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Impact of climate model uncertainties on socioeconomics: A case study with a medium mitigation scenario

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ABSTRACT

Carbon dioxide (CO_2) emissions are strongly associated with economy. The amount of CO_2 that human society can emit in order to achieve a climate target depends on physical and biogeochemical properties in the climate system; these vary among climate models or earth system models (ESMs). Thus, uncertainties in such models, the spread remained when we both consider the range of existing models and observational data for key variables, can affect analysis of future global economy. In this study, using a computable general equilibrium model, we analyze the impacts on socioeconomics under a medium climate mitigation scenario by following three emission pathways considering uncertainties in existing ESMs (the lower and upper bounds as well as the mean). The results indicate that the impacts are larger in the lower bound case, despite the fact that economic and energy demands will increase continuously. In a comparison between the upper and lower bound cases, the carbon price of the latter case is approximately three times higher than that of the former case in 2100. Consequently, primary/final energy demand in the lower bound case becomes 1.0%/14% lower, and more renewables and carbon capture and storage are required to be used. Furthermore, the gross domestic product in the lower bound case is 4.1% smaller. Thus, within the scenario, the socioeconomic impacts caused by ESM uncertainties are not insignificant, but are smaller than the differences in annual and cumulative emissions.

1. Introduction

Several climate change scenarios have been developed related to the Intergovernmental Panel on Climate Change (IPCC), including the Special Report on Emission Scenarios (SRES) [1] and the Representative Concentration Pathways (RCPs) [2–4]. Most recently, the RCP scenarios were developed primarily for the fifth IPCC Assessment Report [2]. These scenarios describe four possible climate futures for the year 2100, as defined by four predicted radiative forcing (RF) trajectories. Four separate integrated assessment modeling teams analyzed different scenarios using their own models and predicted greenhouse gas (GHG) concentration and emission pathways [5–8]. However, multiple GHG concentration and emission pathways can be generated for each predicted 2100 RF (or concentration) level [5–11]. For example, in the RCP scenarios [5–8], each modeling team showed its own GHG emission pathway scenario and the emission pathways of the other scenarios, thus demonstrating that different emission pathways can attain a certain RF level.

Several studies have compared the socioeconomic feasibility and impact of specific GHG concentration (or RF) scenarios using multiple integrated assessment models (IAMs) [9–11]. These studies show varied GHG emission pathways at certain concentration levels because of differences in model types, timing of the emission reductions, assumed technology, and other assumptions, such as future economic and demographic growth.

Using an IAM and a simplified climate model, Rogelj et al. [12] implement a systematic scenario analysis of how different levels of short-term emissions would impact the technological and economic feasibility of achieving the United Nation's (UN) 2 °C global warming target for 2100. They show possible GHG emission pathways for achieving the target using both models. However, they focus on technological and economic perspectives, combining short- and long-term views. Research to integrate climate model studies and socioeconomic model studies has just begun, and consequently there is no documented information on the non-uniqueness of the climate models and their future projections from a socioeconomic perspective. If the spread among the climate models significantly affects economics and society, policymaking

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must follow a different path, including climate, energy, and socioeconomic policies.

In recent days, many climate models have been coupled with ecosystem and other models to consider biogeochemical processes, thus creating earth system models (ESMs). ESM (or climate model) uncertainties include physical uncertainties, such as climate sensitivity and oceanic heat uptake efficiency, and biogeochemical uncertainties, such as the sensitivity of carbon uptake capacity in increasing carbon dioxide (CO_2) concentration or temperature [13]. These factors, in combination, affect the amount of CO_2 that human society can emit for a given concentration pathway.

In the following sections, the uncertainty of ESMs and the allowable emission pathways for the given concentration pathway are defined as their spreads that are consistent within the range of existing ESMs and observational data (see Section 2.3 for detail). That is, the uncertainty is caused by our insufficient knowledge to formulate each process of the earth system and to constrain the parameters by using observational data.

The purpose of this study is to analyze the impact of ESM uncertainties on socioeconomics (including energy). It follows a climate mitigation scenario defined by an RF level using a computable general equilibrium (CGE) model based on multiple GHG emission pathways obtained from an ESM of intermediate complexity (EMIC) while considering the uncertainties in existing ESMs. This study significantly combines climatic model studies (climate aspects) and a CGE model (socioeconomic aspects) and clarifies the meaning of the uncertainties in existing ESMs in terms of the socioeconomic aspects. Here, we examine carbon price, gross domestic product (GDP), energy demand, and the Kaya identity for the socioeconomic aspects. In this study, we use emission pathways to achieve an RF of 4.5 W/m^2 in 2100 (called the "RF4.5 scenario"), which is a medium climate mitigation scenario and one of the four RF levels designed for the RCP scenarios [7].

