Tyndall°Centre
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'Climate change impacts in the UK on a millennial timescale –
Phase 1: coarse scale climate prediction'

Climate Change on the Millennial Timescale

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1. Executive summary

Two intermediate complexity climate models and one simple climate model were used to study the implications to the year 3000 of six long-term carbon dioxide emissions scenarios: (A) minimum emissions (1130GtC) (B) business as usual followed by a rapid cessation in emissions (2660GtC) (C) rapid and (D) slow combustion of all 4000GtC conventional fossil fuel reserves (E, F) the additional combustion of exotic fossil fuel reserves giving a total of 9210GtC or 15000GtC. The models predict 1.2–15.6°C global warming on the millennial timescale, more than quadruple the 0.9–3.7°C they predicted on the centennial timescale, and more than double the 1.4–5.8°C the IPCC predict for the centennial timescale. At the UK scale, warming is 1.2–10°C on the millennial timescale compared to 1–2°C on the centennial timescale or 1–5°C from UKCIP02. Sea level will still be rising at the end of the millennium. The combined effects of thermal expansion and Greenland ice sheet melt are predicted to lead to up to 11.4m sea level rise by year 3000, such that low-lying areas of the UK including much of London would be threatened with inundation. Business as usual leads to abrupt climate changes in one model, including a change in the North Atlantic circulation in the 22nd century. The same model shows a global scale abrupt climate change long after emissions cease, if exotic sources of fossil fuel are exploited. On the millennial timescale, the ocean becomes a less effective carbon sink the more CO_2 is emitted, and the land can become a net carbon source. Total emissions are the primary controller of millennial climate change, but the rate of emissions controls the speed at which changes occur, and to some degree whether abrupt changes occur, including the severity of the transient land carbon source. Two methods were used to analyse uncertainties in the calculations of sea level rise due to thermal expansion and both suggest that the 5-95% confidence interval on our predictions is within ±25% of the mean. However, uncertainties due to climate sensitivity were not fully explored, it being 2–3°C in the models used here, whilst a review of the literature suggests it could be 1.6–11.5°C. Thus, potential climate changes could be much greater than we predict. If we take a sea level rise of 2m as dangerous, since globally it will displace hundreds of millions of people, and we assume climate sensitivity lies in the range 2–3°C, then only by minimising emissions can dangerous climate change be avoided. Furthermore, unless emissions are minimised, ocean surface pH will fall to potential dangerous levels for the marine ecosystem. Finally, only our minimum emissions scenario can prevent global temperatures from rising more than 2°C relative to pre-industrial time, and if climate sensitivity is >3°C even it will not avoid this.

2. Motivation

Most projections of future climate change focus on the century timescale [*Houghton et al.*, 2001; *Houghton et al.*, 1996; *Houghton et al.*, 1990] (known hereafter as IPCC90, 95, 01 respectively). This surely reflects the human lifetime – we have trouble contemplating the state of the world long after we will cease to live in it – as well as the short-term nature of the political process. At best we might consider the world we are leaving for our grandchildren, but a thousand years ahead seems incomprehensible. This is because we are conditioned to thinking exclusively within the anthroposphere (the human world) – given the changes of human society that have occurred over the last thousand years, it seems great folly to try to predict where humanity might be in a thousand years time. However, if we could step up a level and see things from an Earth system (or 'Gaia') perspective, a thousand years would seem but a blink in the eye of geological time. More pertinently we would realise that the century timescale is far too short to cover the full climate consequences of our actions and policies today [*Hasselmann et al.*, 2003]. Projections to the year 2100 typically leave temperature or sea level, to name but two important variables, rising off the graph, and in some cases their rate of change (i.e. the gradient) is increasing. Thus not looking beyond the year 2100 may be a greater folly than trying to do so, despite all the uncertainties it entails. Furthermore, there are management and infrastructure decisions being made in this decade and the next that have consequences beyond 2100, and hence it is important to factor climate change predictions into these decisions.

There is in fact some 'Earth system logic' to looking at the millennial timescale because it is over the order of a thousand years that the ocean-atmosphere-land system will redistribute the carbon added to the atmosphere by human fossil fuel burning and land-use change [*Lenton*, 2000] . Thus the atmospheric concentration of carbon dioxide (CO_2) with its dominant contribution to radiative forcing approaches equilibrium on the millennial timescale. For this reason, carbon cycle modellers have often taken a long-term view, e.g. [*Bacastow and Bjorkstrom*, 1981; *Lenton*, 2000; *Walker and Kasting*, 1992]. Furthermore, any changes in ocean circulation state are likely to approach equilibrium one thousand years hence. However, thermal expansion of the ocean, ice sheets and their contributions to sea level rise, have a longer timescale of response. Also, over thousands of years, acidification of the ocean by CO_2 uptake will cause the dissolution of carbonate sediments thus further enhancing CO_2 uptake, whilst carbonate weathering will replenish the ocean with alkalinity, allowing the gradual re-establishment of carbonate sediments [*Archer et al.*, 1998].

3. Choice of models and scenarios

We used one simple climate model and two different Earth system Models of Intermediate Complexity (EMICs) to study climate change on a millennial timescale (Table 1). We have not used general circulation models (GCMs) because of the ~1000 year timescale being studied and the desire to do sensitivity studies (i.e., to perform multiple runs). Achieving the required integration time with a GCM would have taken many months on expensive computing resources, whilst it took hours or days with the EMICs on free computing resources, and minutes with the simple model.

The simple Earth system model, described in [*Lenton*, 2000], is referred to as SESM and comprises a 7-compartment carbon cycle coupled to an energy-balance function for surface temperature (Table 1). It is forced with CO_2 emissions and predicts atmospheric CO_2, surface temperature, and changes in land and ocean carbon storage. We used it to develop long-term CO_2 emissions scenarios and make an initial exploration of their effects. It has a climate sensitivity (the equilibrium warming for a doubling of CO_2 from the pre-industrial level) of 2.8°C. Further doublings of CO_2 lead to progressively greater warming, for example quadrupling CO_2 gives 6.3°C warming at equilibrium.

Table 1 Earth system Models used in this study

COMPONENT	SESM [*Lenton*, 2000]	GENIE-1 [*Lenton et al.*, 2006]	MOBIDIC [*Crucifix et al.*, 2002]
ATMOSPHERE	Energy balance model, grey atmosphere approximation, globally averaged surface temperature [*Lenton*, 2000]	Energy-moisture balance model, vertically averaged, non-interactive cloudiness ~5° × 10° (36 × 36 equal area) [*Lenton et al.*, 2006]	quasi-geostrophic model, zonally averaged, non-interactive cloudiness 5°, two vertical layers radiative scheme - one-channel multi-layer scheme for the short wave and four bands multi-layer scheme for the long wave [*Gallée et al.*, 1991]
OCEAN	4-compartment model distinguishing high and low-latitude surface ocean, intermediate waters, and deep ocean [*Knox and McElroy*, 1984]	3-D frictional geostrophic model, rigid lid, isopycnal diffusion, parameterisation of the effect of mesoscale eddies on tracer distribution ~5° × 10°, 8 vertical layers [*Edwards and Marsh*, 2005]	primitive equation model with parameterised zonal pressure gradient, zonally averaged , 3 basins, rigid lid, parameterisation of density-driven downsloping currents 5°, 15 vertical layers [*Hovine and Fichefet*, 1994]
SEA ICE	none	0-layer thermodynamic scheme, drift with oceanic currents, two-level ice thickness distribution (level ice and leads) [*Edwards and Marsh*, 2005]	0-layer thermodynamic scheme, prescribed drift, two-level ice thickness distribution (level ice and leads) [*Crucifix et al.*, 2002]
LAND SURFACE	no land surface physics	bucket model for soil moisture, explicit computation of soil temperature, river routing scheme [*Williamson et al.*, 2006]	bucket model for soil moisture [*Gallée et al.*, 1991]
BIOSPHERE	parameterisation of marine export production [*Knox and McElroy*, 1984], vegetation and soil carbon reservoirs [*Lenton*, 2000]	model of ocean biogeochemistry (Ridgwell, 2001), model of terrestrial carbon storage [*Williamson et al.*, 2006], no dynamic vegetation	model of oceanic carbon dynamics* (Crucifix, 2005), model of terrestrial carbon dynamics* [*Brovkin et al.*, 2002], dynamical vegetation model [*Brovkin et al.*, 2002]
INLAND ICE	none	parameterisation of Greenland ice sheet melt [*Lenton et al.*, 2006]	mechanical model (isothermal), vertically averaged with east-west parabolic profile, ice meltwater routing scheme 0.5° [*Crucifix et al.*, 2002]

* These components are not activated in the experiments

The EMICs are known as GENIE-1 and MoBidiC, their main components are summarised in Table 1 and further details are given in the Appendix. GENIE-1 is a new EMIC, developed in the UK in collaboration between the NERC funded GENIE project (www.genie.ac.uk) and the Tyndall Centre, and this is one of its first uses. MoBidiC is a more established model with a range of past applications, developed at the Université catholique de Louvain, Louvain-la-Neuve, Belgium. The main structural differences between them are: (1) GENIE-1 has a fully 3-dimensional ocean with a 2-dimensional (latitude-longitude) single layer atmosphere, whilst MoBidiC has 2-dimensional (latitude-height) atmosphere and ocean models (with the 3 main ocean basins distinguished and connected by an Antarctic circumpolar current). (2) MoBidiC includes an interactive ice sheet model for East Antarctica, West Antarctica and Greenland, whilst GENIE-1 only has a simple parameterization of Greenland ice sheet melt. (3) GENIE-1 has a fully interactive carbon cycle, so it can be forced with CO_2 emissions scenarios and predicts atmospheric CO_2 concentrations, whilst (in the version used here) MoBidiC cannot. These differences in model structure, and a comparison with SESM, enable us to begin to explore the robustness of our results. The two EMICs have different climate sensitivities: MoBidiC is toward the low end of the range of current models at 2.0°C, whilst the default version of GENIE-1 has a more mid-range value of 3.0°C.

