Ensemble mean changes in a simulation of the European climate of 2071-2100 using the new Hadley Centre regional modelling system HadAM3H/HadRM3H

Richard Jones, James Murphy, David Hassell and Ruth Taylor
Hadley Centre, Met Office, Bracknell, UK

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1 Summary

The Hadley Centre has developed a new regional climate modelling system to provide more reliable simulations of the regional implications of global climate change. The underlying principle of adding skilful detail to the coarse resolution changes simulated by coupled atmosphere ocean general circulation models (AOGCMs) remains. However, a more flexible system has been designed to remove large regional circulation errors resulting from the coarse resolution of the Hadley Centre's AOGCM, HadCM3. First, a higher resolution AGCM, HadAM3H, is used to provide the atmospheric response to the global sea-surface temperature (SST) and sea-ice changes simulated by HadCM3. Then HadAM3H drives a European regional climate model (RCM) to provide a high-resolution interpretation of the HadAM3H response over Europe. The RCM, HadRM3H, is essentially a higher resolution regional version of HadAM3H though certain aspects of its formulation have been changed to allow for the impact of the higher resolution on its representation of atmospheric processes. This provides further improvements in the modelling system as it ensures that the RCM behaves consistently with its driving model over large scales.

HadAM3H provides a more accurate simulation of regional climate, including that of Europe, due to a doubling of resolution compared to HadCM3 and other improvements in the model's formulation. The main improvements are a more accurate simulation of the strength and position of the north Atlantic storm track and a more realistic representation of clouds and atmospheric humidity with consequent impacts on radiation and precipitation. These have positive impacts throughout the year with the greatest being in winter when the influence of the storm track is at its highest. As a result, concerns about the reliability of the model's response to climate change resulting from a poor simulation of the current climate are substantially reduced.

The modelling system has been used to provide an ensemble simulation of the response of the climate of Europe to the SRES A2 emissions scenario. Three realisations of the climate of 2071–2100 compared to 1961–90 have been simulated, driven by changes in atmospheric greenhouse gases and aerosols as derived from the A2 emissions and the associated SST and sea-ice changes derived from HadCM3. Boundary conditions from these simulations have then been used to drive the high resolution RCM, HadRM3H, over Europe. As expected, the largest impact on the response in HadAM3H compared to that in HadCM3 is seen in the winter circulation. A strong cylconic anomaly is formed over the North Sea in HadAM3H whereas HadCM3 simulates a broader and weaker pressure reduction centred over the north west Atlantic. Differences in the surface climate response over European land areas are generally small though there are some regional deviations of 1K in temperature and up to .5mm/day in precipitation. Again, as expected, the large-scale response in HadRM3H is close to that of HadAM3H though locally there are large differences. For example, simulated precipitation changes over parts of the UK are larger than +1mm/day in winter and -1mm/day in summer, double the changes predicted by HadAM3H.

2 Introduction

Several simulations of European regional climate and climate change have been undertaken by the Hadley Centre (Jones *et al.* (1995), Jones *et al.* (1997), Noguer *et al.* (1998), Murphy (2000)). These have shown that the RCMs involved (HadRM2, 2a and 2b) provide skilful fine–scale detail in the simulations of current climate and add information

on fine spatial and temporal scales to coarse resolution global model simulations of climate change. As a result, data from the last of these experiments Murphy (2000) is now being made available to the climate impacts community through the LINK project based at UEA. In this experiment, HadRM2 was used to provide a high resolution climate change simulation for Europe driven by (and thus consistent with) the response of the climate of HadCM2 to transient increase of greenhouse gases reaching four times the initial values.

This experiment still remains one of the longest regional climate change simulations undertaken but improvements in modelling, specification of emissions scenarios, computing power and the increased needs of the user community have motivated the development and wider application of a new regional climate modelling system. Specific factors include:

- Whilst HadCM2 was a highly regarded AOGCM, its use of flux correction to maintain a stable climate was regarded as a basic deficiency. This and improvements in the representation of both the atmosphere and ocean lead to the development of the non–flux–corrected AOGCM, HadCM3.

- For its third assessment report, the IPCC developed new, more realistic scenarios of future atmospheric emissions of radiatively important gases (the SRES A1, A2, B1 and B2 scenarios).

- Assessment of regional climate change simulations from AOGCMs (e.g. UKCIP (1998), Giorgi *et al.* (2001)) indicates substantial variability may be observed at regional scales.

- Though HadCM3 is an improvement over HadCM2 both methodologically and scientifically, its simulation of the north Atlantic storm track is worse (Johns *et al.* (1997), Johns *et al.* (2001)) leading to a worse simulation of the surface climatology of Europe.

- Increasing the horizontal resolution of HadAM3 (the atmospheric component of HadCM3) improves the simulation of storm tracks generally (Pope *et al.*, 1999).

- Assessment of previous RCM simulations have shown that resolution–dependent behaviour in the model can lead to errors in the seasonal mean climatology (Jones *et al.* (1995), Noguer *et al.* (1998)).

- Increases of computer power allow multiple multi-decadal high resolution AGCM and RCM simulations over a reasonable time–scale.

The development track implied by the above was thus to move to a two–stage process to provide regional climate simulations. First, use a higher resolution version of the HadAM3 to provide a more accurate interpretation of the impact of the global forcing (derived from the atmospheric emissions and their imfluence on global SSTs and sea-ice). Then use a European RCM to add fine–scale spatial and temporal detail. To maintain consistency, the RCM formulation should be based on the new AGCM though adjusted to remove resolution–dependent behaviour leading to deviations from the large–scale simulation implied by the driving model. From the perspective of the end–use of the data, the use of SRES emissions scenarios was essential as was providing several realisations of the future climate to allow a first assessment of the uncertainty associated with the use of a single simulation. (Clearly, large uncertainties associated with the choice of AOGCM, AGCM and RCM still remain.)

Whilst the higher resolution HadAM3 improved greatly on the HadCM3 simulation of the north Atlantic storm track and thus surface temperatures in most seasons, there was still a significant bias in summer in south–eastern Europe. This is similar to an error seen in previous RCMs (Noguer *et al.*, 1998). As a result it was decided to develop improvements in the physics to reduce this outstanding bias. Work in the EC–funded MERCURE project had shown that improvements in the summer temperature bias in an intermediate version of the RCM had resulted from cloud amounts being increased to more realistic values reducing excessive incoming solar radiation.

One important aspect of the new SRES emissions scenarios is the inclusion of more realistic projections of sulphur dioxide emissions. These produce atmospheric aerosols which effect the incoming solar radiation, directly via reflection and indirectly via forming extra cloud condensation nuclei which make the clouds more reflective. Until recently these effects have only been crudely approximated in GCM simulations and have received little attention in terms of regional simulations. However, it is now widely accepted that they are having an impact on global and, in certain areas including Europe, regional climate. Thus, in order to further improve the models' realism a representation of sulphur chemistry, the resultant sulphate aerosols and their effects on cloud droplet concentrations have been introduced into the new AGCM and RCM.

One aspct of HadCM3 not described above is that in its simulation of surface temperature unrealistic daily maxima and minima were occasionally produced. These quantities are important for impacts of climate and thus need to be well simulated in the context of regional climate. The model's deficiencies were linked to problems with the calculation of surface radiation fluxes and the representation of the coupling of the canopy and the surface. Improvements in these processes have been introduced into the new AGCM and RCM.

