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Uncertainties linked to land-surface processes in climate change simulations

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Abstract The impact of climate change on the hydrology of continental surfaces is critical for human activities but the response of the surface to this perturbation may also affect the sensitivity of the climate. This complex feedback is simulated in general circulation models (GCMs) used for climate change predictions by their land-surface schemes. The present study attempts to quantify the uncertainty associated with these schemes and what impact it has on our confidence in the simulated climate anomalies. Four GCMs, each coupled to two different land-surface schemes, are used to explore the spectrum of uncertainties. It is shown that, in this sample, surface processes have a significant contribution to our ability to predict surface temperature changes and perturbations of the hydrological cycle in an environment with doubled greenhouse gas concentration. The results reveal that the uncertainty introduced by land-surface processes in the simulated climate is different from its impact on the sensitivity of GCMs to climate change, indeed an alteration of the surface parametrization with little impact on model climate can affect sensitivity significantly. This result leads us to believe that the validation of land-surface schemes should not be limited to the current climate but should also cover their sensitivity to variations in climatic forcing.

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1 Introduction

Climate change predictions are more valuable for impact studies if they are provided with an estimate of their error or uncertainty. Such an assessment of uncertainties has already been undertaken for atmospheric general circulation models (AGCMs) as a whole and for some individual parametrization schemes such as clouds and snow (Cess et al. 1991, 1993). Both of these are examples of processes which are involved in the primary feedback loops which determine the overall sensitivity of general circulation models, so evaluating the uncertainties in AGCMs and in these parametrizations is largely synonymous.

Human activities will suffer the greatest impact when increased greenhouse gases induce changes in surface weather or in the hydrological cycle over land as these affect vital human activities such as agriculture and water management. These variables are strongly controlled, in the general circulation models used for climate change studies, by the land-surface scheme to which the AGCM is coupled. Thus, although land-surface schemes do not play a predominant role in determining the sensitivity of climate models to increased greenhouse gases, they can be critical for the variables which are used in impact studies and which in the end affect decisions on adaptation to or mitigation of climate change. We have not included alterations to snow processes when perturbing land-surface schemes in the course of this work, because of their special role in climate sensitivity.

In this European project "Land-surface processes and climate response" an attempt is made to evaluate those uncertainties in climate change predictions which are linked to our inability to model land-surface processes accurately. In previous assessments (Houghton et al. 1996) the spread of model results in inter-comparisons done under present-day climate conditions, as obtained by PILPS or AMIP (Henderson-Sellers et al. 1996; Gates 1992; Wood et al. 1998), was taken as an indication of the large uncertainties one can expect in the sensitivity of these models. For this project, each participating group was asked to perform at least two climate change simulations which would only differ in the land-surface scheme used. This enables us to separate out the uncertainty linked to land-surface schemes from that of the atmospheric models as a whole and to compare them. This approach is needed as, in contrast to cloud or snow parametrizations, land-surface schemes are not directly implicated in the dominant feedbacks which govern the response of the atmosphere to increased greenhouse gases.

This study will identify and analyze the variables and the regions for which land-surface processes contribute significantly to the uncertainty in climate change simulations. We begin with a description of the experiments performed for the project and a brief overview of the models' performance. The statistical method which is used to quantify the uncertainty is then presented. The major regions where land-surface processes are critical for climate under doubled greenhouse gases conditions are then analyzed in detail.

2 Experimental design

Four climate modelling groups were involved in the project "Land-surface processes and climate response"; the Hadley Centre for Climate Prediction and Research (HC), the Laboratoire de Météorologie Dynamique du C.N.R.S. (LMD), the Centre National de Recherche Météorologique/Météo-France (CNRM) and the University of Reading (UR). A fifth group, the (Australian) Bureau of Meteorology Research Centre (BMRC) later carried out similar integrations which will not be presented here. Previous versions of the general circulation models used by these five modelling centers took part in the AMIP (Gates 1992) atmospheric AGCM inter-comparison project. None of these models were found to be outliers in the various analyses which were performed on the AMIP data set. One can thus consider that these four AGCMs are a representative sample of current, state-of-the-art models. For this project, modelling groups were asked to provide fixed sea surface temperature control and time-slice experiments, each 10 years in length, using one version of their atmospheric AGCM coupled to two different or modified land-surface schemes. The time-slice was defined as a doubled carbon dioxide experiment, for which the increased sea surface temperatures and modified sea ice extents were taken from part of a transient coupled experiment carried out with HadCM2 (Mitchell et al. 1995).

Each of the participating AGCMs includes a complex land-surface scheme which has participated in inter-comparison studies (Polcher et al. 1996; Henderson-Sellers et al. 1996). Probably, the best way to introduce into each AGCM the uncertainty in LSSs which was observed in PILPS (Henderson-Sellers et al. 1996) would be to exchange the land-surface schemes (LSS) between atmospheric models. At present this would be technically too difficult to achieve as none of the models include a general interface between the atmosphere and the surface (Polcher et al. 1998), which would make the land-surface schemes plug-compatible. Each participant was therefore asked to alter their surface scheme in a way which fitted with the development plans and interests of their modelling group. This had the disadvantage of leading to a predominance of hydrological changes, as described in the following paragraph. The changes made were those considered by the groups involved to be most representative of the uncertainty in the LSS. The resulting modifications ranged from altering one or more parameters, to the use of a substantially different scheme.

The most extreme change is probably the replacement of the complex root/soil moisture interaction in SECHIBA (de Rosnay and Polcher 1998) by a much simpler bucket soil hydrology (Manabe 1969), which also involves suppression of the sub-grid-scale vegetation. The first Hadley Centre integration used a scheme described in Jones et al. (1995) except that it includes a multilayer hydrology based on Van Genuchten et al. (1991). Their second experiment uses the MOSES scheme (Cox et al. 1999) which includes major improvements in the soil hydrological properties and a representation of stomatal resistance which depends on CO_2 concentration. This version also has altered soil thermodynamics, which can affect the modelled snow. In the ISBA scheme (Noilhan and Planton 1989) used at Météo-France a change to surface conductance was applied in the second $2 \times CO_2$ experiment, to investigate the effects of increased carbon dioxide on plant physiology (Douville et al. 1998). This means that for this model only one control experiment was required. The University of Reading, using the European Centre for Long-range Weather Forecasting (ECMWF) AGCM in climate mode, halved the rooting depth in the ECMWF scheme (Viterbo and Beljaars 1995) in order to investigate the role of the moisture stress of vegetation in a changed climate.

Most of the modifications (summarized in Table 1) made by the groups are centered around the interaction between surface hydrology and vegetation, which has been identified as one of the key problems today in land-surface modelling by Koster and Milly (1997). The other major uncertainty explored by these experiments is possible modification of plant functioning with increased atmospheric CO_2. Changes to the snow parametrizations in the land-surface schemes were not considered because their role in the uncertainties of climate change have already been studied (Cess et al. 1991). The alterations to LSS grew partly from long-term strategies of the participant groups rather than from specific design. In future work a more controlled attempt to sample the models' parameter space in a systematic manner would be beneficial. This would permit the full strength of statistical techniques of the "analysis of variance" (ANOVA) (Rowell 1998) to be brought to bear. It might be argued that a bucket hydrology is not a good example of current best efforts to model the interaction of the land-surface with the atmosphere. We include it in our representative sample because it is still widely used in modelling studies and to provide data for investigating the impacts of climate change. Thus we consider the land-surface changes examined in the experiments presented here to be a conservative estimate of the uncertainty in our current best efforts to model these processes.

