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ABSTRACT

This chapter is an introductory essay to the volume *Climate Change Economics: The Role of Uncertainty and Risk,* edited by V. V. Chari and Robert Litterman. This volume consists of a collection of papers that were presented at "The Next Generation of Economic Models of Climate Change," a conference hosted by the Heller-Hurwicz Economics Institute at the University of Minnesota.

*The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Bank of Minneapolis or the Federal Reserve System.

In the fall of 2014, the Heller-Hurwicz Economics Institute gathered together a group of preeminent economists to discuss the economics of climate change. This volume contains many of the papers presented at that conference. In this introductory essay, I attempt to set the stage for the papers in this volume and discuss the state of economic research in this area.

Climate change poses one of the central challenges of our time. We now have overwhelming evidence that, ever since the Industrial Revolution began, human activity has had a profound impact on the earth's climate system. As commerce and industry have vastly expanded, so has the stock of greenhouse gases in the earth's atmosphere. A significant fraction of these gases have been absorbed by the oceans. The Intergovernmental Panel on Climate Change (IPCC) estimates that this buildup has resulted in a rise in combined land-ocean temperatures of roughly 1°C over the last 130 years (IPCC, 2018). The IPCC estimates that anthropogenic global warming will lead to a rise in 0.2°C for at least the next couple of decades, with the future course depending on the actions we now take. This rise is likely to lead to a rise in the sea level, increased frequency and severity of major climate events such as hurricanes and droughts, and major disruptions in agricultural, industrial, and commercial activity.

While the basic physics are well understood, the detailed effects of the buildup of greenhouse gases in the atmosphere and climate are subject to a fair amount of uncertainty. A buildup of carbon dioxide in the atmosphere through, say, the burning of fossil fuels creates a greenhouse effect by preventing the heat that reaches the earth from being reflected back into space. This effect may well be amplified by other drivers of climate change. Climate scientists are uncertain about the extent of this amplification but are in widespread agreement that it will be substantial. The oceans have some capacity to absorb carbon dioxide, but as they do, the oceans become more acidic, limiting their ability to absorb further levels of carbon dioxide. This acidification in turn threatens the well-being of fisheries and can further destabilize the climate. An important source of uncertainty is the extent to which water from the deeper ocean layers can circulate and replace the acidified upper layers.

In my judgment, however, the greater uncertainties lie with our ability as a species to adapt to climate change, mitigate its effects, and find ways to reduce the buildup of greenhouse gases. The central task of social scientists is to take the findings of climate scientists about the effects of global warming on the atmosphere, climate, land, and oceans and understand the consequences of these physical changes on the economic, social, and political well-being of humanity. Understanding these consequences is the first step in communicating the likely effects of alternative policies aimed at addressing climate change to our fellow citizens.

An apocalyptic vision of climate change is that it will lead, perhaps, to our extinction as a species. That vision is not widely shared among the social and natural scientists who study this problem. The vision that is widely shared is that climate change is an acute, urgent problem that needs to be addressed, and fairly soon, and that it can be done using a variety of tools. These tools include developing new technologies for producing and distributing energy, finding ways to limit the amount of carbon dioxide we emit, and finding ways to remove the carbon dioxide we have already emitted. That is, these problems are well within the scope of our ingenuity. Certainly, the papers in this volume are well within this mainstream of social and natural scientists. It is worth acknowledging that a number of observers have argued that climate change cannot be solved within the framework of capitalist societies (for one example, see Klein, 2014, for a call for a fundamental reordering of our economic and social systems to handle the threats posed by climate change).

In this introduction, I begin by reviewing well-understood arguments for why climate change cannot be addressed without some sort of collective intervention. The obvious agencies for this collective intervention consist of governments and multilateral institutions. I then review how economists analyze the issue of climate change and the consequences of various policies to address it.

Finally, I briefly review the contributions of the papers in this volume. The theme that unifies most of the papers is that uncertainty and risk must be central to the next generation of economic models of climate change. Here, uncertainty refers to the concern that the models we use are, at best, approximations and are subject to misspecification. Well-designed policies should be robust to this misspecification. Risk refers to better understood and more widely agreed upon stochastic fluctuations, particularly in growth rates. Incorporating these considerations typically makes addressing climate change more urgent and increases the magnitude of the desired interventions.

