

**Finance and Economics Discussion Series  
Divisions of Research & Statistics and Monetary Affairs  
Federal Reserve Board, Washington, D.C.**

**Preventing Controversial Catastrophes**

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**2018-052**

Please cite this paper as:

Baker, Steven D., Burton Hollifield, and Emilio Osambela (2018). "Preventing Controversial Catastrophes," Finance and Economics Discussion Series 2018-052. Washington: Board of Governors of the Federal Reserve System, <https://doi.org/10.17016/FEDS.2018.052>.

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# Preventing Controversial Catastrophes \*

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July 17, 2018

## Abstract

In a market-based democracy, we model different constituencies that disagree regarding the likelihood of economic disasters. Costly public policy initiatives to reduce or eliminate disasters are assessed relative to private alternatives presented by financial markets. Demand for such public policies falls as much as 40% with disagreement, and crowding out by private insurance drives most of the reduction. As support for disaster-reducing policy jumps in periods of disasters, costly policies may be adopted only after disasters occur. In some scenarios constituencies may even demand policies oriented to increase disaster risk if these policies introduce speculative opportunities.

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\*We thank Lorenzo Garlappi, Michael Junho Lee, Rafal Wojakowski, Christian Heyerdahl-Larsen and seminar participants at the University of Illinois at Chicago, the University of Minnesota Junior Conference, the Board of Governors of the Federal Reserve System, the International Conference on Capital Markets at INSEAD, the Northern Finance Association annual meeting, ITAM, BI Norwegian Business School, Norwegian School of Economics (NHH), Aalto University, the Luxembourg School of Finance, the Society for Financial Studies Cavalcade, the European Summer Symposium in Financial Markets at Study Center Gerzensee, the European Finance Association annual meeting, the Mid-Atlantic Research Conference, the University of Wisconsin-Madison, and Florida International University for helpful comments. The views in this paper do not reflect those of the Federal Reserve System or its Board of Governors.

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# 1 Introduction

Public policy initiatives often aim —or claim— to reduce or eliminate sources of infrequent economic disasters, while tolerating more common but moderate risks. Examples include the Kyoto Protocol, to reduce the risk of catastrophic global warming, and the Basel III framework, to increase the resiliency of the banking sector and reduce the probability and severity of financial crises. However the probability of rare or hitherto unobserved disasters is difficult to assess. There may be much disagreement about the likelihood or severity of the risk, and about the effectiveness of the policies proposed to reduce said risk, making it difficult to obtain consensus. As a result, controversial disaster risk may be addressed sub-optimally, or even not at all.

In some respects financial markets present a solution: if markets are complete and frictionless, then pessimists who perceive a higher probability of disasters should be able to insure themselves by trading in the financial market with optimists who perceive a lower probability of disasters. Both parties may perceive disagreement per se as a boon: in their corresponding subjective views, optimists sell lucrative insurance that is unlikely to pay out, while pessimists eliminate a likely catastrophe by buying cheap insurance. This raises an additional obstacle to policies oriented to eliminate aggregate disaster risk: optimists have no incentive to eliminate a source of high risk-adjusted returns, and pessimists view the policy as costly in comparison with the insurance available through financial markets.

We measure aggregate willingness to pay (WTP) for disaster-reduction policies in the face of disagreement regarding the likelihood of disasters. We extend the general equilibrium production framework of Pindyck and Wang (2013), by modeling an optimist and a pessimist who disagree regarding the likelihood of jumps that destroy a portion of the aggregate output. We interpret the agents' financial trade as either insurance or speculation, driven by their disagreement.

We assess the magnitude of disagreement's impact on WTP in a stationary calibra-

tion of our model economy, building on theoretical results in Borovička (2016). Both optimists and pessimists survive indefinitely under the objective measure, and unconditional macroeconomic and financial market moments approximate empirical estimates. In comparisons with a homogeneous beliefs calibration reproducing the same moments, we show that disagreement may reduce aggregate WTP to eliminate disasters by as much as 40%. We show that of this 40% total reduction, about 17% reflects crowding out by private insurance, 15% is driven by speculation, and the residual 8% depends on the social welfare criteria we use, which we relate to the political process.

Although the agents trade competitively in financial markets, politically they behave as two equally large voting blocks. Implementing a policy requires approval by a majority, so both agents must find the policy advantageous given its cost: it must be Pareto-improving given the investors' beliefs. Building on the concept of certainty equivalent, we measure aggregate WTP as the uniform consumption tax rate that all agents would accept to fund a disaster-reducing policy. To approximate the political deal making process, we allow for negotiated wealth transfers between agents with different views that are contingent upon approval of a given policy. Transfers increase WTP relative to a scenario where such deal making is forbidden, but even so, WTP remains below that which a utilitarian social planner would support.

We disentangle the effects of disagreement in a series of policy experiments. Agents disagree about the probability of a disaster occurring, but they agree regarding the disaster's severity. We first consider a policy that leaves any perceived speculative gains intact, by reducing the severity of the disaster but not its probability. Compared to an equivalent homogeneous beliefs economy, we find that disagreement reduces WTP by around 17% in this scenario, despite no reduction in speculation. This is the private insurance channel, through which aggregate disaster risk is transferred to the most optimistic investors. If the policy instead eliminates the disaster entirely, rendering the perceived disaster probabilities equal to zero for both investor types, then willingness to

fund the policy is reduced by a further 15%, for a total reduction of 32%. This is because such a policy also eliminates perceived speculative gains. These estimates presume a political process where wealth transfers produce Pareto-efficient outcomes. Absent such transfers, the total reduction in WTP is approximately 40%, i.e., the political channel is responsible for the remaining 8%. This decomposition highlights the quantitative importance of financial markets as a vehicle for crowding out disaster insurance offered by governments.

In another experiment we consider disagreement regarding the policy's effectiveness, and show that agents may wish to adopt policies that introduce or increase disagreement. If the policy is controversial enough, both parties will support it even if they each believe the aggregate consequences are negative. Our results suggest that policy-makers should consider carefully both the existing disagreement about fundamentals before policies are introduced, and the potential disagreement induced by policies. Both will be factors in determining the support for such policies.

Lucas (1987, 2003) estimates WTP to reduce macroeconomic risk by computing the proportion of consumption that a representative agent would forgo to eliminate business cycles. He finds that the agent would be willing to pay very little to eliminate business cycles, although later studies in more general settings have challenged this result. More recently, there has been an increased interest in measuring society's willingness to pay to attenuate the occurrence and impact of disasters. Barro (2009) and Pindyck and Wang (2013) find that a representative agent would be willing to pay substantial taxes on permanent consumption to reduce the severity of disasters, which are defined as exogenous negative jumps in aggregate capital and output. Martin and Pindyck (2015) extend the analysis to the case of multiple disasters, potentially occurring at the same time. Bansal, Kiku and Ochoa (2016) study the impact of disasters driven by global warming and temperature on financial asset prices. Hambel, Kraft and Schwartz (2016) characterize the optimal abatement policy in a model in which disasters are driven by global warming

and carbon emissions.

The models in these studies feature homogeneous agents. We consider instead an economy with heterogeneous agents who disagree about the dynamics of disasters, in which WTP is reduced due to crowding out, speculation, and political channels. Indeed, we show that despite the common intuition that disaster-reduction policies are desired because they reduce aggregate risk, disagreement about disasters may lead agents to perceive disasters as a valuable speculative opportunity, even to the point of demanding the amplification of disaster risk.

Although our theoretical analysis assumes complete and frictionless markets, such that allocations are Pareto efficient, the potential for counterintuitive results has generated interest in alternative measures of efficiency for models with disagreement. Recent examples focused on endowment economies include Brunnermeier, Simsek and Xiong (2014), Gilboa, Samuelson and Schmeidler (2014), and Blume, Cogley, Easley, Sargent and Tsyrennikov (2014). Buss, Dumas, Uppal and Vilkov (2016) study welfare gains or losses from financial market regulation in a general equilibrium production economy, by computing the expected utility of potentially irrational agents under the measure of a rational econometrician. Heyerdahl-Larsen and Walden (2016) introduce an efficiency measure for dynamic production economies, and highlight distinctions that arise between efficiency measures in this more general setting.

Our decision not to follow the above approaches reflects some different objectives. We do not ask which policies should be imposed on potentially irrational constituencies, but rather ask which policies disagreeing constituencies will consent to given the costs. The answer to this question is of practical interest to democratic societies, and avoids some philosophical difficulties related to welfare analysis with disagreement, such as those outlined in Duffie (2014). We also focus on WTP for structural economic changes that may alter speculative opportunities as a byproduct, rather than on financial market

regulations designed primarily to restrict speculative opportunities.<sup>1</sup> Nevertheless, we hope that by better understanding the policies that appeal to disagreeing constituencies, policymakers might craft proposals that are both robust to alternative definitions of efficiency, and palatable to the public from which they must ultimately garner support.

