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Facing future climate change: is the past relevant?

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From a socio-economic perspective, the 'sharp end' of climate research is very much about looking forward in time. As far as possible, we need to know what to expect and approximately when to expect it. However, it is argued here that our approach to climate change (including its scientific basis and its policy implications) is firmly linked to our understanding of the past. This is mainly due to the role played by palaeoclimate reconstructions in shaping our expectations of the climate system, in particular via their ability to test the accuracy of our climate models. Importantly, this includes the intuitive models that each of us carries around in our mind, as well as the more complex numerical models hiding inside supercomputers. It is through such models that palaeoclimate insights may affect the scientific and political judgements that we must make in the face of persistent and ultimately irreducible predictive uncertainty. Already we can demonstrate a great deal of confidence in our current understanding of the global climate system based specifically on insights from the geological record. If further advances are to be made effectively, climate models should take advantage of both past and present constraints on their behaviour, and should be given added credence to the extent that they are compatible with an increasingly rich tapestry of past climatic phenomena. Furthermore, palaeoclimate data should be accompanied by clearly defined uncertainties, and organized in arrays that are capable of speaking directly to numerical models, and their limitations in particular.

Keywords: palaeoclimatology; palaeoceanography; climate prediction; public perception; uncertainty; judgement

1. Selective doubt

In February 2008, a treasury committee called for the creation of a new post in the British government: the Minister for Climate Change. This follows up on the creation in 2006 of the Office for Climate Change to coordinate government policy and act as an advocate for climate change issues. The UK is not alone in signalling the special political importance (at the very least) of climate change: the Australian government, in a recent policy reversal, now includes a department of climate change and appointed its first Minister for Climate Change and Water in December 2007. These developments may be

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symptomatic of a more widespread shift in public discourse on the issue of global climate change. No doubt, part of the reason for this shift is that the scientific assessment of climate change, coordinated by the Intergovernmental Panel on Climate Change (IPCC), has become increasingly emphatic (Solomon *et al.* 2007) and high profile (Kerr & Kintisch 2007). The latest IPCC assessment report has thus indicated scientific confidence and consensus that: (i) global temperatures are rising, (ii) this temperature increase and attendant impacts are attributable to anthropogenic greenhouse gas emissions, and (iii) previously accumulated and future emissions will contribute to further global climate impacts (Pachauri & Reisinger 2007). The shift in public discourse, and public mood, in response to the growing scientific consensus is difficult to characterize precisely. While a number of influential people have publicly relinquished their apparent denial of the reality or importance of global climate change (Brissenden 2006; MacAskill 2007), others continue resolutely with their rejection of the scientific consensus.

The technique used by many deniers is what might be called 'the manipulation of uncertainty into selective doubt'. This takes advantage of scientific uncertainty, for example uncertainty in predictions of global mean temperature, in order to bias our assessment of climate predictions in an unscientific way. That is, it aims either to create the impression that our theories have no predictive power at all or to form the prejudice or unconscious assumption that only part of the existing range of scientific uncertainty needs to be considered seriously. This technique therefore seeks to encourage selective expectations, for example, of no significant change in climate, generally on the basis of prevailing social mores or proposed economic imperatives (e.g. short-term personal gain). Thus, there is no scientific basis for the assertion made by Lawson (2006) that 'while the prospect of catastrophic consequences from global warming cannot be regarded as impossible, nor can [the possibility] … that over the next hundred years or so, the world might enter a new ice age'. Nevertheless, with this equivocation, Lawson appears to wish to induce the selective expectation that cooling is equally plausible as warming (and therefore presumably no change at all), regardless of the available scientific evidence. We are thus encouraged to believe that climate scientists essentially know nothing about future climate and should therefore be ignored, or lampooned as priests in the 'new religion of eco-fundamentalism' (Lawson 2006).

In his 1963 lecture, *This Unscientific Age*, Richard Feynman characterized the process of becoming convinced of telepathy (of which he was in serious doubt) as one of overcoming prejudice. Feynman had a method, and importantly an enthusiasm, for overcoming his self-proclaimed prejudice against telepathy if at all possible, not least owing to the very serious implications of telepathy for his field of study, physics. The method in question is the scientific method, which operates by applying constraints from experiment and observation to eliminate prejudice as far as possible (e.g. Popper 1963). The bottom line in Feynman's anecdote is that a proposition is not incorrect because it is uncertain or more unlikely because it carries major consequences. Rather a proposition gains credibility to the extent that it cannot be shown to be inconsistent with as many other mutually consistent beliefs as possible. Indeed, because uncertainty can never be completely eliminated, the best we can do, in principle and practice, is to diligently cross-check the mutual consistency of our theories to an extent that allows doubt to be sufficiently curtailed for judgements to be made (e.g. Wittgenstein 1975). Some of these judgements may be scientific assessments of 'the balance of evidence', while others may constitute policy recommendations. In the latter case, it is possible that our judgements may incorporate more criteria than are provided by science alone. Personal or social values may certainly colour the application of scientific knowledge in political decisions. Nevertheless, any political decision that fails to take full account of the scientific evidence, through manipulation or selective interpretation, cannot be called reasonable (even if it may be well calculated).

