

An Integrated Assessment Framework for Uncertainty Studies in Global and Regional Climate Change: The IGSM-CAM

Erwan Monier, Jeffery R. Scott, Andrei P. Sokolov,
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The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.


To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Erwan Monier^{*†}, Jeffery R. Scott^{*}, Andrei P. Sokolov^{*}, Chris E. Forest[§] and C. Adam Schlosser^{*}

Abstract

This paper describes an integrated assessment framework for uncertainty studies in global and regional climate change. In this framework, the Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM), an integrated assessment model that couples an earth system model of intermediate complexity to a human activity model, is linked to the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM). Since the IGSM-CAM incorporates a human activity model, it is possible to analyze uncertainties in emissions resulting from uncertainties intrinsic to the economic model, from parametric uncertainty to uncertainty in future climate policies. Another major feature is the flexibility to vary key climate parameters controlling the climate response: climate sensitivity, net aerosol forcing and ocean heat uptake rate. Thus, the IGSM-CAM is a computationally efficient framework to explore the uncertainty in future global and regional climate change due to uncertainty in the climate response and projected emissions. This study further presents 21st century simulations based on two emissions scenarios (unconstrained scenario and stabilization scenario at 660 ppm CO₂-equivalent by 2100) and three sets of climate parameters. The chosen climate parameters provide a good approximation for the median, and the 5th and 95th percentiles of the probability distribution of 21st century climate change. As such, this study presents new estimates of the 90% probability interval of regional climate change for different emissions scenarios. These results underscore the large uncertainty in regional climate change resulting from uncertainty in climate parameters and emissions, and the statistical uncertainty due to natural variability.

Contents

1. INTRODUCTION	1
2. METHODOLOGY	3
2.1 Description of the Modeling Framework	3
2.1.1 The MIT Integrated Global System Model Framework	3
2.1.2 The IGSM-CAM Framework	4
2.2 Description of the Simulations	7
2.2.1 Climate Parameters	7
2.2.2 Emissions Scenarios	8
2.3 Datasets	9
3. RESULTS	9
3.1 Validation	9
3.2 Future Projections	12
4. SUMMARY AND CONCLUSION	17
5. REFERENCES	20

1. INTRODUCTION

For many years, the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change has devoted a large effort to estimating probability distribution functions (PDFs) of uncertain inputs controlling human emissions and the climate response (Reilly *et al.*, 2001; Forest *et al.*, 2008). Based on these PDFs, probabilistic forecasts of

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the 21st century climate have been performed to inform policy makers and the climate community at large (Sokolov *et al.*, 2009; Webster *et al.*, 2012). This effort has been organized around the MIT Integrated Global System Model (IGSM), an integrated assessment model that couples an earth-system model of intermediate complexity to a human activity model. The IGSM framework presents major advantages in the application of climate change studies. A fundamental feature of the IGSM is the ability to vary key parameters controlling the climate response to changes in greenhouse gas and aerosol concentrations, *e.g.*, the climate sensitivity, net aerosol forcing and ocean heat uptake rate (Raper *et al.*, 2002; Forest *et al.*, 2008). As such, the IGSM enables structural uncertainties to be treated as parametric ones and provides a flexible framework to analyze the effect of some of the structural uncertainties present in Atmosphere-Ocean Coupled General Circulation Models (AOGCMs). Another major advantage of the IGSM is the coupling of the earth system with a detailed economic model. This allows not only simulations of future climate change for various emissions scenarios to be carried out but also for the analysis of the uncertainties in emissions that result from uncertainties intrinsic to the economic model (Webster *et al.*, 2012).

Since the IGSM has a two-dimensional zonally averaged representation of the atmosphere, it has been used primarily for climate change studies from a global mean perspective. While future changes in the global mean climate are of primary interest, a large effort must be undertaken to quantify regional climate change. Probabilistic projections of future regional climate change would prove beneficial to policy makers and impact modeling research groups who investigate climate change and its societal impacts at the regional level, including agriculture productivity, water resources and energy demand (Reilly *et al.*, 2012). The aim of the MIT Joint Program is to contribute to this effort by investigating regional climate change under uncertainty in the climate response and projected emissions. For studies requiring three-dimensional atmospheric capabilities, a new capability of the MIT Joint Program modeling framework is presented where the IGSM is linked to the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM). The IGSM-CAM is an efficient modeling system that is capable of deriving probability distributions of various climate variables at the continental and regional levels. First, the IGSM is used to perform Monte Carlo simulation, with Latin Hypercube sampling of the uncertain climate parameters based on probability density functions estimates (Forest *et al.*, 2008). This provides an ensemble simulation of climate change over the 21st century from which probability distributions of changes in any climate variable can be computed. It is then possible to run ensemble simulations of the IGSM-CAM based on a sub-sampling of the IGSM probabilistic projections of global surface air temperature changes by the end of 21st century. As such, probabilistic projections of regional climate change can be obtained efficiently with a smaller number of ensemble members than usually needed for Monte Carlo simulation.

In this paper, a description of the IGSM, including the earth system model of intermediate complexity and the human activity model, and the newly developed IGSM-CAM framework are presented. Then a brief evaluation of the IGSM-CAM present-day climate is performed and a comparison with the models from the Fourth Intergovernmental Panel on Climate Change (IPCC)

assessment report (AR4) (Randall *et al.*, 2007) is shown. Finally, results from 21st century simulations are presented based on two emissions scenarios (unconstrained emissions scenario and stabilization scenario at 660 ppm CO₂-equivalent by 2100) and three sets of climate parameters. The chosen climate parameters provide a good approximation for the median, and the 5th and 95th percentiles of the probability distribution of 21st century climate change. Thus, this study presents estimates of the median and 90% probability interval of regional climate change for two different emissions scenarios.

2. METHODOLOGY

2.1 Description of the Modeling Framework

2.1.1 The MIT Integrated Global System Model Framework

The MIT Integrated Global System Model version 2.3 (IGSM2.3) (Dutkiewicz *et al.*, 2005; Sokolov *et al.*, 2005) is a fully coupled earth system model of intermediate complexity that allows simulation of critical feedbacks among its various components, including the atmosphere, ocean, land, urban processes and human activities. The atmospheric dynamics and physics component (Sokolov and Stone, 1998) is a two-dimensional zonally averaged statistical dynamical representation of the atmosphere that explicitly solves the primitive equations for the zonal mean state of the atmosphere at 4° resolution in latitude and eleven levels in the vertical. The ocean component of the IGSM2.3 includes a three-dimensional dynamical ocean component based on the MIT ocean general circulation model (Marshall *et al.*, 1997b,a) with a thermodynamic sea-ice model and a biogeochemical module with explicit representation of the cycling of carbon, phosphate, dissolved organic phosphorus, and alkalinity (Dutkiewicz *et al.*, 2005, 2009). The ocean model has a realistic bathymetry, and a 2° x 2.5° resolution in the horizontal with twenty-two layers in the vertical, ranging from 10 m at the surface to 500 m thick at depth. The wind stress and the heat and freshwater fluxes are anomaly coupled in order to simulate realistic ocean and atmosphere states.

The IGSM2.3 also includes an urban air chemistry model (Mayer *et al.*, 2000) and a detailed global scale zonal-mean chemistry model (Wang *et al.*, 1998) that considers the chemical fate of 33 species including greenhouse gases and aerosols. The terrestrial water, energy and ecosystem processes are represented by a Global Land Systems (GLS) framework (Schlosser *et al.*, 2007) that integrates three existing models: the NCAR Community Land Model (CLM) (Oleson *et al.*, 2004), the Terrestrial Ecosystem Model (TEM) (Melillo *et al.*, 1993) and the Natural Emissions Model (NEM) (Liu, 1996). The GLS framework represents biogeophysical characteristics and fluxes between land and atmosphere and estimates changes in terrestrial carbon storage and the net flux of carbon dioxide, methane and nitrous oxide from terrestrial ecosystems.

Finally, the human systems component of the IGSM is the MIT Emissions Predictions and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005), which provides projections of world economic development and emissions over 16 global regions along with analysis of proposed emissions control measures. EPPA is a recursive-dynamic multi-regional general equilibrium model of the world economy, which is built on the Global Trade Analysis Project (GTAP) dataset

(maintained at Purdue University) of the world economic activity augmented by data on the emissions of greenhouse gases, aerosols and other relevant species, and details of selected economic sectors. The model projects economic variables (gross domestic product, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO₂, CH₄, N₂O, HFCs, PFCs and SF₆) and other air pollutants (CO, VOC, NO_x, SO₂, NH₃, black carbon and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling and agricultural activities.

