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Six Degrees

Our Future on a Hotter Planet

Mark Lynas

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To my wife, Maria, son, Tom, and daughter, Rosa,
in the hope that most of the predictions here
need not come true.

From the weeping ground there sprang a wind,
flaming with vermillion light,
which overmastered all my senses,
and I dropped like a man pulled down by sleep.

Dante, *Inferno*, Canto III:
Dante enters the First Circle of Hell

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INTRODUCTION

The knock on the door came at night. In the darkness I could see two yellow jackets over black uniforms-the police. They were going door to door, the officers explained, to warn people in the area of the imminent risk of flooding. They handed over a photocopied leaflet, advising that we prepare to turn off the power and move all valuables upstairs, and were gone.

The rain had come two days earlier. It poured with torrential force for most of the day, accompanied by vivid flashes of lightning and intermittent claps of thunder. Roads were awash as flash floods swept off fields. Within hours, the rail link north was cut, and Oxford-like many other towns in the Midlands and southern England-was marooned. Four days later the waters were still rising, as a flood crest surged down the river Thames from more heavily inundated areas upstream. Turning on the television news I saw the pretty cathedral town of Tewkesbury turned into an island, both Cheltenham and Gloucester hit by power failures, and schools closed across the entire region. The rising flood swept over a water treatment plant, leaving a quarter of a million people with no drinking water for over a week. Though my own house was not flooded, whilst writing this I can still smell the stench of rotting waterweed left behind by the river on nearby Port Meadow.

The sheer intensity and violence of the rain reminded me of a tropical storm I rode out a few years earlier on the Outer Banks of North Carolina, whilst researching my first book *High Tide.* There was that same ominous dark quality to the sky, and the rainfall radar on the Meteorological Office website showed the same reds and whites of super-intense precipitation that I had previously witnessed whilst sheltering in the hurricane trackers' van near Cape Hatteras in 2002. Hurricanes generate some of the heaviest rainfall on Earth, and flooding during a hurricane strike is virtually a certainty. As the terrible drama that unfolded in New Orleans when Hurricane Katrina hit in 2005 showed, sometimes this flooding-combined with a monster storm surge-can be deadly.

All these events were windows into a changing world. Global warming is making the hydrological cycle more intense, causing heavier storms and more intense hurricanes to brew up out at sea. Yes, extreme weather has always been with us, but the fact that rising levels of greenhouse gases trap the sun's heat means that more energy is available in the system-so the worst is happening more and more often. The misery suffered in New Orleans three years ago felt to me like an insight into what the twenty-first century may have in store for many more of us, in a thousand locations across the world, as climate change accelerates.

The scenes lingered in my mind even as the city was emptied and the bedraggled survivors of New Orleans and the wider Gulf region were packed off to temporary shelters in Texas and elsewhere, where half a million still remain at the time of writing: arguably the first climate refugees, displaced permanently from their homes. I kept wondering: where next? What will happen as the world warms bit by bit? With up to six degrees Celsius of global warming on the cards over the next hundred years, according to the Intergovernmental Panel on Climate Change (IPCC), what will happen to our coasts, our towns, our forests, our rivers, our croplands and our mountains? Will we all, as some environmentalists suggest, be reduced to eking out a living from the shattered remains of civilisation in Arctic refuges, or will life go on much as before-if only a little warmer?

As I pondered these questions, I had already begun to sift through the latest scientific literature on global warming. I knew from earlier research for *High Tide* that scientists have now made hundreds of projections-mostly based on complex computer models-of how future global warming will affect everything from maize crops in Tanzania to snowfall in the Alps. Occasionally a particularly striking study makes headlines in the newspapers, but the vast majority of these forecasts are buried in obscure specialist journals, destined to be read only by other climatologists. Most of these journals are taken by Oxford University's Radcliffe Science Library, where they sit-undisturbed for weeks or even years on their dimly lit shelves-just a mile or so down the road from my own house. I realised that it was almost as if I had a Delphic Oracle in my back garden or Nostradamus living next door-except that these scientific prophecies were already coming true.

Earlier that year I had begun to make a daily pilgrimage down to the Radcliffe Science Library basement with my laptop, where as the weeks passed by I trawled through tens of thousands of scientific papers. Seasons came and went, and I barely noticed. Each relevant article, I slotted into a spreadsheet-papers about two degrees of global warming went into the two degrees slot, papers about five degrees of global warming went into the five degrees slot, and so on. Not all were computer model projections-some of the most interesting material came from palaeoclimate studies, investigations of how variations in temperatures have affected the planet during previous global warming events in prehistory. These records of past greenhouse episodes, I realised, could be analogues for the future: and they too slotted into my six degrees table according to the temperatures of the climatic periods they represented.

At the end, I found I had something truly unique: a degree-by-degree guide to our planet's future. And so, based on this raw material, the book gradually took shape: my first chapter included all the global warming impacts I could find associated with a one-degree rise in temperature, my second chapter covered two degrees, my third chapter covered three degrees … and on up the scale to six degrees-the worst-case scientific scenario. No scientist and no journalist has ever undertaken this work before with anything like this attention to detail, and never before has so much of this information been presented comprehensibly to a general audience in book form.

As the work emerged, I felt a nagging suspicion that maybe I should be keeping it all secret. *Six Degrees* was beginning to feel like a survival manual, full of indications about which parts of the globe might need to be abandoned, and which would be most likely to remain habitable. Maybe I should be sharing this information only with my family and friends, to give those people closest to me a quiet heads-up? Or perhaps I should get it out as widely as possible, as a sort of cautionary tale, to convince people to campaign for rapid emissions cuts and avoid the worst-case scenarios before it is too late?