These considerations are relevant to the recurrent public/media misunderstanding/manipulation of the scientific uncertainty associated with climate change predictions, because they underline the fact that all knowledge (even rigorously tested knowledge) is framed by a degree of uncertainty, in spite of which we must still make reasoned scientific and political judgements. Most importantly, we are reminded that we must treat this type of uncertainty differently from the uncertainty of a dice roll. A more lucid analysis of this issue has been provided by McIntyre (2007), who has likened our journey into the Anthropocene to that of a car speeding into the fog along an unfamiliar and unmapped, twisty road (McIntyre 1997). We all know what we would do in these circumstances; we would drive cautiously and slowly if possible. But why should we do this? Why do we not settle the matter on the toss of a coin instead (anything could lie ahead: heads I speed up, tails I slow down)? Clearly, it has to do with an evaluation of the penalties associated with forming incorrect expectations. Unless we have been able to repeat an experiment (e.g. future climate) numerous times, it is likely that we will have to evaluate the penalties associated with incorrect predictions on the basis of some pertinent set of experiences. This is one reason for the defensibility of the *precautionary principle*, which need not be timid or without ambition (as the Machiavellian political tradition may testify). Indeed, it is worth noting that precaution can be applied to either action or inaction: precaution itself is hardly a questionable principle.

If we (the public) are to be given a clear and truthful picture of the uncertainty of climate prediction, and more importantly are to evaluate sensibly the choices that the spectre of climate change presents to us, it is imperative that we are able to see the point of the 'McIntyre foggy road' simile. Of course, it is also desirable to dispel the fog itself, and narrow our scientific uncertainties as much as possible. In this perspective, I try to argue that both of these goals are eminently well served by the exposure and analysis of the Earth's past. The history of global climate may serve as a unique pedagogic tool, cautionary tale and calibration metric. The sum of useful knowledge certainly does not lie in the past, but our understanding of the climate system (whether intuitive or objective) would be greatly impoverished without the retrospective provided by the palaeoclimate archive.

2. Looking back to the future

If there is one central value of palaeoclimate reconstruction (with regard to future climate prediction), it is surely its ability to show us what aspects of the climate system we really do *not* understand well enough. It has been said that the past gives us a unique sense of reality by allowing us to feel out the 'contours of the unknown' (Berlin 1996). The value of such groping should not be underestimated, as it informs the content and accuracy of our climate models. This applies to the 'intuitive models' that we all carry around in our minds, as well as the complex numerical representations of physical reality that are hidden away in computers. It is through a hierarchy of models of this breadth that the history of past climate change can inform our expectations of the climate system, either by calibrating our climate extrapolations and parametrizations or by surprising us with phenomena that are not observed today and remain difficult to explain.

(*a*) *A pedagogic tool*

In the public sphere, insights from the past can help to determine how we receive climate change predictions, and in particular how we treat the uncertainty of these predictions. The climate records shown in figure 1 may be used to illustrate this point. At the very most, the clear and consistent link shown in figure 1 between changing atmospheric carbon dioxide (CO_2) concentrations and changing global climate over the last *ca* 800 000 years might be taken to provide a rough (if rather unreliable) 'statistical' model of the global climate (Wolff *et al.* 2005). However, this sort of model has no physical content: correlation is not a proof of causation. Nevertheless, the impact of viewing anthropogenic CO_2 projections within a long-term geological context as shown in figure 1 is unmistakeable: we (the public) are compelled to take questions about the future seriously, and may be motivated to find out more about the climate system as a result. If records such as those shown in figure 1 are able to compel the public to engage with the science of climate change, and to listen seriously and critically to the analyses of the risks associated with climate change, then they would have performed an invaluable task (perhaps the most challenging).

The compelling nature of global climate history is further illustrated by recurrent reference to the past in public debate. Unfortunately, however, this often amounts to a manipulation of palaeoclimate evidence to insinuate a sort of 'plus ça change' theory of global climate (e.g. Lawson 2006; Lomborg 2007). Some examples of past climatic phenomena that have been misconstrued as evidence against an anthropogenic influence on climate (or against the significance of such an influence) include: (i) the rise of Northern Hemisphere temperatures since the Little Ice Age (*ca* 400–200 years ago), implying a non-anthropogenic explanation for warming, (ii) the fact that atmospheric CO_2 started to increase slightly *after* Antarctic temperatures across past deglaciations, implying CO_2 may be a passive climate parameter, and (iii) the fact that a glacial period should 'naturally' occur at some point in the future, thus either counteracting or justifying any anthropogenic warming.

