The Hadley Centre climate model HadGEM1

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1. Introduction

Useful climate predictions depend on having the best available models of the climate system. However, it is increasingly apparent that it is not possible to concentrate on simply producing the most comprehensive and 'accurate' model for such work. 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 high resolution would require computers several orders of magnitude faster than today's machines. For these reasons the Hadley Centre, Met Office has adopted a flexible approach to climate modelling based on a suite of models designed to address 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.

The modelling tools we have available now for climate modelling are:

1. HadCM3 (Gordon et al., 2000, Pope et al. 2000) – a well established coupled climate model that is cheap to run on current computers (for example it can be run on a pc, www.climateprediction.net).
2. FAMOUS - A low- resolution version of HadCM3 designed to run about 10 times faster (Jones et al, 2005). It is well suited to long runs, large ensembles or use on PCs and it's 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.
3. HadGEM1 (Johns et al, 2006, Martin et al., 2006, Banks et al., 2006) – a state of the art Global Environment Model, building on, but substantially changed from HadCM3.
4. Earth system feedbacks (details below) – these have been incorporated separately into coupled ocean atmosphere models (such as HadGEM1 and HadCM3). Work has started in incorporating these into HadGEM2 for the next generation of true Earth System Models.
5. Regional (Buonomo et al, 2006, Wilson et al., 2006) and high resolution models (led by the NERC HiGEM project) – these build on the standard global models.
6. QUMP (Murphy et al. 2004) – Quantifying Uncertainty in Model Predictions using ensembles of scientifically distinct versions of HadCM3.
7. Evaluation (details below) – we have a variety of datasets and tools such as observation simulators for evaluating models and understanding climate, aimed at reducing uncertainty.

This paper gives an outline of the characteristics of our latest climate model, HadGEM1. Further details of more recent developments to reduce systematic biases and produce an updated version, HadGEM1a will be given at the workshop. Full details can be found in the references cited. Evaluation is discussed throughout the paper as it underpins our confidence in the model results.

2. HadGEM1

Full details of HadGEM1 are given elsewhere (see refs above). Table 1 provides a summary of the key model schemes in HadGEM1 and HadCM3 and Fig. 1 provides a schematic of the main benefits of the improvements in processes and functionality in HadGEM1 when compared with HadCM3

