Opportunities for Complexity Theory to Advance Climate Change Research

Brelsford, C., Clewlow, R., Geddes,J., LaCerva, G., Nguyen, H., Wolf, A.

Introduction: Global Sustainability and Climate Change

Although coupled climate-carbon cycle models show a large variation in future climate due to uncertainty in the terrestrial carbon cycle (Friedlingstein), climate models show more profound impact of human activity on climate due in large part to emissions of CO2 by combustion in the energy system and emissions from land use change (IPCC). The human activity embodied in emissions trajectories (http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/) captures a range of different scenarios of human population growth, development, technological change, and trade coupled by a general equilibrium model framework. Just as climate models depend on models of emissions, emissions models depend on an underlying model of the economy that represents the collective behavior of humans via markets. In this white paper, we raise the question whether the underlying models of human interaction used in the context of energy and climate modeling are useful tools, given that they contain several weaknesses, namely (1) a lack of interaction with the climate system (2) ignorance of the presence and interactions of particular actors such as individual firms, utilities, and governments that provide mechanism to the collective behavior (3) an inability to explore how different desired emissions futures might come about.

Recent research highlights the urgency of radically decarbonizing the world energy supply within the next 10-20 years in order to avoid exceeding 2*C warming (Schellnhuber). Substantial technological shifts, particularly in the energy sector, have taken place at a comparable pace historically, but this transformation between energy equilbria is not well captured by general equilibrium models (GEMs). We see the current high-carbon energy mix as a basis of attraction that is resistant to change unless a radical, transformation of the energy system takes the energy mix to a new stable equilibrium that relies heavily on renewable resources. The current energy system is resistant to change because of large capital assets such as power plants (turnover time of capital assets), a lack of a suitable grid for distributing non-dispatchable renewable energy, resistance to change from players who have made prior investments in energy infrastructure (lock in), and in the difficulty of coordinating the behavior of many small actors who require a simultaneous shift by other actors. This resistance to change can be envisioned as a "hump" through which the energy system must pass en route to a low-carbon state.

It is important to emphasize a large number of possibilities already exist for altering the carbon intensity of energy sources, managing a smart grid relying on non-dispatchable renewables, increasing the efficiency of end-use supply in industry and buildings, optimizing the exergy use of the entropy cascade as energy is used in an industrial context, and otherwise reaching the target of a low-carbon economy.

We see an important role for developing agent based models (ABMs) of the energy economy, particularly within the united states, that could be used to explore tipping point behavior of coordinated shifts that would permit a transition over the hump from carbon intensive to renewable energy system. This modeling framework could be used to explore policy options, as traditional energy models (such as Reeds, etc) are, but also explore the role of behavior of individual actors, such as California or Walmart in creating a critical mass that can result in a widespread shift in the economy. Additionally, because the energy system is so capital intensive, it relies heavily on financial markets for investment, so the financial landscape seen by all investors, and the particular investments made by some players can have a strong impact on the evolution of the power supply and end use.

Complexity and Applications to Modeling Global Climate Change

In recent years, the study of complex systems has risen as a new scientific field, attempting to understand the common properties that link technological, societal, and natural systems. Advances in computation have stimulated research in the area of complexity, as a key challenge lies in the formal modeling and simulation of such systems. As the field has matured, new methods and tools have emerged that provide us with an ability to model systems in the areas of biology, human behavior, and engineering, giving us a deeper understanding of patterns and properties that exist within natural and man-made systems. Given the complexity of the global climate system, these methods can provide scientists with a new and useful framework with which to investigate anthropogenic and natural causes of climate change.

A broad base of foundational knowledge contributes to the field of complexity, including probability theory, thermodynamics, information theory, and fractals. Basic tools that are often utilized with the field include statistical mechanics, stochastic dynamics, and computer simulation techniques (Bar-Yam). However, a variety of new tools have recently emerged which provide us with increased understanding of natural and man-made complex systems, including social network theory, system dynamics, and agent-based modeling. These new tools help us understand the underlying properties, patterns and emergent behavior that are inherent in complex systems.

Areas for Further Research

Climate Models

Our ability to predict global scale changes in climate patterns and temperature is quite good. However, our ability to downscale these global predictions to the regional scale is much weaker. As a result, there is significant uncertainty about the specific impacts that global climate change will have on regional scales. Greater ability to quantify the impact of regional scale ecological change on social and economic institutions will allow quantification of regional costs based on a range of possible climate impacts. It will also allow quantification of costs resulting from to ecological change due to over-use, habitat loss, or invasive species. The ability to quantify local costs from a range of climate scenarios is also likely to spur action by personalizing the impacts of climate change.

