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Origin of climate sensitivity differences: role of selected radiative processes in two GCMs

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ABSTRACT

Model differences in projections of global mean and regional climate change due to increasing greenhouse gases are investigated using two atmospheric general circulation models (AGCMs): ECHAM4 (Max Planck Institute, version 4) and CCM3 (National Center for Atmospheric Research Community Climate Model version 3). We replace the ECHAM4 short-wave processes (including routines for short-wave radiation, aerosols, cloud liquid water path and cloud droplet size distribution) with the corresponding parametrizations from CCM3. We also eliminate sea-ice in both models. We find that the resulting 'hybrid'-ECHAM4 model has the same global mean temperature sensitivity (defined as the difference in temperature between the 2× CO_2 and 1× CO_2 integrations at equilibrium) and similar regional temperature change patterns as CCM3. The global mean precipitation sensitivity was only slightly affected; indicating different processes control this.

Investigation of top of the atmosphere radiative feedbacks in the standard-ECHAM4 and hybrid-ECHAM4 models show that the differences in global mean temperature sensitivity and regional temperature change patterns can be attributed primarily to a stronger, negative, cloud short-wave feedback in the tropics of the hybrid-ECHAM4 model. However, comparison of the hybrid-ECHAM4 model to CCM3 reveals large differences in partitioning of the cloud feedbacks between long-wave and short-wave in the two models. This suggests that the global mean temperature sensitivity and regional temperature change patterns respond primarily to the magnitude and distribution of the top of the atmosphere feedbacks and are relatively insensitive to the partitioning between individual processes.

1. Introduction

Attempts to determine the response of the climate system to increasing greenhouse gases (commonly represented as a doubling of CO_2) using general circulation models (GCMs) have produced a wide range of global mean equilibrium surface temperature and precipitation sensitivities (e.g. Mitchell et al., 1990; Gates et al., 1992; Kattenberg et al., 1995; Meehl et al., 2000; Boer et al., 2001; Covey et al., 2003). The pioneering evaluation of the 'Charney Report' (U.S. National Academy of Science, 1979) estimated the range of equilibrium temperature sensitivities from GCMs as 1.5–4.8 °C. According to Boer et al. (2001) 'the previous estimated range for this quantity . . . still encompasses the more recent model sensitivity estimates.' The spread in global mean precipitation sensitivities is even higher, ranging from 1% to 15% (Boer et al., 2001). The spread in sensitivity estimates is generally insensitive to whether the model is an atmospheric general circulation model (AGCM) coupled to a slab mixed-layer ocean at equilibrium or a fully coupled general circulation model (CGCM) at time-of-doubling, although the spread among the fully coupled models at time-of-doubling is somewhat lower (Meehl et al., 2000; Covey et al., 2003).

Several attempts have been made to limit the range of realistic temperature sensitivities, none of which have been wholly successful. One method (see references below) uses models in conjunction with observations to constrain the possible climate sensitivity. Typically a highly simplified climate model with a limited number of adjustable parameters, one of which is the sensitivity of thermal radiation emitted to space to variations in global mean surface temperature, is used to simulate the evolution of the surface temperature response to the evolution of the forcings (such as CO_2 and other greenhouse gases, natural and anthropogenic aerosols, etc.) during the past century and a half. The observed and simulated temperatures, together with

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estimates of internal climate variability and errors in the forcings, are used to limit the range of the sensitivity parameter. Estimates of sensitivity to doubled CO_2 using variants of this approach are 1–9 °C (Andronova and Schlesinger, 2001); 1.4–7.7 °C (Forest et al., 2002); greater than 1.6 °C (Gregory et al., 2002); approximately 2 °C (Harvey and Kaufman, 2002) and approximately 6 °C (Knutti et al., 2002). In another approach, Tsushima et al. (2005) used observations of the differences in surface and top of the atmosphere (TOA) radiative anomalies to estimate the sign and magnitude of various climate feedbacks. While the results of these model-observation hybrid approaches are consistent with the spread in GCM sensitivities, they do not provide clear evidence for narrowing the range of possible sensitivities.

A major stumbling block in reducing the model dependence of climate sensitivity is that the causes are insufficiently known. Dickinson (1986), and more recently Colman (2003) have estimated the range of uncertainty in various climate feedbacks (water vapour/lapse rate, albedo and clouds) and showed that the range of GCM sensitivities is consistent with these uncertainties acting independently in various models. Experiments have been carried out with various modelling groups making coordinated changes in their models to examine the effects on feedback and sensitivity (e.g. Cess et al., 1990; Cess et al., 1991; Colman et al., 1994; Randall et al., 1994; Cess et al., 1996). Other studies have considered the effect of changes in parametrizations on a single model's feedbacks and sensitivities (Senior and Mitchell, 1993; Zhang et al., 1994; Colman and McAvaney, 1995; Rotstayn, 1999; Schneider et al., 1999; Yao and Del Genio, 1999). The Hadley Centre is making a significant effort to document the effects of variations in several uncertain parameters on climate sensitivity (Murphy et al., 2004), by systematically varying values of specific parameters within a single model. They find that for reasonable values of parameters within different parametrization schemes, global mean temperature sensitivities can range from less than 2 °C to more than 11 °C. Despite these studies, it is still not possible to attribute the causes of model dependence in climate sensitivity to specific parameters, parametrizations, or subset of parametrizations.

Two decades of documentation and study of differences in climate sensitivity and feedbacks have thus resulted in little reduction in the range of sensitivities. Certainly, one reason for this failure of the models to converge is the difficulty in estimating the sensitivity of the climate system from observations, as documented above. However, it is also likely that another reason the models have not converged is a lack of detailed understanding of the impact of the differences in model formulation (defined here as the physical parametrizations and numerical structure) on sensitivity differences.

Here we attempt to isolate and understand some of the causes of the different equilibrium sensitivities of two AGCMs to increasing greenhouse gases: the National Center for Atmospheric Research (NCAR) Community Climate Model, version 3 (CCM3; Kiehl et al., 1996) and the Max Planck Institut (MPI) European Centre for Medium-Range Weather Forecasts–Deutsches Klimarechenzentrum: Hamburg (ECHAM4; Roeckner et al., 1996), each coupled to a slab mixed layer ocean with no sea ice. We evaluate the influence of all of the short-wave radiation processes and some associated long-wave processes (specifically routines for short-wave radiation, aerosols, cloud liquid water path and cloud droplet size distribution) by transplanting the CCM3 parametrizations into ECHAM4 and examining the changes in the equilibrium sensitivity for the resulting 'hybrid' ECHAM4 model. The effect of the parametrization replacement is to essentially eliminate differences between the two models in the global mean temperature sensitivity, and to greatly reduce differences in regional temperature change patterns.

This parametrization swapping approach has been applied by Schneider (2002) to understand causes of differences in simulations of tropical Pacific mean climate, annual cycle and variability of two coupled atmosphere–ocean GCMs; the Center for Ocean–Land–Atmosphere (COLA) coupled model and the NCAR Community Climate System Model, version 1 (CCSM1). There, the differences between the AGCMs were eliminated one parametrization at a time, and the procedure identified the impact of model code differences in producing the targeted simulated differences. This approach is somewhat different from the approach of the Hadley Centre project, with changes being made at a higher level in the code (parametrization level rather than parameter level) and focusing on differences between pairs of models. We have chosen the parametrization swapping approach as a first step because when comparing two models, there is generally a one-to-one correspondence in parametrizations, but not necessarily a correspondence between the internal parameters of these parametrizations. For example, while all climate models will have some representation of clear-sky short-wave radiative transfer details of the implementation may vary widely between models.

The paper is organized as follows. In Section 2, we discuss the models used and the specifics of the parametrization transplant procedure. In Section 3, we present some of our results from CCM3 and the control and hybrid versions of ECHAM4, in Section 4 we present a feedback analysis as an aid to interpreting the changes in the hybrid model, and Section 5 presents a summary and our conclusions.

2. Models and methodology

Given that CCM3 and ECHAM4 are closely related controlled systems in which the underlying principles are exactly determined (as represented in the code), and whose behaviour can be measured exactly to any level of detail (the diagnostic output), it is reasonable to expect that the causes of differences in their behaviour can be understood by suitably designed experiments. Here we apply the parametrization swapping technique described in the Introduction to examine the influence of the CCM3 parametrizations of short-wave and cloud radiative properties on ECHAM4. We focus on these processes for a number of reasons. Numerous studies (e.g. Cess et al., 1996 and references therein; Bony and Dufresne, 2005; Webb et al., 2006) have considered the causes of differences in climate model sensitivities and concluded that cloud-radiative feedbacks play a dominant role. Schneider (2002) found that the surface temperature distribution of the COLA AGCM was sensitive to the choice of short-wave parametrization, making it a logical starting point. In addition, examination of the code for each model showed it was possible to exchange the parametrizations.

