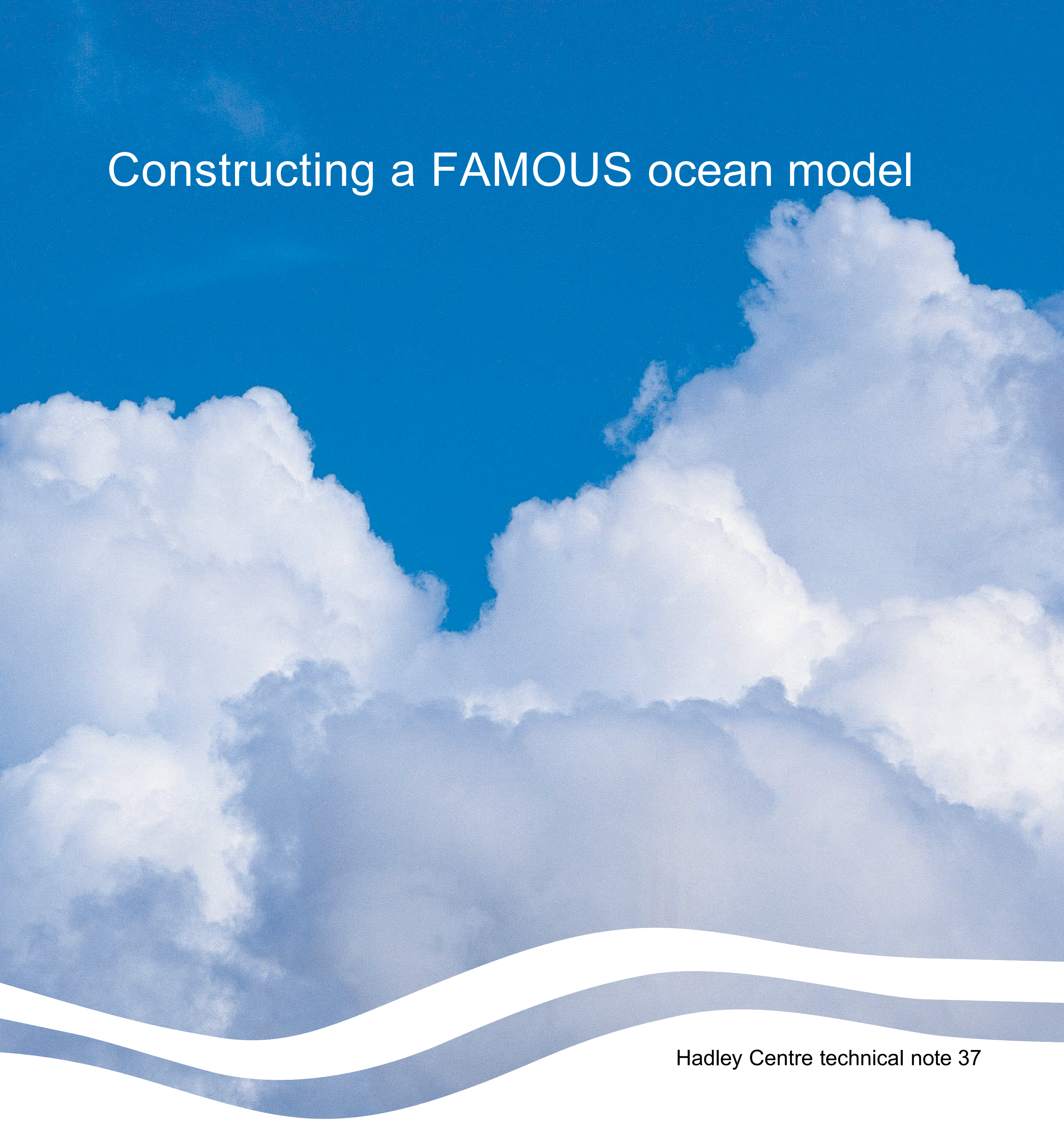
Constructing a FAMOUS ocean model



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Constructing a FAMOUS Ocean Model

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Abstract

The Fast Met Office / UK Universities Simulator project ("FAMOUS") aims to develop a fast GCM, possibly ten times faster than 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 timestep, allow the FAMOUS–ocean model to run without the use of flux adjustments, and about 40 times quicker than HadOM3. Transient climate change simulations carried out using the new ocean component coupled to HadAM3 produce a similar climate sensitivity to the full HadCM3.

1 Introduction

1.1 What is FAMOUS?

State–of–the–art coupled atmosphere ocean general circulation models (AOGCMs), such as 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 (e.g. palaeo-climate simulations of glacial–interglacial changes, or anthropogenic climate change beyond the next 100-200 years). 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 another overhead which further increases their cost. For all these types of experiment, a faster model is required.

So-called Earth system models of intermediate complexity (EMICs, e.g. CLIMBER, Petoukhov *et al* (2000)) have been used very successfully for such simulations as studying the stability of the THC in glacial and interglacial periods (Ganopolski and Rahmstorf (2001)), or the impact of interactive vegetation in simulations of past climates (Kubatzki *et al* (2000)). However, by their very nature they lack certain physical processes - e.g. they do not represent gyre circulations in the ocean which have been suggested to be important in determining THC stability (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 FAMOUS project (**FA**st **M**et **O**ffice / **U**K Universities **S**imulator) at the Met Office in collaboration with NERC. It is hoped that the use of FAMOUS in conjunction with high-resolution AOGCMs such as HadCM3 or HadGEM will allow many more areas of climate and the Earth system to be explored. Basing FAMOUS on existing state–of–the–art GCMs (i.e. HadCM3 now and HadGEM later) 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 parametrised 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 modelling spectrum, with benefits to both.

The FAMOUS model will still be a GCM, but simplified in such a way as to make significant computational savings without loss of too much quality. It is envisaged that the main time savings will be from reduced resolution and increased timestep. This note describes the work that has been carried out on the ocean component of FAMOUS. A speed-up of about a factor of 40 over HadOM3 has been achieved, and the resulting model coupled to the original HadAM3 atmosphere component does not require the use of flux adjustments, and has a similar climate and climate sensitivity to HadCM3. Work is progressing towards a fast version of the atmosphere component.

The differences between HadOM3 and the FAMOUS ocean model can be broadly split into two. Section 2 will describe the reduction in ocean horizontal resolution, and changes to the land–sea mask required to speed up the model without the requirement for flux adjustments, and section 3 will describe changes to the timestepping of the model, and results from the whole package. The success of the ocean component of the project is summarised in section 4.

2 Reduced resolution and the need for flux adjustments

2.1 HadCM3L

The coupled climate–carbon cycle project at the Met Office (Cox *et al* (2000); Cox *et al* (2001)) uses a version of HadCM3, "HadCM3L", with a lowered ocean resolution of 2.5°x 3.75°(compared with 1.25°x 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 build up 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 try to address the sea ice problem and thereby remove the need for flux adjustments.

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 gridpoint at the 2.5°x 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 which 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 further ice, until the Nordic Sea is permanently ice–covered.

2.2 Removing Iceland

Experiments were performed to assess the impact of changing the land–sea mask 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 these experiments were broadly similar, but it was decided 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 800m. The new land sea mask and topography are shown in figure 1 (right panel). The removal of this part of the Earth's topography in the model is justified because it represents an unrealistic barrier to the circulation. Figure 1 (left panel) shows how the presence of Iceland prohibits any flow at all between Iceland and Greenland and allows only limited flow between Iceland and Scotland. The removal of Iceland provides a more realistic link between the Nordic Seas and the main body of the North Atlantic and allows a much more realistic ocean circulation to be modelled.

