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Evaluating Uncertainties in the Prediction of Regional Climate Change

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Abstract. Uncertainties in regional climate change simulations for the 21st century by five coupled atmosphere-ocean General Circulation Models (AOGCMs) (two of them including ensembles of simulations), for different anthropogenic forcing scenarios and 23 regions in the World, are examined. Seasonally and regionally averaged precipitation and surface air temperature for the future period of [2070-2099] as compared to the period of [1961-1990] are considered. The dominant source of uncertainty in the simulation of average regional climate change is due to inter-model variability with inter-scenario and internal model variability playing secondary roles. The range of predicted climate changes by different realizations of the same ensemble is small, and simulated changes exhibit a high level of coherency among different forcing scenarios. Uncertainties in regional changes are 3 K or greater for temperature and 25% of present day values or greater for precipitation. The model biases in reproducing present day climate are ≤1 K to over 5 K for temperature and ≤ 10% to over 100% for precipitation.

1. Introduction

Coupled AOGCMs are the primary tools used to simulate transient climate changes for the 21st century due to greenhouse gas (GHG) and sulfate aerosol forcing of anthropogenic origin [*Kattenberg et al.*,1996]. In order to evaluate climate change impacts, climate information is usually needed at the regional scale (i.e. up to 10^7 km^2) or at the country level. To date, most impact research has employed regional information from AOGCM simulations. However, such information has limitations due to the model coarse horizontal resolution (300-500 km), which has prompted the development of different regionalization techniques [*Giorgi and Mearns,* 1991].

With these premises, an assessment of regional climate changes for the 21st century requires a four step strategy of: 1) A range of forcing scenarios related to different assumptions of future economic and technological development; 2) A range of different AOGCMs, since different models have different representations of physical processes with their respective strengths and weaknesses; 3) Ensemble simulations for each forcing scenario and AOGCM, as non-linearities in the climate system render a model simulation dependent on initial conditions; and 4) use of different regionalization techniques to enhance the regional information produced by the AOGCMs. Therefore, uncertainties in climate change predictions at the regional scale stem from a hierarchy of sources: 1) Uncertainty related to the forcing scenarios [e.g., GHG and aerosol forcings], hereafter referred to as "inter-scenario variability"; 2) Uncertainty related to the use of different AOGCMs, i.e. due to "inter-model variability"; 3) Uncertainty related to predictions by different realizations of a given scenario with a given AOGCM, i.e. due to "internal model variability"; 4) Uncertainty related to sub-GCM grid scale forcings and processes.

Past work has dealt separately with these sources of uncertainty [*Whetton et al.*,1996; *Lal et al.*,1995; *Kittel et al.*,1998; *Hulme and Brown,*1998; *Giorgi and Francisco*,2000]. However, a new suite of AOGCM experiments has become available which allows a comparative study of uncertainties due to the sources 1)-3) above. We present here such a study based on a regional analysis of transient AOGCM simulations. We do not address the issue of sub-GCM grid scale processes but stress that uncertainties in AOGCM regional predictions would be transmitted to any regionalization technique used to enhance such predictions.

2. Models and Experiments

For our analysis we use the 23 regions introduced by *Giorgi and Francisco* [2000] (Fig. 1, see the original paper for the criteria of regional selection) and we analyze output from transient climate change simulations with five AOGCMs available in the Data Distribution Center (DDC) [*Carter and Hulme*,1998]. This output was interpolated onto a 0.5°grid and it was then regionally averaged over the regions of Fig.1. The interpolation procedure is discussed by *Giorgi and Francisco* [2000]. Note that, since the AOGCMs have different land masks, and since only land points are used in the interpolation procedure, the actual shape of the regions encompassing