The AGCMs were run with the same seasonally varying sea surface temperature and sea ice until the land surface reached equilibrium with the atmosphere before the 10 years of each experiment began. Temperature and sea ice changes for the greenhouse gas scenarios were taken from a transient climate change experiment performed with the Hadley Centre coupled ocean-atmosphere AGCM (Mitchell et al. 1995). Average anomalies for

Table 1 A description of the model configurations used in this project

Model	Experiment	Land-surface scheme
HC	A	Old land-surface scheme (Jones et al. 1995)
	B	The MOSES scheme (Cox et al. 1999)
LMD	A	The SECHIBA scheme (de Rosnay and Polcher 1998)
	B	A simplified hydrology
CNRM	A	The ISBA scheme (Noilhan and Planton 1989)
	B	Surface conductance was reduced
UR	A	The ECMWF scheme (Viterbo and Beljaars 1995)
	B	Rooting depth was reduced

each month were calculated from a 20 year period around the time at which CO_2 levels doubled. These were then applied to climatological monthly average values over the period 1979 to 1988 as defined for the AMIP project (Gates 1992). The sea-ice distribution provided by the Hadley Center for the doubled CO_2 could not be used as is because of deficiencies in the control climate, so the simulated shift of the 10% iso-line of sea-ice fraction was transposed to the AMIP data. This solution was chosen because the 10% iso-line in the simulated control climate was very close to present-day observations.

3 Spread in the present and future simulated climates

The upper panel in Fig. 1 shows that the ensemble of 7 control experiments has, over the continents, a cold bias in the tropics and the middle panel shows that they tend to overestimate precipitation in the mid-latitudes. These deficiencies were identified by Lau et al. (1996) in the ensemble of simulations available in AMIP I, thus although the four models used in the present study have evolved since the AMIP I experiments they still include these systematic biases. For cloud cover the deficiencies of the models are not so easily identified as the spread is very large. One must note though, that the large variance around the average could either be caused by large differences between models or the lack of a standard method for defining and inter-comparing cloud cover in AGCMs (Weare and AMIP Modeling Groups 1996). On all graphics the shaded areas are small compared to the ensemble variance, indicating that on this zonal mean diagnostic the land-surface processes changed here do not contribute significantly to the spread between the models. The largest impact of the land-surface processes can be seen at high latitudes in the Northern Hemisphere for precipitation and cloud cover.

In the left column of Fig. 2 it is interesting to note that the LMD AGCM has a consistently larger difference between its A and B experiments, particularly for precipitation and middle latitude temperature, than the other models. The choice of regions (see Fig. 3 for the boundaries) will be justified in Sects. 4 and 5, so it suffices to say that the first five (US to SE) are north of 40°N, and the remaining five are in tropical latitudes. It has been noted previously (Sato et al. 1989; Peylin et al. 1997) that changing from a simple hydrology to a more sophisticated surface scheme has a large effect on surface variables. On the other hand the change of LSS performed at the Hadley Centre and the change in rooting depth in the experiments by the University of Reading are of comparable magnitude in most regions. As both experiments performed at CNRM share the same control integration the difference between A and B experiment is always zero. For these differences in the control climates created by the change in LSS, the models had the same ranking for several other variables (not shown). A complementary comparison of the impact of LSS changes on land-surface processes is available in Gedney et al. (2000).

Turning from the control climates at $1 \times CO_2$ to the difference between $1 \times CO_2$ and $2 \times CO_2$ experiments, the right column of Fig. 2 shows the effect of land surface changes on modelled sensitivity to greenhouse forcing. The range of differences between the A and B experiments in the $2 \times CO_2 - 1 \times CO_2$ anomalies is comparable with those obtained for the control integration clearly indicating that land surface processes are affecting the models' responses to increased CO_2. It is interesting to note that for the anomalies the models cannot be ranked as easily as was the case for the impact

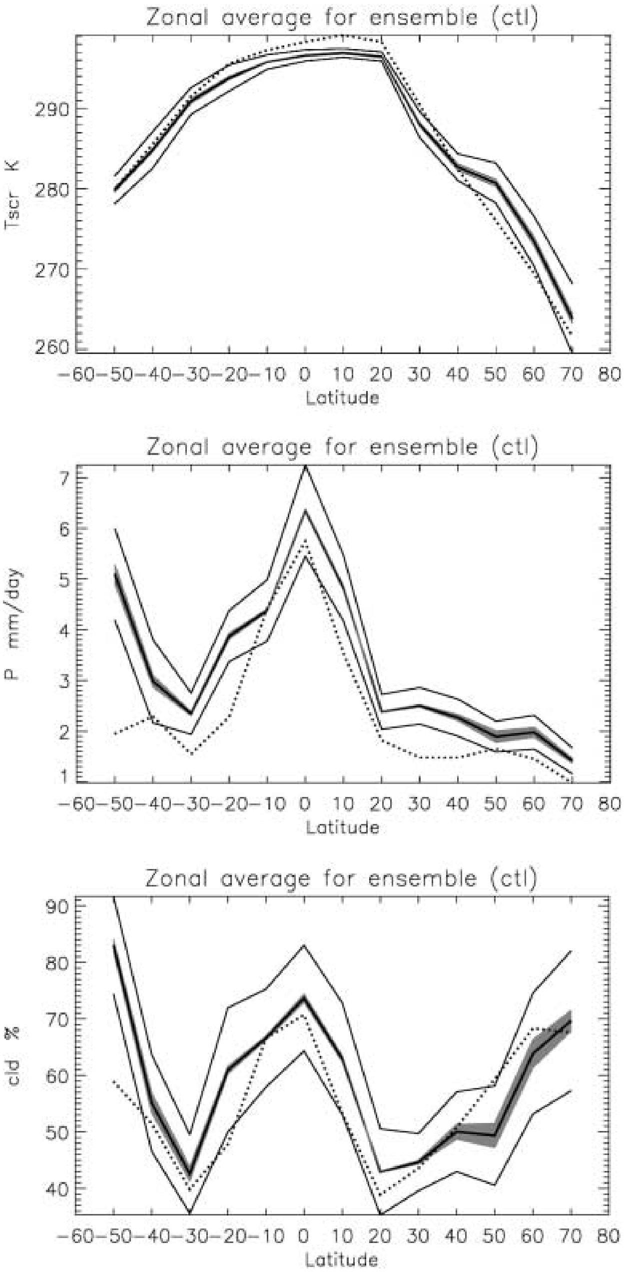


Fig. 1 Zonal and ensemble average over land for the seven control experiments of screen height temperature, precipitation and cloud cover (*bold line*). The *fainter lines* are one standard deviation on either side of the average and indicate the spread across the 10 years and the four models. The *gray shaded area* is the average of the difference between A and B experiments. The observations (New et al. 1999) are displayed with a *dotted line*

