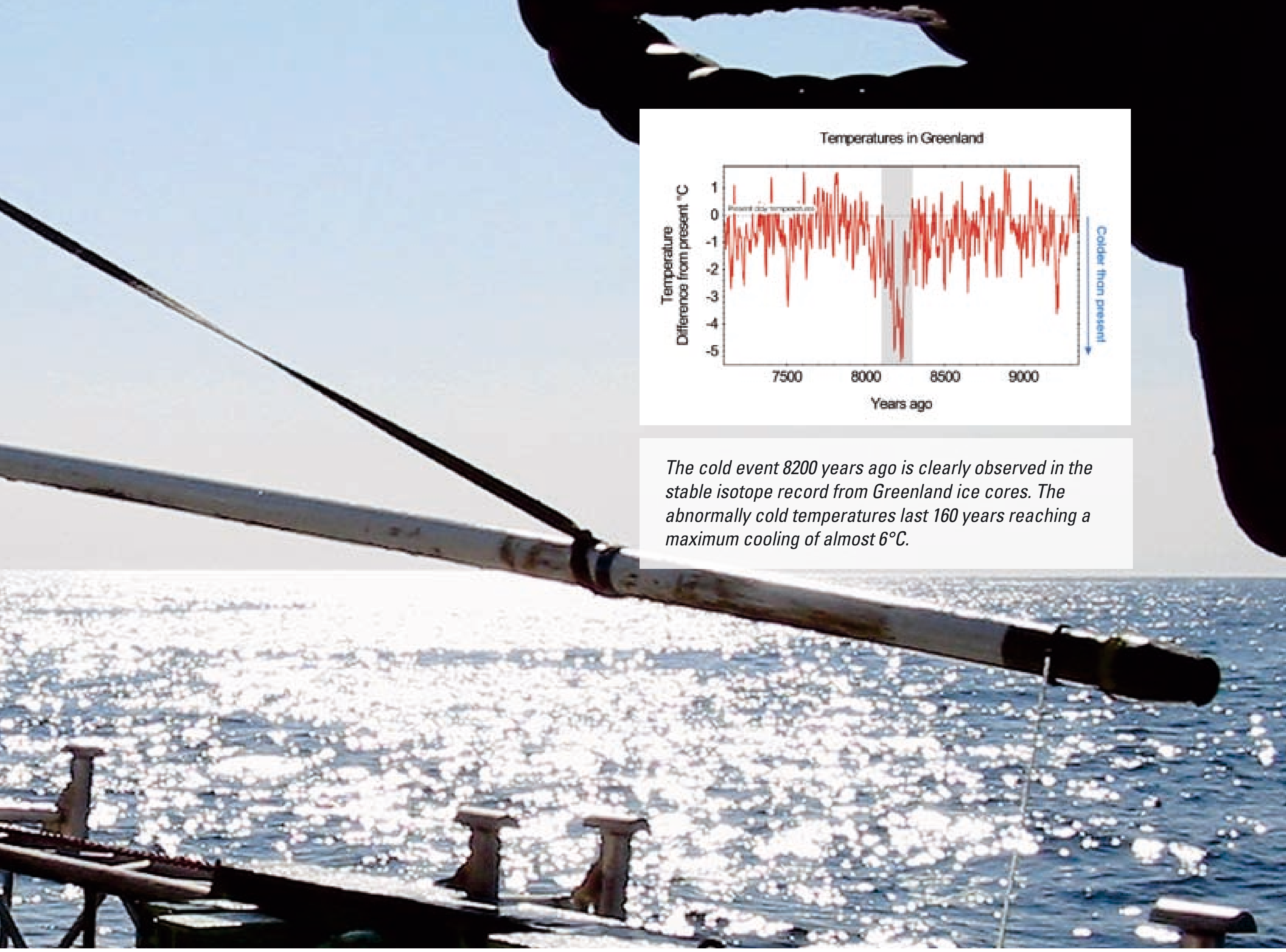
There have been times in the Earth's history when dramatic shifts in temperature of almost 15°C have occurred in a matter of decades. The largest of these events took place during the glacial period (110,000-12,000 years ago), when the world looked very different from today. Vast ice sheets covered much of North America and Europe. However, even the present-day warm period, known as the Holocene, has experienced dramatic and rapid changes in climate across northern Europe and the UK within a human lifespan.

The most prominent climate shift during the Holocene was a rapid cooling 8200 years ago. Scientists have found evidence of cooling in the Pacific and Tasmania as well as northern Europe. The cause, or at least part of it, is attributed to the final collapse of the North American and Scandinavian ice sheets as global temperatures rose following the end of the last ice age. Large volumes of fresh water swept into the North Atlantic, disturbing the sensitive ocean conveyor. Warm water currents from the tropical Atlantic slowed down, never reaching higher latitudes. This led to extreme cold and dry conditions across much of the North Atlantic region with temperatures in Greenland dropping almost 6°C.

The possibility of future abrupt climate change is dependent on the warming and freshening of sensitive areas of the North Atlantic. The event 8200 years ago shows how sensitive the ocean circulation is to changes in conditions, and how a change in the circulation can affect climate.

What is the evidence?

Scientists find evidence of past climate change in a range of different palaeo records such as ice cores, lake sediments, ocean sediments and speleothems (stalagmites and stalactites). These records contain signals of environmental change, such as the amount of snowfall in a year or the amount of organic matter (diatoms and other plankton) deposited on the seafloor. Researchers on the Rapid Climate Change programme collected a range of palaeo records from across the



The cold event 8200 years ago is clearly observed in the stable isotope record from Greenland ice cores. The abnormally cold temperatures last 160 years reaching a maximum cooling of almost 6°C.

Key findings

- Analysis revealed extreme cold and dry conditions across the North Atlantic (Newfoundland, the UK and northern Europe) 8200 years ago.
- Greenland temperatures were almost 6°C colder than present day.
- The shift to colder temperatures took only a few decades and lasted approximately 160 years.
- Ocean records reveal colder and less saline surface waters in the North Atlantic and a slowdown in the Atlantic Heat Conveyor.
- A rush of meltwater into the North Atlantic caused the slowdown and colder conditions.
- Improved model simulations predict that relatively small increases in fresh water could affect the ocean conveyor.

Lake sediments from the ISOMAP-UK (ISOtope calibration and MAPping) project
Liz Fisher and Jim Marshall collect samples from Hawes Water, north-west England.

North Atlantic region to investigate the cold event 8200 years ago.