Our model incorporates the effects of disagreement on aggregate consumption and capital investment. Policies that eliminate disasters will affect aggregate growth by eliminating a source of risk and expected capital losses, and also by eliminating trade in private insurance. We account for both effects. Our framework facilitates comparison with previous studies, such as Barro (2009) and Pindyck and Wang (2013), who investigate willingness to pay to reduce disaster risk in otherwise similar economies, but without disagreement. These studies find relatively high willingness to pay to reduce catastrophic risks. In a sense, their findings support arguments by Allison (2004), Posner (2004) and Parson (2007) that governments should introduce strategies that reduce disaster risk. Introducing disagreement allows us to study the agents' trade-offs between decreasing fundamental risk and reducing private insurance market opportunities. Indeed, disagreeing agents may have much lower willingness to pay to reduce disaster risk, providing one reason for the limited implementation of such policies in practice.

Our experiments also illuminate the timing of policy proposals. The results resemble those of Pastor and Veronesi (2012), although the underlying mechanism is different. For example, we show that aggregate willingness to pay to reduce the severity of disasters will jump when a disaster occurs, even if neither agent learns anything about the frequency or severity of disasters from observing one. Accordingly, disaster-reduction policies are more likely to be adopted after disasters occur. Both our mechanism and learning are in line with the way in which financial regulation has been introduced historically.

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<sup>1</sup>Our policy experiments maintain the assumption of complete financial markets. Related theoretical models with incomplete financial markets are studied in Dieckmann (2011) and Buss, Dumas, Uppal and Vilkov (2016). Davila (2016) characterizes an optimal linear financial transaction tax in a static economy in which investors disagree.

## 2 Willingness to pay with heterogeneous agents

To quantify welfare gains or losses associated with a structural economic change, one typically builds on the notion of certainty equivalent and computes the representative agent's compensation or willingness to pay (WTP) for the change. For example, Lucas (1987, 2003) quantifies the welfare gains to reducing the uncertainty of economic growth. Like Lucas, we will begin with a simple endowment economy example, but with two agents. The simple model illustrates the adaptation of WTP to a heterogeneous agent framework, and allows some closed-form analysis of how disagreement affects WTP. However our approach is quite general. Our main analysis uses a dynamic general equilibrium production economy, described in Section 3, to quantify how disagreement changes WTP for disaster risk reduction.

In a model economy, a set of parameters,  $\Omega$ , describes structural economic characteristics, whereas  $\hat{\Omega}$  is an altered set of parameters reflecting a hypothetical structural change, such as a reduction in uncertainty. One or more variables captures the aggregate economic state; for example,  $C_t$  is the current level of aggregate consumption in an endowment economy. If we ignore distributional concerns and assume a representative agent, we can define WTP in terms of his indirect utility or value function,  $V$ . WTP is expressed as a permanent fractional reduction in aggregate consumption,  $\tau < 1$ , satisfying

$$V(C_t; \Omega) = V((1 - \tau)C_t; \hat{\Omega}). \quad (1)$$

The precise set of parameters and state variables depends on the model — one might substitute capital stock for aggregate consumption, for example — but the concept is general. Here,  $\Omega \rightarrow \hat{\Omega}$  models a government policy proposal, and WTP  $\tau$  is the threshold cost of implementation below which it is strictly beneficial for society to adopt the policy. We assume that the policy arrives, unanticipated, in the current period  $t$ , and would affect how the economy evolves after period  $t$ .

For example, consider a model with two time periods, where the aggregate endowment is  $C_0 \in (0, \infty)$  in period  $t = 0$ , with uncertain growth  $\frac{C_1}{C_0} \in \{\Delta_L, \Delta_H\}$  in period  $t = 1$ , for  $0 < \Delta_L < \Delta_H < \infty$ . The probability of  $\Delta_L$  is  $\pi \in (0, 1)$ . If all agents are identical with expected log utility and time discount factor  $\beta$ , the representative agent value function is

$$V(C_0; \Omega) = \log(C_0) + \beta [\pi \log(C_0 \Delta_L) + (1 - \pi) \log(C_0 \Delta_H)]. \quad (2)$$

The structural parameters are  $\Omega = \{\beta, \Delta_L, \Delta_H, \pi\}$ . An example policy is  $\hat{\Omega} = \{\beta, \Delta_L, \Delta_H, \frac{\pi}{2}\}$ , which reduces the chances of low growth by half. If this particular policy is considered in period  $t = 0$ , WTP satisfying Equation (1) is

$$\tau = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi}{2(1+\beta)}}. \quad (3)$$

Although the assumption of a representative agent has its advantages, real economies are populated by people heterogeneous in preferences, beliefs, and other characteristics. Economic models with heterogeneous agents reveal the limitations of welfare analysis based on the representative agent's WTP. Two major issues are that benefits from structural changes are unlikely to be felt equally by different agents, and a redistribution of wealth often accompanies a major structural change. In order to tackle these issues simultaneously, we calculate WTP for the policy combined with a wealth redistribution that ensures weak Pareto improvement.

We restrict attention to the class of models permitting representative agent value functions of the form

$$V(C_t, X_t; \Omega) \equiv x_{a,t} V_a(C_t, X_t; \Omega) + x_{b,t} V_b(C_t, X_t; \Omega) + \dots + x_{N,t} V_{N,t}(C_t, X_t; \Omega), \quad (4)$$

where each agent type  $i \in a, b, \dots, N$  has value function  $V_i(C_t, X_t; \Omega)$  and Pareto weight

$x_{i,t} > 0$ . The Pareto weights form an additional set of state variables  $X_t = x_{a,t}, x_{b,t}, \dots, x_{N,t}$ . The main additional assumption in Equation (4) is that the current Pareto weights  $X_t$  are sufficient state variables to summarize the effect of heterogeneity upon individuals and the economy. This formulation is relatively flexible, permitting heterogeneous recursive preferences as in Dumas, Uppal and Wang (2000) or Anderson, Ghysels and Juergens (2005), and extending to heterogeneous beliefs as in Borovička (2016) and Baker, Hollifield and Osambela (2016).

Extending our two period example, suppose there are two types of agent, indexed  $i \in \{a, b\}$ , with different beliefs about the probability of low growth in period 1:  $\pi_a \neq \pi_b$ . Otherwise the agents are identical, with expected log utility as before. We normalize Pareto weights to 1, and write agent a's period 0 Pareto weight as  $x_0$ , leaving weight  $1 - x_0$  for agent b. Under the assumptions of complete, frictionless markets, competitive equilibria in the two agent economy are Pareto efficient, and have a representative agent value function of the form in Equation (4):

$$V(C_0, x_0; \Omega) = x_0 V_a(C_0, x_0; \Omega) + (1 - x_0) V_b(C_0, x_0; \Omega), \text{ with} \quad (5)$$

$$V_a(C_0, x_0; \Omega) = \log(x_0 C_0) + \beta [\pi_a \log(x_{1,L} C_0 \Delta_L) + (1 - \pi_a) \log(x_{1,H} C_0 \Delta_H)], \quad (6)$$

$$V_b(C_0, x_0; \Omega) = \log((1 - x_0) C_0) + \beta [\pi_b \log((1 - x_{1,L}) C_0 \Delta_L) + (1 - \pi_b) \log((1 - x_{1,H}) C_0 \Delta_H)], \quad (7)$$

where  $\Omega = \{\beta, \Delta_L, \Delta_H, \pi_a, \pi_b\}$ . Further details of the two period model solution are given in Appendix B.<sup>2</sup>

There is an equilibrium correspondence between the Pareto weights,  $X_t$ , and shares of aggregate wealth. A mapping  $X_t \rightarrow \hat{X}_t$  from some initial weights  $X_t$  to new weights  $\hat{X}_t$  can be viewed as a wealth-transfer scheme that accompanies the change in structural economic parameters  $\Omega \rightarrow \hat{\Omega}$ . With this in mind, our main concept of WTP for

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<sup>2</sup>In particular,  $x_{1,L}$  and  $x_{1,H}$  can be written in terms of  $x_0$  and the model parameters, so  $C_0$  and  $x_0$  are sufficient state variables.

heterogeneous agents follows:

**Definition 1 (Compensated WTP)** *The compensated WTP is the value  $\tau_{comp}$  solving*

$$\begin{aligned} \tau_{comp} &= \max_{\tau, \hat{X}_t} \tau, \\ \text{s.t. } &V_i(C_t, X_t; \Omega) \leq V_i((1 - \tau)C_t, \hat{X}_t; \hat{\Omega}), \forall i. \end{aligned} \tag{8}$$

Compensated WTP is the highest aggregate WTP  $\tau_{comp}$  with transfers  $X_t \rightarrow \hat{X}_t$  such that each agent weakly prefers the new equilibrium to the old. If the policy could be implemented at a cost less than  $\tau_{comp}$ , it would be Pareto improving when coupled with the transfers. Of course  $\tau_{comp}$  generally depends on the economic state, e.g.,  $C_t$  and  $X_t$ . To simplify the exposition, we elide conditioning variables until relevant.

