GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 17, PAGES 3317-3320, SEPTEMBER 1, 2001

Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings

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Abstract. We analyse temperature and precipitation changes for the late decades of the 21st century (with respect to present day conditions) over 23 land regions of the world from 18 recent transient climate change experiments with coupled atmosphere-ocean General Circulation Models (AOGCMs). The analysis involves two different forcing scenarios and nine models, and it focuses on model agreement in the simulated regional changes for the summer and winter seasons. While to date very few conclusions have been presented on regional climatic changes, mostly limited to some broad latitudinal bands, our analysis shows that a number of consistent patterns of regional change across models and scenarios are now emerging. For temperature, in addition to maximum winter warming in northern high latitudes, warming much greater than the global average is found over Central Asia, Tibet and the Mediterranean region in summer. Consistent warming lower than the global average is found in some seasons over Southern South America, Southeast Asia and South Asia, while cases of inconsistent warming amplification compared to the global average occur mostly in some tropical and southern sub-tropical regions. Consistent increase in winter precipitation is found in northern high latitude regions, as well as Central Asia, Tibet, Western and Eastern North America, and Western and Eastern Africa regions. The experiments also indicate an increase in South Asia and East Asia summer monsoon precipitation. A number of regions show a consistent decrease in precipitation, such as Southern Africa and Australia in winter, the Mediterranean region in summer and Central America in both seasons. Possible physical mechanisms that lead to the simulated changes are discussed.

1. Introduction

Projections of regional climatic changes for the 21st century due to anthropogenic forcings are of critical importance for the assessment of climate change impacts on human and natural systems. To date, such projections have been mostly based on the use of coupled AOGCMs and they have been characterized by a high level of uncertainty and very low level of confidence, to the extent that little or no statements have been made concerning specific regional climate change projections, especially for precipitation, other than for some broad latitudinal bands (for example, maximum winter warming in northern high latitudes has been commonly simulated) (*IPCC*, 1996). This uncertainty stems from a hierarchy of sources (*Visser et al.* 1999; *Giorgi and Francisco* 2000): estimates of future anthropogenic forcings (e.g. due to greenhouse gas (GHG) and sulfate aerosol concentration); the response of a climate model to a given forcing; the natural variability of the climate system.

One of the fundamental criteria for increasing the confidence in simulated regional climatic changes is the agreement of simulations across models, especially when this agreement is maintained under different forcing scenarios. Indeed, it can be argued that consistent patterns of regional climatic changes emerging from a wide range of simulations reflect robust signals that are not very sensitive to the differences among models or the details of the forcing scenarios. In this paper we search for consistent regional climate change patterns by comparing results from a series of AOGCM simulations which has recently become available for two different forcing scenarios of transient climate change for the 21st century. In particular, we examine patterns of inter-model agreement in the simulation of regional climatic changes and consistency of these patterns across scenarios.

2. Methods and Models

Our analysis focuses on surface air temperature and precipitation, the two variables most often used in impact studies and surface climate analysis, and at the broad regional, or sub-continental, spatial scale ($10^6 - 10^7$ km^2). This is arguably the minimum scale at which current AOGCMs, which use horizontal equivalent grid point spacing of the order of 300 to 500 km, can be expected to produce reliable information (e.g. *von Storch* 1995). It should be stressed that marked climatic variability can occur at smaller scales and that different techniques can be used to spatially enhance the AOGCM information (*Giorgi and Mearns* 1991).

Data from 18 available transient AOGCM simulations of the period 1860-2100 are analysed, 9 each for two of the marker scenarios developed by the Intergovernmental Panel for Climate Change (IPCC) (*IPCC* 2000), namely the A2 and B2 scenarios. These scenarios are derived from different estimates of future population, economic and technological development. In the A2 scenario GHG emissions continuously increase throughout the 21st century, while in the B2 scenario they start decreasing after about 2050. From the viewpoint of total cumulative GHG emissions, the B2 scenario is considered as "medium-low" and the A2 scenario as "high" (*IPCC* 2000).