North Atlantic gets fresher when the ocean heat conveyor slows down

Sedimentary records from ocean cores drilled in the North Atlantic as part of the Rapid Climate Change programme show a freshening of the North Atlantic surface waters consistent with theories that large volumes of glacial meltwater flooded the North Atlantic. Scientists believe that this was probably caused by rapid flooding from an ice-dammed lake in North America. The isotopic compositions of plankton contained in the sediments reveal a large decrease in the salinity and temperature of the North Atlantic prior to the cooling observed from land-based palaeo records.

Analysis of the ocean sediments for nutrients, biological content and grain size indicates that the southward flow of North Atlantic deep water, which drives the North Atlantic Heat Conveyor, weakened following the influx of cold fresh water from the disintegrating ice sheet. The slowdown in the conveyor lasted approximately 100 years.

Colder atmospheric temperatures

The surface temperature of a particular location can be determined from the isotopic composition of snow or rainfall. In the polar regions (or areas at altitude) the record of past precipitation is contained in the snow and ice, which remains all year round, and can be retrieved by drilling ice cores. Greenland ice cores provide a record of past temperatures dating back several thousand years. Investigation of ice core sections from the Greenland Ice Core Project (GRIP) revealed that 8200 years ago, temperatures in Greenland were almost 6°C colder than present day, and these cold conditions lasted 160 years.

Scientists can also reconstruct temperature changes from the isotopic composition of calcareous deposits in caves

PhD student Tim Daly analysed the stable isotopes of oxygen and hydrogen in the cellulose of sphagnum moss taken from peat samples in Newfoundland. This highlights variations in source water and hence changes in climate and atmospheric circulation during the 8200-year event.

(speleothems – stalagmites and stalactites), the skeletal remains of ocean- and lake-dwelling creatures, and even mosses from peat bogs. These methods showed that temperatures in northern Europe dropped dramatically during the cold event. Lake sediments from north-western England show a decrease of 1.6°C lasting approximately 160 years, while sphagnum moss from peat bogs in Newfoundland reveal similar cold conditions on the east coast of North America.

Could it happen again?

Evidence from ocean records confirms the likely cause of the cold event is the catastrophic flooding of fresh water into the North Atlantic following the collapse of the North American ice sheet. The results verify that dramatic changes in ocean circulation can occur in short timescales and have major impacts on the climate of the North Atlantic region.

The information obtained from the palaeo records has been used to assess whether computer models can correctly predict the influence of freshwater influx on the ocean conveyor and, ultimately, on climate. Models reflect the speed of change observed in the different environmental records but also show that even a relatively modest flow of fresh water can affect the ocean conveyor.

The Atlantic array

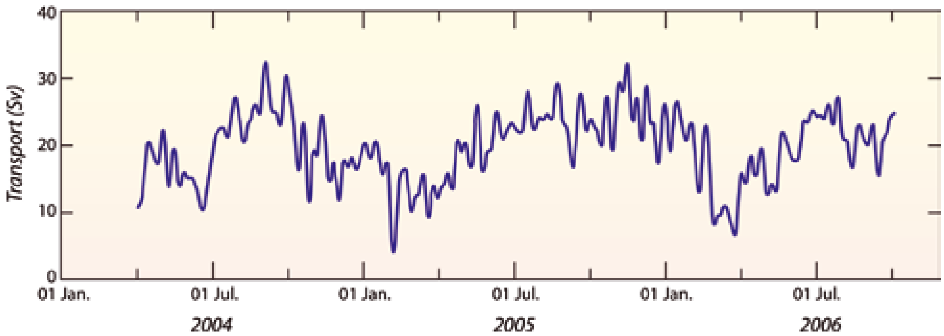
The first continuous Atlantic-wide daily measuring system

Until 2007, scientists had no precise knowledge about the daily, weekly and monthly variability of the Atlantic Meridional Overturning Circulation, or Atlantic Heat Conveyor. But they know the circulation has been prone to sudden and dramatic shifts in the past.

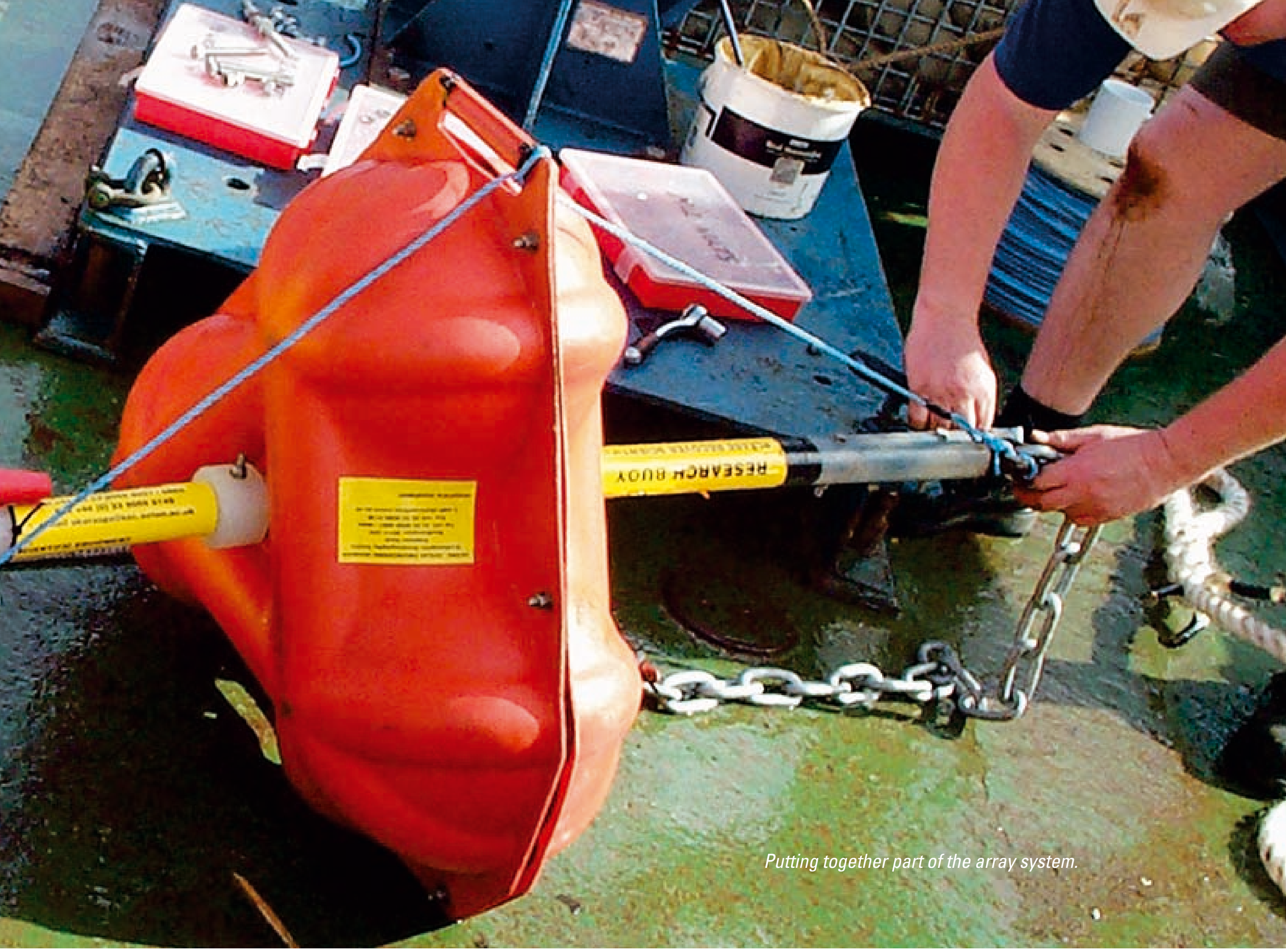
In 2004, scientists installed the first array of scientific instruments across the Atlantic Ocean at latitude 26.5° North.