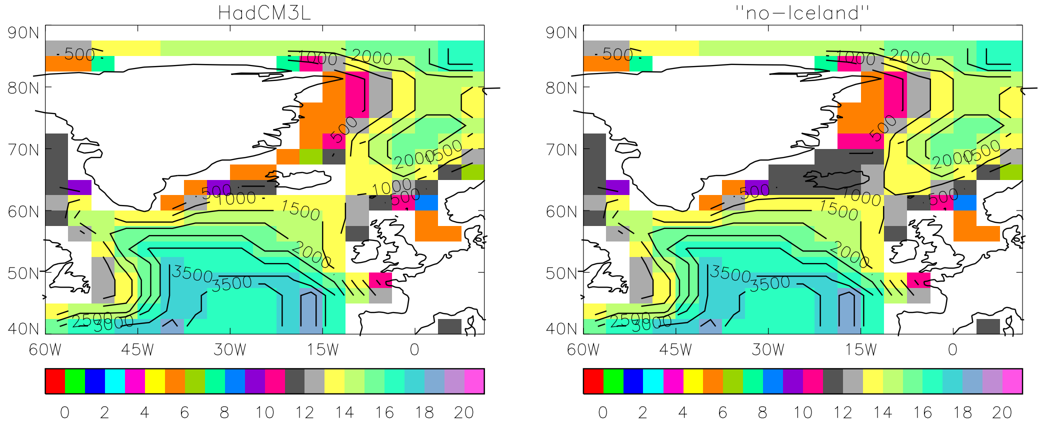

Figure 1: **The land sea mask and ocean topography of HadCM3L in the North Atlantic.** The figures show the land sea mask on the "velocity grid" (i.e. the grid on which ocean momentum values exist) of HadCM3L (left panel) and the modified "no–Iceland" topography (right panel). This grid is offset from the "tracer grid" (where temperature and salinity values exist), and is only defined at points which are surrounded by four ocean points on the tracer grid. Thus, even though Iceland only occupies 2 tracer gridpoints, it occupies 6 velocity gridpoints, 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 800m. Physical depths (m) are contoured.

2.3 Results

The model was run without the use of flux adjustments for 100 years both with the original land sea mask of HadCM3L (hereafter H3LU), and with Iceland removed (hereafter FAM1). 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)).

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 figure 2. The unflux-adjusted control run (i.e. unmodified land-sea mask, H3LU) exhibits a significant 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 0.2. Figure 3 shows winter and summer seasonal ice cover for the final decade of H3LU and FAM1 compared with observations and HadCM3. There is a large build up 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 build up of ice in this region in H3LU is due to the reduced heat transport into this region as a result of a sluggish Gulf Stream at this coarse resolution. This forms a positive feedback with insufficient heat transported into the region, and 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 stream function from H3LU and FAM1 compared with H3L. H3LU lacks the penetration of an overturning cell north of the Iceland-Scotland ridge, at 60°N, whilst in FAM1, the overturning here is present as before but slightly weaker than in H3L.

Similarly, figure 5 shows the northward heat transport in the North Atlantic for the same three runs. The heat transport in FAM1 is similar to H3L, whereas H3LU has much lower heat transport, which all but stops at 60°N.

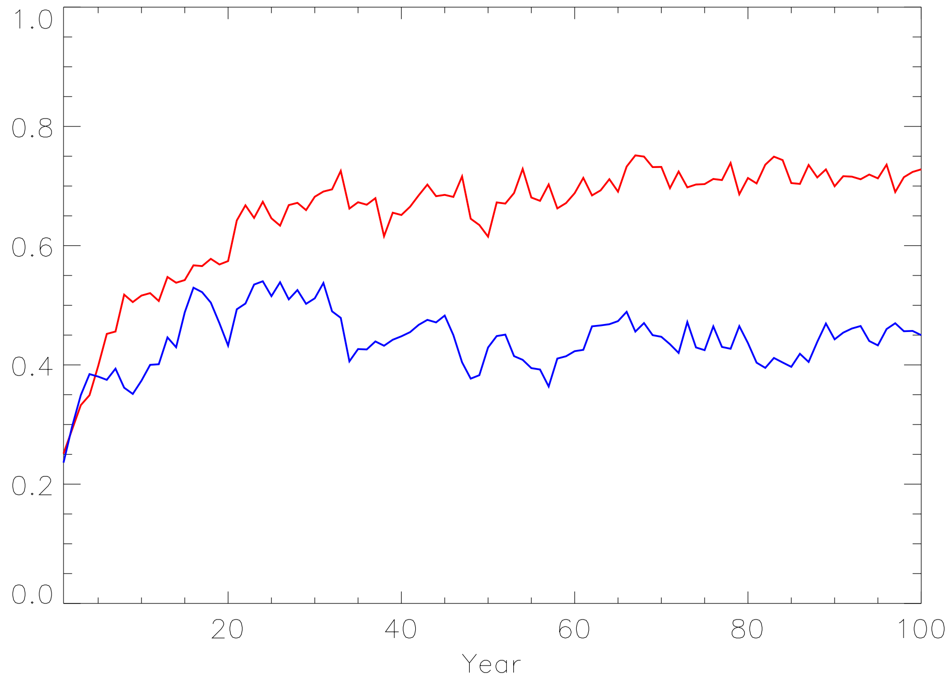

Figure 2: **Annual mean sea ice fraction.** Timeseries of the evolution of the annual mean ice fraction in the North Atlantic in the unflux-adjusted control run (H3LU, red line) and the "no–Iceland" run (FAM1, blue line).

The strength of the Atlantic THC in the main body of the ocean shows very little difference between the two runs, and they both have the same strength as in H3L (about 15 Sv), 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 turning off the flux adjustments. Globally, annual mean SST differences between the control and no–Iceland run (shown later in figure 15) are restricted to the North Atlantic region (owing to the decreased ice, and increased heat transport in the no–Iceland run). There are very few differences between them away from the North Atlantic region.

Overall, it can be concluded that the removal of Iceland from the topography of HadCM3L allows the model to be run successfully without the need for flux adjustments. There is 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 very much limited to the north Atlantic.

Compared with HadOM3 (at 1.25°x1.25°resolution), the reduced resolution of the ocean component results in a speed up of a factor of 4-5.

