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Analysis

Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model

F. Lamperti[a,*], G. Dosi[b], M. Napoletano[c], A. Roventini[b,d], A. Sapio[e]

[a] Institute of Economics, Scuola Superiore Sant'Anna, piazza Martiri della Libertá 33, 56127 Pisa, Italy
[b] Institute of Economics, Scuola Superiore Sant'Anna, Pisa, Italy
[c] Observatoire Français des Conjonctures Economiques (OFCE), SKEMA Business School and Université Côte d'Azur, Nice, France
[d] Observatoire Français des Conjonctures Economiques (OFCE), Nice, France
[e] Parthenope University of Naples, Naples, Italy

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ABSTRACT

In this work we develop an *agent-based model* that offers an alternative to standard, computable general equilibrium integrated assessment models (IAMs). The *Dystopian Schumpeter meeting Keynes* (DSK) model is composed of heterogeneous firms belonging to capital-good, consumption-good and energy sectors. Production and energy generation lead to greenhouse gas emissions, which affect temperature dynamics. Climate damages are modelled at the individual level as stochastic shocks hitting workers' labour productivity, energy efficiency, capital stock and inventories of firms. In that, aggregate damages emerge from the aggregation of losses suffered by heterogeneous, interacting and boundedly rational agents. The model is run focusing on a business-as-usual carbon-intensive scenario consistent with a Representative Concentration Pathway 8.5. We find that the DSK model is able to account for a wide ensemble of micro- and macro-empirical regularities concerning both economic and climate dynamics. Simulation experiments show a substantial lack of isomorphism between the effects of micro- and macro-level shocks, as it is typical in complex system models. In particular, different types of shocks have heterogeneous impact on output growth, unemployment rate, and the likelihood of economic crises, pointing to the importance of the different economic channel affected by the shock. Overall, we report much larger climate damages than those projected by standard IAMs under comparable scenarios, suggesting possible shifts in the growth dynamics, from a self-sustained pattern to stagnation and high volatility, and the need of urgent policy interventions.

1. Introduction

Now I am become Death, the destroyer of worlds.
J. Robert Oppenheimer

This paper presents an *agent-based integrated assessment model* composed of a complex evolving economy populated by heterogeneous, interacting and boundedly rational agents, a simple climate box, and a stochastic damage function endogenously yielding shocks of different magnitudes in response to climate change.

Evaluating the impact of climate change is fundamental to inform policy makers and sustain their decision process. The Paris agreement signed by 195 countries at the 2015 United Nations Climate Change Conference constitutes an unprecedented event (even considering the recent US withdrawal). It binds parties to undertake efforts to keep the global mean surface temperature at the end of the century within the 2° above pre-industrial levels, and eventually to achieve the 1.5-degree target. Apart from the political considerations behind the choice of the objective, the scientific debate is still open about the possible effects of meeting or missing it (Jaeger and Jaeger, 2011; Hansen et al., 2013). Part of the literature sustains that climate change is likely to significantly impact on our societies even in the case limiting global warming to +2° will be achieved (Weitzman, 2009; IPCC, 2014a; Schleussner et al., 2016), while others find that the effects will be marginal, and broadly equivalent to a year of lost economic growth (Tol, 2015).[1]

Given such premises, the impact evaluation remains one of the most challenging and uncertain tasks for both climate scientists — on the natural side — and climate economists — on the social side (Tol, 2009; IPCC, 2014b). Usually, the assessment of damages, and the design of possible corrective policies, is performed relying on Integrated

* Corresponding author.
E-mail addresses: f.lamperti@sssup.it (F. Lamperti), g.dosi@santannapisa.it (G. Dosi), mauro.napoletano@sciencespo.fr (M. Napoletano), a.roventini@santannapisa.it (A. Roventini), alessandro.sapio@uniparthenope.it (A. Sapio).