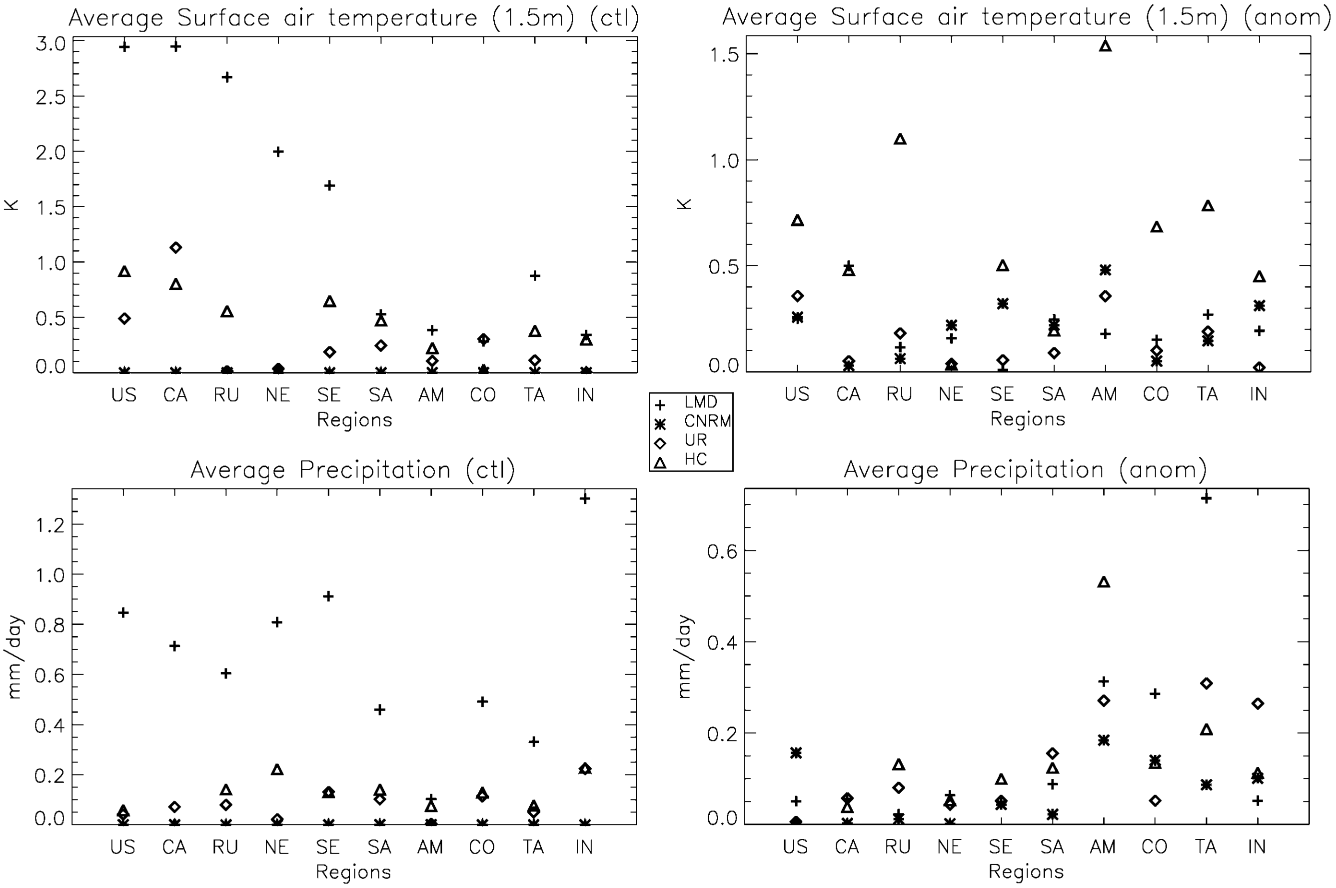
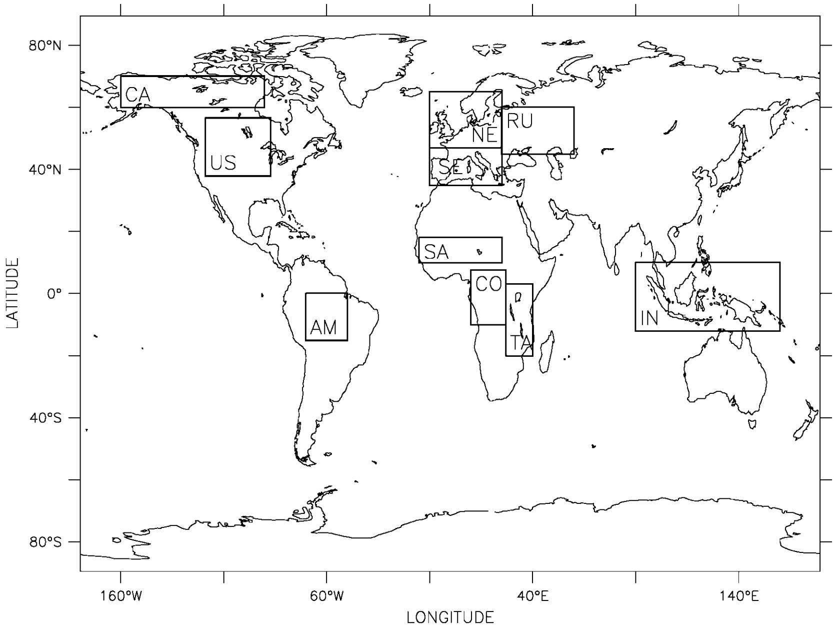


Fig. 2 Annual mean temperature (*upper left panel*) and precipitation (*lower left panel*) absolute differences between A and B experiments carried out with the same atmospheric general circulation model but different land surface schemes for the control climate. The *right column* displays the absolute anomalies of the same variables for 2 × CO_2. The regions are shown in Fig. 3

Fig. 3 Regions used for regional means: *CA* Canada and Alaska (59.9–70.1°N, 90.1–159.9°W), *US* Central North America (37.9–56.6°N, 87.1–118.9°W), *RU* Russia (44.9–60.1°N, 24.9–60.1°E), *NE* Northern Europe (47–65.1°N, 10.1°W–25.1°E), *SE* Southern Europe (34.9–47°N, 10.1°W–25.1°E), *AM* Amazon basin (15.1°S–0.1°N, 70.1–49.9°W), *SA* the Sahel (9.9–18.1°N, 15.1°W–25.1°E), *CO* Congo basin (10.1°S–7.6°N, 9.9–27.1°E), *TA* Tanzanian Plateau (20.1°S–3.1°N, 27.1–40.1°E), *IN* Indonesia, Malaysia and Northern Australia (12.1°S–10.1°N, 89.9–160.1°E)



of the land-surface changes on the control climates (Fig. 2). For surface air temperature the A and B experiments furthest apart are not those of the LMD but those of the Hadley Centre. The signal is less clear for precipitation and large regional differences exist when ordering the models' responses. For other variables the ranking lies between those for temperature and precipitation. The Hadley Centre experiments differ in all aspects of their hydrology and also in their soil thermodynamics, but in complementary experiments it was shown that the largest effect was due to the introduction of CO_2 dependent plant physiology (P. Cox personal communication). From this contrast between the LMD and Hadley Centre experiments one may conclude that an alteration at the surface which strongly affects a model's control climate may have a relatively small impact on its response to anthropogenic climate change, and conversely that an alteration with little apparent effect on the model climatology may yet significantly change its sensitivity.

Figure 4 shows annual and zonal averages of the anomalies caused by the doubling of CO_2 in the same format as Fig. 1. The average of all anomalies (bold line) can be considered as a consensus climate change here and can be evaluated using the inter-model and inter-annual variability (thin lines on either side) as a measure of the uncertainty or noise between models. The impact of land-surface schemes is also shown (gray shading). As expected all models indicate an increase in surface temperature. The spread between models is relatively small (0.75 K) south of 40°N but then increases to values of 2.5 K. This variability is a combination of the difference between AGCMs and the inter-annual variability of the models. The shaded area covers a larger part of the uncertainty interval in the climate anomalies than the control integrations, which indicates that land-surface processes may contribute significantly to the uncertainty in simulated surface temperature changes. This effect is smaller at high latitudes since the land-surface changes made in the present study did not affect the snow parametrization and the inter-annual variability of temperature change is largest.

For precipitation the spread between models is larger than the signal over most latitudes meaning that there is no consensus in the simulated zonal average precipitation change. It is again worth noting that land-surface processes are responsible for a large part of this uncertainty. In contrast to temperature the maximum of inter-ensemble variance is in the tropics with the minimum at the high latitudes. North of 50°N an increase in precipitation is a consistent signal in all experiments. All models predict a reduction in cloud cover in the tropics while in the other regions the signal does not appear to be significant. As for the two other variables the uncertainty introduced by land-surface processes is larger than for the control integrations.

