Central Banking Challenges Posed by Uncertain Climate Change and Natural Disasters*

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Abstract

Climate change poses an important policy challenge for governments around the world. The challenge is made all that much more difficult because of the multitude of potential policymakers involved in setting the policy worldwide. What then should be the role of central banks? How are climate change concerns similar to or distinct from those of other natural disasters? Clarity of ambition and execution will help to ensure that central banks maintain credibility. By adhering to their mandated roles, they retain their critically important distance from the political arena.

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1 Introduction

The potential hazards of climate change have become explicit policy concerns of government officials as well as the general public. Many now understand that long-lasting damages to the planet's capacity to sustain life will occur without action. Economists, since Pigou (1920) have long identified pollution as a negative externality in production and consumption. Individuals, businesses and institutions that engage in activities that increase greenhouse gas emissions are not taking into account the ill-effects of their actions on others, a concern that extends well beyond pollution and into other potential damages in the future that could be induced by climate change. Economists further have proposed directly addressing this market error by imposing a carbon tax, or capping production and creating a market in production licenses; thus making clean production an opportunity for those for whom it is cheapest, and making pollution an option only for those for whom clean alternatives are the most costly. More generally, effective climate policy levers are in the fiscal, not monetary toolkit. Even so, enacting taxes has politically challenging distributional consequences. While classroom exercises focus perhaps too much on deadweight loss triangles; In practice, the tax revenue rectangles are of higher value, and there are limited obvious economic principles to guide how those are distributed to best aid policy aims. Nevertheless, from an overall viewpoint, the most impactful place for climate change policy would seem to be in the fiscal realm of tax legislators and coordinated responses across governments and regions around the world and not from the monetary policy arena.

Why look to monetary policy as a featured way to combat climate change? We have seen political wrangling prevent creation of coherent tax policy or cap and trade policy within countries as well as between countries. Does distance from the political arena make central banks more attractive resources for shaping policy on climate? Does the vital importance of climate for society justify working on it from all possible policy angles at the same time? While some are embracing this as an attractive route, I see three potential dangers.

i) attempts to take on a broader mission without formal and well defined mandates could compromise central bank independence in the longer run;

ii) hastily devised policy rules unsupported by quantitative modeling could backfire if or when climate policy targets are missed, harming reputations of central banks and weakening their ability to act in the future on a variety of fronts;

iii) climate change mitigation targets added to currently well defined mandates may generate excessive expectations and unwarranted confidence in the abilities of central banks to address this important social and economic problem while diverting the attention away from fiscal policy.

The remainder of this paper is devoted to exploring these potential policy pitfalls. My discussion will be organized around the following five topics:

- Modeling systemic risk and climate change in support of rule-based policy for financial stability
- Quantifying the exposure of financial institutions and businesses that receive their loans to uncertain climate change
- Stress testing banks based on long-term possibilities of climate change
- Slanting central bank portfolios towards green technologies
- Comparing climate change challenges of central banks to those connected with other natural disasters

2 Systemic risk and climate change

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be. Lord Kelvin, 1883.

While Lord Kelvin was a mathematical physicist, this charge has also been directed to the social sciences. See, Merton et al. (1984). We could have an interesting discussion about the merits of this dictum, as some find it controversial or naive. To their credit, central banks have used quantitative modeling to support policy-making directed at their mandates. While many have emphasized advantages to rules-based policy making, the merit in such rules gain credibility by quantitative modeling backed up by empirical evidence. Part of the desired transparency and credibility of a policy rule is provided by transparency and credibility in the modeling and evidential support of that rule. Quantitative modeling aids our understanding of how policies address central bank mandates. This enhanced understanding helps to keep some valued distance between policy and politics. Moreover, the construction and use of models opens the door to constructive criticism from outside researchers. Tucker (2019) has discussed why financial stability is different from other central bank mandates because many potential policy levers require opaque execution; but my aim in this section is to revisit if and how models of financial stability might help to remove the opacity of design and ambition of central bank policy in this arena.

I think of the productive use of highly stylized models as a form of "quantitative storytelling." The models we use, as is easily seen in the study of economic dynamics, are not meant to be fully comprehensive. As noted in the well-known quote from George Box:

> Now it would be very remarkable if any system existing in the real world could be exactly represented by any simple model. However, cunningly chosen parsimonious models often do provide remarkably useful approximations. Box (1979)

This "substantive models are expected to be misspecified" perspective extends more generally across scientific applications, although the quality of the approximation varies extensively across disciplines and applications. Nevertheless, we build and use models because they provide guidance that a) helps our understanding of how policy works and b) allows for predictive statements about policy outcomes. While there is very little insight to the observation that models are misspecified, there are reasons to conjecture how the potential misspecification could unravel the insights or overturn the predictions in quantitatively important ways. Entertaining multiple models with differing implications for predictions adds an additional consideration, but acknowledging this multiplicity does not undermine their use. Indeed, the idea of quantitative storytelling with "multiple stories" will capture many policy challenges with dynamic implications.

If we imagine that climate change or natural disasters could induce instability in the banking sector, then perhaps we should just add some big shocks to our models of financial stability. In a later section, I discuss the distinct modeling and measurement difficulties related to exposures to climate change uncertainty. More generally, we are still in the early stages of building quantitative models of so-called "systemic risk" in the financial system. Systemic risk is envisioned as an externality creating a need for central banking policy that extends beyond the microprudential regulation of individual banks. To construct a rules-based approach to systemic risk policy introduces a modeling challenge that I originally wrote about a decade ago. See Hansen (2014). Since writing that essay, we have advanced our understanding; but this progress falls short of providing a model or even a small set of models that are broadly embraced for quantitative predictions.[1] Moreover, the financial crisis exposed limitations in existing models that were used previously to guide central bank policy. It remains to be seen if the quick repairs that emerged will indeed blossom into good guides for future policy directed to financial stability, or if lower dimensional models with more fundamental nonlinearities that have emerged are better suited to provide policy guidance.