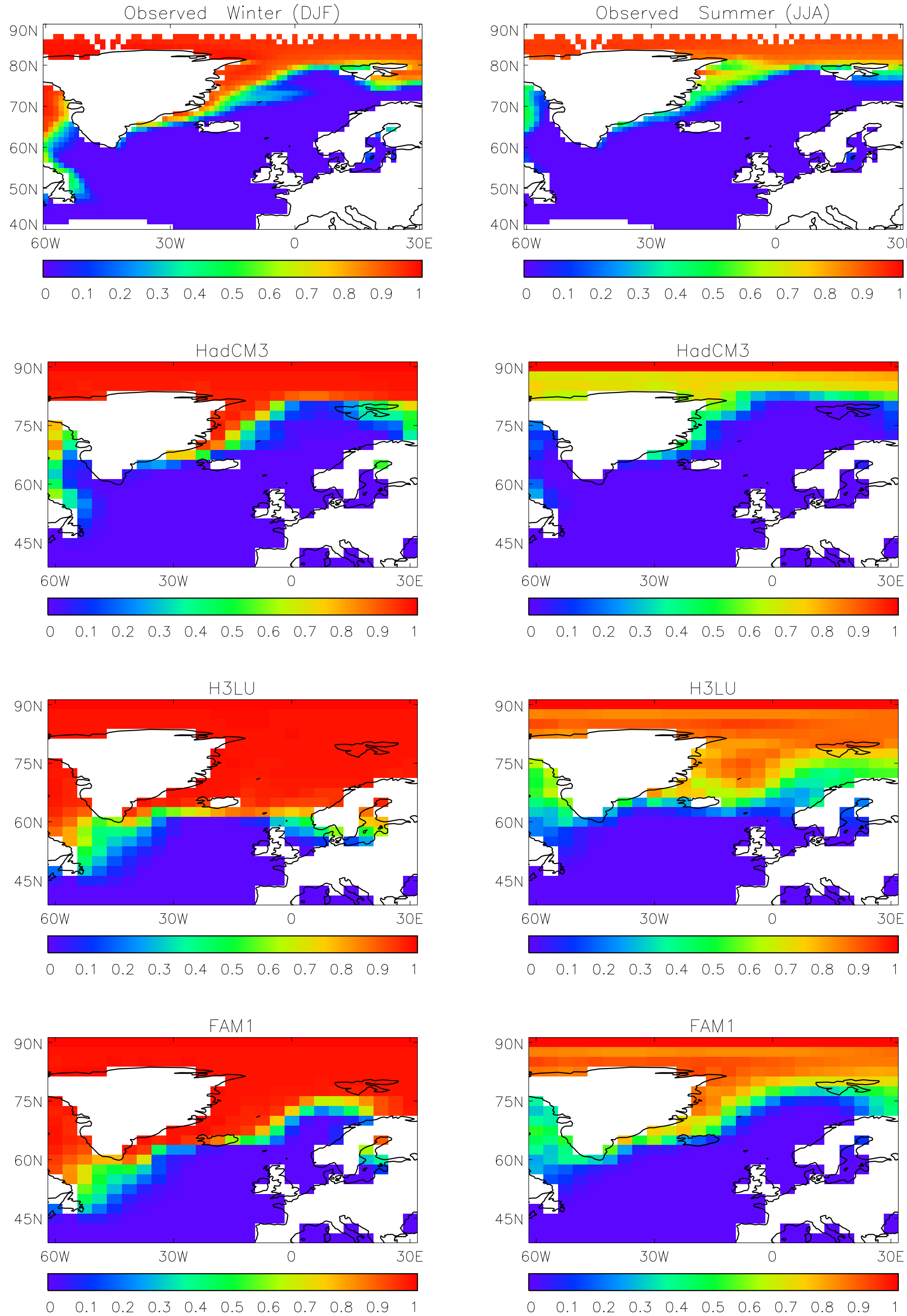

Figure 3: **Winter and summer ice cover.** Observed and modelled ice cover in winter and summer in the North Atlantic. Left–hand side: winter, right–hand side: summer. The top panels show observations, 2nd row panels show HadCM3, 3rd row panels show unflux-adjusted HadCM3L (H3LU) and the bottom panels show "no–Iceland" (FAM1). (Observational data from satellite radiometers was obtained from the US National Snow and Ice Data Center (NSIDC) courtesy of Doug Smith of the Mullard Space Science Laboratory.)

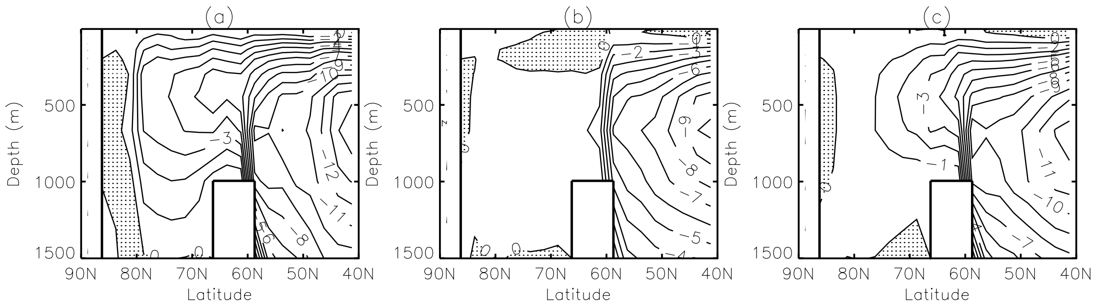

Figure 4: **North Atlantic overturning stream function.** The overturning stream function in the North Atlantic in (a) H3L, which shows a cell of overturning with a strength of about 5 Sv in the far north (i.e. beyond 60°N). (b) In H3LU this cell does not penetrate at all beyond 60°N. (c) FAM1 has re-established this cell with a strength of 3-4 Sv.

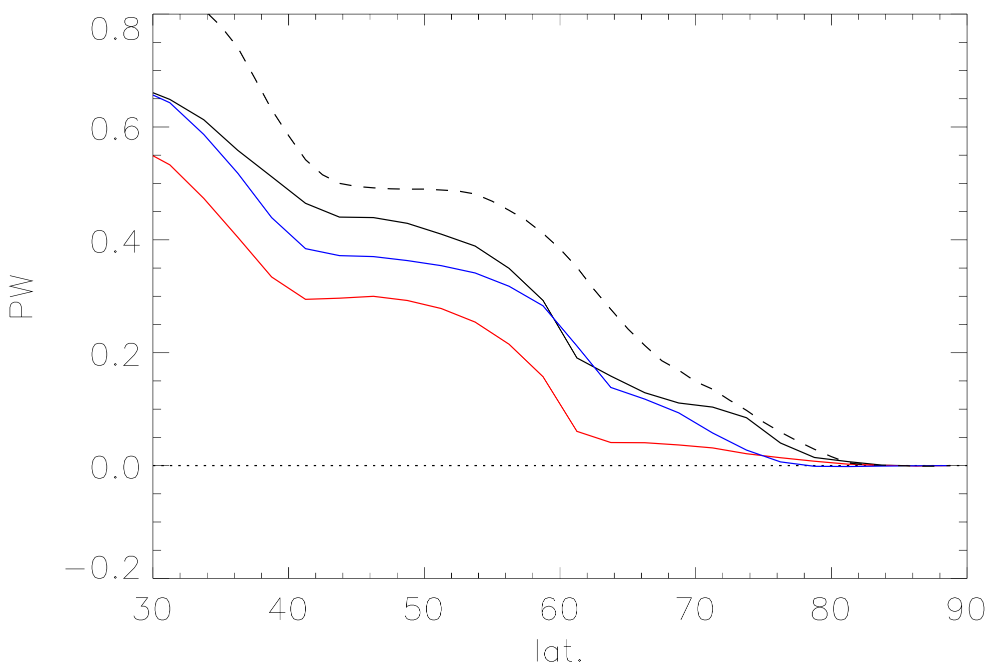

Figure 5: **North Atlantic heat transport.** Total northward heat transport (PW) in the North Atlantic for HadCM3 (black dashed line), H3L (black solid line), H3LU (red line) and FAM1 (blue line).

3 Increased timestep

Further significant savings in the computational time of the ocean component can be made by increasing the length of the timestep. Use of the "distorted physics" technique (Bryan and Lewis (1979); Bryan (1984)) allows a longer timestep to be used without causing numerical instabilities in the model. This scheme is described in section 3.1. 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 behaviour. The scheme has been tested both in terms of the control state it produces and its transient response to rapid climate change. The results are presented in section 3.2.

3.1 Overview of the scheme and its application

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

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

where $(RHS)_u$ is the right hand side of the momentum equation in the un-distorted case. The result is that a timestep can now be used which is a factor of α longer than previously, and will be stable. In the equilibrium solution of $\frac{d}{dt} = 0$ the equation has the same solution as for $\alpha = 1$. The scheme, and extensive tests performed with it in the HadOM2 model (similar in structure, and with the same resolution as HadCM3L, but with some different physical parametrisations), are described by Wood (1998).

The DP scheme also allows for another distortion parameter, γ, to be used which varies with depth and accelerates the behaviour of the deep ocean water-masses, but at the expense of not conserving heat or salinity. This feature of DP has not been used in this study, and $\gamma = 1$ at all model levels.