In the following section more detailed descriptions are given of the changes introduced into the models and the resulting improvements in the simulations. The report closes with a summary of the seasonal mean changes in European and UK climate of 2071-2100 compared to 1961-90 simulated by the various models in a 3-member SRES A2–driven ensemble integration.

3 Description of the new regional climate modelling system

The fundamental model enhancement required to achieve an acceptable present day simulation of European climate was a doubling of the horizontal resolution. This eliminates the failure in HadAM3 to extend the Icelandic storm track north eastwards over the continental landmass in winter. As a result it removes a substantial easterly bias over northern Europe (figure 1) and the associated large negative biases in surface temperature (figure 2).

Unfortunately, though the increase in resolution also improves the summertime circulation (figure 1) it also worsens the warm bias in summer temperatures over a broad region of southern Eurasia, increasing its magnitude and extending it both northwards and westwards (figure 2).

This develops because the increase in resolution upsets a balance of errors operating in HadAM3. The cloud scheme underestimates cloud cover, but this is partly compensated

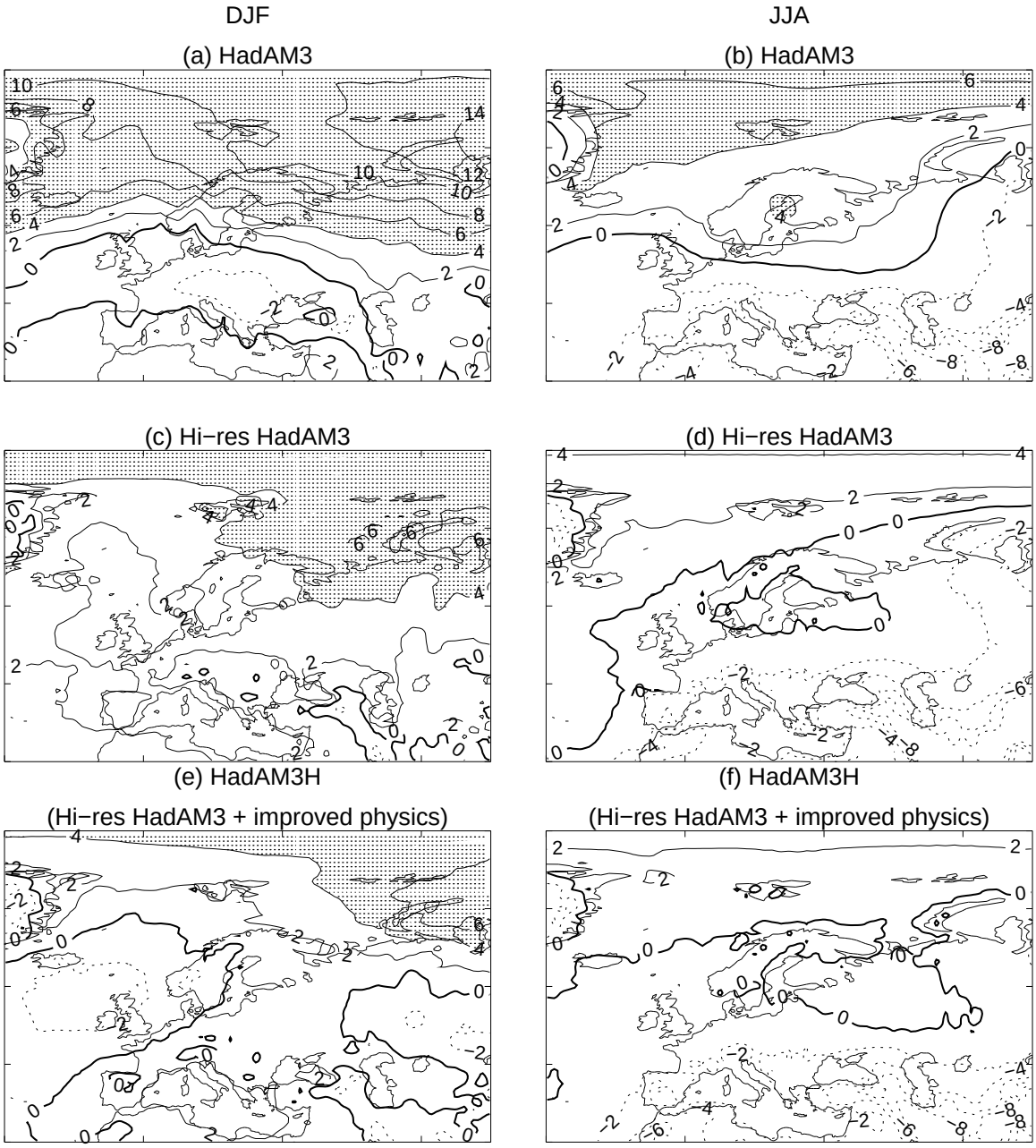

Figure 1: Mean sea level pressure biases (hPa) over western Eurasia — winter and summer biases respectively in HadAM3 (a) and (b), HadAM3 with increased horizontal resolution (c) and (d) and HadAM3H (HadAM3 with increased horizontal resolution and improved physics (e) and (f) with respect to the ERA climatology (Gibson *et al.*, 1997)

by other biases, notably excessive cloud water contents and an insufficiently vigorous hydrological cycle. Increasing horizontal resolution leads to an intensification of the hydrological cycle to a more realistic level (stronger surface winds and evaporation, stronger vertical motion, reductions in atmospheric relative humidity, more heavy precipitation events), but this results in even lower cloud cover leading to excessive surface solar heating and hence an increased erroneous surface warming. In order to achieve an acceptable simulation in summer while maintaining the improvements achieved in winter, the increase in horizontal resolution therefore needs to be accompanied by changes in the model physics.

The first change in the model physics involves an improved calculation of cloud cover. In HadAM3 the cloud cover and cloud water content in a grid box are both calculated from