A major feature of the IGSM is the flexibility to vary key climate parameters controlling the climate response. The climate sensitivity can be changed by varying the cloud feedback (Sokolov, 2006; Sokolov and Monier, 2012) while the net aerosol forcing is modified by adjusting the total sulfate aerosol radiative forcing efficiency. Finally, the rate of oceanic heat uptake can be changed by modifying the value of the diapycnal diffusion coefficient (Dalan *et al.*, 2005a,b). The IGSM is also computationally efficient and thus particularly adapted to conduct sensitivity experiments or to allow for several millenia long simulations. The IGSM has been used to quantify the probability distribution functions of climate parameters using optimal fingerprint diagnostics (Forest *et al.*, 2001, 2008). This is accomplished by comparing observed changes in surface, upper-air, and deep-ocean temperature changes against IGSM simulations of 20th century climate where model parameters are systematically varied. The IGSM has also been used to make probabilistic projections of 21st century climate change under varying emissions scenarios and climate parameters (Sokolov *et al.*, 2009; Webster *et al.*, 2012).

2.1.2 The IGSM-CAM Framework

A limitation of the IGSM is the two-dimensional, zonally averaged atmosphere model that does not permit direct regional climate studies. For investigations requiring three-dimensional atmospheric capabilities, the IGSM is linked to the NCAR Community Atmosphere Model version 3 (CAM3) (Collins *et al.*, 2004), at a 2° x 2.5° horizontal resolution and with 26 vertical levels. **Figure 1** shows the schematic of the IGSM-CAM framework. Because CAM3 is coupled to CLM version 3, it provides a representation of the land consistent with the IGSM. For further consistency within the IGSM-CAM framework, new modules were developed and implemented in CAM in order to modify its climate parameters to match those of the IGSM. In particular, the climate sensitivity is changed using a cloud radiative adjustment method (Sokolov and Monier, 2012). CAM is driven by greenhouse gas concentrations and aerosol loading computed by the IGSM model. Since CAM provides a scaling option for carbon aerosols, the default black carbon aerosol loading is scaled to match the global carbon mass computed by the IGSM. A similar scaling for sulfate aerosols was implemented in CAM and the default sulfate aerosol loading is scaled so that the sulfate aerosol radiative forcing matches that of the IGSM. Finally, the ozone concentrations in CAM are a combination of the IGSM zonal-mean distribution of ozone in the troposphere and of stratospheric ozone concentrations derived from the Model for Ozone and Related Chemical Tracers (MOZART) model. Since the atmospheric chemistry and the land and ocean biogeochemical cycles are computed within the IGSM, the IGSM-CAM is more computationally efficient than a fully coupled GCM, like CCSM3. On the other hand, a limitation

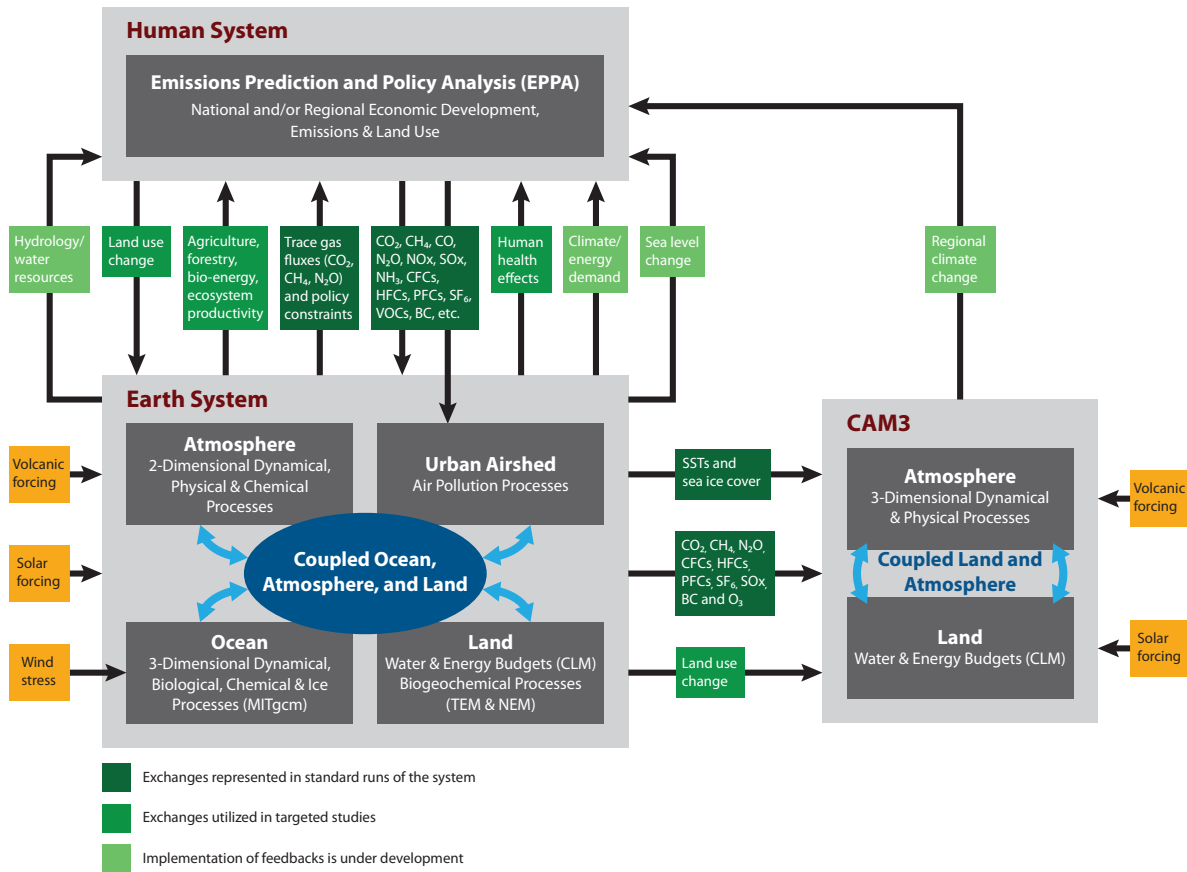


Figure 1. Schematic of the IGSM-CAM framework highlighting the coupled linkages between the physical and socio-economic components of the IGSM2.3 and the linkage between the IGSM and CAM.

of the IGSM-CAM framework is the inability to simulate changes in the spatial distribution of aerosols and ozone.

IGSM sea surface temperature (SST) anomalies drive CAM instead of the full field because the IGSM SSTs exhibit significant regional biases, mainly associated with the coupling of the ocean model to a two-dimensional, zonal-mean atmosphere. **Figure 2** shows the differences between the IGSM SST and the merged Hadley-OI SST observational dataset for winter and summer over three different decades. It reveals that the bias differs between seasons but is fairly constant over the last 100 years. This means that the seasonal cycle of the IGSM SSTs is biased but that the anomalies from, for example, pre-industrial era agree well with the observations. In order to correct the IGSM SST seasonal cycle and to provide more realistic SSTs to the three-dimensional atmosphere, CAM is driven by IGSM SST anomalies from a control simulation corresponding to pre-industrial forcing with an observed 12-month SST climatology corresponding to pre-industrial observed seasonal cycle. The dataset used in this study is the merged Hadley-OI sea surface temperature, a surface boundary dataset designed for uncoupled simulations with CAM, consisting of a merged product based on the monthly mean Hadley Centre SST dataset version 1 (HadISST1) and version 2 of the National Oceanic and Atmospheric Administration (NOAA) weekly Optimum Interpolation (OI) SST analysis (Hurrell *et al.*, 2008).