CO_2 emissions and concentration scenarios

The most important potential contributor to the long-term forcing of the climate system by human activities is the amount of fossil fuel carbon we emit to the atmosphere as the greenhouse gas carbon dioxide (CO_2). The reasons are that the potential emissions of CO_2 are huge and it has a long lifetime in the atmosphere; even after ~1000 years, at least ~15% of CO_2 emitted will remain in the atmosphere [*Lenton*, 2000].

An upper limit on total future CO_2 emissions is set by the size of the available fossil fuel reserves. 'Conventional' resources (including coal, oil and gas) are estimated at 4000-5000 GtC, but 'exotic' resources (including methane hydrates) could total a further 10,000-20,000 GtC, giving 15,000-25,000 GtC altogether [*Hasselmann et al.*, 1997]. The IPCC has little to offer in the way of emissions scenarios beyond the year 2100, except for those that are derived from stabilisation scenarios for CO_2 concentration and inverse models (e.g. page 223 of IPCC01). One exception is scenario B (Table 2) an arbitrary extension of the IS92a 'business-as-usual' scenario involving linearly reducing emissions to zero from 2100 to 2200 (page 324 of IPCC95).

We use a total of six long-term CO_2 emissions scenarios (Table 2 and Figure 1a) to explore the effects of emitting different amounts of fossil fuel carbon and of emitting the same amount at different rates. The scenarios span a range of plausible total fossil fuel emissions, and have been used in previous work, thus aiding inter-comparison. 'A' is a minimum emissions scenario. 'B' is our baseline scenario (described above). 'C' and 'D' explore the effects of emitting all conventional fossil fuel resources rapidly (C) or slowly (D). 'F' takes an upper limit of 15,000 GtC exotic plus conventional fossil fuel resources. 'E' is simply intended to fill the large gap in total emissions between scenarios C/D and F, and it amounts to emitting 9000 GtC after 1990.

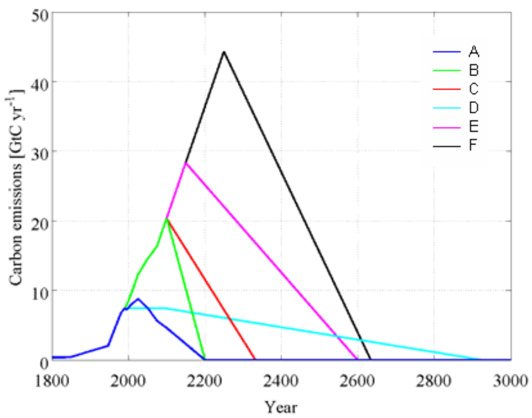
Table 2 Long-term fossil fuel CO_2 emissions scenarios used in this study

Label	Total emission (GtC)	1990-2100	Beyond 2100	Reference
A	1130	IS92c	Linear decline to zero in 2200	[*Lenton*, 2000]
B	2660	IS92a	Linear decline to zero in 2200	IPCC95, [*Lenton*, 2000]
C	4000	IS92a	Linear decline to zero in 2332	[*Lenton*, 2000]
D	4000	1990 level	Linear decline to zero in 2926	[*Lenton*, 2000]
E	9210	IS92a	+0.16 GtC/yr/yr to 2150 then linear decline to zero in 2599	[*Lenton*, 2006]
F	15000	IS92a	+0.16 GtC/yr/yr to 2250 then linear decline to zero in 2634	[*Lenton*, 2006]

Scenario labels are as in [*Lenton*, 2006] and [*Lenton et al.*, 2006]

Both SESM and GENIE-1 have been forced with the six CO_2 emissions scenarios and used to predict atmospheric CO_2 concentrations (Figure 1b). Despite their very different complexity and structure the two models give CO_2 predictions typically within ~10% of each other. SESM predicts a more rapid CO_2 rise but GENIE-1 predicts a slightly higher final concentration. CO_2 concentration in year 3000 for each scenario is: (A) 385-390ppmv (B) 580-604ppmv (C) 841-906ppmv (D) 874-935ppmv (E) 2481-2713ppmv (F) 4539-5015ppmv. For consistency, the CO_2 concentration scenarios predicted by GENIE-1 were used as input to MoBidiC. Thus any differences in climate predictions between the two EMICs are due to differences in the climate models and not the forcing.

(a) (b)



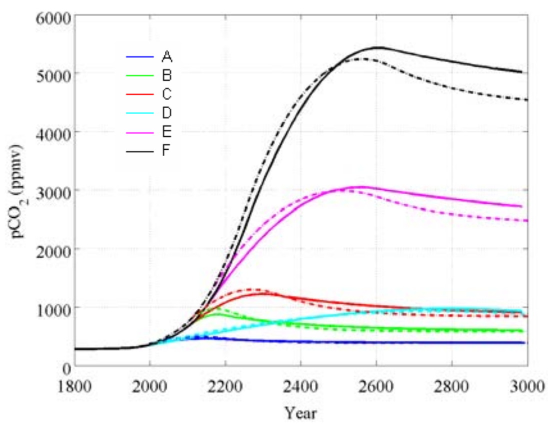


Figure 1 (a) CO_2 emissions scenarios used in this study and (b) predicted CO_2 concentrations in SESM (dashed lines) and GENIE-1 (solid lines).

4. Key results

Global and regional warming could more than quadruple after 2100

Millennial timescale global warming (Table 3) is 1.2-15.6°C in SESM, 1.4-11.6°C in GENIE-1 and 0.9-7.4°C in MoBidiC, whereas on the century timescale it is 2.1-3.7°C in SESM, 1.5-2.4°C in GENIE-1 and 0.9-1.5°C in MoBidiC. Thus the potential global warming on the millennial timescale is more than quadruple that on the century timescale. IPCC01 projects 1.4-5.8°C global warming from 1990 to 2100 from a wider range of models and century timescale emissions (Figure 2). Temperature is generally stabilising by year 3000. For peaked emissions scenarios A-C, temperature may peak and then decline slightly, whereas for scenarios E and F in which exotic fossil fuel resources are emitted, temperature is still rising gradually at the end of the millennium. Even in the minimum scenario A in which emissions decline from 2025 onwards, there is ongoing warming.

Table 3 Global warming in years 2100 and 3000 in the 6 scenarios and 3 models

Scenario	Global warming (°C) from year 1800					
	Year 2100			Year 3000		
	SESM	GENIE-1	MoBidiC	SESM	GENIE-1	MoBidiC
A	2.13	1.45	0.89	1.23	1.44	0.88
B	3.71	2.35	1.45	2.97	3.27	2.00
C	3.71	2.35	1.45	4.73	4.99	2.89
D	2.22	1.50	0.92	4.94	5.02	2.98
E	3.71	2.35	1.45	11.06	9.29	6.19
F	3.71	2.35	1.45	15.59	11.60	7.44