One attractive aspect of compensated WTP is its political interpretation: if agents must vote to approve the structural change at some cost,  $\tau_{comp}$  is the cost ceiling below which the change will receive unanimous support, if the agents are able to bargain over how the joint surplus is split.<sup>3</sup> Although unanimous support seems a high bar for practical politics, our definition loosely applies to votes in the U.S. Senate, where two political parties typically control about 50% of the votes each, and passage of a bill effectively requires a supermajority of 60%. Our definition is also similar in spirit to one informally suggested by Lucas (2003), to calculate certainty equivalent gains or losses separately for each agent, and calculate aggregate WTP as the sum. We formalize this idea, and explicitly incorporate the effect of transfers in equilibrium.<sup>4</sup>

Studying the effect of heterogeneity on WTP also requires a baseline for comparison. One approach is to compare Compensated WTP to alternatives that ignore heterogeneity, by applying the concept in Equation (1) directly to the left side of Equation (4). We call

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<sup>3</sup> $\tau_{comp}$  is the limiting cost at which the joint surplus is reduced to zero.

<sup>4</sup>Although we think of  $X_t \rightarrow \hat{X}_t$  as a set of lump-sum wealth transfers, it is possible to implement the transfers with heterogeneous permanent consumption taxes, more in line with Lucas's concept. While our application of compensating transfers is novel, the idea of compensating transfers is an old one in social welfare analysis; see, e.g., Arrow (1963), Chapter 4.

this Uncompensated WTP.

**Definition 2 (Uncompensated WTP)** *The uncompensated WTP is the value  $\tau_{uncomp}$  solving*

$$V(C_t, X_t; \Omega) = V((1 - \tau_{uncomp})C_t, X_t; \hat{\Omega}). \quad (9)$$

The above definition ignores the disparate impact of the structural change on different agents, as well as treating  $X_t$  as a set of supplementary economic state variables that are unaffected by the structural change. If  $\tau_{uncomp}$  were used for cost-benefit analysis in a model with heterogeneous agents, one potentially undesirable consequence would be the approval of policies that benefit some agents but harm others. This is particularly likely to occur if the harmed agent has a small Pareto weight — that is, if the agent is poor. The difference  $\tau_{uncomp} - \tau_{comp}$  may be viewed as the aggregate cost of compensating agents harmed by the policy.

To quantify the attitudes of each agent towards a policy, we define individual WTP. We focus on ex ante WTP, i.e., without any transfers  $X_t \rightarrow \hat{X}_t$ .

**Definition 3 (Individual WTP)** *Individual WTP for agent  $i$  is the value  $\tau_i$  solving*

$$V_i(C_t, X_t; \Omega) = V_i((1 - \tau_i)C_t, X_t; \hat{\Omega}). \quad (10)$$

In many models featuring competitive, frictionless markets, Compensated WTP is always less than Uncompensated WTP, so long as some agents have different individual WTP. If society requires policies to be Pareto improving, at least net of compensating transfers, then it must accept lower WTP for public policies. The following proposition formalizes this result.

**Proposition 1** *Suppose that the value functions satisfying Equation (4) reflect Pareto efficient allocations, are strictly increasing in aggregate consumption  $C$ , and that individual value functions  $V_i$  are strictly increasing in their respective Pareto shares. Let  $\tau_{min} = \min(\{\tau_i\}_a^N)$  and*

$\tau_{max} = \max(\{\tau_i\}_a^N)$ . Then  $\tau_{max} \geq \tau_{uncomp} \geq \tau_{comp} \geq \tau_{min}$ . The inequalities are strict unless  $\tau_i = \tau_j, \forall i, j \in \{a..N\}$ , in which case all the WTP are equal.

Note that Proposition 1 applies to our simple two period example. While the proposition suggests that heterogeneity may lower WTP, no such conclusion is possible without a homogeneous economy as a point of reference. Our approach is to find a homogeneous agent economy that is observationally equivalent to the heterogeneous agent economy in terms of certain aggregate characteristics, similar in spirit to Jouini and Napp (2007). The total effect of heterogeneity on WTP is then measured by comparing  $\tau$  from Equation (1), based on the homogeneous economy, to  $\tau_{comp}$ , based on the heterogeneous economy. Such a comparison takes into account opportunities for private insurance and speculation that arise when heterogeneous agents may trade with each other, in addition to addressing the necessity that all agents are unhurt by any structural change.

Unfortunately this approach makes a general analysis of heterogeneity's affect on WTP impossible, since the mapping between heterogeneous and homogeneous economies depends on the model under consideration, and on the set of aggregate characteristics that are used to define observational equivalence. Our quantitative analysis based on the dynamic model in Section 3 indicates that, when it comes to disagreement about disasters, heterogeneity does reduce WTP. To formalize key concepts and provide intuition in a simple setting, the next subsection shows that disagreement reduces WTP for disaster reduction in our two period example, where a mapping between heterogeneous and homogeneous economies is derivable in closed form.

## 2.1 Disaster reduction in a two period economy

This section characterizes WTP for disaster reduction in the previous two period example, fully described in Appendix B. We refer to the low growth outcome  $\Delta_L$  as a disaster, and  $\pi_i$  is the disaster probability under agent  $i$ 's beliefs. It is sufficient for the qualitative

results in this section that  $\Delta_L < \Delta_H$ , and  $\pi_a \neq \pi_b$ : disasters needn't be especially severe or rare, and the amount of disagreement is not important so long as it is not zero.

Policies that reduce disaster risk take one of two forms: either they make the disaster less severe, or they make the disaster less likely. When agents disagree, additional insights come from comparing the limiting cases of these two policies, defined as follows.

**Definition 4 (Reduce Severity, two period model)** *The disaster becomes harmless if the policy is adopted. An economy with initial structural parameter values  $\Omega = \{\beta, \Delta_L, \Delta_H, \pi_a, \pi_b\}$  takes new parameter values  $\hat{\Omega} = \{\beta, \Delta_H, \Delta_H, \pi_a, \pi_b\}$  if the policy is adopted.*

Consider an example in which agents are worried about rising sea levels from global warming. Agents disagree about the probability that sea levels will rise. A potential policy is to build a seawall to reduce the severity of the damages from increased sea-levels. If the policy eliminates the potential damages, then the policy is an example of Reduce Severity. Agents can still trade on the likelihood that the seas will rise, although they are not exposed to the resulting damages.

**Definition 5 (Eliminate Disasters, two period model)** *Agents agree that a disaster will not occur if the policy is adopted. An economy with initial structural parameter values  $\Omega = \{\beta, \Delta_L, \Delta_H, \pi_a, \pi_b\}$  takes new parameter values  $\hat{\Omega} = \{\beta, \Delta_L, \Delta_H, 0, 0\}$  if the policy is adopted.*

An alternative policy in the sea level example is to completely remove the risk of the sea-level rising. This is an example of Eliminate Disasters. Agents cannot trade on the likelihood that the sea will rise, since they agree that it will not rise.

Reduce Severity and Eliminate Disasters have the same implication for the aggregate consumption endowment in the two period model: if adopted, growth  $\Delta_H$  is guaranteed in period 1. Without disagreement, WTP for these policies is identical: we show in Appendix B that

$$[\tau|\text{Eliminate Disasters}] = [\tau|\text{Reduce Severity}], \quad (11)$$

where unsubscripted  $\tau$  is WTP in an economy without disagreement.

With disagreement, WTP for Eliminate Disasters is generally different from WTP for Reduce Severity. Eliminate Disasters also alters beliefs and eliminates disagreement, whereas Reduce Severity preserves beliefs, but renders disasters irrelevant to aggregate growth. As emphasized in Simsek (2013), agents may welcome opportunities to speculate on different beliefs. Therefore the form of the policy is important to establish why disagreement impacts WTP.

The following proposition summarizes relative attitudes towards the two policies in the heterogeneous economy.

**Proposition 2** *For any  $x_0 \in (0, 1)$ , individual and social WTP for Eliminate Disasters is lower than WTP for Reduce Severity:*

$$[\tau_a | \text{Eliminate Disasters}] < [\tau_a | \text{Reduce Severity}], \quad (12)$$

$$[\tau_b | \text{Eliminate Disasters}] < [\tau_b | \text{Reduce Severity}], \quad (13)$$

$$[\tau_{uncomp} | \text{Eliminate Disasters}] < [\tau_{uncomp} | \text{Reduce Severity}], \quad (14)$$

$$[\tau_{comp} | \text{Eliminate Disasters}] < [\tau_{comp} | \text{Reduce Severity}]. \quad (15)$$

Proposition 2 confirms that agents value speculative opportunities that exist due to disagreement, and hence they are willing to pay more for Reduce Severity than for Eliminate Disasters, even though the policies have identical implications for aggregate risk. Furthermore, the result is not sensitive to how WTP is measured.

In reality, policymakers may not have complete discretion to choose among options that lower disaster likelihood, such as Eliminate Disasters, and those that reduce disaster severity. Coupled with the fact that WTP for the two policies is identical absent disagreement, this suggests that disagreement will reduce WTP if the best policy options available happen to be those that also reduce disagreement within the population.

The difficulty with the preceding supposition is that comparison between an econ-

omy with disagreement and one without is not straightforward: since the homogeneous economy is different from the heterogeneous economy, it may be that WTP for disaster reduction is generally lower in the homogeneous economy, even though both policies have the same WTP within that economy. That is, we could have  $[\tau|\text{Reduce Severity}] < [\tau_{comp}|\text{Reduce Severity}]$ , for example.