1. Decentralized Mechanisms and Climate Change

Economists have an affinity for social systems that allow people to voluntarily truck, barter, produce, and consume as they fit, unhindered by restrictions other than the usual prohibitions against violating the rights of others, including theft, plunder, and murder. This affinity arises in substantial part because in a voluntary exchange, by definition both buyer and seller are better off than they would be if such an exchange were prohibited. Allowing for voluntary trade also ensures that people are able to specialize in the tasks in which they relatively excel, which in turn promotes their welfare. This affinity arises in part because of the multitude of evidence we now have that allowing people to pursue their interests within appropriate bounds has led to much better outcomes than those in centralized, top-down systems, or in feudal systems that restrict activities by custom and by social prohibitions. The obvious examples that come to mind are the comparisons between East and West Germany, North and South Korea, and the dramatic growth experiences of the East Asian Tigers in the 1960s and 1970s, China after it liberalized in the late 1970s and 1980s, or India after it liberalized in the early 1990s. Some authors (see McCloskey, 2010, for a particularly vivid example) argue that the Industrial Revolution was made possible because of the relative freedoms granted to ordinary people.

For many economists, this affinity comes not just from observation but from mathematical formalizations of market outcomes. The modern formulation is due to Arrow and Debreu (1954), who proved the first and second theorems of welfare economics. (Their work has its antecedents in the earlier work of Adam Smith, Leon Walras, John Hicks, Irving Fisher, and Lionel McKenzie, among many others.) The first theorem asserts that if markets are available for all of the commodities people care about, and if all individuals and firms behave competitively in the sense that they take prices as unaffected by their actions, the resulting outcome is Pareto optimal. That is, no individual can be made better off without making someone else worse off. The second welfare theorem asserts that, with suitable redistribution, any Pareto optimal outcome can be supported as a competitive equilibrium.

The prescriptions for policy seem immediate: ensure that markets are available for all commodities, vigilantly police uncompetitive behavior, and let people trade, truck, barter, produce, and consume as they fit. But economists widely agree that this prescription is woefully inadequate when it comes to externalities such as those induced by pollution and global warming (as well as public goods such as national defense). At a technical level, for an economic theorist, an externality is simply a case of a missing market. When markets are missing, choices by individuals directly affect the welfare of others, resulting in welfare losses. When markets are available, the choices of individuals are mediated through the price system, and since transactions in the marketplace are voluntary, competitive equilibria cannot be Pareto dominated. The deeper question for the theorist is why markets for commodities such as air quality do not arise naturally, in the same way that the market for shoes does.

Rob (1989), Mailath and Postlewaite (1990), and Chari and Jones (2000) use methods from mechanism design and game theory. Here, I will describe the version due to Chari and Jones, mainly because that paper clarifies which of the assumptions in the welfare theorems are questionable in the presence of externalities. Think of a town with n residents, each of whom lives in an equal-sized lot. The residents care both about a consumption good as well as about the quality of air directly above their lots. The town has factories located on its perimeter. These factories produce the consumption good, but in doing so, they also produce smoke, which spreads evenly in the air above each lot. Absent any markets in air quality, it is easy to see that the outcome is likely to be inefficient. In making their production decisions, firms do not take into account that they are reducing the quality of the air above the residents' lots.

The remedy, to an attentive reader of Arrow and Debreu (1954) and Coase (2000), seems obvious: introduce markets in air quality and let the market work its magic. One way of doing so is to require that firms cannot violate the air quality above any resident's lot without that resident's explicit agreement. Somewhat more formally, we think of each resident as having a property right to the quality of air above that resident's lot. Since the smoke, by assumption, spreads evenly over the town, any factory that chooses to emit smoke must purchase the required amount of smoke rights from *each* resident. One way of thinking about this formulation is that residents' smoke rights are perfect complements in producing the consumption good. Having perfect complements does not cause any problems for the validity of the welfare theorems.