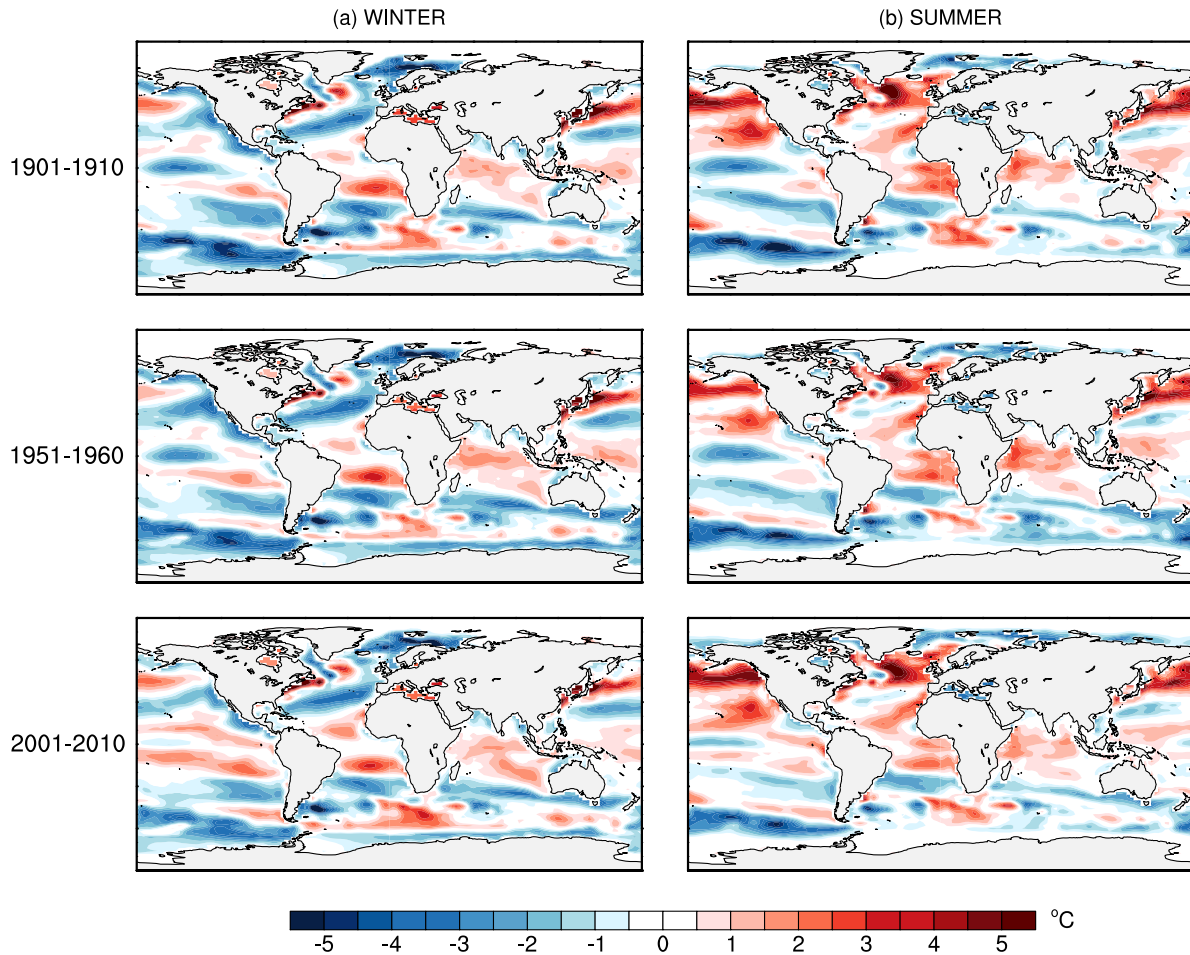


Figure 2. Decadal mean differences between the IGSM sea surface temperature and the merged Hadley-OI sea surface temperature observational dataset for (a) winter and (b) summer over the 1901–1910, 1951–1960 and 2001–2010 periods.

Overall, the IGSM-CAM provides a framework well adapted for uncertainty studies in global and regional climate change since the key parameters that control the climate’s response (climate sensitivity, net aerosol forcing and ocean heat uptake rate) can be varied consistently within the modeling framework. Another major advantage of the IGSM-CAM framework is that it provides an efficient modeling system to derive probability distributions of various climate variables at the continental and regional levels. First, the IGSM2.3 is used to estimate PDFs of climate parameters using optimal fingerprint diagnostics following the procedure in Forest *et al.* (2008). Then, the IGSM2.3 is used to perform Monte Carlo simulation, with Latin Hypercube sampling of uncertain climate parameters, resulting in a 1000-member ensemble. This provides probabilistic projections of climate change over the 21st century. It is then possible to run ensemble simulations of the IGSM-CAM based on a sub-sampling of the 1000-member probabilistic projections of global surface air temperature changes by the end of 21st century. As such, probabilistic projections of regional climate change can be obtained with a smaller number of ensemble members than usually needed for Monte Carlo simulation, *e.g.*, 20 simulations representing every 20-quantiles

of the IGSM probabilistic distribution of global mean surface temperature changes.

2.2 Description of the Simulations

In this study, results from simulations based on two emissions scenarios and three sets of climate parameters are presented. The three sets of climate parameters correspond to the median, and the lower and upper bounds of the probability distribution of 21st century climate change.

2.2.1 Climate Parameters

Because Monte Carlo simulations using the IGSM2.3 are underway, it is not possible to currently identify the median, and the lower and upper bounds of the probability distribution of 21st century climate change from probabilistic distribution of global mean surface changes. Instead this study relies on the marginal posterior probability density function of climate parameters. Based on the methodology described in (Sokolov *et al.*, 2003), the ocean heat uptake rate in all simulations is found to lie between the mode and the median of the probability distribution obtained with the IGSM using optimal fingerprint diagnostics similar to Forest *et al.* (2008). The three values of climate sensitivity chosen represent the median (2.5°C) and the bounds of the 90% probability interval (2.0°C and 4.5°C) based on the marginal posterior probability density function with uniform prior for the climate sensitivity-net aerosol forcing (CS- F_{ae}) parameter space shown in **Figure 3**. These lower and upper bounds of climate sensitivity agree well with the conclusions of the Fourth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR4) that finds that the climate sensitivity is likely to lie in the range 2.0°C to 4.5°C (Meehl *et al.*, 2007). The associated net aerosol forcing was chosen to ensure a good agreement with the observed climate change over the 20th century. This is achieved by choosing

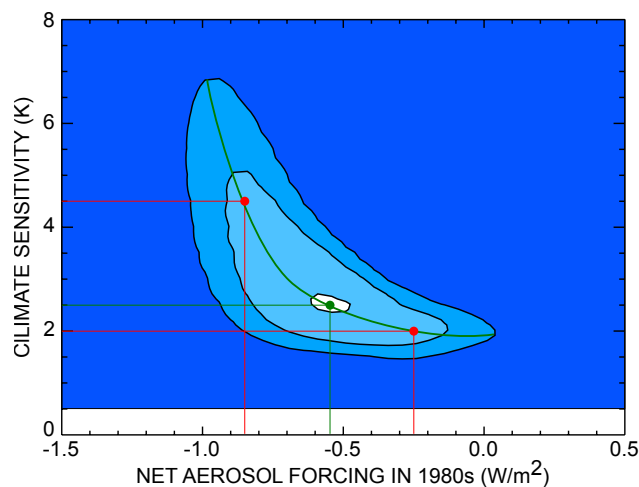


Figure 3. The marginal posterior probability density function with uniform prior for the climate sensitivity-net aerosol forcing (CS- F_{ae}) parameter space. The shading denotes rejection regions for a given significance level – 50%, 10% and 1%, light to dark, respectively. The positions of the red and green dots represent the parameters used in the simulations presented in this study. The green line represents combinations of climate sensitivity and net aerosol forcing leading to the same transient climate response as the median set of parameters (green dot).

the net aerosol forcing that provides the same transient climate response as the median set of parameters (see Figure 3). Because the concentrations of sulfate aerosols significantly decrease over the 21st century in both emissions scenarios, climate changes obtained in these simulations provide a good approximation for the median and the 5th and 95th percentiles of the probability distribution of 21st century climate change.

2.2.2 Emissions Scenarios

The two emissions scenarios presented in this study are a median “business as usual” scenario where no policy is implemented after 2012 and a policy scenario where greenhouse gases are stabilized at 660 ppm CO₂-equivalent (550 ppm CO₂-only) by 2100. **Figure 4** shows the greenhouse gas concentrations and radiative forcing for the two emissions scenarios. These emissions are similar to, respectively, the Representative Concentration Pathways RCP8.5 and RCP4.5 scenarios (Moss *et al.*, 2010). The median unconstrained emissions scenario corresponds to the median of the distribution obtained by performing Monte Carlo simulations of the EPPA model, using Latin Hypercube sampling of 100 parameters, resulting in a 400-member ensemble simulation (Webster *et al.*, 2008). The uncertain input parameters include labor productivity growth rates, energy efficiency trends, elasticities of substitution, costs of advanced technologies, fossil fuel resource availability, and trends in emissions factors for urban pollutants. As opposed to the Special Report on Emissions Scenarios (SRES), this approach allows a more structured development of scenarios that are suitable for uncertainty analysis of an economic system that results in different emissions profiles. Usually the EPPA scenario construction starts from a reference scenario under the assumption that no climate policies are imposed. Then additional stabilization scenarios framed as departures from its reference scenario are achieved with specific policy instruments. The 660 ppm CO₂-equivalent stabilization scenario is achieved with a global