The relatively small climate change signal, when compared to the variance between models, found for precipitation (Fig. 4) and evaporation (not shown) results from a combination of the differences between LSSs and between the AGCMs used (including inter-annual variability). By comparing the four pairs of experiments in which only the land-surface scheme changes with the difference between the four AGCMs where all parametrizations differ, the contribution of the land-surface processes to the noise or uncertainty in the simulated climate change can be quantified. Our approach is illustrated in Fig. 5 with the evaporation changes for two pairs of experiments. Between 30 and 90°N the GCMs give anomalies of opposite sign regardless of the land-surface scheme used. This will have a cancelling effect on the ensemble mean and contribute noise to the consensus. At these latitudes it would appear that the atmospheric AGCM chosen determines the response to the CO_2 forcing. In contrast, the tropical evaporation change is positive for one version of the land surface scheme and negative for the other version in

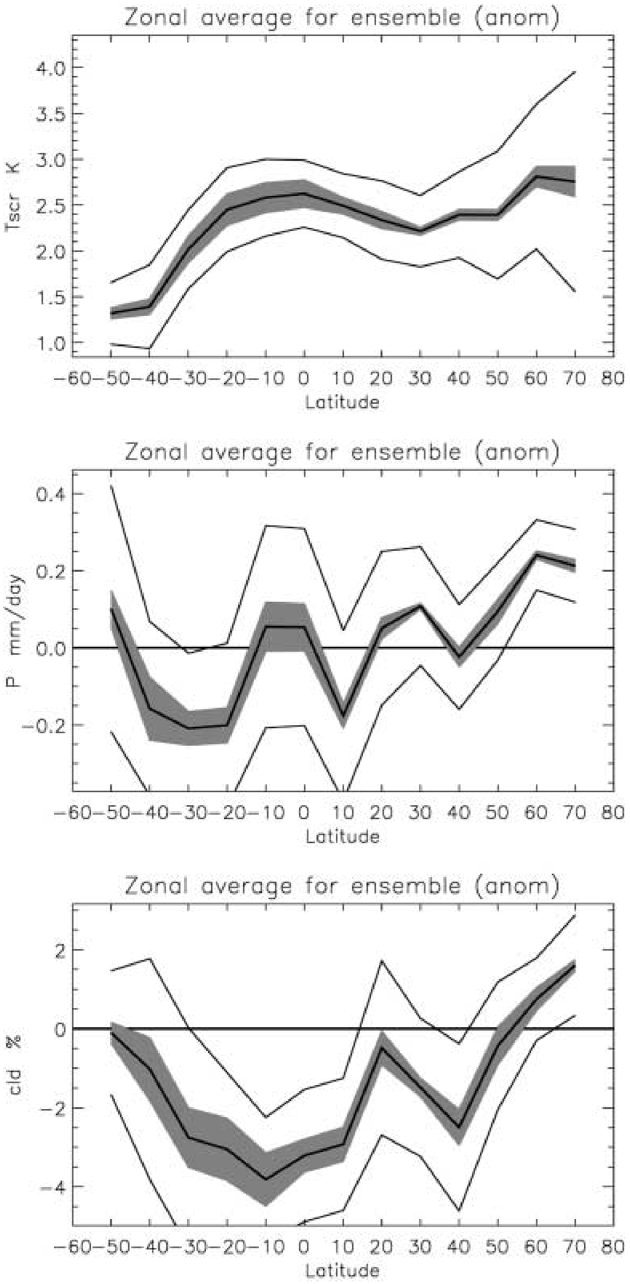
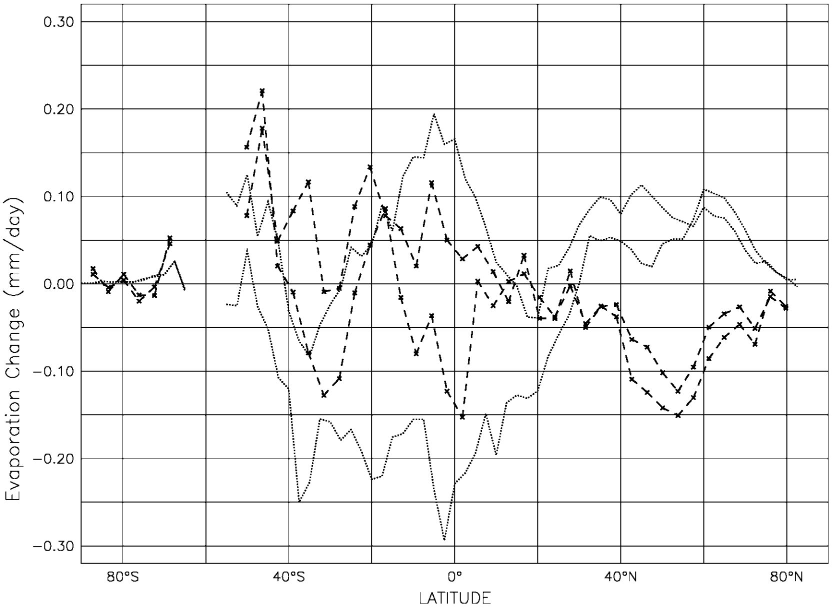


Fig. 4 As Fig. 1 but for climate anomalies obtained in 2 × CO_2 conditions

Fig. 5 Zonal average change in evaporation due to increased CO_2 for the HC simulations (*dotted line*) and the CNRM simulations (*dashed line with crosses*)



each AGCM. At these latitudes processes at the land surface dominate the uncertainty in these experiments. The picture becomes too complicated to analyze when all scenarios are represented on the same graphic, thus we need a diagnostic which quantifies and compares the uncertainty linked to land-surface schemes and the rest of the AGCM. We also need to be able to evaluate the statistical significance of results obtained with this diagnostic.

4 Methodology for evaluating uncertainties

As described in Sect. 3, these simulations show similar biases to those noted in the AMIP analysis. Since the land-surface schemes used here cover the range of complexity identified in PILPS (Henderson-Sellers et al. 1996), the simulations performed by the four models and two land-surface schemes used by each AGCM can be considered to be a representative sample of our ability to simulate the system. It is necessary to make this simplifying assumption in order to develop a quantitative measure of the uncertainty we are investigating. It could of course be argued that our results would be improved by a larger sample size (i.e., a longer time-slice) or more AGCMs/schemes.

We want to measure and compare two spreads; firstly that due to changing the land-surface scheme, and secondly that linked to the atmospheric GCM. In each case the standard deviation will be used as an estimator of uncertainty.

To measure the impact of the land surface on a given variable, $X_{i,k}$ (e.g., evaporation) of year i from the simulation of model k, the data from experiment A ($X_{i,k}$) and B ($X'_{i,k}$) are used to compute the anomalies relative to the average of the two simulations.

$$\delta_k = \overline{X_{i,k}} - \tfrac{1}{2}(\overline{X_{i,k}} + \overline{X'_{i,k}}) \tag{1}$$

$$\delta'_k = \overline{X'_{i,k}} - \tfrac{1}{2}(\overline{X_{i,k}} + \overline{X'_{i,k}}) \tag{2}$$

The over-bars indicate a time average. δ_k and δ'_k are of equal magnitude and give the time averaged distance between the A and B simulations (differing only in their land-surface scheme) and the consensus for AGCM k.

The uncertainty we attribute to the atmospheric component will include not only the differences between AGCMs but also the inter-annual variability. Inherent to each AGCM experiment is a variability linked to the chaotic nature of the atmosphere and when comparing experiments this factor has to be included. (Since our experiments are with atmospheric GCMs only, the greater inter-annual variability of the coupled ocean-atmosphere system is not taken into account.) We assume that this variability contributes to the difference between atmospheric models in the same way as the design of the AGCMs. Furthermore the A experiment is taken as the reference version for each AGCM and the difference between models will be based only on these simulations. This is an arbitrary choice, and in fact the B version would be considered as standard for some models, but we have verified that it has no effect on the results by redoing the computations with the B experiments as references. If we did not limit ourselves to only one simulation from each AGCM, we would be including the effects of the land-surface schemes doubly in the measure of atmospheric GCM uncertainty described later. For each year of each simulation we compute a distance from the multi-year average of all the models:

$$\Delta_{i,k} = X_{i,k} - \tfrac{1}{5}\sum_{k=1,4}\overline{X_{i,k}}\ . \tag{3}$$

δ_k and δ'_k are the anomalies introduced by land-surface schemes around a consensus for the individual AGCM k. The $\Delta_{i,k}$ are the anomalies linked to the AGCM and its internal variability relative to a baseline established by all models. The ratio of the standard deviation for these two quantities thus provides a measure for the uncertainty introduced by altering the land-surface schemes relative to the other differences between AGCMs. We call this the land-surface process uncertainty ratio (R):

$$R = \frac{\sigma(\delta_k, \delta'_k)}{\sigma(\Delta_{i,k})} \quad \text{for } k = (1, \ldots, 4), \quad i = (1, \ldots, 10) \tag{4}$$

Values close to zero mean that land-surface processes, as modified between the A and B experiments, have not had a large impact on the modelled climate, while larger values, e.g., close to unity, indicate that on the contrary our ability to model surface processes is just as critical as our ability to model all the other components of the AGCM combined, including inter-annual variability. When land-surface processes dominate the uncertainty R will be larger than one.