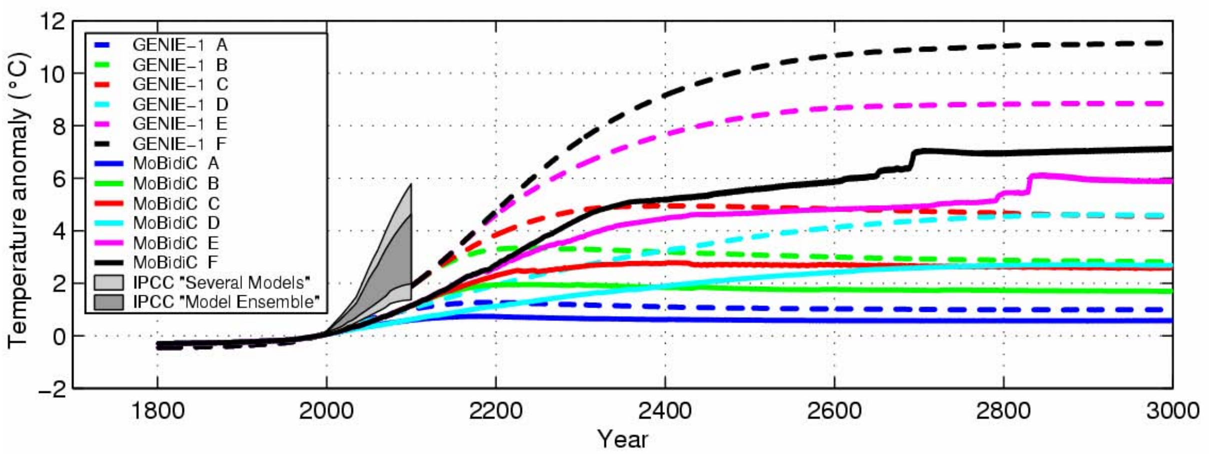


Figure 2 Global warming for all scenarios, comparing GENIE-1 (dashed lines) and MoBidiC (solid lines), with IPCC SRES embedded (using a 1990 baseline)

The spatial patterns of temperature change in GENIE-1 in years 2100 and 3000 are shown in Figure 3 for scenario C. The Southern Ocean warms slowly reflecting the slow warming of the deep ocean. The North Atlantic region has least warming at the end of the millennium due to weakening of the Atlantic overturning circulation. The Arctic and the interior of Eurasia experience the most warming. Amplification of warming in the Arctic agrees with GCM studies, as does the generally greater warming over land than ocean.

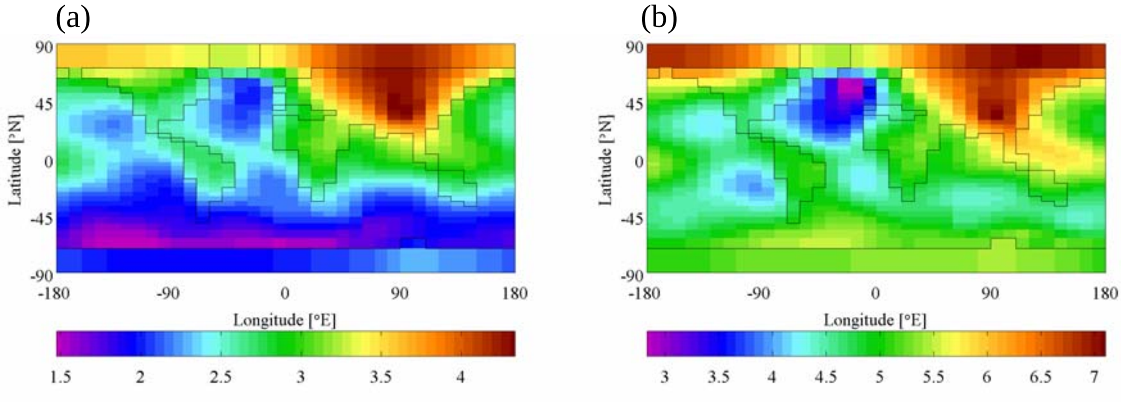


Figure 3 Air temperature change (°C) from pre-industrial in GENIE-1 in (a) year 2100 (b) year 3000 of scenario C (rapid emission of 4000GtC conventional fossil fuel reserves). Note the different scale bars.

Millennial timescale warming in the UK region is 1.5-9°C in GENIE-1 and on continents at the latitude of the UK in MoBidiC it is 1.2-10°C, whereas in 2100 it is only 1-2°C in either model (Figure 4). The UKCIP02 scenarios [*Hulme et al.*, 2002] have annual average UK warming by the 2080s of 1-5°C corresponding to warming rates of 0.1-0.5°C per decade, depending on the emission scenario. The UKCIP02 low emission scenario (matching IPCC SRES B1) follows a path close to scenario A from 2000 to 2100, with 5GtC/yr emitted in 2100, whilst the UKCIP02 high emission scenario (matching IPCC SRES A2 or A1F1) has emissions of almost 30 GtC/yr in 2100, which is higher than the 20GtC/yr in scenarios B, C, E, and F. Hence the lower bound of temperature projections (scenario A) is consistent with the UKCIP02 low emission scenario, whilst the higher bound of temperature projections (scenarios B, C, E and F) fall below the UKCIP02 high emission scenario to 2100.

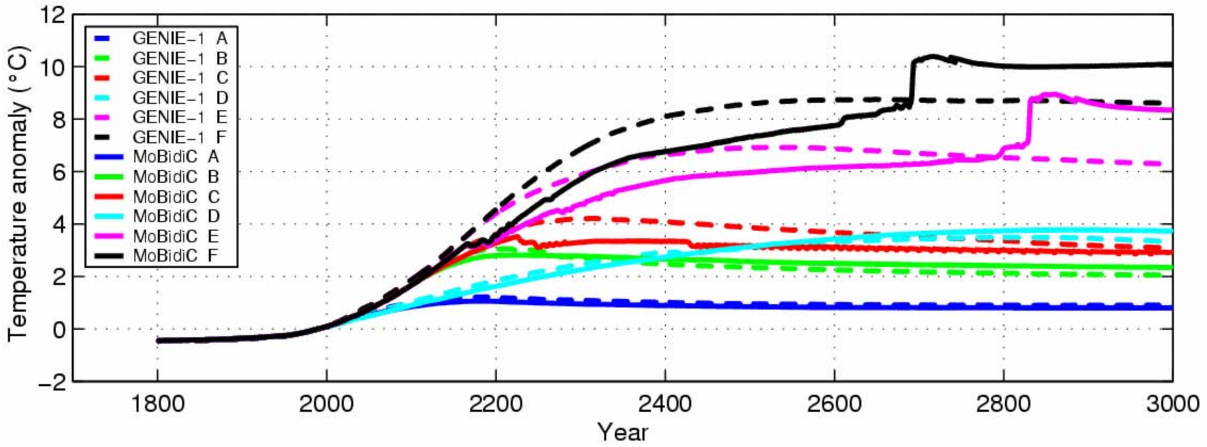


Figure 4 Warming projections for the UK region in GENIE-1 (dashed lines) and the continental European sector at UK latitudes in MoBidiC (solid lines) (1990 baseline).

Sea level will still be rising at the end of the millennium

Potential sea level rise on the millennial timescale (excluding the contribution of Antarctica), is 0.5-11.4m in GENIE-1 and 1.0-8.5m in MoBidiC. In GENIE-1 (Figure 5), 0.5-4.8m is from thermal expansion, plus 0-6.6m from Greenland Ice Sheet (GIS) melt, whereas in MoBidiC 0.5-4.1m is from thermal expansion plus 0.5-4.4m from GIS melt. GIS melt is only completely avoided in scenario 'A' in GENIE-1. In all other combinations of scenario and model, GIS melt begins between the early 22nd and early 23rd century. GIS melt is almost complete in year 3000 of scenario F in GENIE-1 and well on the way to completion under scenario E in GENIE-1 and scenarios E and F in MoBidiC. Collapse of the West Antarctic Ice Sheet, if it occurs, could add up to 4-6m on the millennial timescale [*Oppenheimer and Alley*, 2004], whilst accumulation on the East Antarctic Ice Sheet could lower sea level by ~1m [*Huybrechts and De Wolde*, 1999]. Sea level is still rising in 3000 in all of the scenarios, because the ocean is still taking up heat and expanding, and the GIS is still melting in all but scenario A. IPCC01 project 0.1-0.9m sea level rise from 1990 to 2100. Thus potential sea level rise is an order of magnitude greater on the millennial than the centennial timescale.

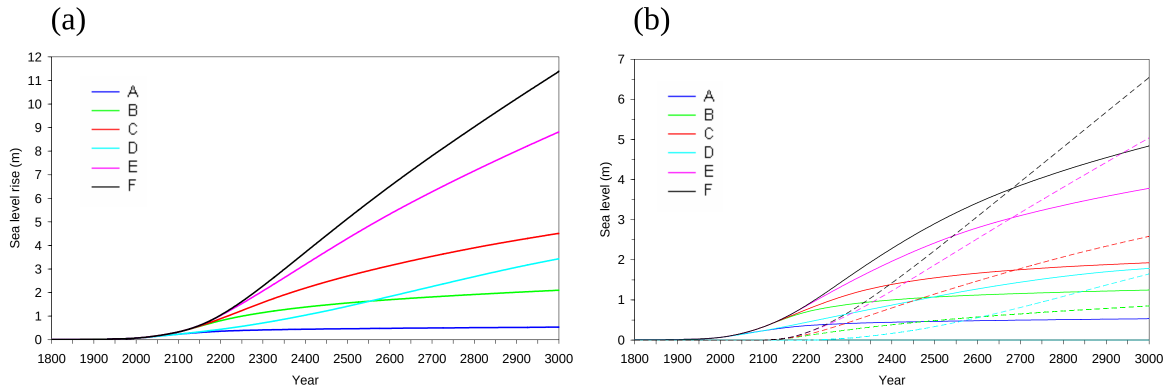


Figure 5 Rise in sea level for all scenarios from GENIE-1 (a) total (b) contributions of thermal expansion (solid lines) and Greenland ice sheet melt (dashed lines). Note that potential changes in the mass balance of the Antarctic ice sheets are not included.