Wood (1998) describes some timestep sensitivities in HadOM2 as a result of interactions between the DP scheme and some of the model's physical parametrisations. The Richardson number dependent diapycnal tracer diffusivity creates a timestep sensitivity when used with DP, and so this his been turned off in FAMOUS. The impact of this is very small due to the coarse horizontal resolution of the model, but would be an issue at finer resolution. The problems associated with spurious waves in the ACC and convection in the GIN Sea have not been considered here. The results presented in section 3.2.1 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 the un-distorted 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 original model timestep for scientific studies. However, 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 the DP model may still be suitable for such use (Kilworth *et al* (1984)). Tests showing that the transient behaviour of the FAMOUS–ocean model is not sensitive to the use of DP are presented in section 3.2.2.

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.

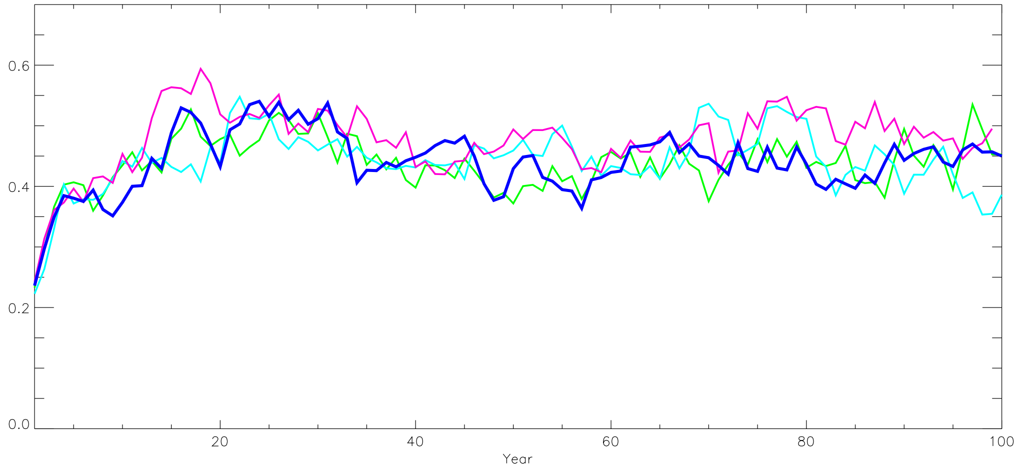

Figure 6: **Annual mean sea ice fraction.** Timeseries of the evolution of the annual mean ice fraction in the North Atlantic in FAM1 (blue line, timestep = 1 hr) and the DP runs FAM2 (green line), FAM6 (cyan line) and FAM24 (magenta line).

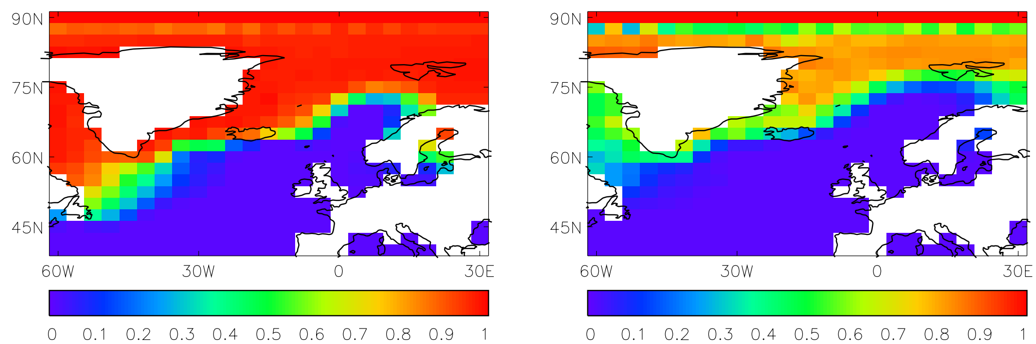

Figure 7: **Winter and summer ice cover.** North Atlantic ice cover in winter (left panel) and summer (right panel) in FAM24.

3.2 Results

3.2.1 Control climate simulations

A set of 100 year experiments was performed to assess the impact of using the "distorted physics" (DP) technique described above. The timestep in the experiments was increased from 1 hour to 2, 6 and 24 hours (hereafter FAM2, FAM6 and FAM24 respectively). The runs all used the no–Iceland configuration described in section 2.2. The only difference between them was the change in timestep, 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 timestep 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 the "no-Iceland" topography of FAM1, are not changed. Figure 6 shows the evolution of the annual mean ice fraction in the North Atlantic during these four runs. There is no significant difference between any of the runs. Figure 7 shows the seasonal maximum and minimum ice cover from FAM24. There is virtually no difference between this and FAM1 (bottom two panels of figure 3).

Similarly, there is very little sensitivity of either the THC or ocean heat transport to these changes to the timestep. Figure 8 (left panel) shows that the overturning in the North Atlantic in FAM24 is very similar to that in FAM1 (see figure 4), with the cell northward of 60°N having very similar form and amplitude. Figure 8 (right panel) shows the total northward heat transport in the North Atlantic

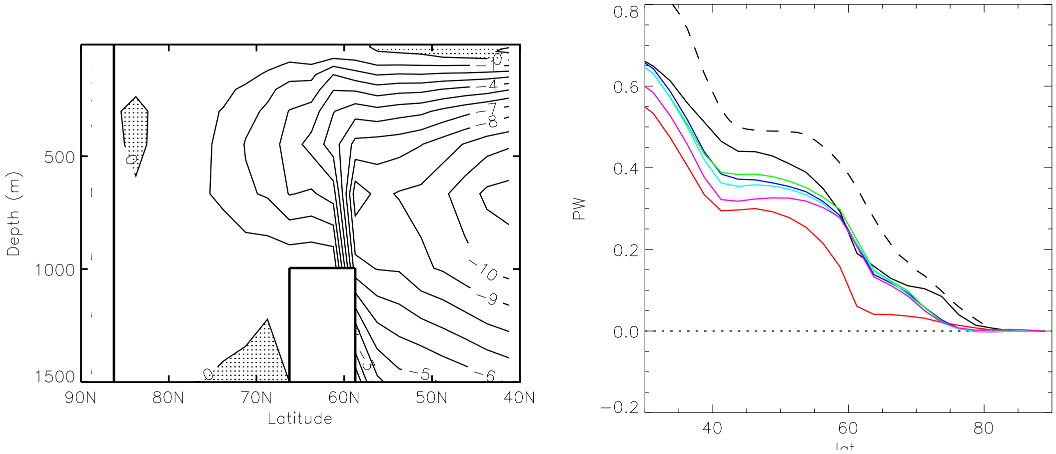

Figure 8: **Overturning streamfunction and ocean heat transports.** North Atlantic overturning streamfunction from FAM24 (left panel), and northward heat transport in the North Atlantic (right panel) from: HadCM3 (black dashed line), H3L (black solid line), H3LU (red line), FAM1 (blue line) and the DP runs FAM2 (green line), FAM6 (cyan line) and FAM24 (magenta line).

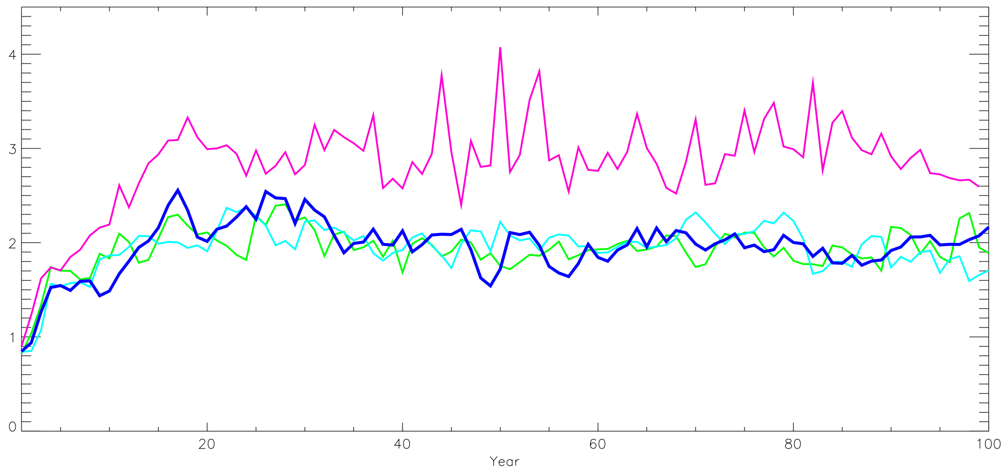

Figure 9: **Annual mean sea ice thickness.** Timeseries of the evolution of the annual mean ice thickness in the North Atlantic in FAM1 (blue line) and the DP runs FAM2 (green line), FAM6 (cyan line) and FAM24 (magenta line).

from the runs with DP.

