A Fast Ocean GCM without Flux Adjustments

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ABSTRACT

The Fast Met Office/U.K. Universities Simulator project (FAMOUS) aims to develop a fast GCM, possibly 10 times faster than the Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3). Such a model would allow long-term climate runs and/or large ensembles of runs to be carried out. It would also be suitable for use on computers other than a supercomputer. Modifications to the geometry of the North Atlantic (including removal of Iceland) and an increase in the ocean time step, allow the FAMOUS ocean model to run without the use of flux adjustments, and about 40 times quicker than the HadCM3 ocean component (HadOM3). Transient climate change simulations carried out using the new ocean component coupled to the HadCM3 atmospheric component (HadAM3) produce a similar climate sensitivity to the full HadCM3.

1. Introduction

State-of-the-art coupled atmosphere–ocean general circulation models (AOGCMs), such as the Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3; Gordon et al. 2000), are the best tool for making predictions of future climate change over the coming century because of the detail in which they are able to represent the processes involved. However, the high computational resources required to run them make them impractical for uses such as very long-term climate change prediction (e.g., palaeoclimate simulations of glacial–interglacial changes, or anthropogenic climate change beyond the next 100–200 yr). They are also not appropriate for large ensembles with perturbed physical parameters or processes, or for use by anyone who does not have access to a supercomputer. The inclusion of ecosystem and chemistry components within GCMs adds a further cost. For example, Cox et al. (2000) used a lowered-resolution ocean component in their GCM that included an interactive carbon cycle (see section 2 for more details). For all these types of experiment, a faster model is required.

Earth system models of intermediate complexity [EMICs; e.g., CLIMBER (Petoukhov et al. (2000)] have been used very successfully for studying the stability of the thermohaline circulation (THC) in glacial and interglacial periods (Ganopolski and Rahmstorf 2001) and the impact of interactive vegetation in simulations of past climates (Kubatzki et al. 2000). However, such models are fast because of low spatial resolution (CLIMBER; Petoukhov et al. 2000), reduced dimensionality (Stocker et al. 1992; Marchal et al. 1998), or very simplified representation of some aspects of physics (Weaver et al. 2001). Their speed makes them practical for purposes for which state-of-the-art AOGCMs are not, but the necessary simplifications may lead them to exclude some processes that could be important to aspects of climate change. For example, they do not well represent the gyre circulations in the ocean or three-dimensional atmospheric dynamics, which have been suggested to be important in determining THC stability (Vellinga et al. 2002; Thorpe et al. 2001).

Therefore, what is needed is a model based on the AOGCMs but significantly faster. Constructing such a model is the goal of the Fast Met Office/U.K. Universities Simulator project (FAMOUS) at the Met Office in collaboration with the Natural Environment Research Council (NERC). It is hoped that the use of FAMOUS in conjunction with high-resolution AOGCMs such as HadCM3 will allow many more areas of climate and the earth system to be explored. Basing FAMOUS on existing state-of-the-art GCMs allows results to be directly related to the model used for policy-relevant climate projections. Thus, processes in the higher-resolution model (HadCM3) can be validated in long simulations or parameter ensembles carried out with the low-resolution model (FAMOUS). Equally, unresolved processes in FAMOUS can be parameterized based on outputs from the higher-resolution GCM. The approach envisaged therefore provides a direct link between high-resolution and intermediate-complexity parts of the earth system modeling spectrum, with benefits to both.

The ocean GCM component of FAMOUS developed

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here is of similar spatial resolution to various other ocean components of coupled GCMs successfully used in recent climate studies, although it is likely to be much faster due to the changes to model time step discussed in section 3. For example, the Goddard Institute for Space Studies GCM has an ocean resolution of 4° × 5° and 13 vertical levels (Russell et al. 1995, 2000). The Geophysical Fluid Dynamics Laboratory (GFDL) also uses a low-resolution version (R15) of their climate model (R30). The R15 model, with an ocean resolution slightly coarser than that of FAMOUS (4.5° × 3.75° and 12 vertical levels), has been used to study climate change (Dixon and Lanzante 1999) and has been shown to have a similar transient behavior to the R30 version (Dixon et al. 2003). Similarly, the National Center for Atmospheric Research Community Climate System Model (CCSM; Blackmon et al. 2001) has a low-resolution ''Paleo-CCSM'' version. This low-resolution version has an ocean resolution slightly finer than that of FAMOUS (3.6° × 1.8°, decreasing to 3.6° × 0.9° at the equator, and 25 vertical levels). It has been shown to have realistic tropical variability (Otto-Bliesner and Brady 2001) and has been used successfully to simulate past climates such as the Last Glacial Maximum (Shin et al. 2003; Liu et al. 2002).

The FAMOUS model will still be a GCM, but simplified in such a way as to make significant computational savings without too much loss of quality. It is envisaged that the main time savings will be from reduced resolution and increased time step. In particular, it is desired that FAMOUS not need to use flux adjustments. Flux adjustments (Gregory and Mitchell 1997; Johns et al. 1997) are artificial fluxes of heat and moisture that are applied to a model to prevent a long-term climate drift. Previous versions of the Hadley Centre coupled model (e.g., HadCM2; Johns et al. 1997) required flux adjustments, but HadCM3 does not. Better representation of atmospheric and oceanic heat transports within the model allow it to remain stable on long time scales without this artificial correction (Gordon et al. 2000). Because the use of flux adjustments has no physical basis, and they may have an impact on the sensitivity of the model to anthropogenic forcing (Gregory and Mitchell 1997), their use is considered undesirable. The simulation of past climates is also hindered if flux adjustments are required because of the lack of knowledge about the state of the system to which the model must be forced. Hence, in the construction of a fast GCM, avoiding the need to impose flux adjustments is important.

Described here is the work that has been carried out to create the ocean component of FAMOUS from HadOM3 (the existing ocean component of HadCM3). A speedup of about a factor of 40 over HadOM3 has been achieved, and the resulting model coupled to the atmospheric component of HadCM3 (HadAM3; Pope et al. 2000) does not require the use of flux adjustments and has a similar climate and climate sensitivity to HadCM3. Work is progressing toward a fast version of the atmosphere component to complete the coupled FAMOUS model.

The differences between HadOM3 and the FAMOUS ocean model can be broadly split into two. The reduction in ocean horizontal resolution and changes to the topography required to speed up the model without the requirement for flux adjustments are described in section 2, and changes to the time stepping of the model and results from model testing are discussed in section 3. The success of the ocean component of the project is summarized in section 4.