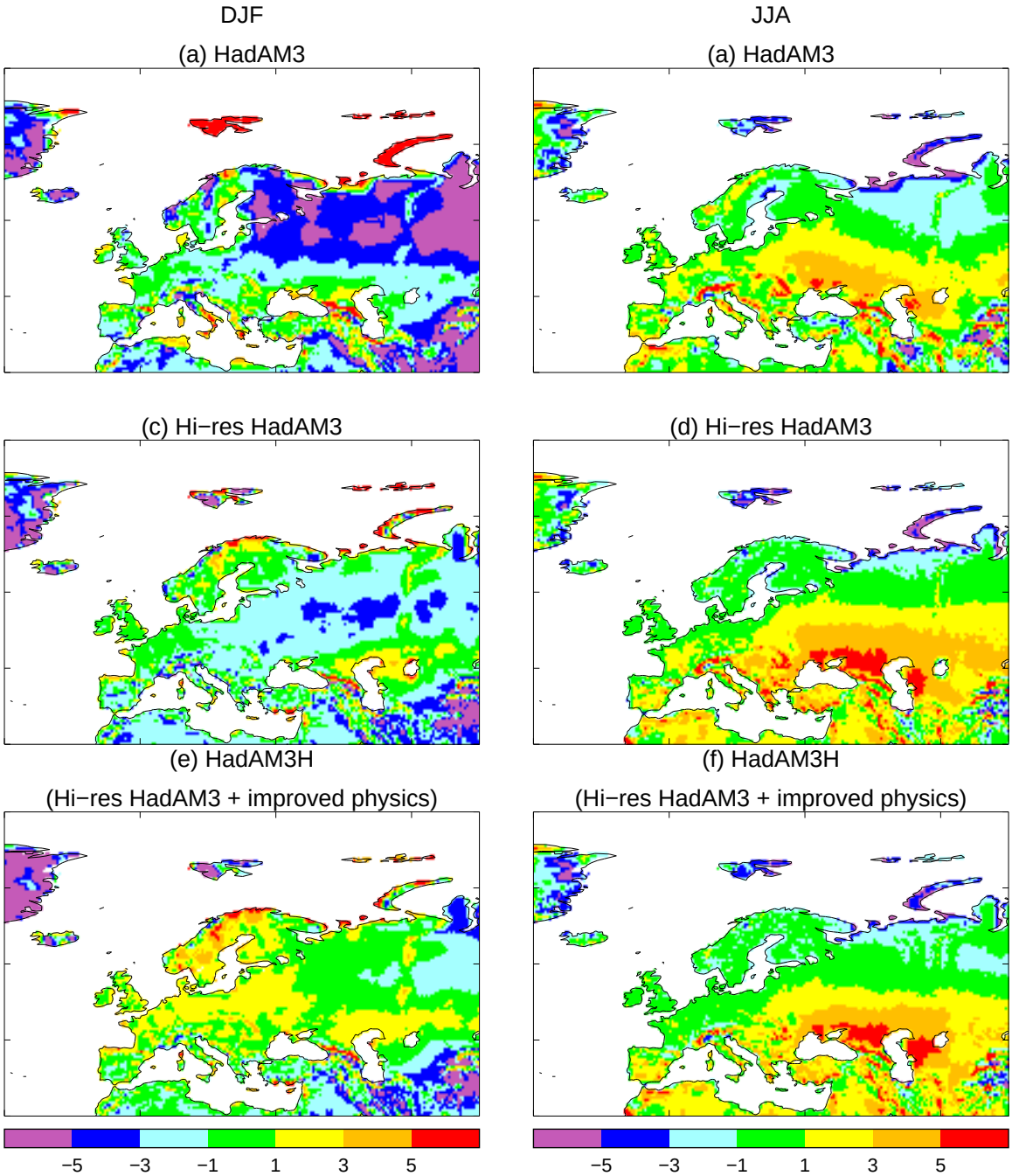

Figure 2: Surface temperature biases (°C) over western Eurasia — winter and summer respectively in HadAM3 (a) and (b), HadAM3 with increased horizontal resolution (c) and (d) and HadAM3H (HadAM3 with increased horizontal resolution and improved physics) (e) and (f) with respect to the CRU climatology (New *et al.*, 1999)

a saturation variable q_c defined as the difference between total water (i.e. water vapour + liquid + ice) and the saturation vapour pressure. It is assumed that the sub-grid scale distribution of q_c can be represented by a symmetric triangular function (Smith, 1990). If RHcrit represents the grid box mean relative humidity above which cloud begins to form, then cloud fraction (C) is represented by a quadratic spline passing through the points (RH=RHcrit, C=0), (RH=1,C=0.5), (RH=1+RHcrit, C=1). When provided with observed grid box values of total water and temperature the Smith scheme reproduces observed cloud water contents quite well but underestimates cloud cover, based on data from stratocumulus regions and the upper troposphere (Wood and Field, 2000). Accord-

ingly, the functional relationship between C and RH is modified to pass through (RH=1, C=0.6) instead of (RH=1, C=0.5). This modification removes the assumption of a symmetric distribution of total water (which does not appear to be justified by observations) in order to allow an improved representation of the observed relationship between cloud fraction and cloud water.

The second change involves the specification of the relative humidity threshold for cloud formation, RHcrit. Values of RHcrit are chosen to represent the effects of unresolved sub-grid scale motions on the distribution of total water within a model grid box. In HadAM3 a fixed value of RHcrit is specified for each model level: at standard resolution this ranges from 0.95 in the lowest layer to 0.7 for layers in the free atmosphere. However, Cusack *et al.* (1999) argued that the assumption that RHcrit does not vary in time or with geographical location is unrealistic. Based on evidence from aircraft observations and high resolution analyses for numerical weather prediction Cusack *et al.* (1999) proposed that σ_{clim}, the standard deviation of q_c within a climate model grid box, can be paramaterised in terms of σ_{3x3} the standard deviation of q_c over neighbouring grid boxes. Specifically

$$\sigma_{\mathrm{clim}} = A(p) * \sigma_{3x3}$$

where $A(p)$ is a coefficient which varies with pressure (i.e. model level) but has no geographical or time dependence. Cusack *et al.* (1999) found that using this relation to predict σ_{clim} (and hence RHcrit) led to reduced biases in cloud and relative humidity in the upper troposphere in the standard resolution version of the model.

The effect of these two changes to the calculation of cloud amounts was to substantially increase cloud cover to more realistic values. This provided a substantial cooling in summer, eliminating the local positive bias over Europe but introducing an overall cool bias. The main reason for this was that the global radiation balance in HadAM3 is maintained by excessive cloud brightnesses compenating for the reduced cloud cover. The former is obtained by using unrealistically high values for the number concentration of cloud droplets (hence reducing the their effective radius, and thus increasing the cloud brightness, for given amounts of cloud water). In addition, the size of cloud droplets is highly dependent on the concentration of cloud condensation nuclei derived from atmospheric sulphate and other aerosols. The concentrations are spatially very inhomogeneous and also include a substantial anthropogenic component over some land areas including Europe. Hence to provide a more realistic treatment of the impacts of clouds on the radiation a model of the sulphur cycle was included.

The model requires five additional prognostic variables to simulate the distribution of sulphate aerosol. These are mass mixing ratios of sulphur dioxide (SO_2), dimethyl sulphide (DMS) and three modes of sulphate. The sulphate modes represent sulphate dissolved in cloud droplets plus two free particle modes assumed to possess lognormal size distributions: the Aitken mode (mean radius 24nm) is produced by gas-phase oxidation of SO_2 and the accumulation mode (mean radius 95nm) is largely the result of cloud processing via the dissolved mode. The model simulates transport of each of the five variables via horizontal and vertical advection, convection and turbulent mixing. The oxidation of DMS to SO_2 and SO_2 to sulphate is calculated from prescribed monthly mean three dimensional fields of the hydroxyl radical (OH), hydrogen peroxide (H_2O_2) and the peroxide radical (HO_2) obtained from simulations of the Lagrangian chemistry model STOCHEM (Collins *et al.*, 1997). The model converts DMS to SO_2 in the presence of OH, while the conversion of SO_2 to sulphate proceeds via oxidation by OH in the gas phase and oxidation by H_2O_2 in the aqueous phase. The latter reaction is a significant sink of H_2O_2,

which is replenished gradually to its prescribed concentration at a rate dependent on the prescribed concentration of HO_2, using the reaction rate employed in the STOCHEM model. Sulphate produced by aqueous phase oxidation is added to the dissolved sulphate variable, while sulphate produced by gas phase oxidation is split between the Aitken and accumulation modes in proportion to their surface areas. Transfers between the sulphate modes occur by evaporation of dissolved sulphate to form accumulation mode, nucleation of cloud droplets on accumulation mode sulphate to form dissolved sulphate and diffusion of Aitken mode sulphate into cloud droplets to form dissolved sulphate. The scheme calculates dry deposition of SO_2 and the sulphate modes at the surface and wet deposition by "rainout" from within clouds and "washout" by precipitation below cloud base.

