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Energy balance climate models and general equilibrium optimal mitigation policies

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ABSTRACT

In a general equilibrium model of the world economy, we develop a two-dimensional energy balance climate model featuring heat diffusion and anthropogenic forcing driven by global fossil fuel use across the sphere of the Earth. This introduces an endogenous location dependent temperature function, driving spatial characteristics, in terms of location dependent damages resulting from local temperature anomalies into the standard climate-economy framework. We solve the social planner's problem and characterize the competitive equilibrium for two polar cases differentiated by the degree of market integration. We define optimal taxes on fossil fuel use and how they may implement the planning solution. Our results suggest that if the implementation of international transfers across latitudes is not possible then optimal taxes are in general spatially non-homogeneous and may be lower at poorer latitudes. The degree of spatial differentiation of optimal taxes depends on heat transportation. By employing the properties of the spatial model, we show by numerical simulations how the impact of thermal transport across latitudes on welfare can be studied.

1. Introduction

The economics of climate change are based on the use of integrated assessment models (IAMs) and focus mainly on the impact of greenhouse gasses (GHGs) emissions on global temperature, as well as the impact from increases of global temperature on economic variables such as output and utility from consumption. IAMs are also used for developing long-term projections regarding climate and economic variables, the cost of climate change, and the formulation of mitigation and climate policies.[1]

The major IAMs which are structured as optimal growth models with a climate component and which are focusing on cost-benefit analysis and policy simulations (e.g. DICE/RICE, MERGE, FUND) simplify the carbon cycle and the climate system considerably, and provide results regarding temperature at a global level. When however the geographical scale is global in terms of temperature and/or damages due to climate change, important aspects of the problem, which are related both to

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[1] See for example DICE/RICE, MERGE, FUND, WITCH.

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climate science and economics are obscured. In particular there are natural mechanisms which induce a spatially non-homogeneous distribution of the surface temperature across the globe. The main drivers of these mechanisms are heat transportation that balances incoming and outgoing radiation, and the differences among the local heat absorbing capacity, the local co-albedo, which is relatively lower in ice covered regions and which changes with time as global warming tends to diminish the ice-cups.

However, these mechanisms are not accounted for by cost-benefit oriented IAMs, and as a result the existing variations in local temperatures are not modeled and therefore they do not affect local damages and their dynamics.[2] This, however, may introduce a serious bias into the result and the policy prescriptions, since it is clear that climate change is going to have impacts with profound regional differentiation across the globe.

From the point of view of climate science these IAMs are zero-dimensional models since they do not include spatial aspects such as heat diffusion. This is not however the case for the one- or two-dimensional energy balance climate models (EBCMs) developed by climate scientists which model heat diffusion across latitudes (one-dimensional) or across latitudes and longitudes (two-dimensional) (see e.g. Budyko, 1969; Sellers, 1969, 1976; North, 1975a,b; North et al., 1981, 1983; Kim and North, 1992; Wu and North, 2007).[3] One-dimensional EBCMs predict a concave temperature distribution across latitudes with the maximum temperature at the equator. This non-uniform temperature distribution is important for understanding the so called temperature anomaly which is the difference between the temperature distribution at a given benchmark period and the current period. Data indicate (Hansen et al., 2010) that since 1880 the anomaly has been relatively higher in high latitude zones, relative to zones around the equator, which suggest spatial non-uniformity in the distribution of temperature over time.

In previous papers, Brock et al. (forthcoming), Brock et al. (2013a), we have explored the properties of the one-dimensional energy balance climate models, showing how they could be coupled to economic growth models in a tractable manner. The analysis revealed new complexities stemming from climate science which also proved to have potential qualitative effects on optimal mitigation policy. The results that could be derived from these models, were however limited in the geopolitical sense, since the spatial analysis remains constrained to interaction across latitudes as opposed interactions across countries or regions.

In the present paper we will take the next natural step following the one-dimensional case, by deriving a two-dimensional model. Here the second dimension will allow for a continuous representation of local temperature anomalies for every latitude and longitude across the surface of the Earth. As with our previous papers, we will be working with a dynamic climate-economy growth model involving both heat diffusion and albedo differentiation across different geographical locations. The solution method is similar to the one-dimensional case but involves finding an alternative orthogonal basis set for the Laplacian of the heat diffusion equation. Due to the added dimensionality this basis set will differ from the Legendre polynomial basis that we used in the one-dimensional models featured in Brock et al. (forthcoming), Brock et al. (2013a), and will now involve an expansion in terms of so called spherical harmonics which are the eigenfunctions of the solution to the two dimensional Laplacian. We believe that this approach which integrates solution methods for two-dimensional spatial climate models, with methods of solving economic models, can help to push the frontier of integrated assessment modeling further by showing how solution methods involving in complex climate models such as Earth system models or general circulation models can be made tractable also when coupled to economic models.[4]

Since EBCMs most likely are new to most economists we have chosen to focus on the basic general equilibrium properties of the derived model under different assumptions regarding international capital markets and their integration. This approach shows of the basic welfare properties of the model and how the fundamental theorems of welfare economics apply within the context of our energy balance climate economy framework. The approach also makes clear how the optimal carbon tax rates should be chosen in order to implement a social planning problem and should thus constitute an important first step for economists working with these types of models. The economic part of the model is an infinite horizon Ramsey-type model allowing for basic heterogeneity among consumers and firms at each respective geographical location on the surface of the Earth identified by its latitude and longitude coordinate. We have chosen to look at two polar cases here. The first two cases concern economies that are either completely open with respect to trade and transfers or completely closed in the sense of being autarkic. In the first case when international trade and transfers are available capital returns and interest rates will be equal across locations. In this case we show that the optimal carbon tax must also be

[2] The DICE/RICE models do not include the spatial transportation of heat, nor the albedo differentials across locations, and perform their analysis in terms of the global mean surface temperature which does not vary across regions during their planning horizons. Nordhauss RICE 2010 divides the world into US, EU, Japan, Russia, Eurasia, China, India, Middle East, Africa, Latin America, other high income, other developing Asia. In the DICE model spatial damages are implicit in the aggregate representation since regional impacts are aggregated to a single measure using a bottom-up approach.

[3] For more on EBCMs see for example Pierrehumbert (2008) (Chapters 3 and 9, especially sections 9.2.5 and 9.2.6 and surrounding material). North et al. (1981) is a very informative review of EBCMs while Wu and North (2007) is a recent paper on EBCMs.

[4] The solution methods for large scale general circulation models are typically divided into *spectral methods* and *finite difference methods*. Spherical harmonics is the usual basis function involved in the spectral method. We could of course had considered other approaches alternative to EBCMs for approximating temperature fields which are based on more complex and computationally costly models, such as pattern scaling (Lopez et al., 2012) or emulation theory (Challenor et al., 2006). Because the purpose of this paper is however to construct the simplest coupled climate economy model with a climate feedback response mechanism in space that responds to changes in the spatiotemporal structure of taxes on fossil fuels, which is still analytically tractable, we considered the EBMCs framework as more appropriate.