Business-as-usual could lead to abrupt climate changes

Following business-as-usual emissions beyond 2100 (scenarios C, E, F), leads to a rapid climate change event in the 22nd century in the MoBidiC model. This should not be treated as a prediction but rather as an indication that continual increase in emissions could lead to an event of this type, whilst stabilised emissions could avoid it. For the same total emissions of 4000GtC, emitting them rapidly (scenario C) leads to the rapid climate change event, whilst emitting them slowly (scenario D) avoids it. The ‘event’, described in greater detail in section 5, involves a reduction in the Atlantic meridional overturning circulation, which includes the current commonly known as the Gulf Stream, and a shift in convection to more southerly latitudes that affects the climate at the latitude of the UK.

Abrupt climate changes could occur long after emissions cease

Abrupt changes can be triggered many decades before they actually occur, and even after emissions have completely ceased, there is still a legacy from decades past (a “sleeping giant” in the climate system). This can be seen in the rapid global warming (Figure 2) and regional warming (Figure 4) events that occur in MoBidiC around 2700 (scenario F) or 2800 (scenario E). These are described in greater detail in section 5. In both cases, when the event happens emissions have been zero for sometime, CO_2 concentration is actually declining, whilst temperature is increasing very gradually due to thermal inertia in the climate system.

The ocean carbon sink becomes less effective the more CO_2 is emitted

The ocean is predicted to be a robust carbon sink that continues to grow in size as emissions increase (hence increasing the gradient of CO_2 between the atmosphere and the ocean). Once emissions start to decline, so does the rate of CO_2 uptake by the ocean (i.e. the size of the ocean carbon sink). Despite the increase in absolute sink size, the fraction of total emissions taken up by the ocean is predicted to decline in future, because the more CO_2 that is added to the ocean and the more it warms, the less effective a carbon store it becomes. The predicted size of the ocean carbon sink for a given emissions scenario, varies considerably between SESM and GENIE-1 (Figure 6a). SESM assumes a fixed ocean circulation, which is unlikely to occur, so more faith should be placed in the GENIE-1 predictions in which ocean circulation weakens. Under the extreme emissions scenario F in GENIE-1, there is a capping of the maximum size of the ocean carbon sink.

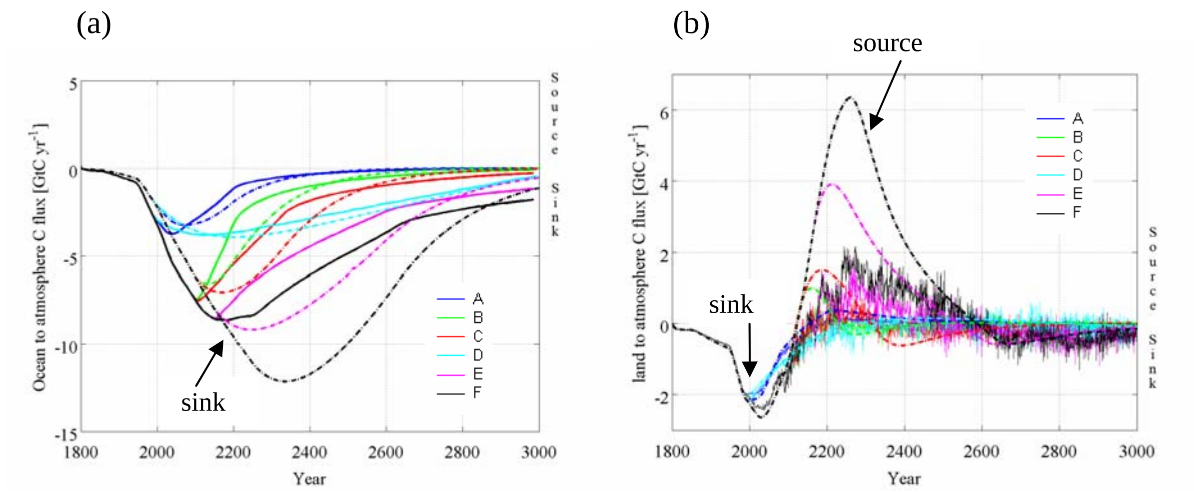


Figure 6 Exchange of CO_2 between the atmosphere and (a) the ocean (b) the land surface, in SESM (dashed lines) and GENIE-1 (solid lines). A negative flux indicates a carbon sink, whilst a positive flux indicates a carbon source.

The land could be a net carbon source on the millennial timescale

The current land carbon sink is predicted to shrink in future and, if emissions continue to increase following business-as-usual, a significant land carbon source is generated as in other simulations [*Cox et al.*, 2004; *Cox et al.*, 2000]. The potential source is much larger in SESM than GENIE-1, but the latter is a more convincing, spatial model which reasonably reproduces the current distribution of land carbon [*Williamson et al.*, 2006] (although inter-annual variability in the land-atmosphere CO_2 exchange in GENIE-1 should be ignored as a model artefact). By the end of the millennium, the land can be left storing significantly less carbon than it did in pre-industrial time. In other words, land carbon loss (mostly from soil) can add to fossil fuel emissions. Attempts to take up CO_2 by planting additional forests would be unlikely to counteract this loss of soil carbon because of the enormous amount of carbon involved.

Ocean pH will fall dramatically for all but the minimum emission scenario

Ocean pH (predicted by GENIE-1 only) can fall by as much as 1.15 units from 8.15 to 7 on the millennial timescale (Figure 7), thus posing a threat to marine calcifying organisms including corals and calcareous plankton [*RoyalSociety*, 2005]. Such fundamental changes to plankton would have large implications for the rest of the marine ecosystem. Under a business-as-usual increase in emissions (scenarios B, C, E and F) pH drops to 7.8 by 2100, eventually reaching minima of 7.74 (B) 7.6 (C) 7.24 (E) and 7.0 (F). Under scenario D, in which emissions are initially stabilised, pH falls much more slowly but still reaches 7.7 by 3000. Only scenario A has a pH drop of less than 0.2 units.

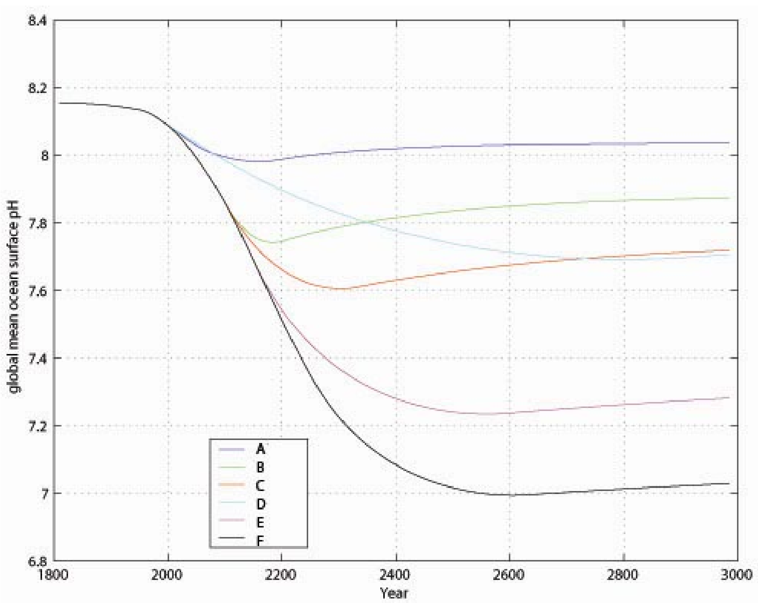
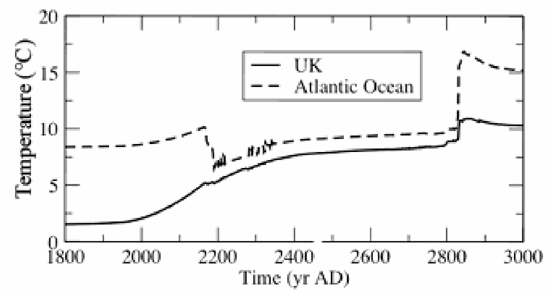


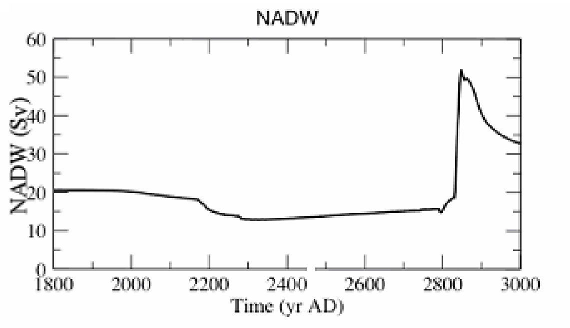
Figure 7 Global mean ocean surface pH in GENIE-1 for the 6 scenarios.