This ratio is a very abstract measure of the uncertainty and a statistical test is needed to evaluate its significance. We have chosen the pool-permutation technique presented in Preisendorfer and Barnett (1983) and Wigley and Santer (1990) as it is distribution free and does not require any a priori knowledge of the behavior of R. The test will center around the distance between the A and B experiments for each model. Our null hypothesis is that the A and B experiments are indistinguishable from each other, and therefore that ratio R should have approximately the same value if the values of $X_{i,k}$ and $X'_{i,k}$ are mixed up (i.e., the effect of the land surface change is effectively removed). When R is not the same our alternative hypothesis is that the A and B experiments are significantly different, that the LSS change introduced has had a measurable effect. The permutations are formed by randomly constructing for each model k a large number of random pairs $Y_{i,k}$ and $Y'_{i,k}$ from the union of the A and B experiments ($X_{i,k} \cup X'_{i,k}$). These $Y_{i,k}$ and $Y'_{i,k}$ are then used to compute the R values which form the test distribution for R. Thus, as an example, a permutation could consist of a $Y_{i,k}$ formed from four years of $X_{i,k}$ (the actual A experiment) and six years from $X'_{i,k}$ (the B experiment). The corresponding $Y'_{i,k}$ for this permutation would then be the remaining six years from $X_{i,k}$ and four from $X'_{i,k}$. Here we have used 500 permutations to form the test distribution, although the significance levels are generally not affected by the number of permutations where n is greater than about 200. The significance is then determined by ranking the value of the ratio obtained for $X_{i,k}$ and $X'_{i,k}$ within the distribution. Where the actual ratio R is larger than 90% or 95% of the values in the test distribution, we conclude that its value is significant at those % levels.

This method will be applied to the effect of land-surface changes on the control experiments as well as to that on the anomalies due to increased greenhouse gases obtained with the models.

5 The uncertainty introduced by land-surface schemes

In this section an attempt will be made to quantify the contribution of land-surface processes to the uncertainties in climate change prediction which were identified in Sect. 3 using the methodology described in the previous section.

5.1 Zonal average sensitivity to land surface processes

The upper panel of Fig. 6 shows ratio R (Eq. 4) calculated for the zonal and annual average control climates of the ensemble of seven experiments. Evaporation is the variable most sensitive to the land-surface changes, which is expected since this variable is the most directly affected when LSSs are modified. For evaporation, the values of R are all greater than 0.3 and are significant at the 95% level. The other variables have smaller values of the ratio, generally lying between 0 and 0.5, but most are statistically significant. Geographically, the effect of surface processes is more strongly felt at mid- to high-latitudes than in the tropics for all the hydrological variables shown, but not for temperature. The high values obtained for precipitation for regions north of 40°N can be attributed to the importance of water recycling and thus evaporation there (Mintz 1984). Temperature is more sensitive to land-surface changes in the tropics than elsewhere, because at these latitudes evaporation controls the surface temperature to a large extent, though this behavior could change if the LSS alterations took the model to a very different area of parameter space.

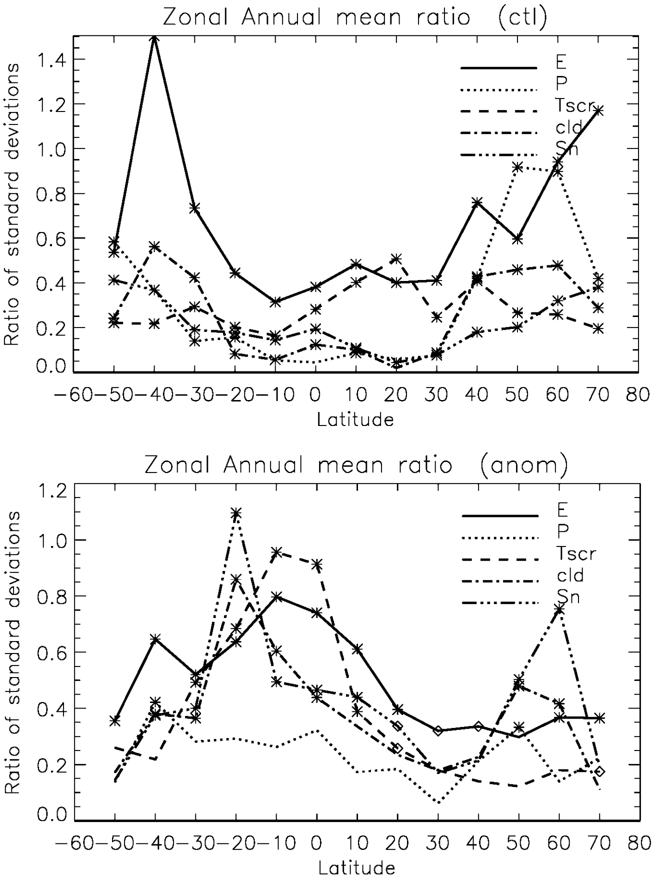


Fig. 6 Uncertainty ratio R (Eq. 4) for 10° latitude bands; the *upper figure* is for the control simulations and the lower is for the difference between control and doubled greenhouse gas simulations. E is evaporation, P is precipitation, *Tscr* is screen temperature, *cld* is percentage cloud cover and *Sn* is net short-wave radiation at the surface. The ratio is dimensionless. An *asterisk* means the value is statistically significant at 95% and a *diamond* at 90%

The curve for evaporation in the lower panel of Fig. 6 displays the same information as Fig. 5 but for all four models. The high values of R in the tropics indicate that the uncertainty in evaporation changes predicted for a 2 × CO_2 climate is largely determined by the LSS. While the low values of R at the high latitudes confirm that the AGCM is dominating the uncertainty.

In Fig. 6 the lower panel shows that generally the ratio is larger for the CO_2 doubling anomalies than for the control experiments. This confirms and quantifies the finding of Sect. 3 that the uncertainty induced by land-surface processes is larger for climate sensitivity than for present day simulations. This has implications for validation strategies in the development of land surface schemes. Use of historical forcing, paleoclimate scenarios or "test" perturbations of the model climate to test the realism of a model's sensitivity may be necessary in addition to straightforward comparisons of control simulations with observations. This is already carried out for the climate system as a whole to some extent through comparisons between models. This extension of validation to include sensitivity is likely also to be relevant for other parametrization schemes within GCMs.

The geographical patterns of the uncertainty are also different for the control and for the anomalies. For instance, the peak impact on the anomalies is in the tropics, from 30°S to 10°N. There is still some evidence of sensitivity to surface processes at mid- to high-latitudes, but this is a lesser effect. Another difference is that *R* is larger for the $2 \times CO_2$ anomalies, although fewer of the values are statistically significant than is the case for the control integrations. Noticeably precipitation is rarely significant so either the land surface processes are having little impact on this variable, or the effect they do have is obscured by noise. Thus longer experiments or more models would be needed to test these results. Evaporation and screen temperature have peaks at the same latitude (between 10°S and the equator) which suggests a feedback link in the response of these variables to the land surface changes and to climate change. This feedback has been noted in several tropical regions (see Sect. 5.2). Noteworthy is the peak in the uncertainty induced by LSSs in the cloudiness response at 20° South and between 50° and 65° North. This confirms the feedback between soil moisture (evaporation) and clouds identified by Meehl and Washington (1988) in the Northern Hemisphere and confirmed by Colman et al. (1994) for the Southern Hemisphere. This seems to be a major factor in amplifying the uncertainty introduced by LSS in climate change predictions. The apparent lack of uncertainty in surface temperature in the Northern Hemisphere is explained by the high internal variability of the AGCMs in this area, as demonstrated by the divergence of the standard deviation of temperature in the upper panel of Fig. 4.