The inputs to the sulphur cycle scheme are (i) surface anthropogenic emissions of SO_2, (ii) elevated anthropogenic emissions of SO_2, which are injected into the third model layer, (iii) natural emissions of SO_2 from quasi-regular volcanic eruptions (sporadic eruptions are neglected), (iv) natural emissions of DMS, mainly from the ocean, arising from biological processes.

Sulphate aerosol affects the Earth's radiation budget via scattering and absorption of incoming solar radiation (the "direct" effect) and changes to the albedo and lifetime of clouds (the first and second "indirect" effects). The direct effect is calculated separately for the Aitken and accumulation modes using Mie theory. The calculation is based on the lognormal size distributions refered to above, with hygroscopic growth of the particles accounted for by making the effective particle size dependent on relative humidity.

The first indirect ("Twomey") effect arises from the action of sulphate aerosols as cloud condensation nuclei (CCN): increasing the number of CCN increases the number of cloud droplets (N_d) and reduces the mean effective radius (r_e) of cloud droplets ($r_e \propto N_d^{-1/3}$ in the model), thus increasing cloud albedo since clouds with smaller droplets reflect more solar radiation (cloud optical depth $\propto r_e^{-1}$ in the model). The value of N_d is determined from A, the number concentration of aerosol particles (Jones *et al.*, 1994) and is also subject to a prescribed minimum value Nmin. Over the oceans A is obtained by adding contributions from sulphate and sea-salt, where the number concentration of sea-salt particles is calculated as a function of near-surface wind speed. Over land A arises from sulphate alone, however natural continental CCN (organic aerosols, dust etc) are represented crudely by increasing the value of Nmin over land compared to that used over the sea.

The calculation of precipitation in HadAM3 does not allow for any dependence on N_d, hence the second indirect effect is not represented. (More recent versions of the model using the precipitation scheme of Wilson and Ballard (1999) do allow for the second indirect effect by accounting for the influence of Nd on the autoconversion of cloud water to rain water).

The cloud changes described earlier in this section refer to the calculation of stratiform clouds, i.e. those due to large-scale dynamical processes. Similar problems of insufficient cloud extents but excessive cloud brightnesses were also present in the HadAM3 representation of convectively generated clouds. The low cloud extents are due to a lack of vertical variation of cloud amount in HadAM3, i.e. there is no representation of the amount of deep convective, or anvil, clouds increasing with height. The excessive brightness of convective clouds in HadAM3 is due to unrealistic amounts of cloud water.

In order to overcome these problems the convection scheme was improved, based on the observed behaviour of anvil clouds, by redistributing the cloud amount predicted by

the current method and by improving the representation of the updraft and the radiative effects (Gregory, 1999). Anvils are associated with deep rather than shallow convection and are ice clouds that tend to have their bases at the freezing level. Thus convective cloud fraction in the presence of deep convection is increased linearly with model level from the freezing level to the cloud top to represent the anvil, and decreased to a constant value below to represent the convective tower. Deep clouds are defined as those having their bases in the boundary layer and their tops above the freezing level. If convection is not diagnosed as deep then no change is made to the cloud fraction.

Convective cloud water is reduced in two ways (i) by excluding water precipitating from a layer from the water path and (ii) by improving the representation of the convective updraft. (i) is justified because rain drops are much less radiatively active than cloud droplets which are significantly smaller. This halves the cloud water though this is still too high compared to observation. (ii) follows from observations indicating that the area of the updraft, which is the basic source of convective cloud water, is only a proportion of the cloud area. Thus it is specified to occur over only a fraction of the area covered by convective cloud allowing convective cloud water to be reduced to observed values.

Using an appropriate choice of the shape of deep convective clouds the long–wave and short–wave cloud forcing in the tropics, where anvil clouds dominate radiative balance, is greatly improved. The anvils thus largely remove compensating excessive incoming shortwave and outgoing longwave radiation fluxes. The reduced cloud water also ensures that the reductions in incoming shortwave do not then give a negative bias. This new representation of convective clouds also improves the simulation in Europe in summer where the heating problem is largely due to excessive insolation.

The final area of improvement concerns the coupling between the soil and the land-surface and the treatment of surface radiation fluxes. In HadAM3 the land surface is coupled to the underlying soil by a heat conduction term. This is appropriate for a bare soil surface but leads to an underestimation of the diurnal cycle for vegetated surfaces. In HadAM3H vegetated surfaces are assumed to be coupled radiatively to the underlying soil, leading to an improved diurnal cycle and the removal of unrealistic peaks in the frequency distribution of minimum temperatures associated with soil freezing in winter. HadAM3 occasionally simulates unrealistically high surface temperatures in arid regions. This occurs because the model only updates radiative fluxes every three hours, preventing rapid rises in surface temperature driven by strong solar heating from being quickly offset by increases in long wave cooling. This problem does not arise in non-arid areas where there is sufficient moisture to allow evaporation to limit the increase in temperature. In HadAM3H the upward surface long wave radiation flux is updated every model timestep (fifteen minutes) thus removing this unrealistic behaviour. These changes have made little impact on the mean climatology of HadAM3H but substantially improve the simulation of temperature extrema.

These improvements to the model physics provide further small reductions in the mean sea level pressure biases (figure 1). More substantial changes are seen in the surface temperature (figure 2). The remaining winter cold bias is removed and in some cases replaced by a warm bias resulting from a general warming. Over Europe in summer much of the warming introduced by the increase in resolution is removed as is much of the warm bias over western Europe in HadAM3. The increased warming to the east of the Black Sea is still present but reduced in intensity and there is still a small warming over the Balkans compared to HadAM3. These changes generally result from the improvements in the simulation of large-scale clouds though the changes in convective clouds have some

influence in summer.

The RCM component of the new regional modelling system, HadRM3H, uses the same formulation as HadAM3H. The resolution is increased to 0.44° which with the rotated co-ordinate system provides a quasi-uniform linear resolution of 50km (150km over Europe in HadAM3H). The vertical resolution is unchanged at 19 levels. Changes have been made to the RHcrit parametrization to allow for the fact that at higher horizontal resolution more of the spectrum of atmospheric motions are resolved and that the relationship between the variablility of humidity at and below the grid scale changes. Also,in the interaction between precipitation and the land–surface, the area of the surface over which this occurs is assumed to be a fraction of a grid–box. Experiments with higher resolution RCMs have shown that this also is dependent on resolution, reflecting the more intense nature of individual precipitation events when dis-aggregated onto a finer grid, and has thus been changed in HadRM3H. Driving this model with HadAM3H provides simulations which are consistent over large–scales (see Taylor *et al.* (2001) for more details).