2. Reduced resolution and the need for flux adjustments

A low-resolution version of the HadCM3 ocean component already exists and is in use. The coupled climate–carbon cycle project at the Met Office (Cox et al. 2000, 2001) uses HadCM3L, a version of HadCM3 with a lowered ocean resolution of 2.5° × 3.75° (compared with 1.25° × 1.25° in HadCM3). The reason for this is to save sufficient computational time to allow practical use of an interactive carbon cycle. However, originally this model simulated a steady buildup of sea ice in the North Atlantic to the point where its control climate was unacceptable for use in the carbon cycle experiments. As a result, artificial fluxes of heat and moisture (flux adjustments; Johns et al. 1997) are required to maintain a stable climate. In constructing an ocean component for FAMOUS, we use HadCM3L as a starting point but then try to address the sea ice problem and thereby remove the need for flux adjustments.

a. Removing Iceland

The North Atlantic circulation, both in reality and in HadCM3, has flow through the Denmark Straits (i.e., between Iceland and Greenland). This flow is not permitted in HadCM3L because the width of the Denmark Straits is less than a single grid point at the 2.5° × 3.75° resolution. As a result there is too little heat transport into this region, allowing the sea ice to build up. The additional ice reduces the amount of deep convection that can occur and thus the amount of deep water formed in this region. The reduced circulation forms a positive feedback with less heat transport and more ice, until the Nordic Sea is permanently ice covered. Figure 1 (left) shows how the original topography prohibits any flow at all between Iceland and Greenland and allows only limited flow between Iceland and Scotland. This problem does not arise in HadCM3 because of the higher resolution.

Experiments were performed to assess the impact of changing the topography of the model to allow flow through the Denmark Straits. Experiments were tried involving receding the coast of Greenland and removing Iceland altogether. The results from both experiments

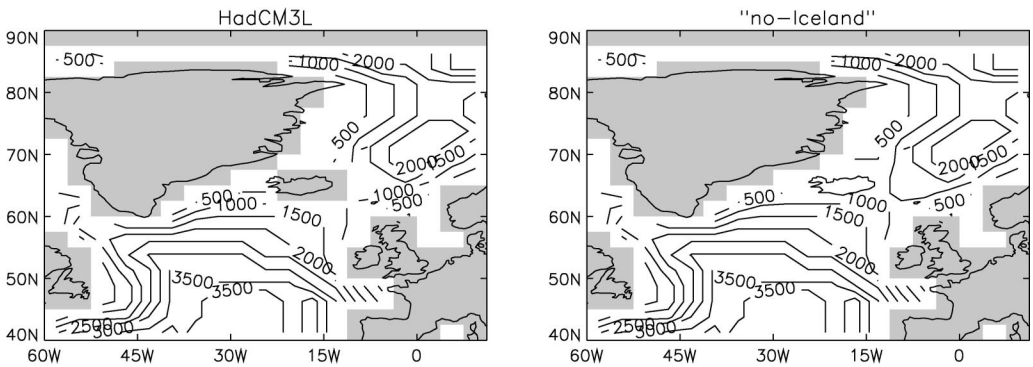

FIG. 1. The land–sea mask and ocean topography of HadCM3L in the North Atlantic, shown on the ''velocity grid'' (i.e., the grid on which ocean momentum values exist) of (left) HadCM3L and (right) the modified ''no-Iceland'' topography. This grid is offset from the ''tracer grid'' (where temperature and salinity values exist) and is only defined at points that are surrounded by four ocean points on the tracer grid. Thus, even though Iceland only occupies two tracer grid points, it occupies six velocity grid points, and the grid does not permit flow between Iceland and Greenland. On the updated grid, Iceland and the Denmark Straits are now 12 model levels deep, corresponding to about 800 m. Physical depths (m) are contoured.

were broadly similar, but subjective assessment of the modeled sea ice extent and North Atlantic overturning streamfunction suggested that the ''no-Iceland'' run was slightly more successful. Along with the removal of Iceland, the topography of the Denmark Straits was deepened to a more realistic depth of 800 m because the work of Wadley and Bigg (1996) suggests that the depth rather than the width of the sill is the important factor in determining the flow. The new land–sea mask and topography are shown in Fig. 1 (right). The removal of this part of the earth's topography in the model is justified because it represents an unrealistic barrier to the circulation. The removal of Iceland provides a more realistic link between the Nordic Seas and the rest of the North Atlantic and allows a much more realistic ocean circulation to be simulated.

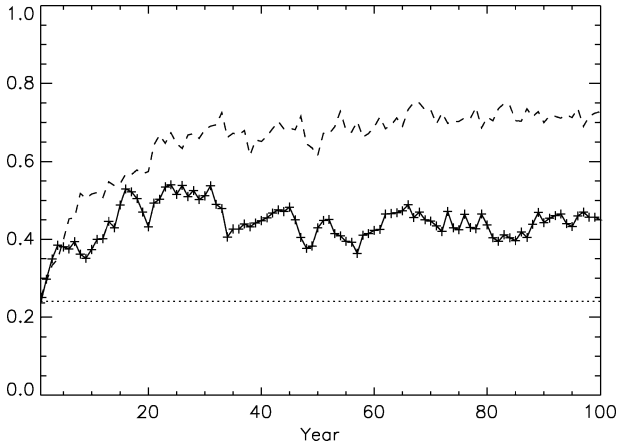

FIG. 2. Time series of the evolution of the annual-mean sea ice fraction in the North Atlantic in the control run without flux adjustments (H3LU, dashed line) and the no-Iceland run (FAM1, solid line with pluses). The dotted line indicates the mean of the 1870s from the HadISST sea ice climatology of Rayner et al. (2003).

b. Results

The model was run without the use of flux adjustments for 100 yr both with the original topography (i.e., unadjusted HadCM3L, hereafter referred to as H3LU), and with Iceland removed (hereafter FAM1). The initial conditions for the run were taken from an existing equilibrium state of HadCM3L. This was a sufficiently long run to determine any long-term drift in the North Atlantic ice fraction or other model variables. The results from these runs were compared with observations and results from both HadCM3 and the flux-adjusted control run of HadCM3L (H3L) as used in the climate–carbon cycle model (Cox et al. 2001). Table 1 lists a summary of the model configurations described in this report, the abbreviations for each configuration, and the symbols used for line plots in the figures throughout the report.

