The Met Office Hadley Centre climate modelling capability: the competing requirements for improved resolution, complexity and dealing with uncertainty


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Predictions of future climate change require complex computer models of the climate system to represent the full range of processes and interactions that influence climate. The Met Office Hadley Centre uses ‘families’ of models as part of the Met Office Unified Model Framework to address different classes of problems. The HadGEM family is a suite of state-of-the-art global environment models that are used to reduce uncertainty and represent and predict complex feedbacks. The HadCM3 family is a suite of well established but cheaper models that are used for multiple simulations, for example, to quantify uncertainty or to test the impact of multiple emissions scenarios.

Keywords: HadGEM; climate models; climate change; uncertainty

1. Introduction

Useful climate predictions depend on having the most comprehensive and accurate available models of the climate system. However, any single model will still have limitations in its application for certain scientific questions and it is increasingly apparent that we need a range of models to address these ranges of applications. There are two primary reasons for this. First, there is inherent uncertainty in predictions, which means that ensemble predictions are needed with many model integrations. Second, technological advances have not kept pace with scientific advances. A model that included the latest understanding of the science at the highest resolution would require computers of several orders of magnitude faster than today’s machines. For these reasons, the Met Office Hadley Centre has adopted a flexible approach to climate modelling based on model ‘families’ within which we define a suite of models aimed at addressing different aspects of the climate prediction problem. All of these models are flavours of the Met Office’s unified weather forecasting and climate modelling system.

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One contribution of 9 to a Theme Issue ‘Climate change and urban areas’.
Our current modelling families are as follows.

(i) **HadGEM1** (Johns et al. 2006; Martin et al. 2006; McLaren et al. 2006). A state-of-the-art global environment model, building on, but substantially changed from our earlier model, HadCM3.

(ii) **HadCM3** (Gordon et al. 2000; Pope et al. 2000). A well-established coupled climate model that is cheap to run on current computers (e.g. it can be run on a PC, www.climateprediction.net).

Specific applications for which we have recently used these models include the following.

(i) **Earth system feedbacks** (see §3 for details). These have been incorporated separately into coupled ocean–atmosphere models in both families, HadGEM1 and HadCM3. Work has been started in incorporating these in-line into our next model family, HadGEM2, which will include our first true Earth system model.

(ii) **QUMP** (Murphy et al. 2004). Quantifying uncertainty in model predictions using ensembles of scientifically distinct versions of HadCM3 (see §4 for details).

(iii) **Regional** (Wilson et al. 2006; Buonomo et al. 2007) and **high-resolution models** (led by the NERC HiGEM project and the UK, NERC and the Hadley Centre, Japan UJCC project). These build on the standard global models, HadGEM1 (HiGEM) and HadCM3 (regional).

(iv) **FAMOUS**. A low-resolution version of HadCM3 designed to run approximately 10 times faster (Jones et al. 2005). It is well suited to long runs, large ensembles or use on PCs and its speed has allowed it to be optimally tuned. Results are directly traceable to HadCM3 and processes of interest in HadCM3 can be studied further in long simulations or parameter ensembles carried out with FAMOUS.

In addition, we have a suite of tools available to us for detailed model evaluation. Notably, this includes a variety of observational datasets, model to satellite approaches and increasing use of the strong links between numerical weather prediction and climate within our unified modelling framework that allows us to evaluate many of the ‘fast’ physical processes on short time scales making use of real-time observations.

This paper presents some of the highlights of the latest developments in some of these modelling systems at the Hadley Centre. Full details on each topic can be found in the references cited. In §2, we focus on HadGEM1 and how it compares with HadCM3. In §3, we discuss Earth system feedbacks. In §4, we outline our approach to quantifying uncertainty. Evaluation is discussed throughout the paper as it underpins our confidence in the model results. In §5, we outline further improvements to the model, which have been incorporated into the next model family HadGEM2. We also point to some key developments for the future.
2. HadGEM1

(a) Simulation of present-day climate

Full details of HadGEM1 are given elsewhere (see references above). Table 1 provides a summary of the key model schemes in HadGEM1 and HadCM3. A key aspect of our strategy is for a unified model (UM), used for both numerical weather prediction and climate modelling. It has therefore been a particular aim in building HadGEM1 to incorporate the new semi-Lagrangian dynamical core, which has recently been implemented in the Met Office’s operational forecast models. In addition, continuing research into climate processes has yielded a number of new physical parametrizations, improving the representation of these processes and adding new functionality to the model. Furthermore, increases in computing resources, coupled with the different behaviour of the semi-Lagrangian dynamics at low resolution, have motivated us to increase the horizontal and vertical resolutions in both the atmosphere and ocean when compared with HadCM3. Taken together, these developments mean that HadGEM1 is very different from its predecessor.