The first two of these examples have been used to argue that, if global climate could change irrespective of atmospheric CO_2 in the past, then CO_2 must not have a significant impact on global climate. This argument is a logical fallacy, in that it operates by 'denying the antecedent' (it infers a lack of causation under the false premise of a single causal pathway, as in the flawed argument that 'if it rains the ground is wet; the ground is wet; therefore it is raining'). Regardless of

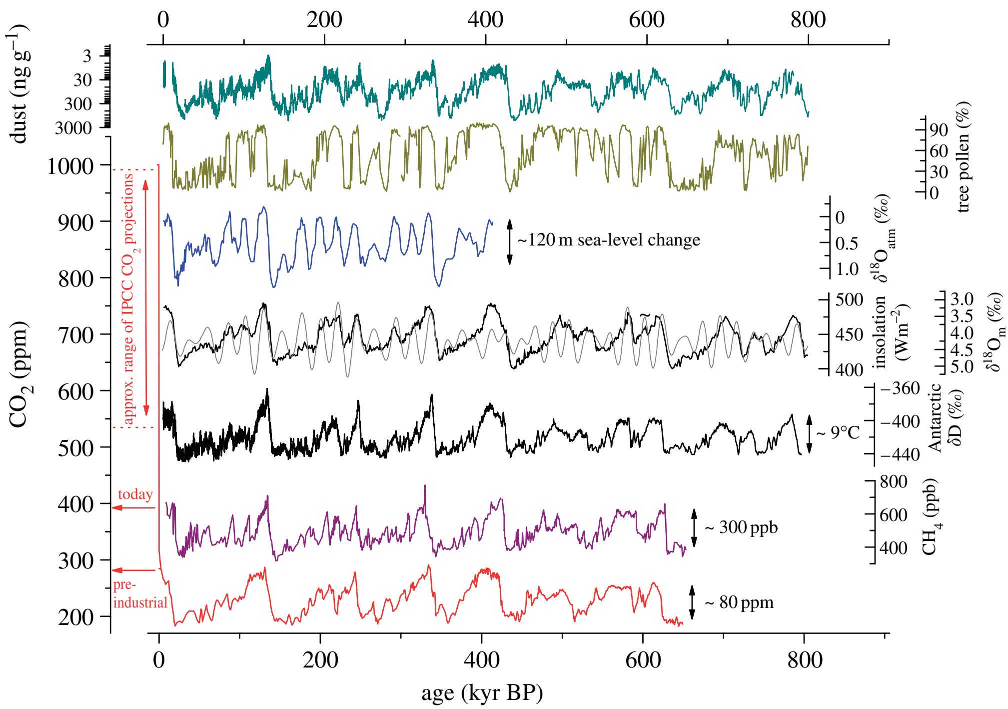

Figure 1. Anthropogenic CO_2, in the context of climate changes over the last 800 000 years. Time axis approaches the present from right to left. Plots show, from top to bottom: (i) dust content of Antarctic ice, suggesting variable supply and/or transport to Antarctica (Lambert *et al.* 2008), (ii) terrestrial vegetation changes recorded in Greece, indicating alternating dry glacials and more temperate interglacials in southern Europe (Tzedakis *et al.* 2006), (iii) stable oxygen isotope fractionation of oxygen gas trapped in Antarctic ice, indicating changes in land-based ice volume, as well as changes in the balance of marine and terrestrial photosynthesis or 'Dole effect' (Petit *et al.* 1999), (iv) stable oxygen isotope fractionation of marine calcite, also indicating changes in land-based ice volume, but including changes in deep-water temperature (black line) (Lisiecki & Raymo 2005), with a record of past Northern Hemisphere summer insolation variability superposed (grey sinusoidal line) (Shackleton 2000), (v) Antarctic temperature, as indicated by stable hydrogen isotope fractionation of Antarctic ice (Jouzel *et al.* 2007), uncorrected for source effects (Cuffey & Vimeux 2001), (vi) atmospheric methane (CH_4) variability, up to pre-industrial times only, and (vii) atmospheric carbon dioxide (CO_2) variability (Siegenthaler *et al.* 2005), including anthropogenic post-industrial era emissions (www.esrl.noaa.gov/gmd/ccgg/trends), and projected CO_2 levels due to future emissions (Nakicenovic *et al.* 2000). Differences between the two sea-level proxies ($\delta^{18}O_{atm}$ and $\delta^{18}O_m$) illustrate the challenge involved in generating accurate long-term ice-volume reconstructions (Shackleton 2000). Note the greatly extended axis for atmospheric CO_2 (y-axis on the left-hand side): atmospheric CO_2 has already increased by as much as glacial–interglacial variability due to post-industrial emissions and projected increases are approximately 2–10 times as large.

this logical fallacy, palaeoclimate reconstructions, in conjunction with numerical models, have shown that while natural (solar and volcanic) forcing of pre-industrial climate can indeed explain the Little Ice Age (and the preceding Medieval Warm Period, *ca* 900–700 years ago), only anthropogenic forcing can adequately explain the extent and rate of post-industrial warming (Jansen *et al.* 2007). Reconstructions of 'palaeo-forcing' are therefore perfectly consistent with both the palaeoclimate response and the anthropogenic warming. That is, we understand the forcing of the last millennium, and the same forcing cannot account for observed post-industrial climate change.