The time evolution of the annual-mean sea ice fraction in the North Atlantic (defined here as the region north of 60°N and between 30°W and 20°E) is shown in Fig. 2. The control run without flux adjustments (i.e., unmodified land–sea mask, H3LU) exhibits a significant, and rapid, increase in ice cover in this region (to more than 70% in the annual mean), whereas the new run with Iceland removed (FAM1) does not. The mean ice cover in the flux-adjusted control (H3L) run is 20%, and in the observations it is 24% [observations are taken from the mean of the 1870s from the Hadley Centre Sea Ice and SST dataset (HadISST) (Rayner et al. 2003)]. Figure 3 shows winter and summer seasonal ice cover for the final decade of H3LU and FAM1 compared with HadISST and HadCM3. There is a large buildup of ice to near-total cover in the Nordic Sea in H3LU. FAM1 keeps a large patch of clear water along the Norwegian coast all year round, and although it still has too much ice, it is much closer to the observations.

The reason for the buildup of ice in this region in H3LU is due to the reduced heat transport into this

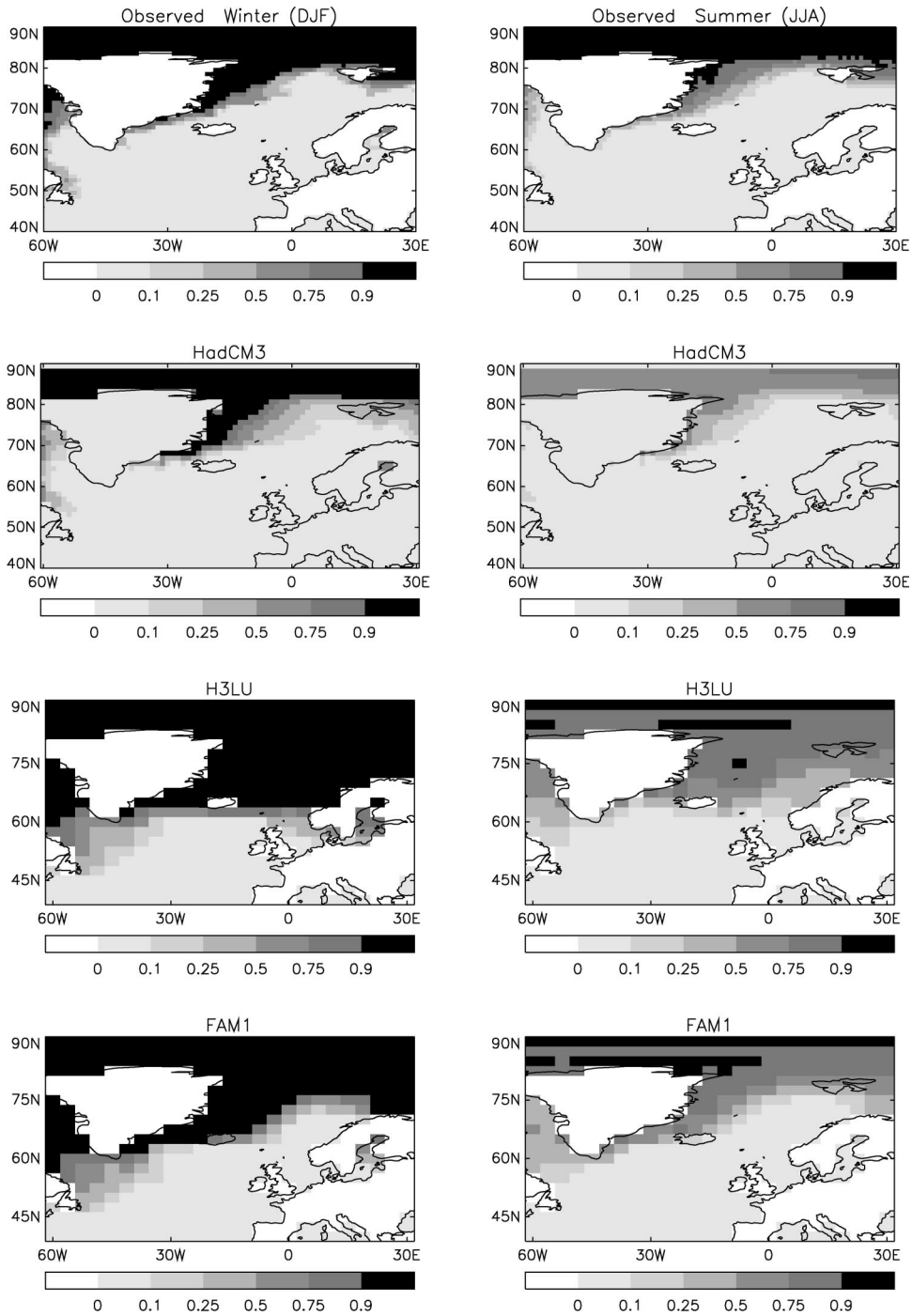

FIG. 3. Observed and modeled ice cover in (left column) winter and (right column) summer in the North Atlantic. Observations are shown from (top row) the HadISST climatology, (second row) HadCM3, (third row) HadCM3L without flux adjustments (H3LU), and (bottom row) the no-Iceland run (FAM1).

region as a result of a sluggish Gulf Stream at this coarse resolution, along with the failure of the model at this resolution to resolve the Denmark Straits. This forms a positive feedback with insufficient heat transported into the region, so there is an increase in ice cover. The increased ice cover inhibits convection and reduces the overturning circulation, thus further reducing the heat transport to the region. Eventually, there is near-total ice cover and no overturning circulation or heat transport penetrating this far north. Figure 4 shows the overturning streamfunction from H3LU and FAM1 compared with H3L. H3LU lacks the penetration of an over-

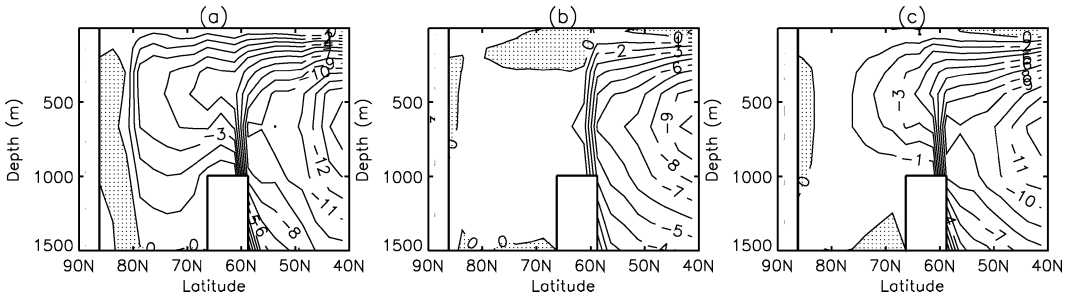

FIG. 4. The North Atlantic overturning streamfunction, (a) in H3L, where there is a cell of overturning with a strength of about 5 Sv in the far north (i.e., beyond 60°N), (b) in H3LU, where this cell does not penetrate at all beyond 60°N, and (c) in FAM1, where this cell is reestablished with a strength of 3–4 Sv.

turning cell north of the Iceland–Scotland ridge, at 60°N, while in FAM1 the overturning there is present as before but slightly weaker than in H3L.