5. Abrupt climate change events

Two abrupt future climate change events can occur in MoBidiC depending on the emissions scenario. These should not be treated as firm predictions – especially not in their timing – rather they provide an illustration of the type of event that might occur in the future.



(a)



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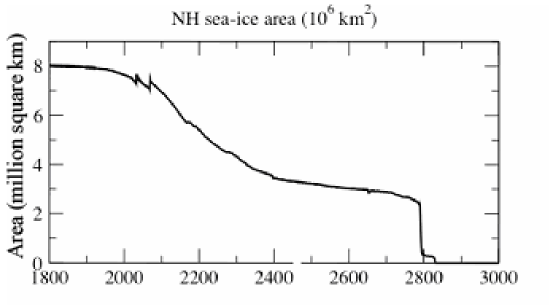

(c)

Figure 8 Abrupt climate change events as seen in the North Atlantic region in MoBidiC under scenario E (a) regional temperatures in °C ('UK' refers to continent at UK latitude) (b) North Atlantic Deep Water (NADW) formation in Sv (c) Northern Hemisphere (NH) sea-ice area in 10^6 km^2.

A regional abrupt climate change in the North Atlantic

Scenarios C, E and F exhibit a rapid climate change event in the 22nd century. This is most apparent in the surface temperature over the Atlantic Ocean (Figure 8a), which drops ~3°C. This temperature change is directly related to a decrease (but not a collapse) of the meridional overturning circulation in the North Atlantic below 500m by up to 8 Sv over 150 years. It is accompanied by a southward shift of the convection sites in the North Atlantic (from 55-60 to 40-45N). The strong ocean surface cooling is mostly localised in the 50-60N latitude band. It is directly related to the change in the location of convection, which consequently induces a modification of the heat transport by the ocean. There is an increase of heat transported both northwards and southwards from this latitude, partly because cold water is transported further south to the convection sites. This divergence of heat causes the striking regional cooling. An increase of precipitation in the high northern latitudes as well as the melt-water flux from the Greenland ice sheet also favour the displacement of the convection sites, through the reduction of salinity in the highest latitudes of the North Atlantic.

A global abrupt climate change

In scenarios E and F, a second abrupt event occurs later in the simulation (in the 2800s in scenario E and in the late 2600s in scenario F). This event has a global impact on the climate, with an increase in global annual mean temperature of almost 1°C (Figure 8b). It corresponds to a rapid (~10 yr) increase in surface temperature over both the continent (>2°C) and North Atlantic (>6°C) at the latitude of UK (Figure 8a). Although sea surface temperature increases over the whole North Atlantic, the warming is strongest at 60-75°N latitude, especially during winter and spring. The event begins with sea-ice rapidly retreating from the Arctic Ocean and later it disappears (Figure 8c). The thermohaline circulation becomes very vigorous, increasing by ~35Sv with convection taking place in the Arctic Ocean and salinity increasing there. Although the sea surface warms in the northern latitudes, ocean intermediate waters cool.

Link between the abrupt climate change events

Such a succession of events has previously been described in response to freshwater input in the North Atlantic [*Crucifix et al.*, 2001]. There is almost no change in climate during the first centuries after the beginning of freshwater input. As soon as freshwater input exceeds a threshold value (0.049 Sv in scenario E), the vertical structure of the water column in the North Atlantic is modified in such a way that the convection is not sustained. In addition to reduction of the meridional overturning and sea surface cooling in the 50-60°N latitude band, a positive temperature anomaly and salt accumulation (mostly in inter-tropical latitudes) develop at intermediate depth of the ocean (this is the first abrupt event). Towards the end of the simulation, when freshwater input is already reduced, salt accumulates at the surface of the North Atlantic Ocean (north of 40°N). This leads to a strengthening of the meridional overturning. Moreover, the heat accumulated at intermediate depth when overturning was reduced, is suddenly released to the atmosphere, inducing a sharp increase in sea surface temperature and in surface air temperature in the northern high latitudes (this is the second abrupt event). This process is called overshoot. The salty and warm intermediate waters are then replaced by cold and freshwater from the south, which leads to the gradual damping of the meridional overturning, and a slow cooling of both the ocean and the continent.

6. Assessing uncertainty: thermal expansion sea-level rise

All future projections are subject to uncertainties due to our imperfect knowledge and imperfect representation of processes in models. Thus far we have presented only one variant of each model. However, there are many aspects of the climate system that are uncertain. One of great importance for both global warming and sea-level rise is the climate sensitivity. This is not well constrained by recent data. The three models used here span a range of 2.0-3.0°C but a review of the recent literature suggests climate sensitivity could lie in the range of 1.6-11.5°C [*Lenton,* 2006]. The cooling at the Last Glacial Maximum may constrain the upper bound at <4°C [*H. Held*, personal communication]. However, the allowed range is still broader than represented in the models used here. Hence our projections of warming should have a wider uncertainty range, and may be too conservative. Consequently our uncertainty in sea-level rise will be increased and so may the absolute value.

As part of the project we undertook a case study to test out two methods for assessing uncertainty in our projections. We chose to consider uncertainty in thermal expansion sea-level rise in GENIE-1 as this is a key model output. Assessing the uncertainty in the ice sheet melt component would require a sophisticated ice sheet model, not available here. We were also restricted in that climate sensitivity in GENIE-1 is largely fixed by the prescribed relationship between atmospheric CO_2 and radiative forcing. Hence we addressed the more limited issue of the uncertainty that remains in the thermal expansion component of sea-level rise even if we had the climate sensitivity well constrained. Thermal expansion of the ocean is controlled by ocean heat uptake, which in turn is affected by a number of physical processes represented by model parameters. We used climate data to constrain these model parameters and tried two different methods: (1) an Ensemble Kalman Filter (EnKF), (2) a Bayesian emulator.

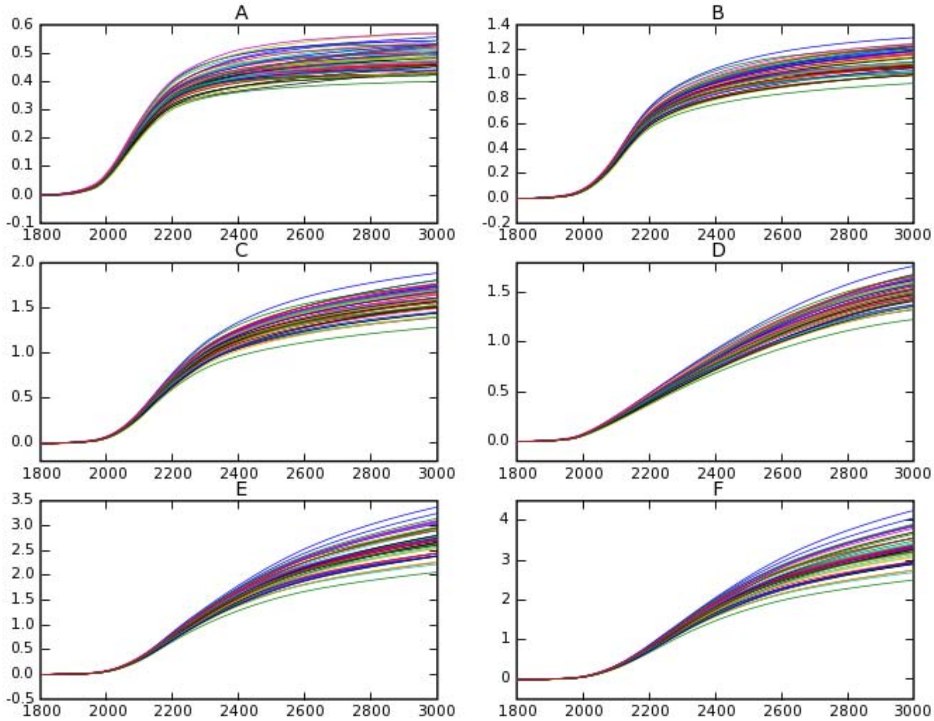

Figure 9 Sea level rise (m) due to thermal expansion for each scenario, from an ensemble of 54 versions of GENIE-1 with climate data assimilated using an Ensemble Kalman Filter.