Even if my assessment of existing quantitative models of "systemic risk" is unduly negative, these models were not built with climate change concerns in mind. Thus, it remains to incorporate climate change into this modeling of financial stability. There exists a suite of integrated assessment models in climate economics that seek to produce measurements of the social cost of carbon. This social cost has the most clear meaning as a Pigouvian tax on carbon emissions necessary to support a social optimum. See, for instance, Golosov et al. (2014), Nordhaus (2017),

[1] Lord Kelvin was over-confident in one of his own attempts at quantification when he erroneously argued that Darwin's theory was flawed because it required a much larger age of the universe than was supported by his calculations. Lord Kelvin failed, however, to consider radioactivity in his computation of the age of the Sun.

Cai et al. (2017), and Barnett et al. (2020). Using this cost in actual policy-making necessarily has less lofty ambitions and conceptually more murky "second-best" type aims. Putting those issues to the side, the integrated assessment models are directed at fiscal policy and not at the stability of the banking system. But even as a contributor to the social cost of carbon, there is skepticism among some researchers about the status of the numbers produced from such exercises. For instance, Pindyck (2013) and Morgan et al. (2017) find existing integrated assessment models in climate economics to be of little value in the actual prudent conduct of policy. Morgan et al. note the value of such model building for enhancing our understanding of an important social problem, a conclusion that I also see as having considerable merit. While there is a substantial body of evidence supporting the adverse human imprint on the environment, uncertainty and knowledge limitations come into play when we build quantitative models aimed at capturing the dynamic transmission of human activity on the climate and adaptation of economic activity to climate change. This uncertainty needn't undermine modeling efforts but should shape how models are used. For instance, Barnett et al. (2020) show how broad-based considerations of uncertainty can be captured mathematically by an uncertainty adjusted probability measure used for social valuation. Even from standard asset pricing calculations, we know the importance of "stochastic discounting" whereby, in effect, discounting depends on how the cash flow being valued is exposed to uncertainty. Even after broadening our conceptualization of uncertainty, such stochastic or probabilistic representations of valuations remain valid with the appropriate adjustments to the probabilities. This observation carries over as well to social valuation as Barnett et al. (2020) show. Discussions in environmental economics about what is the correct discount rate are framed too narrowly for valuation under uncertainty pertinent to climate change and other realms of policy making.

There exist many large scale geoscientific models designed to address climate change as implied by exogenous emissions or atmospheric CO_2 paths that have dynamic richness as well as spatial heterogeneity. It is not tractable to plug these climate models into an economic model with forward-looking economic agents or policy makers. One revealing way to model comparisons is to run common pulse experiments across a set of alternative climate models. In Figure 1, I report the outcome of such experiments as tabulated by Barnett et al. (2021) and based on work by Joos et al. (2013), Geoffroy et al. (2013) and others.

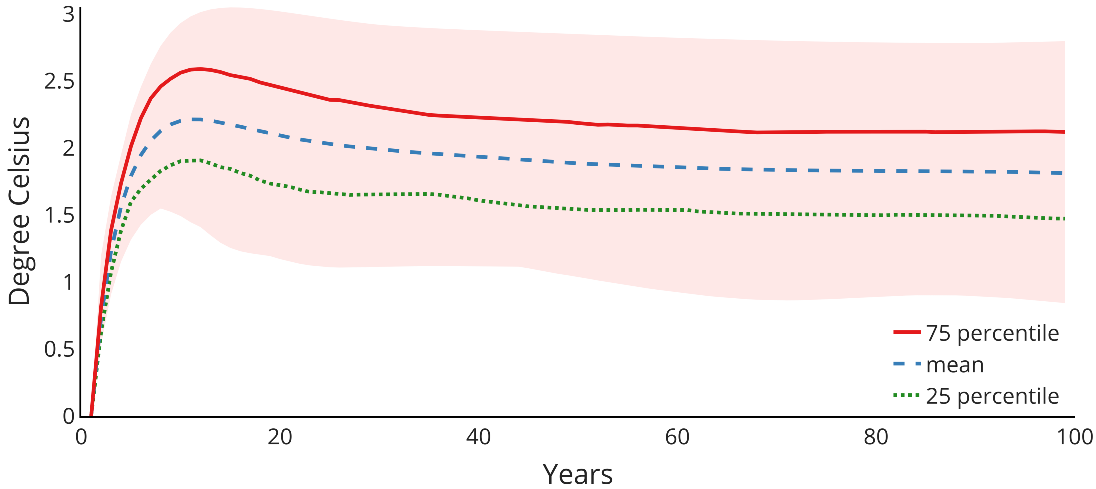


Figure 1: Percentiles for temperature responses to emission impulses. The emission pulse was 100 gigatons of carbon (GtC) spread over the first year. The temperature units for the vertical axis have been multiplied by ten to convert to degrees Celsius per teraton of carbon (TtC). The boundaries of the shaded regions are the upper and lower envelopes. These responses are convolutions of responses from sixteen models and temperature dynamics and nine models of carbon concentration dynamics giving rise to 144 model combinations.

Figure 1 captures the resulting temperature responses across various sets of these 144 models. The maximal temperature response to an emission pulse occurs at about a decade and the subsequent response is very flat, which are the response patterns featured by Ricke and Caldeira (2014). For a further characterization of this heterogeneity, we compute the exponentially weighted average of each of these response functions and use them in our computations. We report the resulting histogram in Figure 2.