Our analysis considers the difference in average temperature and precipitation between the late decades of the 21st

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Paper number 2001GL013150.
0094-8276/01/2001GL013150$05.00

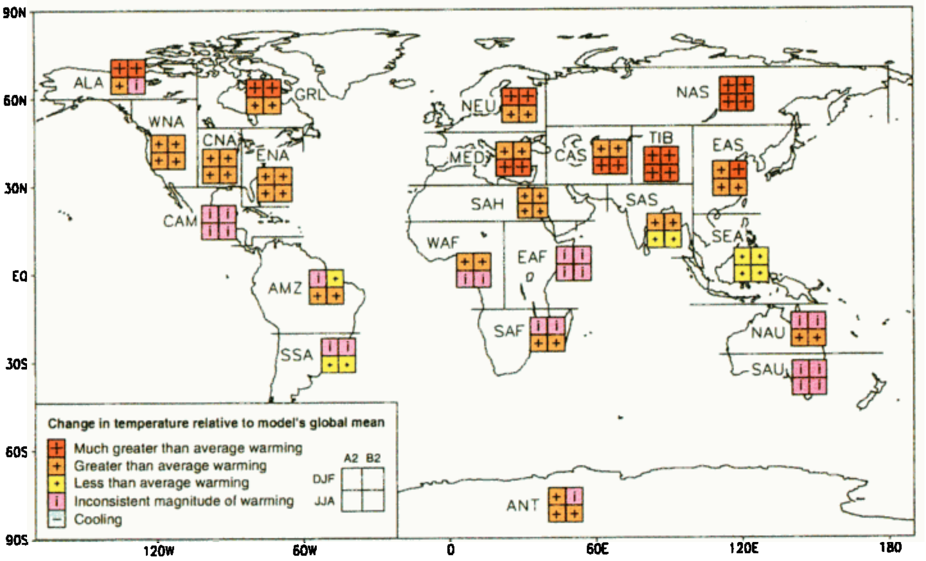

Figure 1. Inter-model agreement in regional temperature change relative to each model's global mean annual change for the A2 and B2 scenarios. Regions are classified as showing either agreement on warming in excess of 40% of the global average ("Much greater than average warming"), agreement on warming greater than the global average ("Greater than average warming"), agreement on warming less than the global average ("Less than average warming"), disagreement among model experiments on the magnitude of regional relative warming ("Inconsistent magnitude of warming") or agreement in cooling ("Cooling"). Agreement is defined by a consistent result from at least 7 out of 9 model experiments. The global mean annual change in the simulations spans 1.2 to 4.5°C for A2 and 0.9 to 3.4°C for B2, and therefore a regional amplification of 40% represents warming ranges of 1.7 to 6.3°C for A2 and 1.3 to 4.7°C for B2.

century, i.e. 2071-2100 (future climate), and the period 1961-1990 (present day climate). We refer to this quantity as "change". Changes are calculated for December-January-February (DJF) and June-July-August (JJA). The data are interpolated onto a common 0.5 degree grid and are averaged over 23 regions covering nearly all land areas in the world and identified by *Giorgi and Francisco* (2000) (see Figures 1-2). Only land areas are considered. The list of experiments and models is given in Table 1. For one experiment (CCC/CGCM2) an ensemble of 3 realizations was conducted, and our analysis refers to the ensemble average. It has been shown that 30-year averages do not vary substantially between different realizations of the same ensemble (*Giorgi and Francisco* 2000).

For temperature, the data analysed is the amplification of the warming at a given region with respect to the annual global average warming. Since the regional temperature changes are affected by the model global temperature sensitivity, this is a more meaningful measure of regional structure than the absolute warming. For reference, the cor-