To make further progress, we must define a homogeneous economy that is, by some criteria, equivalent to a given heterogeneous economy. We argue in Appendix B that one defensible mapping selects identical  $C_0$ ,  $\Delta_L$ ,  $\Delta_H$ , and  $\beta$  across the two economies, and sets disaster probability  $\pi = x_0\pi_a + (1 - x_0)\pi_b$  in the homogeneous economy for  $x_0$ ,  $\pi_a$ , and  $\pi_b$  given in the heterogeneous economy. This definition leaves the two economies with the same set of potential endowment realizations, the same price-dividend ratio for a stock defined as a claim to the endowment, and the same riskless rate. Subject to this mapping, we find that disagreement generally reduces WTP for disaster reduction.

**Proposition 3** *For  $x_0 \in (0,1)$  and any given parameter values in the heterogeneous beliefs economy, WTP for disaster reduction in the mapped homogeneous beliefs economy is higher than compensated WTP for disaster reduction in the economy with disagreement:*

$$[\tau|ED] = [\tau|RS] > [\tau_{comp}|RS] > [\tau_{comp}|ED], \quad (16)$$

Here “ED” abbreviates the policy Eliminate Disasters and “RS” abbreviates the policy “Reduce Severity.” In this sense, disagreement reduces WTP for disaster reduction.

WTP for disaster reduction is weakly greater in the mapped homogeneous beliefs economy than uncompensated WTP in the economy with disagreement:

$$[\tau|ED] = [\tau|RS] = [\tau_{uncomp}|RS] > [\tau_{uncomp}|ED]. \quad (17)$$

Even a policy such as Reduce Severity, which leaves speculative trading opportunities intact, has lower WTP under disagreement, provided it is implemented alongside

compensating transfers ( $\tau_{comp}$ ). At most, WTP is as high with disagreement as without, if we do not require the policy to be Pareto improving ( $\tau_{uncomp}$ ).

In summary, in this simple economic setting, disagreement generally lowers WTP for disaster reduction. Two limitations of this analysis are the restrictive log preference specification, and an inability to realistically calibrate the simple model to data, in order to assess the magnitude of the reduction in WTP. To address these limitations, we calibrate an infinite horizon model with recursive preferences for our main analysis. Our calibrated model includes the channels highlighted in Proposition 3, and also additional channels that cause WTP to further decline relative to the homogeneous economy benchmark. We refer to these additional channels as crowding out by private insurance.

### 3 A dynamic production economy

The benchmark model is a version of Baker, Hollifield and Osambela (2016), who extend Pindyck and Wang (2013) to include heterogeneous beliefs. Here we focus exclusively on disagreement about the likelihood of disasters. In addition to our analysis of the demand for disaster-reduction policies, an important contribution is that we choose the model parameters to match asset pricing and empirical disagreement moments, in Section 4.

The model is a dynamic general-equilibrium production economy with disagreement among agents. It is set in continuous time with an infinite horizon. Let  $K_t$  denote the representative firm's capital stock,  $I_t$  the aggregate investment rate, and  $Y_t$  the aggregate output rate. The representative firm has a constant returns to scale production technology:

$$Y_t = AK_t, \tag{18}$$

with constant coefficient  $A > 0$ . Denote the consumption-capital ratio and the investment-capital ratio as

$$c_t \equiv \frac{C_t}{K_t}, \quad i_t \equiv \frac{I_t}{K_t}, \tag{19}$$

with the aggregate resource constraint

$$c_t + i_t = A. \quad (20)$$

There are two agents with heterogeneous beliefs, and we use  $j \in \{a, b, c\}$  to indicate the subjective beliefs of agents  $a$  and  $b$  about disasters' dynamics, as well as the objective dynamics of disasters  $c$ . Capital accumulation has dynamics

$$\frac{dK_t}{K_t} = \frac{\Phi(I_t, K_t)}{K_t} dt + \sigma dW_t - (1 - Z)dJ_t^j; \quad K_0 > 0, \quad (21)$$

where  $W_t$  is a standard Brownian motion and  $J_t^j$  is a jump process that captures disasters, with mean arrival rate  $\lambda_j$ . If and when a jump occurs,  $K$  falls to  $ZK$ ; the percentage drop in  $K$  is  $1 - Z$ . The random variable  $Z$  is uncorrelated with the Brownian and jump processes, and is independently drawn for each jump from the time-invariant probability density function  $f(Z)$ , with  $0 \leq Z \leq 1$ .<sup>5</sup>

The function  $\Phi(I_t, K_t)$  measures the effectiveness of converting investment goods into installed capital. As in the neoclassical investment literature, e.g. Hayashi (1982), the firm's adjustment cost is homogeneous of degree one in  $I_t$  and  $K_t$ . Let  $\phi(i_t)$  be the increasing, concave, and quadratic function:

$$\phi(i_t) \equiv \frac{\Phi(I_t, K_t)}{K_t} = i_t - \frac{1}{2}\theta i_t^2 - \delta, \quad (22)$$

where  $\theta > 0$  is the adjustment cost parameter and  $\delta$  is the depreciation rate.

The expected growth rate of capital is

$$\phi(i_t) - \lambda_j(1 - \mathbb{E}[Z]) = i_t - \frac{1}{2}\theta i_t^2 - [\delta + \lambda_j(1 - \mathbb{E}[Z])], \quad (23)$$

where  $\lambda_j(1 - \mathbb{E}[Z])$  is the expected percentage decline of the capital stock from disasters.

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<sup>5</sup>All agents agree on the distribution  $f(Z)$ .

Although agents observe discontinuous jumps in capital, they may disagree about the mean arrival rate  $\lambda$ . There are two types of agent,  $j \in \{a, b\}$ , with  $\lambda_a < \lambda_b$ . Because type  $a$  agents perceive a lower probability of disasters, we refer to type  $a$  agents as optimists and type  $b$  agents as pessimists. The two agents are aware of each other's beliefs but they agree to disagree.

From Girsanov's theorem, the change from  $b$ 's measure to  $a$ 's measure,  $\eta_t$ , has dynamics

$$\frac{d\eta_t}{\eta_t} = (\lambda_b - \lambda_a)dt - \left(1 - \frac{\lambda_a}{\lambda_b}\right) dJ_t^b, \quad (24)$$

so that for any  $T > t$  measurable random variable  $M_T$ ,

$$\mathbb{E}_t^a [M_T] = \mathbb{E}_t^b \left[ \frac{\eta_T}{\eta_t} M_T \right], \quad (25)$$

where  $\mathbb{E}_t^j$  denotes agent  $j$ 's conditional expectation.

The change of measure process  $\eta_t$  shows how type  $a$  agents over-estimate or under-estimate the probability of a state relative to type  $b$  agents. Because type  $a$  agents are optimistic about the mean arrival rate of jumps ( $\lambda_a < \lambda_b$ ), type  $a$  agents see a lower likelihood of disasters. For that reason, if and when a jump occurs,  $\eta_t$  falls to  $\frac{\lambda_a}{\lambda_b}\eta_t$ . The absence of jumps over a period of time is more consistent with the type  $a$  agent's beliefs, meaning that  $\eta$  increases deterministically at a rate  $\lambda_b - \lambda_a$  in periods in which disasters are not realized.

All agents have recursive preferences of the Duffie-Epstein-Zin type with the same relative risk aversion coefficient  $1 - \alpha > 0$ , the same constant intertemporal elasticity of substitution  $\frac{1}{1-\rho} > 0$ , and the same subjective discount rate  $\beta$ , with  $0 < \beta < 1$ .<sup>6</sup> We assume complete markets, so the competitive equilibrium is obtained from the solution

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<sup>6</sup>When  $\rho = \alpha$ , the preferences are of the constant relative risk aversion (CRRA) type.

to the planner's problem:

$$\sup_{\{C_{a,t}, C_{b,t}, i_t\}} \inf_{\{v_{a,t}, v_{b,t}\}} \mathbb{E}_0^b \left[ \int_0^\infty \beta \left\{ \eta_t e^{-\int_0^t v_{a,\tau} d\tau} \frac{1}{\alpha} C_{a,t}^\alpha \left[ \frac{\alpha - \rho \frac{v_{a,t}}{\beta}}{\alpha - \rho} \right]^{1 - \frac{\alpha}{\rho}} + e^{-\int_0^t v_{b,\tau} d\tau} \frac{1}{\alpha} C_{b,t}^\alpha \left[ \frac{\alpha - \rho \frac{v_{b,t}}{\beta}}{\alpha - \rho} \right]^{1 - \frac{\alpha}{\rho}} \right\} dt \right], \quad (26)$$

subject to:

$$\begin{aligned} C_{a,t} + C_{b,t} &= (A - i_t) K_t, \\ \frac{dK_t}{K_t} &= \phi(i_t) dt + \sigma dW_t - (1 - Z) dJ_t^b, \\ \frac{d\eta_t}{\eta_t} &= (\lambda_b - \lambda_a) dt - \left( 1 - \frac{\lambda_a}{\lambda_b} \right) dJ_t^b, \end{aligned}$$

where  $v_{i,t}$  are the subjective endogenous discount factors introduced in Dumas, Uppal and Wang (2000),  $C_{j,t}$  is the consumption rate of a type  $j$  agent, and where we use the change of measure  $\eta_t$  to write the planner's objective function under the pessimist's probability measure, without loss of generality.<sup>7</sup>

Equilibrium is determined numerically and is characterized as a function of a single Markovian state variable, the optimist's Pareto share  $x_t \in [0, 1]$ :

$$x_t \equiv \frac{\eta_t e^{-\int_0^t v_{a,\tau} d\tau}}{\eta_t e^{-\int_0^t v_{a,\tau} d\tau} + e^{-\int_0^t v_{b,\tau} d\tau}}, \quad (27)$$

which is driven by the change of measure  $\eta_t$ .