Overall it would seem that all of the runs with increased timesteps are virtually the same as FAM1. There is, however, a difference shown by the run with a timestep of 24 hr - namely in the behaviour of sea ice *thickness*. Figure 9 shows the evolution of the North Atlantic mean ice thickness for the four runs. FAM2 and FAM6 show very similar results to FAM1, but FAM24 has significantly thicker ice (despite the ice *fraction* being the same as the others). The cause or significance of this result has yet to be determined, but the very similar behaviour of FAM24 in all the other diagnostics examined (and its transient behaviour - see section 3.2.2) suggests that this difference may not be important in terms of the overall behaviour of the model.

In terms of speed, the factor by which the ocean component of the model is faster (relative to the 1 hr timestep run) is 1.8, 4.3 and 9.0 for the runs with 2 hr, 6 hr and 24 hr timesteps respectively. Relative to the full resolution HadOM3 these become 7.9, 19 and 40 respectively. Although a further point to keep in mind is that the speed of the ocean code on an MPP machine does not scale exactly with the number of processors used: lower resolution models become increasingly less efficient on a large number of processors due to the increased overheads of processor–to–processor communication.

Hence these time savings only apply to running on 24 PEs on the T3E. A different number of PEs, or a different machine, may give different results.

3.2.2 Transient climate change simulations

A second set of experiments was performed to test the impact of the distorted physics on the transient behaviour of the model. Runs of FAM1, FAM2, FAM6 and FAM24 were started from the no–Iceland control state of FAM1, and a pre-industrial CO_2 concentration of 290 ppmv in 1859. Atmospheric CO_2 concentration was then increased at the rate of 2% per year until 2000. This represents an extreme test of the model's transient behaviour due to the very rapid climate change: CO_2 levels reach 4600 ppmv by present day (increasing by more than 90 ppmv per year at the end of the experiment), and this causes a global mean warming of about 9K (15K over land) in the HadCM3 experiment against which these runs are compared.

The results show that the transient behaviour of FAMOUS is not sensitive to the use of DP or to the choice of ocean timestep. Figure 10 shows the evolution of global mean near–surface temperature change, global mean ice fraction and Atlantic THC strength. The behaviour of all of these is the same for each of the FAMOUS runs, regardless of the timestep. Compared with HadCM3, the results are also encouraging. The change in temperature shows very 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 Sv to 10 Sv (a 33% reduction). In the HadCM3 experiment, the THC decreases from 25 Sv to 10 Sv (a 60% reduction).

The patterns of warming in FAMOUS and HadCM3 both at the surface and 1000m depth at the end of the transient experiment are shown in figure 11. The patterns are very similar, though not identical. Both at the surface and at 1000m FAMOUS simulates very similar patterns of warming to HadCM3. The main differences are at the surface in the North Atlantic. There is a region south west of Iceland which 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 and so the region warms more. North of the Iceland–Scotland ridge, there is a larger warming in HadCM3 than FAMOUS. This is due to the initially higher ice fraction in FAMOUS which takes longer to melt and so delays the warming. At 1000m depth, the pattern of warming is very 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.

In terms of the impact on the atmosphere, figure 12 shows the differences between FAMOUS and HadCM3 in terms of annual mean 1.5m 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. The sensitivity of 1.5m temperature to the rapid climate change of the 2% per year transient experiment is shown in figures 13. The sensitivity of FAMOUS to the rapid climate change (CO_2 levels exceed 4000 ppmv by 1990) is very similar to 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 to 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. Figure 14 shows similar plots for precipitation. The precipitation changes simulated by FAMOUS agree well with 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.

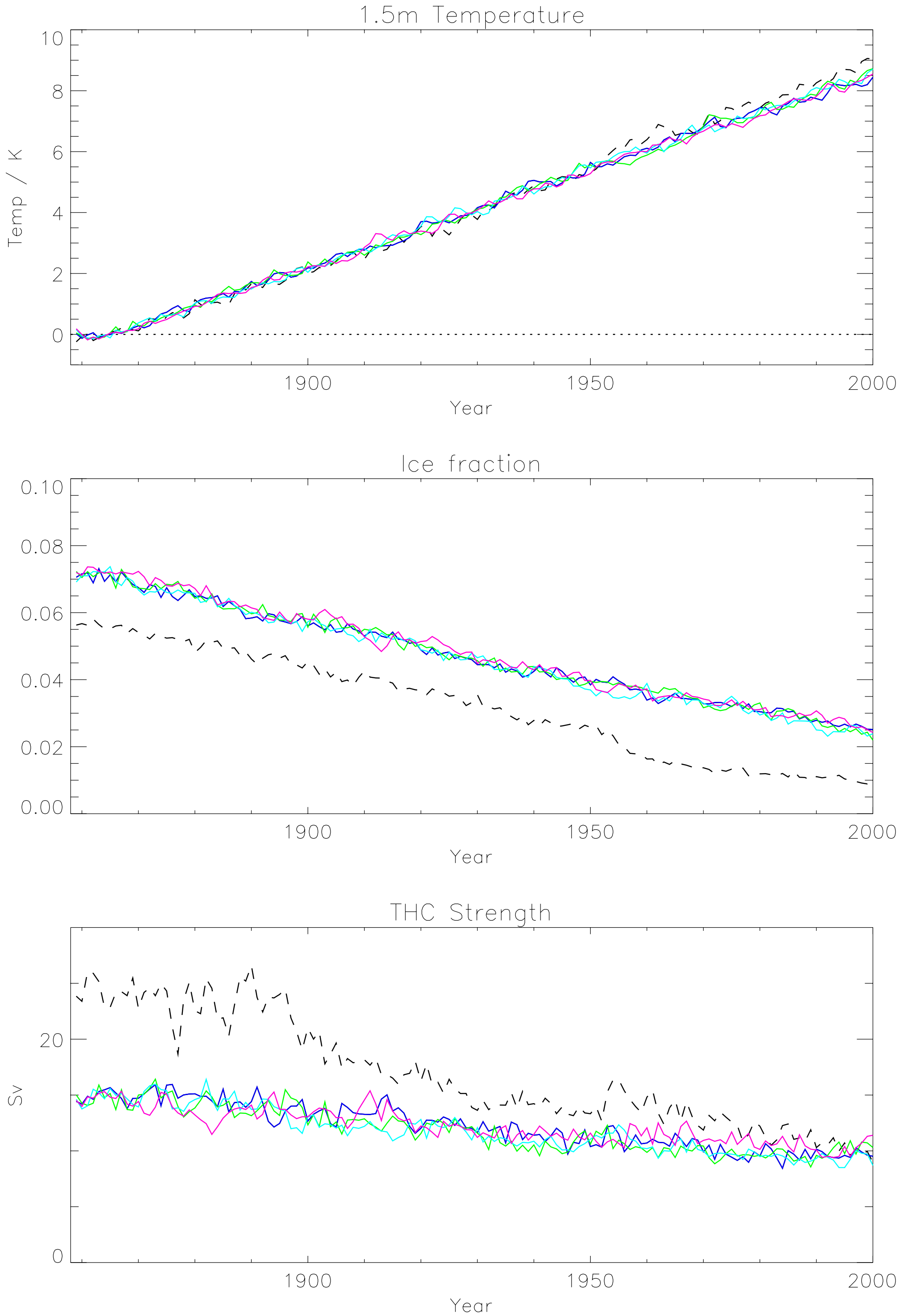

Figure 10: **Results from transient 2% per year CO_2 increase experiments.** The panels show the time evolution of annual–mean global–mean 1.5m temperature change (top), ice fraction (middle) and Atlantic THC strength (bottom). Each panel shows the results from HadCM3 (dashed line), FAM1 (blue line), and the DP runs FAM2 (green line), FAM6 (cyan line) and FAM24 (magenta line).