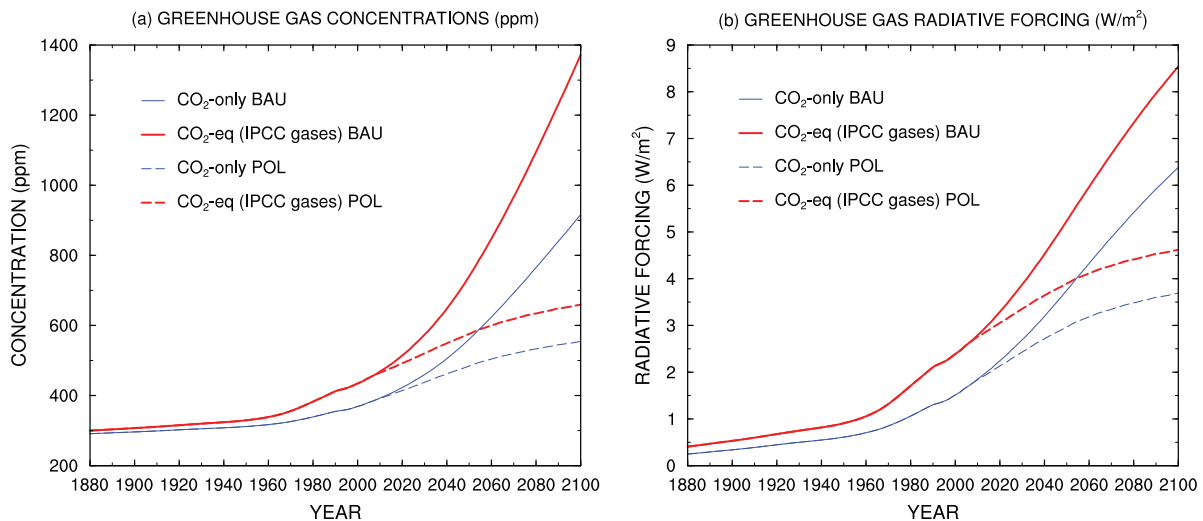


Figure 4. Global mean greenhouse gas (a) concentrations in ppm and (b) radiative forcing in W/m². The median “business as usual” and stabilization scenarios are represented by, respectively, solid and dashed lines while CO₂-only and CO₂-equivalent are represented by, respectively, red and blue lines.

cap and trade system with emissions trading among all regions beginning in 2015. The path of the emissions over the whole period (2015–2100) was constrained to simulate cost-effective allocation of abatement over time.

Summary of the climate parameters and emissions scenarios chosen for each of the simulations presented along with the name conventions used in the remainder of this article is shown in **Table 1**.

Table 1. Summary of the climate parameters and emissions scenarios chosen for each of the simulations presented along with the name conventions used in the remainder of this article.

Climate parameters		Emissions scenario	Name convention
Climate sensitivity	Net aerosol forcing		
2.0°C	−0.25 W/m ²	“Business as usual”	lowCS_BAU
		Stabilization scenario	lowCS_POL
2.5°C	−0.55 W/m ²	“Business as usual”	medCS_BAU
		Stabilization scenario	medCS_POL
4.5°C	−0.85 W/m ²	“Business as usual”	highCS_BAU
		Stabilization scenario	highCS_POL

2.3 Datasets

Besides the merged Hadley-OI sea surface temperature and MOZART ozone, various datasets are used to validate the IGSM-CAM framework. The regional patterns of temperature and precipitation are compared with the HadISST1 climatology of sea surface temperature (Rayner *et al.*, 2003), the Climatic Research Unit (CRU) climatology of surface air temperature over land (Jones *et al.*, 1999) and the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) observation-based climatology of precipitation (Xie and Arkin, 1997). The IGSM-CAM is also compared with all available models from the IPCC AR4 (Randall *et al.*, 2007). Meanwhile, changes in the IGSM-CAM global mean surface air temperature are compared with the GISS surface air temperature observations (Hansen *et al.*, 2010).

3. RESULTS

3.1 Validation

While CAM has been the subject of extensive validation (Hurrell *et al.*, 2006; Collins *et al.*, 2006), the IGSM-CAM framework needs to be evaluated for its ability to simulate the present climate. **Figure 5** shows the observed annual-mean merged SST and surface air temperature over land along with the IPCC AR4 multi-model mean error, the typical IPCC model error and the IGSM-CAM model error, for the median climate sensitivity simulation. IGSM-CAM simulations with low and high climate sensitivity show very similar results since the associated aerosol forcing was specifically chosen to agree with the observed climate change over the 20th century.

While comparing a single model with the IPCC AR4 multi-model mean is useful, it should be noted that in most cases, the multi-model mean is better than all of the individual models (Gleckler *et al.*, 2008; Annan and Hargreaves, 2011). For this reason it is important to consider the typical error as an additional means of comparison and validation of the modeling framework. The IGSM-CAM surface temperature error compares well with the multi-model mean error over most of the globe and is generally within the typical error. The IGSM-CAM surface temperature agrees particularly well with observations over the ocean, with errors less than 1°C. Over land areas, the IGSM-CAM exhibits significant regional biases, but mainly in areas where the IPCC typical error is large. For example, the IGSM-CAM is significantly warmer than the observations over Antarctica, the Canadian Arctic region and the Hudson Bay, and Eastern Siberia. Meanwhile, a significant cold bias is present over the coast of Antarctica and the Himalayas. These errors are generally associated with polar regions, where biases in the simulated sea-ice has large impacts on surface temperature, and near topography that is not realistically represented at the resolution of the model. Nonetheless, the IGSM-CAM reproduces reasonably well the end of

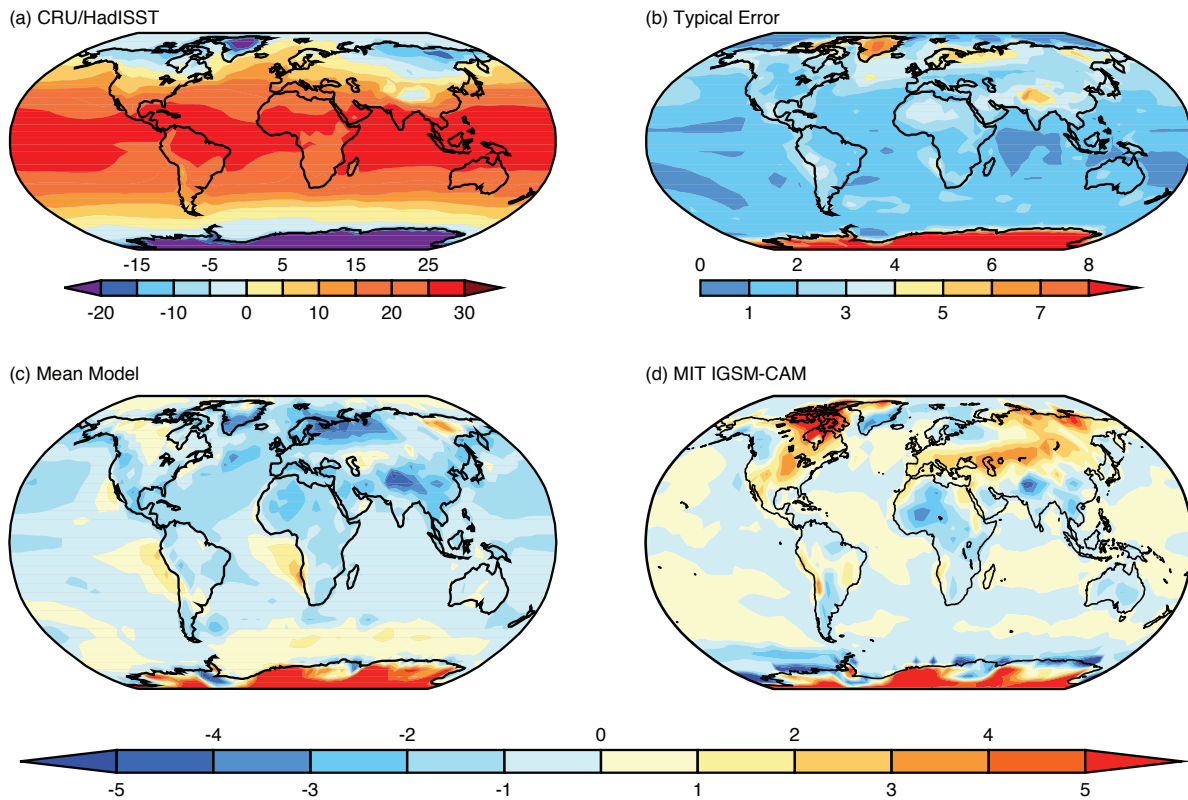


Figure 5. (a) Observed annual-mean HadISST1 climatology for 1980–1999 and CRU surface air temperature climatology over land for 1961–1990. (b) Root-mean-square model error (°C), based on all available IPCC model simulations (*i.e.* square-root of the sum of the squares of individual model errors, divided by the number of models). (c) IPCC AR4 multi-model mean error (°C), simulated minus observed. (d) IGSM-CAM model error (°C), for the median climate sensitivity simulation, simulated minus observed. The model results are for the same period as the observations. In the presence of sea ice, the SST is assumed to be at the approximate freezing point of sea water (−1.8°C). Adapted from Randall *et al.* (2007), Figure S8.1b.