Similarly, the northward heat transport in the North Atlantic (not shown) in FAM1 is similar to H3L, whereas H3LU has much lower heat transport, which all but stops at 60°N.

There is little difference between FAM1 and H3L in the strength of the Atlantic THC south of 60°N, and they both have the same strength as in H3L (about 15 Sv, where Sv $\equiv 10^6$ m^3 s^{-1}), although this is noticeably less than the strength of the THC in HadCM3 (20–25 Sv). Similarly, the ice cover in the Southern Ocean is not affected by the removal of Iceland or the absence of flux adjustments. Globally, annual-mean SST differences between the control and no-Iceland runs (shown later in Fig. 10) are restricted to the North Atlantic region (owing to the decreased ice and increased heat transport in the no-Iceland run). There are only small differences between them away from the North Atlantic region.

Compared with HadOM3 (at 1.25° × 1.25° resolution), the reduced resolution of the ocean component results in a speedup of a factor of 4–5. The removal of Iceland from the model topography allows the model to be run successfully without the need for flux adjustments. The resulting model simulates a small increase in the amount of ice cover in the North Atlantic but by no means as much as in the control run. The impact of this topography change is limited to the North Atlantic.

3. Increased time step

Further significant savings in the computational time of the ocean component can be made by increasing the length of the time step. Use of the ''distorted physics'' technique (Bryan and Lewis 1979; Bryan 1984) allows a longer time step to be used without causing numerical instabilities in the model. An overview of this scheme is given in section 3a. One possible limitation of the technique is that the faster model may not exactly reproduce the same results as the original model, especially regarding the transient behavior. The scheme has been tested in terms of both the control state it produces and its transient response to rapid climate change. The results are presented in section 3b.

a. Overview of the distorted physics scheme and its application

The distorted physics (DP) technique (Bryan and Lewis 1979; Bryan 1984) allows the ocean model to run using a time step that would otherwise result in numerical instability due to fast, internal gravity waves breaking the Courant–Friedrichs–Lewy (CFL) stability criteria for an explicit time-stepping scheme. The DP technique works by replacing the model's momentum equation with one that has the same equilibrium solution but slower internal gravity waves:

$$\frac{du}{dt} = \frac{1}{\alpha}(\mathrm{RHS})_u; \qquad \alpha \geq 1, \tag{1}$$

where $(\mathrm{RHS})_u$ is the right-hand side of the momentum equation in the undistorted case. The result is that a time step can now be used that is a factor of α longer than previously, and it will be stable. In the equilibrium solution of $d/dt = 0$ the equation has the same solution as for $\alpha = 1$. The scheme, and extensive tests performed with it in the HadOM2 model, are described by Wood (1998). HadOM2, the ocean component of HadCM2 (described in Johns et al. 1997), is similar in structure to HadCM3, and has the same resolution as HadCM3L, but has some different physical parameterizations.

The DP scheme also allows for the use of another distortion parameter, γ, that varies with depth and accelerates the behavior of the deep-ocean water masses, but at the expense of not conserving heat or salinity. Danabasoglu et al. (1996) also speculate that the γ parameter may be responsible for the phase lag of their accelerated model in response to seasonal forcing. This feature of DP has not been used in this study, and $\gamma = 1$ at all model levels.

Wood (1998) describes some time step sensitivities in HadOM2 as a result of interactions between the DP scheme and some of the model's physical parameterizations. Wood (1998) found that the model has a time step sensitivity associated with the interaction of the

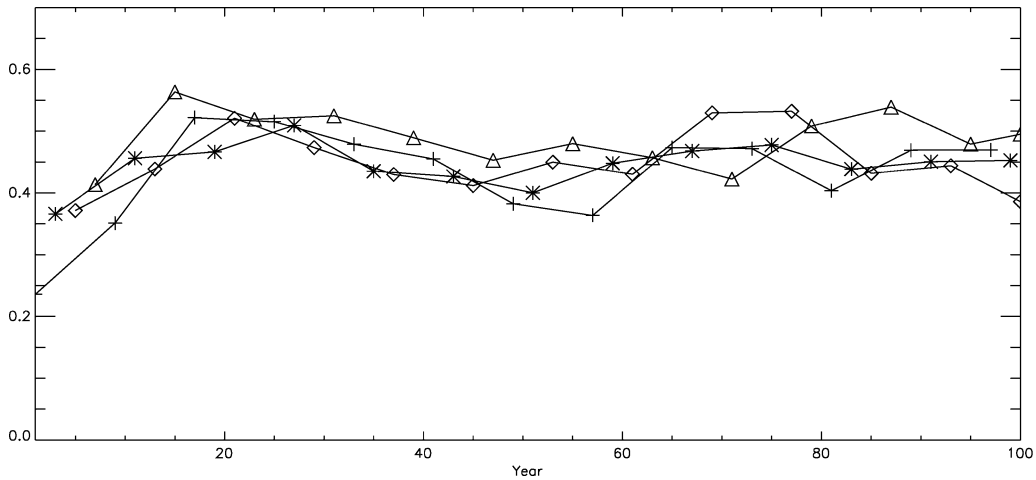

FIG. 5. Time series of the evolution of the annual-mean sea ice fraction in the North Atlantic in FAM1 (solid line with pluses; time step = 1 h) and the DP runs FAM2 (solid line with stars), FAM6 (solid line with open diamonds), and FAM24 (solid line with open triangles). For clarity of plotting, points are only shown for every 8 yr.

Richardson-number-dependent diapycnal tracer diffusivity scheme and the mixed layer scheme. Hence, the Richardson number dependence of the diapycnal tracer diffusivity has been turned off in FAMOUS. The impact of this is small because of the coarse horizontal resolution of the model but would be an issue at finer resolution. The problems reported by Wood (1998) associated with spurious baroclinic waves in the Antarctic Circumpolar Current and convection in the Greenland–Iceland–Norway Sea have not been considered here. The results presented in section 3b(1) show that the equilibrium of the model is not sensitive to the use of DP.