The problem is made more tractable by first coupling both AGCMs to a slab mixed-layer ocean, with sea-ice specified to be zero and an implied oceanic heat-flux (or Q-flux) applied to the control simulations to give the observed climatological SST distributions. We eliminate the parametrized sea-ice in order to concentrate on the effect of the differing AGCM parametrizations. Both models are run with a base CO_2 concentration of 353 parts per million by volume (ppmv) and a triangular 30 (T30) horizontal truncation. The somewhat coarse horizontal resolution is chosen as a practical matter to allow for more rapid turnaround in the numerous experimental runs required. ECHAM4 is run with 19 vertical levels, while CCM3 is run with 18. After examining the coding structure of each model, we determined that transferring parametrizations from CCM3 to ECHAM4 was more feasible than transferring parametrizations from ECHAM4 to CCM3. All experiments described here consist of replacing the short-wave processes code, including the code determining cloud radiative properties, in ECHAM4 with the corresponding parametrization taken from CCM3. The latter changes also have a significant effect on the cloud long-wave fluxes. After transferring the parametrization from CCM3 to ECHAM4, the Q-flux was recalculated so that the new hybrid model had the same control climate SST as the unmodified ECHAM4. Experiments using the original Q-flux field (not shown) indicate that the results are relatively independent of the specification of Q-flux field.

As discussed above, we first replace the ECHAM4 short-wave parametrizations (Fouquart and Bonnel, 1980) with the CCM3 short-wave parametrizations (Brieglieb, 1992). Replacing the short-wave radiation code alone creates a significant (>20 W m^{-2}) TOA radiation imbalance in the hybrid model (not shown). However, when the ECHAM4 cloud liquid water path and effective droplet size parametrizations (Rockel et al., 1991) are replaced with those from CCM3 (Slingo, 1989), the radiative balance is restored (<1 W m^{-2} difference between control and unmodified models; difference absorbed into Q-flux). Replacing the liquid water path or effective droplet size parametrizations separately does not restore the radiative balance. The ECHAM4 aerosol scheme, which is based on the Global Aerosol Data Set (GADS) (Koepke et al., 1997), is also replaced with the CCM3 parametrization, in which aerosols are uniformly distributed in the lowest three layers of the model (Kiehl et al., 1996). This replacement is performed for purely practical reasons, as the ECHAM4 aerosol scheme was not structurally compatible with the CCM3 short-wave radiation code. In the following discussion, standard-ECHAM4 refers to the unmodified ECHAM4 AGCM, while hybrid-ECHAM4 refers to the ECHAM4 AGCM with the CCM3 parametrizations for short-wave, cloud liquid-water path, effective droplet size and aerosols.

It is important to note that the only cloud-related parametrizations which are replaced deal with their radiative properties and not their formation or distribution. In particular, the routines governing cumulus convection, large-scale condensation, cloud fraction and vertical distribution in the hybrid-ECHAM4 are unchanged from the standard-ECHAM4 routines. ECHAM4 and CCM3 use different routines for the calculation of all of these quantities, leaving numerous ways for the standard-ECHAM4, hybrid-ECHAM4 and CCM3 models and simulations to differ.

3. Results

3.1. *Global mean sensitivities*

The equilibrium global mean temperature sensitivities of the two unmodified AGCMs, coupled to slab mixed-layer oceans and including sea-ice, are 2.1 °C for CCM3 and 3.5 °C ECHAM4 (not shown). Eliminating sea-ice reduces these sensitivities to ~1.7 °C for CCM3 and ~2.7 °C for ECHAM4 (Fig. 1a), consistent with a positive sea-ice/albedo feedback. Note that the percent decrease of sensitivity of ECHAM4 is approximately the same as that of CCM3 (~24%) from eliminating sea-ice, indicating that this feedback is about the same for each model. Comparing the global mean temperature sensitivity of the hybrid-ECHAM4 model with that of CCM3 (Fig. 1b), we find that they are nearly identical (1.5 °C for the hybrid-ECHAM4 model versus 1.7 °C for CCM3). This demonstrates that the differences in the global mean temperature sensitivity between the two models can be eliminated almost entirely by removing the collective differences in the short-wave radiation, aerosol, cloud liquid water path and effective droplet size parametrizations.

The control versions of the two models (Fig. 2a) have very similar global mean precipitation sensitivities. The overall sensitivity of the hybrid-ECHAM4 model is reduced from the standard-ECHAM4 model (Fig. 2b), although the picture is complicated by the apparent low-frequency variability in the sensitivity of the hybrid-ECHAM4 model that is not present in the standard-ECHAM4 model. The reduction in precipitation sensitivity is consistent with the reduction in global mean temperature sensitivity (Fig. 1).

3.2. *Patterns of regional climate change*

While the agreement between the hybrid-ECHAM4 and CCM3 global mean temperature sensitivities is significantly improved

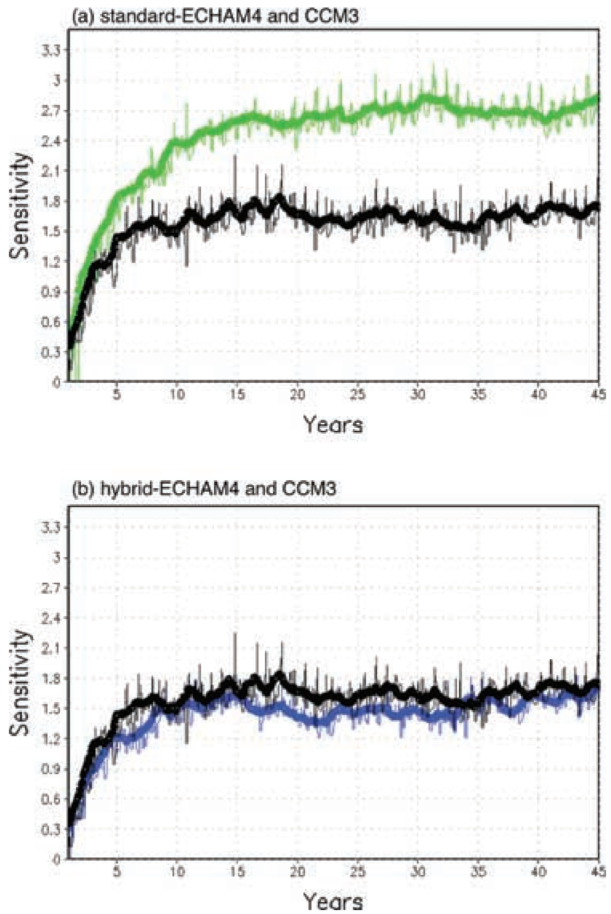

Fig. 1. Comparison of global mean temperature sensitivities for (a) standard-ECHAM4 and CCM3 and (b) hybrid-ECHAM4 and CCM3. Green line in panel (a) is standard-ECHAM4, blue line in panel (b) is hybrid-ECHAM4. Dark line is CCM3 in both panels. Units are in °C.

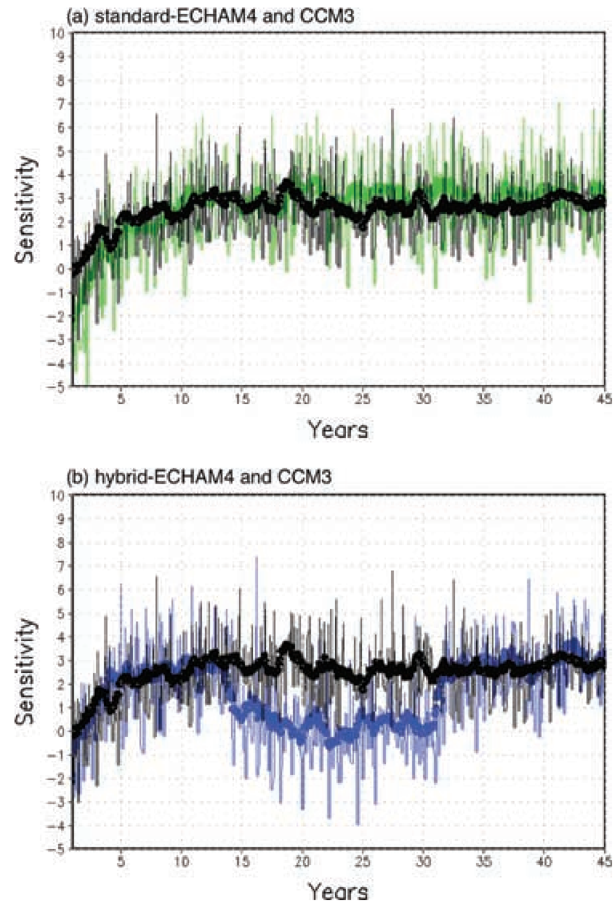

Fig. 2. Comparison of global mean precipitation sensitivities for (a) standard-ECHAM4 and CCM3 and (b) hybrid-ECHAM4 and CCM3. Green line in panel (a) is standard-ECHAM4, blue line in panel (b) is hybrid-ECHAM4. Dark line is CCM3 in both panels. Units are percentage change from 1× CO2 case for each model.

over the standard-ECHAM4 and CCM3 models, there is no guarantee that the regional patterns of climate change are also more similar. As it is changes in the regional climate that will have the greatest direct societal impact, reducing uncertainty in projections of regional climate change is a problem of immense practical as well as scientific interest.

