Climate change from the perspective of complexity economics

Michael W.M. Roos

Ruhr-Universität Bochum

24 February 2021

1 Complexity and climate change

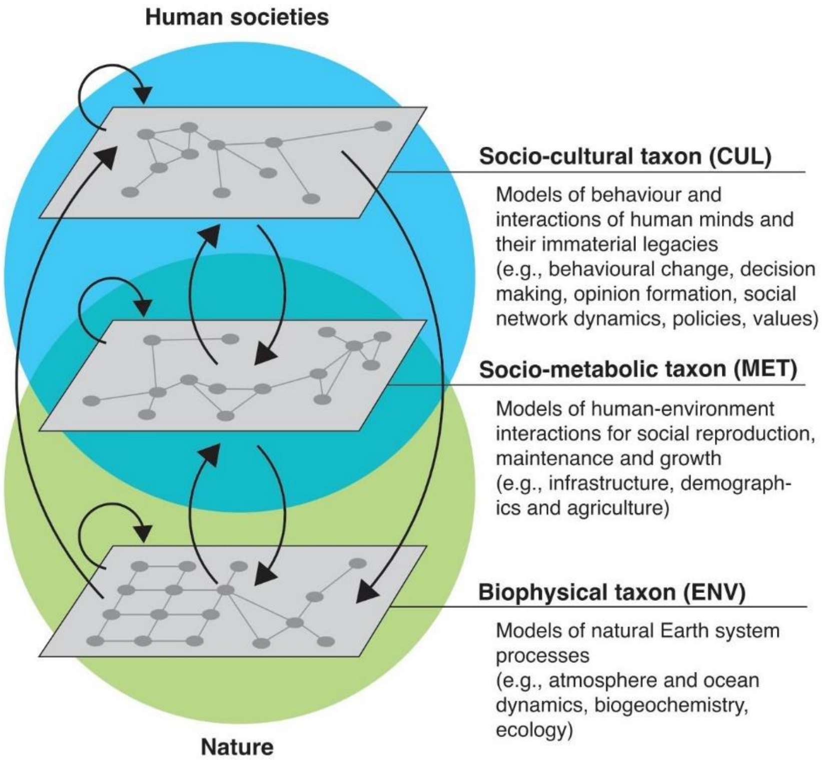
William Nordhaus, who received the Sveriges Riksbank Prize in Economics Sciences in Honour of Alfred Nobel for integrating climate change into long-run macroeconomic analysis, stated that climate change is not only a topic of great importance for humanity but also the ultimate challenge for economics (Nordhaus 2019). I could not agree more on this, but I believe that the neoclassical approach that Nordhaus proposes to deal with the challenge is not fit for purpose (Roos and Hoffart 2021). Neoclassical economics rests on an ontology of stability and permanence, but global warming will bring about radical changes in both ecosystems and social systems. Since neoclassical economics cannot cope with these fundamental structural changes, we need a new approach to climate change in economics. Complexity economics considers the economy as a complex adaptive system and offers a new perspective that provides a better understanding of the climate-related transformations and more adequate implications for public policy.

In everyday language, complexity means "having many parts and being difficult to understand or find an answer to" (Cambridge Dictionary). In science, we speak of complex systems or complex adaptive systems, which are "systems that have a large number of components, often called agents, that interact and adapt or learn" (Holland 2006). The defining characteristic of a system is that it has parts that are linked by relationships and form a unified whole that has a boundary delimiting it from an environment. Furthermore, the set of relationships provides a structure to the system and the parts have a function with regard to the whole. Complex systems are hard to understand, because the non-simple interaction of the parts leads to outcomes that are difficult or even impossible to predict from the behavior of the parts alone. Even more, the behavior can change over time as the parts or agents adapt to their environment and the behavior of other agents.

At least four complexity concepts are highly relevant for the analysis of climate change and its relation to the economy: nonlinearity, emergence, downward causation and adaptation. These concepts help us understand the intricate interplay between temporary order and change. Complexity economics as a branch of the complexity sciences aims at explaining how order arises and vanishes again. As Arthur (2015, p.1) puts it: "Complexity economics sees the economy as in motion, perpetually `computing' itself – perpetually constructing itself anew. Where equilibrium economics emphasizes order, determinacy, deduction, and stasis, complexity economics emphasizes contingency, indeterminacy, sense-making and openness to change". Hence, a focus on change is at the core of complexity worldview, which is the necessary perspective for climate economics. Change has many faces. It can occur gradually and unnoticed for a long time, but sometimes change is fast and disruptive, which means that an established order is destroyed in a short time and rather unexpectedly.