If all the residents are price takers, then markets will indeed work their magic. Chari and Jones argue that this price-taking assumption is especially problematic with perfect complements. One way of understanding their argument is to consider a noncooperative game in which the residents set the prices for their smoke rights. Chari and Jones show that when the number of residents is large, the outcomes are necessarily extremely inefficient. When the number of residents is large, the amount of smoke rights sold is vanishingly small, and there is essentially no production of the consumption good. That is, the market for air quality rights ceases to exist. The reason is that the perfect complementarity feature induced by some manifests itself as a free rider problem. In setting the price for individual smoke rights, no seller internalizes that raising his or her own price reduces revenues to the other residents. Chari and Jones go on to show that endowing the factories with these rights and allowing residents to purchase them does not solve the problem either. In this case, when the number of residents is large, essentially none of the smoke rights are purchased by the residents, and the market for air quality rights ceases to exist.

The problem here is that the price-taking assumption is extremely questionable with perfect complements. Each resident cares only about the quality of his or her own air, and there are no substitutes available for that air. Indeed, everyone's air is a perfect complement to that of others in production. This model illustrates that simply handing out property rights and allowing markets to work will, in general, lead those markets to disappear. When markets are not available, outcomes are likely to be very inefficient. The key idea in this market failure is not so much that the air quality above each person's lot is a different commodity from the air above another's but rather that no good substitutes are available for the quality of any resident's air. The contrast with the market for housing helps to illustrate this point. After all, every house is, in some sense, a distinct commodity. Other houses are, typically, good substitutes for any given house, so it is often reasonable to think of the housing market as competitive.

The observation that the extent of substitutability plays a central role in market failure also shows up in comparing situations with global externalities and those with local externalities. Global externalities correspond to global complementarities and local externalities to local complementarities. Complementarities that are local are pervasive in most forms of team production. Each shoe factory may require cobblers and leather in fixed proportions, but as long as shoe factories compete with each other, the bundle of services provided by cobblers and leather at a given factory is a perfect substitute for the bundle provided at another factory. The market for shoes may then be competitive even in the presence of local complementarities. These observations imply that global externalities are likely to create much more significant social problems than local externalities. The essence of, say, carbon dioxide in the atmosphere is that the molecules drift far and wide and cannot be prevented from migrating, so burning fossil fuel creates global externalities.

Rob (1989) and Mailath and Postlewaite (1990) show that, when people are privately informed about the harm caused by externalities or the value of public goods, any mechanism that respects voluntary participation constraints yields very inefficient outcomes in an ex ante sense, in economies with large numbers of individuals. The voluntary participation constraints require that no individual can be compelled to pay for mitigating externalities or providing public goods. I think of these voluntary participation constraints as conferring strong property rights to individuals, and in this sense as capturing a key property of decentralized mechanisms.

The message of these analyses is that decentralized mechanisms are likely to lead to poor outcomes in the presence of global externalities. Some form of collective intervention is needed. This collective intervention can be thought of as limiting property rights or as limiting the extent of voluntariness in transactions.

This message does not imply that markets have no role in mitigating the effects of externalities. Indeed, they can play a central role in doing so. One example is to endow each factory with a given amount of air quality rights. While residents may have limited incentives to buy these rights, efficient factories have every incentive to purchase these rights from less efficient ones. One notable example of such a trading scheme can be seen in the sulfur dioxide markets that were set up as part of the Clean Air Act of 1990. Acid rain was a sizable and growing problem all through the 1970s and 1980s. The burning of fossil fuel to generate electricity caused sulfur dioxide to enter the atmosphere and fall gently as sulfuric acid when it rained. Allowing utilities to trade permits to emit sulfur, along with a variety of other regulations, ensured that acid rain is no longer a sizable problem. Chan et al. (2015) argue that this market yielded substantially higher benefits than would be obtained under an alternative widely used environmental regulation.

Another example is to tax the emission of smoke. In the context of carbon dioxide, these policies can also be thought of as putting a price on carbon. Such a tax induces the factories in our example to internalize the harmful effects of smoke on residents. Economists have discussed the merits of regulating prices rather than quantities. The seminal analysis in the context of environmental externalities in Weitzman (1974) provides methods for determining when prices are a superior regulatory tool relative to quantities. It is fair to say, though, that compared with the urgent necessity of addressing the problems posed by climate change, the details of price regulation versus quantity regulation seem secondary.