If our understanding of the last millennium is quite tidy, our understanding of glacial–interglacial cycles remains much less so. Since the nineteenth century, it has been suspected that both atmospheric CO_2 concentrations and insolation (the changing exposure of the Earth's surface to solar radiation, due to changes in the Earth's orbit) have played important roles in forcing past glacial–interglacial cycles (Bard 2004). More than 100 years later, we are still lacking a complete synthesis of the processes responsible for past glaciations and deglaciations. Nevertheless, it is quite certain that both processes must have operated through external (insolation) forcing combined with internal (CO_2 and albedo) feedbacks (Jansen *et al.* 2007). This consensus has emerged primarily from the analysis of ice-core and marine palaeoclimate reconstructions (Shackleton 2000; Paillard 2006; Ruddiman 2006*a*,*b*). It underlines the nonlinearity of the deglacial process (Imbrie & Imbrie 1980), which would appear to involve a bistable switching mechanism (Parrenin & Paillard 2003) whereby a threshold amount of Antarctic warming could play a triggering role (Knorr & Lohmann 2007). All of this is the subject of ongoing research. Nevertheless, the fact that Antarctic warming preceded atmospheric CO_2 rise across past deglaciations implies neither logically nor in principle that CO_2 had a passive role in the deglacial process. Rather it underlines emphatically the sensitivity of the climate system to internal feedbacks, including in particular the adjustment of the carbon cycle.

The observation that glacial–interglacial climate changes almost certainly relied on carbon cycle feedbacks makes the proposition that a Northern Hemisphere glaciation is impending or overdue particularly intriguing (the third example listed above). This suggestion has been linked to two possible implications: that anthropogenic warming will soon be reversed naturally, or will have prevented a glacial future. Contrary to the first proposition, it has been suggested based on past relationships between Antarctic temperature, atmospheric CO_2 and insolation that the present interglacial would have naturally lasted at least another 20 000 years (Berger & Loutre 2002; Loutre 2003). This would mimic what occurred the last time that the Earth's orbit was in a configuration similar to the present, during Marine Isotope Stage 11, *ca* 420 000 years ago (Loutre & Berger 2003). Under this interpretation, anthropogenic effects would not be counteracted by a 'natural' glacial cycle any time soon. The second proposition (inconsistent with the first) that anthropogenic warming may have postponed the next glacial is a trickier one. It has drawn support from the hypothesis that significant anthropogenic effects on climate began to accrue well before the industrial era, thus preventing an early glaciation and presumably contributing to the development of human civilization within a warm and relatively stable climatic context (Ruddiman & Thomson 2001; Ruddiman *et al.* 2005). Although the latter hypothesis is hotly debated (Broecker & Stocker 2006; Masson-Delmotte *et al.* 2006), conceptual models that are based on reconstructed palaeoclimate relationships suggest that the next glaciation could in principle be delayed as a result of modern anthropogenic emissions (Archer & Ganopolski 2005). Therefore, regardless of whether the 'postponed early glaciation' hypothesis is correct or not, the ability of human civilization to affect global climate must be emphasized. If Neolithic civilization was already able to delay the next glaciation through its impact on greenhouse gas concentrations, then the modern industrial era will inevitably pack a far greater punch. The most important question is therefore not whether a global glaciation is upon us (it is not), but just *how* warm and/or unstable the extended interglacial period ahead will be. If the future is anything similar to the last exceptionally long interglacial period (MIS 11), then sea level might be expected to rise by tens of metres (Hearty *et al.* 1999; Kindler & Hearty 2000). Although we cannot at present be sure of this sea-level extrapolation, we should consider it seriously given that global mean temperature has probably already risen halfway to MIS 11 levels since pre-industrial times (Hansen *et al.* 2006).

The few examples provided above illustrate how a clear and correct exposure of the Earth's past may provide the public with a robust and balanced perspective on the nature of climate forcing and feedbacks, demonstrating both the limitations of our knowledge of the climate system and the consistency of anthropogenic warming with a host of past climatic phenomena. This use of the palaeoclimate archive appears to have been taken up to great effect by the internet site http://www.realclimate.org.

(*b*) *Calibrations and cautionary tales*

The influence of the palaeoclimate perspective is not restricted to the public sphere of course. In addition to shaping the prejudices of the public (to use Feynman's term), palaeoclimate reconstructions can also influence climate scientists in a more objective, if also less immediate, way by: (i) pointing up specific aspects of the climate system that need to be further developed in our numerical and conceptual models and (ii) directly testing the generality of climate model behaviour. Records of past climate variability can therefore hint at what 'knobs' might be missing from our numerical models and if they might need tweaking.

In general, palaeoclimate studies that aim to inform on climate systematics and future climate prediction will either represent 'calibrations' or 'cautionary tales'. Both approaches can provide invaluable information that might not be obtained otherwise, although both are also subject to distinct limitations. Palaeoclimate calibrations usually aim to provide assessments of 'dangerous' increments in various climate parameters. However, this is usually achieved by assuming a stationary calibration with respect to climate parameters that have not been taken into account or are assumed to remain constant (e.g. insolation, cloud cover, atmospheric dust concentration, vegetation distribution, etc. …). Notably, this type of approach has been used to estimate the expected effects of incremental global warming on ice-sheet stability and sea level (Hansen *et al.* 2006; Overpeck *et al.* 2006). More commonly, palaeoclimate reconstructions provide cautionary tales that are used to illustrate complex climate processes or specific climate events, without necessarily providing a precise description of all the physical mechanisms at work. One important example of this type of contribution is the illustration of thresholds or tipping points in the climate system. Without the geological archive of past climate variability, we would have no grounded notion of all the tipping elements, and respective tipping points, that might exist in the climate system, and still less be able to evaluate them