Why 26.5°N?

This is where the overturning circulation is most vigorous. North of this latitude most of the heat is given off to the atmosphere where winds carry the heat north-eastwards towards Europe: one million million kiloWatts of heat are released to the atmosphere every second over the North Atlantic Ocean. Scientists wanted to measure the overturning circulation where it carries the maximum heat northwards, because long-term changes there can have a significant impact on Europe's central heating system.



The first continuous, daily measurements of the Atlantic Meridional Overturning Circulation. (The strength of ocean currents is measured in Sverdrups (Sv), a million cubic metres per second.)

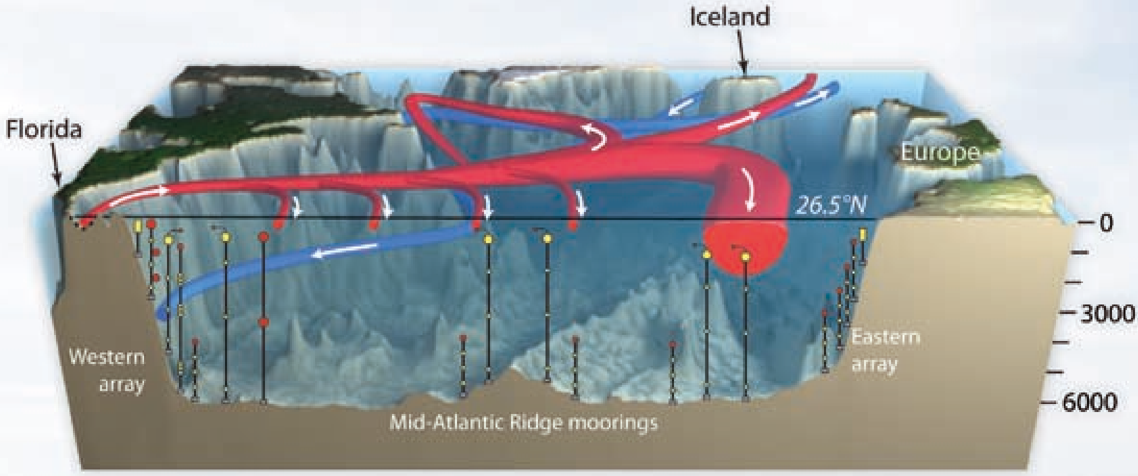


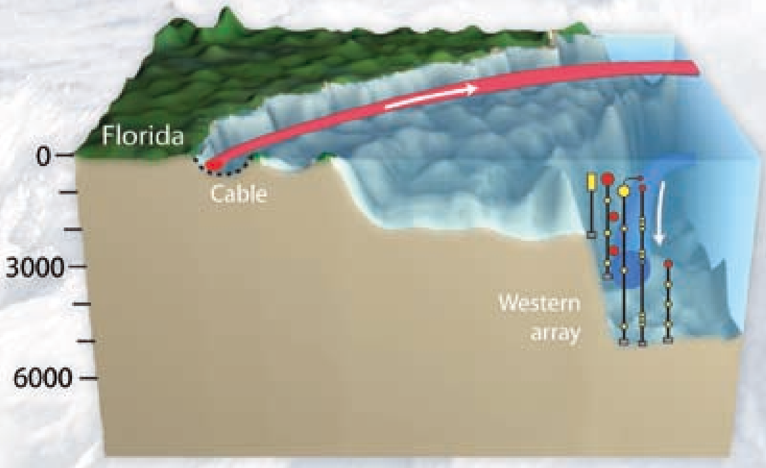
Putting together part of the array system.

Key findings and achievements

- The Atlantic array pilot scheme: it is now possible to make continuous, daily measurements of the strength and structure of the Atlantic Meridional Overturning Circulation or Atlantic Heat Conveyor.
- The system made its first observations on 29 March 2004 and has been in continuous operation since then.
- The monitoring system has already significantly advanced knowledge of the North Atlantic circulation. 'Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5°N', *Science*, 317, 935-38;'Flow compensation associated with the Meridional Overturning Circulation at 26.5°N in the Atlantic', *Science*, 317, 938-9 (August 2007). The journal *Nature* listed both papers in its top ten papers for 2007.
- The year-long average circulation from 29 March 2004 to 31 March 2005 is 18.7±5.6 Sverdrups (Sv)*. Interannual changes in the circulation can be monitored with a resolution of 1.5 Sv.
- Three key components of the circulation (Gulf Stream, wind-driven surface circulation and transatlantic circulation) all contribute significantly to the variations in its strength.

**One Sverdrup = a million cubic metres per second.*





The largest single investment in the Rapid Climate Change programme is an array of scientific instruments stretching across the Atlantic Ocean at latitude 26.5°N, from the west coast of Africa to Miami.

Measuring an ocean-wide circulation

The Atlantic Meridional Overturning Circulation is complex. There are three main components: the Gulf Stream, wind-driven surface circulations and a large transatlantic circulation driven by heat and salinity. The new system measures all these components separately.