However, despite the model having the same equilibrium solution(s) there is no guarantee that its approach to it (them) will be the same as that of the undistorted model. As such, the DP scheme is often seen as a means of spinning up a model quickly to its equilibrium state before reverting to the distortion-free physics for scientific studies. Danabasoglu et al. (1996) examine this issue in some detail and conclude that for their model the equilibrium solutions from DP and non-DP runs are similar, and that only a few years (typically 15) of non-DP running from the DP state is required to readjust to the non-DP equilibrium. Although the DP technique is not commonly used for scientific studies themselves, for studies involving long time scales, such as climate change experiments, the impact of distorting the fast internal gravity waves may be quite small and so a DP model may still be suitable for such use (Kilworth et al. 1984). If conservation of heat and salinity is required, then the γ parameter must be set to unity, as it is for FAMOUS. Tests showing that the transient behavior of the FAMOUS ocean model is not strongly sensitive to the use of DP are presented in section 3b(2).

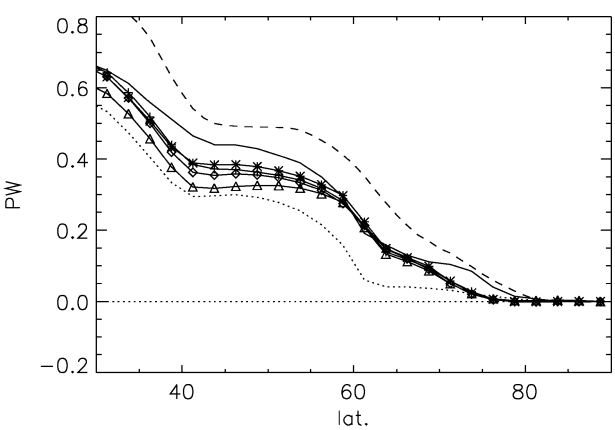

FIG. 6. Northward ocean heat transport in the North Atlantic from HadCM3 (dashed line), H3L (solid line), H3LU (dotted line), FAM1 (solid line with pluses), and the DP runs FAM2 (solid line with stars), FAM6 (solid line with open diamonds), and FAM24 (solid line with open triangles).

It is also possible that the model may have multiple equilibria. In that case, the equilibria of the DP model would be expected to be the same but would not necessarily exhibit the same stability properties. Hence, a model with DP should be used with caution when investigating transitions between multiple equilibria.

b. Results

1) CONTROL CLIMATE SIMULATIONS

A set of 100-yr experiments was performed to assess the impact of using the DP technique described above. The time step in the experiments was increased from 1 h to 2, 6, and 24 h (these runs are referred to hereafter as FAM2, FAM6, and FAM24, respectively), requiring a distortion coefficient, α, of 2, 6, and 24, respectively. The runs all used the no-Iceland configuration of FAM1 described in section 3a. The only difference between

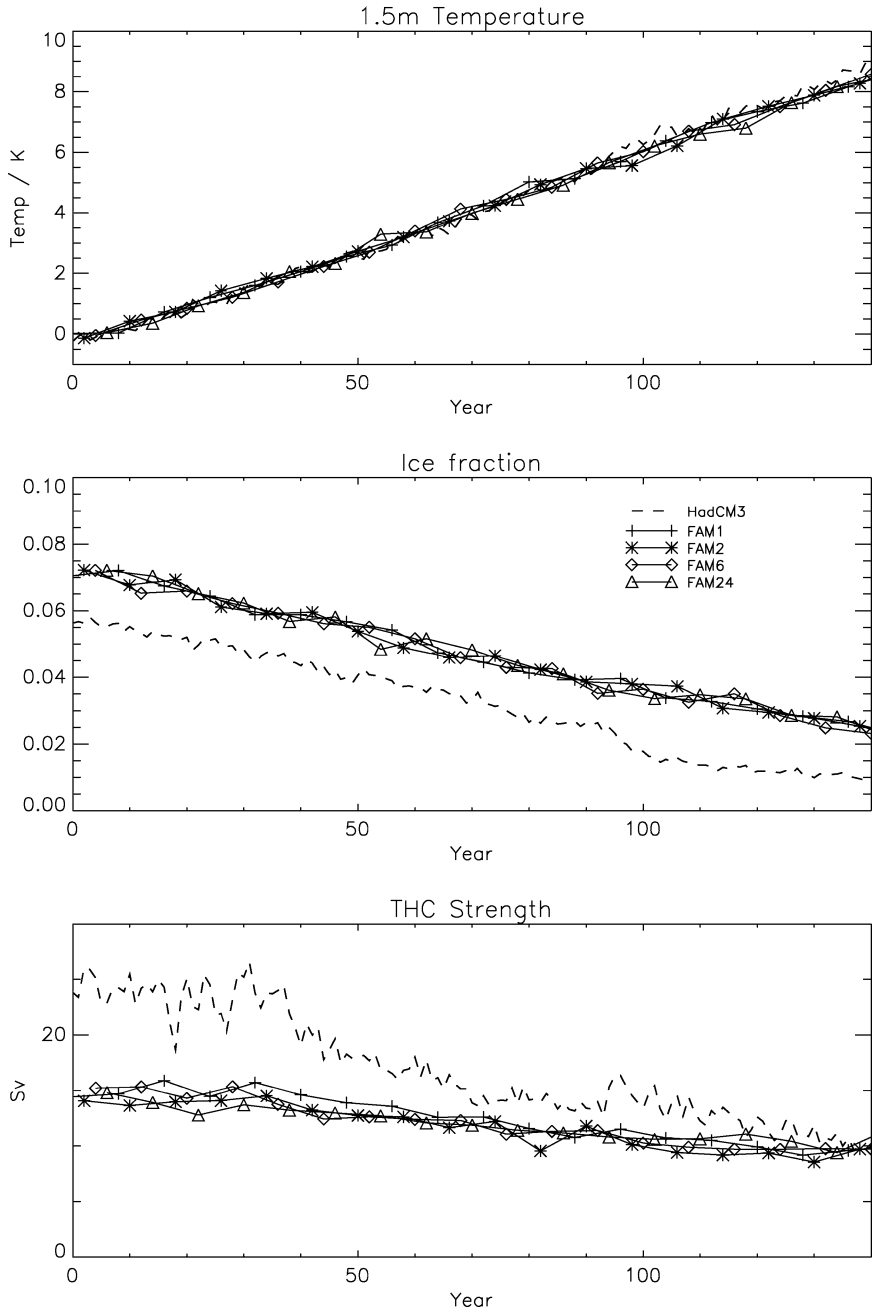

FIG. 7. Results from transient 2% yr^{-1} CO_2 increase experiments. Shown are the time evolution of annual-mean global-mean (top) 1.5-m temperature change, (middle) ice fraction, and (bottom) Atlantic THC strength. The results from HadCM3 (dashed line), FAM1 (solid line with pluses), and the DP runs FAM2 (solid line with stars), FAM6 (solid line with open diamonds), and FAM24 (solid line with open triangles) are shown for each. For clarity of plotting, FAM runs just show points for every 8 yr.

them was the change in time step, except that FAM24 was also changed so that the exchange of fluxes between the atmosphere and ocean components (i.e., the ''coupling'') occurred every 5 days instead of every day.