The optimist's Pareto share  $x_t$  increases deterministically during normal times when  $dJ_t^b = 0$  in which no disasters occur. If and when a disaster occurs,  $x_t$  jumps downwards.

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<sup>7</sup>The agents agree on the investment policy  $i_t$  that maximizes the representative firm's value, given complete financial markets. Garlappi, Giammarino and Lazrak (forthcoming) model investment decisions at the firm level where frictions allow disagreement about the value maximizing policy itself.

The normalized value function for the planner's problem in Equation (26) is:<sup>8</sup>

$$V(x_t, K_t) = \frac{1}{\alpha} H(x_t) K_t^\alpha. \quad (28)$$

When  $x_t$  tends to one or zero, the function  $H$  converges to the homogeneous beliefs solution for the optimist and pessimist, respectively. We numerically solve for  $H(x_t)$ , and the optimal investment-capital ratio  $i(x_t)$ .

The planner's problem is convenient for determining equilibrium, but we are interested in the effects of disasters and disagreement on each agent individually. Following Dumas, Uppal and Wang (2000), the value functions of each agent,  $V_j$  for  $j \in \{a, b\}$  are obtained from the function  $H(x)$  and its first derivative  $H'(x)$ :

$$V_a(x_t, K_t) = \frac{1}{\alpha} (H(x_t) + (1 - x_t)H'(x_t)) K_t^\alpha = \frac{1}{\alpha} H_a(x_t) K_t^\alpha, \quad (29)$$

$$V_b(x_t, K_t) = \frac{1}{\alpha} (H(x_t) - x_t H'(x_t)) K_t^\alpha = \frac{1}{\alpha} H_b(x_t) K_t^\alpha. \quad (30)$$

Aggregate consumption at time  $t$  is  $C_t = [A - i(x_t)] K_t$ , which is shared between the two agents according to

$$C_{a,t} = \omega(x_t) C_t; \quad C_{b,t} = [1 - \omega(x_t)] C_t, \quad (31)$$

where  $\omega(x_t)$  is the consumption share of the optimist. Similarly aggregate wealth at time  $t$  is the value of the stock  $P_t = q(x_t) K_t$ , where  $q(x_t)$  is Tobin's  $q$ . Wealth is shared between the two agents according to

$$P_{a,t} = h(x_t) P_t; \quad P_{b,t} = (1 - h(x_t)) P_t, \quad (32)$$

where  $h(x_t)$  is agent  $a$ 's wealth share.<sup>9</sup> Aggregate and individual wealth and consumption are all linear in the capital stock,  $K_t$ , and agent  $a$ 's wealth and consumption shares

<sup>8</sup>The normalized value function reflects rescaling the sum of current period Pareto weights to unity.

<sup>9</sup>Expressions for consumption share, wealth share, and Tobin's  $q$  can be found in Baker, Hollifield and Osambela (2016).

are increasing in  $x_t$ .

### 3.1 Disaster reduction in a dynamic production economy

Pindyck and Wang (2013) investigate willingness to pay (WTP) to limit the severity of disasters in an economy identical to ours, but with homogeneous agents as in Equation (1). We adopt their distribution for the severity of disasters, and assume  $Z_t$  is i.i.d, with power distribution parameter  $\gamma > 0$ . Omitting the time subscript, the density of  $Z$  is

$$f(Z) = \gamma Z^{\gamma-1}; 0 \leq Z \leq 1. \quad (33)$$

Moments of  $Z$  are

$$E[Z^n] = \frac{\gamma}{\gamma + n}. \quad (34)$$

Suppose that a costly policy or technology exists that could ensure that any disaster that occurs would lead to a loss no greater than  $1 - \underline{Z}$ . That is, the technology would permanently change the recovery size distribution  $f(Z)$  to a truncated distribution given by

$$\hat{f}(Z, \underline{Z}) = \frac{\gamma Z^{\gamma-1}}{1 - \underline{Z}^\gamma}; 0 \leq \underline{Z} \leq Z \leq 1, \quad (35)$$

with

$$\hat{\mathbb{E}}[Z^n] = \frac{\gamma}{\gamma + n} \times \frac{1 - \underline{Z}^{n+\gamma}}{1 - \underline{Z}^\gamma}. \quad (36)$$

Letting  $\Omega = \{\beta, \alpha, \rho, \sigma, A, \theta, \delta, \gamma, \lambda_a, \lambda_b, \lambda_c, f\}$  be the original economic parameters, the economy with truncated disaster risk has parameters  $\hat{\Omega}_f = \{\beta, \alpha, \rho, \sigma, A, \theta, \delta, \gamma, \lambda_a, \lambda_b, \lambda_c, \hat{f}\}$ . Recall, per Equation (24), that there is only disagreement regarding the frequency of disasters  $\lambda_j$  and not regarding the severity of disasters  $Z$ . Therefore a policy  $\hat{\Omega}_f$ , that truncates the distribution of  $Z$ , decreases disaster risk without altering disagreement:

the process  $\eta_t$  remains unchanged, and the policy is never controversial in itself.

Alternatively the policy might reduce the frequency of disasters, from  $\lambda_j$  to  $\hat{\lambda}_j < \lambda_j$ ,  $j \in \{a, b, c\}$ , so parameters change from  $\Omega$  to  $\hat{\Omega}_\lambda = \{\beta, \alpha, \rho, \sigma, A, \theta, \delta, \gamma, \hat{\lambda}_a, \hat{\lambda}_b, \hat{\lambda}_c, f\}$ . A policy  $\hat{\Omega}_\lambda$  decreases disaster risk, but it may also increase or decrease disagreement: the process  $\eta_t$  changes. If  $\hat{\lambda}_a = \hat{\lambda}_b$ , then the policy resolves disagreement: everyone agrees on what the policy will do, even if they disagree on the net benefit to implementing it.<sup>10</sup> Otherwise the policy  $\hat{\Omega}_\lambda$  may be controversial in itself, since agents disagree on its effects.

Whether the policy reduces the severity or frequency of disasters, adopting it will change the equilibrium value function. Rather than listing the parameters as an argument of the value function, we adopt the shorthand that  $V$  is the original value function with parameters  $\Omega$ , whereas the new value function with parameters  $\hat{\Omega}$  is

$$\hat{V}(x, K) = \frac{1}{\alpha} \hat{H}(x) K^\alpha. \quad (37)$$

Modified value functions for the optimist agent  $a$  and the pessimist agent  $b$  follow from Equation (29) and Equation (30), respectively.

### 3.2 Willingness to pay for disaster reduction

The definitions of WTP in Section 2 apply to our model with disagreement about disasters. All of our measures of WTP are in terms of a fractional reduction  $\tau$  in the capital stock. This is equivalent to imposing a permanent consumption tax at the same level  $\tau$ : we can substitute  $K_t$  for  $C_t$  in the definitions in Section 2, without altering their meaning. We assume that agents do not anticipate the possibility of government action: at time  $t$  the irreversible option to impose the policy arrives, and each agent instantaneously

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<sup>10</sup>Here we have in mind that  $\hat{\lambda}_c = \hat{\lambda}_a = \hat{\lambda}_b$  also – the policy really does what everyone believes it will do. But note that the value of  $\hat{\lambda}_c$  does not actually matter for WTP: agents evaluate the policy based on its anticipated effects only.

assesses its worth. To reduce notation, we omit time subscripts, taking  $x$  as the Pareto share at the time the policy arrives.

Using Definition 2, Equation (28), and Equation (37), uncompensated WTP is

$$\tau_{uncomp}(x) = 1 - \left( \frac{H(x)}{\hat{H}(x)} \right)^{1/\alpha}. \quad (38)$$

Similarly, using Definition 3, Equation (29), Equation (30), and Equation (37), individual WTP for each agent  $j \in \{a, b\}$  is

$$\tau_j(x) = 1 - \left( \frac{H_j(x)}{\hat{H}_j(x)} \right)^{1/\alpha}. \quad (39)$$

Compensated WTP, from Definition 1, is not available in closed form. However, we can show uniqueness of  $\tau_{comp}$  and the modified Pareto weight  $\hat{x}$ , capturing the associated wealth transfer.<sup>11</sup>

**Proposition 4** *For any  $x \in (0, 1)$ , there exists a unique  $\hat{x} \in (0, 1)$  with compensated WTP*

$$\tau_{comp}(x) = 1 - \left( \frac{H_a(x)}{\hat{H}_a(\hat{x})} \right)^{1/\alpha} = 1 - \left( \frac{H_b(x)}{\hat{H}_b(\hat{x})} \right)^{1/\alpha}. \quad (40)$$

*Compensated WTP leaves both agents indifferent to whether the policy is implemented or not.*

Finally, the model's individual and representative agent value functions satisfy the conditions for Proposition 1, leading to the following corollary.