The evaluation of HadGEM1 against observations and reanalyses indicates that most aspects of the simulation are significantly improved compared with HadCM3 (Martin et al. 2006). The basic model variables of temperature, winds and moisture are improved in the free atmosphere, as is mean sea-level pressure. These improvements can be attributed to the increased resolution and the new dynamics and physics packages. Some of the most impressive improvements are in the tropopause structure and the reduced surface pressure bias in the Arctic. The transport of both water vapour and tracers is also dramatically improved. Some aspects of variability are less well simulated however, in particular tropical Pacific sea surface temperatures (SSTs), El Niño Southern Oscillation (ENSO) variability and monsoon rainfall. These problems are the subject of ongoing research and there have already been substantial improvements made to a new model family, HadGEM2, which is in the process of being documented (see also §5).

A summary of the key improvements in physical processes in HadGEM1 is as follows.

(i) The new advection scheme results in improved transport of water vapour and tracers, although some compromises have to be made to ensure conservation of tracers.
(ii) The improved representation of clouds and convection improves the representation of clouds, water vapour and radiative properties of the atmosphere.
(iii) Increased horizontal and vertical resolutions improve spatial and temporal variability.
(iv) The new boundary layer scheme and surface tiling improve properties of the boundary layer, interactions with convection and interactions between the atmosphere and the land and ocean surfaces.
(v) The new gravity wave scheme improves tropospheric and stratospheric gravity waves as well as large-scale winds across the globe.
(vi) The inclusion of an interactive sulphur cycle, including the indirect aerosol effects, means that radiative forcing can be represented more realistically.
Table 1. Summary of the key model schemes in HadGEM1 and HadCM3.

<table>
<thead>
<tr>
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<th>HadCM3</th>
<th>HadGEM1</th>
</tr>
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<tbody>
<tr>
<td>atmospheric grid</td>
<td>Arakawa-B grid</td>
<td>Arakawa-C grid</td>
</tr>
<tr>
<td>hydrostatic</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>horizontal resolution</td>
<td>$2.5^\circ$ latitude $\times 3.75^\circ$ longitude</td>
<td>$1.25^\circ$ latitude $\times 1.875^\circ$ longitude</td>
</tr>
<tr>
<td>vertical resolution</td>
<td>19 levels; hybrid pressure; Lorenz grid</td>
<td>38 levels; hybrid height; terrain following near bottom boundary; Charney–Phillips grid</td>
</tr>
<tr>
<td>physics–dynamics coupling</td>
<td>sequential</td>
<td>parallel split (slow processes), sequential split (fast processes) (Dubal et al. 2004)</td>
</tr>
<tr>
<td>dynamics</td>
<td>Eulerian advection, split-explicit time integration (Cullen 1993)</td>
<td>semi-Lagrangian advection, conservative monotone treatment of tracers; semi-implicit time integration (Stamford et al. 2003; Davies et al. 2005)</td>
</tr>
<tr>
<td>boundary layer</td>
<td>local Richardson number mixing scheme (Smith 1990, 1993)</td>
<td>non-local mixing scheme for unstable boundary layers (Lock et al. 2000); local Richardson number scheme for stable boundary layers (Smith 1990, 1993)</td>
</tr>
<tr>
<td>microphysics</td>
<td>Senior &amp; Mitchell (1993); evaporation of precipitation as in Gregory (1995)</td>
<td>mixed-phase scheme including prognostic ice content; solves physical equations for microphysical processes using particle size information (Wilson &amp; Ballard 1999)</td>
</tr>
<tr>
<td>convection</td>
<td>mass flux scheme (Gregory &amp; Rowntree 1990); convective downdraughts (Gregory &amp; Allen 1991); convective momentum transport (Gregory et al. 1997)</td>
<td>revised scheme including diagnosed deep and shallow convection; new thermodynamic closures at lifting condensation level; new CMT parametrization based on flux–gradient relationships; parametrized entrainment/detrainment rates for shallow convection; based on ideas from Grant &amp; Brown (1999) and Grant (2001); convective anvil scheme (Gregory 1999)</td>
</tr>
<tr>
<td>gravity wave drag</td>
<td>Gregory et al. (1998)</td>
<td>gravity wave drag scheme with low-level flow blocking (Webster et al. 2003)</td>
</tr>
<tr>
<td>orography</td>
<td>derived from US Navy 10’ dataset</td>
<td>derived from global land-based one kilometre base elevation (GLOBE) dataset at 1’ resolution</td>
</tr>
<tr>
<td>hydrology</td>
<td>MOSES-I (Cox et al. 1999)</td>
<td>MOSES-II (Essery et al. 2001); nine surface tile types plus coastal tiling; seasonally varying vegetation (Lawrence &amp; Slingo 2004)</td>
</tr>
<tr>
<td>clouds</td>
<td>Smith (1990); prescribed critical relative humidity for cloud formation (RH-crit)</td>
<td>Smith (1990); parametrized RH-crit (Cusack et al. 1999b); vertical gradient area cloud scheme (Smith et al. 1999)</td>
</tr>
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(Continued.)
(vii) A new land hydrology scheme and improved vegetation scheme (including a seasonal cycle but not interactive vegetation) are included to give better radiation and water balance and improved representation of rivers and run off into the sea.