Obviously I chose the second, more optimistic course. But a related question continued to bug me as I did early public presentations of *Six Degrees* material, particularly when I overheard a conversation in the toilets after one event in which an audience member apologised to another for dragging them out to something so depressing. I was truly shocked. Depressing? It had honestly never occurred to me that *Six Degrees* might be depressing. Yes, the impacts presented are terrifying-but they are also, in the main, still avoidable. Getting depressed about the situation now is like sitting inert in your living room and watching the kitchen catch fire, and then getting more and more miserable as the fire spreads throughout the house-rather than grabbing an extinguisher and dousing the flames.

It also dawned on me gradually when I tried to explain the book to non-specialists that most ordinary people have not got the slightest idea what two, four or six degrees of average warming actually means in reality. These still sound like very small changes when the mercury swings by fifteen degrees between night and day. To most of us, if Thursday is six degrees warmer than Wednesday, it doesn't mean the end of the world, it means we can leave the overcoat at home. Such are the vagaries of everyday weather. But six degrees of global average change is an entirely different prospect.

Consider this: 18,000 years ago, during the deepest freeze of the last ice age, global temperatures were about six degrees colder than today. In that frigid climate, ice sheets stretched across North America from sea to shining sea. As glacial grooves in the rocks in Central Park attest, New York was buried under a thick slab of ice, more than a mile deep as it stretched into the heart of the continent. Northern New Jersey was buried, as was all the Great Lakes area, and almost the entirety of Canada. Further south, the agricultural heartland of states like Missouri and Iowa would have been freezing tundra, blasted by dust-laden winds sweeping down from the ice cap, and underlain by layers of solid permafrost. During the ice age, humans were displaced far to the south, where places that are now subtropical, like Florida and California, maintained a temperate climate.

In addition, temperature swings were astonishingly rapid-several degrees in the space of a decade as the climate warmed and then cooled again. At one point, about 70,000 years ago, a huge supervolcano eruption in Indonesia blew thousands of cubic kilometres of dust and sulphur into the atmosphere, cutting off the Sun's heat and causing global temperatures to plummet. Humans were nearly wiped out in the ensuing ‘nuclear’ winter: the entire global human population crashed to somewhere between 15,000 and 40,000 individuals, a survival bottleneck which is still written in the genes of every human alive today. By implication, if six degrees of cooling was enough to nearly wipe us out in the past, might six degrees of warming have a similar effect in the future? That is the question this book seeks to answer.

Back in the summer of 2005, as I began my journey into humanity's likely future, I felt like Dante at the gates of the Inferno-privileged to see what few others have laid eyes upon, but also deeply worried by the horrors that seemed to lie ahead. Just as the poet Virgil was Dante's guide as he set forth into the Inferno, my guides are the many talented and passionate scientists who conducted the original research studies on which this book is based. I offer them my thanks, and hope they feel well represented by what follows.

> 'Set out then, for one will prompts us both.
> You are my leader, you my lord and master,'
> I said to him, and when he moved ahead
> I entered on the deep and savage way.

A technical note

As befits the task of any popular science writer, I have tried to make each case study come alive as much as possible without losing the rigour of the original document. Where the science itself has evolved through the years, I have tried to work this into the story. There were drawbacks of course: almost all the studies use different models, each model employing different underlying assumptions, so comparing them can sometimes be rather like comparing chalk and cheese. Each study also contains uncertainties, often expressed in quantitative terms-such is the nature of good science-and carefully weighed, thoughtful statements by the authors which cannot always be accurately reflected in a broad-brush, generalist approach such as this. I leave readers with queries about any of the information presented to follow up references and judge the original work for themselves. Do not complain to me either if you have doubts about the methodologies employed by the original studies: I am not a climatologist, I am merely the interpreter.

I might also add at this point, for the benefit of any readers who feel somewhat out of depth with the generally 'scienticised' nature of the climate change debate, a very general note of background on global warming. Essentially, this term (which I use interchangeably with 'climate change', although technically they do mean slightly different things) refers to the increase in global atmospheric temperatures as a result of increasing concentrations of greenhouse gases in the air around us. That greenhouse gases have a warming effect, rather like an extra blanket around the globe, is indisputable, and has been established physics for over a hundred years. These gases cause a 'greenhouse effect' because they are opaque to long-wave infrared radiation: heat coming in from the Sun is short-wave, and so passes straight through, but when this heat is re-radiated by the Earth, its wavelength is longer, and some is trapped by the gases-just as glass in a greenhouse also traps heat. If there were no greenhouse gases at all in the atmosphere, the Earth's average temperature would be about —18°C.

Since the beginning of the Industrial Revolution, concentrations of the principal greenhouse gas, carbon dioxide (CO_2), have risen by a third, whilst those of methane-another potent greenhouse gas-have doubled. Although there have been fluctuations between the decades, global temperatures have also risen in the last 150 years by about 0.8°C, and are expected to rise even faster over the next century as CO_2 levels rise further still. Partly these future temperature rises will be the result of emissions already in the past, and partly they will reflect rapid expected rises in greenhouse gas emissions from human activity. That we can avoid higher temperature increases by cutting back emissions is a key point that I seek to illustrate in this book.