The regional patterns presented in this section were calculated as follows. The figures show the results or differences of averages taken over the last 25 yr of each integration. To assess the robustness of the resulting patterns, the 25-yr periods used to calculate each figure were subdivided into separate 12-yr periods. Averages over each 12-yr period recovered the patterns shown here with only very minor changes (not shown). This check was repeated for each figure with similar results.

While the standard-ECHAM4 model climate sensitivity is greater than in CCM3 (Fig. 1a), this increase in climate sensitivity is not uniform (Fig. 3a). Differences in the regional temperature change patterns are largest over the Northern Hemisphere (NH) landmasses and Antarctica, where the standard-ECHAM4 model warms substantially more than CCM3. Standard-ECHAM4 also generally warms more in the tropics, but is notably less sensitive in the north Atlantic region. This is consistent with the results of Räisänen (2001), who found that global mean temperature sensitivity in a given model was a poor predictor of north Atlantic regional sensitivity. The regional differences in temperature change are similar in many respects to the differences in the coupled version of the two models noted in Cash et al. (2005). The fact that the mixed-layer models without sea-ice used in this study reproduce the increased warming over land and the sharp reduction in warming over the north Atlantic in ECHAM4 relative to CCM3 indicates that these features are due to differences in the AGCMs rather than ocean dynamics.

When we compare the hybrid-ECHAM4 model to CCM3 (Fig. 3b), we find that the differences in regional temperature change patterns are substantially reduced. The large differences over landmasses have been almost entirely eliminated and the differences over the tropical oceans have also been greatly

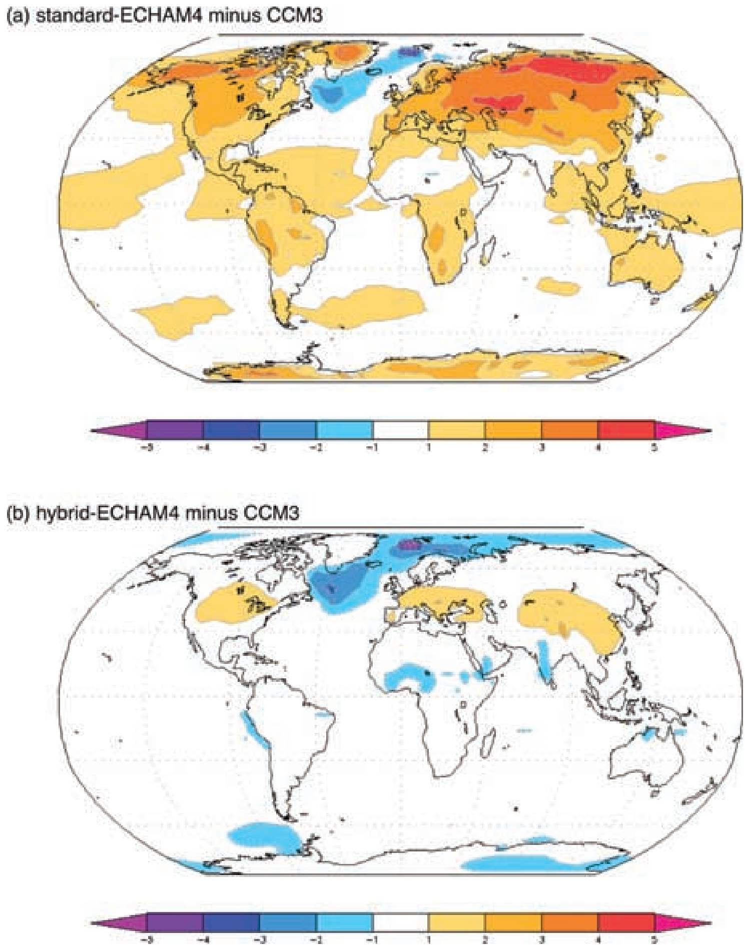

Fig. 3. Differences in regional temperature change patterns for (a) standard-ECHAM4 and CCM3 and (b) hybrid-ECHAM4 and CCM3. Twenty-five-year annual means, units are °C.

reduced. Overall, the global mean rms difference between the two models is reduced from 1.4 °C for the standard-ECHAM4 model to 0.6 °C for the hybrid-ECHAM4 model. Interestingly, the magnitude of the differences over the North Atlantic and over the Arctic increases slightly in the hybrid model, indicating that processes other than those we have considered are required to explain the differences in this region (it should be noted these changes in pattern, like those discussed for precipitation below, are robust to a subsetting of the data and unlikely to be affected by sampling).

When we examine the regional temperature change patterns of the standard-ECHAM4 (Fig. 4a) and hybrid-ECHAM4 (Fig. 4b) models separately, a number of features are apparent. Despite the lack of sea-ice, both versions of ECHAM4 show clear polar amplification of the warming signal. Polar amplification is also present in CCM3 (not shown). Thus, polar amplification is not dependent on ice-albedo feedback, at least in these models, although ice-albedo feedback undoubtedly amplifies the warming further. This is consistent with the results of Aleexev et al. (2005), which found polar amplification of warming in an aqua-planet model. It is also interesting to note that warming in both standard-ECHAM4 and hybrid-ECHAM4 is increased over the landmasses. However, in hybrid-ECHAM4 this occurs primarily in the mid-latitudes, while in standard-ECHAM4 the warming is amplified over all landmasses.

As one might expect, the differences in regional precipitation change patterns show more local structure than the temperature sensitivities for both the control (Fig. 5a) and hybrid (Fig. 5b) models. When compared to CCM3, the standard-ECHAM4 model has two broad bands of increased precipitation over the oceans at 60 °N and 60 °S (Fig. 5a). In the tropics, the standard-ECHAM4 model is more sensitive than CCM3 immediately to the north and south of the equator in the central Pacific and Indian Ocean, and less sensitive in a narrow band stretching southeast from the central Pacific towards the tip of South America. These differences tend to follow the climatological regions of deep convection in the two models (not shown).

For the hybrid-ECHAM4 model, we find that the differences in extratropical precipitation regional change patterns are greatly reduced (Fig. 5b), with little sign of the prominent bands at 60 °N and 60 °S present in the standard-ECHAM4 model. Differences also generally decrease over land. However, in the tropics, the overall structure of the precipitation differences is similar for both versions of ECHAM4, although the hybrid-ECHAM4

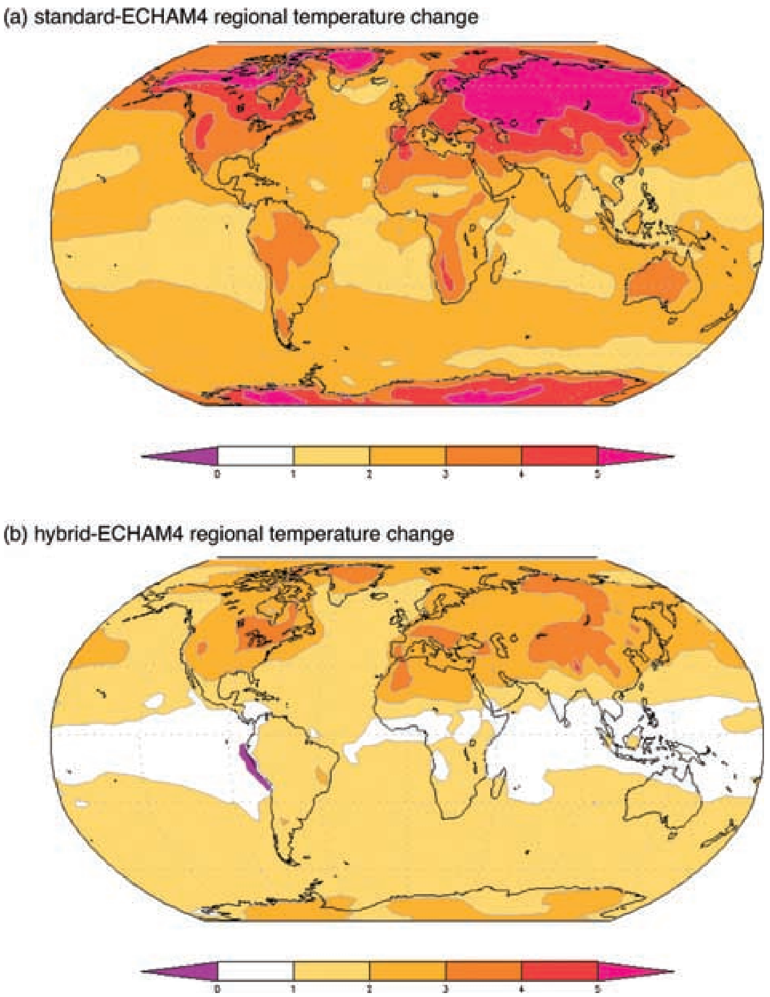

Fig. 4. Regional temperature change patterns for (a) standard-ECHAM4 and (b) hybrid-ECHAM4. Twenty-five-year annual means, units are °C.

model shows an intensification and westward shift of the anomalies along the equator. The region of precipitation change is now concentrated in the western Pacific, and its longitudinal extent is greatly reduced.