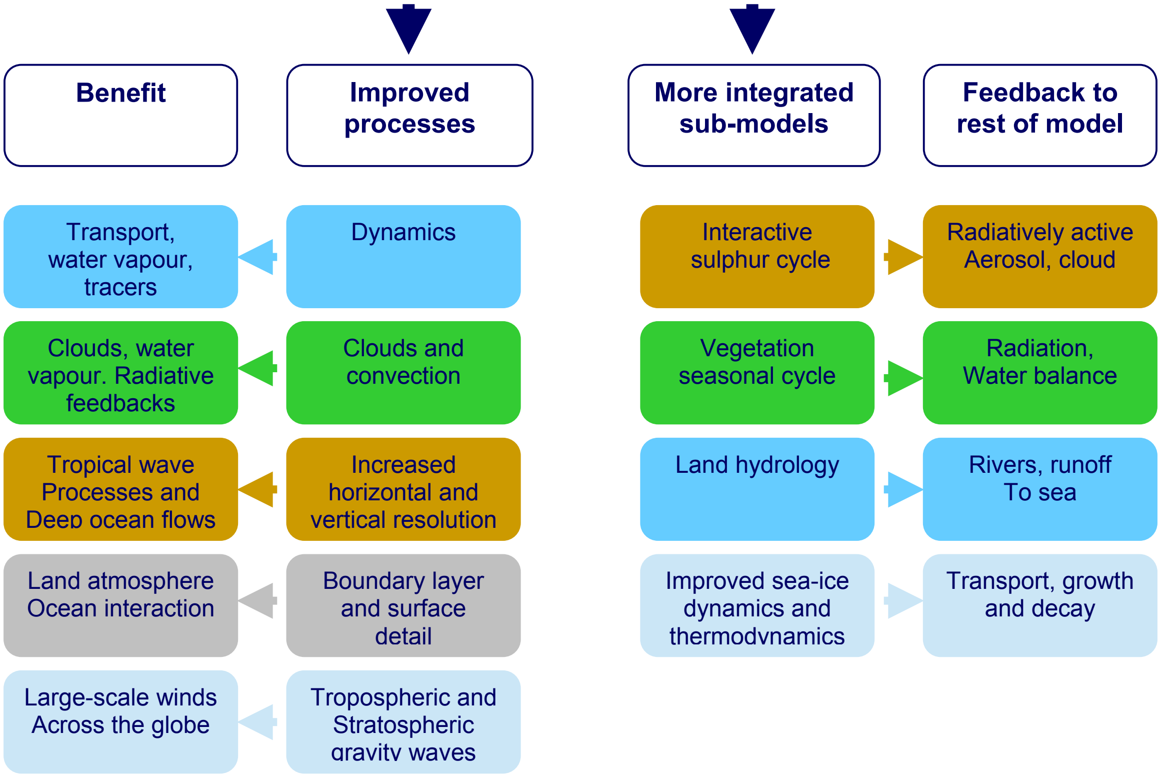
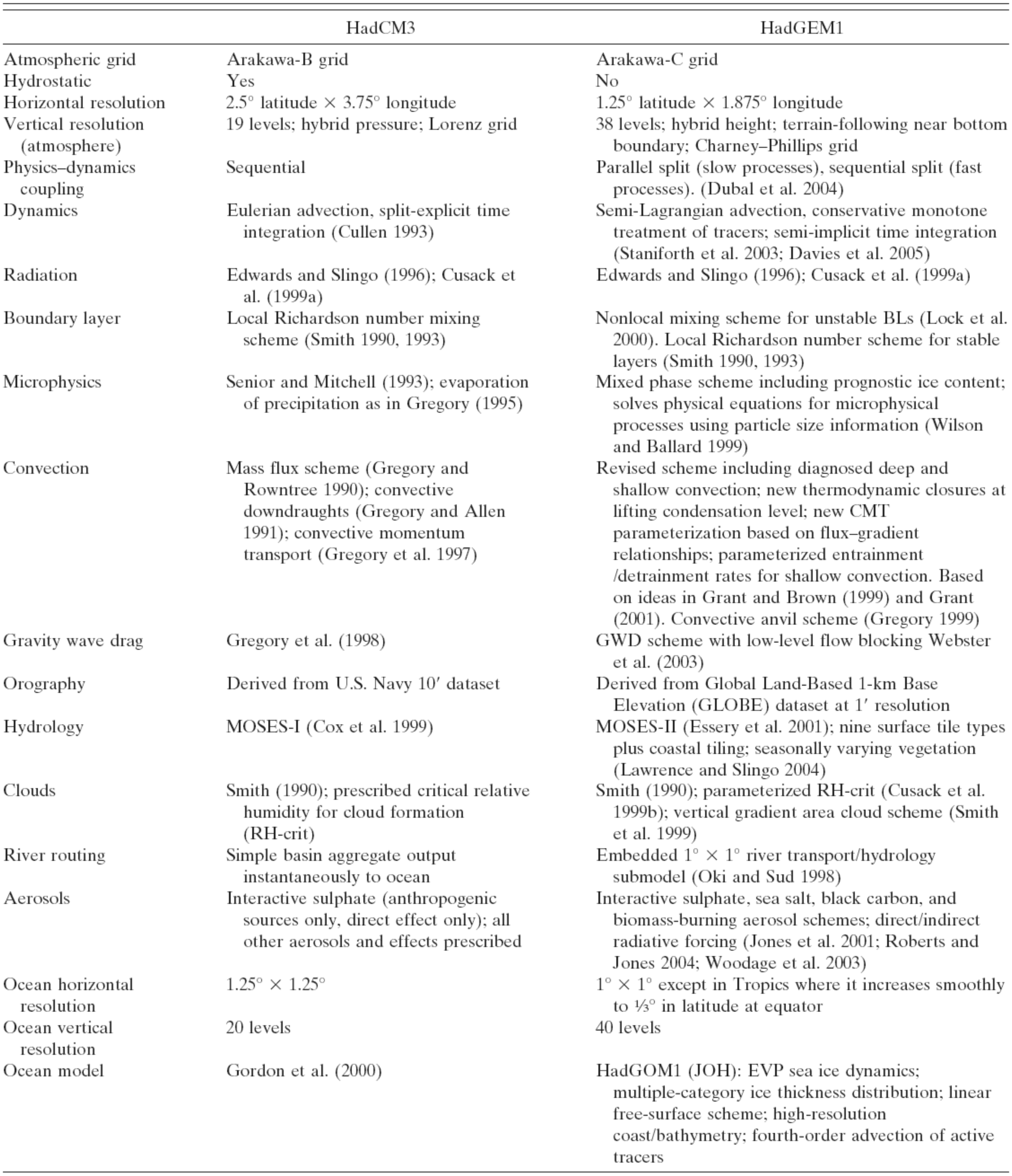


Fig. 1: Major improvements in HadGEM1 compared with HadCM3.