Although I have done my best to ensure that the correct impact studies are presented in the correct chapters, there are occasions when the decision about what to put where is somewhat arbitrary. Many-most, in fact-papers do not state the precise global average temperature change that their study refers to, particularly if they are focusing on a regional change. A study on Arctic sea ice, for example, may be based on a range of different future carbon dioxide concentrations, none of which are interpreted as global temperature averages by the authors, leaving me with the difficult choice of estimating which chapter is the best fit. Different studies using the same future CO_2 concentrations do not necessarily share the same temperature projections, moreover: all models have different 'sensitivities' to atmospheric greenhouse gas increases, further complicating the procedure. It is important to emphasise, however, that all of the material in this book comes from the peer-reviewed scientific literature-at no point do I base predictions on less reliable sources like newspaper articles or campaign group press releases.

It is also important to note that the temperature scale of this book is based on the IPCC's landmark 1.4 to 5.8°C temperature range, published in its 2001 Third Assessment Report, which gives us predictions of *up to* six degrees. This is reflected in the structure of the chapters that follow. The three degree chapter, for example, covers global temperatures of 2.1°C to 3°C, whereas the six degree chapter covers 5.1°C to 5.8°C. In February 2007 the IPCC published its Fourth Assessment Report (AR4), which broadened the range of temperature projections for 2100. For the lowest emission scenario, where global greenhouse gas emissions dip sharply, warming by 2100 could be as low as 1.1°C, according to the AR4, whereas for the highest emissions scenario, global warming could reach 6.4°C. In other words, the range is broader, and the worst-case scenario is even more drastic than in the 2001 IPCC report-seven degrees on this book's scale.

The Fourth Assessment Report of the IPCC also surveys in detail the expected impacts of future climate change, covering much of the same territory as this book and referencing many of the same papers. The language is sufficiently non-technical for most laypeople to find it perfectly comprehensible-something of an improvement on previous reports. I would in particular direct interested readers to the Working Group II section of the AR4, in particular a table in the Summary for Policymakers which outlines in a simple degree-by-degree scale the expected impacts of warming from 1 to 5°C. (Why the table does not extend to six degrees, despite this being within the temperature scenario projections given by the IPCC, is not explained.) The full text of all IPCC reports is available on the web at www.ipcc.ch.

An admitted pitfall in choosing a temperature-based structure for this book is that it makes giving dates very hazardous. The world could become two degrees warmer by 2100, for instance, or it could already have hit that level as early as 2030. The speed of warming is crucial in determining the capacity of human civilisation and natural ecosystems to adapt to the changing climate, and readers are urged to bear this in mind. The other option of running through the twenty-first century decade by decade would, I feel, have been even more problematic given that the dates attached to different emissions scenarios and temperature changes are highly uncertain. This book only deals with what scientists call ‘transient’ climate change: because of the thermal inertia of the oceans it will take centuries for temperatures to stabilise at any given concentration of greenhouse gases into a so-called ‘equilibrium’ state.

I have also on occasion explored rather speculatively what the changes projected by today's scientists might mean for society in future. Might China invade Siberia to secure subarctic *Lebensraum* in a globe where only narrowing zones remain habitable? Might India and Pakistan's struggle over the diminishing headwaters of Himalayan rivers turn nuclear as their people go thirsty? Of course, I would be foolish to expect these predictions to come true in any literal sense-history teaches us that human events are too unpredictable to support such a deterministic approach. But of this I have no doubt: climate change is the canvas on which the history of the twenty-first century will be painted. Forewarned is forearmed.

Onward, then. Let us enter the Inferno together.

1°

1

ONE DEGREE

America's slumbering desert

It would be easy to walk right past them. Not many hikers pass this way, and those that do are unlikely to give a second thought to a few old stumps rooted in the river bed. In any case, this lonely spot, where the West Walker River canyon is at its narrowest as it plunges down the eastern flanks of California's Sierra Nevada, is not a place to linger-the area is notorious for sudden downpours and flash floods. The river runs almost the width of the entire gorge, and there's no place to climb to safety if the heavens open.

But these stumps have a story to tell. Dead trees can talk, in a way. An astute hiker or an observant angler would be puzzled: what are they doing in a river bed, a place now treeless because of the constant flowing water? Investigated by scientists in the early 1990s, the tree stumps were found to be Jeffrey pines-a common enough species for the area, but one that certainly doesn't normally root in rivers. What's more, these trees were old. Very old. Tissue samples revealed that the stumps dated from medieval times, and grew during two specific periods, centred on AD 1112 and 1350.

The mystery deepened when similar old stumps were revealed in Mono Lake, a large saltwater body a hundred kilometres to the south of Walker River, near the state border with Nevada. It's a spectacular location, famous for broad skies and sunsets, with little to interrupt the gently rolling arid landscape other than a few extinct volcanoes. The Mono Lake tree stumps belonged not just to pines, but also to other native species like cottonwoods and sagebrush, all rooted far below current-day natural lake levels and only revealed thanks to water diversion projects that supply far-away Los Angeles. Again, carbon dating revealed the same two time intervals as for the Walker River trees. Clearly, something significant had happened back in medieval times.

More evidence came from deeper in the mountains, hidden in two locations today famous for their giant sequoia groves-Yosemite and Giant Sequoia National Parks. These enormous trees, which in terms of total wood volume stand as the largest living organisms on Earth, are also among the oldest. Some living trees are up to 3,000 years old. And because each annual growth cycle leaves a clear ring, these monumental plants are also an excellent record of past climate. Over a decade ago, scientists sampling wood from dead giant sequoias noticed old fire scars on the edges of some of their rings. These scars were especially frequent during this same medieval period-between AD 1000 and 1300-as the old trees in West Walker River and Mono Lake were growing. Wildfires had raged in both national parks twice as frequently as before, and there can only be one plausible explanation-the woods were tinder-dry.