(viii) Improved sea-ice dynamics and thermodynamics improve the transport, growth and decay of sea ice.

These improvements are described in detail by Martin et al. (2006). Here, we have chosen to highlight two major improvements that are particularly important in the response of the model to global warming, namely cloud and sea ice.

One of the most significant improvements in HadGEM1 has been in the representation of clouds and cloud radiative properties (Martin et al. 2006). This is of particular relevance to climate prediction, as clouds continue to provide the major source of uncertainty when considering estimates of climate sensitivity from contemporary models (Ringer et al. 2006; Soden & Held 2006; Webb et al. 2006). In HadGEM1, we have succeeded in improving the distributions of different cloud types (low or high altitude, optically thick or thin) while at the same time retaining a simulation of the top-of-atmosphere radiation budget, which compares very favourably with that observed. This indicates that we have eliminated many compensating errors associated with clouds that were present in HadCM3, the most apparent being a tendency to generate small amounts of extremely optically thick cloud rather than larger amounts of thinner (‘intermediate thickness’) cloud. Figure 1 shows an example of this and illustrates the improvement in the representation of low-level cloud, i.e. where the cloud top is below approximately 700 hPa in the atmosphere. Recently, Bony & Dufresne (2005) found that tropical cloud feedbacks in current coupled climate change experiments differ most in areas of large-scale subsidence, consistent with
Figure 1. Comparison of low-level cloud simulated in HadGAM1 and HadAM3 (the atmosphere-only versions of HadGEM1 and HadCM3) with satellite observations from the International Satellite Cloud Climatology Project (ISCCP). Low-level cloud is defined as being below 680 hPa. Cloud is further classified in terms of optical thickness into ‘thick’ and ‘intermediate’ thickness categories (adapted from Martin et al. (2006)).
the hypothesis that low clouds play a key role. Webb et al. (2006) have confirmed this by providing direct evidence of considerable low-top cloud responses in areas which contribute most to inter-model differences in global cloud feedback and climate sensitivity. Uncertainties in cloud feedbacks are also discussed in §4.

Another major improvement in HadGEM1 is in the representation of sea ice (McLaren et al. 2006). The geographical ice extent generally agrees well with observations, especially in winter, with the exception of the HadGEM1 winter ice being too extensive in the North Pacific. In the Arctic, HadGEM1’s lead fraction is within the observational range of HadISST and values derived from RGPS. The seasonal cycle of ice area is improved in HadGEM relative to HadCM3 (not shown), with the winter maximum now occurring at the correct time in both the Arctic and the Antarctic. The spatial distribution of ice thickness in HadGEM1 is also much improved relative to HadCM3, particularly in the Arctic (figure 2), where the thickest ice is now banked up against the Canadian Archipelago as observed. Sensitivity experiments suggest that the spatial pattern of ice thickness is improved by the new sea-ice dynamics scheme, and that the magnitude of the ice thickness is improved by resolving the sub-grid-scale ice thickness distribution.

(b) Simulation of future climate response

The transient climate change response in the two models has been compared in an idealized scenario in which atmospheric carbon dioxide concentrations are increased by 1% per annum for 80 years. This scenario has previously been shown to lead to statistically significant changes in global and regional climate for a range of climate quantities of interest. The values of effective climate sensitivity and total ocean heat uptake in HadGEM1 are found to be similar to those in HadCM3 and, consequently, the global mean surface warming is also similar.

On a regional scale, more differences are evident between the two models, with differences in patterns of the climate feedback parameter, surface warming (figure 3) and precipitation all being evident. In the atmosphere above the surface level and in the ocean below the surface, there are noticeable differences in the structure of temperature change. Figure 3 shows that HadGEM1 warms more than HadCM3 over the Arctic Ocean and northern Canada and Alaska, with differences of 1°C or more in some places. At mid-latitudes and over large areas of land, HadGEM1 warms less than HadCM3 again by 1°C or more in some places. Indeed, HadGEM1 actually cools south of Greenland at the time of CO₂ doubling, in an area likely to be affected by changes in the thermohaline circulation.