The evaluation of HadGEM1 against observations and reanalyses indicates that most aspects of the simulation are significantly improved compared to 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.

These improvements are described in detail in Martin et al. We have chosen instead to highlight two major improvements that are particularly important in the response of the model to global warming, namely cloud and sea ice.

Table 1: Summary of HadCM3 and HadGEM1 configurations.



	HadCM3	HadGEM1
Atmospheric grid	Arakawa-B grid	Arakawa-C grid
Hydrostatic	Yes	No
Horizontal resolution	2.5° latitude × 3.75° longitude	1.25° latitude × 1.875° longitude
Vertical resolution (atmosphere)	19 levels; hybrid pressure; Lorenz grid	38 levels; hybrid height; terrain-following near bottom boundary; Charney–Phillips grid
Physics–dynamics coupling	Sequential	Parallel split (slow processes), sequential split (fast processes). (Dubal et al. 2004)
Dynamics	Eulerian advection, split-explicit time integration (Cullen 1993)	Semi-Lagrangian advection, conservative monotone treatment of tracers; semi-implicit time integration (Staniforth et al. 2003; Davies et al. 2005)
Radiation	Edwards and Slingo (1996); Cusack et al. (1999a)	Edwards and Slingo (1996); Cusack et al. (1999a)
Boundary layer	Local Richardson number mixing scheme (Smith 1990, 1993)	Nonlocal mixing scheme for unstable BLs (Lock et al. 2000). Local Richardson number scheme for stable layers (Smith 1990, 1993)
Microphysics	Senior and Mitchell (1993); evaporation of precipitation as in Gregory (1995)	Mixed phase scheme including prognostic ice content; solves physical equations for microphysical processes using particle size information (Wilson and Ballard 1999)
Convection	Mass flux scheme (Gregory and Rowntree 1990); convective downdraughts (Gregory and Allen 1991); convective momentum transport (Gregory et al. 1997)	Revised scheme including diagnosed deep and shallow convection; new thermodynamic closures at lifting condensation level; new CMT parameterization based on flux–gradient relationships; parameterized entrainment /detrainment rates for shallow convection. Based on ideas in Grant and Brown (1999) and Grant (2001). Convective anvil scheme (Gregory 1999)
Gravity wave drag	Gregory et al. (1998)	GWD scheme with low-level flow blocking Webster et al. (2003)
Orography	Derived from U.S. Navy 10′ dataset	Derived from Global Land-Based 1-km Base Elevation (GLOBE) dataset at 1′ resolution
Hydrology	MOSES-I (Cox et al. 1999)	MOSES-II (Essery et al. 2001); nine surface tile types plus coastal tiling; seasonally varying vegetation (Lawrence and Slingo 2004)
Clouds	Smith (1990); prescribed critical relative humidity for cloud formation (RH-crit)	Smith (1990); parameterized RH-crit (Cusack et al. 1999b); vertical gradient area cloud scheme (Smith et al. 1999)
River routing	Simple basin aggregate output instantaneously to ocean	Embedded 1° × 1° river transport/hydrology submodel (Oki and Sud 1998)
Aerosols	Interactive sulphate (anthropogenic sources only, direct effect only); all other aerosols and effects prescribed	Interactive sulphate, sea salt, black carbon, and biomass-burning aerosol schemes; direct/indirect radiative forcing (Jones et al. 2001; Roberts and Jones 2004; Woodage et al. 2003)
Ocean horizontal resolution	1.25° × 1.25°	1° × 1° except in Tropics where it increases smoothly to ⅓° in latitude at equator
Ocean vertical resolution	20 levels	40 levels
Ocean model	Gordon et al. (2000)	HadGOM1 (JOH): EVP sea ice dynamics; multiple-category ice thickness distribution; linear free-surface scheme; high-resolution coast/bathymetry; fourth-order advection of active tracers

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 and 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 cloud. Figure 2 shows an example of this and illustrates the improvement in the representation of low-level cloud. Further work on the uncertainties in cloud feedbacks is discussed in section 4.