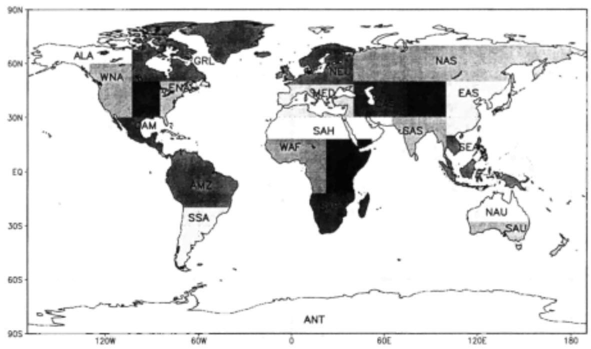

Figure 1. Regions used in the analysis. SAU=Southern Australia; NAU=Northern Australia; AMZ= Amazon Basin;SSA= Southern South America;CAM=Central America;WNA= Western North America; CNA=Central North America;ENA= Eastern North America; ALA=Alaska; GRL=Greenland and Northern Territories; MED=Mediterranean Basin; NEU= Northern Europe;WAF=Western Africa; EAF=Eastern Africa; SAF=Southern Africa;SAH=Sahara;SEA=Southeast Asia; EAS =East Asia; SAS=South Asia; CAS =Central Asia; TIB= Tibet;NAS=North Asia;ANT= Antarctica. *Giorgi and Francisco* (2000) provide the regions' definition in terms of latitude and longitude.

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complex coastal areas is somewhat different between different AOGCMs. Admittedly, both the use of a particular interpolation scheme and the different coastlines in the models may add a factor of uncertainty whose importance, however, is reduced by taking averages over broad regions such as in Fig.1. Only land points common to the regional AOGCM land mask and to the base grid are considered in the averaging.

All AOGCM runs covered the period of 1860 to 2099 with transient forcing due to GHG and sulfate aerosol effects. We extracted the 30-year period of [1961-1990] to represent present day climate conditions and the period of [2070-2099] for future climate conditions. The variables examined are average surface air temperature and precipitation for December-January-February (DJF) and June-July-August (JJA), i.e. variables used in previous studies [e.g. *Kattenberg et al.*, 1996; *Kittel et al.*,1998; *Giorgi and Francisco*, 2000] and of importance for climate change impact work. Here we limit our analysis to averages over the 30-year periods and do not examine inter-annual climate variability. We indicate with the term "sensitivity" the difference between the averages for the [2070-2099] and [1961-1990] periods and with the term "bias" the difference between simulated and observed averages for the [1961-1990] period. Units for precipitation sensitivity and bias are percent of present day precipitation and percent of observed precipitation, respectively.

Results from five AOGCMs were analyzed: the HADCM2 model from the Hadley Centre for Climate Research and Prediction, (*Mitchell and Johns*,1997; *Johns et al.*,1997; horizontal atmospheric resolution of 3.75°×2.5° lon × lat); the first version of the Canadian Climate Center coupled model (CCC; *Boer et al.*, 2000a,b; resolution of 3.7°×3.7° lon × lat); the coupled model from Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO; *Gordon and O'Farrell*, 1997; resolution of 5.6°×3.2° lon × lat); the coupled model of the Center for Climate Research Studies (CCSR; *Hasumi and Suginohara*,1998; of 5.6°×5.6° lon × lat); the ECHAM4/OPYC atmospheric model of the Max Planck Institute for Meteorology (MPI; *Bacher et al.*, 1998; resolution of 2.89°×2.89° lon × lat). All these models include ocean flux corrections for heat and moisture.

The following future climate (i.e. post-1990) forcing scenarios are considered: F1GHG: 1% year^{-1} compounded GHG increase (after 1990) and no aerosol effects; F1SULF: 1% year^{-1} compounded GHG increase and inclusion of aerosol effects; FdGHG: 0.5% year^{-1} compounded GHG increase and no aerosol effects; FdSULF: 0.5% year^{-1} compounded GHG increase and inclusion of aerosol effects. For the F1SULF and FdSULF experiments, historical (i.e. pre-1990) GHG and aerosol forcing and post-1990 aerosol forcing are from the IS92a scenario of *IPCC* [1992]. For the F1GHG and FdGHG experiments, historical IS92a GHG forcing and no historical aerosol forcing are included. Only direct aerosol radiative effects are included in these simulations as a perturbation to the surface albedo. Note that this set of scenarios is not comprehensive of the full scenario range presented in *IPCC* [1992].

We analysed the following simulations: ensembles of four realizations of all four scenarios for the HADCM2; one realization of the F1GHG and F1SULF scenarios for the CSIRO (the CSIRO uses 0.9% year^{-1} compounded GHG increase), CCSR and MPI (the MPI F1SULF experiment only extended to 2050); one realization of the F1GHG scenario and an ensemble of three realizations of the F1SULF scenario for the CCC. Different realizations of the same scenario start at different times in corresponding multi-century control experiments (i.e. experiments with pre-industrial levels of GHG and no aerosol forcing), and thus employ different initial conditions of atmosphere, ocean and land surface (e.g. soil moisture).