The patterns of radiative forcing in the two models are similar (Johns et al. 2006; using slab ocean experiments), so the differences in surface warming must be due to differences in local feedbacks, including latent heat damping. Following Boer & Yu (2003), we have estimated local climate sensitivity and analysed the contributing factors. Given the changes in the global cloud distribution described above, we would expect the cloud-related feedbacks to differ between the models. For example, HadGEM1 has a weaker short-wave cloud feedback than HadCM3 over South America and southern Africa, corresponding to the lower temperature increases in these regions seen in figure 3. Over the Amazon, the dominance of the strong short-wave feedback contributed to the strong carbon cycle feedback in HadCM3 (Cox et al. 2000) and this is likely to be reduced in HadGEM1. Differences in the feedbacks related to low-level clouds are also apparent: there is
a weaker negative feedback (leading to greater warming) over the southern tropical trade cumulus regions, whereas a weaker positive feedback (and thus reduced warming) occurs over the Pacific stratocumulus region. There are also differences between the models’ clear-sky feedbacks. HadGEM1 has stronger clear-sky short-wave feedback at high latitudes, particularly over the Northern Hemisphere ocean, presumably resulting from the changes to both sea-ice dynamics and thermodynamics and the retreat of sea ice.

Although the global mean climate sensitivities are very similar (the effective climate sensitivity is 3.1 and 2.8 K in HadCM3 and HadGEM1, respectively), changes in the local feedbacks due to the many differences between the models can lead to substantially different local temperature increases due to increased CO\textsubscript{2}. The generally improved representation of cloud in HadGEM1, for example, should, all other things being equal, enable us to have greater confidence in this model’s predicted cloud feedbacks. The detailed analysis provided by Johns et al. (2006) demonstrates that, individually, the many changes between HadCM3 and HadGEM1 lead to both increases and decreases in the globally averaged climate sensitivity, with their cumulative effect being relatively small. Differences between the geographical patterns of the feedbacks may arise due to interactions between the changes or through the individual feedbacks combining nonlinearly.

3. Earth system processes

There is growing recognition that different parts of the Earth system affect one another and both improved projections of climate change and reliable evaluation of mitigation options require us to include these feedbacks in models. To illustrate this, we focus on a number of Earth system components.

(a) Carbon cycle processes

Inclusion of Earth system components such as the carbon cycle allows us to extend our research from scientific questions such as how atmospheric composition
will affect climate to more politically relevant questions such as how anthropogenic activity will affect climate, through changes in atmospheric composition.

The land and ocean are currently taking up about half of the anthropogenic emissions of carbon dioxide, suppressing the rate at which CO$_2$ increases and climate change.

**Figure 3.** 1.5 m temperature change after 80 years in model integrations in which CO$_2$ is increased by 1% per year. (a) HadCM3, (b) HadGEM1 and (c) HadGEM1–HadCM3.
warms. However, this uptake of carbon is known to be sensitive to climate, so climate change will feedback on itself by modifying the natural carbon cycle: an effect normally excluded from general circulation model climate projections, but which may produce significant acceleration of climate change (Cox et al. 2000).

Climate change acts to weaken both the natural terrestrial and ocean uptake of CO$_2$ from the atmosphere. Faster decomposition of dead plant material exceeds increases in vegetation productivity due to higher CO$_2$ levels, leading to release of carbon from the world’s soils. In the oceans, warmer temperatures reduce the chemical solubility of CO$_2$ and also decrease the mixing of CO$_2$ to depth due to stratification of the surface waters. A recent study of 11 coupled climate–carbon cycle models found unanimous agreement that climate change will reduce natural carbon uptake, providing a positive feedback and accelerated climate change (Friedlingstein et al. 2006). Le Quere et al. (2007) present observational evidence that recent climate changes may already be weakening the natural carbon sink in the Southern Ocean.

(b) Carbon cycle implications

Stabilization scenarios are receiving increasing amounts of interest both politically and scientifically. At present, about half of anthropogenic CO$_2$ emissions are absorbed naturally, but there is growing consensus that this fraction will reduce due to the action of climate change on the natural carbon cycle. Such climate–carbon cycle feedbacks will therefore influence the amount of carbon emissions required to stabilize atmospheric CO$_2$ levels (Jones et al. 2006). Simulated feedbacks between the climate and the carbon cycle (figure 4) imply a reduction of 21–33% in the integrated emissions (between 2000 and 2300) for stabilization, with greater fractional reductions necessary at higher stabilization concentrations. Any mitigation or stabilization policy that aims to stabilize atmospheric CO$_2$ levels must take into account climate–carbon cycle feedbacks or risk significant underestimate of the action required to achieve stabilization.