4. Feedback analysis

In the preceding section, we demonstrate that replacing a fraction of the ECHAM4 model code with the corresponding routines from CCM3 eliminates most of the differences in the global mean temperature sensitivity, as well as differences in the regional temperature change patterns. To help relate these code changes to physical processes, we apply a feedback analysis of the type used by Boer and Yu (2003).

The local feedback parameter λ_1 is defined as

$$\lambda_1 = -\Lambda = \frac{f - R'}{\overline{T'}},$$

where f denotes the radiative forcing due solely to the doubling of CO_2, R' is the top of the atmosphere radiative perturbation at each grid point (defined as the equilibrium difference in the $2\times$ and $1\times$ CO_2 integrations) and $\overline{T'}$ is the global mean temperature sensitivity. Here we assume f to be a uniform 4 W m^{-2}, based on values cited by the IPCC (Ramaswamy et al., 2001). We further decompose R' into contributions from long-wave clear-sky (R_{LA}, considered to include a 4 W m^{-2} response to CO_2), short-wave clear-sky (R_{SA}), cloud long-wave (R_{LC}) and cloud short-wave (R_{SC}) perturbations. Using this decomposition, we can calculate the contribution of each radiative term to the total local feedback parameter. Following the convention of Boer and Yu (2003), we present here the 'signed' feedback parameter $\Lambda = -\lambda$ so that negative values correspond to a negative temperature feedback.

4.1. Global means

The magnitude of the total global mean feedback (Λ, Table 1, column 1) increases from -1.7 W m^{-2} C^{-1} in the standard-ECHAM4 model to -2.8 W m^{-2} C^{-1} in the hybrid-ECHAM4 model. The hybrid-ECHAM4 model value is close to the CCM3 value (-2.5 W m^{-2} K^{-1}). The slightly stronger feedback in

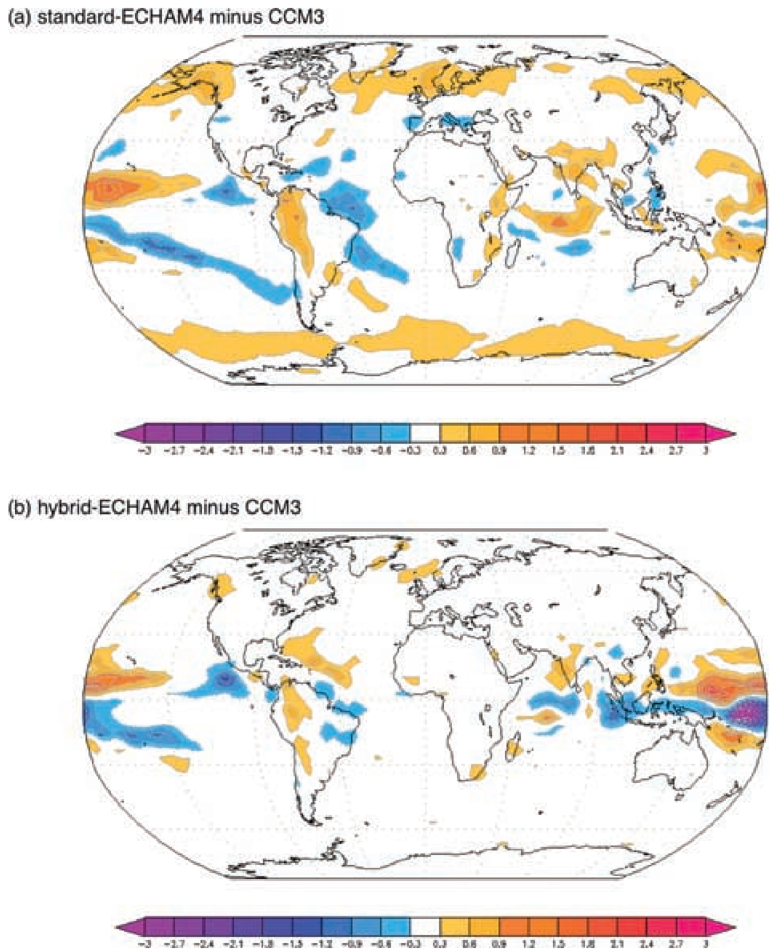

Fig. 5. Differences in regional precipitation change patterns for (a) standard-ECHAM4 and CCM3 and (b) hybrid-ECHAM4 and CCM3. Twenty-five-year annual means, units are mm d^{-1}.

Table 1. Global mean feedback values for the standard-ECHAM4 model, hybrid-ECHAM4 model and CCM3. Subscripts denote components of the total feedback term, with, C representing cloudy-sky, A clear-sky, S short-wave and L long-wave. Values are in W m^{-2} C^{-1}, with negative values denoting an increase in upward directed radiation

	Λ	ΛC	Λ_A	Λ_S	Λ_{SC}	Λ_{SA}	Λ_L	Λ_{LC}	Λ_{LA}
Standard-ECHAM4	−1.7	−0.1	−1.6	0.0	−0.6	0.6	−1.7	0.5	−2.2
Hybrid-ECHAM4	−2.8	−1.1	−1.7	−1.6	−2.1	0.5	−1.2	1.0	−2.2
CCM3	−2.5	−0.6	−1.9	−0.2	−0.4	−0.2	−2.3	−0.2	−2.1

the hybrid-ECHAM4 model is consistent with its slightly lower global mean temperature sensitivity relative to CCM3.

Decomposing the global mean feedback term into contributions from clouds (Λ_C column 2) and clear-sky (Λ_A column 3), we find that the total cloud feedback in the standard-ECHAM4 model is nearly zero (−0.1 W m^{-2} C^{-1}), much weaker in magnitude than either the hybrid-ECHAM4 model (−1.1 W m^{-2} C^{-1}) or CCM3 (−0.6 W m^{-2} C^{-1}). The magnitudes of the clear-sky terms are relatively similar across the three models. Thus, it appears that the greater magnitudes of the global mean feedback in the hybrid-ECHAM4 model and CCM3 are due primarily to the cloud feedbacks. Considering the individual feedback terms (columns 4–9), we find that the greatest difference between the standard-ECHAM4 and hybrid-ECHAM4 models lies in the cloud short-wave feedback (Λ_{SC}; −0.6 W m^{-2} C^{-1} versus −2.1 W m^{-2} C^{-1}). This indicates that changes in the cloud radiative properties are of primary importance in creating the differences in the two models, as we might expect from the parametrizations chosen for replacement.

However, when we compare the hybrid-ECHAM4 model and CCM3, we find that there are significant differences in the partitioning amongst the individual feedback terms, despite the similarities in global mean temperature sensitivity, regional temperature change patterns and global mean total feedback. In the hybrid-ECHAM4 model the magnitude of the short-wave (Λ_S) and long-wave feedbacks (Λ_L) (columns 4 and 7, respectively) are similar, while in CCM3 the magnitude of the short-wave feedback is nearly zero and the total is dominated by the long-wave term. The CCM3 total-short-wave (Λ_S) and cloud-short-wave feedbacks (Λ_{SC}) are actually more similar to those of the standard-ECHAM4 model than those of the hybrid-ECHAM4 model. It thus appears that the large increase in the hybrid-ECHAM4 short-wave cloud feedback is compensating for differences in the cloud long-wave (Λ_{LC}, negative in CCM3) and clear-sky short-wave (Λ_{SA}) feedbacks.

Given that the hybrid-ECHAM4 model and CCM3 global mean temperature sensitivities and regional temperature change patterns are similar, these quantities must be relatively insensitive to the partitioning between the individual terms. It also indicates that the parametrizations chosen for replacement in this study do not represent a unique means of removing the difference in global mean temperature sensitivities and regional temperature change patterns between ECHAM4 and CCM3. The replacement of any suite of parametrizations resulting in a similar increase in the magnitude of the global mean total feedback parameter might produce similar results.