4 Simulations of the European climate of 2071-2100 resulting from the SRES A2 emissions scenario

The new regional climate modelling system described above was then used to provide simulations of climate change over Europe resulting from the SRES A2 emissions scenario. The simulations were based on three HadCM3 integrations forced by observed emissisions of greenhouse gases and sulphate aerosols from 1860 to 1990 and then the SRES A2 scenario to 2100. The only difference between the three simulations was the initial conditions and thus they represent three realisations of how the climate may evolve under the A2 emissions scenario. To provide a control state as validation for the regional modelling system results and for comparison with the future climate simulations, HadAM3H was integrated for the years 1961-1990 using observed SSTs and sea-ice and observed emissions of greenhouse gases and sulphur dioxide. Again different initial conditions (taken from the HadCM3 ensemble members) were used at the start of these integrations to give an ensemble realisation of the current climate. The future climate simulations were then integrated with the SRES A2 emissions and using SSTs and sea-ice changes from HadCM3 added to the observed values (again from different initial conditions from the HadCM3 ensemble). Boundary conditions from these 6 HadAM3H integrations and the respective emissions, SSTs and sea-ice were then used to drive the ensemble HadRM3H simulation.

The impact of using the higher resolution AGCM is clearly seen in the changes in winter mean sea level pressure simulated by HadAM3H compared to HadCM3 (figure 3). The cyclonic anomaly simulated by HadAM3H is both deeper and is centred over northern European waters rather than in the Atlantic. This leads to stronger westerly and south-westerly flow over much of western Europe. The better simulation of the storm track in the HadAM3H control simulation suggest that this response is probably more realistic than that of HadCM3. The surface pressure changes are much more similar in summer (though the gradients are a little steeper in HadAM3H) which suggests that in the absence of a large differences in the control simulations the models are responding more consistently.

Certainly, in the case of surface temperatures and precipitation, the changes in HadCM3 and HadAM3H have similar patterns and magnitudes (compare figures 4 and 5 with the

right hand panels of figures 6 and 7). There is a small increase in the temperature response (1K) over parts of western and central Europe in winter in HadAM3H which is consistent with the enhanced westerlies. This also has an impact in winter precipitation which shows a somewhat larger enhancement in these areas in HadAM3H. In summer over most of the region the responses are more similar. The main exception is north of the Black Sea where HadCM3 has a larger temperature and precipitation response. In this case one would be somewhat suspicious of the response in HadAM3H given the larger positive temperature and negative precipitation bias (not shown) in the model over this region.

The picture for the European land area is thus one of substantial warming, with a maximum in excess of 7K, in the north in winter and the south in summer, and a minimum of 2–3K over parts of the UK. The precipitation response is more variable with increases over all but the far south and the Norwegian mountains in winter and decreases in all but the far north and the Baltic in summer. Comparison of the HadRM3H results with that of its driving model (figures 6,7 and 8) clearly demonstrate the consistency of the large–scale responses. The last of these figures also shows that this consistency is maintained for an individual realisation. There is, however, clearly substantial local detail simulated by the RCM. In the case of the UK in summer (for the first ensemble member) it simulates a substantial increase in the magnitude of the shift to wetter winters and drier summers simulated by HadAM3H (figure 9).

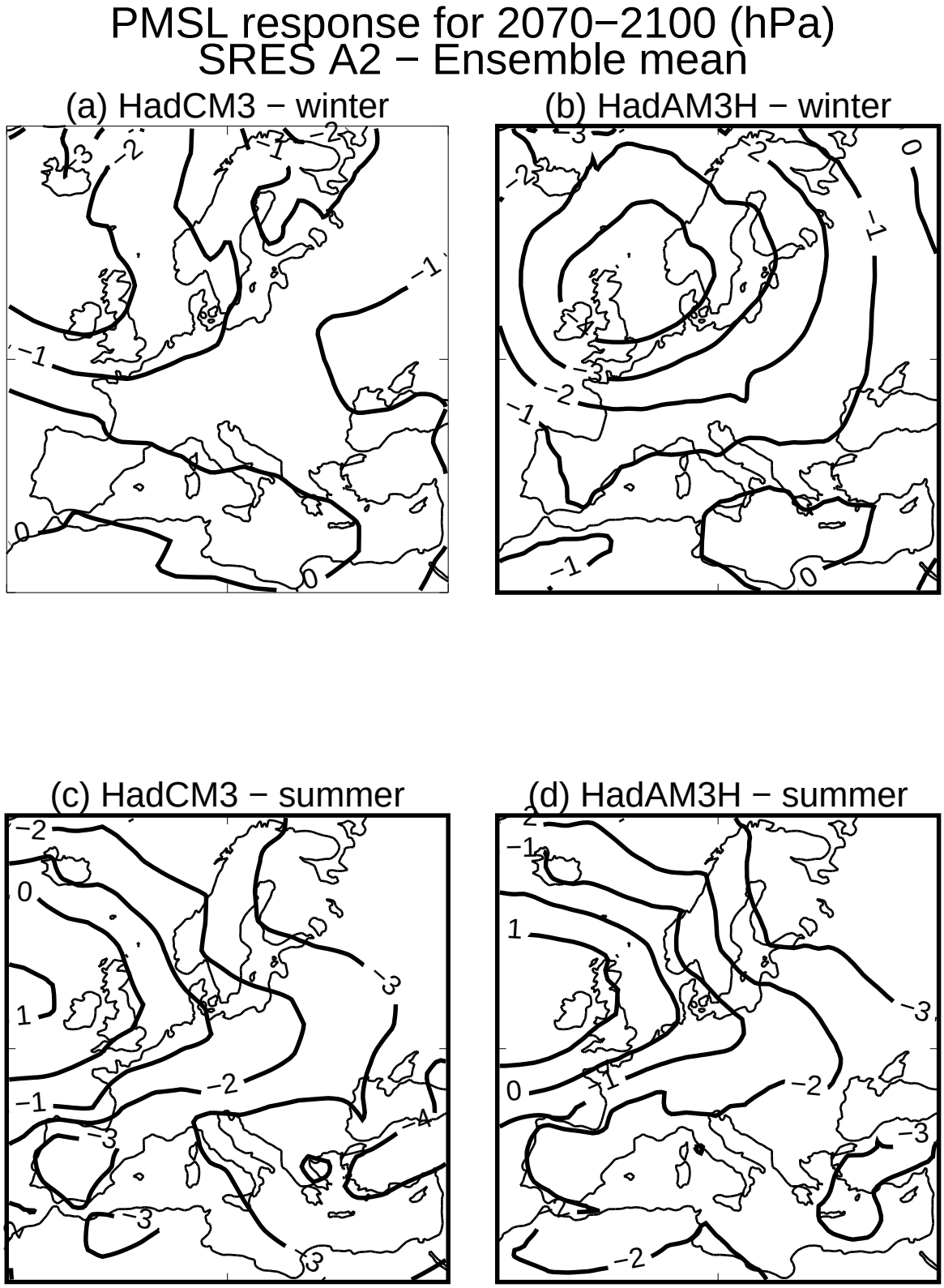

Figure 3: Ensemble mean mean sea level pressure changes over Europe for 2071-2100 compared to 1961-90 from three HadCM3 and HadAM3H simulations driven by the SRES A2 emissions scenario and the latter by the associated SST and sea-ice changes in the three HadCM3 simulations.