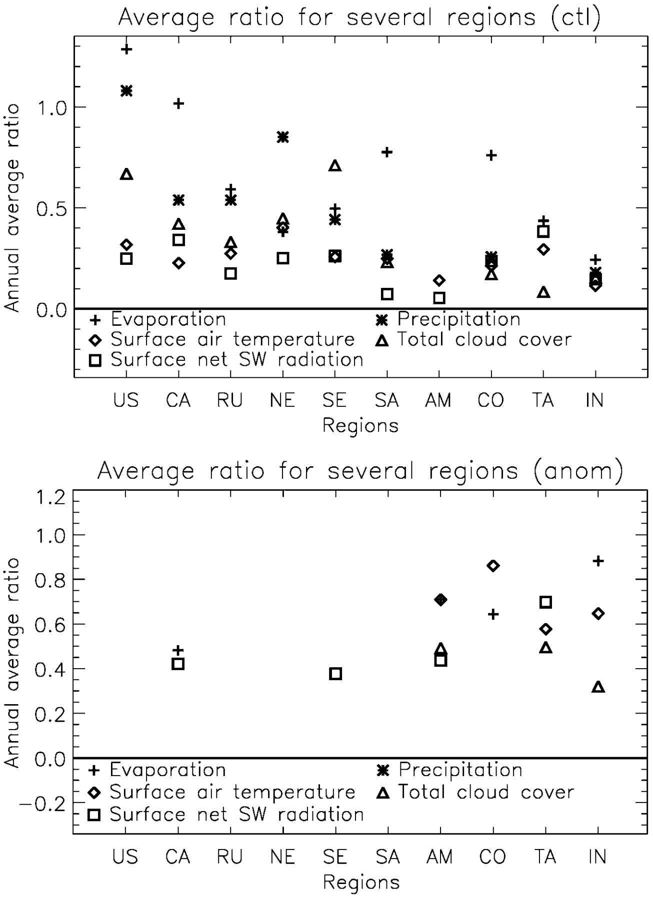


Fig. 7 Uncertainty ratio *R* for regional and annual averages in control simulations (*upper panel*) and anomalies due to greenhouse forcing (*lower panel*). Only values with a statistical significance above 90% are shown

5.2 Regional sensitivity to land-surface processes

The latitudes which appear sensitive to land surface processes in the zonal averages were chosen for closer examination by defining several regions (Fig. 3). The averages are more meaningful when computed over relatively homogeneous climate regimes and this permits uncertainties in the annual cycle to be explored. The annual mean ratios for the 10 regions in Fig. 7 support the conclusions of the analysis of zonal average values. The first five regions (all north of 40°N) have larger values of *R* in their control simulations than the five tropical and sub-tropical regions, although all have several significant values. The Amazon basin appears to be the least sensitive region to land-surface processes as far as the control climate is concerned. There are more significant points for the control climates (upper figure) than for the response to increasing greenhouse gases in the lower figure, which indicates again that the sampling of years and models is perhaps insufficient, or the statistical technique employed too simple. The most significant values of *R* for the climate anomalies are obtained in the tropics, which confirms the contrast in sensitivity between the tropical and extra-tropical regions which has already been noted in the zonal averages. The lack of significant results for the Northern Hemisphere regions may be due to the increased variability which is introduced by the smaller regions. Looking at the annual cycle of *R* will allow us to recover some signal.

The Sahel is an anomalous region as it is the only tropical area which does not show any significant value of the ratio for the sensitivity to a doubling of CO_2 (Fig. 7) while all five variables discussed here are affected by land-surface processes in the control climate. A detailed analysis shows that the response of precipitation to increased CO_2 is very different from one AGCM to the other. Some increase rainfall at the end of the rainy season while others decrease it or modify the beginning of the wet period. These responses are characteristic of the AGCMs and are only slightly affected by land-surface processes. It has an impact on all other variables in this region. In the Sahel, all the models have a rainy season which starts too early in the year but the deficiencies or differences between the models' simulated control climates are not larger than in other regions.

Thus we cannot attribute the contrasting responses to greenhouse gas forcing to differences in control climate regime. This suggests that the diversity in AGCM sensitivities we find in the Sahel is linked to the complexity of its climate and climate feedbacks, rather than to large biases in the control climates, and that the effects of altering the land-surface schemes are of secondary importance for the climate sensitivity in this region.

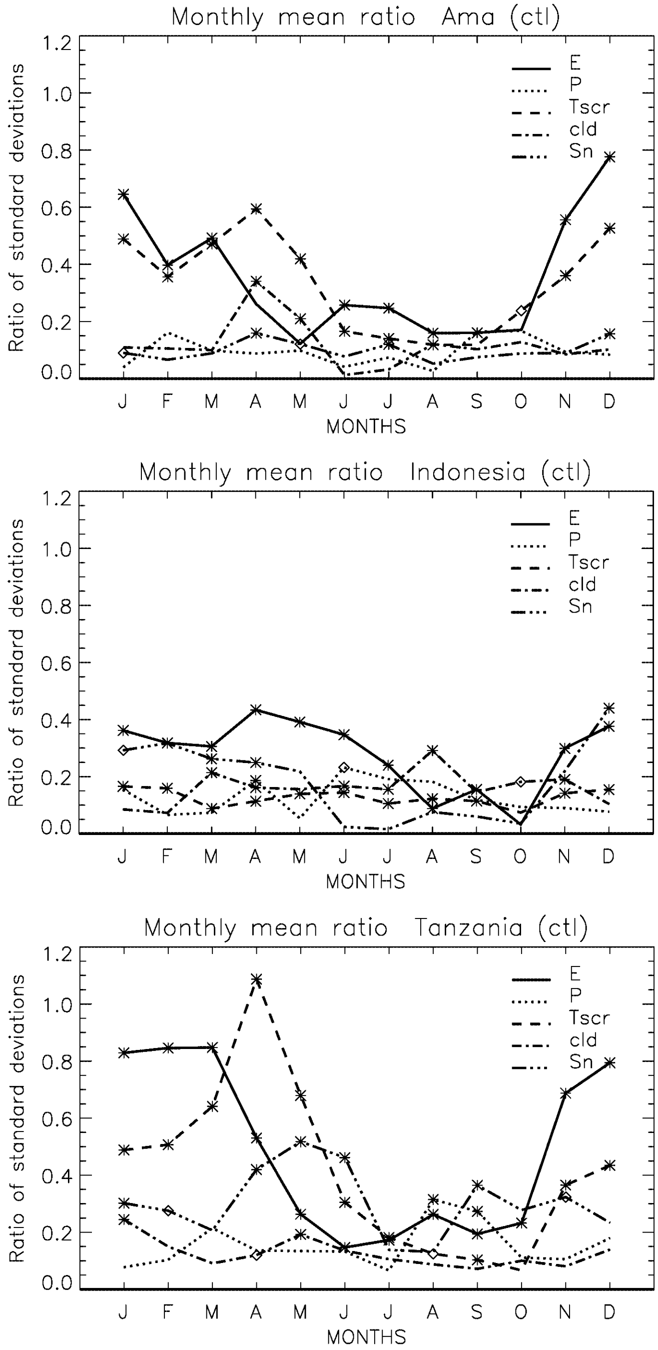


Fig. 8 Annual cycle of the uncertainty ratio *R* (as described in text) for control climates in the Amazon (*upper*), Indonesia (*middle*) and Tanzania (*lower*). The regions are shown in Fig. 3. An *asterisk* means the value is statistically significant at 95% and a *diamond* at 90%

The annual cycle of the uncertainty ratio *R* for the control climate for 2 of the 3 tropical regions (Fig. 8) shows the dominance and close correlation of evaporation and surface air temperature. These two variables are most affected by the changes in the surface schemes. The strongest signal is obtained during the rainy season which is from November to April for Tanzania and Amazonia. In Indonesia there is no marked rainy season but only a short period from July to September where precipitation falls to about 5 mm/d, which could explain the different response. Although the largest contribution to the uncertainty for temperature and evaporation is the change made in the LMD-GCM it can not be considered for the tropical regions to be an outlier for these variables as shown in Fig. 2. Precipitation is a variable where the uncertainty introduced by land-surface processes appears to be small most of the time, insignificant and constant throughout the year. When the curves for each model are examined it becomes clear that large differences are induced by the land-surface processes during the rainy season but as the variability of the GCMs is also large the signal is not picked up by the ratio *R*. In contrast, during the dry season the variability and the differences are small and it is only during two months of this season that a signal is detected in Tanzania. This shows that the measure chosen here to quantify uncertainty works as expected. Interesting behavior can be noted at the end of the rainy season in all three regions when the ratio for either cloud cover or net surface solar radiation peaks.