4.2. *Regional analysis*

The similarity of the global mean total-feedback terms appears to explain the similarity of the global mean temperature sensitivities in the hybrid-ECHAM4 model and CCM3; however it is not clear why the regional temperature change patterns are also similar. The clear-sky long-wave (Λ_{LA}) regional feedback pattern (Fig. 6)

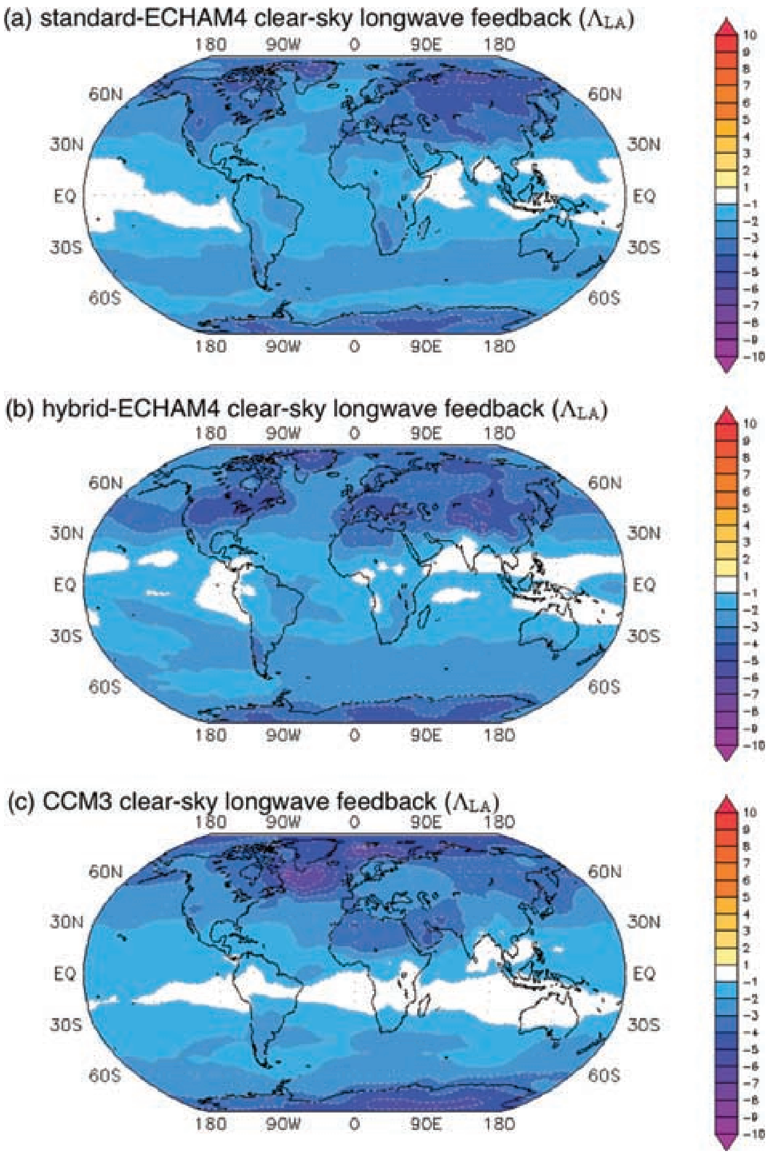

Fig. 6. Clear-sky long-wave feedback for (a) standard-ECHAM4 model, (b) hybrid-ECHAM4 model and (c) CCM3. Units are W m^{-2} per degree global mean temperature sensitivity.

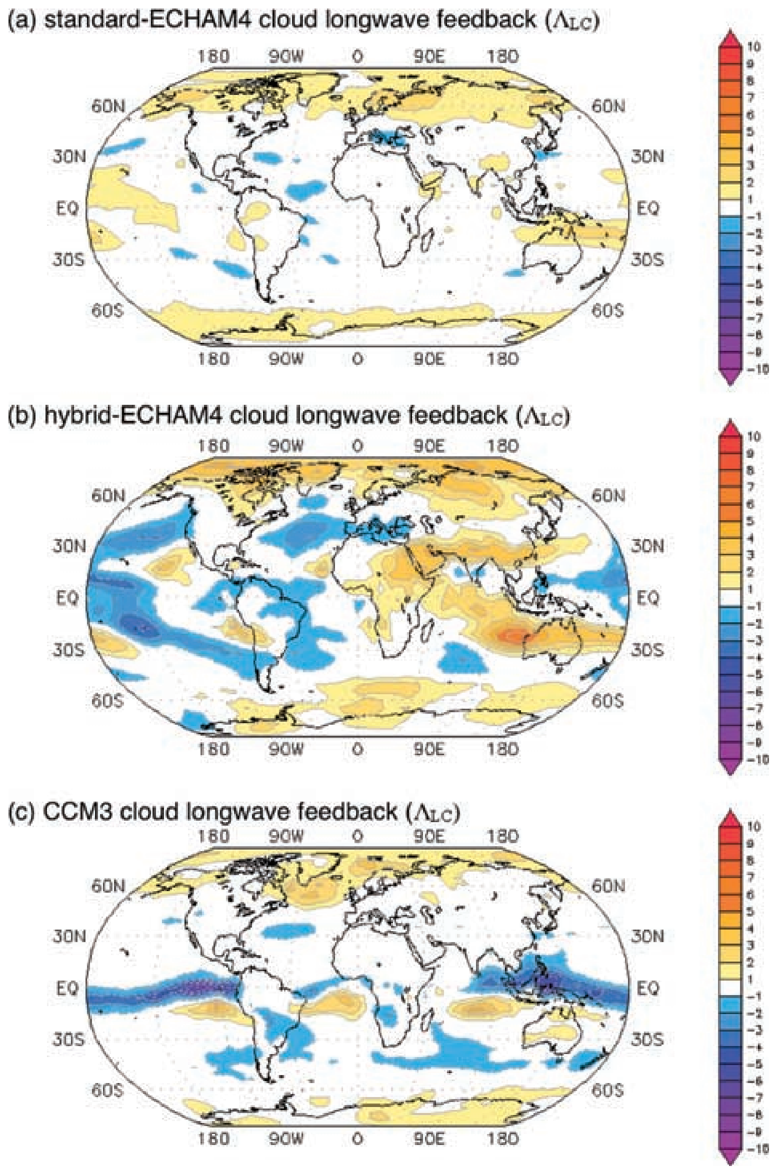

Fig. 7. Cloud long-wave feedback for (a) standard-ECHAM4 model, (b) hybrid-ECHAM4 model and (c) CCM3. Units are W m^{-2} per degree global mean temperature sensitivity.

is dominated by the direct response to the CO_2 radiative forcing and changes in the surface temperature (compare to Figs 3 and 4). All three models have their largest amplitudes at high-latitudes. However, the standard-ECHAM4 model (Fig. 6a) and the hybrid-ECHAM4 model (Fig. 6b) have their highest values over land, while in CCM3 (Fig. 6c) the highest values are over the North Atlantic. All values are negative, reflecting the direct response to increasing CO_2 and surface temperature. Thus, this term appears to be a response to differences in regional temperature change between the different models, rather than a cause.

In contrast to the clear-sky long-wave feedback terms, the cloud long-wave feedback terms in the standard-ECHAM4 (Fig. 7a) and hybrid-ECHAM4 (Fig. 7b) models are positive over the high-latitude landmasses. Likewise, there is a prominent centre of positive feedback in CCM3 (Fig. 7c) over the North Atlantic. This distribution of sensitivity among the three models is consistent with the differences in regional temperature change and suggests a local contribution to temperature changes in these regions.

In the tropics there is less correspondence between the cloud long-wave feedback patterns and regional temperature change patterns, due to the greater impact of the other feedback terms. The regional feedback patterns are generally similar between the control- and hybrid-ECHAM4 models, except in the central Pacific, consistent with the differences in precipitation change (Fig. 3). However, the magnitude of the feedback increases significantly in the hybrid-ECHAM4 model. Although there is considerable cancellation this increase is clearly reflected in the global and zonal mean values (see Table 1 and Fig. 10). In contrast, the tropical cloud long-wave feedback in CCM3 is

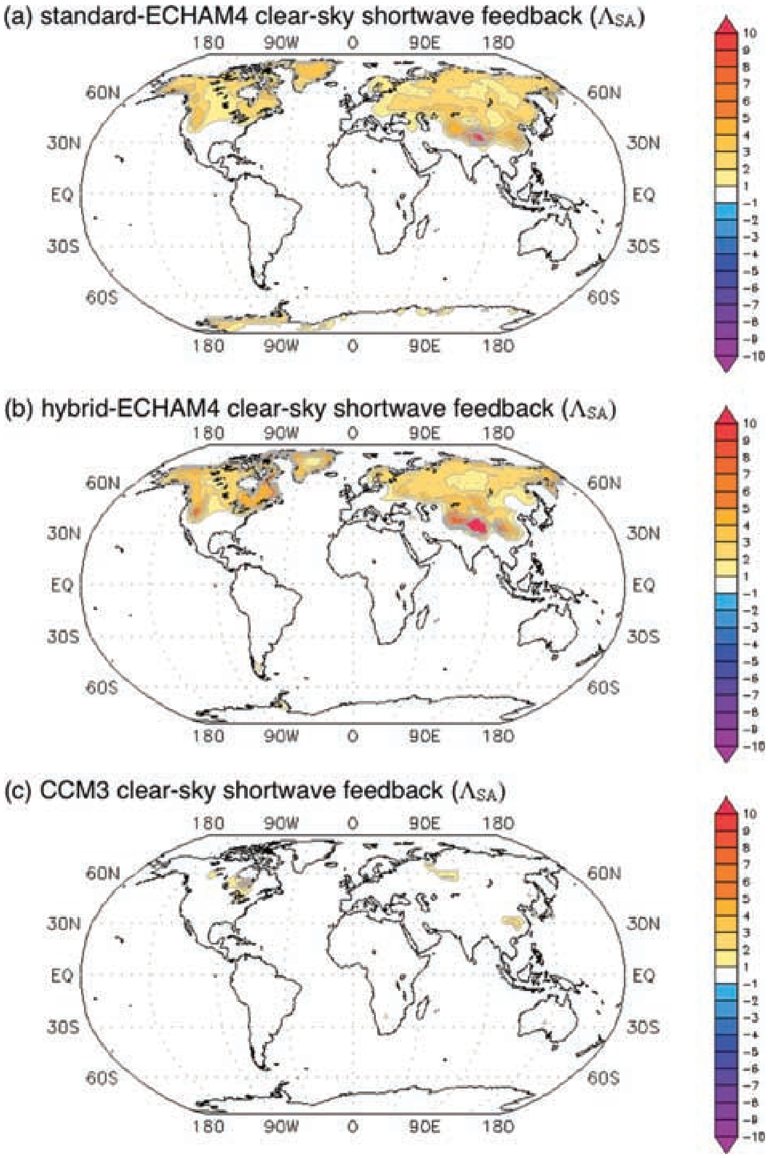

Fig. 8. Clear-sky short-wave feedback for (a) standard-ECHAM4 model, (b) hybrid-ECHAM4 model and (c) CCM3. Units are W m^{-2} per degree global mean temperature sensitivity.