Transatlantic circulation

An array of scientific instruments attached to 22 moorings measure depth, temperature, salinity and pressure on the continental slopes off the Bahamas, off Morocco and on either side of the mid-Atlantic Ridge. These are deployed and recovered annually and allow the team to continuously observe the strength and structure of the transatlantic circulation at 26.5°N.

At the western boundary, off the east coast of the US, the researchers, with US colleagues, directly measure the velocity of the deep, cold, southward-flowing currents using current meters attached to moorings.

Wind-driven surface circulations

The near-surface waters of the ocean tend to move northwards at this latitude under the influence of trade winds and the Earth's rotation. Continuous satellite wind measurements allow researchers to estimate these currents.

The Gulf Stream

In the Florida Straits, colleagues in the US measure the flow based on the way that sea water conducts electricity. As the Gulf Stream moves through the Earth's magnetic field it induces variable electric currents in the telephone cable lying on the seabed from Florida to the Bahamas. The team can measure the currents and work out the total transport of the Gulf Stream on a daily basis.

The North Atlantic and Arctic Oceans are critical components of the ocean-climate system. Warm tropical waters flow northwards, releasing heat to the North Atlantic region, and eventually flow into the Arctic Ocean. Cold waters sink in the northern North Atlantic and flow southwards forming the Atlantic Heat Conveyor.

The sum of the parts

The instruments continuously monitor each of these components of the overturning circulation. Their sum gives, on a daily basis, the total strength and structure of the AMOC. Measurements started on the 29 March 2004 and will continue to 2014, giving a decade of observations.

Results

For the first time, scientists can say with confidence that the average strength of the AMOC from 29 March 2004 to 31 March 2005 is 18.7 Sv. Three main circulations (the Gulf Stream, the transatlantic circulation and the wind-driven circulation in the upper ocean) contribute about equally to the AMOC's variability of ±5.6 Sv. Over periods longer than about ten days the measured flow north and south at 26.5°N is found to balance (as expected from theory), confirming the validity of the monitoring system measurements.

Why is this important?

The array has demonstrated that it is possible to make efficient and accurate measurements of a complex circulation on an ocean-wide scale. This is leading to new understanding of coupled ocean-atmosphere dynamics. In particular, the data are now being used to critically evaluate the realism of coupled climate models that predict future changes in the Atlantic circulation.

The system monitors interannual changes in the circulation with a resolution of 1.5 Sv. This means large, abrupt changes should be readily observed. Ten years of uninterrupted measurements will ensure that any seasonal cycles are well defined and help refine the nature of interannual variations, whether they are oscillations, trends or shifts.

The day after tomorrow

Modelling, prediction and forewarning

The value of the Rapid Climate Change programme is its role in improving the accuracy of climate models and providing forewarning of abrupt change.

Even with the best information on the current state of the climate system and using the best predictive computer models, scientists will struggle to accurately predict future climate. But, it is possible to test climate models' abilities to reproduce past climate change and then assess the uncertainties surrounding their predictions of future rapid change.

Scientists working on the Rapid Climate Change programme used a range of computer models to examine both past, present and future change. Although the main focus of the programme is on the role of the Atlantic Heat Conveyor, scientists also investigated important elements of the climate system in other parts of the world, such as changes in El Niño in the Pacific Ocean.

El Niño

El Niño is a naturally varying climate phenomenon in the Pacific which causes droughts and flooding in regions as far apart as Africa and India. Scientists know a major shift in El Niño occurred 6000 years ago. Researchers on the Rapid Climate Change programme studied this shift using coral records from the tropical Pacific and the Met Office Hadley Centre climate model.

A model's ability to reproduce both past and present climatic conditions gives researchers more confidence in its ability to predict the future. Scientists knew the model accurately reproduces 20th-century climate, but could it represent other climate states as well?

The data obtained from the corals have shown that El Niño was considerably weaker 6000 years ago, though globally, the average climate of that period was broadly similar to today. The main difference is a variation in the seasonality of the orbit of the Earth around the sun. The model captures the qualitative aspects of the weakening of El Niño, although the magnitude of change in the model is less than that inferred from the coral work. This shows the importance of considering uncertainties in both the coral reconstructions of past climate and the model simulations to quantitatively assess the ability of models to simulate changes in climate.

Changes in the Atlantic Ocean – 50-year reconstruction

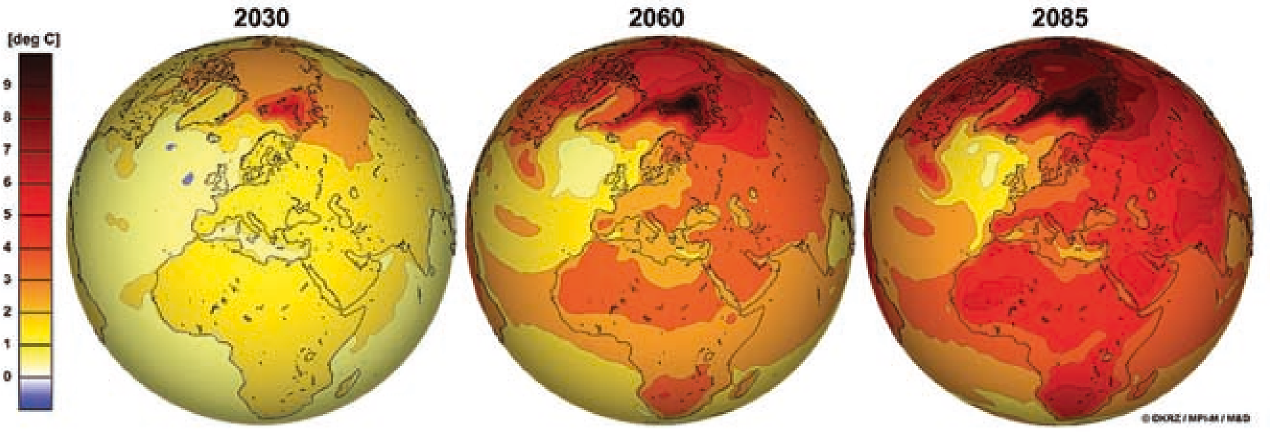
To put the new measurements of the Atlantic Heat Conveyor in context requires some knowledge of past changes. As

Coring giant corals in the tropical Pacific to obtain records of past climate changes.

University of Edinburgh.