Raging wildfires, dry rivers and lakes-the pieces of the jigsaw were beginning to make sense. The area we now call California had in medieval times been hit by a mega-drought, lasting at different periods for several decades, and altering both landscape and ecosystems on a scale that dwarfs today's drought episodes. But just how geographically widespread was this event? Evidence from another lake, far away on the Great Plains of North Dakota, provides a partial answer. Moon Lake, like Mono Lake in California, is a closed basin, making it saline. Salinity fluctuates with the climate: in sequences of wet years, more fresh water ends up in the lake and salt levels go down. The converse is also true: in dry years, more water evaporates, leaving a more concentrated salty brine behind. Canadian scientists have now reconstructed long-term records of Moon Lake's saltiness by sampling the remains of tiny algae called diatoms-whose type and number fluctuate with salinity levels-from old lake sediments. Lo and behold, back before AD 1200, a series of epic droughts had swept the Great Plains, the return of which-the scientists agreed-‘would be devastating’.

An insight into the devastating nature of such a drought was gained by a team of biologists working in northern Yellowstone National Park, a good 1,500 kilometres to the south-west of Moon Lake, in Wyoming. They drilled into sediments spilled out by rivers, only to discover a peak in muddy debris flows-the product of flash floods-about 750 years ago. These flash floods had poured off mountainsides denuded of forest cover by frequent fires: so rather oddly, these flood debris flows are actually a classic sign of drought. It appeared that the whole of the western United States had been struck at the same time.

The effect on Native American populations in this pre-Columbian era was indeed devastating. Whole civilisations collapsed, beginning in the Chaco Canyon area of modern-day New Mexico. One of the most advanced societies on the continent at their peak, the Pueblo Indian inhabitants of Chaco Canyon erected the largest stone building on the North American continent before the European invasion, a ‘great house’ four storeys high, with over 600 individual rooms-much of it still standing today. Yet when the big drought came in AD 1130, they were vulnerable-population growth had already diminished the society's ecological base through the overuse of forests and agricultural land. Most people died, whilst the survivors went on to eke out a living in easily defended sites on the tops of steep cliffs. Several locations show evidence of violent conflict-including skulls with cut marks from scalping, skeletons with arrowheads inside the body cavity, and teeth marks from cannibalism.

Indeed, the whole world saw a changing climate in medieval times. The era is commonly termed the ‘Medieval Warm Period’, a time when-so the oft-told story goes-the Vikings colonised Greenland and vineyards flourished in the north of England. Temperatures in the North American interior may have been 1 to 2°C warmer than today, but the idea of a significantly warmer world in the Middle Ages is actually false. Recent research piecing together 'proxy data' evidence from corals, ice cores and tree rings across the northern hemisphere demonstrates a much more complicated picture, with the tropics even slightly cooler than now, and different regions warming and then cooling at different times. However small the global shift, the evidence is now overwhelming that what the western US suffered during this period was not a short-term rainfall deficit, but a full-scale mega-drought lasting many decades at least. As recently as 2007 US scientists reported tree-ring studies reconstructing medieval flows in the Colorado River at Lees Ferry, Arizona, showing that the river lost 15 per cent of its water during a major drought in the mid-1100s. For sixty years at a time, the river saw nothing but low flows-none of the floods that normally course down the Colorado arrived to break the dry spell. Indeed, the remarkable coincidence of these dates with evidence from New Mexico suggests that this was the very same drought that finished off the Chaco Canyon Indians.

To see the worst that even such a small change in climate can do, consider that most undramatic of places-Nebraska. This isn't a state that is high up on most tourists' 'to do' lists. 'Hell, I thought I was dead too. Turns out I was just in Nebraska,' says Gene Hackman in the film *Unforgiven*. A dreary expanse of impossibly flat plains, Nebraska's main claim to fame is that it is the only American state to have a unicameral legislature. Nebraska is also apparently where the old West begins-local legend in the state capital Lincoln insists that the West begins precisely at the intersection of 13th and O Streets, a spot marked by a red brick star.

But perhaps the most important Nebraska fact is that it sits in the middle of one of the most productive agricultural systems on Earth. Beef and corn dominate the economy, and the Sand Hills region in central Nebraska sports some of the most successful cattle ranching areas in the entire United States.

To the casual visitor, the Sand Hills look green and grassy, and in pre-European times they supported tremendous herds of bison-hence their high productivity for modern-day beef. But, as their name suggests, scratch down a few centimetres and the shallow soil quickly gives way to something rather more ominous: sand. These innocuous-looking hills were once a desert, part of an immense system of sand dunes that spread across thousands of kilometres of the Great Plains, from Texas and Oklahoma in the south, right through Kansas, Colorado, Wyoming, North and South Dakota, to as far north as the Canadian prairie states of Saskatchewan and Manitoba. These sand dune systems are currently 'stabilised': covered by a protective layer of vegetation, so not even the strongest winds can shift them. But during the Medieval Warm Period, when temperatures in the Great Plains region may only have been slightly warmer than now, these deserts came alive-and began to march across a fertile landscape which today is a crucial food basket for humanity. This historical evidence indeed suggests that even tiny changes in temperature could tip this whole region back into a hyper-arid state.