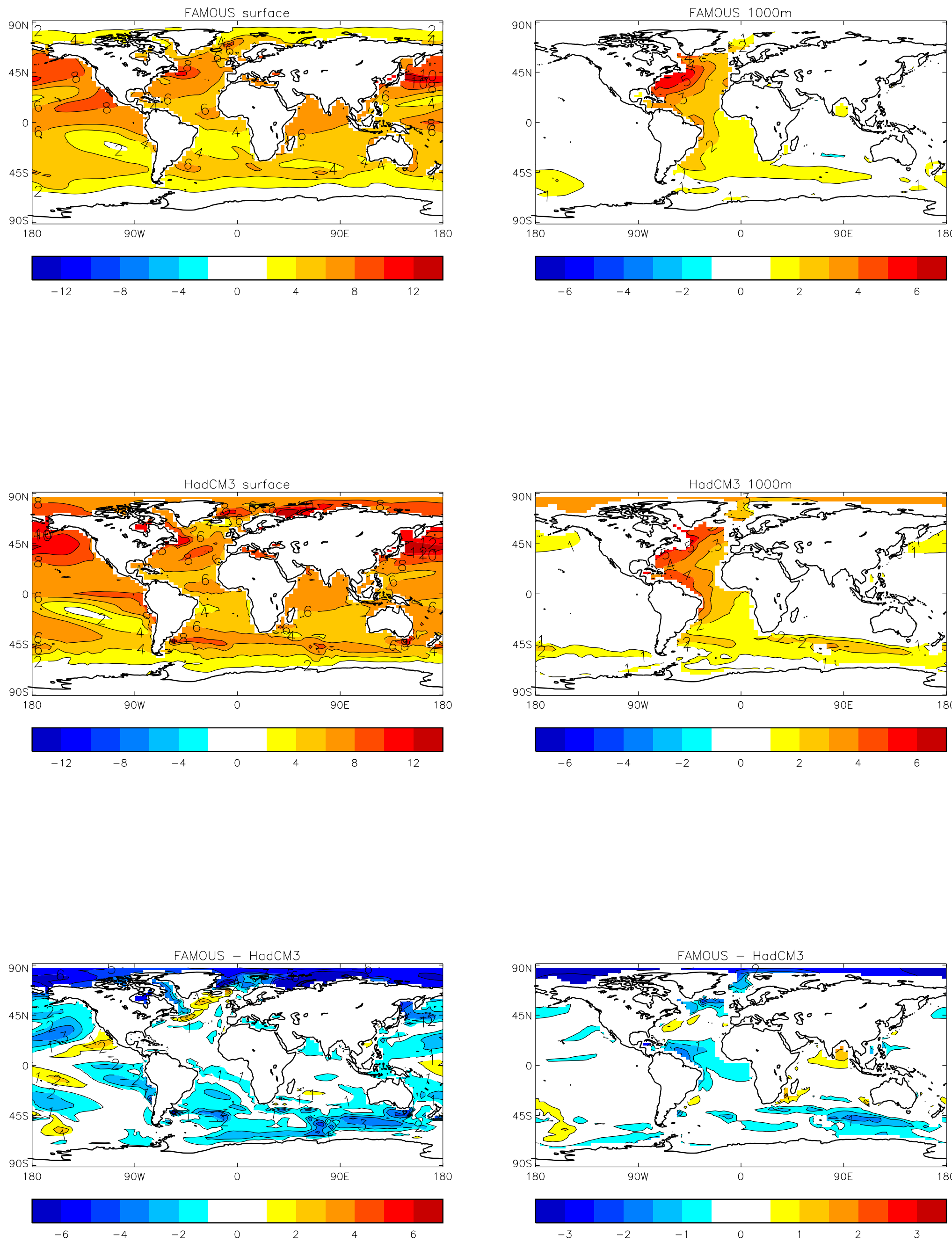

Figure 11: **Pattern of ocean temperature changes.** The panels show the pattern of ocean temperature changes between 1990s and 1860s from the transient climate change experiments at the surface (left–hand side) and 1000m depth (right–hand side). Top: FAMOUS, middle: HadCM3, bottom: FAMOUS-HadCM3 such that red colours denote enhanced warming in FAMOUS and blue colours denote reduced warming relative to HadCM3. Note the different scale for 1000m depth, and the difference plots.