Model biases for the [1961-1990] period are calculated by comparison with the observed dataset of the Climatic

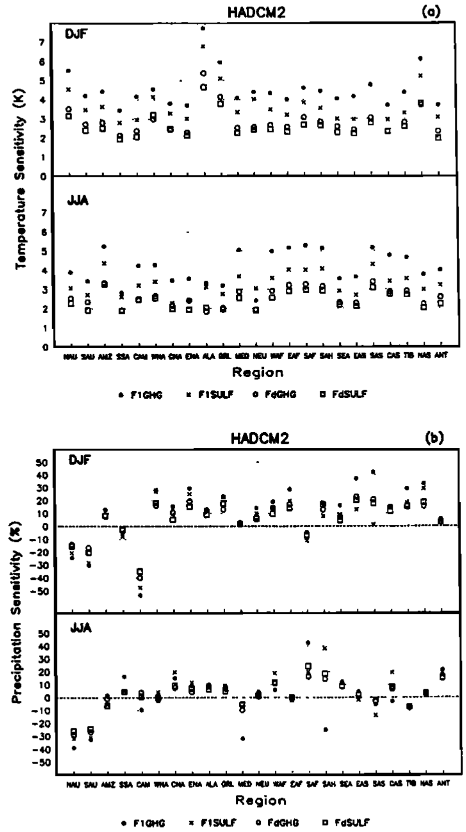

Figure 2. Ensemble average sensitivities [2070-2099] minus [1961-1990] values) for the HADCM2 simulations of four different forcing scenarios. a) Surface air temperature (K); b) Precipitation (% of [1961-1990] value).

Research Unit (CRU) of the University of East Anglia [*New et al.*, 1999] which is defined on the 0.5° grid of Fig. 1. *New et al.* [1999] estimate that uncertainties in observed climate averages for the period of 1961-1990 are of the order of 0.5 to 1.3 K for temperature and up to 10-25% for precipitation, and are largest over regions with poor station coverage and high spatial variability, such as Greenland,, the Himalaya-Tibetan area, Southeast Asia and parts of Africa.

3. Results

Figures 2a,b illustrate the effect of inter-scenario variability by showing the ensemble average temperature and precipitation sensitivities in the HADCM2 runs for the four scenarios. The simulated regional warmings are mostly in the range of 2-5 K, with maximum warming in the F1GHG scenario and minimum warming in the FdSULF scenario. Over the cold climate regions of Alaska, Greenland and North Asia, the warming is up to 6-8 K due to the snow/ice feedback mechanism. The temperature sensitivities are greater in the F1GHG scenario than in the FdGHG scenario by 1.5-3 K, which can be taken as a measure of inter-scenario variability.

For precipitation,the sensitivities are mostly positive,resulting from an intensified hydrologic cycle in future climate conditions,with a few exceptions (e.g. Australia) possibly related to regional shifts in storm tracks. The magnitude of the sensitivities goes from ≤10% to 30% except for Central America in DJF and Southern Africa and Sahara in JJA. There is a high level of coherency, at least in sign,between regional precipitation sensitivities of different forcing scenarios. The spread (i.e. the difference between the maximum and minimum value)of precipitation sensitivities associated with