One method of improving capacity to understand the social and economic impacts of ecological change is through integrating models. There are complex interactions between individual human choices, institutional actions, and the stability or health of a nearby ecosystem. Agent based models and complex systems approaches can help us understand both the mechanisms through which ecological change impacts human institutions, and the interactions between systems of very different types. One example of a system that uses agent based modeling to link legal, environmental and economic institutions with the physical behavior of a network of dams on a river basin. When the linked human and natural system is modeled correctly, historical data can be used to validate the model, and trade offs between hydroelectric power generation and ecosystem health, biodiversity, and endangered species survival can be quantified. Additionally, when the model includes rigorous water demand models, the first area of failure under different policy and climate scenarios can be modeled.

Technology Invention, Innovation, and Diffusion

Decarbonization of the energy system in time to avert global warming over ~2 deg. C will require an enormous engineering undertaking. The climate system imposes tough deadlines for decarbonization past which severe negative impacts are irreversible [Schellnhuber]. Large portions of the energy system will have to be replaced quickly. Coal plants may need to be decommissioned early (i.e. even before their costs are fully amortized). Carbon sequestration and storage has large uncertainties associated with its effectiveness, and no current commerical implementations.

The time lag between invention (first reduction to practice of an idea) and innovation (first factory and commercial implementation to sell or distribute a product created by the invention) is highly variable, and the variation of this lag does not appear to have decreased any over the last century [Grubler]. The factors that determine whether the lag between invention and innovation will be long or short is poorly understood [Grubler]. However, the social networks that surround inventors and connect them (or not) to financiers, managers, and industrialists are crucial to turn inventions into products sold in the marketplace [Hargadon].

The process of diffusion of technology is somewhat better understood, though this knowledge gives no reason to be sanguine [Grubler]. A speed up of diffusion of low carbon technology through the energy system could be accomplished in several ways. World governments could increase the price of carbon and increase both the efficiency of the energy system and the and the conversion rate of fossil to renewable energy. Note that agreement likely has to be a global one to prevent leakage [Grubler]. Even so, the amount of coal infrastructure in large countries like the United States and China will be difficult to replace in time to avoid dangerous climate change. Authoritarian governments have, in general, a greater ability to more quickly impose much faster change in their technical systems than democratic ones [Grubler].

If the leaders of the world's countries fail to implement policies to increase rates of of decarbonization, the task will fall entirely to their societies to undertake. Individual consumer behaviors could change to reduce demand for fossil energy (both direct and embedded in manufactured goods). The processes by which such a shift would be governed are complex in their own right. The processes by which such a shift would be governed are complex themselves and desrver further study, but we will concentrate mostly on the technical and human aspects of the energy system itself and not on the demand that drives it.

The complexity of human decision making in adopting technical changes is an important subject for further study. For instatnce, the savings associated with an efficiency imporovement can be converted into a return on investment [Pearce & Denkenberger]. That is, the efficiency improvement is not evaluated on the same basis as other investments a company might make. Important topics for further research include the behavioral economics of these decisions as made by real humans (e.g. do psychological experiments on whether managers are more likely to adopt an improvement if shown its benefits in terms of return on investment instead of payback time). Even more important is to better understand the social networks around decision makers and how these affect their decisions. These networks, are hierarchical and it would be interesting and useful to see how influence at different levels of the organization (foremen, engineers, managers) affect one another. Better understanding about how humans adopt technology improvements would help us better model the process of technology diffusion.

An important determinant of the rate of technology diffusion is its cost. The learning curves that describe reductions in costs of varioius technologies are still not well understood, although various models have been proposed. For example, some models use the design structure matrix as a representation of the complexity of the technology [J. McNerney, J. D. Farmer, S. Redner, and J. E. Trancik, "The Role of Design Complexity in Technology Improvement", arXiv:0907.0036v1 (30 June 2009)]. However, typically such models assume random improvements to the components of the technology. Although they can reproduce some aspects of technological development (e.g. the emergence of power laws) in some limits, they do not capture novelty (i.e. changes in the connectivity of the design structure matrix). They typically do not include any notion of how humans actually work on improving technology or how design changes will impact rates of adoption (aside from the effect of the price reduction). Most crucially, the models can point out potential bottlenecks in further technical development, but do not show how to speed that development up.