**Corollary 1** *Define  $\tau_{min}(x) = \min(\tau_a(x), \tau_b(x))$  and  $\tau_{max} = \max(\tau_a(x), \tau_b(x))$ . For any  $x \in (0, 1)$ ,  $\tau_{max}(x) \geq \tau_{uncomp}(x) \geq \tau_{comp}(x) \geq \tau_{min}(x)$ . The inequalities are strict unless  $\tau_a(x) = \tau_b(x)$ , in which case all the WTP are equal.*

In his critical analysis of the integrated climate model literature (Pindyck, 2013), Robert Pindyck argues that most analyses disregard the possibility of catastrophic cli-

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<sup>11</sup>See Appendix A for proof.

mate change when estimating the social cost of carbon (SCC). While acknowledging disagreement regarding the probability of a catastrophic increase, he argues (p. 869) that “even if a large temperature outcome has low probability, if the economic impact of that change is very large, it can push up the SCC considerably.” Corollary 1 suggests that if we go one step further and account for disagreement regarding the probability of catastrophe, even an efficient political system should yield a lower estimate of the SCC than one obtains from a representative agent model, similar to  $\tau_{uncomp}$ , because all large constituencies must at least view the policy as harmless net of transfers and costs, more in line with  $\tau_{comp}$ .

This reduction is *in addition* to any change in the SCC that would result from an active *private* market for catastrophe insurance. Pindyck argues (p. 870) that “one can think of a [greenhouse gas] abatement policy as a form of insurance: society would be paying for a guarantee that a low-probability catastrophe will not occur (or is less likely).” In this light, accounting for the possibility of a private insurance market—which is present in our model—seems critical.

In the context of a simple two period model, Proposition 3 shows that disagreement, coupled with complete markets, reduces WTP by a nonnegative amount even before compensation is considered. The next section performs similar analysis using our dynamic production economy, with more realistic preferences. This model is suitable for assessing in magnitude how disagreement changes WTP, and also supports a number of robustness exercises.

## 4 Numerical examples

Previous studies quantifying WTP for disaster reduction fall into two broad categories. One focuses on estimates of physical disaster arrival rates and distributions, requiring broad and long international datasets for GDP or consumption growth, as for example

in Barro and Ursua (2008) and Barro (2009). The other approach finds implied disaster arrival rates and distributions that rationalize financial market data, such as the risk premium, skewness, and kurtosis of stock returns, as for example in Pindyck and Wang (2013). Since our dynamic model reduces to Pindyck and Wang (2013) when there is no disagreement, we follow their approach, extended to incorporate measures of disagreement. In Appendix D, we consider an alternative calibration based on Barro (2009) and Barro and Jin (2011). We also present robustness results and additional tables for our baseline calibration in Appendix C.

Fitting the model to financial market moments is of additional interest in our case, as stock returns reflect heterogeneous subjective perceptions of risk, and accounting for disagreement can alter market-implied estimates of physical disaster probabilities. In previous studies, such as Chen, Joslin and Tran (2012), the magnitude of this effect would be difficult to quantify. This is because only one agent survives at long horizons, typically the agent with the most accurate beliefs (see e.g., Yan (2008)); therefore it is not possible to calibrate unconditional model moments to data. However with recursive preferences, agents who disagree may survive indefinitely, as shown by Borovička (2016). Our model shares this survival property, which we exploit when calibrating unconditional model moments to the data. As a result, we are able to quantify the effect of disagreement on empirically plausible model parameters.

Our calibration procedure is new to the literature on heterogeneous beliefs. In a nonstationary equilibrium, David (2008) estimates model parameters with disagreement to fit observed time-series data over a 30-year period, and reports moments based on 30-year paths of the model bootstrapped from the data. We calibrate model parameters under both the subjective and objective measures, and report unconditional moments that approximate limiting behavior of our model as  $t \rightarrow \infty$ . Although Borovička (2016) and Baker, Hollifield and Osambela (2016) also feature a nondegenerate stationary distribution, unconditional moments are not calibrated to data in their numerical examples.

Taking the empirical moments and parameter estimates of Pindyck and Wang (2013) as a starting point, we minimally augment the set of moments to identify separate jump arrival rate parameters for the optimist ( $\lambda_a$ ), the pessimist ( $\lambda_b$ ), and under the objective measure ( $\lambda_c$ ). The first eight data moments in Table 2 are from Pindyck and Wang (2013). From the Philadelphia Fed’s Survey of Professional Forecasters, we add the mean annualized current quarter 25th and 75th percentile GDP growth forecasts.<sup>12</sup> We jointly choose values of  $\lambda_a$ ,  $\lambda_b$ , and  $\lambda_c$  so that the optimist’s expected output growth rate matches the mean 75th percentile forecast, whereas the pessimist matches the mean 25th percentile forecast, with  $\lambda_c$  such that a nondegenerate stationary distribution exists for  $x_t$ , and the remaining moments approximately match the data under the physical measure. Because the presence of disagreement biases subjective expected returns on individual wealth upward, introducing disagreement tends to increase investment.<sup>13</sup> Relative to Pindyck and Wang (2013), we increase  $\delta$  by 0.3% to offset the effect of investment, leaving the remaining parameters identical to those they identify. Parameter values are reported in Table 1, under the column “Disagreement.”

In targeting the dispersion of GDP growth forecasts from the SPF, we avoid beliefs with unrealistic economic or financial market implications, as discussed in Appendix C. For example, institutional and individual investors on average perceive stock market crash risk that is an order of magnitude higher than the historical frequency, based on survey data summarized in Goetzmann, Kim and Shiller (2016). Their survey responses are also very dispersed. A calibration capturing such beliefs would be at odds with a variety of empirical financial and macroeconomic moments. By contrast, our agents perceive moments in a range consistent with historical observations, including for stock market crash risk. Based on historical observation, Goetzmann, Kim and Shiller (2016) suggest the probability of a one-day stock market crash similar to October 28, 1929 is

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<sup>12</sup><https://www.philadelphiafed.org/research-and-data/real-time-center/survey-of-professional-forecasters/historical-data/dispersion-forecasts>

<sup>13</sup>This applies when the elasticity of intertemporal substitution is greater than one, as it is in our calibration.

perhaps 1% to 1.7% per six months. Our optimist puts the probability at 0.92%, our pessimist puts it at 1.62%.

Although we do not formally estimate the model, Table 2 shows that our calibration fits the data well. Our contribution here is to produce such results while ensuring that the agents have empirically plausible disagreement, and survive indefinitely, without requiring unorthodox parameter values for preferences. Figure 1 plots the density of Pareto share  $x_t$  after 50, 500, and 1,000 years, assuming initial value  $x_0 = 0.5$ . Densities are approximately identical at 500 and 1,000 years, showing that the main state variable has approximately the long run stationary distribution after 500 years or so. The optimist has an average Pareto share of 53.1% in the long run, but the density has broad support. The figure also shows densities for the optimist's wealth share  $h$ , which has a long run mean of 46.9%, also with broad support, but closer to normal in distribution than his Pareto share. The bottom panel of Figure 1 shows the mapping from  $x$  to  $h$ , which has large and positive derivatives near  $x = 0$  and  $x = 1$ . This rescales the regions where the PDF of  $x$  is very steep, explaining why it is relatively unlikely that either agent has most of the wealth at long horizons, even though it is more likely that one agent has a large (but not 100%) Pareto share at long horizons. In summary, both agents play a meaningful economic role indefinitely.

We wish to compare our unconditional WTP estimates with disagreement to those from an equivalent model without disagreement, insofar as that is possible. Perhaps the obvious approach would be to use exactly the results from Pindyck and Wang (2013), but our calibration does not precisely match their selected moments from the data. Therefore we replicate their estimation procedure, but target the unconditional moments produced by our model, identifying parameters values without disagreement to exactly match the first eight moments from our model, as shown in the "No disagreement" column on Table 2. This is analogous to the homogeneous economy mapping used in Section 2.1, but with an expanded set of moments to identify all of the dynamic model parameters.

Resulting parameter values for the model without disagreement are in the right column of Table 1. As expected, differences from the values in Pindyck and Wang (2013) are small. However the objective mean arrival rate in the case without disagreement is higher than the objective mean arrival rate  $\lambda_c$  in the case with disagreement: 0.76 versus 0.7. By endogenously amplifying tail risk, disagreement might explain part of the difference between the high disaster frequency needed to rationalize stock return moments, and the relatively lower direct empirical estimates in Barro and Ursua (2008).

Our measures of WTP reflect conditional comparisons across economies, where the initial economic parameters reflect the status quo and a potential public policy modifies a subset of parameters. Table 3 summarizes parameter values for four policy experiments. The first three experiments have initial parameters per the Table 1.

The first experiment, which we call “Reduce Severity,” truncates the distribution of  $Z$  such that disasters destroy a negligible fraction of capital: disasters still occur, but society is extremely well prepared to handle them. This is analogous to the policy of the same name in the two period economy, given by Definition 4. The second experiment, which we call “Eliminate Disasters,” sets the arrival rate of disasters to zero under all measures. This is analogous to the policy of the same name in the two period economy, given by Definition 5.