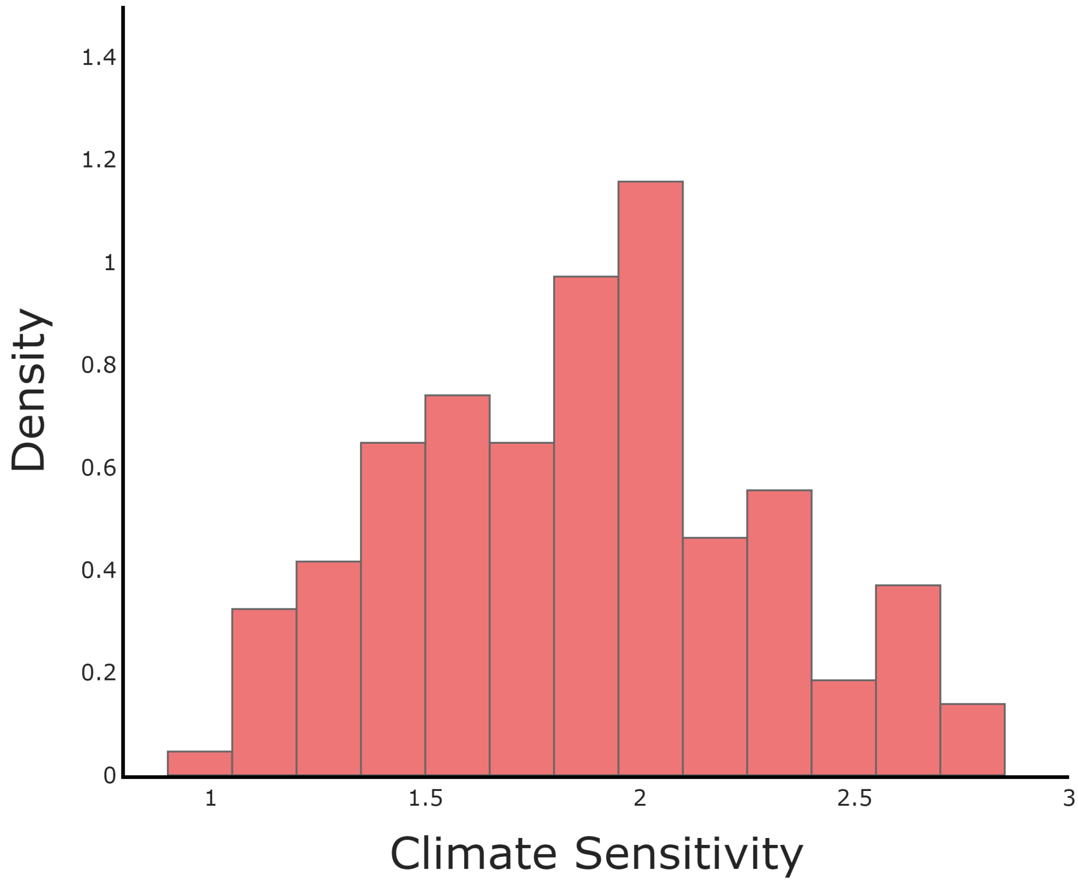


Figure 2: Histograms for the exponentially weighted average responses of temperature to an emissions impulse from 144 different models using a rate $\delta = .01$.

This very linear characterization of the climate dynamics masks some potentially important nonlinearities.[2] Nevertheless, it gives a convenient representation of the cross-model heterogeneity in how the emissions today alter temperature in the future. In building integrated assessment models, economists add simple depictions of damage functions, often static, that are intended to capture productivity losses induced by climate change. Uncertainty again comes into play because of our limited knowledge of how economies will adapt to climate change and how this will play out over time. It is damage function uncertainty that is the "Achilles heel" of integrated assessment models of climate change. Adding financial instability on the list of important modeling components leaves quite a bit of guess work left for prudent decision-making.

In the fiscal realm, there has been much discussion of the social cost of carbon. While this

[2]In contrast to a linear model, pulse sizes can matter for how emissions influence carbon concentration beyond a simple scaling. Depending in part on the size of the pulse, this linearity is at least partially offset by what is called the Arrhenius equation.

construct is not always coherently defined, its conceptual simplicity is in the stylized environment of a fictitious social planner taking account of climate change when solving a social optimization problem that includes fossil fuel emissions and accounts for the resultant environmental damages. The social cost of carbon is a shadow price for emissions from the vantage point of the planner implemented hypothetically by a Pigouvian tax. The varied attempts for computing the social cost of carbon have revealed sensitivity to modeling assumptions and potentially sizable uncertainty adjustments depending on the aversion that the planner has for the exposure to this uncertainty. Deducing the social cost trajectories to be used for actual policy implementation remains an interesting and important research challenge. Unfortunately, these computations are not easily transported to the study of financial stability.

While there are many qualitative models that speak to systemic risk, credible quantitative modeling is still in its very early stages. As I have argued, some progress has been made in assessing the uncertainties related to climate change, but the quantitative climate/economic models to date have not been designed with financial stability as their primary aim. Encouraging central banks to fly blindly into a new realm could also prove harmful to central bank reputations. Proceeding with a pretense of knowledge might support an activist monetary policy to address climate change in the short run but damage central bank reputations over the longer run. Any excessive confidence in our understanding could backfire over the longer haul and damage credibility through false promises of success. For these reasons, I am skeptical that quantitative modeling can provide the meaningful support for rules-based systemic risk policies that pertain to externalities that climate change imposes on the financial stability.

An investment in building better quantitative models that explore how climate change might challenge financial stability is a worthy venture. We could argue that bad numbers are better than no numbers, but I prefer an appeal to modern decision theory under uncertainty to address model ambiguity or misspecification concerns. I see virtue in the use of decision theory as a language for how to frame decision-making in an uncertain environment, even if it is used only at an informal level. Application of decision theory, however, will not eliminate knowledge gaps that we are looking to fill when speculating about potential externalities that climate change uncertainty might impose on the financial system. Rather, it will provide a coherent way to acknowledge these gaps.