The lack of understanding of the technology development process hinders investments in portfolios of technologies, each with its won learning curve (and uncertainties in that learning curve). Although som general admonitions can be made about the unit scale of a technology and its prospects for improvement can be made (other things equal, the smaller the unit scale the faster the development), no theory exists to better choose investments in technology portfolios, especially under large uncertainties.

Some thoughts on the more technical aspects of models and dynamics (with primary application to climate change):

We can distinguish between several types of models:

- models that make specific numerical predictions;
- models that help define kinds of system behavior that is possible.

How can models be made to better bracket or provide an idea of the parts of the system we have control over, and those we do not? Can it quantify how much control we have in different behavior regimes (i.e. phases) exhibited by the model? For example, interval computing could bracket the absolute limits of numerical model predictions independent of floating point errors. How can the probabilities of runaway processes (e.g. runaway global warming) be better assessed?

What are the specific tradeoffs in the types of assumptions made between differential equation based models (e.g. neoclassical economics models) and, for example, agent-based models? In the former, one makes assumptions about the motivations of collections of agents. In the latter, one makes assumptions about the ability and motivations of the individual agents (at least at the beginning of the model). There has already been several centuries of mathematical research on solutions to sets of differential equations, including much numerical work over the past century. The mathematics that would describe, in a rigorous way, the behavior of an agent based model is still preliminary or perhaps not even invented yet. Therefore, many trials of agent-based models must be run to get results. The uncertainties, predictive power, and ultimate limits of prediction such models is an important area for further research.

The implementation of models as computer code is crucially important, especially as models of human actions, biology, and small scale inputs are connected to climate models. Although some scientists, including those currently implementing the large scale climate models, are either trained in computational science and good programming practices or work directly with software engineers who are, most scientists do not know how to program computers effectively and in such a way that the quality of their computer codes can be assessed [Greg Wilson, "Where's the real bottleneck in scientific computing?", American Scientist, Jan-Feb 2006]. How can effective quality control for the large scale integrated models be assured, especially when integrating components written by subject area specialists and not by trained computational scientists?

Dynamic Models

Even though climate change is widely acknowledged to be real, imminent and therefore requires concrete, aggressive actions we still need models that better approximate the uncertainty pertained in the upcoming events. We need to be aware that some systems are so complex that uncertainty is present as an inherent part and hence is not an imperfection that our models should correct. Aiming for perfection we tend to judge models based on how well they respond to our expectations and impose on them a fixed set of assumptions while there are mechanisms that we do not fully understand or know to exist. Alternative to this aggregate approach, complexity theory puts forward agent based modeling (ABM) and cellular automata (CA) among other ways to better identify and understand emergent behaviors and outcomes of climate change, while still addressing its spatio-temporal multi-processes aspects. Applications of CA include urban growth, wild fires, deforestation which are products of human behavior and which have grave impacts on the ecosystem, locally and globally. But as our world is filled with tiles it is cumbersome to specify the evolving state of every cell nor add a third dimension to our cell world. ABM does not require a complete set of states for every agent, allows them to be mobile, in addition to situation-appropriate characteristics. ABM is popular with modeling epidemics, utility markets, transportation systems, diffusion of new energy technologies and mitigation/ adaptation solutions etc. However these models are difficult to calibrate and validate.

As we better understand the system through the emergent actions and outcomes the uncertainty to what degree and extent we should combat climate change lessens. Neo-classical economics captures this uncertainty in discount rates. Taking into account our current most compromising and conservative scenario of a 2 centigrades increase in the Earth's temperature we should invest approximately 2% of the rich countries's GDP to battle against climate change. This is more relevant with strong sustainability, which demands the existing stock of natural capital must be preserved and enhanced because its functions and performance cannot be duplicated by manufactured capital than weak sustainability, which contends that manufactured capital of equal value can take the place of natural capital. To take care of the time dimension researchers now incorporate inter-generational equity to the evaluation of discount rates. However more work needs to be done in order to formulate rules that can better apply these ideas in our integrated assessment modeling.