The results show that the control climate of the model is not particularly sensitive to the use of DP or choice of time step value chosen (at least within the range tested here). In particular, the improvements to the sea ice problem in the North Atlantic, which were delivered by FAM1, are not changed. Figure 5 shows the evolution of the annual-mean ice fraction in the North Atlantic during these four runs. There is no significant difference

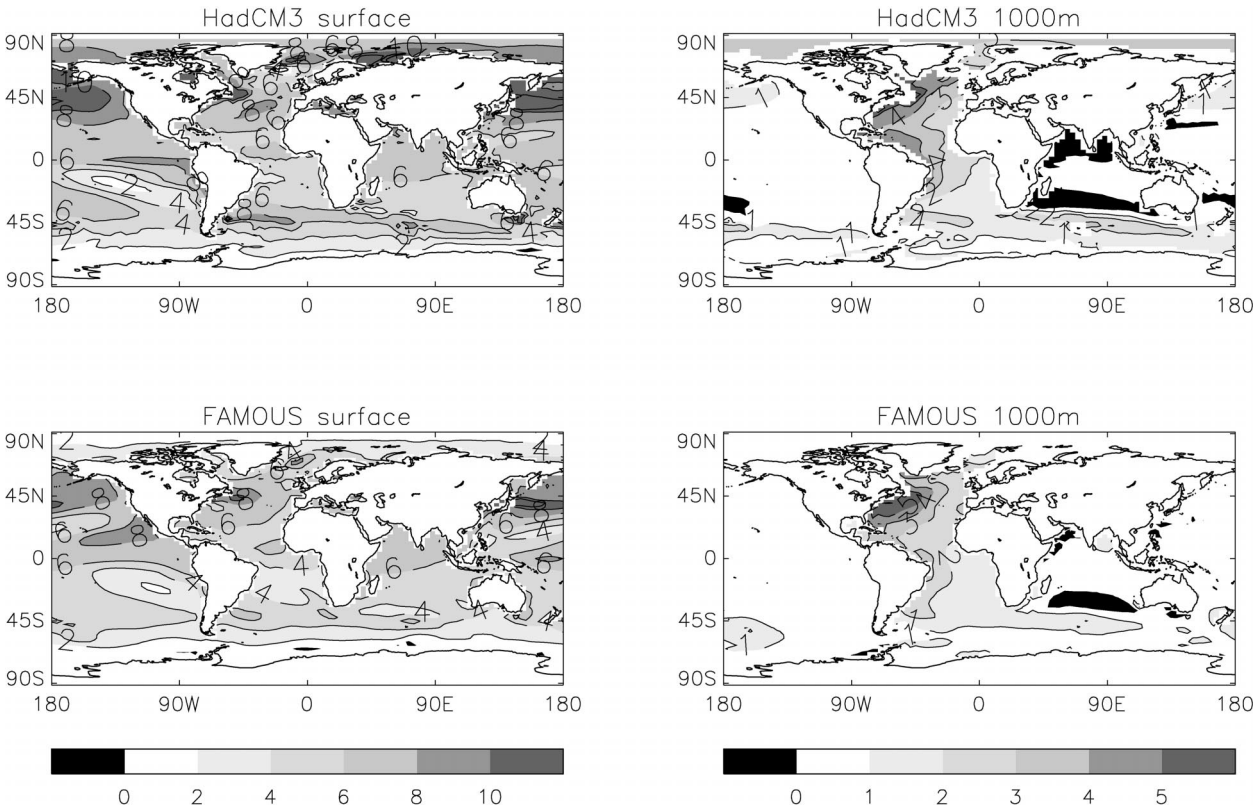

FIG. 8. The (top) HadCM3 and (bottom) FAMOUS pattern of ocean temperature changes between the final ($CO_2 \approx 4000$ ppmv) and the first ($CO_2 \approx 290$ ppmv) decade of the 140-yr transient climate change experiments at (left) the surface and (right) 1000-m depth. Note the different scale for the 1000-m-depth plots.

between any of the runs. There is virtually no difference in seasonal maximum and minimum ice cover between FAM24 and FAM1.

Similarly, there is little sensitivity of either the THC or ocean heat transport to these changes to the time step. The overturning in the North Atlantic in FAM24 (not shown) is similar to that in FAM1, with the cell northward of 60°N having very similar form and amplitude. Figure 6 shows the total northward heat transport in the North Atlantic from the runs with DP. The lines for the FAM runs are close together, although there is a reduction in heat transport for FAM24.

Overall, none of the runs with distorted physics and extended time steps show large differences from FAM1. In other words, the model is insensitive to the use of the DP scheme and a time step up to 24 h.

Compared with HadCM3, FAMOUS performs well in terms of annual-mean 1.5-m temperature and precipitation in the control state. Although FAMOUS tends to be too cold throughout the Northern Hemisphere, the precipitation patterns are similar to HadCM3, especially over land.

In terms of speed, the model runs with DP and time steps of 2, 6, and 24 h are faster by factors of 1.8, 4.3, and 9, respectively. Relative to the full-resolution HadOM3 these become 8, 19, and 40 times faster, respectively.

2) TRANSIENT CLIMATE CHANGE SIMULATIONS

A second set of experiments was performed to test the impact of the distorted physics on the transient behavior of the model. FAM1, FAM2, FAM6, and FAM24 runs were started from the no-Iceland control state of FAM1, and a preindustrial CO_2 concentration of 290 ppmv in 1859. Atmospheric CO_2 concentration was then increased at the rate of 2% yr^{-1} for 140 yr. This represents an extreme test of the model's transient behavior due to the very rapid climate change: CO_2 levels reach 4600 ppmv (increasing by more than 90 ppmv yr^{-1} at the end of the experiment), and this causes a global mean warming of about 9 K (15 K over land) in the HadCM3 experiment against which these runs are compared.