(c) Radiative forcing from ozone

After CO$_2$ and water vapour, the most important greenhouse gases are methane and ozone. Unlike the first two, methane and ozone react chemically within the atmosphere. Ozone in fact is not directly emitted into the atmosphere (except in very small quantities), but is produced by the chemical reactions of hydrocarbons and oxides of nitrogen. These same compounds also affect the rate at which methane is removed from the atmosphere. Thus, anthropogenic emissions of hydrocarbons and oxides of nitrogen although not necessarily greenhouse gases themselves will have an indirect climate forcing through their effect on methane and ozone (e.g. Derwent et al. 2001; Collins et al. 2002).

The combined effects of anthropogenic ozone precursors can be calculated using three-dimensional chemistry models. Results are subject to uncertainty both globally and regionally, as seen in the recent multi-model intercomparison of Gauss et al. (2006), which included STOCHEM results coupled to both HadAM3 and HadGEM1. However, there is a consensus that twentieth century changes in tropospheric ozone have contributed a positive radiative forcing of approximately 1 W m$^{-2}$ in parts of the tropics and maybe a small cooling forcing in high southern latitudes. Consideration of the interactions with other components of the Earth
system, such as deposition to vegetation and biogenic VOC emissions, is required in order to simulate future tropospheric ozone levels.

(d) Impact of climate change on ozone and methane

As well as reactive gases affecting climate, work by Johnson et al. (2001) has shown that changes in climate can also affect the atmospheric concentrations of reactive greenhouse gases. The rate of loss of ozone from the troposphere increases with the concentration of water vapour. This is expected to increase in a warmer climate. One of the by-products of this ozone loss reaction is the OH radical. Reaction with this OH radical is the main destruction route for methane. A compounding factor is that this destruction rate is temperature dependent, increasing as temperature increases. The overall effect of climate change on chemical reaction rates therefore is to increase the destruction of both methane and ozone—a negative feedback. Figure 5 shows the impact of climate change on methane and ozone in HadCM3. Both are expected to increase in the future, due to increasing anthropogenic emissions; however, all other things being equal, the rates of increase will be less than expected without allowing for climate change. There are, however, other factors to consider. Collins et al. (2003) showed that the influx of stratospheric ozone into the troposphere was likely to increase in the future, due to changes in the atmospheric circulation. Sanderson et al. (2003) predicted an increase in hydrocarbon emissions from vegetation in a warmer climate, and Gedney et al. (2004) predicted an increase in methane emissions from natural wetlands. Sanderson et al. (2007) showed that increasing CO₂ levels in HadGEM1 would decrease the removal of tropospheric ozone by plants due to CO₂-induced stomatal closure reducing the flux of O₃ into stomatal cavities (figure 6). The uncertainties in all these processes are sufficiently large that it is not yet possible to conclude whether climate change will increase or decrease the greenhouse forcing from ozone and methane.
**Impact of ozone on plant productivity**

Excessive $O_3$ concentrations can damage plant cells and therefore reduce productivity, with the risk of decreasing crop yield (McKee & Long 2001; Morgan et al. 2003, 2004). As an illustration of this, Sitch et al. (2005) used an off-line vegetation model driven by changes in climate, $CO_2$ and $O_3$, consistent with the IS92a emissions scenario, and compared the terrestrial carbon storage in simulations with and without $O_3$ physiological effects. $O_3$ concentrations were projected to increase by 10–20% over the most populated parts of the temperate and tropical regions, and this was simulated to reduce terrestrial carbon storage by up to 4 kg C m$^{-2}$ in the eastern USA, Europe, north and Southeast Asia and the tropics, a reduction of approximately 25%. When $O_3$ effects were investigated with and without $CO_2$ effects, it was found that $O_3$ damage was reduced under higher $CO_2$ concentrations as a result of $CO_2$-induced stomatal closure reducing the flux of $O_3$ into stomatal cavities (as described above).

**Ocean biogeochemistry**

The production of dimethyl sulphide (DMS) by ocean phytoplankton has long been thought to form part of a feedback process on global climate.