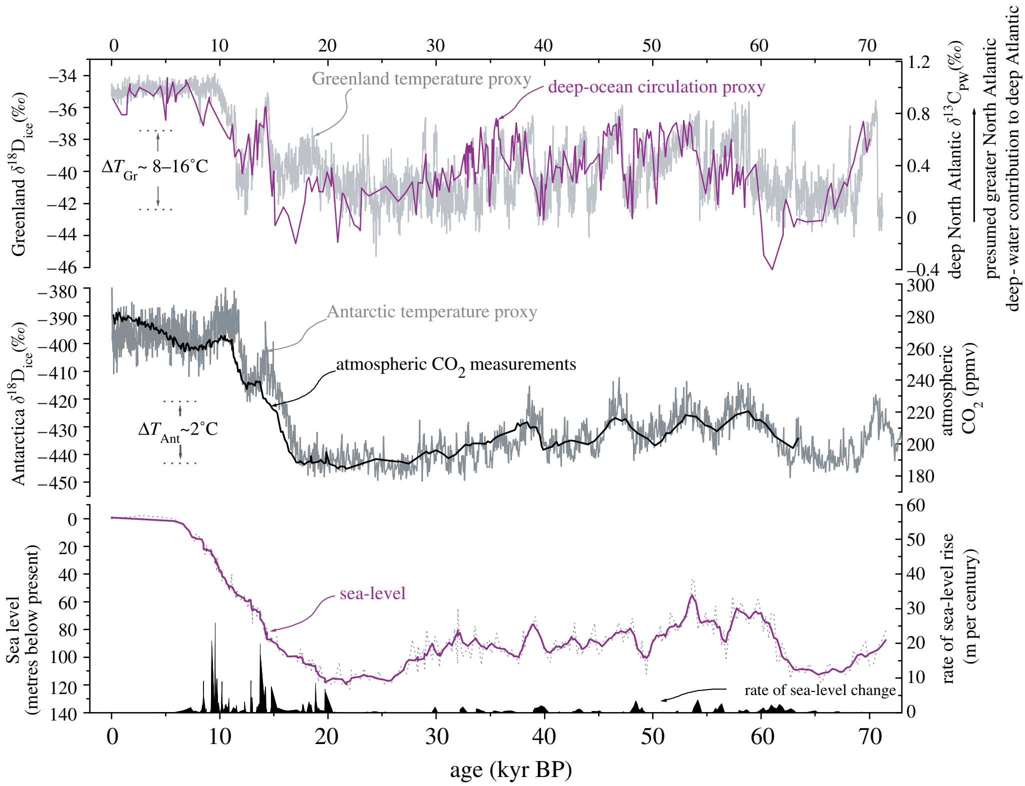

Figure 2. Abrupt global climate change during the last glacial period. Top plots show proxy estimates of past changes in Greenland temperature, indicated by stable oxygen isotope fractionation in Greenland ice (grey line) (Johnsen *et al.* 2001), and deep-ocean circulation in the Northeast Atlantic, indicated by the stable carbon isotope fractionation in the bottom-dwelling foraminifer Planulina wullerstorfii (purple line) (Skinner *et al.* 2007). Middle plots show Antarctic ice-core records of Antarctic temperature, as indicated by stable hydrogen isotope fractionation in Antarctic ice (grey line) (Jouzel *et al.* 2007), and atmospheric CO_2 (black line) (Indermuhle *et al.* 2000; Monnin *et al.* 2001). Bottom plots show reconstructed sea-level variability, based on a compilation of absolutely dated corals and shelf deposits (since 21 000 years before present) (Lambeck & Chappell 2001) and Red Sea stable oxygen isotope modelling (Siddall *et al.* 2003) (dotted grey line, with five-point smoothed solid purple line); and inferred rates of sea-level change (black-filled line). Care must be taken in interpreting the precise relative timing of these archives. The prevailing (yet still debated) paradigm is that the records shown here are linked through ice-sheet instability thresholds and resulting ocean circulation-mediated changes in Atlantic heat transport (EPICA community members 2006).

sensibly (Overpeck & Webb 2000; Alley *et al.* 2003; Lenton *et al.* 2008). Of course, at the same time, without numerical models our interpretation of the 'tipping mechanisms' that operate in the climate system would equally be limited.

An example of past threshold behaviour is illustrated in figure 2, which shows past sea level and climate change since *ca* 70 000 years before present. These records demonstrate a fascinating aspect of our climate system that could not have been discovered or characterized effectively through direct observation and theorizing alone: the Earth's capacity for intense and abrupt changes in climate

(Alley *et al.* 2003). The changes shown in figure 2 were linked to ice-sheet instabilities and greenhouse gas fluctuations, and were telecommunicated across the globe, affecting monsoon systems, tropical rain belts and vegetation distribution (Wang *et al.* 2001, 2006; Sanchez Goni *et al.* 2002; Hughen *et al.* 2004). The world in which these impressive climate changes occurred was clearly very different from today, and we know that this played a major role in their occurrence (e.g. McManus *et al.* 1999; Schulz *et al.* 2002). Nevertheless, the records shown in figure 2 provide a unique 'laboratory' in which specific theories of climate variability can be tested. Climate theory, as encapsulated in a given model, can hardly be called general if it is not compatible with the full range of past climate behaviour. Arguably, this should apply to climate behaviour during both warmer and colder regimes, even if it is a warmer regime that we may expect to inhabit in the future.