The results show that the transient behavior of FAMOUS is not sensitive to the use of DP or to the choice of ocean time step. Figure 7 shows the evolution of global-mean near-surface temperature change, global-mean ice fraction, and Atlantic THC strength. The behavior of all of these is the same for each of the FAMOUS runs, regardless of the time step. Compared with

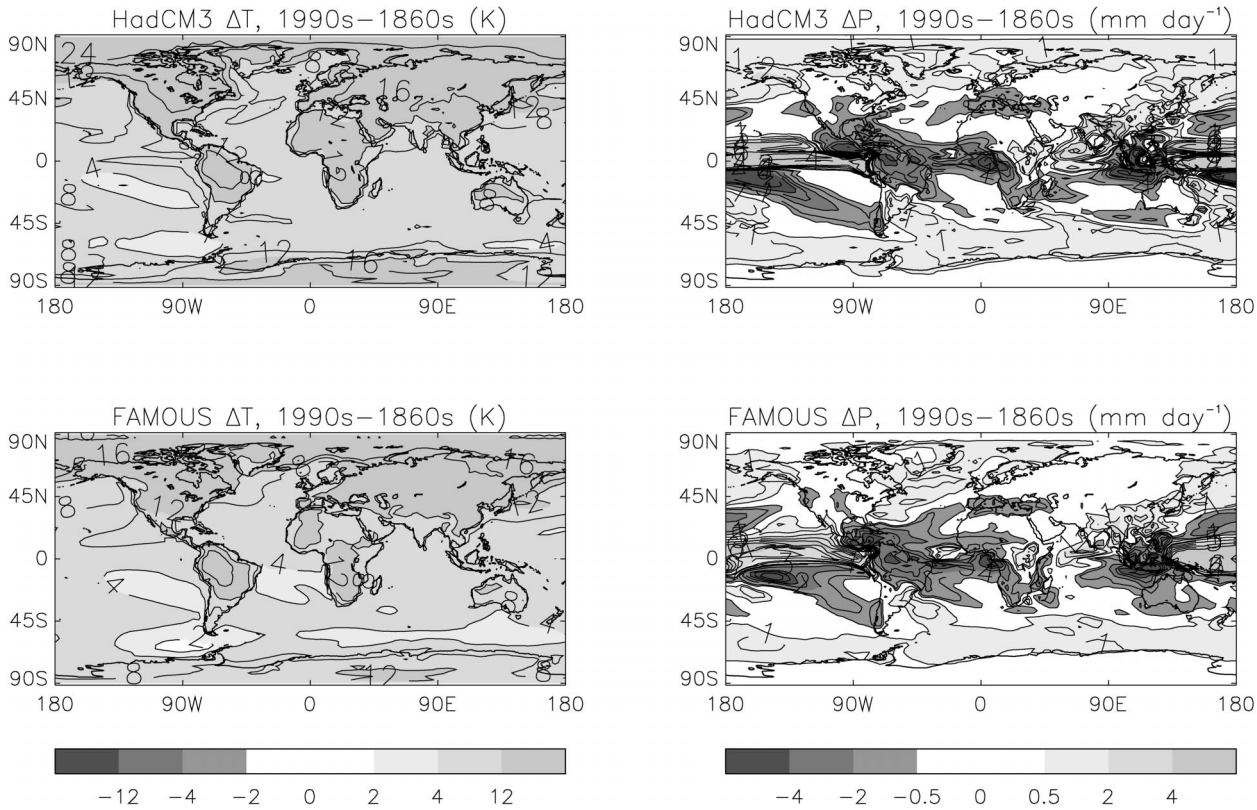

FIG. 9. The 1.5-m temperature and precipitation changes during the transient experiment: (top) HadCM3 and (bottom) FAMOUS changes in (left) temperature and (right): precipitation for the final decade ($CO_2 \approx 4000$ ppmv) relative to the first decade ($CO_2 \approx 290$ ppmv).

HadCM3, the results are also encouraging. The change in temperature shows similar sensitivity throughout the run, as does the ice fraction, which decreases steadily throughout, although FAMOUS has too much ice initially. The THC strength does not behave identically to HadCM3, though. It is initially too weak in FAMOUS, and then decreases more slowly in response to the climate change. By the end of the experiment it has decreased from 15 to 10 Sv (a 33% reduction). In the HadCM3 experiment, the THC decreases from 25 to 10 Sv (a 60% reduction).

The patterns of warming in FAMOUS and HadCM3 both at the surface and 1000-m depth at the end of the transient experiment are shown in Fig. 8. The patterns are very similar, though not identical. Both at the surface and at 1000 m FAMOUS simulates patterns of warming similar to those of HadCM3. The main differences are at the surface in the North Atlantic. There is a region southwest of Iceland that shows only a weak warming in HadCM3 but a stronger warming in FAMOUS. This is caused by the decrease in the strength of the THC in HadCM3, which transports less heat to the region and counters the warming from the radiative forcing. In FAMOUS, the initially weaker THC has a weaker response, so the region warms more. North of the Iceland–Scotland ridge, there is a larger warming in HadCM3 than in FAMOUS. This is due to the initially higher ice fraction in FAMOUS, which takes longer to melt and so delays the warming. At 1000-m depth, the pattern of warming is similar and reflects the transport to depth of warmed surface waters. It is of slightly higher magnitude in HadCM3, because of the more vigorous overturning, which transports the warmed surface waters to depth more quickly.

The sensitivity of 1.5-m temperature and precipitation during the 2% yr^{-1} transient experiment is shown in Fig. 9. The sensitivity of FAMOUS to the rapid climate change (CO_2 levels exceed 4000 ppmv by the end of the experiment) is similar to that of HadCM3. The warming in FAMOUS is similar in distribution but of slightly lower magnitude. In particular, mid-to high-latitude land in the Northern Hemisphere warms by 2°–4°C more in HadCM3 than in FAMOUS. There is also a band of enhanced warming in FAMOUS over the North Atlantic Gulf Stream region. The precipitation changes simulated by FAMOUS agree well with those of HadCM3. Given the extreme nature of the forcing in this experiment, it is very encouraging that FAMOUS can reproduce the basic climate change sensitivity of HadCM3.