Key outcomes

- Comparisons of climate models with palaeo data of past changes.
- Incorporating ocean data into models to better represent changes in the conveyor.
- Improved modelling of changes in the Greenland ice sheet.
- Quantifying the effect of changes in the Atlantic Heat Conveyor on weather systems reaching the UK.
- Intercomparison of rapid climate change processes in climate models of different levels of complexity.
- New statistical tools to quantify risk and probability of rapid climate change.



Future surface air temperature increases due to global warming. Note that the slowdown of the ocean conveyor leads to less warming in the North Atlantic region. Max-Planck Institute for Meteorology, Hamburg climate model. The institute is a partner in the Rapid Climate Change programme (IPCC Scenario AIB).

noted in the introduction, prior to the Rapid Climate Change programme, no continuous measurements of the conveyor existed. Evidence-based knowledge rested on five snapshots of the circulation taken over 50 years. To overcome this scarcity of direct measurements, the scientists worked with the European Centre for Medium Range Weather Forecasting to bring together all the ocean data on temperature and salinity acquired over the last 50 years and combined it with a computer model of the ocean. This allowed researchers to reconstruct the behaviour of the conveyor over that period.

The results suggest that some slowdown could have occurred. They are now checking the results with improved models that can capture more details of the ocean circulation. Such a reconstruction can help understand recent changes and, by comparison with climate models, allow researchers to gauge the quality of those models and so their predictions of future change.

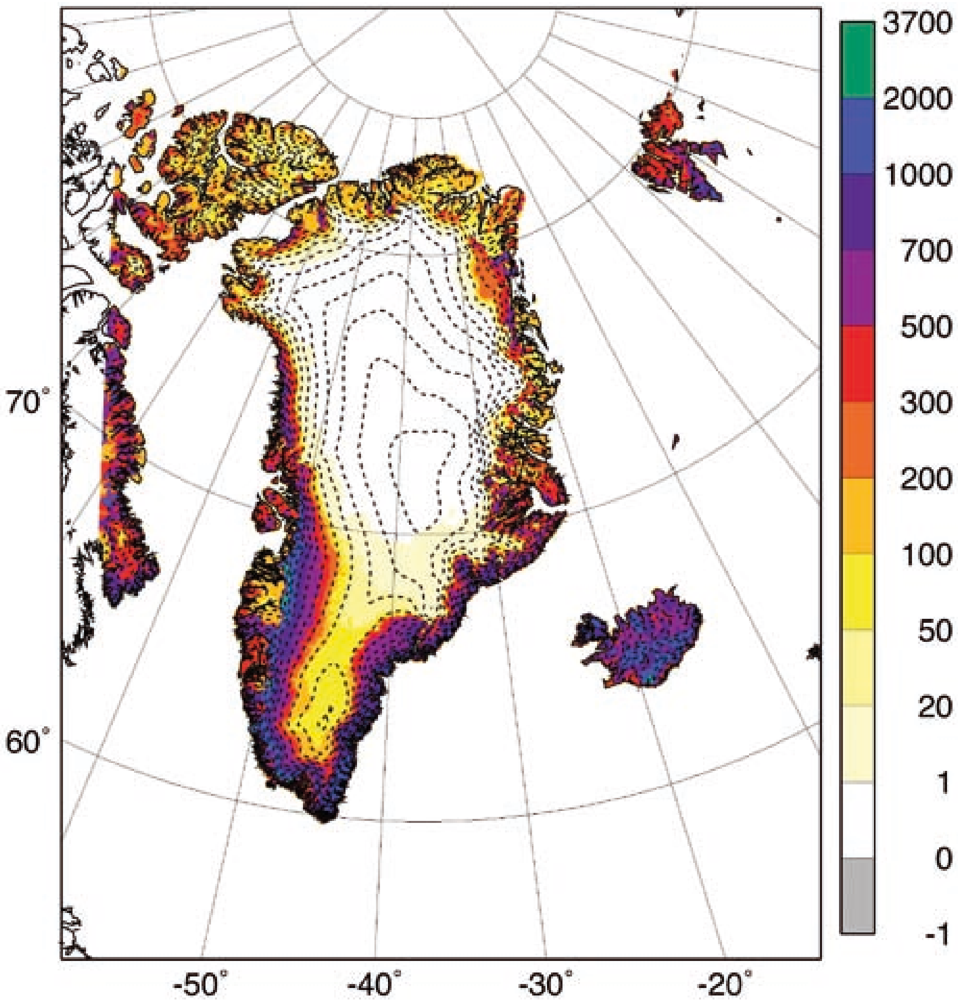
Modelling the Greenland ice sheet

Future changes in the input of fresh water into the North Atlantic might disrupt the Atlantic Heat Conveyor. The Greenland ice sheet is an important source for that fresh water. Therefore improved modelling of the behaviour of the ice sheet is necessary to make better predictions of future changes in melting. This requires more detailed models of the Greenland ice sheet on a regional scale. The Rapid Climate Change programme has developed such improved models. These models show good agreement with the observed rate of melting.

Changes to storm tracks reaching the UK

People in the United Kingdom are less concerned with what the Atlantic Heat Conveyor is doing *per se* than with how changes in the conveyor will affect weather and climate. Using climate models, researchers have looked at the response of the storms tracking across the Atlantic to changes in the strength of the conveyor. The initial results suggest that, as the conveyor slows, more storms occur and tend to track farther north, penetrating deeper into Europe. The exact behaviour predicted varies with how much detail the model can capture, for example, in the detailed pattern of the North Atlantic sea-surface temperature, which affects the atmosphere above it and so the behaviour of storms tracking across the ocean. Such detail is a function of the computer power available – the more detailed the model, the more computer power is required to run it.

Greenland ice sheet melting determined using a regional climate model. The results shown are for 1989. The model is able to reproduce the observed melting rates (in units of mm water equivalent).



Utrecht University

Risk and probability of a slowdown

In 2007, the UN's Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report concluded that it is very likely that the Atlantic Ocean conveyor will slow down during the 21st century. The IPCC models show a range of 0-50 per cent reduction, and an average reduction across the models of 25 percent by the end of the century. To determine the source of this uncertainty, Rapid Climate Change researchers are comparing models of different levels of complexity.