In order to understand climate change we must look at what Donges et al. (2018) call the *World-Earth system*, which is a planetary-scale system of subsystems as shown in Figure 1. By *Earth system* Donges et al. (2018) mean the "natural", ecological, or environmental subsystems of the Earth including climate that are governed by the laws of physics, chemistry or ecology. In Figure 1 these subsystems are called the biophysical taxon (ENV).

Figure 1: Subsystems of the World-Earth system and their interactions



Source: Donges et al. (2018)

The *World* is the subsystem of human societies, their cultures and artefacts described by the socio-cultural taxon (CUL). Human behavior, decision making and collective social dynamics determine the dynamics of the World. The World and the Earth have an intersection described by the socio-metabolic taxon (MET) that contains the processes and subsystems that form the material basis and products of societies. Economies and the "technosphere" belong to the socio-metabolic taxon. As indicated by the arrows, there are interactions between the taxa and self-interactions. For example, the ENV -> MET interaction comprises climate impacts on the economy. CUL -> MET includes socio-economic policies and governance choices that influence the economy and also encompasses the influence of cultural values, norms and lifestyles on consumption and production. Donges et al. (2018) argue that quantitative World-Earth models which integrate biophysical, socio-cultural and socio-metabolic processes are needed to understand climate change and its impact on human societies, but they are currently not available. There is a plethora of Earth system models from the biophysical taxon alone and there are many Integrated Assessment Models (IAMs) from the socio-metabolic taxon, but there are few formalized models in the socio-cultural taxon, which is the domain of the social sciences including economics. Comprehensive World-Earth models such as one presented in Donges et al. (2020) are just being developed.

Complexity economics has an important role to play in the development of World-Earth models. All subsystems in the World-Earth system are complex: the climate system (Rind 1999), ecosystems and the biosphere (Levin 2005), the economy (Arthur 1999) and societies (Sawyer 2005). Economists are not experts for the analysis of the systems in ENV, but they can contribute to the study of the systems in MET and CUL and in particular to the study of interactions between MET and CUL and MET and ENV. The current state of the art is that more and more models are developed that take into account that the economy and the biophysical systems are complex. Especially the complexity concept of nonlinearity with the related topics of tipping elements and critical transitions has received attention in the recent years. These models are reviewed in Section 2 of this paper.

The interactions between the economy and the socio-cultural system in the context of climate change have been studied less so far. Emergence, downward causation and adaptation are crucial concepts to understand whether and how the World responds to climate change. An enormous complication of human social systems compared to natural systems is that humans have individual and collective mental models or images of their world upon which they act (Boulding 1956). We can never know how the world really is, but inevitably construct mental models which are cognitive representations of the external world. If we want to understand behavior, we must analyze how mental models emerge and change. Recently, Beckert (2016) and Shiller (2019) introduced the concept of narratives into economics. Narratives can be defined as shared stories, by which individuals and groups try to make sense of their world which can be seen as an important element of the formation of mental models. Complexity economics hence should include the study of narratives. Some first attempts how this can be done and elements for future, more comprehensive models are discussed in Section 3.

Science itself produces narratives and the complexity narrative of climate change is very different from the neoclassical one. I argue that a new economic narrative of climate change based on the complexity worldview is necessary in order to achieve a more effective and potentially pre-emptive societal adaptation to global warming. Section 4 concludes with some thoughts on the implications for our economic system.

2 Nonlinearity, tipping elements and critical transitions

A heuristic definition of nonlinearity is that there is no proportionality between causes and effects, i.e. small changes in a system can have large consequences and the effects of large changes can be rather small. The interaction between parts is an important reason of nonlinearity because it can lead to the amplification or attenuation of individual behaviors. Complex systems are characterized by nonlinear dynamics that cannot be captured by linear difference or differential equations. Systems with nonlinear dynamics feature chaotic behavior and bifurcations at which the system's behavior changes qualitatively.