The graphs for the northern latitude regions (Fig. 9) clearly show that land-surface processes mainly affect, in the control climate, those variables involved in the water cycle. Large values for the uncertainty ratio are obtained during the spring and early summer for evaporation, precipitation and cloud cover. This result indicates that the soil drying phase is probably the process most affected by the changes performed in this sample of models and the associated uncertainty most affects the simulated climate at high latitudes. Local evaporation is important for the continental climate regime in these latitudes, which is governed by water recycling. Surface temperature still displays a significant uncertainty but it is smaller than for the variables mentioned. Land-surface processes do not contribute to the uncertainty during winter in Canada and the US region as the energy available at the surface is small and the climate is driven by the large-scale circulation. The situation is different in Southern Europe where the contrast between the energy available in summer and winter is not as large and thus large values of *R* are obtained for evaporation at the end of the winter. Even so, during spring, cloud cover and precipitation dominate the uncertainties as in the two other regions. Compared to the tropical regions it appears that land-surface processes are more critical in the high latitudes for the variables chosen here. This does not necessarily mean that climate is more sensitive to surface processes in the high latitudes as here the impact of LSS changes is compared to our ability to simulate

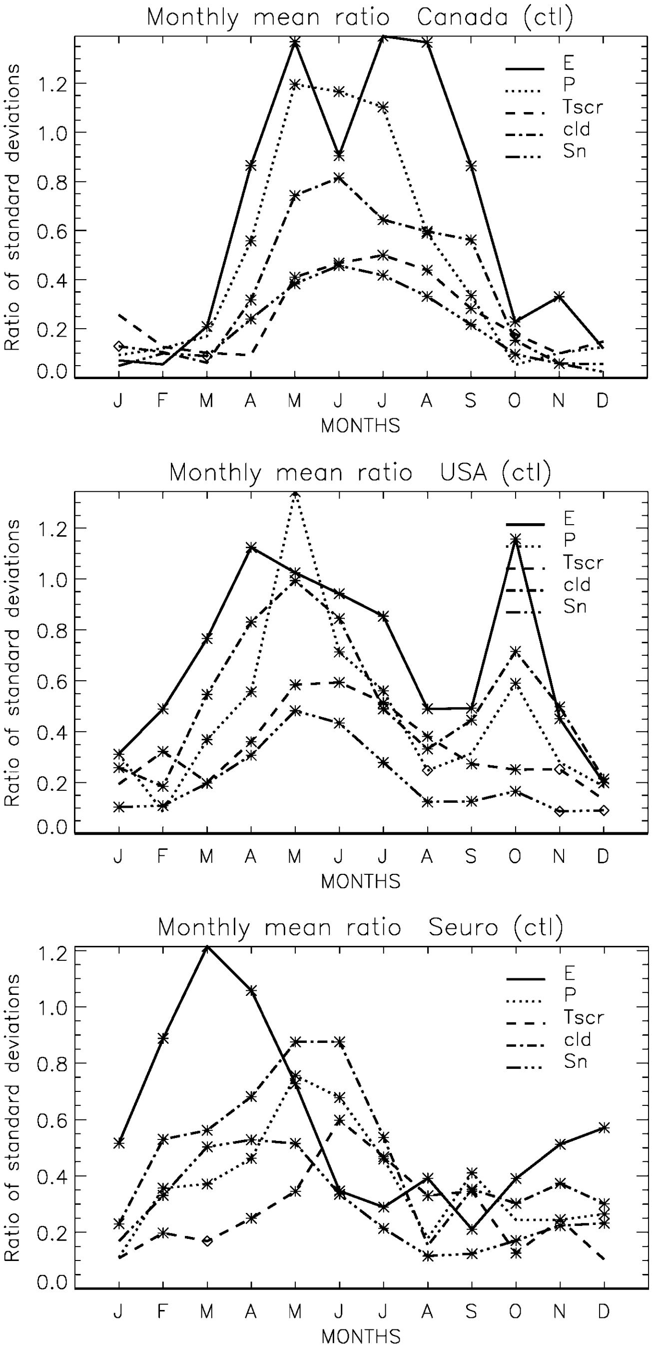


Fig. 9 As Fig. 8 but for the Canadian, Central North American and South European regions

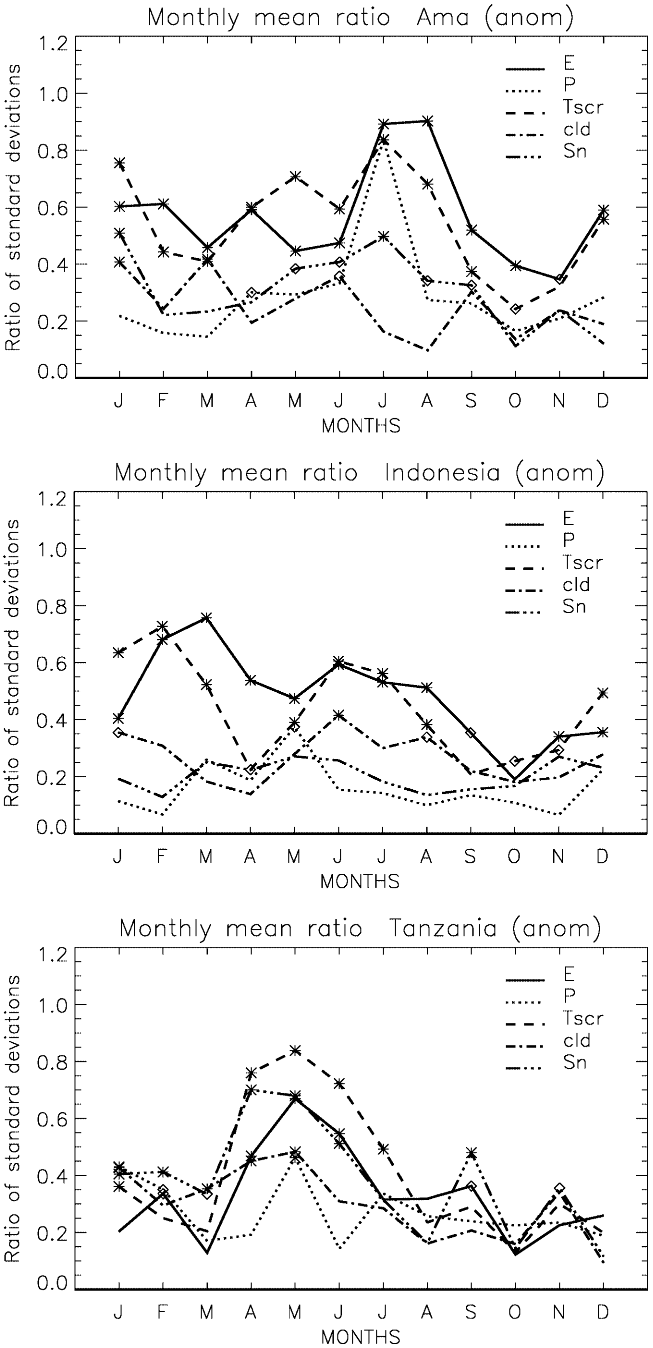


Fig. 10 The annual cycle of the uncertainty ratio *R* for sensitivity to increased greenhouse gas forcing for Amazon (*upper*), Indonesia (*middle*) and Tanzania (*lower*). An *asterisk* means the value is statistically significant at 95% and a *diamond* at 90%

the climate, as evaluated with this ensemble of four models, and not to a reference simulation. This result might thus only be a reflection of a better agreement between AGCMs in the high latitudes.