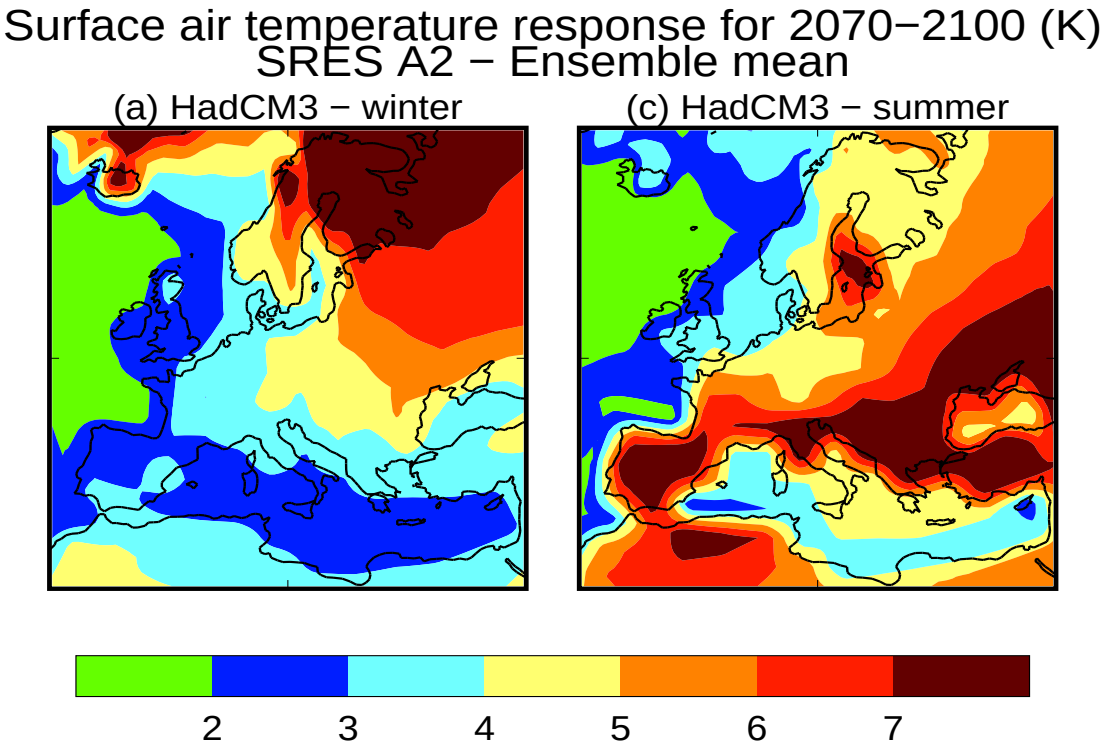

Figure 4: Ensemble mean temperature changes over Europe for 2071-2100 compared to 1961-90 from three HadCM3 simulations driven by the SRES A2 emissions scenario.

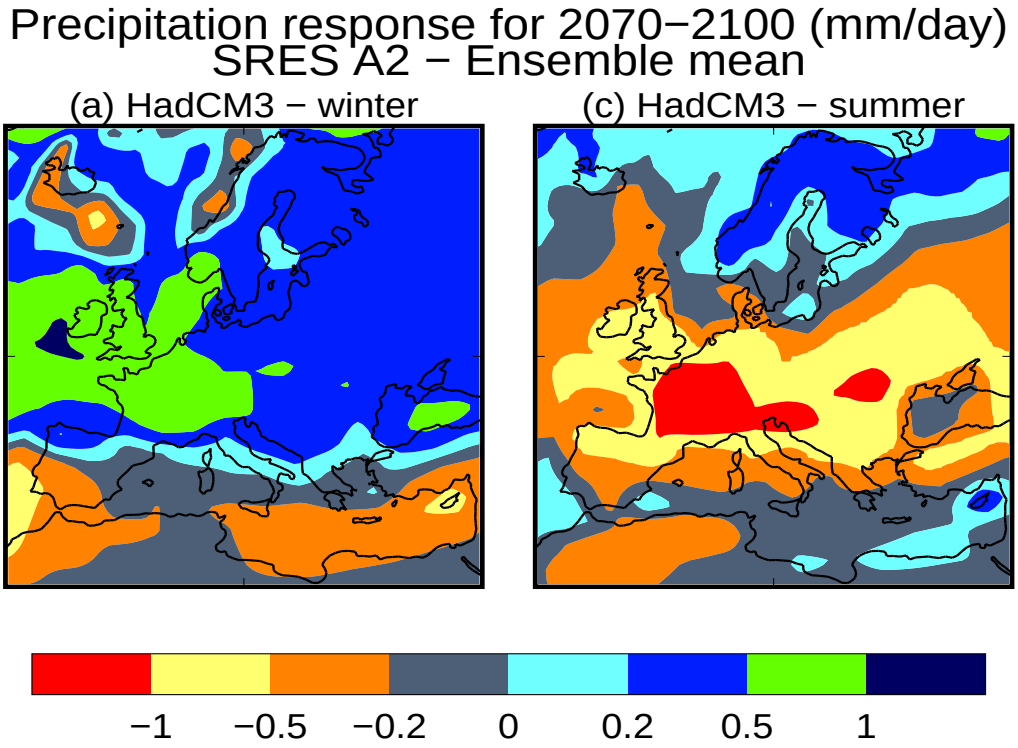

Figure 5: As figure 4 but for precipitation.