The EnKF is an ensemble of 54 versions of GENIE-1 each with different settings for 12 parameters that have been constrained by climate data. The ensemble we used was from earlier tuning of the atmosphere-ocean-sea-ice core of GENIE-1 known as ‘C-GOLDSTEIN’ [*Hargreaves and Annan*, 2005]. Each model variant should be treated as equally plausible, and the ensemble as a whole is meant to represent the joint uncertainty in the model and the data. In statistical terms, it is a sample of the posterior probability distribution defined by prior beliefs and climate data. The climate data used were surface air temperature and humidity, ocean temperature and salinity. Note that sea level data were not used to constrain the model as sea level rise thus far is of the order 15-20cm and much of it is thought not to be due to thermal expansion. The climate sensitivity of all members of the ensemble is similar and on average it is ~3.0°C. Results are shown in Figure 9.

The ensemble results for thermal expansion sea level rise show that uncertainty related to the modelled physical climate parameters is of the order of ±25% about the mean. The ensemble members generally lie below the un-tuned model version shown in Figure 5b. In other words, the un-tuned model may be over-estimating thermal expansion of the ocean given its climate sensitivity. However, if the real climate sensitivity is higher than 3.0°C then the thermal expansion of the ocean will be greater because more heat will enter the ocean.

The Bayesian 'emulator' is a statistical technique for predicting the output of a computer program without actually running it. The computer program may be of any kind that requires a set of input parameters: here the system is the GENIE-1 model, and the parameters are a list of 11 physical quantities whose precise values are not known. The emulator requires a "training set" of a few runs of the computer program together with their output. Given a set of parameters, the emulator uses this training set to predict what the program would have given, if run with those parameters. An emulator can also estimate the errors on its predictions. Results are shown in Figure 10.

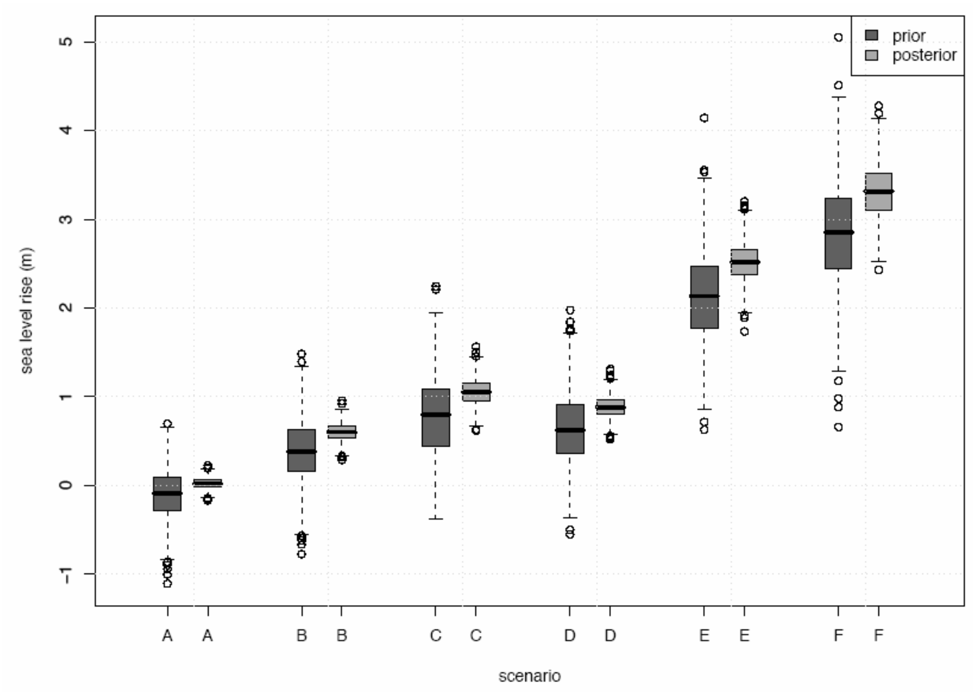

Figure 10 Sea-level rise due to thermal expansion for each scenario, from an emulator of GENIE-1 unconstrained (prior) and constrained (posterior) by observational climate data. The box plots show median (dark horizontal line), upper and lower quartiles (shaded box), 5th and 95th percentiles (dotted lines) and outliers (isolated points).

The posterior values of sea-level rise have smaller uncertainty but bigger means for each of the six scenarios, indicating that climate data do constrain the future projections and shift them toward higher values (although they are still lower than the un-tuned model – Figure 5b). The posterior emulator results show for a given scenario that uncertainty in thermal expansion sea level rise expressed as the 5-95% confidence interval is of the order of ±25% about the mean, with only a few outliers. This agrees with the level of uncertainty obtained from the EnKF technique. For scenarios E and F the two methods give similar mean sea level rise. For scenarios A-D the posterior mean from the emulator is significantly below that from the EnKF. Note that for scenario A, some part of the sea-level rise posterior uncertainty distribution is negative, indicating a sea-level fall. This is a counter-intuitive result, and we can reject it as physically implausible. It arises from the remaining uncertainty in the model parameters allowed by this technique.

7. Scoping study: downscaling the results

GENIE-1 has an average grid-box resolution of ~630 km on an equal area grid (cells of ~394000 km^2), while MoBidiC provides information for five degree latitudinal bands averaged over the entire Eurasian continent. Thus there is a need for downscaling from the relatively coarse outputs of the EMICs to provide detailed regional information about UK climate. Most of the development work on downscaling methodologies in recent years has focused on downscaling for the next 100 years from the global climate model (GCM) scale (with a typical spatial resolution of 400 km over Europe in the current generation of models). Two approaches are typically taken. First, dynamical downscaling in which regional climate models (RCMs), with a typical spatial resolution of 50 km by 50 km for models whose domain covers the European region, are nested within the coarser GCM [*Christensen*, 2005]. Second, statistical downscaling, in which present-day relationships between local and larger-scale climate are applied to model output for the future, on the assumption that these relationships will be unchanged [*Goodess et al.*, 2005].

Table 4 Potential methods for downscaling from the EMIC simulations

Method	Description
Change factor	Future minus present-day differences are calculated at the highest model spatial resolution and added to an observed high-resolution climate data set (e.g. 5km UK climate data used in UKCIP02 [*Hulme et al.*, 2002])
Transfer-function based statistical downscaling	A transfer function, typically a regression relationship, is constructed to predict local surface conditions (e.g. 5 km gridded temperature) from larger-scale conditions (e.g. temperature from one GENIE-1 grid box). The statistical relationships are quantified using observed data, and then applied to the larger-scale EMIC output.
Pattern scaling	The climate-change pattern derived from a three-dimensional (global or regional) climate model is standardised using a 'scaling variable', i.e. by dividing by the global-mean warming for a particular climate-change experiment, in order to express the climate change per unit change in the scaling variable, i.e. per °C global warming. The standardised pattern can then be re-scaled using projected changes in the scaling variable taken from one or two-dimensional climate models.

The longer duration of the millennial simulations and the coarser resolution of EMICs compared with GCMs, means that existing downscaling methods are not immediately suitable for application to the simulations described in this report. In particular: (1) RCMs are very computer intensive – 300 year long runs are not feasible – and cannot be nested directly within EMICs. (2) Many statistical downscaling methods use large-scale atmospheric circulation to predict local climate, however, such dynamical processes are not well represented in EMICs. (3) Some of the emissions scenarios used here lead to very large projected climate changes, including abrupt changes associated with North Atlantic ocean circulation changes, thus extreme care is needed to ensure that present-day and linear relationships are not over-extrapolated.

Three potential methods for down-scaling EMIC simulations have been identified and are detailed in Table 4. The change factor method can be used to provide information at a higher spatial resolution immediately, but no added value or skill is provided concerning the spatial pattern of change. Thus it is recommended that future work should explore the transfer-function and pattern-scaling methods.

The transfer-function method requires work to identify the optimal local/larger-scale resolutions to use, i.e., those at which observed relationships are strongest and, for the larger-scale, at which the EMIC performance is considered more reliable. It is considered to offer good potential for temperature, but is unlikely to be a suitable method for rainfall (because of weaker observed relationships and lower reliability of EMIC rainfall). Furthermore, present-day statistical relationships may not be applicable given major changes in the larger-scale climate, particularly major and abrupt changes in North Atlantic circulation.

The pattern scaling method was used to construct the UKCIP02 scenarios [*Hulme et al.*, 2002] and is widely used in integrated assessment modelling [*Goodess et al.*, 2003]. Used with care, the approach is appropriate for monthly temperature and rainfall, but may be less appropriate for daily information and extremes. Software packages for pattern scaling are available (e.g., SCENGEN [*Wigley et al.*, 2000] and CLIMGEN) but would need modification to use regional temperature taken from the EMICs as the 'scaling variable' rather than global temperature, and to incorporate information from multiple regional climate models [*Christensen*, 2005], ideally presented in a probabilistic format (in order to reflect uncertainties). Further work would be required to determine whether the patterns are still applicable at times of major change in North Atlantic circulation. If not, then a method would be required to identify when such conditions occur in the EMIC simulations, together with output from appropriate three-dimensional climate model runs to describe the patterns during such periods.