4. Summary

The FAMOUS project aims to develop a fast version of HadCM3. Such a model could be used to perform

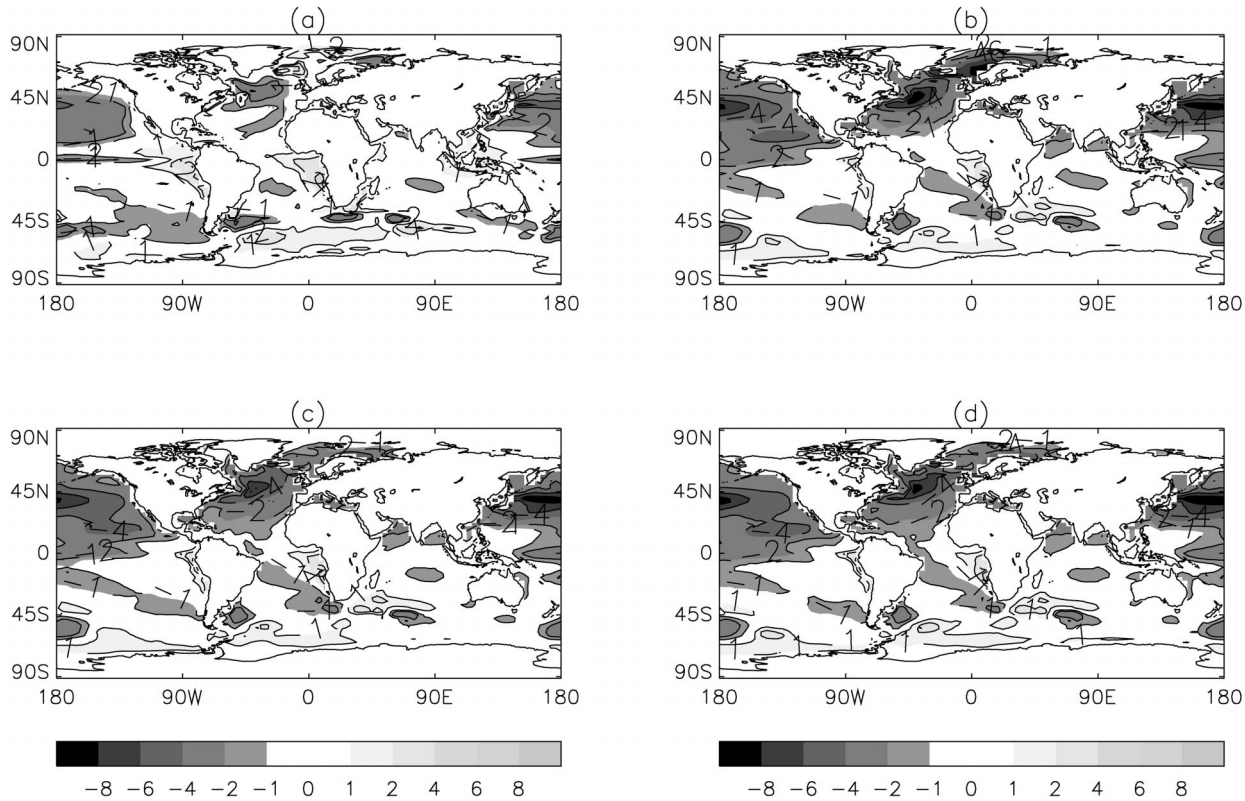

FIG. 10. Errors (K) relative to GISST climatology in SSTs simulated by (a) HadCM3, (b) H3LU, (c) FAM1, and (d) FAM24.

long climate integrations and large multimember ensembles, and have the added benefit of not requiring a supercomputer. However, it is important that the quality of the model is not degraded too much; in particular, it should not require the use of flux adjustments. This report describes the changes to the horizontal resolution and time step of the ocean component of HadCM3 to produce a fast version that can still be run without the use of flux adjustments. The work has been successful in producing an ocean component that will run about 40 times faster than HadOM3, does not require flux adjustments when coupled to the original atmosphere component, HadAM3, and which has a performance sufficiently similar to that of HadCM3 to allow it to be used for scientific investigations.

The progress toward this ocean model is summarized in Fig. 10, which shows SST errors relative to the Global Sea Ice and SST (GISST) climatology (Rayner et al. 1996). Figure 10a shows the SST errors of HadCM3, and Fig. 10b shows the same for HadCM3L without flux adjustments (H3LU). The difference between the two runs therefore demonstrates the effect of reducing the horizontal resolution from 1.25° × 1.25° to 2.5° × 3.75°. The most significant difference is in the North Atlantic, which becomes much colder in the low-resolution model. This is because of the excessive buildup of sea ice that occurs there, as discussed in section 2. The rest of the Northern Hemisphere also cools slightly, probably due to the influence of the North Atlantic cooling on the atmosphere. The differences in the Southern Hemisphere are small.

Figure 10c shows the errors in the FAMOUS run with Iceland removed (FAM1). The differences between this and Fig. 10b demonstrate the impact of this topography change, which removes the need for flux adjustments. The differences are confined mainly to the North Atlantic region, where the cold bias caused by the buildup of ice in the lower-resolution model is significantly reduced. This is a result of the increased flow that now penetrates beyond the Scotland–Iceland ridge and provides heat transport to the region, preventing the large buildup of sea ice. The mean SST error relative to GISST in the region north of 60°N and between 30°W and 20°E is (a) +0.8 K in HadCM3, (b) −4.6 K in H3LU, and (c) reduced to −2.6 K in FAM1 (''no-Iceland'').

Finally, Fig. 10d shows the errors in the distorted physics run with a time step of 24 h (FAM24). The impact of this change, relative to Fig. 10c is small. The mean temperature error relative to GISST in the region north of 60°N and between 30°W and 20°E is now −2.7 K.

The ''bottom line'' of the experiment is that the results from the lowered-resolution ocean run, without Iceland, with a 24-h time step and coupled to the full-resolution atmospheric component, HadAM3, are similar to the

original HadCM3 results (i.e., Fig. 10a versus 10d). There are still some differences between the two models. There is a general cooling of the Northern Hemisphere ocean in FAMOUS and an associated increase in sea ice cover in the North Atlantic. FAMOUS also has a weaker THC and hence smaller THC response to an increase in CO_2, but the overall behavior of FAMOUS is similar to that of HadCM3. Both the control climate and the transient response to strong radiative forcing are similar, and thus we judge that the model would be acceptable for use in scientific investigations. The time saving of a factor of 40 in the ocean component exceeds the project target of a factor of 10.

Although much effort has been made to ensure that this model can be run without the use of flux adjustments, they could still be used if required. Their use would ensure that the surface temperature climatology was very close to the required values. In some studies this may be more important than the potential impact on the transient behavior of the model.

The next stage of the FAMOUS project will be to construct a fast version of HadAM3 to which the FAMOUS ocean model can be coupled. It is envisaged that the time savings in the atmosphere component will come from a reduction in horizontal and maybe vertical resolution. A horizontal resolution of $5^\circ \times 7.5^\circ$ will be tested with both 19 and 11 model levels (compared with the current $2.5^\circ \times 3.75^\circ$ and 19 levels of HadAM3). A time step of 1 h (compared with the current value of 30 min) may be possible, but there is no ''distorted physics'' equivalent for the atmosphere model, so a much longer time step is not an option.

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