In fact time and the quantification of the values of human, plant and animal life and diversity are not the only limits of current integrated assessment models (IAMs). Full consequences of policies we are considering might not be obvious until years after. Many events can occur during this phase lag, further troubling the refinement and verification of the models. While we would like to increasingly capture and integrate the complexity of the physical, social and economics systems this is not yet time when our available computational power is sufficient nor is our scientific knowledge complete. For this reason, expanding the models may compound the uncertainty in each sub-models and further complicate the already large chaotic overall models. Overall IAMs are useful for us in exploring the solutions space. Comparison of those models is worthwhile to see our different paths towards decarbonization and the various scenarios where we can have a carbon-free economy.

Wider Applications of Complex Models

There are a number of reasons why we believe complexity and modeling needs to be addressed and further funded within the arena of sustainability science. Sustainability can be seen as a complex system with many interacting parts (J. D. Farmer, J. West), particularly those in which human systems and environmental systems overlap and interact. Modeling and complex systems science allows for fine-grained understanding of human activity (both at the individual and group levels) within the context of physical ecosystem models. Such modeling can lead to more effective policies and will help us to understand our resilience in the face of climate change and resource depletion. We may also be able to identify key areas of vulnerability, unpredictable self-reinforcing feedback mechanisms between human/environment changes, and the ability to quantify the amount of leverage and relative importance of specific human behaviors. Moreover, these models give us useful scenarios to model the avenue towards a specific future of our choosing, given ever-changing constraints and boundaries.

The sheer number of nodes in our economic systems, and the complexity of understanding the behaviors of 6.5 billion different actors, necessitates agent-based models and an understanding of non-linear dynamics, emergent phenomenon, and scaling properties when addressing sustainability. Within a complex systems model, each time step changes initial conditions, thus affecting the next time step, as well as the overall model behavior. This is indeed much more realistic than general equilibrium models which follow the same set of assumptions throughout each time step, regardless of potential changes in the scenario. As such, complex systems models help us to test the underlying assumptions implicit within various projection scenarios for future population, GHG emissions, and resource use. They also allow us to quantify the level of inter-dependency and resilience present in human-environment networks.

The ability to rank the feedbacks within the field of human leverage is immensely useful when trying to quantify which policies will lead to the quickest and most profound changes towards a sustainable world. Given the spatial heterogeneity of governments, economies, cultural beliefs, and material wealth across the world, the current linear, normative models fail to adequately embody human/environment interactions. For example, the current IPCC climate models implicitly make assumptions about demand growth, population growth, consumption patterns, and technology adoption. However, these assumptions are not dynamic and do not change as the climate model changes. In this way, the human realm (policy, economics, psychology) is decoupled from the impact of climate change. The Reeds integrative assessment model layers many fields of interaction, but does not allow for interactive dynamics between the various sectors. It is thus providing incomplete information as to the most prescriptive policy actions. Complex systems and ABMs, on the other hand, allows for overlaps between many different systems and creates a dialog between energy, economy, and policy (Grubler).

Other possible uses for this type of modeling include: human migration within climate change scenarios, dynamics of infectious diseases, modeling stranded assets and lock-in, transition from one technology to another, clean energy technology transfer from developed to developing countries, environmental resource supply and management, and various aspects of behavior economics. For example, potential urban growth can be modeled with various development policy scenarios, allowing for a better understanding of how policy affects land-use changes over the long run (for examples, see http://vimeo.com/2110376, and http://vimeo.com/3322084). A similar approach could be used to model land-use changes over time due to policy-driven incentives in the bio-fuels market or electricity consumption between two cities with different rate structures. As another example, water resource management has become a pressing issue in the world (http://www.wri.org/publication/content/8261) and is tied to both a rise in population growth and standards of living. Using systems models, we may be able to better recognize the forcing agents and potential tipping points, both on a global scale and for individual aquifers and watersheds. This will help us determine appropriate policy measures to manage this resource.

Many earth systems have feedback mechanisms, that once activated are no longer under our control (Meadows, England). We often do not see the consequences of our actions until after we have activated these irreversible tipping points, after which the efficacy of changing our behaviors is limited (Edenhofer). These feedback loops occur within human systems as well, and may cause unintended consequences in the ways we sustainable manage our resources. Complexity helps us to capture the limits of a particular system, its tipping points, emergent behaviors, and non-linear phase changes. By looking at sustainability with a longer time horizon, within a dynamic, complex systems model, we will be more likely to take action where it really matters and before it’s too late.