Running a computer climate model is a costly business, especially as they become better at resembling the real world. These complex models put immense pressure on computing resources, particularly if the models need to run hundreds or thousands of times in order to work out probabilities of an event occurring. Pioneering work by scientists on the programme has led to powerful statistical tools that allow approximations of a climate model to run many times extremely quickly. This provides a very efficient route to getting a large set of results from which to calculate probabilities. These tools are known in the trade as emulators. Application of emulators extend beyond climate science to any modelling problem that involves a wide set of starting conditions that you might want to change. The tools hold particular benefits for price modelling, for example, calculating the cost to insurers of extreme weather events. The programme's researchers are already talking to the financial services sector about future collaborations. What is clear is that a slowdown of the conveyor will have a regional climatic impact and that the scale of that impact depends on the magnitude and rate of the slowdown. Despite the progress made, challenges remain. Not least whether researchers can improve climate forecasts on shorter (decadal) timescales. This is a major challenge for Rapid-WATCH, the follow-on phase of the Rapid Climate Change programme. It is also central to the NERC strategy *Next Generation Science for Planet Earth*, which seeks to develop risk-based predictions of the future state of the climate on regional and local scales, spanning days to decades.

Knowledge Exchange

Working with stakeholders

Findings from the Rapid Climate Change programme are nationally and internationally significant, both to the scientific community and policy-makers. The Rapid Climate Change programme has a responsibility to ensure key scientific findings are effectively communicated to the user community.

Martin Mlecko

As UK policy-makers plan and implement strategies to increase resilience to the changing climate, it is important the scientific community advise of the risks associated with abrupt climate change. It is also important that policy-makers and other stakeholders are involved in planning of research at an early stage to ensure research programmes deliver the information policy-makers require in a format they can use. Since 2003, the Rapid Climate Change programme has had an active knowledge exchange strategy to meet these goals.

The Rapid Climate Change programme has pro-actively contacted key UK organisations and decision makers who stand to benefit from the programme's research. The key stakeholders include the United Kingdom Climate Impacts Programme (UKCIP) and the Marine Climate Change Impacts Partnership (MCCIP), led by the Department for Environment, Food and Rural Affairs (Defra). The make-up of the stakeholder community, assembled over the programme's life, reflects our desire to interact with both central and devolved government departments and agencies to help inform both national and regional issues.

The team has carefully considered how best to communicate the key results, taking into account contributions to major reports, their own briefing material and maximising the value of face-to-face briefings and dedicated stakeholder presentations.

For a large number of stakeholders, the first port of call for expert advice on climate change impacts remains UKCIP. The Rapid Climate Change team works closely with UKCIP to maintain a series of guidance notes on the Atlantic conveyor. These summarise present knowledge and highlight recent findings. The team has also contributed to the Atlantic conveyor section of the UKCIP2008 Climate Scenario reports.

The programme is a founding scientific partner of the Defra-led MCCIP – a new initiative uniting scientists, government agencies and non-governmental organisations to provide advice on climate change impacts within UK and adjacent waters. A key product of the MCCIP initiative is the Annual Report Card summarising major advances within the scientific field. The Rapid Climate Change programme has played an active role in the 2005-06 and 2006-07 reports.

The Rapid Climate Change programme has also focused significant resources on consolidating its understanding of

©iStockphoto.com/George Cairns

The Rapid Climate Change user community

The programme has been successful in forging relationships with a broad spectrum of UK climate-change stakeholders including:

- Defra
- The Welsh Assembly
- The Scottish Government
- Willis Analytics
- Natural England
- The Scottish Environmental Protection Agency
- The Environment Agency
- The Parliamentary Office of Science and Technology
- The World Wide Fund For Nature

how climate science is used by stakeholders, particularly informing policy. The programme's steering group contains a representative from Defra. These steps have been augmented by personnel secondments from the programme to Defra's offices in the past two years. All of these initiatives have proved invaluable in expanding the team's knowledge of government operation and how best to tailor knowledge-exchange activities to meet demand. One direct change implemented as a result of such secondments has been to provide Defra (and other stakeholders) with manuscripts of all policy-relevant publications from the programme accompanied by summary briefing notes. These are especially useful in aiding Defra officials to prepare ministerial briefings and in updating knowledge-bank entries which aid the policy-forming process.

The team has also built relationships with the financial and private sectors, especially where exposures to abrupt climate change are evident. These sectors are particularly interested in the programme's emulator technology, which can produce probabilities of events occurring, where chances can be influenced by a large number of variable parameters. The programme developed these emulator technologies to test the sensitivity of the Atlantic Heat Conveyor to a collapse as a result of global warming. But these powerful tools have wider applications. The Rapid Climate Change team is currently exploring the possibility of working alongside reinsurers to develop applications for use in catastrophe risk pricing.

Rapid WATCH

The Rapid Climate Change core team continue to identify new stakeholders across the private and public sectors and looks forward to making even further progress during the transition between the Rapid Climate Change programme and its successor, Rapid WATCH, which runs to 2014.

Rapid Climage Change data

Two NERC data centres, the British Atmospheric Data Centre and the British Oceanographic Data Centre, store and distribute data from the programme. www.bodc.ac.uk/projects/uk/rapid/

The Marine Climate Change Impacts Partnership (MCCIP)

MCCIP is a Defra-led partnership between marine stakeholders, the UK government and the scientific community, providing advice on climate change and its impacts.

The partnership produces an annual report card summarising the physical climate change under way in UK and adjacent waters, recent findings concerning impacts, and knowledge on future change. The report is circulated to all UK MPs and the stakeholder community.

As a founding partner, the Rapid Climate Change programme provides scientific expertise and is represented on the MCCIP steering committee.

The 2007-08 MCCIP Annual Report provides detailed information on a number of topics including:

- regional changes in sea surface and air temperature;
- observed and future changes to the Atlantic conveyor, including the first year's observations from the 26°N array of scientific instruments;
- ocean acidification;
- regional coastal erosion.

The full report and supporting information is available online: www.mccip.org.uk

The UK Climate Impacts Partnership (UKCIP)

Established in 1992, UKCIP plays an integral role connecting stakeholders with the latest scientific findings and scenarios of future climate change.

The partnership provides detailed advice to help users adapt and increase resilience to climate change risk.

Risks from abrupt climate change, relating to the Atlantic Heat Conveyor, are a frequent source of concern. The Rapid Climate Change programme assists UKCIP to maintain user guidance notes, summarising the present level of understanding of these risks, and assessing the likelihood of future change.

In 2008, UKCIP release the latest suite of climate-change scenarios for the 21st century. For the first time, gridded, probabilistic information on key climatic variables will be accessible via a web portal. Three written reports accompany these data:

- the climate of the United Kingdom and recent trends;
- future terrestrial scenarios;
- future marine scenarios.