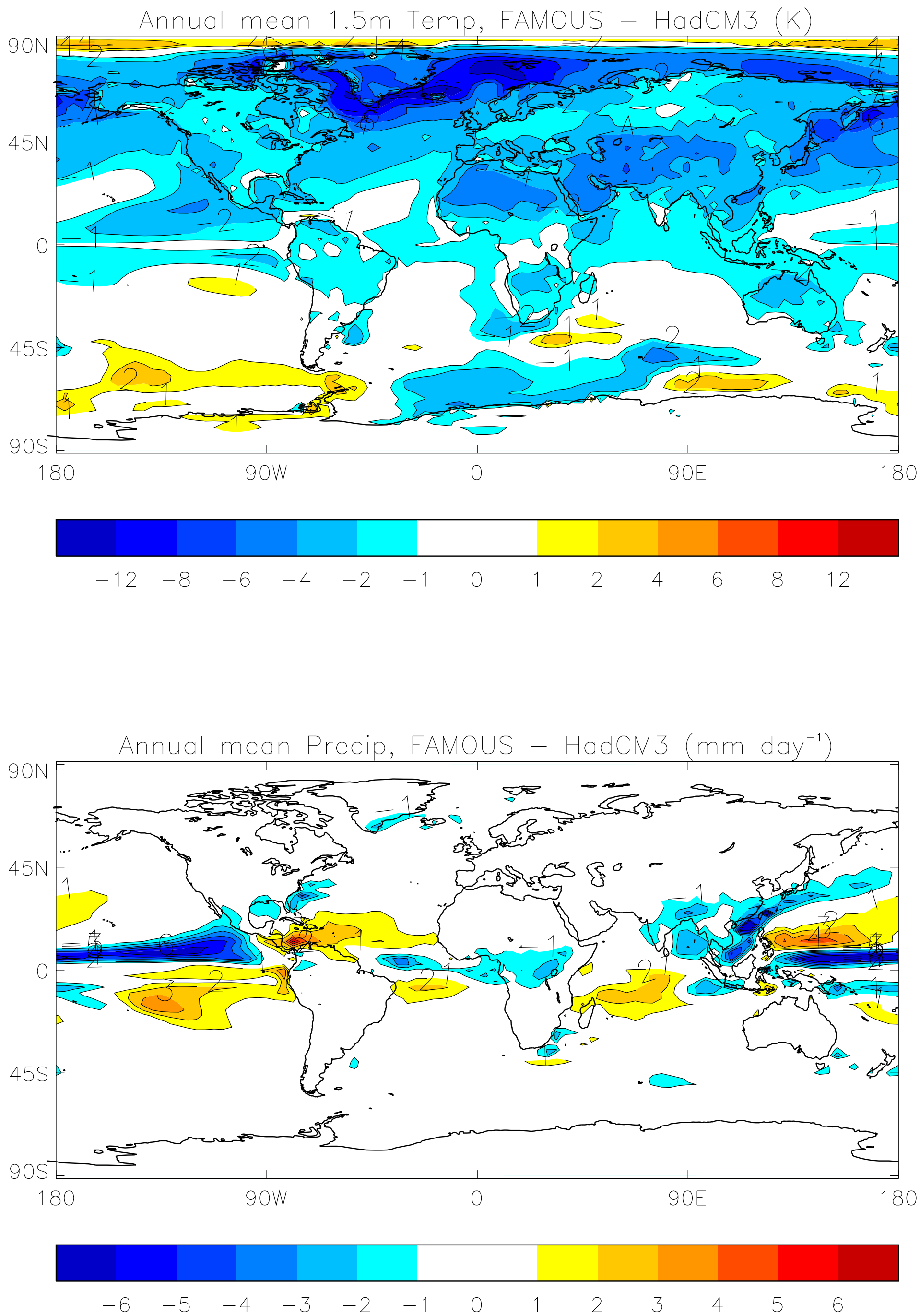

Figure 12: **Atmospheric parameters.** Differences between FAMOUS and HadCM3 control states for annual mean 1.5m Temperature (top panel) and precipitation (bottom panel).

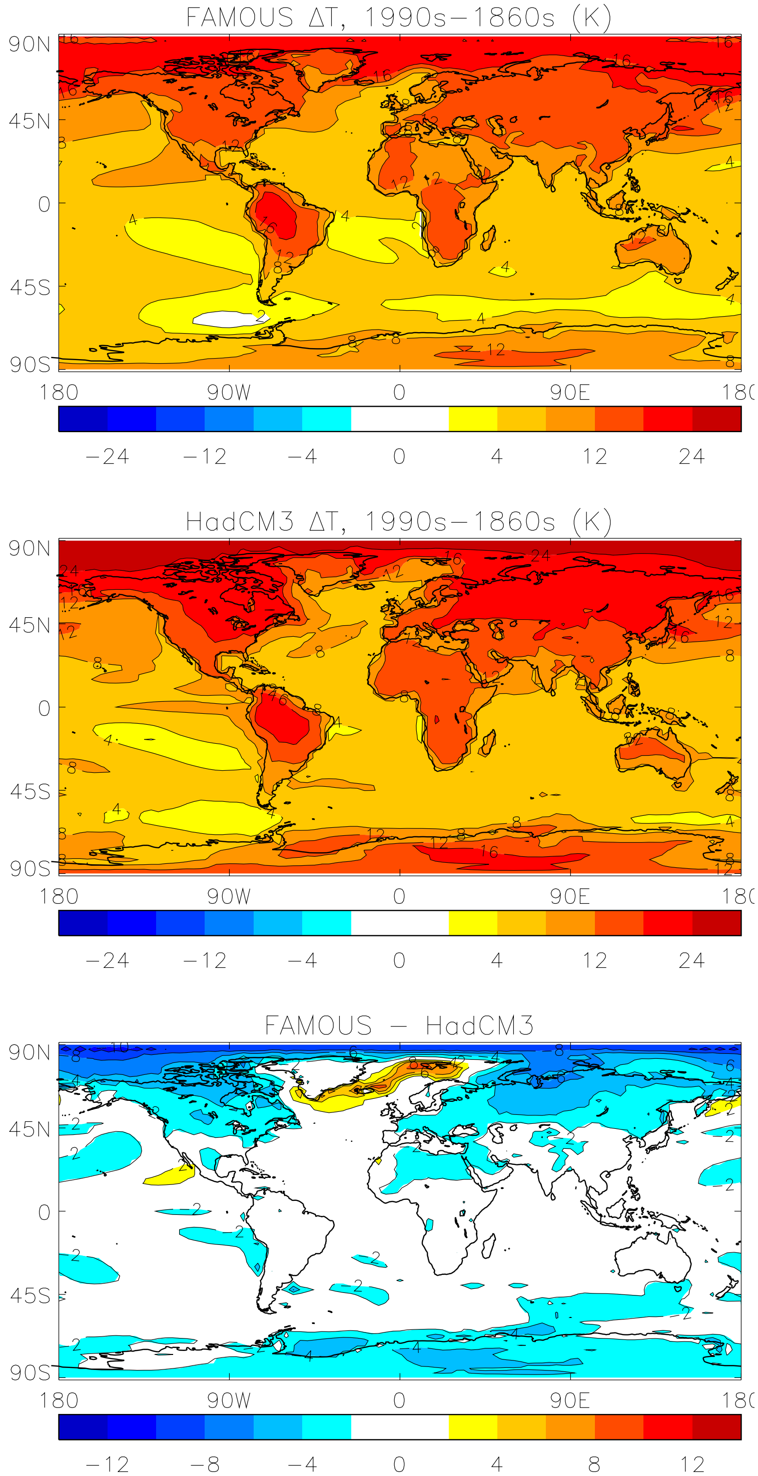

Figure 13: **1.5m Temperature changes during the transient experiment.** FAMOUS (top) and HadCM3 (middle) changes in temperature for the 1990s relative to 1860s, when CO_2 reaches more than 4000ppmv in the 2% CO_2 run. The bottom panel shows the differences between the two.