dominated by a narrow region of negative values along the equator in the Pacific, with only a relatively weak compensating positive feedback in the tropics. The region of negative feedback coincides with the climatological maximum in precipitation in CCM3 (not shown).

One of the most notable differences between the ECHAM4 models and CCM3 is in the clear-sky short-wave feedback term (Fig. 8). While both the standard-ECHAM4 model (Fig. 8a) and the hybrid-ECHAM4 model (Fig. 8b) have large positive values over the NH hemisphere landmasses, there is relatively little feedback in CCM3 (Fig. 8c). This is due to a greater equatorward extent of the mean snow cover for the ECHAM4 models in the 1$\times$ CO_2 case (not shown), and a consequently greater impact on the reflected short-wave in the 2$\times$ CO_2 case as the snow retreats. However, while the clear-sky short-wave feedback is essentially identical in the standard-ECHAM4 (Fig. 8a) and the hybrid-ECHAM4 models (Fig. 8b), there are large differences in the regional temperature change patterns (Fig. 4). Thus, despite the differences in the clear-sky short-wave term between the standard-ECHAM4 and CCM3 over the NH landmasses, it cannot explain the difference in regional temperature change between the two ECHAM4 models.

The cloud short-wave feedback (Fig. 9) is negative over most of the domain in both ECHAM4 models, with the largest values concentrated in the tropics. As with the cloud long-wave term (Fig. 7), we find that the feedback in the standard-ECHAM4 model (Fig. 9a) and the hybrid-ECHAM4 model (Fig. 9b) have generally similar patterns, with positive feedbacks off the west coasts of most of the continents and near 30 °N and 30 °S. The feedback in both models is negative at most points outside

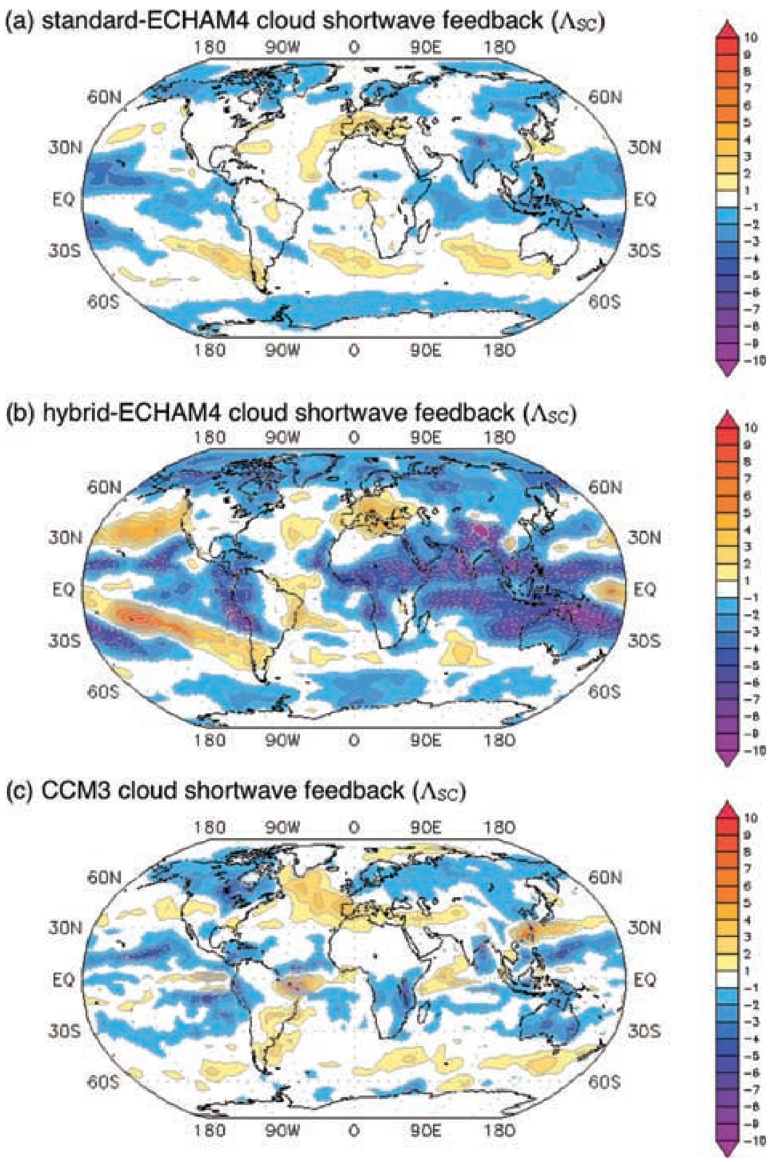

Fig. 9. Cloud short-wave feedback for (a) standard-ECHAM4 model, (b) hybrid-ECHAM4 model and (c) CCM3. Units are W m^{-2} per degree global mean temperature sensitivity.

of these regions. Although the patterns are relatively similar between the standard-ECHAM4 and hybrid-ECHAM4 models the hybrid-ECHAM4 magnitudes are almost *double* those of the standard-ECHAM4 model, highlighting the impact of the parametrization replacements. Magnitudes in the hybrid-ECHAM4 model are also larger over the land, again indicating a degree of local control over regional temperature changes. The magnitudes in the hybrid-ECHAM4 model are also much larger than those we find in CCM3 (Fig. 9c).

4.3. Discussion

The primary effect of the parametrization replacements in the hybrid-ECHAM4 model is to increase the magnitude of the negative cloud short-wave feedback relative to the standard-ECHAM4 model. While the positive cloud long-wave feedback also increases the negative cloud short-wave feedback dominates, leading to an overall reduction in global mean temperature sensitivity. The clear-sky long-wave and short-wave feedbacks are essentially unchanged in the hybrid-ECHAM4 model, suggesting that the key parametrization changes are those related to cloud radiative properties, particularly cloud liquid water path and effective droplet size distribution. While there are some changes in cloud distribution (not shown), the majority of the changes in feedback appear to be due directly to the changes in cloud properties.

Although the global mean feedback and temperature sensitivity are very similar between CCM3 and the hybrid-ECHAM4 model there are clear differences in the individual feedback terms. In CCM3 the global mean cloud long-wave feedback is negative, in contrast with both ECHAM4 models. The regional cloud long-wave feedback patterns are also different, particularly in the tropics, indicating that differences in the tropical circulation and parametrizations for cloud formation are playing an important role. Rather than moving closer to the CCM3 value the hybrid-ECHAM4 model cloud long-wave feedback is similar in pattern to the standard-ECHAM4 pattern and becomes more positive. The cloud long-wave term in the hybrid-ECHAM4 model term is actually less similar to CCM3 than in the standard-ECHAM4 model. This difference is compensated for by the increase in the magnitude of the cloud short-wave feedback term, particularly in the tropics, in the hybrid-ECHAM4 model.

There does not appear to be a close correspondence between the regional feedback (Figs 6–9) and regional temperature change (Figs 3–4) patterns. The largest differences in the feedback terms are in the tropics, while the largest changes in temperature are over the high-latitude landmasses. This is in contrast to the results of Boer and Yu (2003), which found that regional temperature change and feedback patterns were generally similar. Instead, it suggests that the changes in the tropics are strongly influencing the rest of the model domain. This is consistent with Alexeev et al. (2005), which demonstrated that the surface temperature response of an idealized 'aquaplanet' GCM to an increase in radiative forcing is sensitive to the partitioning of the forcing between the tropics and extratropics. In their model, the influence of changes in radiative forcing in the extratropical regions tends to remain confined to the extratropics while radiative forcing changes in the tropics produce a more uniform, global response.