Because the first experiment preserves disagreement regarding the arrival rate of disasters, whereas the second experiment resolves disagreement, a comparison of the results illustrates the value of private market opportunities for speculation. We can see that Reduce Severity preserves speculation, by examining the dynamics of our main state variable. When a jump occurs, the optimist’s Pareto share  $x$  is reduced by

$$\frac{\frac{\lambda_a}{\lambda_b} \frac{x_t}{1-x_t}}{1 + \frac{\lambda_a}{\lambda_b} \frac{x_t}{1-x_t}} - x_t. \quad (41)$$

The above expression is independent of the jump size  $Z$ , and our Reduce Severity exper-

iment leaves  $\lambda_a$  and  $\lambda_b$  unchanged. So the agents risk exactly the same Pareto share on jumps after the policy is adopted as beforehand. Furthermore, Reduce Severity leaves the wealth share bet upon jumps approximately unchanged. Unconditionally, a jump reduces the optimist's wealth share by 4.49% in our initial economy, versus 4.56% for a jump occurring shortly after adoption of the Reduce Severity policy. By this measure Reduce Severity increases speculation, but only by a small amount. Conditional differences are also small. By contrast, jumps have no effect on either the Pareto share or the wealth share following the Eliminate Disasters experiment: speculation is entirely eliminated.

In the remaining two experiments, the policy's effectiveness itself is controversial: adopting the policy increases disagreement. In the third experiment, which we call "Good Controversial," both agents believe the policy reduces the arrival rate of disasters, but the magnitude of the reduction is disputed. A comparison of this experiment with the previous two experiments suggests that less effective, controversial policies may be favored over more effective, uncontroversial ones. The fourth experiment, which we call "Bad Controversial," modifies the initial parameters such that agents agree at first, and shows that they are even willing to pay for a policy that increases aggregate risk but opens opportunities for speculation.

#### **4.1 Reduce Severity vs. Eliminate Disasters: Unconditional WTP**

How do estimates of unconditional WTP from a model with disagreement compare to those from a model without disagreement? Table 4 shows that estimates of WTP from the model with disagreement are significantly lower than estimates from the model without disagreement. For now, we focus on  $\tau_{comp}$  when measuring WTP with disagreement. WTP for Reduce Severity is 55.3% without disagreement, against 46.1% with disagreement. That is, incorporating plausible disagreement about disaster risk implies a proportional reduction in WTP of around 17%, even when the policy preserves speculative opportunities, as with Reduce Severity. For Eliminate Disasters, which eliminates all

disaster risk and also speculative opportunities, WTP is 55.7% without disagreement, against 38.1% with disagreement. That is a proportional reduction of around 32%. Note that Eliminate Disasters eliminates strictly more disaster risk than Reduce Severity, yet WTP for Eliminate Disasters is below that of Reduce Severity with disagreement.<sup>14</sup> This is consistent with Proposition 2: agents value speculative opportunities in the dynamic model, just as they do in the two period model.

Consistent with Proposition 1, WTP is also reduced as a result of wealth transfers needed to achieve Pareto improvement, i.e.,  $\tau_{comp} < \tau_{uncomp}$ . From Table 4, the average difference between  $\tau_{comp}$  and  $\tau_{uncomp}$  is small, around 0.2%, although the average transfers range from 2% to 7%. The reduction in WTP is relatively small because, through the price system, the transfers alter individual agent WTP in an offsetting way. But what if such large transfers are politically infeasible, and consensus must be achieved without them? This scenario roughly corresponds to  $\tau_{min}$ . The potential for wealth transfers is important:  $\tau_{min}$  is only 43.3% for Reduce Severity and 33.8% for Eliminate Disasters, each significantly lower than  $\tau_{comp}$ . Absent transfers, the total proportional reduction in WTP for Eliminate Disagreement reaches roughly 40%.

Based on our two period model, Proposition 3 indicated that the costs of compensation, and the perceived value of speculative opportunities should entirely account for any reduction in WTP due to disagreement. That is,

$$[\tau|\text{Reduce Severity}] = [\tau_{uncomp}|\text{Reduce Severity}],$$

because  $[\tau_{uncomp}|\text{Reduce Severity}]$  involves no compensation and preserves speculation. Yet Table 4 shows that uncompensated WTP for Reduce Severity is only 46.4%, against 55.3% without disagreement. In our calibrated dynamic model, additional gains from

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<sup>14</sup>Reduce Severity and Eliminate Disasters each consider nearly complete elimination of disaster risk. In unreported additional experiments we find similar proportional reductions in WTP when the policy would only partially mitigate disaster risk. Results are also insensitive to small changes in the truncation threshold for Reduce Severity.

trade among agents further reduce the economic cost of disasters relative to the matched homogeneous economy. We refer to these effects collectively as crowding out by private insurance.

While many factors differentiate the dynamic model from the simple two period example, the preference specification — recursive Duffie and Epstein (1992a) utility, rather than log utility — plays a pivotal role. The choice of elasticity of intertemporal substitution (EIS), governed by parameter  $\rho$ , is particularly important. In Appendix E, we show that WTP is relatively higher in the homogeneous economy than in the heterogeneous economy when  $EIS > 1$ , but it is approximately equal when  $EIS \approx 1$ , and it may be relatively smaller when  $EIS < 1$ . Risk aversion, governed by parameter  $\alpha$ , plays a less important role. Our dynamic economy results are also affected by the inclusion of production, which is summarized in Appendix F.

Overall these results support some intuitive rules-of-thumb for crafting policies to address controversial catastrophes. First, policies that complement private remedies, as opposed to supplanting them, are more likely to be implemented at a given cost. This is supported by the difference in WTP estimates from Reduce Severity versus Eliminate Disasters. Second, policies that adequately compensate perceived losers are more likely to be supported at a given cost. This is supported by the substantial differences between  $\tau_{comp}$  and  $\tau_{min}$ .

## 4.2 Reduce Severity vs. Eliminate Disasters: conditional WTP and dynamics

To understand the motivations of the two agents and the interplay between them, it is helpful to examine WTP conditional on the value of the main state variable, the optimist's Pareto share  $x$ . Figure 2 plots WTP against  $x$  for the first two experiments. The green solid line is  $\tau_a$ , the red dashed line is  $\tau_b$ , the magenta dot-dash line is  $\tau_{comp}$ , and the black dotted line is  $\tau_{uncomp}$ . Dotted horizontal lines also indicate homogeneous economy

WTP for each agent.

WTP for Reduce Severity is shown in the top panel of Figure 2, in which the economy starts with the baseline parameters in Table 1. The government proposes a policy that renders disasters nearly harmless: disasters will destroy at most 0.1% of the capital stock. However the likelihood of disasters, on which agents disagree, is unchanged from the baseline:  $\lambda_a$  and  $\lambda_b$  are unaltered, and disagreement remains.

Optimists are, of course, more reluctant to pay to reduce disaster severity. If there were only optimists in the economy ( $x = 1$ ), they would be willing to pay about 36% of their consumption to reduce the severity of disasters. When pessimists are included ( $0 < x < 1$ ), optimists provide insurance to them in exchange for a speculative premium. Through insurance, pessimists transfer their disaster risk exposure to optimists. Hence optimists now carry a much higher disaster exposure and would therefore be more willing to pay to attenuate their disaster exposure. For this reason, the optimist's WTP  $\tau_a(x)$  is decreasing in  $x$ .

Consider now a situation in which there are only pessimists in the economy ( $x = 0$ ). They would be willing to pay over 50% of their consumption to reduce the severity of disasters. When optimists are included ( $0 < x < 1$ ), pessimists pay them for insurance against disaster risk. Through insurance, pessimists transfer their disaster risk exposure to optimists. Hence pessimists now carry a much lower disaster exposure, and would be less willing to pay to attenuate their disaster exposure. For this reason, the pessimist's WTP  $\tau_b(x)$  is also decreasing in  $x$ .

Regarding our two measures of aggregate WTP,  $\tau_{uncomp}(x)$  and  $\tau_{comp}(x)$ , two broad results stand out. First, WTP is decreasing in  $x$ , regardless of the measure used. This is not surprising given that each agent's WTP is decreasing in  $x$  as well. Second, the result that  $\tau_{comp}(x)$  is not dramatically lower than  $\tau_{uncomp}(x)$  applies conditionally as well as unconditionally. This is the case in our other experiments also, suggesting that negotiated agreements between constituencies could generate nearly as much funding

as policies imposed for the collective good over the objection of one constituency. Note however that  $\min(\tau_a, \tau_b)$  —always equal to the optimist’s WTP  $\tau_a$  for Reduce Severity— is generally much lower than  $\tau_{comp}(x)$ . So WTP may be much lower if transfers are impossible, and all constituencies must be satisfied that a policy is worth its cost.

Eliminate Disasters also begins with initial parameters in Table 1, but this time the policy sets  $\hat{\lambda}_a = \hat{\lambda}_b = 0$ . The implications for exogenous aggregate risk are nearly identical to Reduce Severity, which left only a small amount of residual disaster risk. But Eliminate Disasters also resolves disagreement, and the agents in our economy view this policy very differently from the previous one.