People who remember the 1930s Dust Bowl might think they have seen the worst drought nature can offer. In the toughest Dust Bowl years, between 1934 and 1940, millions of acres of Great Plains topsoil blew away in colossal dust storms. One, in May 1934, reached all the way to Chicago, dumping red snow on New England. Hundreds of thousands of people, including 85 per cent of Oklahoma's entire population, left the land and trekked west. All this took only an average 25 per cent reduction in rainfall-enough for ploughed farmland to blow away, but the giant dunes stayed put. What awoke the dunes from their long slumber nearly a thousand years ago was drought on an altogether different scale-with dramatically less rainfall, sustained over decades rather than just years.

In a world which is less than a degree warmer overall, the western United States could once again be plagued by perennial droughts-devastating agriculture and driving out human inhabitants on a scale far larger than the 1930s calamity. Although heavier irrigation might stave off the worst for a while, many of the largest aquifers of fossil water are already overexploited by industrialised agriculture and will not survive for long. As powerful dust and sandstorms turn day into night across thousands of miles of former prairie, farmsteads, roads and even entire towns will find themselves engulfed by blowing sand. New dunes will rise up in places where cattle once grazed and fields of corn once grew. For farmers, there may be little choice other than to abandon agriculture completely over millions of square kilometres of what was once highly productive agricultural land. Food prices internationally would rise, particularly if serious droughts hit other areas simultaneously. And although more southerly parts of the United States are expected to get wetter as the North American monsoon intensifies, residents here may not welcome an influx of several million new people.

Further east, however, agriculture may actually benefit from warmer temperatures and higher rainfall. Rather as California offered sanctuary of a sort to displaced Okies' during the Dust Bowl, the Midwest and Great Lakes areas will need to provide jobs and sustenance to those who can no longer scratch a living from the sandy soils far out west, once the rains stop falling and the desert winds begin to blow.

Already the day after tomorrow?

Just as farmers on the High Plains of North America are watching their fields and grasslands blowing away in the relentless heat, their kinfolk across the Atlantic may be grappling with another problem: extreme cold. One of the most counter-intuitive projected impacts of global warming is the possible plunging of temperatures throughout north-west Europe as the warm Atlantic current popularly known as the Gulf Stream stutters and slows down. This is the scenario fictionalised in an exaggerated form by the Hollywood disaster epic *The Day After Tomorrow*, where a collapse in the Atlantic current triggers a new ice age, flash-freezing New York and London (although the good guy still gets the girl). Real-world scientists were quick to lambast the film for flouting the laws of thermodynamics, but they also acknowledged that the reality of a slowdown in the North Atlantic Ocean current may still be pretty scary, especially for those who live in a part of the world which is used to a mild maritime climate far out of keeping with its high northern latitude.

A short technical aside is required here. Only a small part of the great current that delivers warm water into the North Atlantic is actually the real Gulf Stream: it, as its name suggests, is a stream of warm subtropical water heading north-east out of the Gulf of Mexico, which eventually becomes part of the much larger system of currents known to scientists as the Atlantic Meridional Overturning Circulation. The MOC is partly driven by the cooling and sinking of water at high latitudes off the coast of Greenland and Norway, where freezing Arctic air lowers its temperature and squeezes fresh water out as sea ice, leaving behind a heavy, salty brine which quickly sinks to the bottom of the ocean. From there it begins a return journey south-eventually surfacing (1,200 years later) in the Pacific. Scientists have long feared that a freshening and warming of the Norwegian and Greenland seas-due to higher rainfall, run-off from melting land glaciers and the disappearance of sea ice-could stop this water sinking, and shut down the great ocean conveyor. Hence the famous 'Shutdown of the Gulf Stream' scenarios familiar from newspaper headlines and the Hollywood movie.

Far-fetched it may seem, but Atlantic circulation shutdown has always been more than just a theory. It has happened before. At the end of the last ice age, 12,000 years ago, just as the world was warming up, temperatures suddenly plunged for over a thousand years. Glaciers expanded again, and newly established forests gave way once more to chilly tundra. The period is named the 'Younger Dryas', after an arctic-alpine flowering herb, *Dryas octopetala*, whose pollen is ubiquitous in peaty sediment layers dating from the time. In Norway temperatures were 7-9°C lower than today, and even southern Europe suffered a reversal to near-glacial conditions. On the other side of the Atlantic, cooling also occurred, and there is evidence of rapid climate change from as far afield as South America and New Zealand.

The culprit seems to be the sudden shutting-off of the Atlantic circulation due to the bursting of a natural dam holding back Lake Agassiz, a gigantic meltwater lake which had pooled up behind the retreating North American ice sheets. When the dam broke, an enormous surge of water (the lake's volume was equivalent to seven times today's Great Lakes) is thought to have poured through Hudson Bay and out into the Atlantic. This freshwater surge diluted the North Atlantic seas and stopped them being salty enough to sink, interrupting the deep ocean current and triggering climatic destabilisation across the world.

Obviously today there are no gigantic ice lakes waiting to flood into the North Atlantic, but global warming could still interrupt the formation of deep water by melting sea ice and causing greater freshwater run-off from Siberian rivers. Despite the rapidly melting ice cap, however, for many years there was no evidence that changes in the Atlantic MOC were actually happening, and many oceanographers had begun to pooh-pooh the theory. That was until the RSS *Discovery*, a scientific research vessel owned by the British government, began a routine cruise across the Atlantic in 2004. The ship's scientific team set themselves the task of sampling seawater at various depths on a line drawn between the Canary Islands in the east and Florida in the west, aiming to repeat similar measurements taken in 1957, 1981, 1992 and 1998. They had not expected to discover anything terribly exciting; in fact the team leader Professor Harry Bryden confided to one journalist: ‘In 1998 we saw only very small changes. I was about to give up on the problem.’