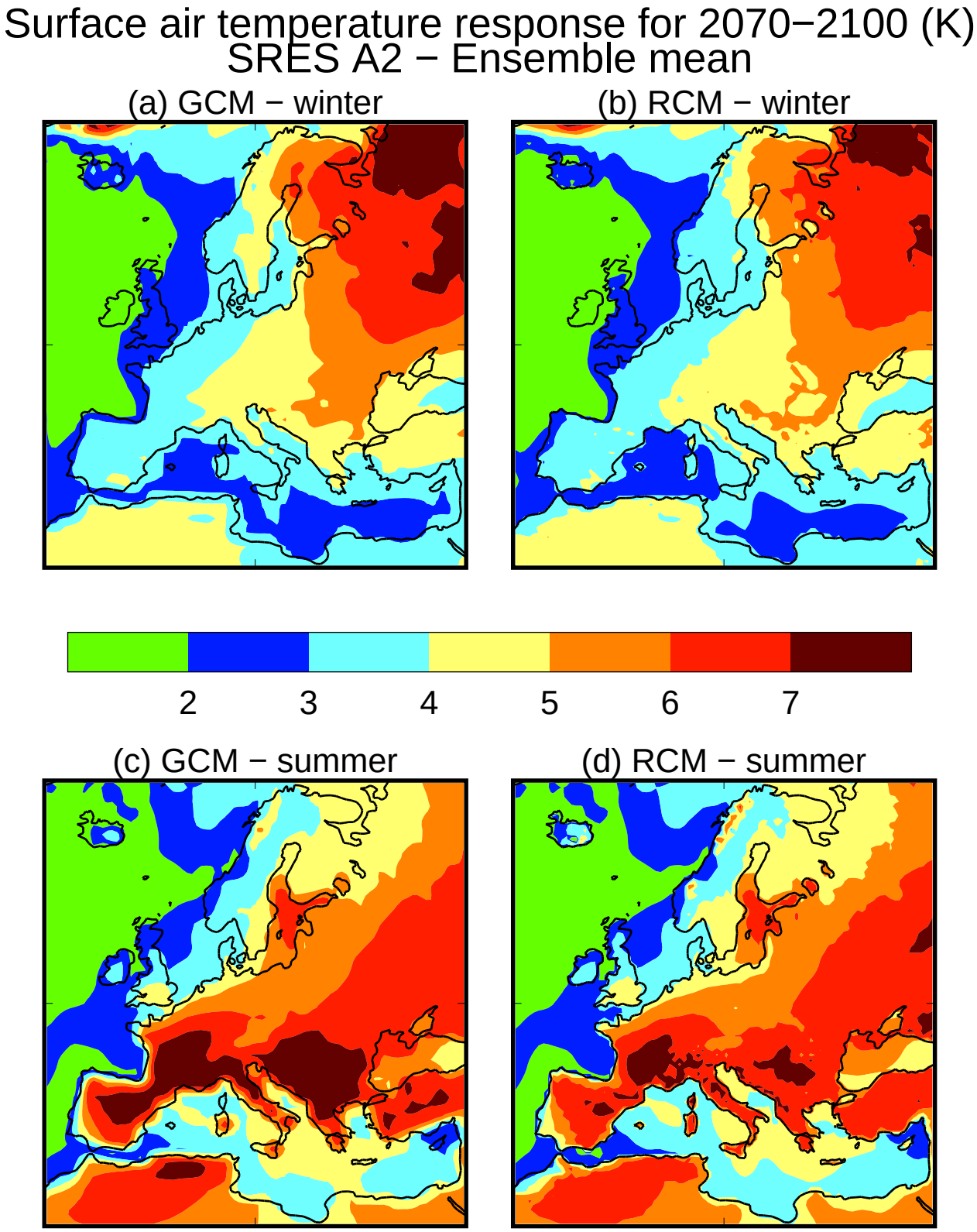

Figure 6: Ensemble mean temperature changes over Europe for 2071-2100 compared to 1961-90 from three HadAM3H and HadRM3H simulations driven by the SRES A2 emissions scenario and associated SST and sea-ice changes in three HadCM3 simulations.