9. Policy implications

Rate of emissions control the rate of climate change

The rate of global warming depends on how emissions change. Increasing emissions leads to an increasing rate of warming (e.g. this century in scenarios B, C, E and F). Stabilised emissions lead to a roughly constant rate of warming (e.g. this century in scenario D). Declining emissions lead to a declining rate of warming that may be followed by a peak and slight decline in temperature (e.g. scenario A after 2025). A rapid release of 4000 GtC (scenario C) induces a more serious transition of land carbon from sink to source of carbon than a slow release (scenario D).

Total emissions are the primary controller of millennial climate change

Although the rate of warming and any peak in global warming are sensitive to the rate of emitting a given amount of fossil fuel, global warming on the millennial timescale is not. This can be seen by comparing scenarios C and D (Figure 2) in which 4000GtC are emitted at different rates. In a given model they arrive at the same temperature in year 3000: 3°C in MoBidiC and 5°C in GENIE-1, due to their differing climate sensitivities. However, sea level rise *is* somewhat sensitive to the rate of emitting a given amount of fossil fuel (Figure 5). By 3000 it is 3m (MoBidiC) or 4m (GENIE-1) if 4000GtC is emitted slowly (scenario D) but 4m or 5m if it is emitted rapidly (scenario C).

Only by minimising emissions can dangerous climate change be avoided: in all except the most stringent emissions reduction scenario Greenland ice sheet melt begins between the early 22nd and early 23rd century.

We take as a definition of "dangerous" climate change a global sea level rise of 2m, because it will flood large areas of Bangladesh, Florida and many low lying cities, and displace hundreds of millions of people [*Nicholls*, 2004; *Oppenheimer and Alley*, 2004; *van Lieshout et al.*, 2004]. The only scenario that can avoid this is our minimum emissions case (A). That allows a modest increase in global CO_2 emissions to 8.8GtC/yr in 2025 followed by a roughly linear decline to zero emissions in 2200. According to GENIE-1, all the other scenarios (including stabilising emissions at the 1990 level until 2100 and then gradually reducing them) commit future generations to passing 2m sea level rise sometime between 2300 and 2600. A key reason is that the assumed local temperature rise threshold for Greenland ice sheet melt (2.7°C) is exceeded causing it to melt gradually and add to sea level. Similarly, only the minimum emissions scenario can prevent dramatic reductions in ocean pH or prevent global temperatures from rising by more than 2°C in 3000 relative to pre-industrial times (the EU's suggested limit to avoid dangerous climate change). However, if climate sensitivity is greater than 3°C, even the minimum emissions scenario could not prevent some of these suggested limits from being exceeded. A recent assessment suggests that there is a 60% likelihood that climate sensitivity exceeds 3°C and a ~5% likelihood that it exceeds 8°C [*Stainforth et al.*, 2005].

The United Kingdom in year 3000

For the UK, projections of sea-level rise due to climate change must be combined with estimates of changes in land elevation due to isostatic adjustment of the crust following the last ice-age. At present, for example, South East England is sinking by ~2mm/yr whilst parts of Scotland are rising at >1mm/yr. Extrapolating to the millennial timescale, London is projected to sink by ~2m regardless of climate change. Add to this up to ~11m of sea-level rise due to climate change and at some point low-lying areas of the UK including large parts of London would have to be abandoned.

9. Conclusion and suggestions for future work

We have presented a sobering picture of potential climate change on the millennial timescale. Whilst great uncertainties remain, our relatively conservative assumptions, for example regarding climate sensitivity or the exclusion of the Antarctic ice sheets, still produce the result that only by starting to reduce CO_2 emissions in the very near future, and continuing to reduce them such that they are zero by year 2200, can we avoid dangerous climate change on the millennial timescale. If climate sensitivity turns out to be greater than 3.0°C even this minimum emissions scenario would likely commit us to warming of more than 2.0°C and slow melt of the Greenland ice sheet.

Our main outputs in addition to this report have been scientific papers: (1) a review of climate change to the end of the millennium [*Lenton*, 2006], (2) a description of a new land surface scheme for fast Earth system modelling [*Williamson et al.*, 2006], (3) a description of a new Earth system Model of Intermediate Complexity (GENIE-1) and application to millennial climate change [*Lenton et al.*, 2006].

We have a number of suggestions for taking the work forward, in particular generating information on UK scale impacts. The best approach depends somewhat on the variable of interest, e.g. temperature, sea-level, or precipitation.

We have outlined in section 8 an approach for downscaling temperature from the coarse grid of e.g. GENIE-1 using a pattern scaling approach. To predict changes in atmospheric circulation and precipitation requires a dynamical atmosphere model, rather than the simplified atmosphere models used here. The Hadley Centre models, HadCM3 or the new HadGEM1 are currently limited to expensive, rare simulations on the millennial timescale. The FAMOUS model [*Jones et al.*, 2005] (a low-resolution version of HadCM3) could be run for a number of CO_2 concentration scenarios on the millennial timescale, and a version of it with a closed carbon cycle should become available in the next 1–2 years. Alternatively, the Reading IGCM [*de Forster et al.*, 2000] (a faster 3D atmosphere model being used in the GENIE project) would give the scope to do larger ensembles of simulations.

To make our projections of sea-level rise more comprehensive we would need to include the Antarctic ice sheets in a model and consider the contributions of smaller ice caps, large reservoirs, etc. The Antarctic ice sheets can be coupled within the GENIE framework, but the current state of knowledge is such that all projections of their behaviour should be treated with extreme caution. For less uncertain aspects of the Earth system, real progress can be made in making probabilistic millennial projections and rigorous assessments of uncertainty, using an EMIC such as GENIE-1 and the methods explored in section 7.

An ideal tool for taking the work forward should be the Tyndall Centre's Community Integrated Assessment System (CIAS), currently in development, which will provide a framework include GENIE, data and patterns from Hadley Centre model runs, a downscaling tool based on pattern scaling, a statistical approach to extreme events, and impacts models.

Appendix: Model descriptions

SESM

SESM comprises a 7-compartment carbon cycle coupled to an energy-balance function for surface temperature. The carbon cycle compartments are atmosphere, vegetation, soil, high-latitude surface ocean, low-latitude surface ocean, intermediate waters and deep ocean. CO_2 is exchanged with the atmosphere by vegetation and soil through processes of photosynthesis (gross primary productivity), plant respiration and soil respiration. Litter fall transfers carbon from vegetation to soil. Photosynthesis is a function of CO_2 and temperature. Plant respiration is a function of temperature and vegetation carbon. Soil respiration is a function of temperature and soil carbon. Together these responses determine whether the land is a net carbon sink or source under land-use change, increasing CO_2 and global warming. CO_2 is also exchanged between the atmosphere and each of the surface ocean boxes. Uptake or release of CO_2 by the surface ocean depends on the concentration difference of CO_2 between the atmosphere and ocean. It is also affected by temperature, which alters the thermodynamic constants of seawater chemistry. An excess of CO_2 in the atmosphere drives the ocean carbon sink, whilst warming damps its size. The CO_2 fertilisation effect on photosynthesis is tuned so that the model achieves the 1990 level of atmospheric CO_2 when forced with historical emissions.

GENIE-1

GENIE-1 comprises atmosphere, ocean, sea-ice, land surface physics, land carbon cycle, and marine biogeochemistry components. It is based on the ocean-atmosphere-sea-ice model C-GOLDSTEIN [*Edwards and Marsh*, 2005]. The frictional geostrophic ocean model, GOLDSTEIN, is three dimensional, but significantly more efficient than extant 3-D global ocean models based on the primitive equations. The model has 8 depth layers and shares a horizontal grid of 36 by 36 equal area grid cells with the other components of the coupled model. The sea-ice component is a dynamic and thermodynamic model. The atmospheric energy moisture balance model (EMBM) is based on that in the UVic model [*Weaver et al.*, 2001]. Prescribed fields of atmospheric albedo are calculated by making the approximation that there are two reflective layers that make up the planetary albedo, one at the top of the atmosphere - the atmospheric albedo - and one at the surface interface, which is suitable for our 1-layer atmosphere. The prescribed annual mean wind field used for advection of moisture is replaced with a set of monthly mean fields to promote seasonal variability in the precipitation, which is important for the accurate simulation of vegetation carbon.