But 2004 was different. Bryden and his colleagues found that less warm water was flowing north at the surface and less cold water was flowing south at depth. Overall, the Atlantic circulation had dropped by 30 per cent, equivalent to the loss of 6 million tonnes of water flow per *second*. No wonder Professor Bryden admitted that he was ‘surprised’. Suddenly the slowing-down of the great Atlantic current system was no longer just a hypothesis postulated for the distant future. It was already happening.

The media reaction was instantaneous. ‘Current that warms Europe weakening’, warned CNN. NPR's *All Things Considered* show led with Atlantic Ocean's heat engine chills down'. In Europe, the response was one of understandable concern. Alarm over dramatic weakening of Gulf Stream', reported the UK's *Guardian* newspaper on 1 December 2005. ‘Global warming will bring cooler climate for the UK’ was the *Telegraph's* take on the same story. A couple of paragraphs down, the paper reported one expert as confirming that ‘an average temperature drop of a degree or two within decades would herald more extreme winters’.

Older readers would have shuddered at the thought of a return to winters as bitter as that of 1962-3, when the UK was blanketed in snow for more than three months, and temperatures hit a low of–16°C in southern England. In places the sea froze, and ice floes appeared in the river Thames at London's Tower Bridge. That season was about 2.7°C colder than average-almost exactly the temperature drop predicted for London in one modelling study investigating the possible result of a 50 per cent drop in the warm Atlantic current. Was Europe's new ice age just around the corner?

Apparently not. Almost exactly a year later, and with much less fanfare, *Science* magazine reported that ‘a closer look at the Atlantic Ocean's currents has confirmed what many oceanographers suspected all along: there's no sign that the ocean's heat-laden “conveyor” is slowing’. Instead of just the snapshot data generated by a few irregular ship cruises, nineteen permanent instrument-laden sensors had now been stretched across the Atlantic between West Africa and the Bahamas-and they were able to deliver a much more consistent picture. A year of continuous monitoring, Harry Bryden now reported to a conference in Birmingham, showed that his original 30 per cent decline was just a part of random natural variability after all, the sort of thing that happens constantly from one year to the next.

This result was a triumph for the modellers, most of whom had for years been pouring cold water on the European ice age theory. They agreed that huge volumes of freshwater would need to surge into the North Atlantic in order to shut off the Gulf Stream-far more than currently being generated by melt from Greenland or higher precipitation in Siberia. Rather than plunging overnight, the ocean circulation might decline by a stately 25 to 30 per cent or so, but only after at least 100 years of sustained greenhouse gas emissions. Even then, it wouldn't cool Europe-it would simply moderate the otherwise rapid rise in temperatures.

As the IPCC concluded in 2007: ‘it is … very unlikely that the MOC [Atlantic Meridional Overturning Circulation] will undergo a large abrupt transition during the course of the 21st century’. Although all of them showed some weakening by 2100, none of the models assessed by the IPCC supported the collapse scenario. And even with this MOC slowdown, the IPCC reported that ‘there is still warming of surface temperatures around the North Atlantic Ocean and Europe due to the much larger effects of the increase in greenhouse gases’. The IPCC's judgement was final: there would be no new ice age for Europe.

Africa's shining mountain

The amateur adventurer Dr Vince Keipper had waited years for this day. Nearing the summit of Kilimanjaro, the highest point on the African continent, Keipper and his group were looking forward to panoramic views of the surrounding Kenyan and Tanzanian plains. They had climbed through the steep and treacherous Western Breach and past the towering ice cliffs of the Furtwängler Glacier. The weather was perfect, with only a few clouds far beneath. Then, not far from the top of the 5,895-metre peak, a loud rumbling sound from behind them brought the group to a sudden halt. ‘We turned around to see the ice mass collapse with a roar,’ remembered Keipper. ‘A section of the glacier crumbled in the middle, and chunks of ice as big as rooms spilled out on the crater floor.’ Keipper and his group knew they had had a lucky escape: they might have been buried had the collapse happened only a few hours earlier. They also knew that the event they had just witnessed had a powerful symbolic resonance: right in front of their eyes, the highest peak in Africa was melting.

Kilimanjaro has become something of a poster child for the international climate change campaign. The Swahili words *kilima* and *njaro* translate as ‘shining mountain’, testament to the power of this massive volcano to inspire awe in onlookers through the ages. A recent aerial photo of the crater, with little more than a few ice fragments encrusting its dark sides, was the centrepiece for a touring global warming photography exhibition sponsored by the British Council in 2005. During the 2001 UN climate change conference in Marrakech, Morocco, Greenpeace sent a team to Kilimanjaro to hold a press conference by video link from beside one of the mountain's disappearing glaciers. Kilimanjaro's international celebrity status has also attracted the attention of climate change deniers, who suggest that deforestation on the mountain's lower slopes is more to blame for glacial retreat than global warming.