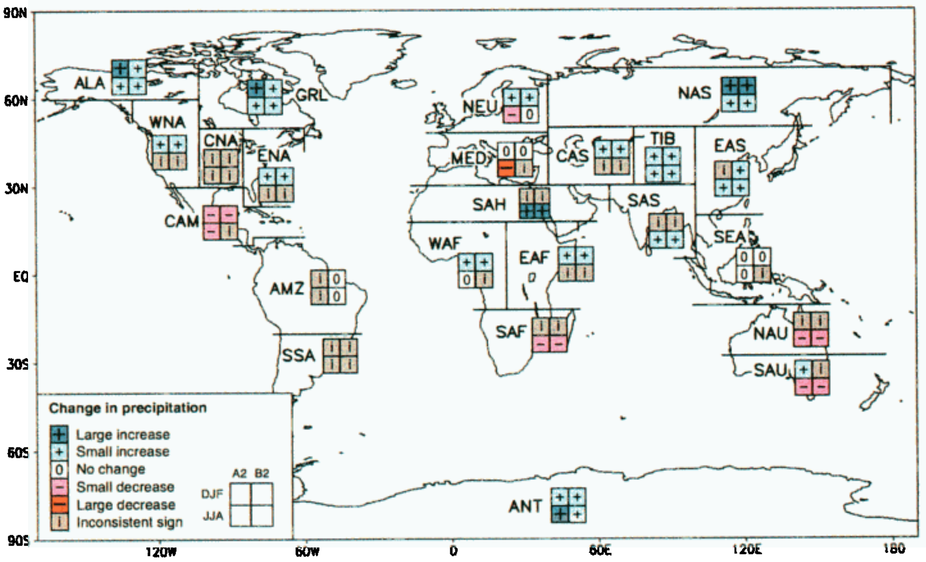

Figure 2. Inter-model agreement in regional precipitation change for the A2 and B2 scenarios. Regions are classified as showing either agreement on increase with an average regional change greater than 20% (of present day values) ("Large increase"), agreement on increase with an average regional change between 5 and 20% ("Small increase"), agreement on a change between -5 and 5% ("No change"), agreement on decrease with an average regional change between -5 and -20% ("Small Decrease"), agreement on decrease with an average regional change of less than -20% ("Large Decrease"), or disagreement ("Inconsistent sign"). Agreement is defined by a consistent result from at least 7 out of 9 model experiments.

Table 1. List of AOGCM experiments and corresponding global temperature change, ΔT (K), defined as the difference between global annual surface air temperature for the periods 2071-2100 and 1961-1990. Also given are references for the models and/or simulations analysed.

Institution/Model	ΔT-A2	ΔT-B2
CCSR-NIES / V2[1]	4.53	3.38
MRI / V2[2]	1.25	0.92
CCC / CGCM2[3]	3.59	2.49
CSIRO / Mk2[4]	3.50	2.71
NCAR / CSM[5]	2.29	1.71
DOE-NCAR / PCM[6]	2.35	1.80
GFDL / R30-C[7]	2.87	2.18
MPI-DMI / ECHAM4-OPYC[8]	3.11	2.34
UKMO / HADCM3[9]	3.38	2.42

1:*Nozawa et al.* (2001); 2:*Noda et al.* (1999); 3:*Flato and Boer* (2001); 4:*Gordon and O'Farrell* (1997); 5:*Dai et al.* (2001); 6:*Washington et al.* (2001); 7:*Knutson et al.* (2001); 8:*Stendel et al.* (2000); 9:*Johns et al.* (2001)

responding global temperature changes are reported in Table 1. Note that all regions in all scenarios undergo warming in future climate conditions. For precipitation the analysis is performed on the sign and magnitude of the change.

In the analysis, we look for inter-model agreement, which is defined as a consistent result from at least 7 out of 9 model experiments, a choice that allows for the occurrence of "outliers". Also, thresholds are used to identify small and large changes (see figures 1-2). These thresholds were chosen to best illustrate the spatial structure of the change signal and are not tied to impact-related or region-specific considerations.

3. Results

For temperature (Figure 1) most regions (about 75% of cases) show inter-model agreement on the magnitude of regional warming amplification, with substantial consistency across the two scenarios. The high latitude and high elevation winter maximum warming signal is evident in both scenarios (i.e. for the Alaska (ALA), Greenland (GRL), Northern Europe (NEU), Northern Asia (NAS) and Tibet (TIB) regions). However, general cross-scenario consistency of maximum warming amplification with respect to the global average is also found over Central Asia (CAS), Tibet (TIB) and the Mediterranean (MED) in JJA. The high latitude winter warming is mostly due to the snow-ice/albedo feedback mechanism whereby warming causes a decrease in snow and ice cover, and thus a decrease in local albedo which increases the absorption of solar radiation at the surface and enhances the warming. The cases of consistent maximum summer warming are more difficult to explain and are likely tied to more regionally specific processes. There are many regions with consistent medium warming amplification in all scenarios, while consistent simulations of warming lower than the global average are found over Southern South America (SSA), Southeast Asia (SEA) and South Asia (SAS) in JJA and Southeast Asia (SEA) in DJF. The cases of inconsistent warming amplification occur mainly in tropical and southern sub-tropical regions despite scaling by the global average, which indicates that model-dependent regional processes become more important in these regions.

In a warmer world the hydrologic cyle is expected to intensify, so that global precipitation tends to increase in response to greater surface evaporation. However, at the regional scale other factors influence precipitation changes: shifts in general circulation features, such as storm tracks or the intertropical convergence zone; intensification or weakening of regional circulations, such as the monsoon; changes in regional anomaly regimes associated with phenomena such as the El Nino Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO); regional hydrological feedbacks, e.g. between precipitation and evaporation; regional changes in atmospheric stability. As a result, although precipitation increases globally, it may decrease over given regions.