The Efficient Numerical Terrestrial Scheme (ENTS) [*Williamson et al.*, 2006] has been designed as a minimal representation of land surface physics, hydrology and carbon cycling for use in a spatially resolved context. It has single pools of vegetation carbon, soil carbon and soil water at each land grid point. CO_2 is exchanged with a well-mixed atmosphere box. Vegetation takes up CO_2 from the atmosphere through photosynthesis, and returns some of it through respiration. A flux representing leaf litter and plant mortality transfers carbon from vegetation to the soil. Soil respiration returns CO_2 to the atmosphere. Photosynthesis depends on atmospheric CO_2 following Michaelis-Menten kinetics (a hyperbolic response) with a half saturation constant of 145ppmv [*Lenton*, 2000]. Photosynthesis, vegetation respiration and soil respiration all have different temperature responses chosen such that ENTS accurately captures the spatial patterns of carbon storage in vegetation and soil when driven off-line with NCEP data. An important feature, based on field studies, is that soil respiration is more sensitive to warming in cold boreal ecosystems than in warm tropical ones. The capacity of the water 'bucket' in each land grid cell depends linearly on soil carbon content between limits for desert and forest.

The marine biogeochemical model, BIOGEM, is based on [*Ridgwell*, 2001] and described further in [*Cameron et al.*, 2005]. BIOGEM vertically re-distributes a set of geochemical tracers that are being advected within the ocean, according to processes of biological uptake, particulate matter remineralization and air-sea gas exchange. In GENIE-1 these tracers are carbon (DIC), alkalinity (ALK) and phosphate (PO_4) (in addition to temperature and salinity). Nutrients, together with DIC, are taken out of solution in the sunlit surface ocean layer through biological action and exported in particulate form (as particulate organic matter, POM) to deeper layers. As it settles through the water column, POM is subject to remineralization processes (primarily bacterial metabolism), resulting in the release of dissolved constituent species. Remineralization in the ocean is implemented according to a predetermined profile of relative sinking flux. Associated with the biological fixation of carbon is the formation of $CaCO_3$ and further removal of DIC in addition to ALK. $CaCO_3$ is similarly dissolved in the water column following a prescribed remineralization profile. All particulate material (POM and $CaCO_3$) reaching the sediment surface is instantaneously remineralized and the dissolved constituents returned to the overlying ocean cell. CO_2 is exchanged with a well-mixed atmosphere box across the air-sea interface. The setup of BIOGEM used here is as described in [*Cameron et al.*, 2005]. Surface ocean phosphate is restored toward zero with a timescale of 6 years and this drives the biological carbon pump. Restoration to zero is more self-consistent than restoring to observations, because in our future scenarios ocean circulation can change radically. This parameterization is still rather crude compared to more numerically expensive schemes with multiple nutrients and/or multiple functional types of organism.

Simple parameterizations of the change in sea level due to the thermal expansion of the ocean and from the melting of the Greenland ice sheet are included. The parameterization of Greenland ice sheet melt is based on the results of the millennial global warming studies in which the contribution of Greenland melt to sea level rise is approximately linear in time and temperature, above a warming threshold [*Huybrechts and De Wolde*, 1999]. Our parameterization is a sea level rise of 0.98 mm K^{-1} yr^{-1} above a threshold of 2.6 K local warming from the pre-industrial annual average air temperature over Greenland. An upper bound is imposed of 7 m of sea level rise corresponding to the complete melting of the Greenland ice sheet. The Greenland melt-water is added as a freshwater flux to the surface ocean, evenly distributed among the 6 ocean grid boxes around Greenland. We choose not to include changes in mass of the Antarctic ice sheets on the grounds that current projections, especially for the West Antarctic Ice Sheet, are highly sensitive to the basal flow and viscosity parameterizations [*Huybrechts and De Wolde*, 1999]. The contribution of Antarctica to global sea level on the millennial timescale is of uncertain sign but is estimated to be of smaller magnitude than Greenland melt.

MoBidiC

MoBidiC represents most of the components of the climate system (atmosphere dynamics, the deep ocean, the continental biosphere, the ice sheets and their underlying bedrock) in a simplified way, compared with more detailed state-of-the art models. It is a 2 dimensional (latitude-altitude) sectorially averaged model. The meridional resolution is 5 degrees. Each zonal band is divided into 13 sectors representing the different continents and oceans, with a distinction between snow-free, snow-covered and ice-covered surfaces over the continents, and ice-free and ice-covered surfaces over the oceans. Each surface type interacts separately with the zonally averaged atmosphere (Table 1). The ocean component is described through a primitive-equation ocean model in which the variables are sectorially averaged over each of the three ocean basins (the Atlantic, the Pacific and the Indian oceans) [*Hovine and Fichefet*, 1994] [*Crucifix et al.*, 2001] [*Crucifix and Loutre*, 2002]. A simple thermodynamic sea-ice component is coupled to the ocean model. The continental biosphere is represented by a dynamical terrestrial vegetation model, VECODE [*Brovkin et al.*, 1997]. MoBidiC includes up to five ice sheets, representing the ice sheets of North America, Greenland and Eurasia in the Northern Hemisphere [*Gallée et al.*, 1992] and Eastern and Western Antarctica in the Southern Hemisphere [*Dutrieux*, 1997] [*Crucifix et al.*, 2001]. The model includes a run-off scheme and iceberg calving in order to account for the possible impact of meltwater on ocean salinity [*Crucifix and Berger*, 2002]. The coupled climate model is forced by the astronomically derived insolation for each day and latitude and by the atmospheric CO_2 concentration (there is no interactive carbon cycle). The model climate sensitivity to a doubling of the atmospheric CO_2 concentration is 2.0°C, towards the lower end of the IPCC sensitivity range of 1.5–4.5°C from GCMs (IPCC90, 95, 01).

Comparisons between the simulated pre-industrial climate state and modern observations [*Crucifix et al.*, 2002] show that MoBidiC satisfactorily captures the large scale features of climate. The seasonal cycle of the zonally averaged surface temperature compares favourably with data although there is a cold bias in the northern polar regions for MoBidiC and surface temperatures are slightly overestimated in the 30-50°N latitude band and in the equatorial regions. The model also captures the main ocean features, e.g. sea surface temperatures (SST), sea-surface salinities (SSS), distribution of water masses, meridional overturning. The main deficiency is the absence of convection in the Atlantic Basin north of 60°N, which produces a surface cold bias in the northern polar regions, mainly in winter (locally as much as 5°C). Moreover, the model overestimates salinity and temperature (by about 0.4 psu and 1°C, respectively) of NADW. It also underestimates the salinity gradient between tropical and equatorial areas.

Several snapshot simulations, i.e. the Last Interglacial (126 kyr BP), Last Glacial Maximum (21 kyr BP), and transient simulations, i.e. the Holocene (9 kyr BP to present), the last interglacial (126 to 115 kyr BP), were performed with MoBidiC to evaluate its ability to simulate past climates [*Crucifix et al.*, 2002] [*Crucifix et al.*, 2001] [*Crucifix and Loutre*, 2002]. Sensitivity experiments performed over the Holocene illustrate the strong impact of the vegetation shift both on oceans and continents, especially in spring and early summer but the synergy is weak between vegetation and oceans throughout the Holocene [*Crucifix et al.*, 2002]. During the Last Interglacial, most of the cooling occurs between 122 and 120 kyr BP when the boreal tree-line shifts southward. The simulated temperature changes are in reasonable agreement with those estimated from pollen data for SW Europe [*Sánchez Goñi et al.*, 2000]. The vegetation shift is a fundamental component of the response of the climate system to the orbital forcing during interglacial periods and a key component involved in the glacial inception. Comparison between several EMICs suggests that MoBidiC might be over sensitive to this vegetation-albedo-temperature feedback [*Brovkin et al.*, 2003]. MoBidiC has recently been used to simulate MIS-11, starting at 420 kyr BP and forced by both insolation and CO_2 for 70 kyr. Simulated and reconstructed climate are in broad agreement especially during the first part of MIS-11. They suggest a long warm period [*McManus et al.*, 2003] followed by a rapid southward retreat of the tree line in the Northern latitudes.

Finally, the model has also been used to simulate the transient climate behaviour over the last glacial-interglacial cycle. In that experiment, all the components (atmosphere, ocean, vegetation, ice sheets) of the model are interactive. Over the last 126 kyr, the atmospheric

CO_2 concentration varies according to [*Petit et al.*, 1999] and insolation changes is computed according to [*Berger*, 1978]. There is a generally increasing trend in continental ice volume from the last interglacial until the last glacial maximum. The maximum continental ice in the Northern Hemisphere is simulated at 18 kyr BP with a volume of more than 40×10^6 km^3. The simulated annually averaged surface temperature experiences variations of up to 2.1°C in global mean. These variations are larger for the Northern Hemisphere (2.8°C) and lower for the Southern Hemisphere (1.5°C).

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