20th century surface temperature compared with other available GCMs.

Figure 6 shows a similar analysis for precipitation. The IGSM-CAM is generally able to simulate the major regional characteristics shown in the CMAP annual mean precipitation, including the lower precipitation rates at higher latitudes and the rainbands associated with the Inter-Tropical Convergence Zone (ITCZ) and midlatitude oceanic storm tracks. Nonetheless, the IGSM-CAM model error shows clear regional biases with patterns similar to the mean IPCC model error, but with larger magnitudes. For example, the IGSM-CAM precipitation presents a wet bias in the western basin of the Indian Ocean and a dry bias in the eastern basin, like in the IPCC mean model. The patterns of precipitation bias over the Pacific Ocean and the Atlantic Ocean are also very similar in the IGSM-CAM and IPCC mean model. The typical IPCC model error reveals that many of the IPCC models display substantial precipitation biases, especially in the tropics, which often approach the magnitude of the observed precipitation (Randall *et al.*, 2007). The substantial biases in the simulated present-day precipitation can explain the lack of consensus in the sign of future regional precipitation changes predicted by IPCC models in parts of the tropics. Compared with the IPCC models, the skills of the IGSM-CAM framework in

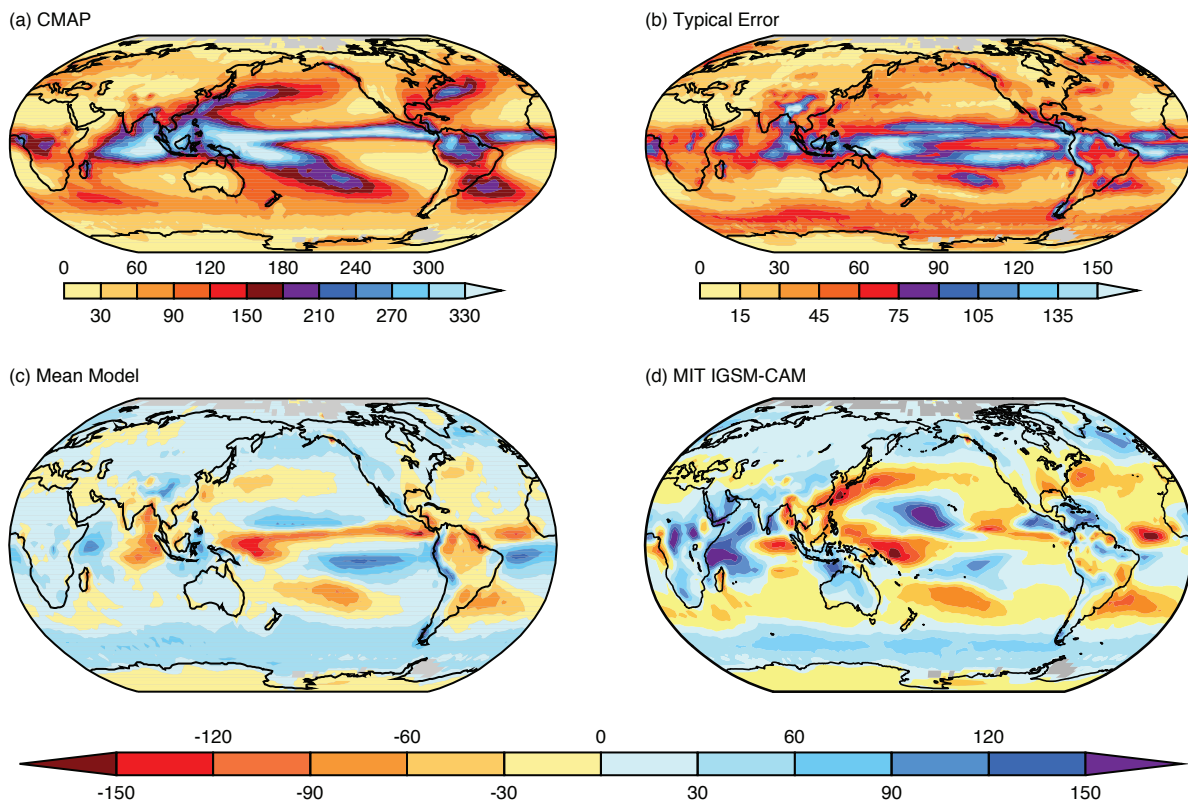


Figure 6. (a) Observed annual-mean CMAP precipitation climatology for 1980–1999 (cm). (b) Root-mean-square model error (cm), based on all available IPCC model simulations (*i.e.* square-root of the sum of the squares of individual model errors, divided by the number of models). (c) IPCC AR4 multi-model mean error (cm), simulated minus observed. (d) IGSM-CAM model error (cm), simulated minus observed. The model results are for the same period as the observations. Observations were not available in the gray regions. Adapted from Randall *et al.* (2007), Figure S8.9b.

simulating present-day annual mean precipitation are reasonably good.

Altogether, Figure 5 and Figure 6 demonstrate the ability of the IGSM-CAM framework to reproduce present-day surface temperature and precipitation reasonably well compared with the general circulation models available in the IPCC AR4. A similar analysis was also performed for other variables, including radiative fluxes and moisture fields, showing similar skills.

3.2 Future Projections

Figure 7 shows the changes in global mean surface air temperature and precipitation anomalies from the 1951–2000 period. It shows a broad range of increases in surface temperature by the end of the 21st century, with a global increase between 3.7 and 7.2°C for the “business as usual” scenario and between 1.7 and 3.7°C for the stabilization scenario (based on the 2091–2100 mean anomalies). This is in very good agreement with Sokolov *et al.* (2009) who performed a 400-member ensemble of climate change simulations with the IGSM version 2.2 for the median unconstrained emissions scenario, with Latin Hypercube sampling of climate parameters based on probability density functions estimated by Forest *et al.* (2008). They find that the 5th and 95th percentiles of the distribution of surface warming for the last decade of the 21st century are respectively 3.8 and 7.0°C when only considering climate uncertainty. This confirms that the low and high climate sensitivity simulations presented in this study are representative of, respectively, the 5th and 95th percentiles of the probability distribution of 21st century climate change. Furthermore, the IGSM-CAM global mean surface air temperature anomalies at the end of simulations (year 2100) are in excellent agreement with the IGSM output (shown by the horizontal lines in Figure 7). This demonstrates the consistency in the global climate response

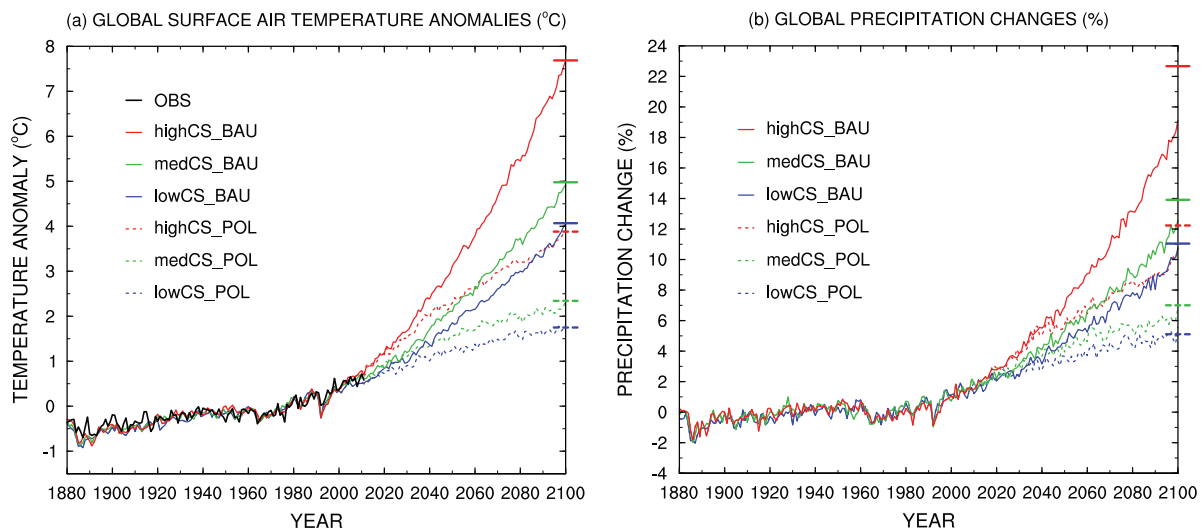


Figure 7. (a) Global mean surface air temperature anomalies (°C) from the 1951–2000 mean for the 6 IGSM-CAM simulations and for the GISS surface air temperature observations (until 2011). (b) Global mean precipitation changes (%) from 1951–2000 for the 6 IGSM-CAM simulations. The reference policy is shown in solid lines and the stabilization policy in dashed lines. The simulations with a climate sensitivity of 2.0, 2.5 and 4.5°C are shown respectively in blue, green and red. The 2100 anomalies from the IGSM simulations are represented by the horizontal lines on the right Y-axis.