DMS is the major source of sulphate aerosol over the ocean, forming cloud condensation nuclei and affecting cloud properties. The CLAW hypothesis (Charlson et al. 1987) states that changes in oceanic DMS supply to the

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atmosphere may cause changes to aerosols and clouds and hence global climate. Changes in the amount of radiation reaching the ocean may feedback on the planktonic production of DMS. Climate simulations with HadCM3 have shown that oceanic DMS emissions do form part of a global negative feedback process (Gunson et al. 2006).

\[ g \] Role of mineral dust

Mineral dust aerosol is found throughout the troposphere, where it interacts directly with both short- and long-wave radiation. Changes in the world’s ecosystems and climate have the potential to modify the atmospheric dust content, providing a feedback on climate change and affecting the ecosystems themselves. When vegetation and climate change from a coupled climate–carbon cycle model simulation were used to drive the mineral dust scheme in the atmosphere-only model version, HadAM3, the global mean dust load increased by a factor of approximately 3 (Woodward et al. 2005). Such changes would be likely to lead to impacts on marine ecosystems, where dissolved iron delivered by atmospheric transport of dust can be a very important micronutrient. Changes in the supply of iron to the surface ocean may form a significant climate feedback in the future by affecting biological activity and hence ocean carbon uptake and oceanic production of DMS. An iron-cycling version of the HadOCC ocean carbon cycle model will be implemented in a model version in the HadGEM2 family and coupled to the atmospheric dust scheme.

\[ h \] Earth system models

In order to understand the overall feedbacks of chemistry and ecosystems on climate, the relevant processes need to be included within the climate model. The current generation of climate models have been tested with some of these

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feedbacks individually (figure 7a). Figure 7a schematically represents the couplings present in the Hadley Centre models that generated the results for the IPCC Fourth Assessment Report. Aerosols are coupled interactively to the climate model, but the chemical fields to drive the aerosols and supply reactive greenhouse gases are coupled off-line through the supply of data files. Similarly, the cycling of carbon through ecosystems is not included in HadGEM1, and only in separate experiments with HadCM3LC. Figure 7b represents the next generation ‘Earth system’ model. In this configuration, the chemistry and the ecosystem models will be coupled interactively to the aerosols and the climate. This will allow the important feedbacks to be quantified. Our next generation family of models, HadGEM2, will include versions in which the main key processes and their interactions are incorporated (figure 7b).
4. Quantifying uncertainty in predictions of climate change

While great progress has been made in recent years in building more accurate physically based models of the climate system, uncertainties in the projections made by the models still remain (e.g. Collins 2007). There are three principal sources of uncertainty in climate predictions, which are as follows.

(i) Those which arise owing to unknown future emissions of greenhouse gases and other forcing agents related to both human and natural activities.
(ii) Those due to internally generated chaotic fluctuations in the system—e.g. the phase of the ENSO at some point many decades in the future.
(iii) Those due to the simplifying assumptions made in building climate models. In particular, the representation of sub-grid-scale physical processes.

The latter source of uncertainty has been assessed in the past using the rather ad hoc approach of comparing the outputs of different climate models in international assessment exercises (e.g. Cubasch et al. 2001). In recent years, the Hadley Centre has been at the forefront of the development of a new method of quantifying uncertainties in climate predictions and producing predictions in terms of the probabilities of different outcomes (probability distribution functions (pdfs); Murphy et al. 2004, 2007).

While the method can in principle be applied to quantify all sources of uncertainties, the main focus of the project so far has been on the latter source, i.e. the one arising from the representation of physical processes in models. These sub-grid-scale processes are parametrized by means of simplified physically based or empirical relationships between the large-scale resolved model variables and the small-scale processes such as those associated with clouds and radiation. Such relationships, loosely termed the ‘model physics’, are controlled by parameters that are, in themselves, uncertain. By perturbing these model parameters, it is possible to generate an ensemble of possible future outcomes based on different versions of the same climate model (Murphy et al. 2004, 2007; Stainforth et al. 2005). Information from these ensembles of models may then be assembled together with information from the real climate system to produce pdfs of climate change for a range of different variables.

Figure 8 shows an example of the simulation of historical and future global mean temperature change using a ‘perturbed physics’ ensemble approach (Collins et al. 2006). It can be seen that perturbing the model parameters does result in a relatively wide spread of outcomes on centennial time scales. While the magnitude of global mean temperature change is not necessarily an indicator of the magnitude of regional change and its impacts, it does provide a useful benchmark and to that extent highlights how uncertainties in model formulation translate to uncertainties in predictions. Perturbed physics ensembles have been analysed in detail to show, rather like the small ensemble of the world’s climate models, that climate feedbacks associated with clouds and radiation are the principal driver of uncertainties in global mean temperature change (Webb et al. 2006).