None of the contrarian rhetoric cuts any ice, so to speak, with Lonnie Thompson, a glaciologist at Ohio State University and a man who is deservedly one of America's most celebrated natural scientists. Thompson pioneered the drilling of ice cores in inaccessible mountain regions, bringing back ice tens of thousands of years old from glaciated peaks as remote and far apart as Peru's Nevado Huascarán and Tibet's Dasuopu, often pushing himself to the edge of human endurance in the process. In

1993 Thompson and his drilling team camped for 53 days at 6,000 metres between the two peaks of Huascarán, perhaps setting a world record for high-altitude living. (I stayed there for one night in 2002-one of the most freezing, wind-blasted and wretched nights of my life.) At one point a gale blew Thompson's tent, with him inside, towards a precipice-until he jammed his ice axe through the floor. 'I don't understand,' he once remarked, 'why anyone would want to climb a mountain for fun.'

As Thompson was one of the first to recognise, this mountain ice contains a unique record of climate variations down the ages-preserved in layers of dust, isotopes of oxygen and tiny bubbles of gas trapped within the frozen layers of water. Once carried down in freezer boxes and analysed in the laboratory, these icy signatures trace everything from droughts to volcanic eruptions from decades and centuries past. They also tell a story about past temperature changes: the two isotopes of oxygen, ^{16}O and ^{18}O (which have different atomic weights due to the presence of two more neutrons in the latter's nucleus), vary in abundance with water temperature, so their proportions in ice cores are a good 'proxy' record of ancient climates.

Thompson and his team also drilled on three of Kilimanjaro's remaining glaciated areas, and in October 2002 concluded that 80 per cent of the mountain's ice had already melted during the past century. The news made international headlines, along with Thompson's prediction that the rest of the ice would be gone by between 2015 and 2020. As he readily admitted, this prediction was not based on complex computer modelling or any other advanced techniques. 'In 1912 there were 12.1 square kilometres of ice on the mountain,' he told journalists from CNN. 'When we photographed the mountain in February of 2000, we were down to 2.2 square kilometres. If you look at the area of decrease, it's linear. And you just project that into the future, sometime around 2015 the ice will disappear off Kilimanjaro.'

If there was an urgency in Thompson's voice, this was because he knew that recent melting had already begun to destroy the unique record of past climate preserved in Kilimanjaro's glaciers.

In their analysis of dust layers in the ice, the scientific team found evidence of a marked 300-year drought four thousand years ago; a drying so severe that it has been linked to the collapse of several Old World civilisations across North Africa and the Middle East. The ice also indicated much wetter conditions even longer ago, when huge lakes washed over what is now Africa's dry Sahel. Close to the surface Thompson's team discovered ice containing a layer of the radionuclide chlorine-36, fallout from the American 'Ivy' thermonuclear bomb test on Eniwetok Atoll in 1952. With this precise time control, the scientists could tell that ice which would have preserved a record of climate fluctuations since the 1960s had already melted away.

Moreover, the oldest ice at the base of the cores proved to be over 11,000 years old, showing that at no time since the last glacial epoch has the peak of Kilimanjaro been free of ice. This discovery made Thompson's ice cores even more valuable, for the simple reason that within as little as ten years the sawn-up circular cores in Ohio

State University's walk-in freezer will be the only Kilimanjaro ice left anywhere in the world. With this in mind, Thompson and his team have already decided that some of the ice will be kept intact for future generations of scientists to dissect with new technologies, possibly unlocking climatic secrets still undreamt of today.

The efforts of climate change deniers to suggest that there is something special about the disappearance of Kilimanjaro's glaciers are undermined by similar changes taking place in mountain ranges right across the world, not least in the Rwenzori Mountains of Uganda, nearly a thousand kilometres to the north-west. In this remote region, where Uganda borders the Democratic Republic of the Congo, the fabled ‘Mountains of the Moon’ generate such heavy rainfall (about 5 metres per year) that the cloud-shrouded peaks are only visible on a few days out of every year, and form the main headwaters of the river Nile. At the top of the highest peak, the 5,109-metre Mount Stanley (named after the explorer, who passed by in 1887), ice and snow deny the summit to all but the most determined mountaineers. Yet as at Kilimanjaro, glacial retreat in the Rwenzoris has been profound: the three highest peaks have lost half their glacial area since 1987, and all the glaciers are expected to be gone within the next two decades.

Elsewhere in the world, disappearing mountain glaciers pose a major threat to downstream water supplies. But Kilimanjaro's ice cap is so small that its final disappearance will make little difference to the two major rivers-the Pangani and the Galana-which rise on its flanks. Instead, the crucial water link for Kilimanjaro is not the glaciers, but the forests. The montane forest belt at between 1,600 and 3,100 metres provides 96 per cent of the water coming from the mountain-this lush tangle of trees, ferns and shrubs not only captures Kilimanjaro's torrential rainfall like a giant sponge, but also traps moisture from the clouds which drape themselves almost permanently around the mountain's middle slopes. Much of this water drains underground through porous volcanic ash and lavas, and emerges in waterholes-vital for local people as well as for wild animals-far away on the savannah plains.

So is Kilimanjaro's water-generating capacity safe from global warming? Not quite: rising temperatures and diminishing rainfall increase the risk of fires, which have already begun to consume the upper reaches of montane forest. By the time the glaciers have disappeared, so will the higher forests, depriving downstream rivers of 15 million cubic metres of run-off every year, according to one estimate. In contrast, the loss of glacial water input will likely add up to less than 1 million cubic metres annually: significant, but not catastrophic. The diminishing water supply will affect everything from fish stocks to hydroelectric production downriver in poverty-stricken Tanzania. Much of the mountain's world-famous biodiversity (Kilimanjaro hosts twenty-four different species of antelope alone) will also be threatened by the weather changes.

As the snows disappear, so will much of the wildlife and the verdant forests that tourists currently trek through on their arduous journey to the roof of the African continent.