Earth system scientists emphasize the importance of tipping elements in biophysical systems. Scheffer et al. (2001) describes the possibility of catastrophic shifts (also called *regime shifts* or *critical transitions*) in ecosystems. The paper is inspired by catatrophe theory and argues that many natural systems are characterized by so-called fold bifurcations (or saddle-node bifurcations) at which a small change of a variable that measures environmental conditions can lead to a sudden and large change of the state of the system. Scheffer et al. (2001) argue that catastrophic shifts are a likely phenomenon in many large-scale ecosystems such as coral reefs, woodlands, deserts and oceans. The concept of tipping points is the basis of the so-called *Planetary Boundaries* (Rockström et al. 2009, Steffen et al. 2015), which should not be transgressed by human activities in order to avoid nonlinear, abrupt environmental change within continental-scale to planetary-scale systems threatening human existence. It is highly likely that of the nine identified planetary boundaries two were already transgressed at the time of their first description in 2009 and several others, among them climate change, are in the zone of uncertainty with increasing risk. Lenton et al. (2008) identify 15 possible tipping elements in the climate system. They discuss the possibility to determine critical values and ways to find out whether the system is close to potential tipping. They conclude that for at least seven tipping elements in the climate system, tipping could start in the 21st century. Anderies et al. (2013) present a model of carbon stock dynamics, in which there is interaction between terrestrial, marine and atmospheric carbon stocks, influenced by human activity namely land-use changes and the use of fossil fuels. The change in the atmospheric carbon stock leads to climate change, which in turn affects net ecosystem production. The model has multiple interacting tipping points that move with changes in the system in highly non-linear ways. The authors conclude that the notion of clearly defined tipping points of single variables that can be analyzed in isolation is misleading. Instead, a systems approach is necessary that takes the interaction between different planetary boundaries into account. They leave the question open whether a single, detectable, global tippping point might emerge from the aggregate of many local and regional tipping points.

The research in the Earth sciences emphasizes the many nonlinearities of the natural systems and the resulting danger of critical transitions. The links to economic activities are discussed, but the economic system is not modelled in detail and economic activity is exogenous. While neoclassical climate economics is aware of potential tipping points in the climate system and ecosystems (e.g. Cai et al. 2015, Lemoine and Traeger 2014, Brock et al. 2015), it does not give it the same role as the Earth sciences. Simply introducing the possibility of tipping of environmental systems into IAMs is not enough from a complexity perspective. The complexity view stresses that systems can undergo critical transitions that lead to a qualitative change of their behavior. The neoclassical IAMs, however, rest on assumptions that preclude such changes, e.g. the substitutability of enviromental goods and produced goods, intertemporal optimization and stable and unique equilibria.

Chen (1997) might be seen as the first model in complexity climate economics. His simple model assumes a stable climate system with a unique equilibrium and a two-sector general equilibrium economy with intertemporal utility maximization. The manufacturing sector contributes to global warming via CO2 emissions, which negatively affects the agricultural sector. Production losses in agriculture due to higher temperature lead to an increase in the relative market price for agricultural output causing a reallocation of labor from manufacturing to agriculture. This mechanism in principle is a stabilizing feedback effect, because it leads to lower production in manufacturing and hence less temperature increase. The central result of Chen's analysis is that despite the assumption of a stable climate system and a stabilizing market mechanism in the economy, the interaction of the two systems can generate climate cycles and even chaotic dynamics, if the rate with which the climate system returns to the equilibrium temperature is low. If economic growth due to productivity growth in manufacturing is added, cycles and chaos can result even with parameter values that would otherwise lead to a stable no-growth equilibrium. Hence the coupling of two system which are individually stable can be an unstable, chaotic system due to a `coordination failure' of the two systems.

Rosser (2001) discusses the relevance of catastrophes in economics, for instance the collapse of fisheries. He argues that systems with catastrophic dynamics pose a greater threat to mankind than models with chaotic dynamics, since as long as chaotic dynamics remain within bounds agents might be able to learn how to cope with them. Rosser (2002) makes the same point but also argues in contrast to Chen's assumption, both the climate system and some economic systems are like to be chaotic. The coupling of chaotic systems can generate global oscillations which are not chaotic, but have very large amplitudes.

Kellie-Smith and Cox (2011) present a stylized model of economy-climate interaction. It has the form of a predator-prey model, in which global wealth has the role of the prey that supplies the predator of global warming and is reduced by the impacts of global warming. The crucial assumption is that global warming suppresses economics growth. The function that relates the capacity of economic wealth creation to temperature is a highly abstract way to capture the insight that the structure of the economy changes in response to climate change, although in a black-box fashion. In contrast to the IAMs in the tradition of Nordhaus' DICE model, economic and climatic oscillations can occur for some parameter constellations in the model of Kellie-Smith and Cox (2011). With economic growth rates and decarbonization rates as observed between 1970 and 2005 the model generates strong global warming with a collapse of global wealth in the 21st century due to climate damages. The model hence allows for a regime shift in the economy from a regime with stable long-term growth to a regime with strong oscillations or even instability, if decarbonization rates are too low relative to the rate of economic growth.