Further steps are required to derive pdfs for transient regional climate change from the perturbed physics ensembles. The 17-member ensemble of Collins et al. (2006), with coupling to a dynamic ocean model, was limited in size by computer
resources and is clearly insufficient to fully sample modelling uncertainty (29 model parameters were simultaneously varied here). For this reason, a technique has been developed to augment ensemble size by time-scaling patterns of equilibrium climate change obtained from much larger ensembles of perturbed physics experiments with coupling to a simpler mixed-layer (‘slab’) ocean model (Williams et al. 2001), and forced by pre-industrial and twice pre-industrial CO2. In this way, we can estimate the transient regional response for a larger fraction of parameter space in a cost-effective way (Harris et al. 2006). Figure 9 shows ‘plumes’ of evolving uncertainty in change in two key variables over the historical and future period under a single emissions scenario, with 245 time-scaled equilibrium simulations here contributing to the spread in response. Although this is a relatively large ensemble, it does not represent an unbiased sample relative to some choice of the prior distribution of uncertain model parameters, so the plumes in figure 9 should be regarded as sample-dependent frequency distributions rather than pdfs. However, information from this ensemble can be used to construct an emulator (Rougier & Sexton 2007), which is a statistical model that allows us to predict the model response at any untried point in parameter space. By sampling this emulated equilibrium response and time scaling, we can derive pdfs for our model’s predictions of transient regional climate change for any underlying distribution of uncertain model parameters. A further step in the derivation of pdfs is comparison with observations of current climate and historical trends, in order to down-weight parts of the model pdf that compare less well with observations than with those parts which compare better, for example in examining the response to past historical or palaeoclimate forcings. This application of observational constraints will be the next stage in our work in ensemble climate prediction.

Figure 8. Time series of global, annual mean temperature from two perturbed physics ensembles of HadCM3. Temperatures are expressed as anomalies with respect to a period of 1860–2000. The black lines are curves which use the ensemble members described by Collins et al. (2006). The grey lines are from a new ensemble with much reduced North Atlantic and Arctic SST and salinity biases, which also sample a slightly larger range of atmospheric and surface feedbacks. (The number of ensemble members makes it difficult to distinguish the different curves but the desire is to illustrate the existence of ensemble spread and the increase in spread with time.) The thick black curve shows observed record of global mean temperature change.
The ensemble simulations and pdfs shown in figures 8 and 9 only have perturbations made to parameters relevant to atmospheric and surface processes. While these processes do exert a leading-order control on the sensitivity of the physical climate system, other processes in the ocean and related to chemistry and carbon cycle feedbacks must also be quantified. Work to run ensembles in which parameters in those model components are varied is currently underway. In addition, the sensitivity to various methodological assumptions needs to be tested and the output pdfs compared with those derived using alternative approaches (e.g. Stott & Kettleborough 2002).

The science of probabilistic and ensemble climate prediction is still rather young but is growing quickly. We expect probabilities and quantitative risk assessment of climate change to become a key tool in the policy arena in the near future.

The ensemble approach provides useful information about the probability of extreme events. The rarity of such events means that some estimate of uncertainty is required to make meaningful statements about extremes. Figure 10a,b shows the change of hot and average days in summer and wet and average days in winter, respectively, for two grid boxes. These show that average days change in a different way to extreme days. The average summer’s day representative of Washington is between 2 and 8° warmer (with a few outliers over 10°). The hottest day of summer, on the other hand, has temperature increases with a much larger range of values between 2.5 and 14°. The average winter’s day representative of Southeast England is between 25% drier and 50% wetter, whereas the wettest day is between 0 and 50% wetter. Hence, changes in global mean temperature, or even changes in the average local values of a particular quantity, cannot be used to infer the pattern of change in extreme events.

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5. Summary and further work

This paper has outlined some of the current approaches to climate modelling used by the Met Office Hadley Centre by illustrating some of our latest results. The competing requirements for complexity, resolution and addressing uncertainty have led us to develop a number of modelling families within which there are a hierarchy of models whose physical mechanisms can be thought of as being consistent or ‘traceable’ to one another.

The new HadGEM family of models includes substantial improvements in the representation of clouds and sea ice, which are important for climate sensitivity. The transport of water vapour and other tracers has improved, improving the water balance and representation of chemistry and aerosols. Boundary layer and land surface representation has improved, together with gravity wave representation. In HadGEM1, some aspects of variability are less well simulated, in particular tropical Pacific SSTs, ENSO variability and monsoon rainfall. These problems were the focus of targeted model development, which has led to the definition of HadGEM2-AO, the new atmosphere–ocean component model, within the HadGEM2 model family. Ongoing research will define an Earth system version of this model, HadGEM2-ES.

HadGEM2-AO is currently being documented in detail, but an outline of the improvements is given here. In the atmosphere submodel, the representation of aerosols is much improved relative to HadGEM1; two natural aerosol species, mineral dust and secondary organic aerosols, have been added to the model. Improvements to the existing sulphate and biomass burning aerosols have also been made, based on observations from dedicated field campaigns.