within the framework, largely due to the consistent sea surface temperature forcing and the matching climate parameters in between the IGSM and CAM. Meanwhile, the changes in global mean precipitation show increases between 9.7 and 17.4 mm/year for the “business as usual” scenario and between 5.1 and 9.7 mm/year for the stabilization scenario (based on the 2091–2100 mean anomalies). However, it should be noted that the IGSM-CAM global mean precipitation anomalies in 2100 differ from that of the IGSM because the IGSM and CAM have very distinct parameterization schemes. Figure 7 indicates that implementing a 660ppm CO₂-equivalent stabilization policy can significantly decrease future global warming, with the lower bound warming (from the 1951–2000 mean) below 2°C and the upper bound equal to the lower bound warming of the unconstrained emissions scenario. It also presents evidence that the uncertainty associated with the climate response is of comparable magnitude to the uncertainty associated with the emissions scenarios, thus demonstrating the need to account for both.

Figure 8 shows maps of changes in annual mean surface air temperature between the 1981–2000 and 2081–2100 periods. The analysis of the global mean changes in surface air temperature and precipitation already revealed that the range of uncertainty in the future climate change is large, with similar contributions from uncertainty in the climate parameters and in emissions. Figure 8 provides a new perspective on the uncertainty in climate change with a regional dimension. It shows that the pattern of surface warming exhibits a distinct polar amplification and a stronger response over land. The warming is significantly weaker over the ocean, except over the coast of Antarctica and over the Arctic Ocean where melting sea-ice leads to a stronger warming. Over high latitude land areas, the warming ranges between 5° and 12°C for the “business as usual” scenario and between 2° and 6°C for the stabilization scenario. These results indicate that several regions are at risk of severe climate change, with major potential impacts. For example, the high climate sensitivity simulation for “business as usual” scenario shows Northern Eurasia warming by as much as 12°C in the annual mean and 16°C in wintertime

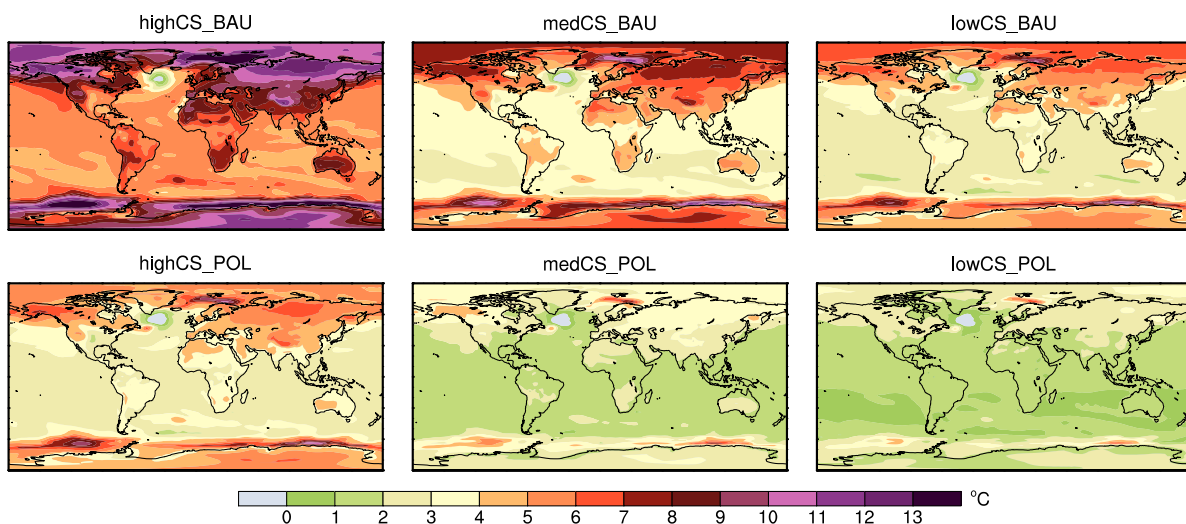


Figure 8. Changes in annual mean surface air temperature (°C) for all simulations for the period 2081–2100 relative to 1981–2000.

(not shown). Such warming would lead to severe permafrost degradation (Lawrence and Slater, 2005) and the resulting formation of new thaw lakes could lead to enhanced emissions of greenhouse gases, such as methane (Walter *et al.*, 2006). Similarly, Western Europe would warm by 8°C in the annual mean and 12°C in summertime. To put this in perspective, during the European summer heat wave of 2003, Europe experienced summer surface air temperature anomalies (based on the June-July-August daily averages) reaching up to 5.5°C with respect to the 1961–1990 mean (Garcia-Herrera *et al.*, 2010). That heat wave resulted in more than 70,000 deaths in 16 countries (Robine *et al.*, 2008). A warming of 12°C in summertime would likely result in serious strain on the most vulnerable populations and could lead to serious casualties.

Maps of changes in annual mean precipitation are shown in **Figure 9**. The precipitation changes show general patterns that are consistent among all simulations. Precipitation tends to increase over most of the tropics, at high latitudes and over most land areas. In contrast, the subtropics and midlatitudes experience decreases in precipitation over the ocean. Increases in precipitation over land are largely restricted to the Western United States, Europe (except Northern Europe), Northwest Africa, Southeast China, Central America and Patagonia. The magnitude of these patterns of precipitation changes generally increases with increasing warming so that the high climate sensitivity simulation for the “business as usual” scenario presents the largest overall precipitation changes. However, several regions exhibit changes in precipitation of different signs among all the simulations. That is the case of Australia, Mainland Southeast Asia, India and Southeast Africa. These regions tend to experience decreases in precipitation for the simulations with the least warming but increases in precipitation with the strongest warming. These results emphasize the fact that only one GCM was used in this study, leading to overall agreement in the regional patterns of precipitation change among all simulations. Nevertheless, there exists regional uncertainty associated with differences in the climate sensitivity (Sokolov and Monier, 2012) as well as aerosol forcing.

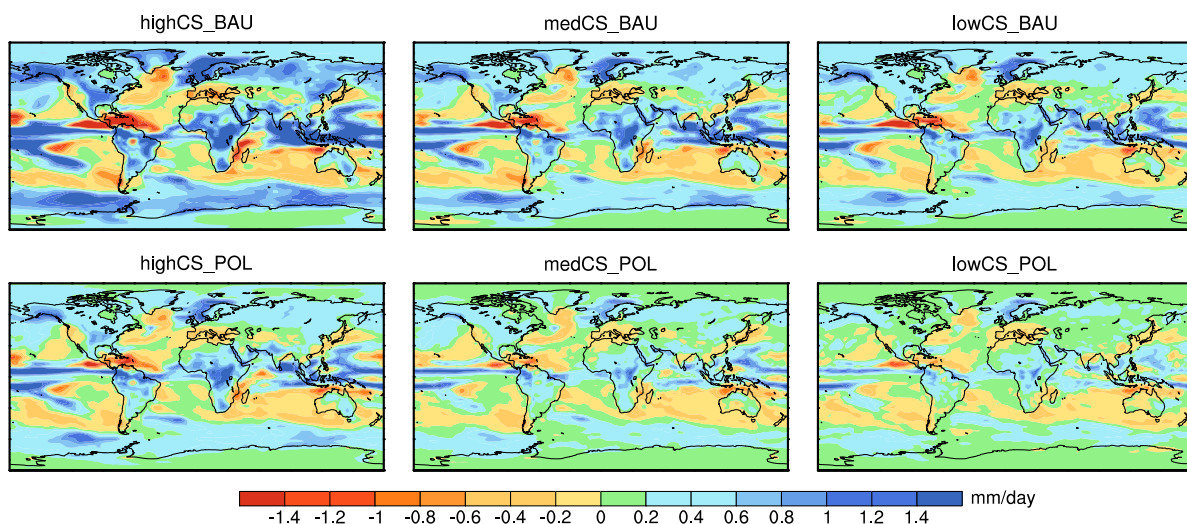


Figure 9. Changes in annual mean precipitation (mm/day) for all simulations for the period 2081–2100 relative to 1981–2000.