The model of Nitzbon et al. (2017) incorporates human activity into the carbon cycle model of Anderies et al. (2013). It shows explicitly how economic production and population growth depend on the ecosystem. Production requires energy, which stems from the use of either biomass or fossil fuels. Population growth depends on well-being which in turn depends on terrestrial carbon. Terrestrial carbon is present in plants and soils which provide provisioning ecosystem services (e.g. food, raw materials) and regulating ecosystem services (e.g. waste decomposition, treatment of wastewater). The human use of biomass and fossil fuels as energy in the production process causes emissions that increase atmospheric carbon responsible for higher temperature. Nitzbon et al. (2017) show that the Earth system without human activity has two stable equilibria: a *desert state equilibrium* with no terrestrial carbon and a *forest state equilibrium* with a positive level of terrestrial carbon. The forest state equilibrium represents the Holocene carbon cycle until pre-industrial times. In the version of the model that represents the global capitalistic society, humans use fossil fuels and biomass in an excessive fashion. The overuse of biomass leads to a transition of the ecosystem from the basin of attraction of the forest state equilibrium to the basin of attraction of the desert state equilibrium. Hence, terrestrial carbon rather suddenly collapses leading to an economic collapse, too. In contrast to the neoclassical IAMs, ecosystem services related to the availability of terrestrial carbon cannot be substituted and are crucial for production and human well-being. Climate effects are present in the model, but they do not affect population or production directly. The effects of higher atmospheric temperature only affect the rate of change of terrestrial carbon via photosynthesis and land to air respiration. This is rather disconcerting, because the model suggests that neoclassical IAMs focus on the wrong risks, as they just consider the direct damages of higher temperature on the economy and ignore that all human activity rests on ecosystem services that cannot be substituted.

Nonlinearities, tipping points and critical transitions must be a crucial element of economic climate models. It is especially important to acknowledge that Earth systems which are the inevitable basis of economic activity can collapse, if planetary boundaries are transgressed (Dasgupta 2021). This message has not reached neoclassical climate economics yet, which assumes that ecosystem services can be substituted and that the economy does not change qualitatively in response to changes in the Earth system. In neoclassical IAMs, climate change only causes damages to output (and potentially to capital and labor), but does not affect the way in which the economy operates. While the discussed non-neoclassical models point to this problem at an aggregate level, they do not explicitly model the processes that lead to societal and economic transformations.

3 Emergence, downward causation and adaptation

Emergence means that there are patterns or properties at the system level that cannot be found at the level of the parts. Furthermore, the emergent properties at the system level may be unexpected given the knowledge about the parts. The definition of emergence requires that we consider at least two levels of analysis: the system or macro level and the micro level of the parts. Patterns or properties at higher levels emerge from the interaction of parts at lower levels in a bottom-up process.

Importantly, complex systems can also generate downward causation by which a higher system level affects the behavior of the lower-level parts. In social systems examples of downward causation abound: social norms, collective worldviews, shared beliefs, fads, fashions and animal spirits are created by the interaction of agents and once they are there, they guide or constrain the agents' behavior. Adaptation means that individuals or social entities improve their ability to thrive in their relevant physical and social environment. Human agents adapt by individual learning as well as collectively by changes in institutions. As a consequence of adaptation, the behavior of human agents changes.

It is common to distinguish informal institutions – often called culture - such as values, social norms or customs, and formal institutions such as laws, constitutions, treaties, written agreements, party platforms and so on. According to Khalil (2012), cultural economics claims that formal institutions are the result of culture, such that culture is a fundamental factor of economic behavior. Williamson (2000) distinguishes four different levels of social analysis, which are characterized by different time scales. The lowest level 4 is that of neoclassical economics, which is concerned with resource allocation and takes all forms of institutions as given. Decisions at this level are made continually and their outcomes provide feedback to the higher levels. Level 3 is the level of governance or transaction cost economics, which is part of the so-called New Institutional Economics (Williamson 2000). This level deals with contractual and organizations issues that are adjusted on a time scale from 1 to 10 years. Level 2 is the domain of positive political theory and focuses on the formal rules of the game. Finally, at level 1 social theory analyzes the embeddedness of formal institutions and economic behavior into informal institutions or culture. According to Williamson (2000), formal institutions change within decades, but informal institutions may even need centuries to evolve. Incorporating the interactions between the economy and the socio-cultural systems requires that we understand the emergence of new institutions such as climate treaties, how institutions affect the behavior of individual agents (downward causation) and how existing institutions change in response to climate change (adaptation).