3 Quantifying Exposures to Climate Uncertainty

In addition to arresting systemic risk, another role for financial regulation is to monitor exposure of financial institutions to "big shocks" to the economy. If regulated firms are poorly prepared for pervasive turbulence, then this could hinder the provision of financing for productive ventures. In the theory of finance, there is a construct called "systematic risk" that is conceptually distinct from the "systemic risk" construct offered as a central rationale for macro-prudential policymaking. In the standard asset pricing setting, systematic risk is present because of exposure to aggregate shocks and this exposure requires compensation in financial markets. The presence of systematic risk is not evidence of a market failure. Tucker (2019) correctly notes that microprudential regulation is not really distinct from its macroeconomic counterpart as the collective response of the banking sector to a macroeconomic shock may still be under the watchful eyes of regulators. I find it useful to distinguish the notion of systemic risk, meant to represent a justification for regulation based on an externality, from systematic risk, which is featured in models of asset pricing. Market prices for the risk exposures to systematic risk are determined endogenously as part of market equilibrium and can be modeled as such or can be represented flexibly. Why might climate change or other natural disaster shocks require the special attention of central banks in their regulatory role? The standard toolkit of financial engineering may be poorly adapted for quantifying such exposures, leaving the financial sector ill-prepared. Going forward, progress can be made by broadening how we conceptualize this uncertainty.

In the case of climate change, we might worry about quantifying the exposures to potentially big climate shocks. But over what time horizon do we expect this shock to play out and with what advanced warning signals? There are repeated references in the literature to *physical risks* and *transition risks* related to climate change. One possible source of physical risks are so-called tipping points that have been discussed in the geoscientific literature. See for instance, Lenton et al. (2008) for a discussion of sources of tipping points and Cai et al. (2015) for a discussion of their implications for cost benefit analyses. But while this uncertainty may unfold essentially instantaneously at geo-scientific time scales, that notion is very different from the high-frequency perspective we often see in financial engineering. While "tail risk" might seem like a correct static analogy, the potential nonlinear unfolding of degradation of the environment induced by climate change seems more like a large deviation type assessment with a compounding or mushrooming of bad outcomes over a short time horizon rather than a single tail event. Another possible source of physical risk is the geoscientific model uncertainty that I displayed in the first two figures. This uncertainty is likely to be resolved slowly as researchers sift through the implications of various models of climate change. Economists often use damage functions as simplified ways to capture the economic consequences of climate change. Damage function uncertainty is an example of "transition risk." As a source of uncertainty, it is substantial now because of the lack of evidence of how the global economy will respond to climate change and because of our limited understanding of economic adaptation. As we inflict more serious damages on the environment, learning about damages could well occur much more rapidly.

It would seem, at least in the shorter run, that uncertainty in policy responses to climate change and other shorter term vulnerabilities are likely to command the most attention of businesses and financial institutions. Policy uncertainty is another form of transition risk. Currently, enterprises are left to speculate about when more severe constraints or regulations might be imposed in the future and what their form will be. A primary example of this is the well known stranded asset problem whereby a surprise change in future policy could make carbon-based assets lose their value. While central banks seeking policy transparency may avoid adding to policy uncertainty, the private sector and regulated financial institutions themselves provide finance for businesses that are left to speculate about unknown policy interventions. Engle et al. (2020) assembled and used textual evidence to form portfolios designed to hedge climate change risk. Their analysis is being extended to provide evidence about the quantitative magnitude of the climate uncertainty components. Textual analysis from newspapers, while revealing, may give a distorted perspective with little press attention to risks that unfold over longer horizons.[3] Moreover, policy uncertainty may itself be induced by more fundamental uncertainty linked to climate change. Nevertheless, policy uncertainty outside the realm of central banking is likely to be a source of so called transition risk related to climate change that can unfold over shorter periods of time. Interestingly, in the near term, this leaves central banks engaged in overseeing financial institutions that are compelled to respond to policies initiated elsewhere.[4]

In terms of assessing exposure to "physical risk" or even "transition risk," what are we expecting from large scale financial institutions? How do we expect regulators to assess their exposure as climate change unfolds over decades or at least multiple years and not days? Transparency in policy requires clear answers to these questions.

It is good to proceed with oversight plans with eyes open. It is naive to expect research departments of either central banks or financial institutions to have an easy time with climate change risk assessment. It makes good sense for many firms, financial and non-financial, to assess their longer term vulnerability to climate change. Thus, they should at least have incentives to do this on their own. Given that we have much to learn, it will be a challenge for a regulator to monitor the credibility of climate risk management. Both the regulators and the regulated are exploring new territory in terms of uncertainty quantification.

When thinking about uncertainty and models, I find formal notions of risk to be narrow of a construct. This is particularly true for climate change. Instead of risk, I find the following categorization to be revealing from the standpoint of uncertainty quantification:

i) risk - unknown outcomes with known probabilities

ii) ambiguity - unknown weights to assign to alternative probability models

iii) misspecification - unknown ways in which a model might give flawed probabilistic predictions

[3]This may not be an important bias when forming hedge portfolios even if it down weights uncertainty that plays out slowly or only emerges well into the future.

[4]Recently Kling et al. (2021) have used a the ND-GAIN (Notre Dame Global Adaptation Initiative) climate vulnerability index to measure exposure to climate change. The ND-GAIN is a country-wide measure, however, meant to help prepare both the private and public sector for climate change.

Risk and risk aversion are typically presented and studied in economics classes. Rational expectations adds even more constraints on how decision makers confront uncertainty. Specifically, dynamic, stochastic equilibrium models often assume that economic agents and policymakers, say in Ramsey-type problems, know the model consistent probabilities. In many settings, this may well be a very good approximation, but when evidence is sparse the application of rational expectations becomes less compelling. Confronting ambiguity over models is what the statistics and econometric disciplines have wrestled with for decades. Here, I think of a model as inclusive of the parameter values, and I do not draw a distinction between unknown parameters and unknown models.[5] The elegant Bayesian approach imposes a subjective prior that gives an initial weighting over alternative models and updates these probabilities as evidence unfolds via Bayes' rule. A robust Bayesian explores prior sensitivity, which can be important when the evidence is weak along some dimensions.