Figure 10 shows the estimates of the median and bounds of the 90% probability interval of mean changes in surface air temperature ($^{\circ}\text{C}$) over the globe and the seven continents for the period 2081–2100 relative to 1981–2000. It further confirms the wide range of uncertainty in the future global and regional climate change associated with both the uncertainty in emissions and the climate response. Under the unconstrained emissions scenario, every continent would warm by at least 2.8°C within the 90% probability interval, with the least warming in South America and Australia and Oceania. Meanwhile, Europe and Antarctica would warm by as much as 9.5°C . The stabilization scenario shows significant reduction in warming over all continents. Generally, the upper bound warming under stabilization scenario and the lower bound warming for the “business as usual” scenario agree well.

Figure 10 also presents the 95% confidence interval for the median and bounds the 90% probability interval derived from the standard error of the difference of the means between the 2081–2100 period and 1981–2000 period. The standard error of the difference essentially quantifies the variability within the two periods (present-day and future) and thus the statistical uncertainty in the temperature change. Generally, a larger warming is associated with a wider

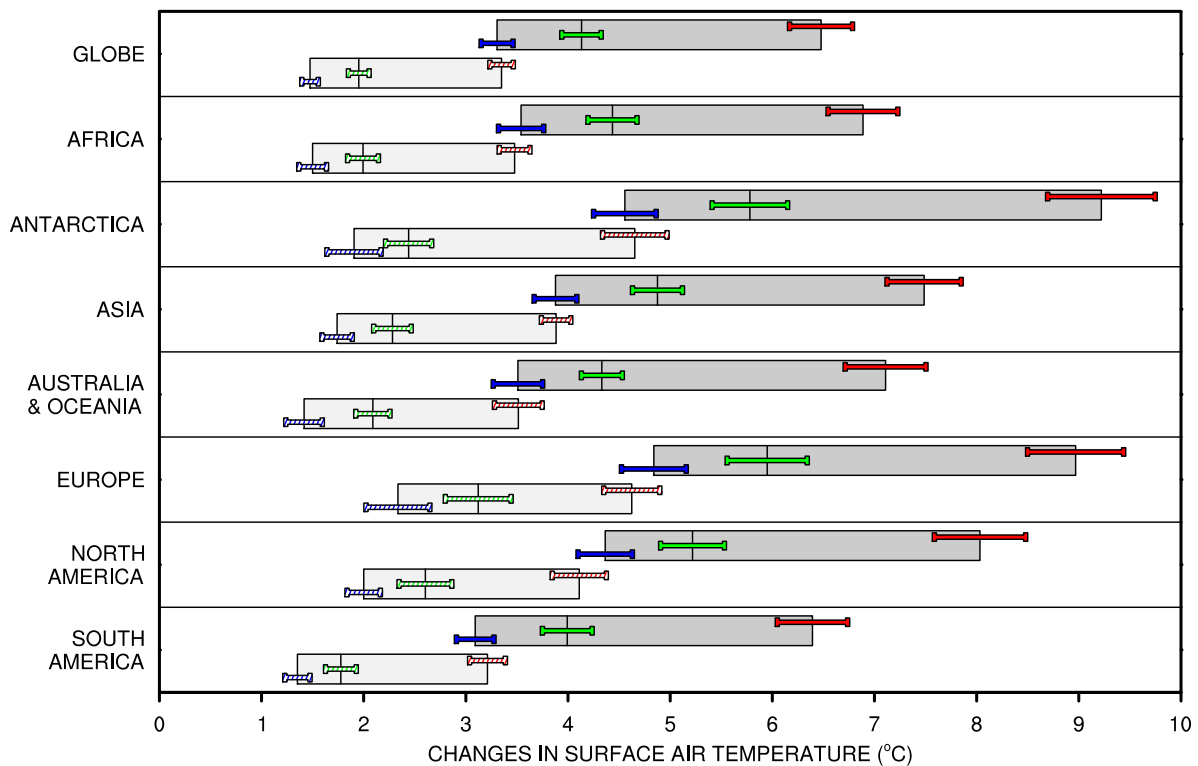


Figure 10. Estimates of the median and bounds of the 90% probability interval (gray boxes) of mean changes in surface air temperature over the globe and the seven continents for the period 2081–2100 relative to 1981–2000. The whiskers represent the 95% confidence interval of the median (green), and lower (blue) and upper (red) bounds derived from the standard error of the difference of the means between the 2081–2100 period and 1981–2000 period. The “business as usual” scenario is shown in dark gray and solid whiskers while the stabilization policy scenario is shown in light gray and striped whiskers.

confidence interval. The upper bound temperature changes for the “business as usual” scenario present the widest confidence intervals, as large as 1°C over Antarctica and Europe. When taking into account the statistical uncertainty in the warming, the 90% probability intervals of mean changes in surface air temperature for each continent increase by 7 to 13%.

Figure 11 shows the same analysis for precipitation. While all continents experience increases in precipitation, the regional precipitation response is more varied than for temperature. For example, Europe shows little increase in precipitation and a narrower 90% probability interval compared with Africa, Asia or South America. Meanwhile, the lower bound and median changes in precipitation is insignificant over Australia and Oceania for the stabilization scenario. This is in part due to the choice of regional averaging. Europe and Australia and Oceania are continents where different regions present opposite signs in the precipitation changes, *e.g.*, Northern Europe shows moistening while the rest of Europe shows drying (see Figure 9). What is particularly striking is that the width of the 95% confidence intervals derived from the standard error of the difference of the means is substantially larger for each continent than for the globe. This indicates that the variability in regional precipitation is much larger than for the global mean. This puts

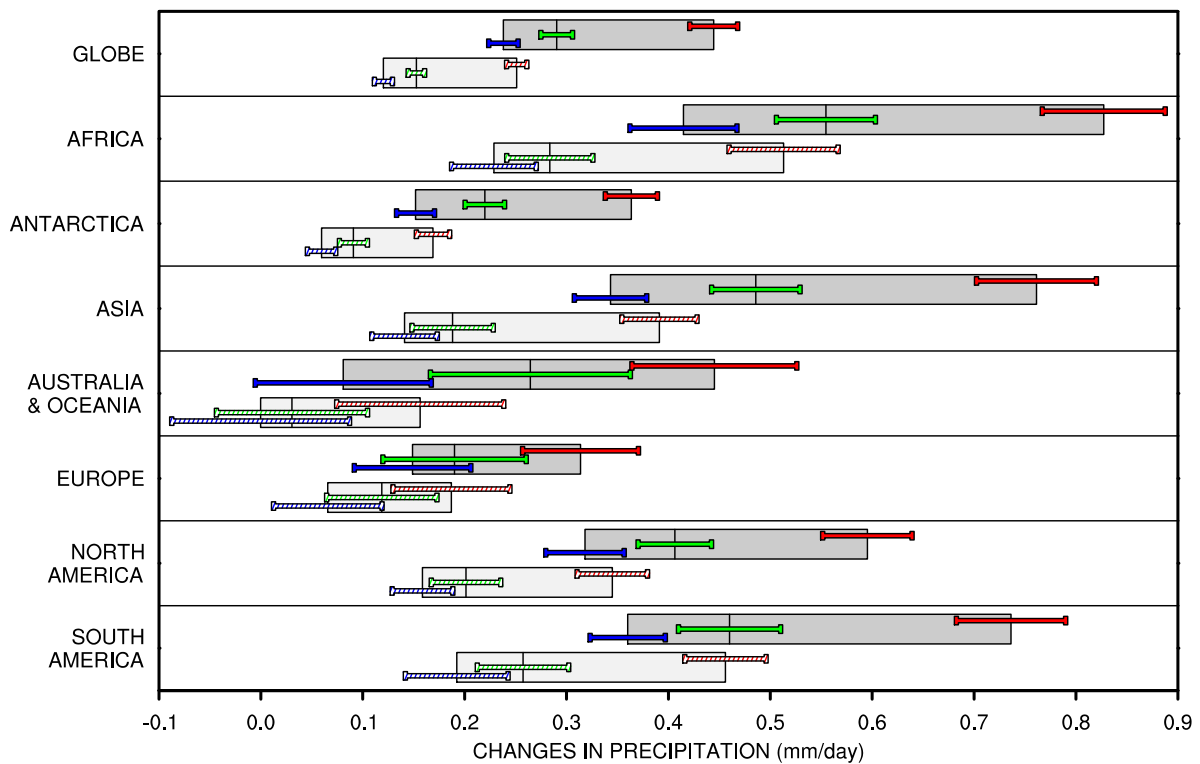


Figure 11. Estimates of the median and bounds of the 90% probability interval (gray boxes) of mean changes in precipitation (mm/day) over the globe and the seven continents for the period 2081–2100 relative to 1981–2000. The whiskers represent the 95% confidence interval of the median (green), and lower (blue) and upper (red) bounds derived from the standard error of the difference of the means between the 2081–2100 period and 1981–2000 period. The “business as usual” scenario is shown in dark gray and solid whiskers while the stabilization policy scenario is shown in light gray and striped whiskers.

some of the results based on the bounds of the 90% probability interval alone into perspective. For several continents, the statistical uncertainty associated with natural variability is of similar magnitude to the uncertainty from the climate parameters, represented by the 90% probability interval (gray boxes). That is the case for Europe and Australia and Oceania where the confidence intervals of the median and bounds of the 90% probability interval overlap. In addition, the confidence intervals of the median and lower bound changes in precipitation overlap for the stabilization scenario for every continent. Finally, when the 95% confidence intervals are considered, the 90% probability intervals of mean changes in precipitation for each continent increase by 10 to 55%.