Comparing the standard-ECHAM4 model (Fig. 10a) and hybrid-ECHAM4 (Fig. 10b) zonal mean feedbacks to CCM3, we find that the regions where the ECHAM4 feedbacks are more positive than in CCM3 are generally unchanged. The largest change in going from the standard-ECHAM4 model to the hybrid-ECHAM4 model is in the tropics, where the net effect of clouds switches from positive to negative relative to CCM3. There are also significant changes in the magnitudes of the cloud long-wave and short-wave feedback terms in the hybrid-ECHAM4 model over the northern high-latitudes, but these changes tend to cancel. The zonal-mean results thus help to confirm the impression from comparing Figs 6–9, namely that the increase in tropical cloud short-wave feedback in hybrid-ECHAM4 is primarily responsible for the similarity in global mean sensitivity and regional temperature change between CCM3 and the hybrid-ECHAM4 model.

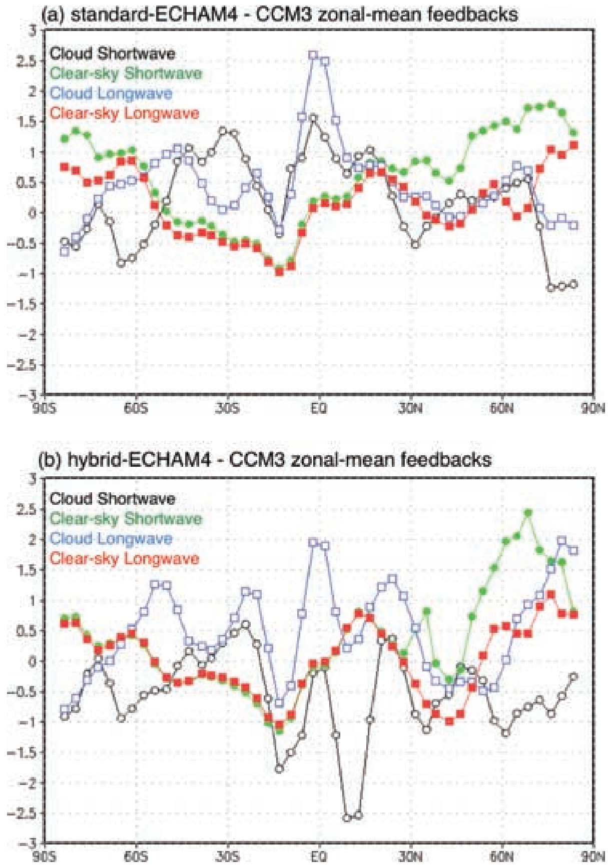

Fig. 10. Differences in zonal-mean feedback terms between (a) standard-ECHAM4 and CCM3 and (b) hybrid-ECHAM4 and CCM3. Units are W m^{-2} per degree global mean temperature sensitivity.

5. Summary and conclusions

In this study, we analyse results from a 'hybrid' version of ECHAM4. The hybrid-ECHAM4 is created by replacing the standard-ECHAM4 parametrizations for short-wave radiation, cloud liquid water path, effective droplet size and aerosols with the corresponding parametrizations from CCM3. We find that the global mean temperature sensitivity is considerably reduced in the hybrid-ECHAM4 model relative to the standard-ECHAM4 model (1.5 °C versus 2.7 °C), and is nearly identical to the CCM3 value (1.7 °C). In addition, we find that most of the differences in the regional temperature change patterns are reduced when the hybrid-ECHAM4 model is compared to CCM3 in place of the standard-ECHAM4 model.

The results of the sensitivity analysis indicate that differences in the response of ECHAM4 and CCM3 can be attributed at least in part to differences in the short-wave and associated long-wave process parametrizations. While this result is broadly supported by the feedback analysis, we find significant differences remain between the hybrid-ECHAM4 model and CCM3 in the partitioning between the cloud long-wave and short-wave feedbacks. In some ways the hybrid-ECHAM4 model behaves as though it is a third, entirely separate model, rather than as a mixture of the standard-ECHAM4 model and CCM3. The larger negative cloud short-wave feedback in the hybrid-ECHAM4 model, relative to CCM3, compensates for the stronger positive cloud long-wave and clear-sky short-wave feedbacks. The fact that the largest reduction in net downwelling radiation in the hybrid-ECHAM4 model is in the tropics reduces warming at all latitudes, consistent with Alexeev et al. (2005).

In light of the common perception that changes in cloud fraction and distribution are critical for determining climate sensitivity, it is noteworthy that parametrizations related to the generation and distribution of clouds were not modified in creating the hybrid model. The fact that these parametrizations were not changed may contribute to the differences between CCM3 and the hybrid-ECHAM4 model in the cloud-feedback partitioning. Of course, changes in one parametrization will still influence many aspects of the system through changes in the surface and TOA energy budgets. This possibility must particularly be kept in mind when interpreting the results of the feedback analysis. Changes in cloud properties and distribution may 'mask' or 'unmask' the effects of clear-sky feedbacks such as surface albedo and Planck radiation, and thus changes in cloud radiative forcing do not necessarily imply a cloud feedback (Soden et al., 2004; Soden and Held, 2006). More directly, change in the cloud liquid water path and effective droplet size calculations also produce changes in the long-wave feedback. These changes appear to be of secondary importance, however, when compared to the impact on the cloud short-wave properties. It is not yet fully understood how the changes in the short-wave processes made in the hybrid-ECHAM4 model lead to the preferential increase in reflected short-wave radiation in the tropics with increasing CO_2, or why that reduction is of the right magnitude to so closely reproduce the sensitivity of CCM3. The fact that routines governing cloud formation and distribution were not altered does seem to play a role in the differences in the regional patterns of the cloud feedbacks between ECHAM4 and CCM3, and this is a clear area of future research.

In comparing the results from the mixed-layer models considered here and the fully coupled models as considered in Cash et al. (2005), a more complete picture of the differences in climate sensitivities between ECHAM4 and CCM3 emerges. In both the mixed-layer models and the coupled models (Fig. 11) ECHAM4 tends to warm more over land and less over the North Atlantic. However, while the mixed-layer models are able to reproduce those features of the coupled run, standard-ECHAM4 warms more than CCM3 over the north Pacific and high-latitudes of North America. The mixed-layer models also do not reproduce the coupled model results in the high-latitudes of the Southern Hemisphere (likely due at least in part to the lack of sea-ice). These results are consistent with Cash et al. (2005), which found that the differences in the two coupled models in the north Pacific were forced by tropical SST changes not found in our mixed layer models, therefore involving the dynamical oceans. Similarly, Cash et al. (2005) found that large-scale circulation differences over the North Atlantic could give rise to ECHAM4′s weaker temperature increase in this region, and that these circulation differences were not due to differences in tropical SSTs but rather to internal differences in the two models. The fact that these differences persist when the AGCMs are coupled to mixed-layer oceans with no sea-ice supports the conclusion that the differences in sensitivity in the North Atlantic are due to differences in the numerical and physical parametrizations of the AGCMs, and not due to model ocean dynamics. That these differences in sensitivity persist in the hybrid-ECHAM4 model indicates that short-wave processes do not play an important role in producing the differences in the two models in this region and are therefore due to other parametrizations.

It is hoped that by reducing the possible causes of sensitivity differences between the two models to a relatively small number of specific parametrizations that the accuracy of both models in representing the climate system may be improved. The way in which each model represents cloud optical properties and cloud-short-wave interactions must be carefully compared with

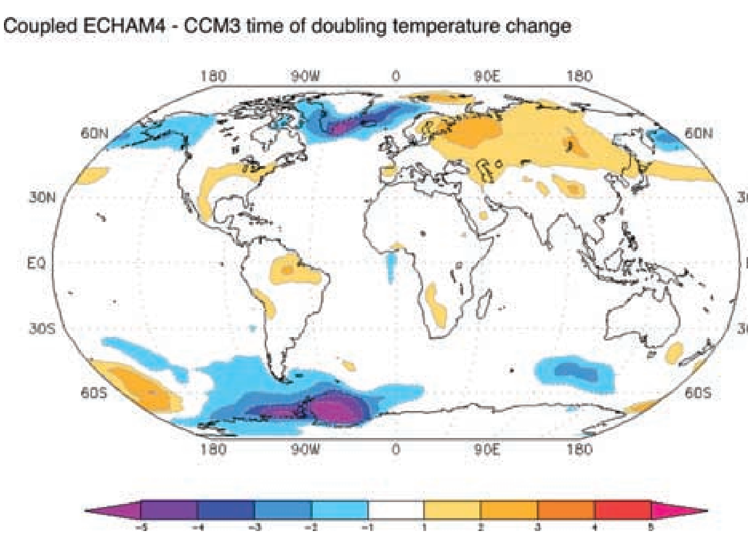

Fig. 11. Differences in regional temperature change patterns from ECHAM4+OPYC and NCAR–CSM transient coupled simulation. Twenty-year annual means taken around time of doubling, units are °C. Adapted from Cash et al. (2005), Fig. 1.

observations. If one parametrization scheme is a demonstrably better representation of the behaviour of the real atmosphere, then it suggests that model's representation of the climate system's response to increasing greenhouse gases is more likely to reflect the behaviour of the real system. If neither parametrization is demonstrably better, then the climate sensitivity of each model should be considered equally plausible.