A "let-the-data-speak" mentality is sometimes embraced by looking to "uninformative priors." The rationale for using such priors is to minimize the impact of subjective prior distributions. In the simplest of learning situations, data dominate priors making prior sensitivity less of an issue. But for challenges such as climate change, these is much we do not know about the geoscientific dynamics. If anything, understanding of the possible damages to the economy induced by climate change is even more sparse. At least along some dimensions, we seem quite far from a situation where data dominate priors. Moreover, the model construction itself needed to render subjective probabilities meaningful requires subjective judgements, and different models can have substantially different implications for policy. Finally, the models themselves are abstractions or simplifications and by their very nature are misspecified. This opens the door to speculating how things might go wrong when using a model to guide policy, including in prudent business practice. This form of uncertainty may be hardest one to address. If we knew what was wrong with a model, and we knew that this failing might have important consequences, then we would fix the model. Misspecification concerns emerge because we are unsure as to how to provide such a repair.

Decision theory has explored similarity and differences between risk and ambiguity as defined by i) and ii). Most prominent is the often used expected utility rationalized by theory of subjective probability combined with the independence axiom. See, in particular, Savage (1954)'s elegant axiomatic justification. Alternative approaches include dynamic versions of the smooth ambiguity model put forward by Klibanoff et al. (2009) and the recursive multiple priors model of Epstein and Schneider (2003) as a dynamic extension of the max-min utility model of Gilboa and Schmeidler (1989). Consider, for instance, the model heterogeneity revealed by Figure 2. This histogram is constructed by treating all models equally. The baseline probabilities are the same. Alternative climate science experts might assign other than equal weights. Prior sensitivity includes an

[5] In other words, each parameter configuration indexes an alternative model.

investigation of how important this cross model weighting is for the decision problem under consideration.

Statisticians, econometricians and control theorists have explored different aspects of model misspecification, but formally incorporating the category iii) misspecification uncertainty into decision theory has received less attention. There is some work along these lines by Hansen and Sargent (2007), Hansen and Sargent (2020), and Cerreia-Vioglio et al. (2021). In practice, this is arguably the hardest of the components to address. If we knew how a model was misspecified, we would presumably fix it. Instead the aim is to accommodate model deviations posed in flexible ways. But for this type of exercise to have a meaningful outcome, there has to be some bound or penalization restricting the potential forms and magnitudes of the misspecification. Ignoring misspecification leaves models users guilty of taking their pre-specified set of models too literally.

Approaches along these lines give guidance for how to conduct sensitivity analysis when there is model uncertainty of the nature that seems pertinent for climate change. In effect, this theory provides low-dimensional characterization tradeoffs between a full commitment to baseline probabilities and probabilities that result from changing subjective inputs in ways that have adverse consequences for decision makers. Part of any meaningful uncertainty quantification is a form of sensitivity analysis. The formulation of decision problems sharpens the focus of uncertainty quantification by integrating into the analysis the answer to the question, "sensitivity to what?" I argue that these uncertainty tradeoffs are revealing not only to policy makers but also to "risk management" efforts by private sector firms. They should be pertinent to both the entities being regulated as well as to the regulators themselves.

In a recent statement that has some notable similarity to the one that I quoted from Lord Kelvin, Governor Andrew Bailey of the Bank of England wrote:

> What we cannot measure we cannot manage, so it is important that financial firms and their clients use the TCFD framework and the latest tools available to measure, model and disclose the climate risks and opportunities they are exposed to today and in different future climate scenarios.

There is a lot to unpack in this quote. The first is the reference to the TCFD (Task Force on Climate-related Financial Disclosures) framework. While disclosure of information could be revealing to potential investors and to regulators, TCFD framework was remarkably vague into terms of how to synthesize information, certify its quality or put this information to good use. As I have argued the measurement/modeling challenges are nontrivial because we are potentially pushing economies beyond realm of modern experience. We need more than the familiar tools of risk analysis. Finally, who will do the modeling and why should we have confidence in the modeling outcomes?

As I mentioned previously, private sector firms, including financial institutions, have incentives to do their own uncertainty management. Given this, why not offload most of the modeling efforts to the private sector firms and have the regulators trust their outcomes without getting lost in the actual details of the model constructions and subjective inputs? If indeed the regulator and regulated incentives were aligned, this could reduce the monitoring to that of a second set of eyes to achieve a common objective. But there are good reasons that the incentives are not fully aligned as part of the rationale for regulation. The European Central Bank has previous experience with using risk models of the regulated. Behn et al. (2021) documented systemic understatement of risk exposures when regulatory assessments rely on the modeling output of the large financial institutions. Indeed, sensitivity to subjective inputs gives model builders wiggle room in their risk assessments suggesting the importance of broadening how regulators conceive of uncertainty when assessing the exposures of the regulated. Without identifying the flexibility in the model specifications used by private sector banks, the door is wide open for slanting model predictions about implications of climate uncertainty.

Given both past experience with model based regulation and the uncertainties associated with climate change, a productive strategy going forward would be for central banking research departments, private banks risk assessment teams, and academics actively engaged in related research to collaborate in how to best measure climate change uncertainty exposure. This research could include exploring alternative models related both to the physical and the transitional components to climate change uncertainty. These efforts would be well directed to go beyond realm of standard risk management methods to investigate formally sensitivity to modeling assumptions needed for designing prudent courses of action and for helping to fill in knowledge gaps. Such efforts would be most effective by exposing the impact of the subjective modeling inputs rather than disguising them and assessing their consequences. While I view this as no easy task, such an investment would seem to be vital to a central bank climate agenda in assessing vulnerability of the financial system to climate change.