4. SUMMARY AND CONCLUSION

This paper describes a new framework where the MIT IGSM, an integrated assessment model that couples an earth system model of intermediate complexity to a human activity model, is linked to the three-dimensional atmospheric model CAM. The IGSM-CAM modeling system is an efficient and flexible framework to explore uncertainties in the future global and regional climate change. Because it incorporates a human activity model, it is possible to analyze uncertainties in emissions that result from uncertainties intrinsic to the economics model, from parametric uncertainty, to uncertainty in future climate policies. Because the climate parameters can be consistently changed within the modeling framework, the IGSM-CAM can be used to address uncertainty in the climate response to future changes in greenhouse gas and aerosols concentrations. Because the atmospheric chemistry and the land and ocean biogeochemical cycles are computed within the IGSM, the IGSM-CAM is more computationally efficient than a fully coupled general circulation model. Finally, the IGSM-CAM can be used to derive probability projections of climate change at the continental and regional levels, in a computationally efficient manner. First, probabilistic projections of future climate change are obtained by performing Monte Carlo simulation with the IGSM, with Latin Hypercube sampling of the uncertain climate parameters (climate sensitivity, net aerosol forcing and ocean heat uptake rate). Then IGSM-CAM ensemble simulations can be run based on a sub-sampling of the IGSM probabilistic projections of global surface air temperature changes by the end of 21st century. Following this methodology, probabilistic projections of regional climate change can be obtained efficiently with a smaller number of ensemble members than usually needed for Monte Carlo simulation and within running a fully coupled general circulation model.

It should be noted that there are some limitations to this modeling framework. While the IGSM is a fully coupled earth system model that includes a three-dimensional ocean model and a simplified zonal-mean atmospheric model, the three-dimensional atmospheric model the IGSM-CAM framework does not feedback to the ocean model. For this reason, the IGSM-CAM is not suitable to investigate regional climate processes in the coupled ocean-atmosphere system, *e.g.*, the impact of climate change on El Niño-Southern Oscillation. The results presented in this paper are also based on just one particular GCM, the NCAR CAM version 3. For this reason, the IGSM-CAM cannot cover the full uncertainty in regional patterns of climate change. While, several regions show changes in precipitation of opposite signs in the simulations presented in

this study (*e.g.*, India, Australia or Mainland Southeast Asia), the range of regional response is not as large as that evidenced among all available IPCC models. Furthermore, unlike the perturbed physics approach which can produce several versions of a model with the same climate sensitivity but with very different regional patterns of change, the cloud radiative adjustment method can only produce one version of the model with a specific climate sensitivity (Sokolov and Monier, 2012). Nonetheless, the IGSM-CAM has several advantages over more traditional methods used to assess regional uncertainty, like perturbed physics ensembles or pattern scaling methods.

When using a perturbed physics approach, the range of climate sensitivity generated in most GCMs does not cover homogeneously the range of uncertainty obtained based on the observed 20th century climate change (Knutti *et al.*, 2003; Forest *et al.*, 2008; Sokolov and Monier, 2012). Moreover, in most cases, the values of climate sensitivity obtained by the perturbed physics approach tend to cluster around the climate sensitivity of the unperturbed version of the given model. Furthermore, each version of the model with a different perturbation is weighted equally regardless of the obtained climate sensitivity, even though the values of climate sensitivity are not equally probable. In comparison, any value of climate sensitivity within the wide range of uncertainty can be obtained in the IGSM-CAM framework, which allows Monte Carlo type probabilistic climate forecasts to be conducted where values of uncertain parameters not only cover the whole uncertainty range, but cover it homogeneously. Meanwhile, pattern scaling methods have been shown to be more accurate for temperature than for precipitation and for investigating changes in seasonal and annual means (Mitchell, 2003). In addition, pattern scaling methods lead to a significant reduction in the variability of the original GCM ensemble simulations (Lopez *et al.*, 2011), thus making the method unlikely to work for some quantities like variability and extremes (Meehl *et al.*, 2007). On the other hand, the IGSM-CAM can be used to investigate probabilistic projections of variables that do not scale well along with changes in the occurrence of extreme events, like changes in midlatitude storm track intensity or number of frost days.

The IGSM-CAM framework was used to simulate present-day climate and then compared to all available IPCC models from the AR4. The IGSM-CAM simulates reasonably well the present-day annual mean surface temperature and precipitation compared with other GCMs. The IGSM-CAM exhibits significant surface temperature bias over regions where most models show systematic errors. These errors are generally associated with polar regions and are caused by biases in the simulated sea-ice, or associated with topography not properly resolved in the model. The IGSM-CAM is also able to simulate the major regional characteristics of observed annual mean precipitation, including the ITCZ and midlatitude oceanic storm tracks. The IGSM-CAM precipitation bias shows patterns and magnitudes similar to the IPCC typical model error, with the largest errors located in the tropics. Overall, the IGSM-CAM compares reasonably well with the other available GCMs.

This paper presents simulations based on two emissions scenarios and three sets of climate parameters. The two emissions scenarios tested are an unconstrained scenario and a stabilization scenario at 660 ppm CO₂-equivalent by 2100. Meanwhile, the three values of climate sensitivity

chosen provide a good approximation for the median, and the 5th and 95th percentiles of the probability distribution of 21st century climate change. As such, these simulations provide estimates of the median and 90% probability interval of climate change at the continental and regional levels for two different emissions scenarios. Results show that the uncertainty associated with the climate response is of comparable magnitude to the uncertainty associated with the emissions scenarios, both at global and regional scales. This demonstrates the need to account for both sources of uncertainty in climate change projections. Furthermore, several continents are at risk of severe climate change, with increases in annual mean temperature above 8°C in Europe, North America and Antarctica for the unconstrained emissions scenario. The implementation of a policy scenario significantly decreases the projected climate warming. Over each continent, the upper bound climate warming under the policy scenario is comparable with the lower bound increase in temperature in the “business as usual” scenario and underscores the effectiveness of a global climate policy, even given the uncertainty in the climate response. Estimates of the 95% confidence interval derived from the standard error of the difference of the means was also computed for the median and bounds of the 90% probability interval of warming. The standard error quantifies the variability within the two periods analyzed (present-day and future) and thus the statistical uncertainty in the warming. When taking into account the statistical uncertainty, the 90% probability intervals of mean changes in surface air temperature for each continent increase by 7 to 13%.

Meanwhile, changes in precipitation show an increase over all continents but with a more regionally varied response than temperature. For example, Europe shows little increase in precipitation and a narrower 90% probability interval compared with Africa, Asia or South America. The 95% confidence intervals of the precipitation changes are much wider than for temperature, such that they put some of the results based on the bounds of the 90% probability interval alone into perspective. For several continents, the statistical uncertainty in precipitation changes associated with natural variability is of similar magnitude to the uncertainty from the climate parameters. For Europe and for Australia and Oceania, the confidence intervals of the median and bounds of the 90% probability interval overlap, essentially indicating that the probability distribution is no different than a uniform distribution. Finally, when the statistical uncertainty in mean precipitation changes is taken into account the 90% probability intervals over each continent increase by 10 to 55%. This highlights the need to take into consideration statistical uncertainty due to natural variability when investigating bounds of probable changes, particularly for variables like precipitation.

While this paper provides useful information on bounds of probable climate change at the continental and regional scales, ensemble simulations are necessary to obtain probability distribution of future changes. Once Monte Carlo simulations using the IGSM2.3 are performed, IGSM-CAM ensemble simulations will run based on a sub-sampling of the IGSM probabilistic projections of global surface air temperature changes. In addition, further work is required to investigate aspects of climate change other than changes in the mean state. For example, changes in the frequency and magnitude of extreme events, such as heat waves or storms, are of primary

importance for impact studies and to inform policy makers. For this reason, the IGSM-CAM framework will be utilized for a wide range of applications on continental and regional climate change and their societal impacts.

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