Regardless of which tool we employ, the main reason why we need economic methods is to help us to understand the benefits and costs of pollution. Pollution clearly has costs in that it affects air quality. But production of the consumption goods we seek and desire often comes with the undesirable side effect that smoke is produced. It is rarely desirable that we have all of one or all of the other. Determining the trade-offs between these conflicting goals is the kind of task at which economists specialize.

2. Models of Climate Change

In 2018, William Nordhaus, joint with Paul Romer, received the Nobel Memorial Prize in Economic Sciences for pioneering the analysis of the economic effects of climate change. The Integrated Climate Assessment models that he played a key role in developing have two main modules. The natural science module maps economic activity, such as the burning of fossil fuels, into effects on the atmosphere, such as air temperature. The economic module maps the characteristics of the atmosphere into economic activity. A typical example of these modules is the simplest version of the Dynamic Integrated Climate and the Economy (DICE) model. In this version, the many aspects of the atmosphere are captured in a single variable, temperature. The natural science module maps fossil fuel emissions into temperature. The economic model is a version of the Cass-Koopmans growth model, with forward-looking agents. In this model, a single composite consumption investment good is produced using a production that uses capital, labor, and energy from fossil fuels. The efficiency with which these inputs are transformed into the composite good, total factor productivity (TFP), is affected by temperature. This efficiency grows over time at an exogenously specified rate. The composite output good can be used either for consumption or to accumulate capital through investment.

Even the simplest version of the model has all the essential features needed to understand the economic effects of climate change. A dynamic model is essential because many of the effects of climate change will be felt far off into the future. Forward-looking agents are also useful to capture the idea that expectations about the future path of TFP are appropriately incorporated into current investment decisions. The separation of the natural science module and the economic model is a useful way of incorporating changes in climate models emanating from the natural sciences and developments in our understanding of how private agents make economic decisions. The key externality is that the path of emissions affects TFP and economic aggregates, but no individual actor takes into account that his or her choice of fossil fuel use affects the time path of temperature and the resulting path of aggregate outcomes. Extensions of the model have been made to account for heterogeneity among regions of the world, leading in particular to the Regional Integrated Climate and the Economy (RICE) model. Nordhaus (2018) contains a comprehensive discussion of the most recent versions of these models.

The model is designed to allow us to analyze the trade-offs confronting policymakers. Consider, for example, a policy that reduces current fossil fuel emissions. This reduction has a cost in reducing current output and a benefit of raising future output by reducing future temperatures. That is, reducing emissions is a form of investment, so a model that focuses on investment decisions is the sensible benchmark. In principle, economists could outline a number of scenarios associated with various policies and allow policymakers to choose an appropriate policy.

This principle is, of course, hard to implement in practice because it might require us to present policymakers with a possibly infinite number of scenarios. An easier process is to compute the *social cost of carbon*. The social cost of an activity that creates an externality is the sum of the marginal damages on all individuals expressed in consumption-equivalent terms. Calculating this social cost in static environments is straightforward in principle. Even in such environments, one needs to know the status quo point at which these marginal damages are calculated. One way of avoiding these complications is to calculate the Pigouvian tax that is needed to sustain some point on the Pareto frontier. With these corrective taxes, one could then sustain this point as a competitive equilibrium. In dynamic environments such as those in the DICE model and its successors, the social cost of carbon, then, is not a single number; rather it is a sequence of numbers, each corresponding to the Pigouvian tax at each date. In environments with uncertainty, it is a sequence of numbers for each date and exogenous state of the economy. While reporting on this kind of calculation to policymakers is difficult, it has the advantage of describing, with some specificity, the policy interventions needed to sustain efficient allocations.