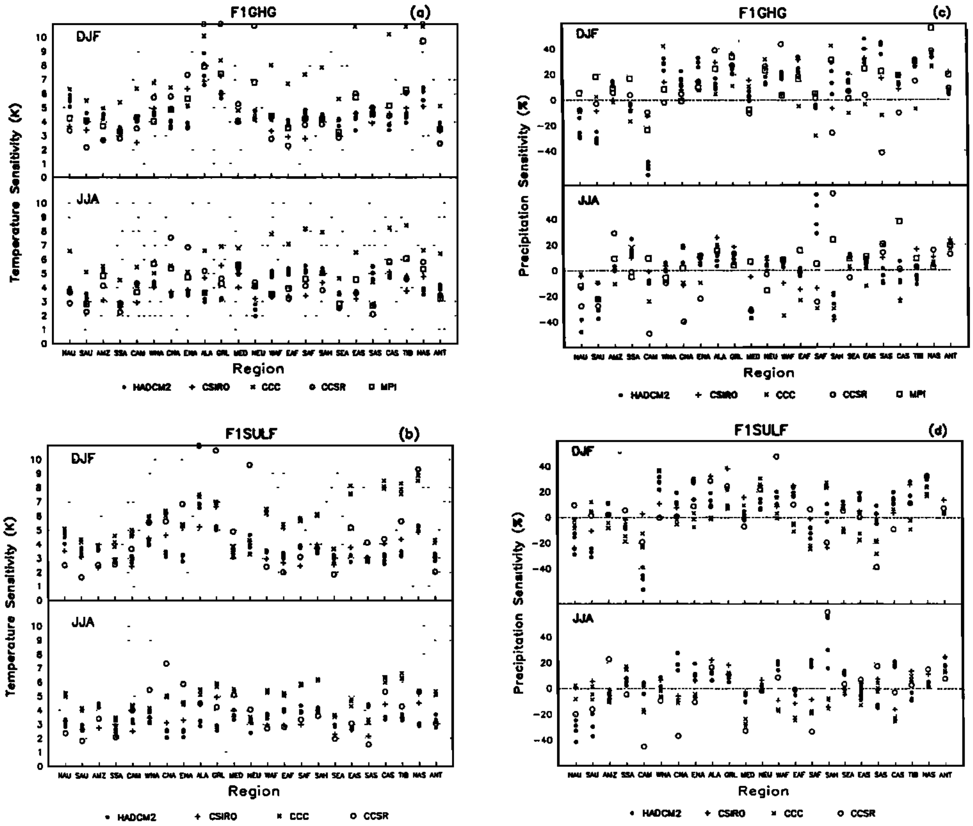

Figure 3. Sensitivities ([2070-2099] minus [1961-1990] values) for different simulations (individual realizations) of two scenarios. a) Surface air temperature (K), F1GHG scenario; b) Surface air temperature (K), F1SULF scenario; c) Precipitation (% of [1961-1990] value), F1GHG scenario; d) Precipitation (% of [1961-1990] value), F1SULF scenario.

inter-scenario variability varies from region to region, up to 20-30%, but it is mostly of the order of 15% or less.

The effects of inter-model and internal model variability are illustrated in Figs. 3a-d, which present temperature and precipitation sensitivities for the F1GHG and F1SULF scenarios. For temperature (Figs. 3a,b), the effect of internal model variability is much less pronounced than that of inter-model variability. The temperature sensitivities of different realizations of the same ensemble are close to each other, both for the HADCM2 and CCC models. We calculated t-tests between 30-year averages of pairs of realizations of the same ensemble and found that the average seasonal temperatures did not differ from each other at the 5% confidence level in the vast majority of cases. The spread of temperature sensitivities due to internal model variability is generally less than 1 K. This result is consistent with an analysis of the multi-century control HADCM2 run, for which we examined an 8-member ensemble of 30-year periods. We found that the spread of the 30-year averages of DJF and JJA regional temperatures was less than 0.7 K in all regions and season except for Central and Eastern North America and Northern Europe, (spread of 1 K to 1.5 K). By contrast, the spread due to inter-model variability is generally greater than 2 K, with many instances of up to 4-7 K, in both scenarios.

Similar conclusions are found for precipitation, although the internal model variability appears more pronounced for precipitation than for temperature. Both for the HADCM2 and CCC experiments, in most cases the precipitation sensitivities associated with different realizations of the same ensemble have the same sign, be it positive or negative, and the spread associated with internal model variability is mainly of the order of 10-20%. Similarly, in the 8-member ensemble of 30-year periods for the HADCM2 control run the spread of DJF and JJA precipitation was less than 10% of the ensemble mean value in 33 out of 46 cases and it was more than 20% of the ensemble mean in only 3 cases. By comparison, the spread associated with inter-model variability is in the range of 20-80% with many instances for which the sensitivities produced by different models are of opposite sign. We computed t-tests between 30-year averages of [2070-2099] and corresponding [1961-1990] values, which indicated that all the temperature sensitivities in Figs. 2 and 3 were statistically significant at the 5% confidence level, while the number of statistically significant precipitation sensitivities varied among models, regions and seasons.