Existing IAMs follow the neoclassical tradition of taking institutions as given. Economic behavior in these models depends on exogenously given consumer preferences and economic constraints. Policy variables, such as a carbon tax, can influence the economic constraints. While IAMs take into account interactions beween the economy and the climate system, they only ask how exogenous policy change would affect the economy, but ignore endogenous feedback from the economy or the climate system on policy and institutions. However, the explicit consideration of formal and informal institutions is crucial to analyze climate change. The implementation of effective climate policies such as carbon taxes, binding international mitigation agreements, or national laws means that formal institutions must change, which is only possible with a change of the underlying informal institutions. We will only understand whether, how and when mankind will implement effective climate policies, if we understand the mechanism behind institutional evolution.

Three strands of literature are helpful to understand the evolution of institutions and its impact on climate from a complexity perspective. First, there are some examples of World-Earth models with more sophisticated interactions between the CUL taxon and the other taxa than in the IAMs. Second, agent-based models exist that formalize the emergence and change of institutions. Finally, a qualitative strand of the literature emphasizes that narratives are important for sustainability and the new literature on narrative economics tries to formalize the concept of narratives and its influence of economic behavior.

Janssen and de Vries (1998) present a World-Earth model in which a \`battle of perspectives´ takes place. Three groups of agents (hierarchists, egalitarians and individualists) hold different perspectives on how climate change affect the world (worldview) and what should be done against climate change (management style). The worldview affects four parameters of the socio-economic model and are assumed to differ between the three groups: climate sensitivity, the pace of technological improvements, damage costs and mitigation costs. The preferred management styles of the groups are expressed by simple policy rules. Hierarchists want to balance the risks of climate change and the social costs from stagnating economic growth. If temperature increase is low, they invest in order to generate stable economic growth and choose a slow transition away from fossil fuels. Egalitarians aim at preventing a climate catastrophe and hence choose a fast fossil transition and zero economic growth. Individualists support a high rate of economic growth and speed up the slow fossil fuel transition only if climate damages exceed a threshold. Each perspective is supported by a proportion of the agents and global climate policy is a weighted average of the management styles. Agents adapt their types if their observations of how the system behaves does not match their expectations, which is modelled by a genetic algorithm. Janssen and de Vries show that adaption is too weak to prevent temperature from rising well above 2°C, if the dominant management style and worldview at the end of the 20th century are individualist, but the system in fact behaves according to the egalitarian worldview. In the system dynamics World-Earth model in Roos (2018), economic investment decisions and climate policy depend on society's values which can be either materialistic or post-materalistic. If the majority of the world population holds materialistic values, economic and political efforts to mitigate climate change will be weak. Effective mitigation of climate change requires that a large fraction of the population has post-materialistic values and is willing to sacrifice consumption for spending on the decarbonization of the economy. Societal values are endogenous and respond to the state of the economy and the natural environment. Climate-induced environmental damages lead to a shift in values towards more post-materialism and hence more mitigation efforts. However, if values respond more strongly to changes in the environment than to changes in income, initial successes in mitigation and environmental protection can be self-defeating and lead to strong global warming. Donges et al. (2020) present *copan:CORE* which is an open simulation framework for World-Earth models. They use a stylized model implemented in copan:CORE to illustrate how endogenous sociocultural processes interact with the economy and the climate. To be precise, they model people's awareness of the state of the natural environment, social learning about the environment and voting on climate policy. An interesting result of their paper is that that state of the climate system and atmospheric temperature in 100 years depends on the social learning rate. Only if social learning occurs more than once per year the social processes matter for the climate outcomes.

Behaviors that influence climate directly like the consumption of GHG-emitting goods or indirectly like voting on climate policy depend on agents' knowledge, awareness and worldview of the consequences of their actions and the individual and social evaluations of the outcomes. Elsenbroich and Gilbert (2014) argue that most human behavior is governed by social, moral or legal norms. They define norms as rules of conduct derived from social behavioral expectations, moral values or the code of law. Social behavioral expectations can depend on opinions, which are purely socially constructed knowledge whose truth or falsity is decided by vote of a group. Elsenbroich and Gilbert (2014) present a variety of agent-based models that have been used to explain how norms emerge, how they diffuse and how they affect individual behavior. They use these models to explain anti- or pro-social behavior, in particular why people commit crimes. Conte et al. (2014) is a collection papers that also discuss agent-based models of norms, explicitly using the complexity concepts of emergence and downward causation. The volume presents outcomes of the EMIL (Emergence In the Loop: simulating the two-way dynamics of norm innovation) project funded by the European Union, which developed a normative agent architecture accounting for norm dynamics, emergence and innovation and a multi-agent simulation platform based on this architecture. Building on the theoretical foundations of institutional economics, Ghorbani (2013) and Ghorbani et al. (2013) develop a meta-model called