Section 2 of the paper describes the model, scenarios, and emission pathways. In Section 3, we show the results of the analysis, focusing on GDP and energy demand. Finally, in Section 4, we draw conclusions.

2. Methods

2.1. Model

We use a CGE model to analyze the impact of ESM uncertainties on socioeconomics for achieving a RF of 4.5 W/m^2 in 2100. This model is based on Masui et al. [5], Matsumoto and Masui [14,15], and Okagawa et al. [16]. The CGE model is economic in nature, widely known as a top-down approach for analyzing the economic implications of climate change issues and the related policy designs [14,15,17–19].

The model used here is a multi-regional and multi-sectoral recursive dynamic CGE model on a global scale, with energy and environmental components. Though model details are included in Appendix A, an overview is provided here. The model, also referred to as an IAM, is disaggregated into 24 geographical regions, each producing 21 economic goods/services (Table 1) and having a final demand sector. Within the energy sector, electric power is disaggregated into detailed technologies, including thermal, hydro, nuclear, and renewables. Moreover, carbon capture and storage (CCS) technology can be selected as an advanced technology for power generation. Each industrial sector is represented by a nested constant elasticity of substitution (CES) production function (see Fig A1 in Appendix A).

Each industrial sector produces goods/services delivered for the international and/or domestic markets. In each domestic market, the supplied goods/services are consumed as final consumption, investment, and/or intermediate input for industrial sectors. For each period, the total investment demand is set exogenously to meet a prescribed future economic growth rate (see Section 2.2.1).

The final demand sector in each region owns all production factors (e.g., capital, labor, land, and resources) and supplies them to the industrial sectors to earn income for final consumption and savings. The final demand for each goods or service is determined to maximize the utility represented by a CES function.

The model endogenously handles the global emissions of 10 gases, including CO_2, and is run to follow the emission pathways described in Section 2.3 between the base year (2001) and 2100.

The model considers global GHG emissions trading, assigning emissions to regions in proportion to their projected population from the year 2050 onwards. Between the base year and 2050, regional GHG emission limits were set by linear interpolation of emissions (known as contraction and convergence).

The model is calibrated to reproduce economic activity and energy levels in the base year using the following data: the Global Trade Analysis Project (GTAP) 6 database [20] for economic activity levels; the Emission Database for Global Atmospheric Research (EDGAR) v4 database [21] for GHG emissions; and the International Energy Agency (IEA) energy balance tables [22,23] for energy.

2.2. Scenarios

2.2.1. Reference scenario

The RF4.5 scenario described in Section 2.2.2 is an emission reduction scenario achieved by introducing climate policies. It indicates that, without policy intervention, RF will exceed 4.5 W/m^2. Before analysis of the RF4.5, a business-as-usual scenario, or a reference scenario, was developed. The reference scenario assumes that no policies and measures are introduced solely aiming to control GHG emissions beyond those already in place; it also assumes that existing policies are not renewed when they expire.

The reference scenario is based on several assumptions. Demographic assumptions are based on a medium variant of the UN World Population Prospects [24]. Future economic growth assumptions are based on the Sustainability First scenario presented in the UN Environmental Programme [25]. Finally, technological improvement is based on the SRES B2 scenario, a moderate scenario in the SRES [1]. These assumptions are applied to both the reference and RF4.5 scenarios.

The following details summarize the reference scenario: The global population grows from 6.1 billion in the base year to 9.8 billion in 2100, with a peak between 2080 and 2090 (Fig. 1a). Global GDP reaches $230 trillion[1] in 2100 (Fig. 1b), and the global primary energy demand reaches 1178 EJ in 2100 (Fig. 1d–e). Globally, fossil fuel demand, particularly coal, will increase continuously during this century because of its relatively low cost. Consequently, total CO_2 emissions increase to 25.1 GtC/yr (Gigatons of carbon per year) in 2100 (Fig. 1c), and the total RF reaches 7.2 W/m^2 in 2100.

2.2.2. RF4.5 scenario

In this study, we use a scenario based on RCP4.5 (a medium climate mitigation scenario), originally developed by Thomson et al. [7], to investigate the socioeconomic impacts derived from

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[1] In this study, we use the price in the base year (2001). That is, $230 trillion means 230 trillion in 2001 constant US dollars.