Figure 10. (a) Relative likelihood changes in temperature for the hottest and average summer day due to the doubling of CO₂ concentrations for the grid box containing Washington, DC. (b) Relative likelihood changes in precipitation for the wettest and average winter day due to the doubling of CO₂ concentrations for the grid box containing the southeast of England. Wettest (hottest) day is calculated by ranking 20 years of winter (summer) data for each ensemble member and each CO₂ concentration and selecting the 20th highest value. The average day is taken as the median of the ranked data. Distributions are calculated from the differences between 1×CO₂ and 2×CO₂ pairs for each ensemble member. Sample contains 128 perturbed physics members where all the perturbed parameters are perturbed simultaneously.
Improvements to both the atmosphere and the ocean have been included, which contribute to improvements in the wind stresses and SSTs in the tropical Pacific and associated improvements in ENSO variability. The convection scheme now exhibits a smoother and more realistic mass flux profile due to new functionality that allows the scheme to detraining moisture less sharply near the tropopause. Consequently, this change improves the vertical structure of diabatic heating and was shown to have a positive effect in reducing the strength of easterly wind stresses in the equatorial Pacific region. Changes to the ocean submodel for HadGEM2-AO are designed to improve the tropical simulation by reducing mixing. A revised vertical diffusivity profile in the top 1000 m (but still within the uncertainties of observational estimates) was used in HadGEM2-AO. This helps to warm the tropical SSTs by reducing the mixing of cooler subsurface water. Horizontal momentum mixing is now made a function of latitude such that the mixing coefficient is a minimum at the equator and increasing towards the poles, instead of the constant value used in HadGEM1. The result is a reduction in tropical viscosity that leads to a reduction in the westward currents on the equator, in better agreement with observations.

HadGEM2-AO uses a new method for returning soil water content in supersaturated soil layers to the saturation value; excess soil water is now drained out of the bottom of the layer instead of being pushed back out the top of the layer. This helps to reduce the Northern Hemispheric warm biases over land as seen in HadGEM1, as does a simple exponential decay lifetime applied to convective cloud amount, which alleviates the intermittency of the convection scheme. Early tests show that these improvements mean that carbon cycle feedbacks can realistically be included in the Earth system model, HadGEM2-ES, within the HadGEM2 model family.

Overall, the general performance of the HadGEM2 atmosphere is at least very similar to, and in most cases better than, HadGEM1, using an r.m.s.-based index of global model skill. Aspects of variability such as the Indian summer monsoon and ENSO are also improved in HadGEM2-AO, although there is still scope for further improvement and this is being addressed as part of our development towards the next model family, HadGEM3.

Despite recent improvements in climate modelling, including those outlined above in HadGEM2-AO, one of the most challenging issues in model development is tracing back systematic deficiencies in observable climate properties (e.g. ENSO, monsoon, blocking, etc.) to fundamental improvements in model formulation. Recent research has shown that some of the key climate model shortcomings (e.g. aspects of the monsoon and equatorial wind simulations in HadGEM1) can be traced back to short NWP simulations. Many of the fast physics processes can also be investigated on NWP time scales and upper ocean–atmosphere interaction on seasonal time scales. The Met Office Unified Model, which is the basis of the HadGEM models, is in a prime position to exploit these various aspects of model traceability across space and time scales.

A new challenge for climate research is to adapt to the changing requirements of policy makers towards mitigation and adaptation advice and research into climate impacts. Mitigation advice requires quantification of the climate impact on the global carbon cycle and other Earth system feedbacks, but the current uncertainty is large. Understanding the cause of this uncertainty and constraining it through improved process representation and observational
constraints is a key challenge of climate modelling. A traceable hierarchy of models is required to address these issues. Complex models are required to understand processes and ensure that they are accurately represented. Simpler and cheaper versions of the same models are required to explore and quantify uncertainty and to perform multiple ‘what if’ scenarios. As we move forward to developing a full range of traceable models within our new model families such as HadGEM3, these questions will continue to be addressed using cheaper and less complex models (such as the standard and FAMOUS versions of HadCM3).

Adaptation advice and detailed impacts information require detailed information on climate change at a regional scale from seasonal, through decadal to centennial time scales. Improved representation of physical processes and increased vertical and horizontal resolutions will be required to improve regional climate and important aspects of variability. Developments in NWP (as outlined above) and seasonal forecasting using the HadGEM families of models will all contribute to such improvements. However, it is probable that substantial increases in computer power will also be needed to fully realize the benefits of improved models.

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