MAIA (Modelling Agent system based on Institutional Analysis) for conceptualizing socio-technical systems. The framework can be used to develop agent-based models of socio-technical systems in which institutions emerge and structure social behavior and interaction. Ghorbani and Bravo (2016) present an agent-based model of institutional emergence patterns observed in common pool resource problems. Important common pool resources in the context of climate change are forests, water basins or the atmosphere. The model shows that institutions emerging through collective behavior without centralized planning can help the management of common pool resources.

Narratives are sense-making stories. Guske et al. (2019) characterize them as social constructs that describe reality in a teleological way, because they help people to interpret the world, point to root causes of problems, identify accountable actors and suggest courses of action. Narratives convey values and norms, create group identity and point to desirable future developments. They are crucial for societal change, because they affect the chances that innovations are accepted by framing them in a positive or negative way (Macnaghten et al. 2019). Luederitz et al. (2017) identify four sustainability transition narratives that can be found in the scientific literature and public discourses: (1) the green economy, (2) low-carbon transformation, (3), ecotopian solutions and (4) transition movements. These narratives frame the sustainability problem in different ways and advocate alternative solutions how societies can achieve sustainability. Narratives have the descriptive dimension of explaining what the system is and how it works and the normative dimension of postulating how it ought to be and which goals it should achieve. They are hence linked to the models discussed before that include worldviews and values as determinants of climate policies. The emergence, the evolution and the way narratives affect behavior are key processes in the socio-cultural taxon. In the public discourse different narratives compete for hegemony. When the discourse "congeals" (Goode and Godhe 2017) dominant narratives develop into a *social imaginary* which is the taken-for-granted way ordinary "people imagine their social existence, how they fit together with others, how things go on between them and their fellows, the expectations that are normally met, and the deeper normative notions and imagines that underlie these expectations" (Taylor 2004, p. 23). Levy and Spicer (2013) propose the concept of a *value regime* which "refers to the broader political-economic settlement linking an imaginary with [a] specific set of technologies, production methods and market structures" (p. 673). The value regime extends the concept of *sociotechnical regimes* from transition theory (see Geels and Schot 2007) by the role of cultural factors such as narratives and imaginaries. As Guske et al. (2019) explain, science is an important source of narratives of a sustainable economy which could become crucial for societal transformations if they resonate with narratives in non-scientific discourses.

Luhman and Boje (2001) view discourses as complex systems in which multiple narratives emerge from the conscious or unconscious behavior of individuals. Some narratives "stick" due to the story-telling power of their originators and give those agents power by constraining the behavior of other agents. Recently, narratives received some attention in economic theory (Beckert 2016, Benabou et al. 2018, Shiller 2019). Shiller (2019) proposes to use epidemiologic models like the well-known SIR-model to analyze the spread of narratives in a population. However, agent-based models might be more suited to study the evolution of narratives if discourses are understood as complex systems. There is a considerable literature on opinion dynamics (see Sobkowicz 2009), which mainly focuses on the diffusion of opinions in a population. This literature could be a good starting point of more complex models that represent narratives in a more sophisticated way. Narratives are more complicated objects than opinions and they affect behavior which should be part of such models. Currently, agent-based models of narratives in the context of climate change do not exist, but they would be an important field for further research.

4 Conclusion

Complexity economics and neoclassical economics tell different narratives of climate change. Neoclassical equilibrium economics tells the story of optimal gradual mitigation of climate change that is best achieved by a price on GHG emissions by which maximizing market agents individually internalize the social cost of carbon. In contrast, the complexity view warns us that our ecosystems become unstable and collapse, if we push the economy beyond the limits of the safe operating space. Preventing climate disaster is not so much a question of the right carbon price, but of the appropriate formal and informal institutions that facilitate cooperation inside and outside the market.