If we consider the spread of the sensitivities in Figs. 2 and 3 as a measure of uncertainty in the simulation of regional climate change, it is evident that the largest source of uncertainty is inter-model variability. Both the HADCM2 and CCC experiments indicate that the smallest contribution to uncertainty is due to internal model variability. Figure 2 also shows that, for the HADCM2 model, the regional sensitivities for different scenarios exhibit similar trends despite the fact that the aerosol forcing is local in nature, while the GHG forcing is global, and that the radiative forcing of aerosol and GHG differ in sign.

Our analysis gives some indications for specific regions: 1) Temperature sensitivities are highest for the cold climate regions, likely as a result of the snow/ice albedo feedback mechanism; 2) The inter-model range in temperature sensitivities is largest over the Asian and African regions, Alaska, Greenland and Northern Europe; 3)Aerosol effects tend to reduce the temperature sensitivities over most regions but do not strongly affect the precipitation sensitivities;4)In only a few cases all models agree in the sign of the precipitation sensitivities (noticeably, most models indicate negative precipitation changes over Northern and Southern Australia, Central America and the Mediterranean in JJA); 5) Regional

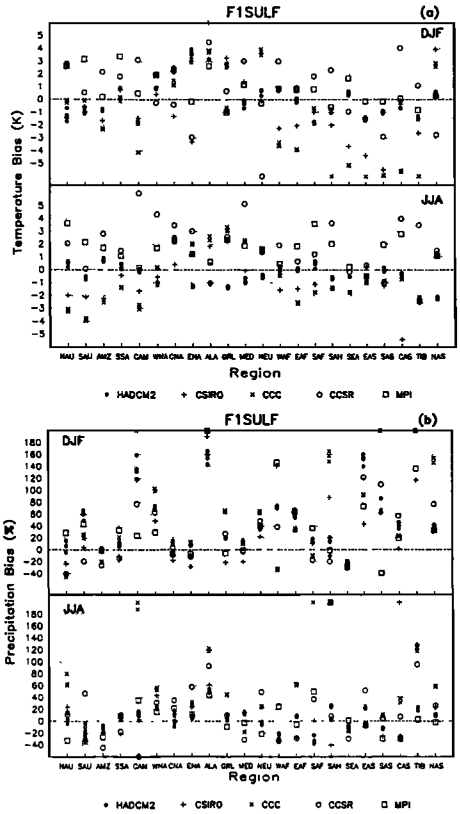

Figure 4. Regional biases (simulated minus observed values for the [1961-1990] period) for different model simulations of the F1SULF scenario. a) Surface air temperature (K); b) Precipitation (% of observed value).

precipitation sensitivities are positive in the majority of cases during DJF, while a more balanced occurrence of positive and negative sensitivities is found in JJA.

As a second measure of uncertainty we can take the models' ability to reproduce present day climate, as measured for example by the bias. Figures 4a,b present the regional temperature and precipitation biases for all F1SULF simulations with respect to the CRU observations. The biases, as well as their inter-model ranges, vary from ≤1 K to 4-6 K for temperature and ≤10% to >100% of observed values for precipitation. The biases for different realizations of the same ensembles are close to each other, both in the HADCM2 and CCC models, which is again an indication of low internal model variability. The performance of the models in reproducing observed averages is highly variable from region to region and there is no model that ubiquitously shows lower biases than the others. Comparison of Figs. 2,3 and 4 shows that, as was also concluded by *Kittel et al.* [1998] for a previous generation of AOGCM experiments, the models tend to agree with each other better in simulating sensitivities than in reproducing present day climate.

4. Conclusions

Our results indicate an estimated uncertainty in simulated regional and seasonal sensitivities by coupled AOGCMs for the future climate period of [2070-2099] of 3 K or greater for surface air temperature and 25% (of present day values) or greater for precipitation. Inter-model variability represents the primary source of uncertainty in the prediction of regional climate change by AOGCMs, with inter-scenario and internal model variability playing less prominent roles, at least for our set of scenarios and the ensemble simulations. In particular, the model sensitivity to the treatment of ice and snow processes greatly affects inter-model variability over cold climate regions. The model biases for present day climate varied widely among models and regions.

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