[1] The interested reader might want to look at Jaeger and Jaeger (2011) and Schellnhuber (2010) about the process that lead to the establishment of the 2-degree goal and the different views in the literature. We also point at Rogelj et al. (2016) for a discussion on the (in)effectiveness of planned nationally determined contributions in achieving the target.

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Assessment Models (IAMs). Generally speaking, Integrated Assessment can be seen as the effort of combining scientific knowledge that encompasses both natural and social aspects into a model that could help frame problems and envision policy solutions. IAMs dramatically differ in their level of detail and the complexity and interconnections they consider. For example, some models represent the whole Earth system with a small number of fairly simple equations (Nordhaus, 2014), while others include thousands of equations drawn from physics, chemistry, biology, and economics (Reilly et al., 2013). Beyond dimensionality, there are two streams of research concerned with the modelling of climate impacts (see Weyant, 2017, for a recent assessment of strengths and weakness of IAMs). On one side there are those, pioneered by Nordhaus (1992), that populate the economics literature. These models are mainly concerned with cost–benefit analysis and the study of optimal policies correcting the externalities brought about by climate change (see Golosov et al., 2014, for a recent example). Differently, models reviewed within the IPCC reports are employed to project socio-economic conditions under different scenarios and to assess a variety mitigation pathways. Clarke et al. (2009, 2014) provide an excellent overview of these IAMs while Emmerling et al. (2016) offers a detailed example.

Looking at the last 20 years of research experience, Weyant (2017) recently reviewed the status of the whole integrated assessment literature emphasizing both strengths and weaknesses of the field. Following Nordhaus (2014), he identifies the main contribution of IAMs in the provision of conceptual frameworks for the development of insights about highly complex, non-linear, dynamic, and uncertain phenomena, which can be used to perform useful counter-factual "if…, then…" exercises. However, IAMs have been fiercely criticized by an increasing number of scholars both on the theoretical and empirical grounds (see Pindyck, 2013; Stern, 2013; Stern, 2016; Weitzman, 2013; Revesz et al., 2014; Farmer et al., 2015; Balint et al., 2017, among many contributions). Many of these criticisms refer to issues, such as the arbitrariness of the damage function and the discount rate for future outcomes, affecting both the categories of models introduced above. To the purposes of the present paper, we focus on two crucial modelling choices: the representations of the economic system and damages. In particular, most IAMs build on a general equilibrium economy where representative agents (e.g. producers, consumers, farmers) frictionlessly interact in efficient markets. In such a framework, climate damages are seen as a predictable loss in some form of production — either aggregate, as in DICE (Nordhaus, 1992), or sectoral, as in FUND (Tol, 1997), or regional, as in PAGE (Hope, 2006) — to which a social planner can rationally react.

In this paper we aim at providing an alternative to such representations drawing on the literature of complex systems and, in particular, agent-based modelling (ABM, Tesfatsion and Judd, 2006). The call for interest for the application of ABMs to climate change analysis dates back to Moss et al. (2001) and Moss (2002a), and it has recently increased in insistence (Farmer et al., 2015; Stern, 2016; Balint et al., 2017). Agent-based models consider the real world as a *complex evolving system* (more on this in Farmer and Foley, 2009; Dosi, 2012; Dosi and Virgillito, 2016; Kirman, 2016), wherein the interaction of many heterogeneous agents, possibly across different spatial and temporal scales, gives rise to the emergence of aggregate properties that cannot be derived by the simple aggregation of individual ones. Moreover, agent-based models offer flexible tools to study the evolution of persistently out-of-equilibrium systems, where behaviours that are nearly stable for long time may change dramatically, stochastically, and irreversibly in response to small endogenous shocks (Balint et al., 2017).[2]

A new generation of agent-based models studying the intricate links between economic growth, energy, and climate change at regional, national, and global level has blossomed in the last years (see Gerst et al., 2013; Hasselmann and Kovalevsky, 2013; Wolf et al., 2013; Ponta et al., 2016; Safarzyńska and van den Bergh, 2017 and the survey in Balint et al., 2017). A similar picture emerges from the so-called ecological macro-economic models (see the review in Hardt and O'Neill, 2017), which develop at the crossing of stock-flow consistent modelling, system dynamics and input–output analysis but fall short of considering agent-heterogeneity.[3] However, little effort has been devoted to the development of integrated frameworks, wherein the economy and the climate may endogenously interact.