It might seem that the policy message of whether we should focus on carbon prices or institutions is a rather technical matter, but in fact the issue is far deeper. Beinhocker (2020) argues that neoclassical economics and complexity economics are at the center of two fundamenally different imagined world orders. The current order of market capitalism that will lead to ecological disaster is based on the economic and political ideology of neoliberalism, for which neoclassical economics provides the theoretical foundations. Neoclassical economics, in turn, rests on the untenable assumption of homo economicus and the moral philosophy of maximizing utilitarianism. The required new order to prevent ecological collapse reconstructs the whole edifice: it starts at a moral philosophy that builds on prosocial behaviors and reciprocity. A behavioral theory that describes how real humans behave and complexity economics that acknowledges that real economics are complex adaptive systems lead to a completely different economic and political ideology which Beinhocker calls *Market Humanism*. The economic system resulting from all this – the *Eudaimonic Economy* – would promote human and non-human flourishing within safe planetary boundaries. The ultimate challenge for economics hence is to imagine that our world could be completely different from how it currently is.

References

Anderies, J. M.; Carpenter, S. R.; Steffen, W.; Rockström, J. (2013). The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries. Environmental Research Letters 8 (4), 44048.

Arthur, W. B. (1999). Complexity and the economy. Science 284 (5411), 107–109.

Arthur, W. B. (2015). Complexity and the Economy. Oxford: Oxford University Press.

Beckert, J. (2016). Imagined futures. Fictional expectations and capitalist dynamics. Cambidge, MA: Harvard University Press.

Beinhocker, E. D. (2020). Can complexity economics save the world? In: Arthur, W.B.; Beinhocker, E.D.; Stanger, A. (eds). Complexity economics – Dialogues of the applied complecity network. Proceeding of the Santa Fe Institute's 2019 fall symposium. Santa Fe: SFI Press.

Benabou, R.; Falk, A.; Tirole, J. (2018). Narratives, imperatives, and moral reasoning. NBER Working Paper No. 24798.

Boulding, K. E. (1956). The image: Knowledge in life and society. Ann Arbor: University of Michigan Press.

Brock, W. A.; Engström, G.; Xepapadeas, A. (2015). Energy balance climate models, damage reservoirs, and the time profile of climate change policy. In: Bernard, L.; Semmler, W. (eds.). The Oxford handbook of the macroeconomics of global warming. Oxford: Oxford University Press, 19–52.

Cai, Y.; Judd, K. L.; Lenton, T. M.; Lontzek, T. S.; Narita, D. (2015). Environmental tipping points significantly affect the cost-benefit assessment of climate policies. Proceedings of the National Academy of Sciences of the United States of America 112 (15), 4606–4611.

Chen, Z. (1997). Can economic activities lead to climate chaos? An economic analysis on global warming. The Canadian Journal of Economics 30 (2), 349- 366.

Conte, R.; Andrighetto, G.; Campenni, Marco (eds.) (2014). Minding norms. Mechanisms and dynamics of social order in agent societies. New York: Oxford University Press.

Dasgupta, P. (2021). The economics of biodiversity: The Dasgupta Review. London: HM Treasury.

Donges, J. F.; Lucht, W.; Heitzig, J.; Barfuss, W.; Cornell, S. E.; Lade, S. J.; Schlüter, M. (2018) Taxonomies for structuring models for World-Earth system analysis of the Anthropocene: subsystems, their interactions and social-ecological feedback loops. Earth System Dynamics. DOI: 10.5194/esd-2018-27.

Donges, J. F.; Heitzig, J.; Barfuss, W.; Wiedermann, M.; Kassel, J. A.; Kittel, T.; Kolb, J. J.; Kolster, T.; Müller-Hansen, F.; Otto, I. M.; Zimmerer, K.B.; Lucht, W. (2020). Earth system modeling with endogenous and dynamic human societies: the copan:CORE open World-Earth modeling framework. Earth System Dynamics 11 (2), 395–413.

Elsenbroich, C.; Gilbert, N. (2014). Modelling norms. Dordrecht: Springer Netherlands.

Geels, F.W.; Schot, J. (2007). Typology of sociotechnical transition pathways. Research Policy 36, 399 – 417.

Ghorbani, A. (2013). Structuring socio-technical complexity. Modelling agent systems using institutional analysis. Delft: Next Generation Infrastructures Foundation (NGInfra PhD thesis series, 61).

Ghorbani, A.; Bots, P.; Dignum, V.; Dijkema, G. (2013). MAIA: a Framework for Developing Agent-Based Social Simulations. Journal of Artificial Societies and Social Simulation 16(29), [9]. https://doi.org/10.18564/jasss.2166

Ghorbani, A.; Bravo, G. (2016). Managing the commons: a simple model of the emergence of institutions through collective action. International Journal of the Commons 10 (1), 200–219.