Our analysis shows that models simulate a number of consistent patterns of precipitation change (Figure 2). Inter-model agreement in the sign of precipitation change occurs in about 65% of cases, and when this agreement is found, the sign of the change is generally coherent across scenarios. Consistent increase in winter precipitation is found at high latitude northern regions as well as Central Asia (CAS), Tibet (TIB) and the Western and Eastern North America (WNA and ENA) regions. This increase in precipitation is likely due to increased moist energy within eastward travelling mid and high latitude storms. Alaska (ALA), Greenland (GRL), Northern Asia (NAS) and Tibet (TIB) also show consistent increase in summer precipitation. Over the African continent, we find consistent precipitation increase over the Eastern and Western Africa (EAF, WAF) regions in DJF and a large increase over the Sahara (SAH) region in JJA, where however present day precipitation is very low.

Both the A2 and B2 experiments indicate a consistent enhancement of summer monsoon precipitation in the South Asia and East Asia regions (SAS and EAS), a result that was not found in earlier simulations (Giorgi and Francisco 2000). Contrast in land-ocean warming and a reduced counterbalancing aerosol cooling over these regions in the A2 and B2 scenarios (compared to earlier scenarios) are likely responsible for this result. A general model consensus in the simulation of little or no precipitation change is found over Southeast Asia (SEA) in both seasons and the Mediterranean (MED) in winter.

Several regions show consistent decreases in precipitation: Central America (CAM), the Mediterranean (MED) and to a lesser extent Northern Europe (NEU) in summer (in the B2 scenario 6 out of 9 models simulated a precipitation decrease over the MED region), and Southern Africa (SAF) and Australia (NAU and SAU) in winter. Causes for these changes can be identified. Over the Mediterranean region, a potential mechanism for reduced summer precipitation is an intensification of the surface pressure high which would induce a nortward shift of the summer Atlantic storm track and a reduction of the moisture supply from the Atlantic (*Machenhauer et al.* 1998). Two influences may lead to precipitation decreases in the Australian regions. First, a number of models show an El Nino-like warming pattern in the Pacific that would be expected to have a drying influence over Australia (*Meehl et al.* 2000a). Second, some models simulate a southward shift in hemispheric circulation features which would weaken the midlatitude westerlies over southern Australia, especially in winter (*Fyfe et al.* 1999; *Kushner et al.* 2001). The latter process could also contribute to the winter drying over the Southern Africa region.

4. Summary and Discussion

In summary, while previously little or no statements could be made concerning regional climatic changes (other than for some broad latitudinal bands), our analysis of a wide range of recent experiments shows that better agreement is emerging on simulated regional climate change patterns spanning across models and scenarios, both for temperature and precipitation. Note that many of our results (except the increase in Asian summer monsoon precipitation) are also generally consistent with a smaller set of simulations for earlier forcing scenarios studied by *Giorgi and Francisco* (2000). The inter-model agreement increases the confidence in the simulated changes, while the inter-scenario consistency indicates that the regional structure of the changes is not very sensitive to the details of the forcing scenarios.

Clearly, some of our specific regional results depend on a number of choices, such as the definition of regions, seasons and thresholds for inter-model agreement and the coarseness of our categories. As an example of this dependence we repeated the precipitation analysis using the model median instead of the model mean to define the large, small and no precipitation change categories, and we found that the classifications agreed for the different methods in 90% of relevant cases. This result, along with the inter-model consistency across scenarios indicates that, although some specific regions might be sensitive to the threshold choices, the general patterns we find are robust. We also note that the regional biases in the simulations (simulated minus observed averages for the 1961–1990 period) were mostly in the range of +/- 4°C for temperature and -40% to 80% for precipitation, values that represent a general improvement over previous generation models (*Kittel et al.* 1998). This result and the general improvement of the AOGCM performance in simulating phenomena like ENSO and the monsoons (*Meehl et al.* 2000b; *Sperber et al.* 1999) further increase the confidence in the simulated changes. More work is needed to better identify the dynamical processes that lead to the simulated changes; to quantify the uncertainty associated with these changes; and to understand the effects on the simulated changes of systematic model errors and differences among models.

Acknowledgments.
We thank the Hadley Centre for Climate Prediction and Research of the U.K. Meteorological Office (UKMO), the Canadian Climate Center (CCC), the Commonwealth Scientific and Industrial Research Organization (CSIRO), the Max Plank Institute for Meteorology (MPI), the Centre for Climate Study Research (CCSR), the Meteorological Research Institute (MRI), the Danish Meteorological Institute (DMI), the National Center for Atmospheric Research (NCAR), and the Geophysical Fluid Dynamical Laboratory (GFDL) for making available the results of their AOGCM simulations. We also thank the Data Distribution Center (DDC) for making available some of the model output.

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(Received March 9, 2001; accepted June 25, 2001.)