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References

Andronova, N. and Schlesinger, M. E. 2001. Objective estimation of the probability distribution for climate sensitivity. *J. Geophys. Res.* **106**(D19), 22 605–22 612.

Alexeev, V. A., Langen, P. L. and Bates, J. R. 2005. Polar amplification of surface warming on an aquaplanet in "ghost forcing" experiments without sea ice feedbacks. *Clim. Dyn.* **24**, 655–666.

Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A. and co-authors. 2001. Projections of future climate change.In: *Climate Change 2001. The Scientific Basis*. (eds J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and co-editors). Cambridge University Press, Cambridge, 525–582.

Boer, G. J. and Yu, B. 2003. Climate sensitivity and response. *Clim. Dyn.* **20**, 415–429.

Bony, S. and Dufresne, J.-L. 2005. Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.*, doi:10.1029/2005GL023851.

Brieglieb, B. P. 1992. Delta-Eddington approximation for solar radiation in the NCAR Community Climate Model. *J. Geophys. Res.* **97**, 7603–7612.

Cash, Benjamin A., Schneider, Edwin K. and Bengtsson, Lennart 2005. Origin of regional climate differences: Role of boundary conditions and model formulation in two GCMs. *Clim. Dyn.* **25**, 709–723, doi:10.1007/s00382-005-0069-5.

Cess, R. D., Potter, G. L., Blanchet, J. P., Boer, G. J., Ghan, S. J. and co-authors. 1990. Intercomparison and interpretation of climate feedback processes in nineteen atmospheric general circulation models. *J. Geophys. Res.* **95**, 16 601–16 615.

Cess, R. D., Potter, G. L., Zhang, M. H., Blanchet, J. P., Chalita, S. and co-authors. 1991. Intercomparison of snow-climate feedback as produced by 17 general circulation models. *Science* **253**, 888–892.

Cess, R. D., Zhang, M. H., Ingram, W. J., Potter, G. L., Alekssev, V. and co-authors. 1996. Cloud feedback in atmospheric general circulation models: an update. *J. Geophys. Res.* **101**, 12 791–12 794.

Colman, R. A. 2003. A comparison of climate feedbacks in General Circulation Models. *Clim. Dyn.* **20**, 865–873.

Colman, R. A. and McAvaney, B. J. 1995. Sensitivity of the climate response of an atmospheric general circulation model to changes in the convective parameterization and horizontal resolution. *J. Geophys. Res.* **100**, 3155–3172.

Colman, R. A., McAvaney, B. J., Fraser, J. R., Rikus, L. J. and Dahni, R. R. 1994. Snow and cloud feedbacks modeled by an atmospheric general circulation model. *Clim. Dyn.* **9**, 253–265.

Covey, C., AchutaRao, K. M., Cubasch, U., Jones, P., Lambert, S. J. and co-authors. 2003. An overview of results from the Coupled Model Intercomparison Project. *Global Planet. Change* **37**, 103–133.

Dickinson, R. E. 1986. How will climate change? *The Greenhouse Effect, Climate Change and Ecosystems*. (eds B. Bolin, B. R. Doos, J. Jager and R. A. Warrick), SCOPE 29, Wiley, Chichester, 206–270.

Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R. and Webster, M. D. 2002. Quantifying uncertainties in the climate system properties with the use of recent climate observations. *Science* **295**, 113–117.

Fouquart, Y. and Bonnel, B. 1980. Computations of solar heating of the Earth's atmosphere: A new parameterization. *Beitr. Phys. Atmos.* **53**, 35–62.

Gates, W. L., Mitchell, J. F. B., Boer, G. J., Cubasch, U. and Meleshko, V. P. 1992. Climate modeling, climate prediction and model validation. In: *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*. (eds J. T. Houghton, B. A. Callander and S. K. Varney). Cambridge University Press, Cambridge, 97–134.

Gregory, J. M., Stouffer, R. J., Raper, S. C. B., Stott, P. A. and Rayner, N. A. 2002. An observationally based estimate of the climate sensitivity. *J. Climate* **15**(22), 3117–3121.

Harvey, L. D. D. and Kaufman, R. K. 2002. Simultaneously constraining climate sensitivity and aerosol radiative forcing. *J. Climate* **15**(20), 2837–2861.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G. A., Mitchell, J. F. B. and co-authors. 1995. Climate models—projections of future climate. In: *Climate Change 1995. The Science of Climate Change*. (eds J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell). Cambridge University Press, Cambridge, 285–357.

Kiehl, J. T., Hack, J. J., Bonan, G. B., Boville, B. B., Briegleb, B. P. and co-authors. 1996. Description of the NCAR Community Climate Model (CCM3). *NCAR Technical Note*. NCAR/**TN-420+STR**, Boulder, Colorado.

Knutti, R., Stocker, T. F., Joos, F. and Plattner, G. K. 2002. Constraints on radiative forcing and future climate change from observations and climate model ensembles. *Nature* **416**, 719–723.

Koepke, P., Hess, M., Schult, I. and Shettle, E. P. 1997. *Global Aerosol Data Set*, Report No. 243, Max-Planck-Institut für Meteorologie, Hamburg, ISSN 0937-1060.

Meehl, G. A., Boer, G. J., Covey, C., Latif, M. and Stouffer, R. J. 2000. The Coupled Model Intercomparison Project (CMIP). *Bull. Amer. Met. Soc.* **81**, 313–318.

Mitchell, J. F. B., Manabe, S., Tokioka, T. and Meleshko, V. 1990. Equilibrium climate change. *Climate Change*: *The IPCC Scientific Assessment*. (eds J. T. Houghton, G. J. Jenkins and J. J. Ephraums). Cambridge University Press, Cambridge, 131–172.

Murphy, J., Sexton, D. M., Barnett, D. N., Jones, G. S., Webb, M. J. and co-authors 2004. Quantification of modeling uncertainties in a large ensemble of climate change simulations. *Nature* **430,** 768–772.

Räisänen, J. 2001. CO_2-induced climate change in CMIP2 experiments: quantification of agreement and role of internal variability. *J. Climate* **14**, 2088–2104.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J. and co-authors. 2001. Radiative forcing of climate change. In: *Climate Change 2001. The Scientific Basis*. (eds J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and co-editors). Cambridge University Press, Cambridge, 349–416.

Randall, D. A., Cess, R. D., Blanchet, J. P., Chalita, S., Colman, R. and co-authors. 1994. Analysis of snow feedbacks in fourteen general circulation models. *J. Geophys. Res.* **99**, 20 757–20 771.

Rockel, B., Raschke, E. and Weyres, B. 1991. A parameterization of broad band radiative transfer properties of water, ice, and mixed clouds. *Beitr. Physik Atmos.* **64**, 1–12.

Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M. and co-authors. 1996. The atmospheric general circulation model ECHAM-4: model description and simulation of present-day climate. *Max Planck Institute for Meteorology Rep.* **218**, Hamburg, Germany, 90.

Rotstayn, L. D. 1999. Climate sensitivity of the CSIRO GCM: Effect of cloud modeling assumptions. *J. Climate* **12**, 334–356.

Schneider, E. K., Kirtman, B. P. and Lindzen, R. S. 1999. Upper tropospheric water vapor and climate sensitivity. *J. Atmos. Sci.* **56**, 1649–1658.

Schneider, E. K. 2002. The causes of differences between equatorial Pacific SST simulations of two coupled ocean-atmosphere general circulation models. *J. Climate* **15**, 449–469.

Senior, C. A. and Mitchell, J. F. B. 1993. Carbon dioxide and climate: the impact of cloud parameterization. *J. Climate* **6**, 393–418.

Slingo, A. 1989. A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci.* **46**, 1419–1427.

Soden, B. J., Broccoli, A. J. and Hemler, R. S. 2004. On the use of cloud forcing to estimate feedback. *J. Climate* **17**, 3661–3665.

Soden, B. J. and Held, I. M. 2006. An assessment of climate feedbacks in coupled ocean-atmosphere models. *J. Climate* **19**, 3354–3360.

U. S. National Academy of Sciences 1979. Carbon Dioxide and Climate: A Scientific Assessment. National Academy of Sciences, Washington, 22.

Tsushima, Y., Abe-Ouchi, A. and Manabe, S. 2005. Radiative damping of annual variation in global mean surface temperature: comparison between observed and simulated feedback. *Clim. Dyn.*. doi:10.1007/s00382-005-0002-y.

Webb, M. J. and co-authors. 2006. On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles. *Clim. Dyn.*. doi:10.1007/s00382-006-0111-2.

Yao, M.-S. and Del Genio, A. D. 1999. Effect of cloud parameterization on the simulation of climate change in the GISS GCM. *J. Climate* **12**, 761–779.

Zhang, M. H., Hack, J. J., Kiehl, J. T. and Cess, R. D. 1994. Diagnostic study of climate feedback processes in atmospheric general circulation models. *J. Geophys. Res.* **99**, 5525–5537.