The computation of the social cost of carbon requires us to be specific about both the natural science module and the economic model, as well as the particular point on the Pareto frontier that we choose to support. A substantial part of the discussion around the appropriate computation of the social cost of carbon has centered on the appropriate point on the Pareto frontier that is to be sustained. This discussion is necessarily not easily resolvable because it involves a comparison of the well-being of those currently alive and the well-being of as yet unborn generations. Nordhaus has argued that market interest rates are a useful starting point. The idea is that this interest rate is determined in part by a variety of government policies in other areas, such as social security and long-term investments. These interest rates reflect the weights policymakers have chosen to put on future generations. From this perspective, we use the revealed preference of policymakers in democratic societies to determine the appropriate weight to put on all generations. Nicholas Stern (2007) has argued that market forces are not necessarily the best guide to the ethical question of how much weight to put on future generations. Brock (1977) has argued that, in the presence of externalities, the market discount factor may be higher than the social discount factor. Given this controversy, the best course for economists as policy advisers may well be to compute the social cost of carbon at each date (and state) under various weights for future generations and leave it to our fellow citizens to choose from the menu of items.

We now have some of these estimates at hand. The scientific background report of the Nobel Committee (NobelPrize.org, 2018) has summarized some of the canonical findings using recent versions of the DICE model. With Nordhaus's best guesses for parameterizing the model, the committee reports that the social cost of carbon is currently roughly $30 per metric ton of carbon dioxide, rising over time to about $64 in 2030 and $154 in 2050. To put this in terms that may be easier for most of us to understand, a tax of $30 per metric ton of carbon dioxide corresponds to a gasoline tax of about 30 cents per gallon. The appropriate weighting of the well-being of future generations is critical in computing the social cost of carbon. For example, using a social discount rate of 0.1% as Stern prefers, the social cost of carbon is currently roughly $290 per metric ton of carbon dioxide, rising to roughly $380 in 2030 and $615 in 2050. Adopting the Stern proposal would require a tax of roughly $3 per gallon of gasoline. While such a policy would involve a significant reordering of our economic activities, it is hardly a call for a wholesale abandonment of our current economic systems. After all, the average tax on gasoline among advanced economies is already over $2.50 per gallon!

The current state-of-the-art Integrated Climate Assessment models represent an important starting point in developing our understanding of how the economy will respond to various policies intended to address climate change. It is conceptually possible to adapt these models to incorporate *risk.* By risk, I mean that the economy is subject to fluctuations that follow a well-understood stochastic process on which the agents in the model agree. Cai and Lontzek (forthcoming) and Golosov et al. (2014) are leading examples of this exercise. Incorporating risk does change the optimal policy responses, sometimes quite dramatically.

The frontier of research in this area now attempts to incorporate uncertainty, ambiguity, and learning. As we will see, incorporating these features may require more urgent and more aggressive policies.

3. Uncertainty, Risk, and Ambiguity in Climate Change Economics

The papers presented at the conference are all very closely related to one another, but it is useful to break them into three categories. One set of papers attempts to incorporate uncertainty in a broad sense into economic models of climate change. By uncertainty, I mean situations in which we are not sure what natural science or economic model to use, not sure about what parameters to use for each model, and in which we are concerned that our models are misspecified in various ways. The papers by Brock and Hansen (forthcoming), Anderson, Brock, and Sanstad (forthcoming), and Wagner and Zeckhauser (forthcoming) fall into this category. A second set of papers uses asset pricing theory and empirics to develop climate change models and argues that this theory and the associated data may lead to very different policy implications from the current generation of models. This category includes the papers by Daniel, Litterman, and Wagner (forthcoming) and Bansal, Kiku, and Ochoa (forthcoming). A third category is policy and consists of Weitzman (forthcoming) and Mehra (forthcoming).

Brock and Hansen emphasize that the models developed by natural scientists are highly diverse. For example, the models' forecasts of the rise in temperature under current policies differ by over 2°C for 2050. As they emphasize, the differences arise both from modeling differences and from differences in assumptions about the trajectory of greenhouse gas emissions. The natural science models are subject to misspecification. Computational constraints require physicists to use approximations, such as linearizations, which may neglect potentially important nonlinearities. Furthermore, the economic module is also subject to this kind of misspecification. Given these concerns, they review the growing literature on decision theory in environments with ambiguity and provide concrete ways in which we can incorporate these concerns about uncertainty. Their paper is essentially an exceptionally useful instruction manual for the next generation of economic models of climate change.