On the other hand, there has been much value to the intellectual interactions between internal and external researchers that study closely related problems. There is reason for optimism because many central banks have already been investing in climate expertise and research departments at central banks have been constructive contributors to research in other areas pertinent to central bank policy. The NGFS (Network for Greening the Financial System) shows the willingness of central banks to coordinate best practices of their approaches to climate change. But there are also limits to in-house approaches to research. In house research within central banking on their own without external collaboration are often of limited value, as internal researchers sometimes face short response times and are eager to adapt to the announced priorities of central bank leaders. An investment in an open and cooperative approach that strongly encourages the active participation of external researchers with central bank encouragement seems a promising approach in the future. To be successful, this approach will need to recognize and appreciate the challenges and not oversell the current set of research tools available to address climate change and its uncertainties. The highly visible IPCC (Intergovernment Panel on Climate Change) successes were tied to its aims at information and insight sharing across researcher communities and disciplines, whereas what is needed is the encouragement to critically evaluate current approaches and nurture the development of new methods to meet the modeling and measurement challenges posed by climate change uncertainty as it unfolds in the near term and compounds over decades.

4 Scenarios and Stress testing

Tucker (2019) argued that an important virtue of stress testing is its transparency in the central banks' role of monitoring financial firms under their purview. In their book cleverly entitled, "Green Swan," Bolton et al. (2020) called for new paradigms to confront the extreme uncertainty related to climate change and see stress tests based on long-horizon scenarios as central to the answer. In regards to stress testing based on scenarios, they write:

> Unlike probabilistic approaches to financial risk management, they seek to set up plausible hypotheses for the future. This can help financial institutions integrate climate-related risks into their strategic and operational procedures (*e.g.* for the purpose of asset allocation, credit rating or insurance underwriting) and financial supervisors assess the vulnerability of specific institutions or the financial system as a whole.

This view of long-horizon scenarios is common in writings about central bank climate change prudential policy. For instance, researchers at the Dutch Central Bank seek to use stress testing to confront climate related tail events without being distracted by probabilities:

> The first important aspect of the framework is that choosing a stress test approach leads to a focus on tail events rather than on a central path projection. The reason is the large degree of uncertainty surrounding climate change and the energy transition. One may argue that the uncertainty is fundamental, in the sense that probabilities of various transition paths cannot even be known (Vermeulen et al. (2019)).

In the remainder of this section, I consider what I see as pitfalls in this method in ways that leave the door open to better approaches.

In a comprehensive statement of planned policy, the Bank of England (2019) gave the following examples of thirty-year scenarios:

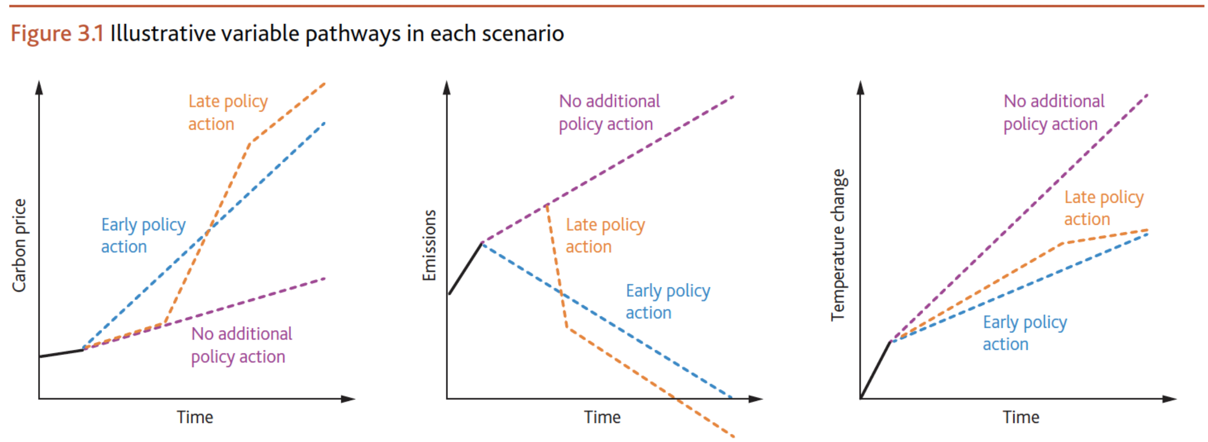


Figure 3: Figure taken from Bank of England (2019).

It is noteworthy that the quote from Bolton et al. (2020) contrasts the forward-looking scenarios with probabilistic approaches and yet makes reference to "climate related risks." Perhaps this use of the term "risk" differs from that given by i) in the decision theory categorization described previously. More importantly, it is apparently a virtue to avoid the need to assign probabilities to the alternative scenarios. Moreover, while these scenarios are specified as deterministic functions of time, there are overlapping components to the trajectories with subsequent branching at dates along the way. There could be scope for the branch uncertainty induced by ambiguity in future policies. While the branching structure has a dynamic structure, it then also becomes pertinent when it is known which branch will be followed. Is this known *ex ante* or revealed along the way? As we look over longer horizons, the potential number of branches would quite possibly increase along the way. In other words, uncertainty often compounds over time in financial markets.

While central banks may find comfort in avoiding the assignment of probabilities to scenarios and prefer to trivialize information revelation, private sector decision makers must execute some form of contingent dynamic planning inclusive of responses to new information as it arises. Moreover, they will face forward-looking financial markets with embedded compensations for exposures to climate change. We should expect these market compensations to fluctuate as form of transition risks. The dynamic revelation of information is something that they confront routinely.

I turn again to decision theory under uncertainty to help us speculate about private sector behavior even to assess the prudence of such behavior in the role regulator or supervisor. As I have argued, decision theory has value in both conceptualizing and quantifying how decisions depend on a tradeoff between best guesses and possible bad outcomes. It provides a way to depict formally a sensitivity analysis with a low-dimensional representation parameterized by how averse the decision maker is to uncertainty. In its extreme form, it can lead to simplistic worst-case analyses devoid of probabilistic considerations. However, it would be unwise for economic policy to push the private sector to such an extreme. How then are policy makers expecting regulated institutions to respond to scenarios specified devoid of probabilities?