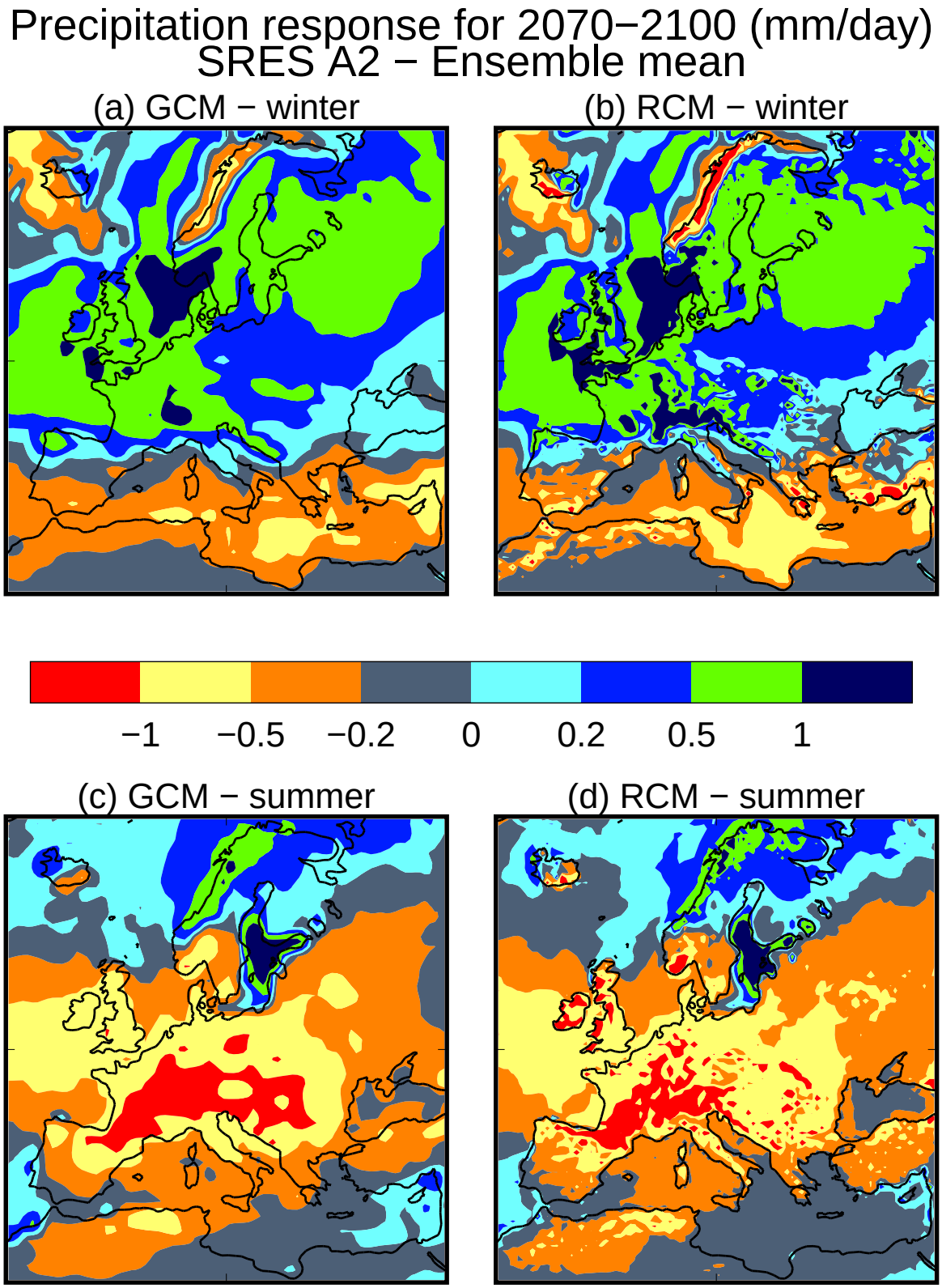

Figure 7: As figure 6 but for precipitation

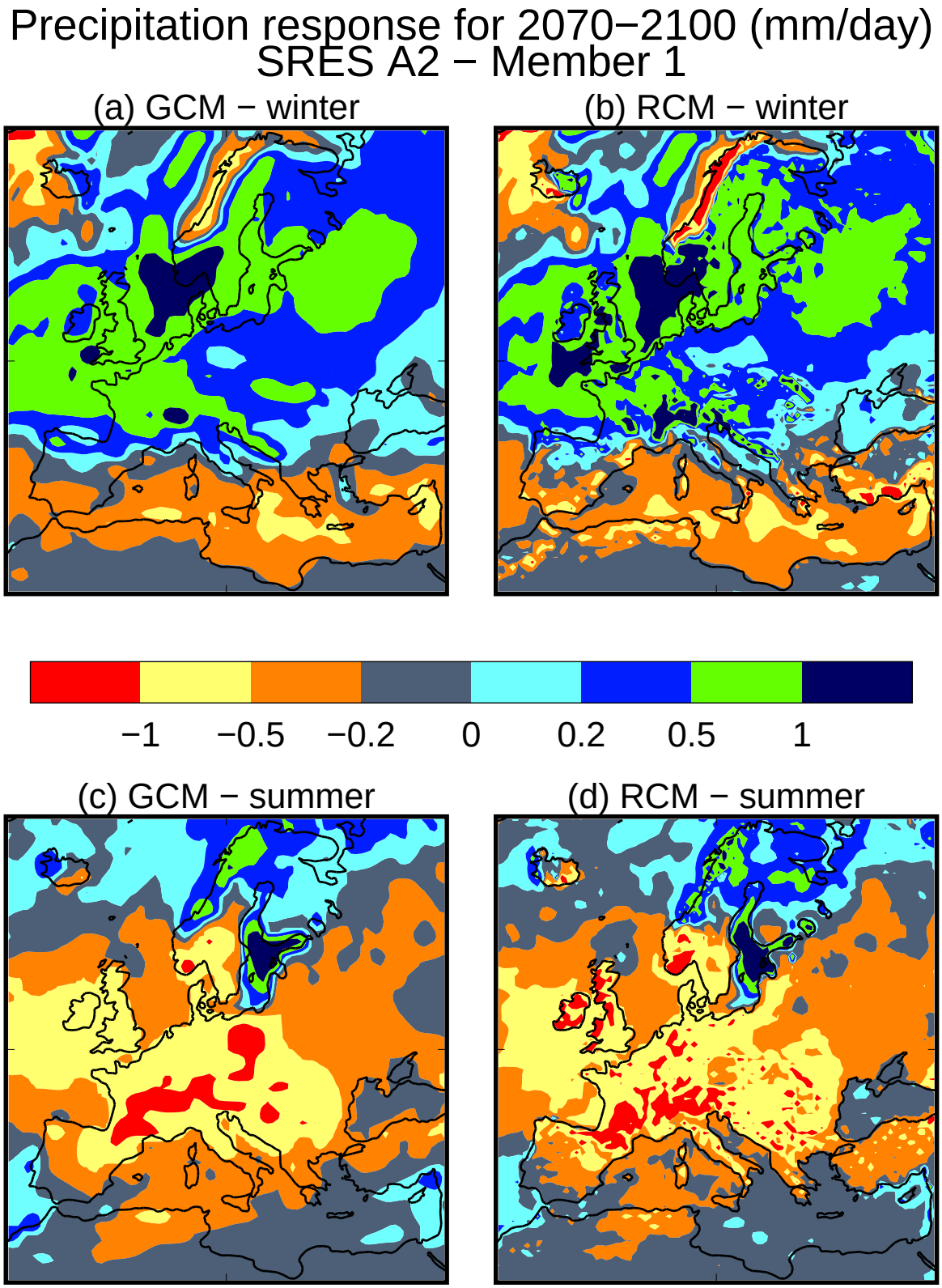

Figure 8: As figure 7 but for the first ensemble member.

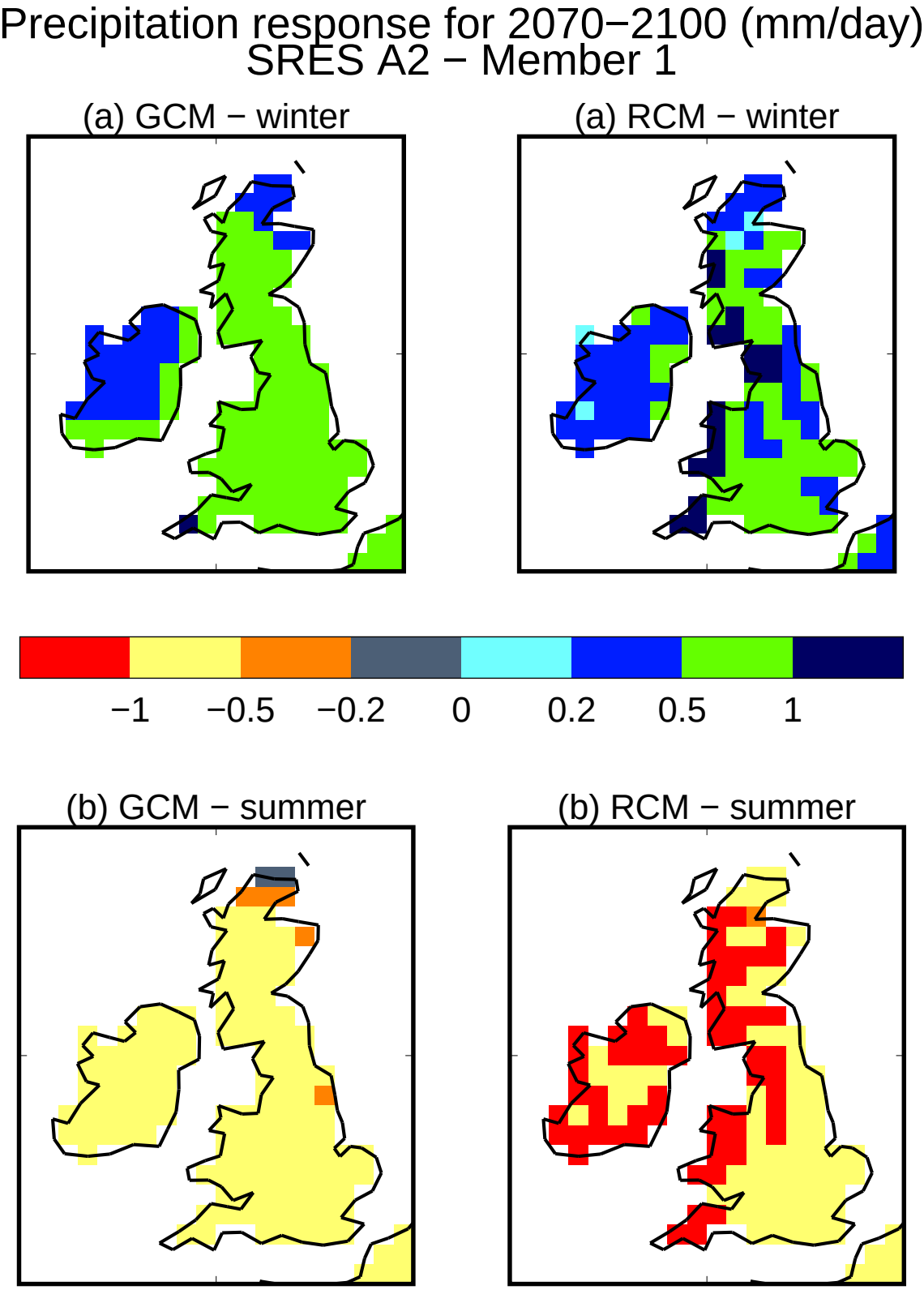

Figure 9: The detail of figure 8 over the UK.

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