For these reasons, we develop the *Dystopian Schumpeter meeting Keynes (DSK)* model, which is, to the best of our knowledge, the first attempt to provide an agent-based integrated assessment framework. It builds on Dosi et al. (2010, 2013, 2017b) and extends the *Keynes + Schumpeter* (K + S) family of models, which account for endogenous growth, business cycles and crises. The model is composed by heterogeneous firms belonging to a capital-good industry and to a consumption-good sector. Firms are fed by an energy sector, which employ *dirty* or *green* power plants. The production activities of energy and manufacturing firms lead to CO_2 (equivalent) emissions, which increase the Earth surface temperature in a non-linear way as in Sterman et al. (2013). Rising temperatures trigger micro-stochastic climate damages heterogeneously impacting on workers' labour productivity, and on the energy efficiency, capital stock and inventories of firms. The DSK model accounts both for frequent-and-mild climate shocks and low-probability but extreme climate events. Technical change occurs both in the manufacturing and energy sectors. Innovation determines the cost of energy produced by dirty and green technologies, which, in turn, affect the energy-technology production mix and the total amount of CO_2 emissions. In that, structural change of the economy is intimately linked to the climate dynamics. At the same time, climate shocks affect economic growth, business cycles, technical-change trajectories, greenhouse gas emissions, and global temperatures.

Beyond the structure of the economic system, the DSK model introduces an additional innovation concerning the treatment of climate damages. Exploiting the heterogeneity of agents and some recent evidences on the variegate effects of climate change on our society (Carleton and Hsiang, 2016; Hsiang et al., 2017), we employ a stochastic damage function that generates micro-level shocks hitting agents through a variety of channels. Such an approach ideally extends the treatment of capital vs. labour impact channels adopted, e.g., in Naqvi (2015) and Dietz et al. (2016). To keep consistency with the literature we sample shocks from a distribution whose mean follows a pattern similar to that of DICE2013 (Nordhaus and Sztorc, 2013), which we employ as the reference model to compare our simulations with.[4]

We find that the choices about how to model the economic system and the interaction of economic agents hide large implications for impact evaluation and the assessment of how aggregate climate damages materializes. First, our simulation results show that the DSK model is able to replicate a wide array of micro- and macro-economic stylized facts and climate-related statistical regularities. Second, the exploration of different climate shock scenarios reveals that the impact of climate change on economic performances is substantial, but highly heterogeneous, depending on the type of climate damages. More specifically,

[2] The adoption of agent-based integrated assessment model is sometimes seen also as a way to ease stakeholder participation and scenario plausibility exploration (Moss et al., 2001; Moss, 2002a). Indeed, the higher degree of realism of agent-based models (Farmer and Foley, 2009; Farmer et al., 2015; Fagiolo and Roventini, 2017) allows to involve policy makers in the process of the development of the model employed for policy evaluation (Moss, 2002b).

[3] Some interesting attempts at providing mixed system dynamics and agent-based frameworks (Monasterolo and Raberto, 2018), as well as stock-flow consistent and structural growth macro-simulation models (Rezai et al., 2013; Fontana and Sawyer, 2016; Dafermos et al., 2017) are appearing.

[4] Our choice of DICE as a comparison term is motivated by two reasons. First, DICE is one of the most widely used IAMs in the literature and the 2013 version is one of the most recent but also largely tested. Second, the purpose of this paper is to offer a simple integrated assessment model, as DICE, where key assumptions on the economic system and its functions are proposed.