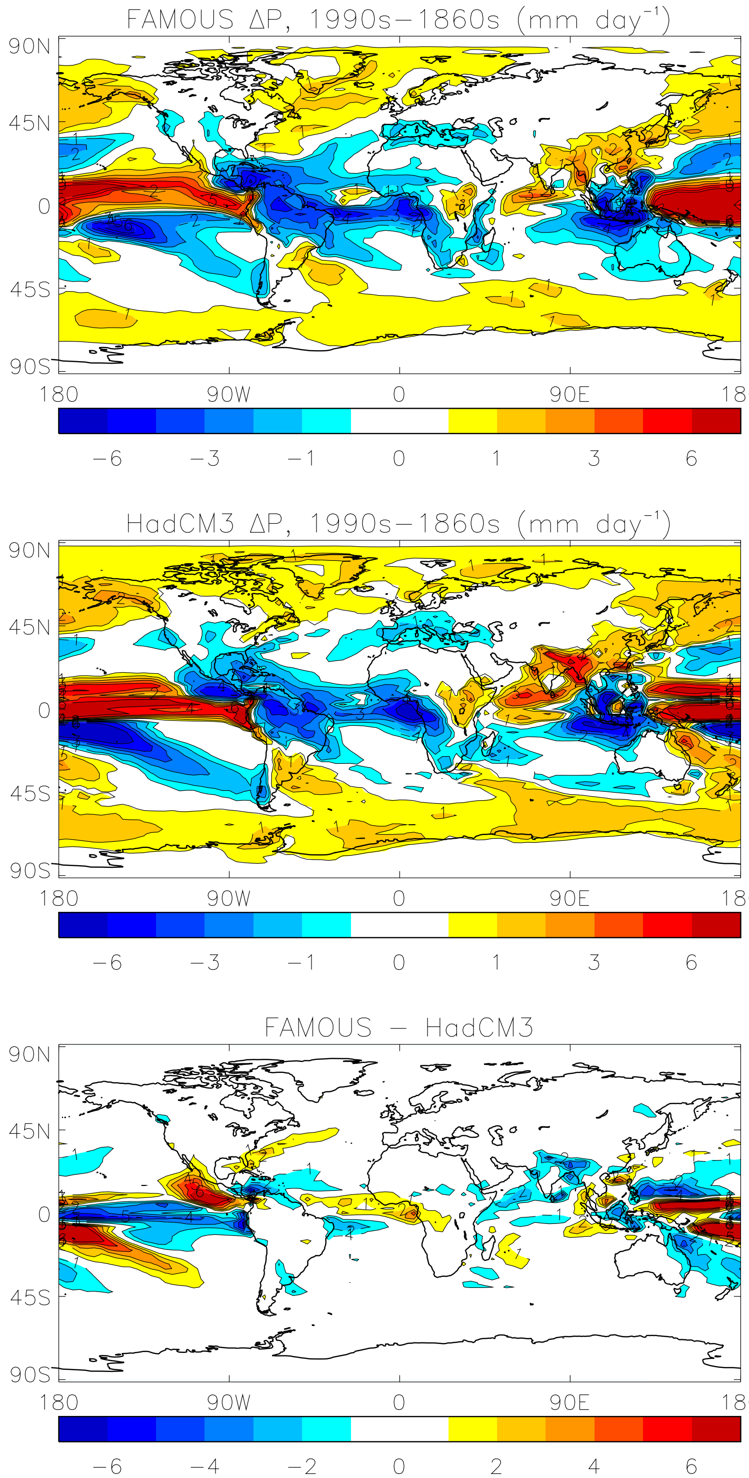

Figure 14: **Precipitation changes during the transient experiment.** FAMOUS (top) and HadCM3 (middle) changes in precipitation for the 1990s relative to 1860s, when CO_2 reaches more than 4000ppmv in the 2% CO_2 run. The bottom panel shows the differences between the two.

Name	**Description**	**Resolution** "high"=1.25°x1.25° "low"=2.5°x3.75°	**Flux Adjusted**	**Timestep** (hr)	**Iceland**	**Line Colour** in figures 2, 5, 6, 8–10
HadCM3	HadCM3	high	no	1	yes	black (dashed)
H3L	HadCM3L flux-adjusted	low	yes	1	yes	black (solid)
H3LU	HadCM3L unflux-adjusted	low	no	1	yes	red
FAM1	FAMOUS 1 hour timestep no Iceland	low	no	1	no	blue
FAM2	FAMOUS distorted physics 2 hour timestep	low	no	2	no	green
FAM6	FAMOUS distorted physics 6 hour timestep	low	no	6	no	cyan
FAM24	FAMOUS distorted physics 24 hour timestep	low	no	24	no	magenta

Table 1: Abbreviations and descriptions of model configurations and the colour used in the line-plots of figures 2, 5, 6, 8, 9, 10.

4 Summary

The FAMOUS project aims to develop a fast version of HadCM3. This report describes the changes to the horizontal resolution and timestep of the ocean component to produce a fast version which can still be run without the use of flux adjustments. The work has been successful in producing an ocean component which will run about 40 times faster than HadOM3, does not require flux-adjustments when coupled to the original HadAM3 atmosphere component, and which has a performance sufficiently similar to that of HadCM3 to allow it to be used for scientific investigations.

Table 1 lists a summary of the model configurations described in this report, the abbreviations for each configuration and the colour scheme used for line plots in the figures throughout the report.

The progress towards this ocean model is summarised in Figure 15 which shows SST errors relative to the GISST climatology (Rayner *et al* (1996)). Panel (a) shows the SST errors of HadCM3. Panel (b) shows the same for the unflux-adjusted HadCM3L (H3LU). The difference between the two runs therefore demonstrates the effect of reducing the horizontal resolution from 1.25°x 1.25°to 2.5°x 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 build up of sea ice which 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 very small.

Panel (c) of figure 15 shows the errors in the run with Iceland removed (FAM1). The differences between this and panel (b) demonstrate the impact of this change. The differences are confined mainly to the North Atlantic region where the cold bias caused by the build up of ice in the lower resolution model is significantly reduced. This is a result of the increased flow which now penetrates beyond the Scotland–Iceland ridge and provides heat transport to the region, preventing the large build up 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 +0.8K in HadCM3 (panel a). In H3LU it is -4.6K (panel b), and in FAM1 ("no–Iceland", panel c) this error is reduced to -2.6K.

Finally, panel (d) shows the errors in the distorted physics run with a timestep of 24 hours (FAM24). The impact of this change, relative to panel (c) is very small. The mean temperature error relative to

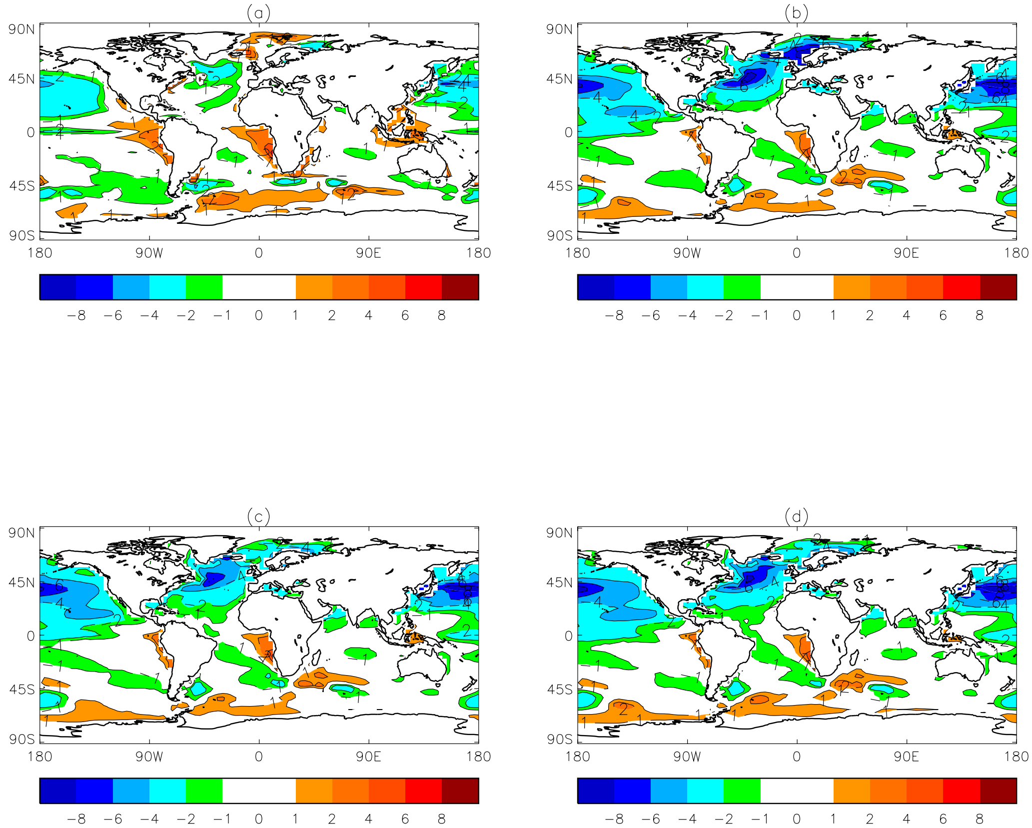

Figure 15: **SST errors relative to climatology.** Errors relative to GISST in SSTs simulated by (a) HadCM3, (b) H3LU, (c) FAM1 and (d) FAM24.

GISST in the region north of 60°N and between 30°W and 20°E is now -2.7K.

The "bottom line" of the experiment is that the results from the lowered resolution ocean run, without Iceland, with a 24 hour timestep and coupled to the full resolution HadAM3 atmospheric component are similar to the original HadCM3 results. (i.e. panels (a) vs (d)). There is a general cooling of the northern hemisphere ocean, but the overall behaviour of the model is similar. Both the control climate and the transient response to strong radiative forcing are similar to HadCM3, and thus 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.

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. 5°x 7.5°horizontal resolution will be tested with both 19 and 11 model levels. A timestep of 1 hour (compared with the current 30 minutes) may be possible, but there is no "distorted physics" equivalent for the atmosphere model, so a much longer timestep is not an option. A "coastal tiling" scheme will be used to enable the coupling of the atmosphere and ocean components which may have different land-sea masks owing to the difference in horizontal resolution.

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