One mathematically coherent use of scenarios without assigning probabilities across them is to ask the regulated financial institutions to use each scenario as a conditioning event. In spite of the mathematical coherence of conditioning, when applied within this setting, conditioning would undermine the substantive value of the scenario analysis. Since each scenario contains a set of paths for economic, financial and policy variables for up to thirty years, the conditioning on a path provides an extensive and unrealistic picture of the future. Essentially, each scenario implies an incredible omniscience along some dimensions. A more interesting use of conditioning is to allow for information revelation at different branching dates along alternative trajectories. This would naturally lead to construction of a much more extensive set of scenarios with the inclusion of intermediate branching points and feature them within trajectory uncertainty. I have a hard time seeing how this approach can lead to meaningful outcomes when the regulator or the regulated abandon probabilistic reasoning altogether.

A different (idealized) proposal for the construction and use of scenarios is as follows: Let financial institutions determine a set of contingency plans or recursively specified decision rules meant to perform well over a wide range of possible scenario trajectories. The differing trajectories could include alternative branches and an associated information structure for information revelation. Such a plethora of trajectories would compel private sector institutions to confront uncertainty points without being pushed to the non-probabilistic extremes of decision making. It would leave or offload a hard measurement-modeling challenge to the private sector, which is arguably a virtue. Central banks could then investigate collectively how these plans behave under even a small number of alternative scenarios of the type they find to be of particular interest. However, for this to give revealing information to an external observer, it would be important that the private sector NOT condition on a small set of scenarios when charting their course of action going forward.

Of course, it would be quite a burden on both the regulator and regulated to share and verify such contingency rules, especially as knowledge of climate change uncertainty may evolve dynamically. Moreover, the regulator would need to rely on models of climate change and equilibrium valuation and policy responses to capture investor responses to price changes. Some simplifications will most definitely be necessary, and some compromises would have to be made relative to idealized proposal. I described a way for such an approach to be tractable. There is much scope for devising clever and revealing approaches to stress testing that are more model based and use nontrivial bounds on probabilities in their formulation. While I see the potential benefits to such an approach, the cost it imposes on the private sector participants must also be considered in its design and execution. But without central banks' evaluating the prospective private sector behavior across a rich array of dynamically specified scenarios, I fail to see how the stress testing can effectively sidestep the omniscient conditioning embedded in each of these scenarios. This dynamic perspective also raises important issues as to how effectively regulators can trust the stated dynamic commitments by the private sector actors. It is better that such issues be out in the open than disguised by more static perspectives.

It is useful to compare the proposed climate uncertainty stress tests with the stress-test framework that emerged after the financial crisis. These latter stress tests are also static in nature, designed, say to assess how well the bank balance sheets hold up to a one-time liquidity/valuation shock. These assessments pertain to a time scale that is very different from the thirty-year perspective envisioned to address climate change concerns.

There may be virtue to having central banks push regulated financial institutions to assess their exposures to climate change over multiple decades as part of their long-term planning. But there are also reputational costs to overselling what can be learned from the currently conceived stress tests. Rethinking in a fundamental way the design and execution of such tests could lead to improved oversight in the future. In so doing, it would be better to embrace decision theory under uncertainty than to run from it.

5 Green, Vulnerability and Market Neutrality

In addition to carbon pricing and related policies, there is an important role for fiscal policy to invest in research and development of technologies that can accelerate the transition to a green economy. There are interesting conversations to be had about how to structure such investments in ways that spend public revenues wisely. When it comes to governments handing out money, discussions about how best to do this can get diverted by politicians only too willing to engage in "home bias" when assessing the value of such investments. Nevertheless, shifting what should be fiscal policy into the realm of monetary policy to add distance from the political arena has three important limitations: First, the tools of monetary policy are not nearly as potent as those of fiscal policy to address the need for green-oriented research and development or more generally to confront climate change. Second, such a shifting could pull monetary policy under an even closer watchful eye of politicians in the future unless it is clearly part of some well-understood mandate. Third, it moves central banks into an arena to which their current expertise is limited.

In their initial call to action, NGFS (2019), one of the NGFS (Network for Greening the Financial Sector) contributors recommendations is as follows:

> Acknowledging the different institutional arrangements in each jurisdiction, the NGFS encourages central banks to lead by example in their own operations. Without prejudice to their mandates and status, this includes integrating sustainability factors into the management of some of the portfolios at hand (own funds, pension funds and reserves to the extent possible).

Similarly, the BIS publication Bolton et al. (2020) include the argument:

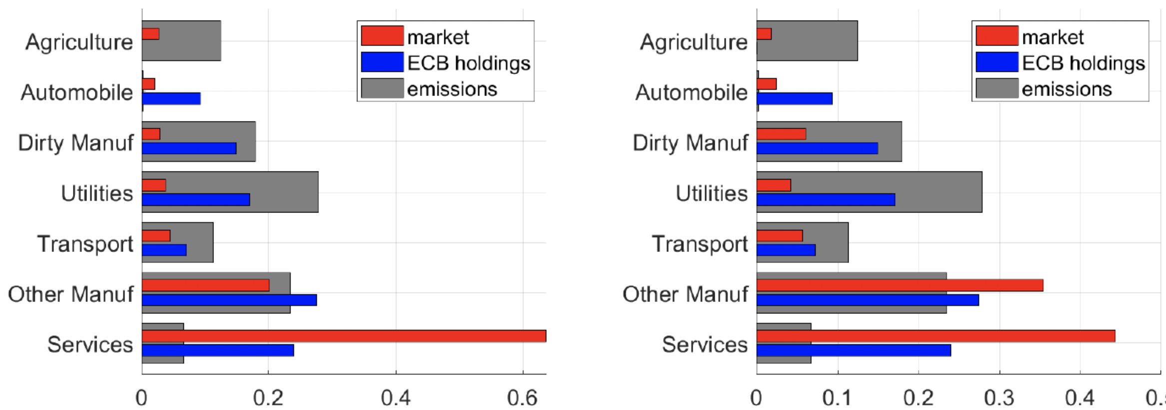
> Beyond approaches based strictly on risks, central banks and supervisors can help disseminate the adoption of so-called environmental, social and governance (ESG) standards in the financial sector, especially among pension funds and other asset managers.