Notably, we are still unable to explain adequately (i.e. simulate) the type of changes that are illustrated in figure 2. This is perhaps most worrying in the case of rapid sea-level fluctuations (Chappell 2002; Siddall *et al.* 2003, 2008), which occurred over several centuries and were linked to regional temperature swings and rain belt transitions that were effected within a mere decade (Wang *et al.* 2006; Svensson *et al.* 2008). The point is *not* that the past will necessarily repeat itself, but that our climate theories are not so general or complete as to encompass climate adjustments under different boundary conditions from today's. Of course, a distinction can be made between 'complete models' and 'adequate models': greater complexity need not result in greater predictive accuracy. Nevertheless, it is crucial that we assess objectively what constitutes a model that is adequately complete. The past may help in this regard by revealing unexpected feedback mechanisms or teleconnections. Insights of this nature become especially valuable when they bear on mechanisms that generate threshold behaviour or enhanced sensitivity in the climate system. One is reminded of the McIntyre foggy road simile described above (McIntyre 1997); we can probably afford to be ignorant of small risks, but we cannot afford to misevaluate veritable catastrophes (Oppenheimer & Alley 2005). The long-term history of ice-sheet instability underlines our increasingly worrying uncertainty regarding the rate of Greenland Ice Sheet and West Antarctic Ice Sheet destruction (Witze 2008), and highlights the *upper* uncertainty limit of the most recent IPCC sea-level predictions (Hansen 2005). Precisely because of theoretical limitations (Solomon *et al.* 2007), these IPCC predictions were unable to incorporate the type of ice-sheet dynamics that probably contributed to the palaeoclimate archive (albeit under very different conditions), and that are now becoming apparent through direct observation (Zwally *et al.* 2002; Rignot *et al.* 2004; Rignot & Kanagaratnam 2006).

(*c*) *Model testing*

It has been argued above that the confrontation of palaeoclimate reconstructions with theory-based simulations may point up aspects of climate theory that require urgent attention and improvement. These improvements can very often be achieved without further recourse to palaeoclimate information, through additional work in the laboratory, in the field or at the blackboard. However, in some instances, they may also be achieved through a direct test of model simulations against palaeoclimate reconstructions. Theoretical models of the climate system will always be inaccurate to some degree. In large part, this is because models necessarily have a limited 'structure', or scope of representation (Smith 2002; Stainforth *et al.* 2007). Restrictions on temporal and spatial scales in physical climate models are obvious examples. Slab oceans, simple energy balance atmospheres, abiotic worlds, static vegetation and uniformly parametrized oceanic 'eddy diffusion' are further examples of very useful simplifications that can result in informative and predictive models of some form. Uncertainties in model predictions can, and do, arise from structural simplifications such as these (Smith 2002; Stainforth *et al.* 2007). In highly complex global climate models, uncertainties also arise from parametrizations ('knob settings') and inherent chaotic behaviour, both of which may be tackled without specific geological hindsight (Stainforth *et al.* 2005, 2007; Knight *et al.* 2007). However, if we are to assess the degree to which model truncations may result in qualitatively impaired behaviour, access to independent historical information is imperative. For diurnal or seasonal processes, direct observations obviously provide a basis for verification and improvement of model behaviour. However, for climatic phenomena, which by definition operate on larger spatial and/or temporal scales, the longer term (geological) perspective cannot be ignored. This is especially true for the evaluation of climatic phenomena that are not already directly observed today. The Palaeoclimate Modeling Intercomparison Projects (PMIP and PMIP2) and the palaeoclimate extension of the Quantifying Uncertainties in Model Prediction project (PalaeoQUMP) are examples of palaeoclimate data–model comparisons that ultimately aim to improve climate simulation abilities (Joussaume & Taylor 2000; Edwards *et al.* 2007). In this context, it is worth noting that model verification is strictly only valuable (in a Popperian sense) when it fails, as long as we are able to manage the implications of this failure to the benefit of our collective judgements (Hulme 2007). This underlines the use of testing models where they are the weakest, first and foremost.

Clearly, the relationship between climate prediction (climate theory) and palaeoclimate reconstruction involves some mutual reliance. If reconstructions of past climate behaviour are to influence climate theory, and eventually our predictions, it must be through the intermediary of numerical modelling. However, this is not only because numerical models can provide physical interpretations of palaeoclimate data, but also because models require a diversity of data for their justification and improvement, particularly when the theory incorporated in numerical models remains incomplete or is truncated in the interest of numerical tractability. It is the margins of our predictive abilities that require the most attention if our theories are to be developed further, and palaeoclimate data are probably best suited to test models at the edge of their ability.

3. Looking forward in palaeoclimate research

In §2, it was argued that palaeoclimate reconstructions affect our understanding of climate change on two levels: firstly through effective public engagement and secondly through a dialogue with numerical climate models and the climate systematics that they incorporate. The first of these channels could suggest a useful role for the 'historical turn' in the education and communication of science, including the science of climate change. History is perhaps the most captivating form of non-fiction, and when recounted analytically is especially good at illustrating how to cope with predictive uncertainty. This is a point often made, and expressed most clearly, by social historians (Hobsbawm 1981). The past, perhaps through its combination of immediate cogency and persistent opacity, demonstrates very nicely how the unknown abuts the known, and how we can (and very often do) make sound judgements on the basis of limited knowledge. In this sense, the past provides a wealth of 'priors' for the unconscious modelling of the risks of climate change (i.e. for informing public perception and judgement), and for the more deliberate design of coping strategies that are premised on uncertainty (Dessai & Hulme 2004).