Researchers on the Rapid Climate Change programme have co-authored a section on the Atlantic conveyor summarising recent observations from the programme, and additional sources, and projections of future changes.

Amy Balkin/Cape Farewell

Outreach

Information, education, inspiration

Will the possibility of a cooler Europe confuse people when what society needs is clear facts so it can take firm action? The Rapid Climate Change programme has ignited fierce debate among scientists and environmentalists. It has also inspired art, informed education and captured the imagination of the media and public alike.

Media and the public

In 2007, climate change entered the media mainstream. With this came passionate debate about how to present the complex and contradictory ideas inherent in the Rapid Climate Change programme to a wider audience. But public interest in the programme really took off in 2004 with the release of the Hollywood blockbuster *The Day After Tomorrow*. This media attention continues to this day, fuelled by regular releases of new results. It reached a highpoint in December 2005 when the science journal *Nature* published results which suggested a marked slowdown of the Atlantic conveyor over the last 50 years. A deluge of interview requests flowed in from around the world. Photos, figures, quotes and misquotes from the programme found their way into radio, TV, newspapers, magazines and websites too numerous to count.

The *Nature* paper, based on sporadic and infrequent measurements stretching back over five decades highlighted the urgent need for continuous measurements to understand the natural variability of the Atlantic Heat Conveyor.

A second peak in media attention followed nearly two years later, coinciding with the publication of the first year-long results from the Atlantic array. These landmark results were published in two back-to-back papers in the American journal *Science* on 17 August 2007.

Scientists from the programme have done their best to temper sensationalism without giving the impression that there is absolutely no need for concern. This is not always easy. The Atlantic Heat Conveyor and its effect on European climate cannot fit into a 30-second soundbite any more than a slowdown of the circulation can be confirmed by a few days of zero flow.

Art, education and climate change

The programme has encouraged and attracted innovative

'Ice Texts' by artist and film-maker David Buckland draw attention to the peril of melting Arctic ice.

David Buckland/Cape Farewell

Cape Farewell's 2007 Youth Expedition took 12 students from UK, Germany and Canada to the Arctic to join science projects.

Dan Harvey/Cape Farewell

approaches to outreach and communication. From the outset, it has had the support of professional artists and writers. American science writer Dallas Murphy took part in an early science expedition, an experience that features prominently in his book *Follow the Water.* German photographer Martin Mlecko crewed on a recent voyage to the array at 26° North. His photos now feature both in exhibitions and online.

In the UK, the Rapid Climate Change programme has had a long and fruitful collaboration with Cape Farewell – a group of artists, writers, scientists and educators led by photographer David Buckland. This has brought the 'art of climate change' into science conferences through art exhibitions and after-dinner talks, and the science of climate change into numerous touring exhibitions, a variety of TV and radio programmes, books, articles, news coverage, and public panel debates. The programme has lent scientific support to Cape Farewell's work and expeditions – most recently the 2007 Youth Expedition. Through Cape Farewell, the programme has contributed to GCSE teaching material which looks set to form part of the new UK science curriculum.

Key outcomes

- The programme has attracted significant and sustained media interest, nationally and internationally.
- Working with artists and writers, the programme has increased public awareness of the role played by the ocean in the global climate system.
- Information about rapid climate change is now included in the curriculum for UK schools.

PAST PRESENT FUTURE

Rapid WATCH (2008-14)

Will the Atlantic Thermohaline Circulation Halt?

From pilot scheme to decadal measuring system.

The flagship of the Rapid Climate Change programme, a pilot scheme to measure the Atlantic Meridional Overturning Circulation, has been a success. This is a major achievement which the American journal *Science* has described as a 'bold initiative'. The Natural Environment Research Council has committed a further £16.1 million to complete a full decade of observations, up to 2014. This follow-on programme is called Rapid WATCH (Will the Atlantic Thermohaline Circulation Halt?).

The measurements will be used with other observations of the North Atlantic and computer models to determine the state of the ocean circulation, and to improve predictions of future changes. This next phase of research will involve scientists from Canada, Germany and the USA. Close collaboration with the Met Office Hadley Centre will allow results from the programme to feed into the centre's decadal prediction system. This will lead to improved climate prediction, both globally and in particular for the UK and north-west Europe, where the impact of changes in the conveyor are largest.

The Natural Environment Research Council's initiative has led to other major projects: the European Union has funded THOR (ThermoHaline Overturning – at Risk?); and in the US, scientists are developing a programme to improve modelling and prediction, and to make measurements further north and south in the Atlantic. These initiatives provide opportunities for further international collaboration.

In this next phase the observations and modelling will become the basis of a major decision: should the observing system move from research to operational status beyond 2014? The decision will be based on an assessment of the scientific and, in broad terms, socio-economic benefits of an operational-monitoring system for the Atlantic conveyor. This will include an estimate of the timescale on which the full benefits of such a system would be realised.

'I recognise that major steps like the Rapid Climate Change programme are critical to improving our understanding and prediction of climate. These major steps take considerable courage and foresight by both scientists and their funders. The leadership shown by NERC is critical to realising these improvements.'

John Church, Chair of the Joint Scientific Committee of the World Climate Research Programme, 2007.

PAST PRESENT FUTURE

Projects and contacts

Principal Investigator	Institute	Title
Professor H. Bryden/ Dr S. Cunningham (previously Professor J. Marotzke) hlb@noc.soton.ac.uk scu@noc.soton.ac.uk	National Oceanography Centre, Southampton	Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N
Professor A. Watson a.watson@uea.ac.uk	University of East Anglia	Time series of transient tracers in North Atlantic deep waters
Professor C. Hughes C.Hughes@pol.ac.uk	Proudman Oceanographic Laboratory	A monitoring array along the western margin of the Atlantic
Dr D. Cromwell ddc@noc.soton.ac.uk	National Oceanography Centre, Southampton	Measuring the Meridional Overturning Circulation from space: a feasibility study

From MOC Observing System Announcement of Opportunity (jointly with NSF)