The uncertainty introduced by LSSs into the response of the climate to doubling CO_2 in tropical regions (Fig. 10) is larger than for the control climate and it also occurs at a different time in the annual cycle (Fig. 8). The variables which are most affected are in both cases evaporation and surface temperature. The covariance is relatively high for both variables and suggests a dominance in the uncertainty of the temperature change associated to evaporation changes. This result is consistent with the peak for these variables in the zonal means (Fig. 6). Major differences exist in the annual cycle of the ratio for the control climate and for doubled CO_2 anomalies. The uncertainty maximum cannot be placed as easily within the annual cycle for the climate changes as for the control runs. Large values of *R* are obtained during the entire dry season for Amazonia, whereas for Tanzania they occur at the end of the rainy season. In both regions these times also correspond to maximum values of uncertainty in cloud cover and net solar radiation at the surface. This effect is more marked in Tanzania. Because of a lack of marked annual cycle over Indonesia the evolution of the uncertainty cannot be placed in a climatological context but it can still be noted that evaporation and air temperature are dominant at the same times. In Amazonia there is agreement between the models in predicting a reduction in precipitation of about 2 mm/d, but with a large inter-annual variability, while in Tanzania there is no consensus between models. The largest values of the uncertainty ratio are thus associated with relatively small absolute changes in meteorological variables, mostly during the dry season, and not with the large but highly variable climate anomalies in the rainy season. This leads us to conclude that the GCMs' wet season response to greenhouse forcing depends more on their ability to simulate the characteristics of these regional climates than on their land-surface schemes.

As noted previously the uncertainty for climate anomalies in the high latitudes is smaller than for the control simulations. In the three regions depicted in Fig. 11 the seasonally varying signal is also much smaller. Evaporation again is the variable with the highest values but it is only during the summer that statistically significant values are reached. The region in which the importance of land-surface processes during the summer is most visible is Southern Europe. During that time significant values for the cloud cover uncertainty are also found, indicating that this ensemble of models presents the mechanisms proposed by Meehl and Washington (1988). In all three regions the uncertainty in the surface temperature change is small and only rarely significant. Over the Canadian region net solar radiation is affected by the land-surface changes but this is probably caused by the introduction of soil-freezing in the Hadley Centre B experiment as none of the groups modified their snow scheme.

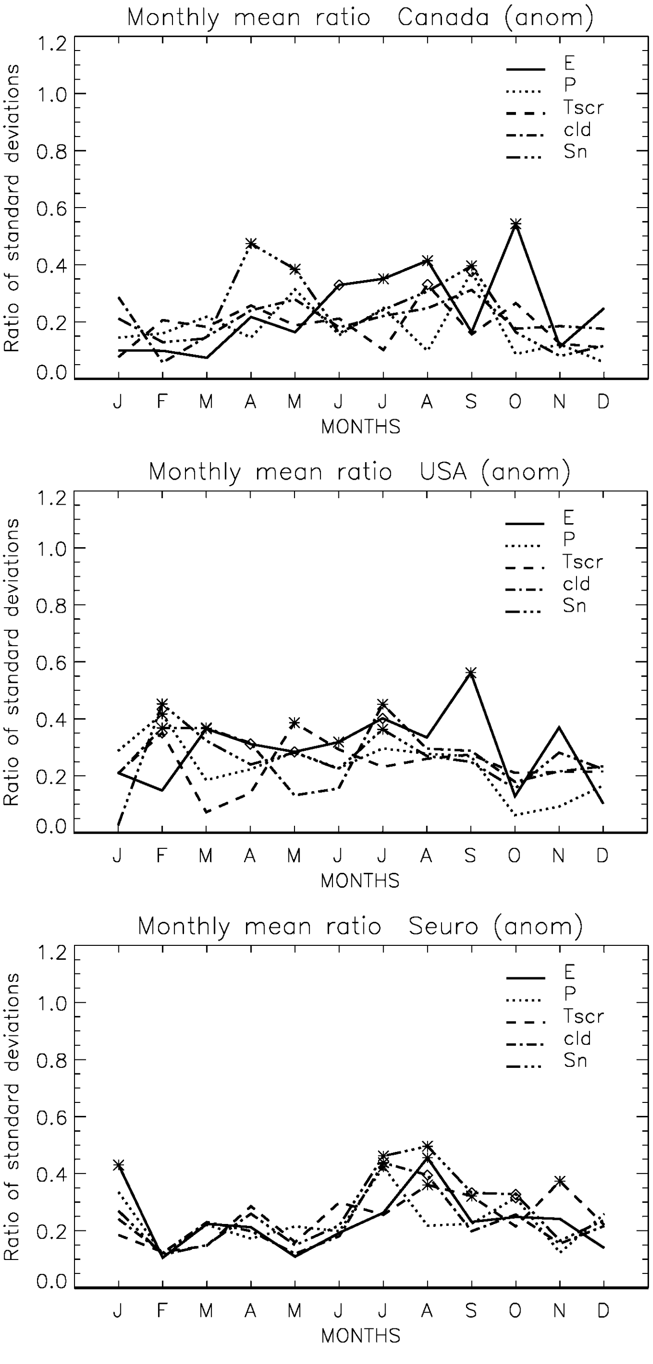


Fig. 11 As Fig. 10 but for the Canadian, Central North American and South European regions

6 Conclusions

In a study involving four AGCMs, each performing control and $2 \times CO_2$ experiments with two differing land-surface schemes, we have demonstrated the effect these schemes can have on climate predictions. In particular we have shown that our ability to predict those meteorological variables required in most studies of the impacts of anthropogenic climate change over land masses is limited by our ability to model processes at the land surface on the scale required by AGCMs.

The usefulness of the statistical method we derive in Eq. 4 is limited by the size of the ensembles used to calculate the variances. We had only two land surface scheme variants for each AGCM, limiting the accuracy of our measure of LSS uncertainty, and an ensemble of only four AGCMs with which to compare it, whereas a larger number would enable us to sample more fully the range of responses observed in PILPS (Henderson-Sellers et al. 1996). As mentioned in Sect. 5.2, better attribution of the effects of the land-surface changes might be achieved with a more controlled experimental design which would allow more elaborate ANOVA techniques. Longer time-slices would allow statistically significant results to be derived for noisier variables such as precipitation. The potential for investigating land-surface feedbacks and sensitivities would be greatly enhanced if some of the land-surface schemes were given a plug-compatible interface (Polcher et al. 1998), allowing the exchange of schemes between AGCMs. Taking into account these points on experimental design, we would recommend that climate modellers refine their understanding of the uncertainties associated with GCMs by performing studies similar to this one for other parametrization schemes.

Our analysis shows that the size, significance and geographical distribution of the uncertainty introduced into our ensemble of experiments by the LSS changes was not the same for the control experiments as for the $2 \times CO_2$ climate change anomalies. Using the uncertainty ratio R presented in Eq. 4 we have shown that the uncertainty derived from altering the LSS was generally greater for climate sensitivity than for control simulations. In the Northern Hemisphere mid- and high-latitudes surface processes significantly affected the control simulations, most strongly during summer, but only a small impact was noted on the anomalies. In the tropics land-surface processes play a modest role in the uncertainties of simulating current climate, except for a few variables during the rainy season. On the other hand, these regions show the largest contribution of surface processes to the uncertainty in predicted climate change with the highest values obtained during the dry season. In analyzing the ensemble of both control and doubled CO_2 simulations we found that evaporation was the most strongly affected of the variables we examined by the changes to LSS. The behavior of the other variables led us to distinguish between two types of climatic region. In tropical areas, the LSS changes led, through the controlling of surface temperature by evaporation, to changes in surface air temperature. In the extra-tropical regions we studied, the same LSS changes had a stronger influence on the hydrological cycle and little effect on temperature.

An important finding of this study is that in some GCMs an LSS change which had little impact on the control climate could nevertheless alter the response to a doubling of greenhouse gas concentration significantly, and vice versa. Identifying the regions where surface processes impact our ability to simulate the current climate or its sensitivity is essential for the development of validation strategies for land-surface schemes, and this study is a step in that direction. GCM development must include an assessment of sensitivity to systematic climate forcing in addition to validation of control climate. Our description of the uncertainties should be of interest to the climate impacts community in the difficult decisions they have to make about trusting climate change scenarios from general circulation models. Since the quality of the control simulation for a given model does not guarantee a correct sensitivity to climate change, more attention has to be paid to validating the sensitivity of the land-surface scheme (and other parametrizations) to systematic variations in climatic forcing. We conclude that the climatic impact community should look more closely at land-surface schemes and the bearing they have on the simulated consequences of climate change for human activities.

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