The importance of the dialogue between palaeoclimatology and numerical modelling has implications for both modellers and palaeoclimatologists. For theoreticians and modellers, these are relatively straightforward: a model or theory is not strictly general, and may not be adequate for many applications, if it is unable to explain past climatic phenomena, especially those that surprise us. This does not imply that all climate models should be run out for several millennia or subjected to 'hosing experiments' that simulate massive glacial-era iceberg discharges into the North Atlantic. Rather, it might imply a piecemeal analysis of key elements of the climate system and their sensitivity to different forcing and boundary conditions. First and foremost, this should involve the investigation of 'tipping elements' and their thresholds in the climate system (Lenton *et al.* 2008), for which observational data come primarily from the palaeoclimate archive (Overpeck & Webb 2000; Alley *et al.* 2003; Hansen *et al.* 2006). In this way, palaeoclimate insights would help to decide which models might be inadequately complete to be truly predictive (it will be much more difficult to decide which models are adequate (see, for example, Knutti 2008)).

For palaeoclimatologists, the dialogue with numerical modelling requires that data should be produced and/or arranged in *arrays* that are able to speak directly to numerical models, and their weaknesses in particular. The goal should be to provide robust criteria (as explicit deliverables) for the evaluation and improvement of model behaviour. Arguably, the greatest strength of palaeoclimate reconstruction is not so much in the provision of precise quantitative data (e.g. temperature fields or threshold values) as in the illustration of robust qualitative test criteria. Most notably, this includes relational properties, such as the phasing of climate parameters or the sign of spatial gradients and temporal trends. These might at first appear to be blunt instruments for testing highly complex climate models, but they are in fact fundamental to any analysis of causal processes. The key point here is that the mechanisms responsible for a particular climate state are not necessarily verified by calibrating the realism of that state. One can get the picture right for the wrong reasons, since precision of representation does not guarantee accuracy of explanation. This problem of 'equifinality' is why models that produce consistent equilibrium states need not respond to perturbations in the same qualitative way (Beven 2002).

Some specific recommendations can be made in the field of palaeoceanography, where relational criteria will typically comprise either two spatial dimensions or a spatial dimension and a time dimension (i.e. where we can either produce proxy maps or arrays of proxy time series). Given limitations on resources, and on the

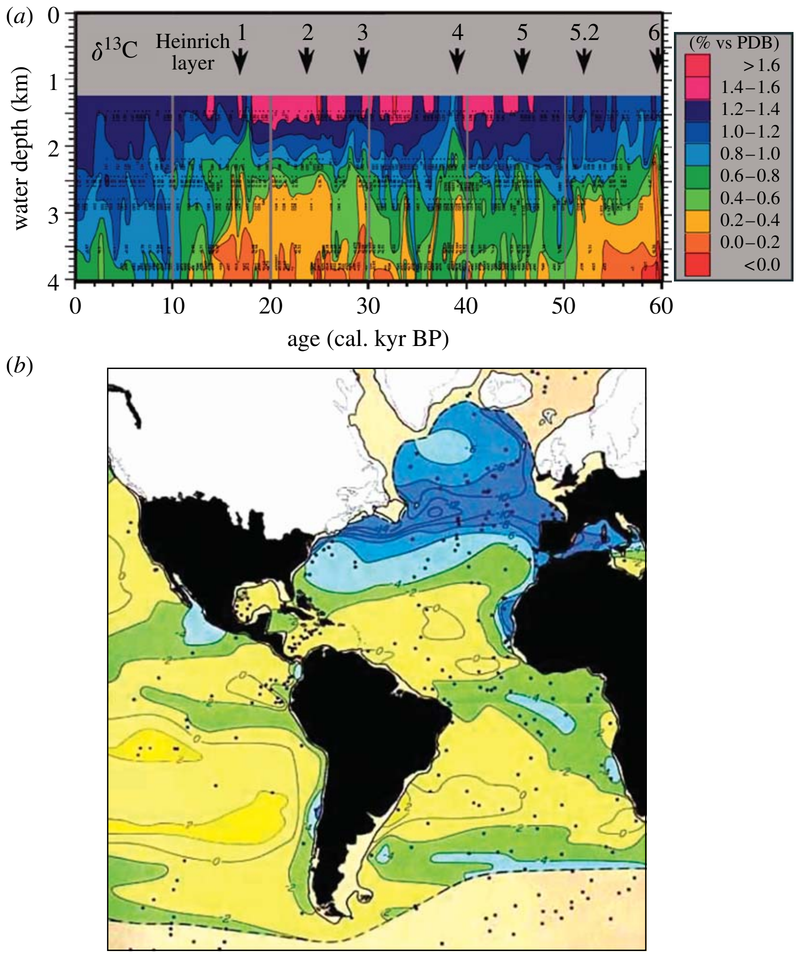

Figure 3. (*a*) Hovmöller diagram reproduced from Sarnthein *et al.* (2000), showing changes in North Atlantic deep-water $\delta^{13}C$ (a proxy indicator of deep-ocean circulation change) through time and across water depth. (*b*) The CLIMAP reconstruction of August sea-surface temperature changes relative to present (contours of 2°C), based on census counts of planktonic foraminifera species preserved in deep-sea sediments from the height of the last glacial period (CLIMAP Project Members 1976). Figure (*a*) contains a time dimension, while (*b*) does not.