Anderson, Brock, and Sanstad is a state-of-the-art application of the methods advocated by Brock and Hansen to a specific model of climate change. Their baseline model builds on conventional DICE models. The important departure is that the agents in this model are concerned about model misspecification and are modeled as being averse to ambiguity in the sense of Hansen and Sargent (2001). They estimate the model using world data from 1952 to 2011. Remarkably, they show that a policymaker who does not think climate change affects productivity but who is concerned about the possibility that he or she might be wrong chooses policies that are very similar to those of a policymaker who does believe that increased temperature lowers productivity and is also concerned about model misspecification. In the words often attributed to Oliver Cromwell, "I beseech ye, think ye that ye might be wrong" may be the best message to climate change skeptics.

Wagner and Zeckhauser show that uncertainty in our understanding of the effects of climate change can affect the desired policy response in sizable ways. In particular, they show that changes in the peakedness of a distribution induced by changes in kurtosis can have substantial effects on the appropriate policy response, even holding fixed the mean and standard deviation. Given our uncertainties about the natural science module and the economic model, their analysis suggests that conventional estimates of the social cost of carbon may severely underestimate the true cost.

Daniel, Litterman, and Wagner develop a new model, labeled the EZ-Climate Model, which they argue is a tractable and superior model for analyzing policy compared with the conventional DICE and RICE models. Asset pricing theory and empirics have long warned us that the standard constant relative risk aversion (CRRA) preferences model of consumption and saving is inconsistent with asset price data and have argued that a model with Epstein-Zin preferences may be the better route to follow. The models differ only in the presence of risk. In addition, they incorporate learning about the effect of damages, and a number of other features. They show that their model has implications for policy that are very different from those in DICE and RICE models. Daniel, Litterman, and Wagner show that the optimal policy has a high effective tax on emissions, which declines over time as uncertainty is resolved. The main reason for this finding is that with Epstein-Zin preferences, a form of the precautionary principle applies. The equity premium puzzle is essentially that participants in equity and bond markets are willing to pay a high price in terms of forgone returns to protect themselves from very bad events, even if such events are quite unlikely. This observation suggests that, as a society, we should be willing to pay a high price to purchase insurance against the possibility that the damages from climate change turn out to be more severe than we now think.

Bansal, Kiku, and Ochoa use data on equity prices and temperature fluctuations to calibrate a model with long-run risk and Epstein-Zin preferences. They show that the social cost of carbon initially is three times as large as in the conventional DICE model. One important force that drives these results is that Epstein-Zin preferences imply a desire to resolve uncertainty early. In the version of their model with CRRA preferences, the planner postpones abatement efforts for nearly 50 years. In the version with Epstein-Zin preferences, in contrast, the planner acts aggressively and immediately. Given that models with CRRA preferences are inconsistent with the data on the equity premium puzzle and other asset pricing puzzles, and given that risk is an important component of climate change, it is clear that the next generation of models will have to use the Bansal, Kiku, and Ochoa framework as a starting point.

Global warming is clearly a *global* problem. Addressing the externalities from fossil fuel emissions requires, as I have already argued, collective intervention. Designing this collective intervention requires the cooperation of member states. Achieving cooperation has proved difficult in practice. Weitzman (forthcoming) builds on his earlier work (Weitzman, 1974) to argue that it may be possible to achieve desired outcomes if we could get countries to agree on a single internationally binding minimum price rather than by assigning quantity targets and allowing for trade, as under a cap and trade system. The main idea for the superiority of a system that requires agreement on a single price rather than separate quantity targets is that it can help to overcome a free rider problem. With a single price, each country understands the trade-offs in setting the price. In determining the common price, each country's costs from a higher price are offset by the resulting decrease in aggregate emissions. In negotiating quantity targets for emissions, each country has an incentive to attempt to get a higher quantity for itself at the expense of others.

Mehra argues that evaluating alternative policies vis-a-vis their effect on asset values can be misleading in terms of welfare. The main reason is that interest rates are endogenous in a world in which policies affect the growth rate of consumption. He goes on to forcefully argue that the role of economists in a world with heterogeneity (and unborn generations) is simply to describe consequences for each class of agents and leave the choice of which point to choose on the Pareto frontier to our fellow citizens.

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