Many studies have shown that uncertainty in models' climate sensitivity to CO2 doubling are largely due to differences in the strengths of their cloud feedbacks (e.g. Senior & Mitchell 1993.) More recently, Bony and Dufresne (2006) found that tropical cloud feedbacks in current coupled climate change experiments differ most in areas of large scale subsidence, consistent with 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. This study used mixed-layer ocean coupled experiments from the CFMIP (Cloud Feedback Model Intercomparison Project) and QUMP (Quantifying Uncertainty in Model Predictions, Murphy et al 2004) projects.

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 (Figure 3) , 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 Antarctic.. The spatial distribution of ice thickness in HadGEM1 is also much improved relative to HadCM3 (not shown), particularly in the Arctic 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 gridscale ice thickness distribution.

The transient climate change response in the two models has been compared in an idealised scenario in which atmospheric carbon dioxide concentrations are increased at 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 (Fig. 4) 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 4 shows that HadGEM1 warms more than HadCM3 over the Arctic Ocean and northern Canada and Alaska, with differences of 1ºC or more in some places. At mid latitudes and over large areas of land HadGEM1 warms less than HadCM3 again by 1ºC 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.

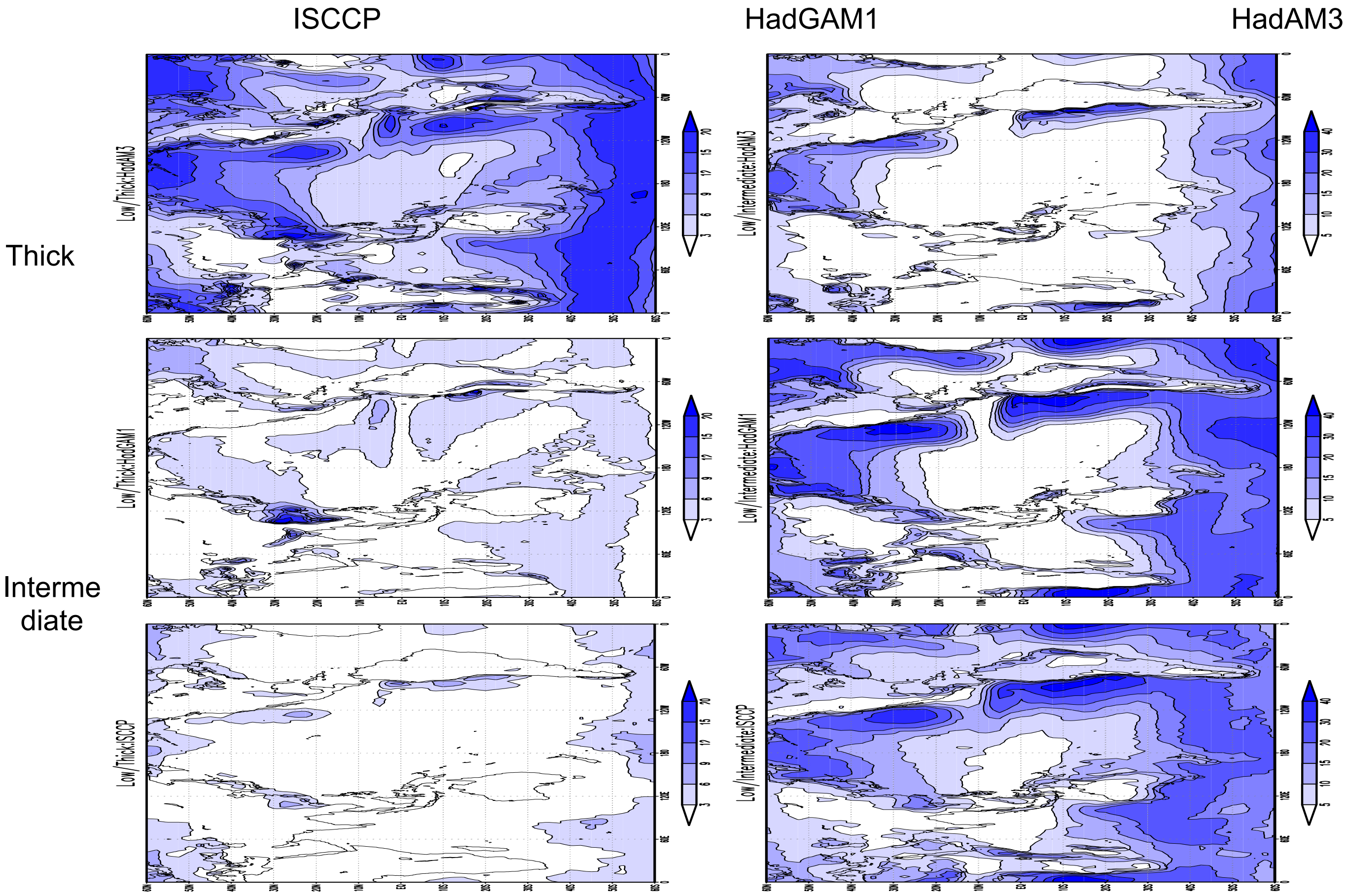


Fig. 2: Comparison low-level simulated in HadGEM1 and HadCM3 with satellite observations from the International Satellite Cloud Climatology Proejct (ISCCP). Low-level cloud is defined as being below 680 hPa. Cloud is further classified in terms of optical thickness into 'thick' and 'intermediate' thickness categories. (from Martin et al. 2006)

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 the work of Boer and Yu (2003a) we have estimated local climate sensitivity and analysed the contributing factors. HadGEM1 has weaker shortwave cloud forcing (accounting for the lower temperatures) than HadCM3 over northern South America and central and southern Africa. Over the Amazon the dominance of the strong shortwave feedback contributed to the strong carbon cycle feedback in HadCM3 (Cox et al., 2000) and this is likely to be reduced in HadGEM1. HadGEM1 has stronger clear-sky shortwave forcing at high latitudes, particularly over the northern hemisphere ocean, as a result of the changes to both sea-ice dynamics and thermodynamics and the retreat of sea ice. This preliminary analysis indicates that many of the differences in response in the two models are due to differences in the behavior of cloud and sea ice. As we demonstrated above the changes are the result of improvements introduced into HadGEM1.