time available to deploy these resources (i.e. to report results), one could argue that the most efficient way of providing robust relational test criteria specifically for numerical ocean models would be to focus on 'space–time property' plots, rather than maps. One example of such a diagram, based on palaeoceanographic data (Sarnthein *et al.* 2000), is reproduced in figure 3*a*, alongside the pioneering CLIMAP reconstruction of glacial age sea-surface temperatures in the Atlantic (figure 3*b*). A conjecture (not proven rigorously here) is that there are fewer causal pathways that may account for figure 3*a* than can account for figure 3*b*. If true, this would not detract from map reconstructions such as CLIMAP, but it would illustrate an important point of principle and of pragmatism by emphasizing the value of temporal (causal) constraints. Furthermore, it is worth considering just how difficult it can be to align distal palaeoclimate records chronostratigraphically for the purposes of selecting 'time slices' to map out, especially if one is dealing with high-resolution records of non-identical abrupt changes. The challenge is amplified further if investment in time-series resolution must be sacrificed in favour of investment in spatial coverage, as is often the case.

It would therefore be extremely difficult to generate just two maps of the Atlantic Ocean, one for a North Atlantic stadial (cold event) and one for the subsequent interstadial (warm event). Indeed, this could not be realized adequately using the existing data. By contrast, the challenge of precisely aligning records within a more localized region (such as a water depth transect) is greatly reduced. At the same time, more useful metrics can be provided for data–model comparisons. Hence, while the type of data shown in figure 3*b* might give us some indication of *what* things were similar to those in the past, the type of data shown in figure 3*a* might also be able to suggest *how* they came to be that way. One might therefore propose that palaeoceanographers should spend more time generating space–time property diagrams (currently, only a handful exist). Of course, many would argue that palaeoceanographers should simply spend more time generating temporal or spatial arrays of any type at all. Although one cannot argue with this suggestion, limitations on resources will inevitably require us to make choices in order to optimize our efficiency and scientific impact. Part of the rationale behind the proposition made here is that, in addition to explicitly focusing greater attention on the fundamental importance of stratigraphic correlations and chronologies, significant jumps in our understanding of the ocean–climate system are much more likely to be achieved each time disparate space–time property diagrams are synchronized or compared with model outputs.

One further implication that arises from the palaeoclimate–numerical model dialogue in particular concerns both model simulations and palaeoclimate reconstructions alike. This is the need for greater emphasis to be placed on the definition (i.e. the classification and, if possible, quantification) of simulation and proxy data uncertainty. This requirement does not amount to the simple addition of error bars on proxy data. Rather it refers to a more pressing need for dedicated statistical methods (yet to be developed and widely disseminated in the modelling and palaeoclimate communities) that are able to deal with the complex and often unquantifiable uncertainties inherent in climate extrapolations (Stainforth *et al.* 2007). It is important to note that, while being derived from contrasting principles, model forecasts and proxy reconstructions can actually incorporate very similar types of uncertainty. Proxies are models of climate parameters after all. The most obvious parallels are between model 'inadequacies' (e.g. crude parametrizations, or the complete lack of climate components) (Stainforth *et al.* 2007) and proxy 'biases' (e.g. habitat variability or physiological plasticity) (Bauch *et al.* 2003; Skinner & Elderfield 2005). Both of these types of uncertainty bear on the perils of extrapolation, and neither is easily quantified, let alone explicitly characterized. For example, one cannot always say *how* the seasonal or depth habitat of a foraminifer proxy carrier has changed through time, even if one knows that it did. This would mean that we could not say what aspect of the climate the proxy was sampling. As a result of these fundamental limitations on uncertainty quantification, the replication of results (multiplying our simulations and reconstructions) will become increasingly important. It is likely that, in the future, much greater attention will be focused on the formulation and communication of uncertainty in a manner that allows our prior expectations (which may not actually be 'known') to be usefully declared and therefore objectively manipulated (e.g. Buck & Millard 2004).

In summary, the past certainly is relevant to how we face up to the prospect of future climate change. Primarily, its relevance resides in its influence on the judgements that we make, whether these are intuitive or scientific judgements of what constitutes cause for concern or objective assessments of where extra research efforts should be focused. Palaeoclimate insights can also have a more direct influence on climate systematics to the extent that they inform our numerical models of the climate system. Given the unique nature of anthropogenic forcing relative to the immense diversity of past climatic conditions, probably only a subset of the climatic insights provided by palaeoclimate reconstructions will be of direct relevance to our immediate predictive needs. Nevertheless, everything we learn about past climate dynamics contributes directly to our knowledge of the climate system, and as such contributes to the foundations of any numerical model that seeks to be sufficiently complete, as well as adequately predictive. For scientists and the wider public alike, history may thus provide an invaluable antidote to both explanatory hubris and fanciful speculation.

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