Principal Investigator	Institute	Title
Professor A. Willmott ajwil@pol.ac.uk	Proudman Oceanographic Laboratory	Processes controlling dense water formation and transport on Arctic continental shelves
Dr S. Josey sxj@noc.soton.ac.uk	National Oceanography Centre, Southampton	The role of air-sea forcing in causing rapid changes in the North Atlantic Thermohaline Circulation
Dr E. Wolff ewwo@bas.ac.uk	British Antarctic Survey	High resolution anatomy of rapid climate transitions in the last glacial period from a Greenland ice core
Professor I. N. McCave mccave@esc.cam.ac.uk	Cambridge University	Hydrographic and flow changes at sharp climate transitions in the North Atlantic MOC, 0-16ka BP
Professor R. Williams ric@liv.ac.uk	Liverpool University	The role of sloping topography in the overturning circulation of the North Atlantic
Professor K. Briffa k.briffa@uea.ac.uk	University of East Anglia	Quantitative applications of high-resolution late Holocene proxy data sets: estimating climate sensitivity and thermohaline circulation influences

Principal Investigator	Institute	Title
Professor B. Hoskins b.j.hoskins@reading.ac.uk	Reading University	The atmospheric water vapour budget and its relevance to the THC
Dr E. Guilyardi ericg@met.rdg.ac.uk	Reading University	The role of salinity in ocean circulation and climate response to greenhouse gas forcing
Professor A. Tudhope sandy.tudhope@ed.ac.uk	Edinburgh University	Improving our ability to predict rapid changes in the El Niño Southern Oscillation climatic phenomenon
Professor A. Watson a.watson@uea.ac.uk	University of East Anglia	Circulation, overflow, and deep convection studies in the Nordic Seas using tracers and models
Professor I. Fairchild i.j.fairchild@bham.ac.uk	University of Birmingham	Atlantic Seaboard Climate Responses including Bounding Errors (ASCRIBE)
Professor H. Bryden hlb@noc.soton.ac.uk	University of Southampton	Extending the time series of Atlantic Meridional Overturning backwards in time using historical measurements
Mr P. Challenor pc@noc.soton.ac.uk	National Oceanography Centre, Southampton	The probability of rapid climate change
Dr S. Bacon shb@noc.soton.ac.uk	National Oceanography Centre, Southampton	Cape Farewell and Eirik Ridge: interannual to millennial thermohaline circulation variability
Dr N. Wells ncw@noc.soton.ac.uk	University of Southampton	The determination of heat transfer and storage, and their changes in the North Atlantic Ocean
Professor C. Pain c.pain@imperial.ac.uk	Imperial College, London	Better understanding of Open Ocean Deep Convection (OODC) with reference to THC
Dr J. Holmes j.holmes@ucl.ac.uk	University College, London	ISOMAP UK: a combined data-modelling investigation of water isotopes and their interpretation during rapid climate change events
Professor J. Bamber j.bamber@bristol.ac.uk	University of Bristol	The role of the cryosphere on modulating the thermohaline circulation of the North Atlantic

From 1st Announcement of Opportunity

Principal Investigator	Institute	Title
Dr William E.N. Austin wena@st-andrews.ac.uk	University of St Andrews	Can Younger Dryas atmospheric ^{14}C concentration be attributed to North Atlantic surface ocean ventilation?
Dr Sheldon Bacon shb@noc.soton.ac.uk	National Oceanography Centre, Southampton	Arctic Regulation of Thermohaline Circulation (ARTHER)
Dr Mark R. Chapman Mark.Chapman@uea.ac.uk	University of East Anglia	Multi-decadal variability through the early and late Holocene in the subpolar North Atlantic
Professor Jonathan Gregory j.m.gregory@reading.ac.uk	National Centre for Atmospheric Science, Reading	Understanding uncertainty in simulations of THC-related rapid climate change
Professor Jonathan Gregory j.m.gregory@reading.ac.uk	National Centre for Atmospheric Science, Reading	UK coupled model intercomparison project on the thermohaline circulation
Professor Keith Haines kh@mail.nerc-essc.ac.uk	Environmental Systems Science Centre, Reading	Assimilation in ocean and coupled models to determine the thermohaline circulation
Professor Brian J. Hoskins b.j.hoskins@reading.ac.uk	Reading University	The impact of climate change on North Atlantic and European climate regimes
Professor John Lowe J.Lowe@rhul.ac.uk	Royal Holloway, of London University	A precise chronology for establishing the timing changes in North Atlantic thermohaline circulation (THC), and its climatic consequences, 16-8 cal ka BP
Professor David Marshall marshall@atm.ox.ac.uk	Oxford University	Attribution of ocean climate change signals in the Atlantic
Professor Rowan Sutton rowan@met.reading.ac.uk	Reading University	Probabilistic forecasting of the Atlantic Meridional Overturning Circulation and associated rapid climate change
Professor Andy Watson a.watson@uea.ac.uk	University of East Anglia	Time Series of Transient Tracers (TESTT)

From 2nd Announcement of Opportunity

Principal Investigator	Institute	Title
Professor Grant R. Bigg ice grant.bigg@sheffield.ac.uk	University of Sheffield	Punctuated disintegration of the NW European sheet and rapid climate change
Professor Henry Elderfield harrye@esc.cam.ac.uk	University of Cambridge	Variations of the Atlantic MOC during rapid changes: calibration, modelling and palaeoceanographic observations (VAMOC)
Professor Sandy Harrison Sandy.Harrison@bristol.ac.uk	University of Bristol	Impact of changing freshwater flows on the THC and European climate
Dr Timothy J. Osborn t.osborn@uea.ac.uk	University of East Anglia	To what extent was the Little Ice Age a result of a change in the THC?
Dr M.R. van den Broeke broeke@phys.uu.nl	Institute for Marine and Atmospheric Research, Utrecht University	Mass balance and freshwater contribution of the Greenland ice sheet: a combined modelling and observational approach

From Joint International RCN/NWO/NERC Announcement of Opportunity

NATURAL ENVIRONMENT RESEARCH COUNCIL

The Natural Environment Research Council (NERC) uses an annual budget of £400 million to fund independent environmental research in the United Kingdom. The priorities we develop with our researchers and stakeholders provide a focus for the marine, polar, atmospheric, earth, terrestrial and freshwater science communities.

The research is often multidisciplinary and in collaboration with other national and international partners. NERC runs a fleet of research ships and scientific aircraft. We have bases in some of the world's most hostile environments and invest in satellite technology to monitor environmental change on a global scale.

NERC's research and collaborative centres maintain and develop UK national capability across the disciplines that make up environmental science. We fund centres and universities to carry out research and to train and support a world-class community of environmental scientists.

In 2001, NERC set up the £20 million Rapid Climate Change programme to investigate the fundamental processes that cause climate to change abruptly.

Rapid Climate Change programme
www.nerc.ac.uk/research/programmes/rapid/

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