Interest in ESG-based portfolios have been increasing over time. Indeed, some investors may be willing to forgo a portion of their financial returns in exchange for assurances that the funds they invest in satisfy ESG standards. But there is little reason why such investors need central banks to take on the role certifying the extent to which business or funds meet ESG standards. ESG interested investors will look for profitable investments after accounting for the fund specific attributes they find to be attractive. There is little reason to see why quantifying and assessing portfolio assets cannot be done more effectively by the private sector as they would have a clear incentive to do so. More ambitiously, shifting investor incentives for the potential benefit of society fits squarely in the domain of fiscal policy. In contrast to nurturing green investment, there is well-defined regulatory role for central banks to assess *vulnerability* to climate change of private sector ventures that are financed by banks.

There is a related issue connected to monetary policy that has more subtle implications. Especially since the financial crisis, monetary policy has been engaged in asset purchases as a version for "unconventional monetary policy." More than one essay could be, or actually has been, written on the extent to which this has been a successful approach over a sustained period of time. In this paper, I sidestep that question and focus on how such policy could or should be altered because of climate change. I will draw on insights from a very recent paper: Papoutsi et al. (2021). Arguments have been put forth that asset purchases should be constrained to be market neutral along with a simple rule for implementation.[6] In their paper, Papoutsi et al. build a simple but pedagogically revealing multi-sector model with a climate change externality to show that there are subtleties in imposing market neutrality that are missed by these simple rules. They also document, as shown in the figure reported below, that the outcome of ECB asset purchases in the corporate bond market is most certainly not tilted green. The actual ECB portfolio is vested quite heavily in carbon intensive sectors in contrast to service sectors, which have low consumption of fossil fuels. Slanting ECB corporate bond holdings to be more green is in clear conflict with the stated aims of market neutrality, for better or for worse. Finally, within the confines of their model, they solve a social planner problem in which carbon taxes set appropriately vitiate the need for investment slanting on the part of the planner. It is only in a second-best world without carbon taxation where portfolio slanting is needed to improve social

[6] The ECB imposed market neutrality by restricting bond purchases to be proportional to the outstanding bonds in their portfolio.

welfare. Their analysis illustrates nicely how portfolio slanting practiced by monetary authorities can be a weak substitute for fiscal policy that taxes carbon emissions.



(a) Market measured by capital income (b) Market measured by total assets to revenues

Figure 1: Sector shares of the market portfolio, ECB holdings, and emissions

This figure is constructed the year-end 2017 data. In figure (a) market shares are measured as capital income by sector (capital income = value added - wages). In figure (b) market shares are measured as output (from Eurostat) times the ratio of total assets to revenues (from Orbis) by sector. Emission intensity is measured by Scope 1 air emissions by sector. The ECB portfolio includes only securities held under the corporate sector purchase programme (CSPP) that was initiated in March 2016. By construction, all sector shares sum up to one. Data sources: SHS (ECB), Orbis, and Eurostat. Definition of sectors: Dirty Manufacturing includes: oil and coke, chemicals, basic metals, nonmetallic minerals manufacturing; Other Manufacturing includes: food, beverages, tobacco, textiles, leather, wood, paper, pharmaceuticals, electronics, electrical equipment, machinery, furniture, construction, and other manufacturing.

6 How do Climate Change Challenges differ from other Natural Disasters?

An important consideration when comparing climate change to other natural disasters is the time frame over which the uncertainty will play out. Climate change may be special because of the relatively long time horizon of interest. This is in sharp contrast to the advent of the COVID pandemic in which both economic and policy responses played over days and weeks.

Central banks have a mandate for the provision of liquidity, sometimes taking the form of lender of last resort. We have seen the need for such flexibility both in the handling of the 2007-

2008 financial crisis and the advent of the COVID pandemic. These are examples of situations when rapid responses are critical to the functioning of financial markets and the provision of liquidity necessary to avoid unproductive market freezes. The pandemic, in particular, is a natural disaster that triggered the need for *ad hoc* decision making under limited information. Other natural disasters in the future may well trigger the need for similar responses.

Currently, climate change does not seem to pose a challenge of this nature. Current concerns about climate change uncertainty would seem better conceived of as playing out over several years or decades instead of a rapid acceleration unfolding over days and weeks. This difference is clearly reflected in part by the decision to run stress tests with thirty-year horizons.

In the future, could climate change conceivably catch us by complete surprise and trigger a liquidity crisis? As I mentioned before, some models of climate change include tipping points that may cause a major disruption in the future that unfolds quickly. The important question pertains to the extent of whether there will be early warning signals. How far in advance might we have strong signals about the impending disaster? Additionally, climate change could trigger more localized or region-specific problems for which a rapid strike of central bank policy could be helpful. Our hope is that prudent policy outside the realm of monetary policy can help us avoid even this possibility.

7 Conclusion

Climate change is an important challenge for policy. Fiscal policy has some levers that can truly have an impact, including taxation of carbon emissions or subsidies for research that aids the development of new technologies that pose much less of a threat to the environment. How best to develop and use quantitative research to guide fiscal policy in the face of uncertainty remains a fertile avenue for future research. Monetary policy can support these objectives and promote sound strategies for quantifying longer term impacts of exposure to climate change uncertainty. Indeed, there will be societal benefits that will accrue for this that can be mutually beneficial for financial institutions as well as central banks in their role of monitoring a broadly-conceived banking sector. On the other hand, monetary policy is a weak substitute for sensible fiscal policy. Central banks that overstate their ability to contribute run the risk of both losing their distance from the political arena and providing false hope for a public looking for how best to tackle climate change.

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