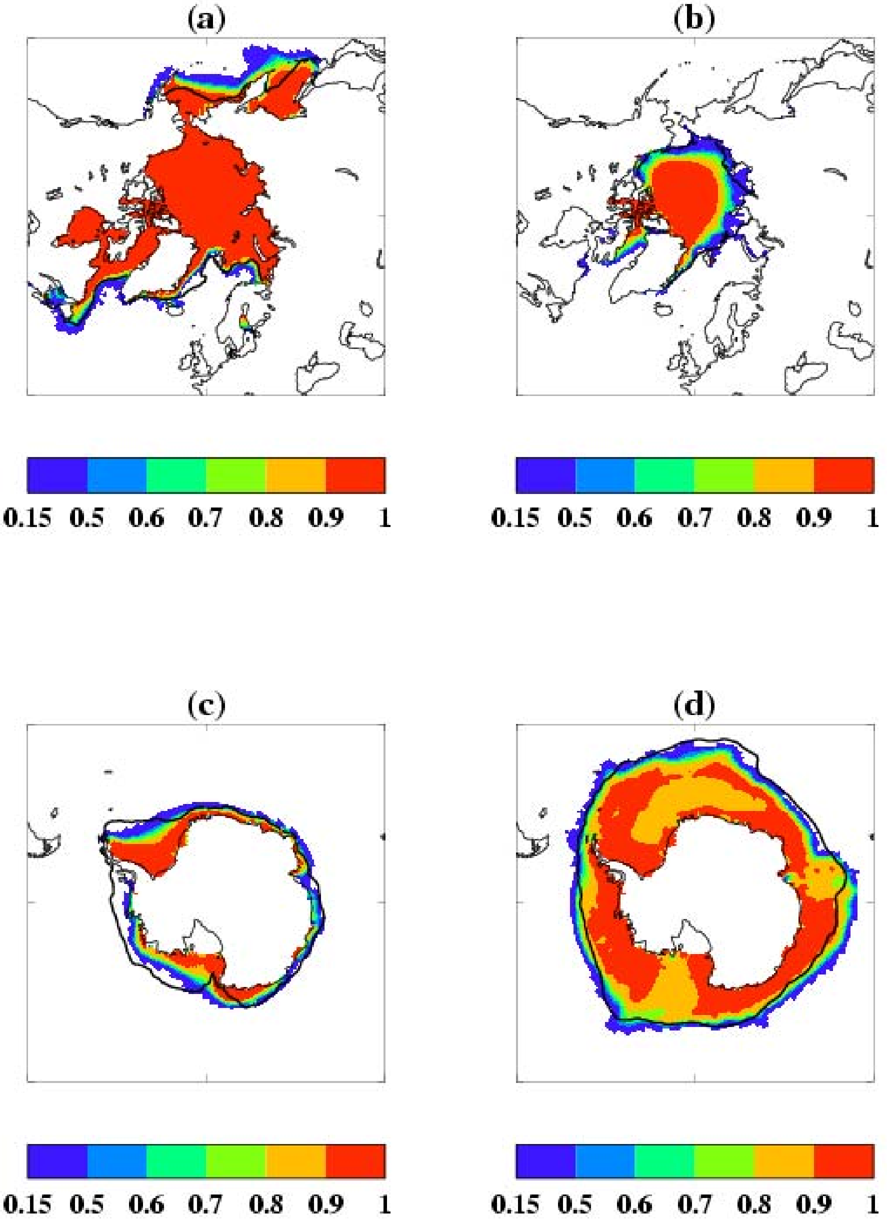


Fig. 3: Model ice concentration for March (a and c) and September (b and d) (mean over 230 years). Thick lines show the 0.15 contours for HadISST data for the period including SSMI data (1979-2002). Model data less than 0.15 has been excluded.

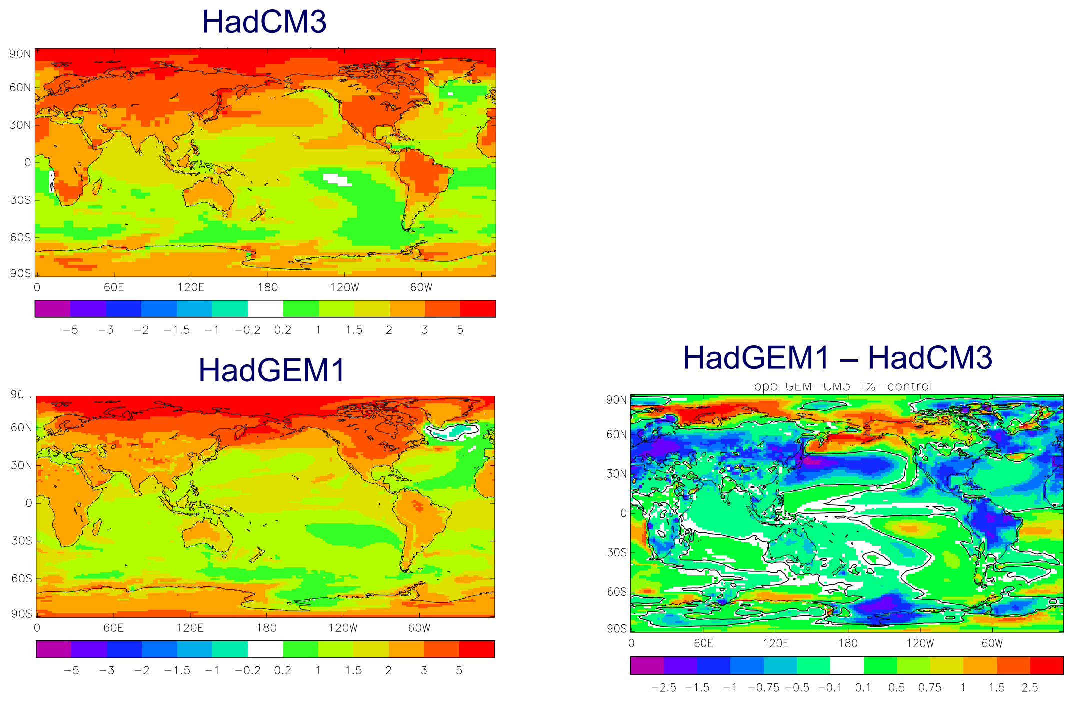


Fig. 4: 1.5m temperature change after 80 years in model integrations in which CO_2 is increased by 1% per year.

3. Summary

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. Some aspects of variability have been degraded however, in particular tropical Pacific SSTs, ENSO variability and monsoon rainfall. These problems are the subject of ongoing research and there have already been substantial improvements.

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