Far to the north of Kilimanjaro, in the Sahel, another drought-stricken area could by this time be experiencing some blessed relief. The Sahelian region of North Africa has long been synonymous with climatic disaster: during the 1970s and 80s famines struck the area with such severity that they sparked massive humanitarian relief efforts like Band Aid and Live Aid. Reporting from Ethiopia's refugee camps in 1984, the BBC's Michael Buerk spoke of a ‘biblical famine’ as the camera swept slowly over the dead and dying. Over 300,000 people perished during earlier famines in the 1970s.

The Sahel is an immense area, stretching in a wide belt east to west across northern Africa from Senegal on the Atlantic coast to Somalia on the Indian Ocean. For the most part savannah and thorn scrub, it is a climatic transition zone between the hyper-arid Sahara to the north and the lush tropical forests which grow nearer to the equator in the south. Intermittent rains mean that nomadic cattle herding has long been a dominant way of life, with people wandering far and wide through the seasons in search of grazing for their livestock. It is often assumed that global warming will further desiccate the Sahel, allowing the Saharan dunes to march south into Nigeria and Ghana, and displacing millions in the process. Although the forecasts are tentative and uncertain, both palaeoclimatic studies and computer models suggest that the reverse might be true. As other parts of Africa shrivel in the heat, could the Sahel end up as a refuge?

For clues to how the area's climate might alter, we need to venture north into the great Sahara. Here, the world's largest desert has also seen the highest temperature ever recorded on Earth: a truly blistering 58°C. The Sahara covers an area so huge that the entire contiguous United States would comfortably fit inside. This desert doesn't just have sand dunes, it has sand mountains, some reaching to nearly 400 metres in height. It is so completely uninhabitable that only a sprinkling of people get by in a few dwindling oases and at the desert's edge.

But scattered over this enormous area are clear signs that a very different Sahara existed many thousands of years ago. Neolithic paintings and rock carvings have been discovered in places where settled human existence is utterly impossible today. This ancient art depicts elephants, rhinoceroses, giraffes, gazelles and even buffalo-all animals which currently roam only hundreds of kilometres to the south. In Egypt's hyper-arid Western Desert, where less than 5 mm of rain falls on average each year, arrowheads and flint knives for hunting and butchering big game have been unearthed by archaeologists. At one site in south-western Libya, archaeologists even discovered tiny flint fish-hooks-again in an area where no trace of surface water persists now.

Other indications of a wetter past have also been discovered. Although anyone crossing Egypt's dry Safsaf Oasis by camel would today see little more than rock and dunes, radar pictures taken from the space shuttle *Endeavour* in 1994 clearly show whole river valleys buried beneath the sands. These ghostly watercourses even include major tributaries to the Nile flowing out through modern-day Sudan, all long-dry and forgotten beneath the dust. In southern Algeria, huge shallow lakes once gathered, supporting plentiful populations of fish, birds and even Nile crocodiles. The carbon dating of freshwater snails and desiccated vegetation preserved in these old lake beds shows that between five and ten thousand years ago the desert edge retreated 500 kilometres further north, and at different times almost disappeared altogether.

On the borders of what is today Chad, Nigeria and Cameroon, an immense lake, over 350,000 square kilometres in area, extended across the southern Sahara. Nicknamed Lake Mega-Chad, after its modern-day remnant Lake Chad, this gigantic inland sea was the largest freshwater body that Africa had seen for the last two and a half million years. It would have been only slightly smaller than today's largest lake, the Caspian Sea. Strange ridges of sand, which today lie marooned far away in the desert, reveal the shores of the old lake, as do the shells of long-dead molluscs which once thrived in its warm, shallow waters. The flat landscape between the marching dunes testifies to the erosive power of its long-vanished waves.

Common sense suggests that a major lake in such an arid area could only have been maintained by much higher rainfall, and longer-term records do indeed show that the Saharan region has experienced repeated wet and dry episodes over cycles of many thousands of years. The coldest periods of the ice ages tended to be the driest in the Sahara, whilst warm interglacials brought rain-allowing life to emerge once again. During the early Holocene epoch, 9,000 to 6,000 years ago, the northern hemisphere summer sun was slightly stronger than today, thanks to a small cyclical shift in the Earth's orbit around the sun. The increased heating warmed up the giant North African landmass to such an extent that it powered a monsoon-just like the one that brings annual summer rains to the Indian subcontinent today.

Monsoons are based on the simple principle that land surfaces heat up quicker in the summer than the surrounding oceans. This creates an area of low pressure as the hot air in the continental interior rises, sucking in cooler, moister air from the neighbouring seas. These rain-bearing winds bring torrential summer downpours to monsoonal climates such as India's, where agricultural life revolves with this annual cycle. The African summer monsoon is weaker and less generally recognised, but is still the only source of reliable rainfall for the Sahel. Climate models project that land surfaces will warm much faster than the oceans during the twenty-first century, potentially adding a boost to summer monsoons. So with one degree of global warming, this monsoon could begin to gain power and penetrate once again far into the African continent, greening the Sahara.

But will it actually happen? Before anyone makes plans to move large-scale food production to the central Sahara, a note of caution needs to be sounded. During the early Holocene, an additional monsoon driver was the difference in the distribution of solar heat between the two hemispheres. This time the whole globe is heating up, so the past is not a perfect analogue for the future. Moreover, it would be wrong to get the impression that the more humid Sahara was some kind of verdant wonderland-rainfall totals mostly only reached 100 mm or so, enough to support