Goode, L.; Godhe, M. (2017). Beyond capitalist realism – Why we need critical future studies. Culture Unbound 9 (1), 108–129.

Guske, A.-L.; Jacob, K.; Hirschnitz-Garbers, M.; Peuckert, J.; Schridde, S.; Stinner, S.; Wolff, F., Zahrnt, D.; Ziesemer, F. (2019): Stories that change our world? Narratives of the sustainable economy. Sustainability 11 (21), 6163. DOI: 10.3390/su11216163.

Holland, J.H. (2006). Studying complex adaptive systems. Journal of System Science and Complexity 19, 1 -8.

Janssen, M.; Vries, B. de (1998). The battle of perspectives: a multi-agent model with adaptive responses to climate change. Ecological Economics 26 (1), 43–65.

Khalil, E.L. (2012). Why Europe? A critique of institutionalist and culturalist economics. Journal of Economic Surveys 26(2), 351 – 372.

Kellie-Smith, O.; Cox, P. M. (2011). Emergent dynamics of the climate-economy system in the Anthropocene. Philosophical Transactions. Series A, Mathematical, physical, and engineering sciences 369 (1938), 868–886.

Lemoine, D.; Traeger, C. (2014). Watch your step: optimal policy in a tipping climate. American Economic Journal: Economic Policy 6 (1), 137–166.

Lenton, T. M.; Held, H.; Kriegler, E.; Hall, J. W.; Lucht, W.; Rahmstorf, S.; Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences of the United States of America 105 (6), 1786–1793.

Levin, S. A. (2005). Self-organization and the emergence of complexity in ecological systems. BioScience 55 (12), 1075 – 1079.

Levy, D. L.; Spicer, A. (2013). Contested imaginaries and the cultural political economy of climate change. Organization 20 (5), 659–678.

Luederitz, C.; Abson, D. J.; Audet, R.; Lang, D. J. (2017). Many pathways toward sustainability: not conflict but co-learning between transition narratives. Sustainability Science 12 (3), 393–407.

Luhman, J. T.; Boje, D. M. (2001). What is complexity science? A possible answer from narrative research. Emergence 3 (1), 158–168.

Macnaghten, P.; Davies, S. R.; Kearnes, M. (2019). Understanding public responses to emerging technologies: a narrative approach. Journal of Environmental Policy & Planning 21 (5), 504–518.

Nitzbon, J.; Heitzig, J.; Parlitz, U. (2017). Sustainability, collapse and oscillations in a simple World-Earth model. Environmental Research Letters 12 (7),74020. DOI: 10.1088/1748-9326/aa7581.

Nordhaus, W. (2019). Climate change. The ultimate challenge for economics. American Economic Review 109 (6), 1991–2014.

Rind, D. (1999). Complexity and climate. Science 284 (5411), 105–107. DOI: 10.1126/science.284.5411.105.

Rockström et al. (2009). A safe operating space for humanity. Nature 461(24), 472 – 475.

Roos, M. (2018). Endogenous economic growth, climate change and societal values: a conceptual model. Computational Economics 52, 995 – 1028.

Roos, M., Hoffart, F. (2021). Climate economics. A call for more pluralism and responsibility. Palgrave Studies in Sustainability, Environment and Macroeconomics. Palgrave Macmillan.

Rosser, J. B. (2001). Complex ecological-economic dynamics and environmental policy. Ecological Economics 37, 23 - 37.

Rosser, J. B. (2002). Complex coupled system dynamics and the global warming policy problem. Discrete Dynamics in Nature and Society 7 (2), 93–100.

Sawyer, R. K. (2005). Social emergence. Societies as complex systems. Cambridge: Cambridge University Press.

Scheffer, M.; Carpenter, S.; Foley, J. A.; Folke, C.; Walker, B. (2001). Catastrophic shifts in ecosystems. Nature 413 (6856), 591–596.

Shiller, R. J. (2019). Narrative economics. How stories go viral and drive major economic events. Princeton: Princeton University Press.

Sobkowicz, P. (2009). Modelling opinion formation with physical tools: call for closer link with reality. Journal of Artificial Societies and Social Simulation 12, 1, [11].

Steffen et al. (2015). Planetary boundaries: guiding human development on a changing planet. Science 347(6223), 1259855, DOI: 10.1126/science.1259855

Taylor, C. (2004). Modern social imaginairies. Durham and London: Duke University Press.

Williamson, O.E. (2000). The new institutional economics: taking stock, looking ahead. Journal of Economic Literature 38(3), 595 – 613.