WTP is plotted against  $x$  in the bottom panel of Figure 2. The optimist’s WTP is always below his homogeneous economy level, and it remains relatively insensitive to  $x$ , except in the neighborhood of  $x = 1$ . As with Reduce Severity, the pessimist’s WTP  $\tau_b(x)$  is decreasing in  $x$ , but it decreases far more rapidly for Eliminate Disasters, crossing the optimist’s WTP around  $x = 0.98$ . Relative to Reduce Severity, the most important difference is that  $\tau_a(x)$  is flat or increasing in  $x$  for Eliminate Disasters.

Two channels explain the patterns in Figure 2. The first channel is the expected speculative gain. Each agent perceives highest potential speculative gains when his wealth share is the lowest, since there the price system appears most distorted in his view. According to this channel, WTP for a policy that eliminates speculative opportunities should be increasing in  $x$  for the optimist and decreasing in  $x$  for the pessimist.

The second channel is exposure to disaster risk. The optimist is most exposed to disaster risk when he has low wealth ( $x$  near 0), whereas the pessimist is most insured against disaster risk when he has low wealth ( $x$  near 1). According to this channel, WTP for a policy that eliminates disaster risk should be decreasing in  $x$  for both the optimist and the pessimist. These two channels offset for most of the domain of  $x$  for the optimist, while there is a marked negative slope for the pessimist because the two channels amplify each other. For Reduce Severity the first channel is absent, and WTP is

decreasing in  $x$  for both agents.

For all interior values of  $x$ , each agent has strictly lower individual WTP for Eliminate Disasters than for Reduce Severity. Predictably, lower individual WTP translates to lower aggregate WTP. But the opposite responses of the optimist and the pessimist to an increase in  $x$  in the neighborhood of  $x = 0.98$  lead to nonmonotonic WTP for Eliminate Disasters:  $\tau_{comp}$  and  $\tau_{uncomp}$  both turn from decreasing to increasing.

To provide some intuition regarding dynamics and also a simple linkage to financial markets, Figure 3 shows a hypothetical 6-year path of the economy, where a rare sequence of events — four consecutive disasters of average size — occurs at the start of the 5th year. To clarify the mechanism we set realizations of the Brownian shock to zero. The path of the aggregate stock price, shown in the top panel, rises during the first 5 years and then falls with the disaster. The middle panel shows WTP for Reduce Severity over this path of the economy. Because  $\tau_{uncomp}$  is nearly identical to  $\tau_{comp}$ , we omit it from the plot. WTP gradually drops as stocks rise, but then rises quickly as stocks fall during the disaster. The reason for these dynamics is that the stock price is increasing in  $x$ , while WTP is decreasing in  $x$ . In this example,  $\tau_{comp}(x)$  rises after the disaster not because of learning, but because of a shift in wealth towards the pessimist. The wedge between the agents' WTP  $\tau_a(x)$  and  $\tau_b(x)$  also grows larger as time passes without a disaster and drops when the disaster occurs. So for Reduce Severity, an increase in WTP coincides with a closing of the gap between  $\tau_a(x)$  and  $\tau_b(x)$ .

The bottom panel of Figure 3 shows WTP for Eliminate Disasters, with identical starting conditions and shocks to the path described for Reduce Severity. Again the optimist has the lowest WTP, but for Eliminate Disasters it is relatively insensitive to  $x$ , in contrast to the pattern observed for Reduce Severity. On the other hand, the pessimist's WTP gradually drops as stocks rise, but then rises quickly as stocks fall during the disaster — a similar response to that observed for Reduce Severity. Similarly,  $\tau_{comp}(x)$  drops during the initial boom and rises with the disaster, the same as for Reduce Severity.

But the initial decline in  $\tau_{comp}(x)$  occurs even though  $\tau_a(x)$  and  $\tau_b(x)$  are converging during the initial boom. So for Eliminate Disasters, an increase in  $\tau_{comp}(x)$  coincides with a divergence of individual WTP following a disaster, the opposite of Reduce Severity.

Although it is possible to construct counterexamples for different model parameters, results from our calibration suggest that society is most likely to adopt risk reduction policies in the wake of a disaster, when WTP rises. Pastor and Veronesi (2012) study theoretical connections between economic growth, the stock market, and government policy changes, and also find that policy change is likely to occur after a sharp downturn. The mechanism driving their result — learning that the current policy is ineffective — is different from ours. Related empirical evidence that structural reform tends to follow crises includes Bruno and Easterly (1996), who study inflation crises, Alesina, Ardagna and Trebbi (2006), who expand analysis to budget deficits, and Ranciere and Tornell (2015), who study trade reforms.

### 4.3 Controversial policies

The experiment Eliminate Disasters featured two effects in opposition: eliminating aggregate risk was appealing, but eliminating disagreement was unappealing. These effects can be made to work in the same direction if the policy itself is controversial, in that it increases disagreement. The policy experiment we call Controversial Good, summarized in Figure 4, shows such an example. Once again initial parameters are as in Table 1. Consider a policy to reduce the likelihood of disasters, without eliminating disasters entirely. Suppose the optimist believes the policy will make disasters very infrequent, setting  $\hat{\lambda}_a = 0.01$ , whereas the pessimist believes the disaster likelihood will decline to  $\hat{\lambda}_b = 0.2$ . So the agents agree that the policy will reduce the likelihood of disasters, but they disagree about how much. Furthermore, disagreement about the likelihood of disasters actually increases because of the policy, from three-fold to twenty-fold for the pessimist relative to the optimist.

We start by comparing the unconditional results in Table 4. Absent the effects of disagreement, we see in the top row that WTP for Controversial Good would be strictly lower than for either Reduce Severity or Eliminate Disagreement, regardless of whether we adopt the pessimist's or the optimist's view as to controversial policy's effectiveness. But with disagreement, as in the subsequent rows of the table, unconditional WTP for the strictly less effective Controversial Good policy is always higher than WTP for either Reduce Severity or Eliminate Disagreement, precisely because the controversial policy increases disagreement. This is true for all measures of WTP with disagreement.

Comparing Figure 4 with the bottom panel of Figure 2, we see that the same result holds conditionally except when  $x$  is near 0 or 1. And in contrast to the previous experiments, the pessimist values the Controversial Good policy most highly when his Pareto share is small. If the policy is adopted, disagreement with the optimist widens and aggregate risk falls, such that the pessimist sees disaster insurance more as a source of speculative gain than a means to eliminate risk. So while the pessimist does not especially value the elimination of aggregate disaster risk when his Pareto share is small — he is already insured through trade with the optimist — the fact that markets primarily reflect the optimist's valuations implies greater opportunities for speculative purchase of insurance after the policy is implemented. Hence when the optimist's Pareto share  $x$  increases, so does the pessimist's WTP.

If introducing controversy into a policy can increase WTP to reduce disaster risk, will agents also agree to pay for a policy that increases risk but introduces speculative opportunities? Yes, provided the perceived value of speculative opportunities exceeds the increase in aggregate risk. To provide such an example, the policy experiment we call Controversial Bad modifies the initial parameters in Table 1 so there is no disagreement before the policy implementation ( $\lambda_a = \lambda_b = 0.1$ ), and disasters present only a minor risk, destroying 1% of capital for sure if they occur ( $Z = 0.99$  with probability one). Controversial Bad will increase the frequency of these minor disasters, but the

optimist perceives only a small increase ( $\hat{\lambda}_a = 0.11$ ) whereas the pessimist perceives a large increase ( $\hat{\lambda}_b = 0.4$ ).

As shown in Figure 5, although both agents recognize the policy as destructive, they both have positive WTP for nearly all interior values of  $x$ . Consequently all measures of aggregate WTP are positive in this region also. The requirement that  $x$  is not too close to 0 or 1 reflects that both agents must have a sufficient share of aggregate wealth to generate nontrivial speculative trade, otherwise the increase in aggregate risk dominates and WTP is negative. Examining the magnitude of aggregate WTP, all measures of WTP exceed 10% of aggregate consumption for most values of  $x$ . This perverse example highlights that disagreement is not a second-order concern when calculating WTP, and can even be the most important factor when evaluating controversial policies.

## 5 Conclusion

We study aggregate willingness to pay for disaster reducing policies in a dynamic general equilibrium production economy with recursive preferences and disagreement about the likelihood of disasters. Using a careful calibration of our stationary model, we show that disagreement may reduce WTP by as much as 40%, with 17% corresponding to a private insurance channel, 15% corresponding to a speculation channel, and 8% corresponding to a political channel. This novel decomposition highlights the quantitative importance of financial markets as a vehicle for crowding out disaster insurance offered by governments.

Our model illustrates a central tension in the demand for such disaster reduction policies: agents dislike tail risk per se, but disagreement creates valuable private insurance market opportunities, which transfer risk to those most willing to bear it. To our knowledge, we are the first to highlight this trade off, which should be of interest to policy makers. We also provide results on the dynamics of WTP for disaster-reduction

policies. Generally, policies to reduce the severity of disasters are supported at higher cost immediately after a disaster occurs.

Recent theoretical work such as Brunnermeier, Simsek and Xiong (2014) and Gilboa, Samuelson and Schmeidler (2014) considers alternative definitions of allocative efficiency with disagreement, whereas we study structural changes that are Pareto efficient when accompanied by wealth transfers. We highlight policies that are mutually acceptable to economic agents with irreconcilable beliefs. If such agents represent political constituencies that must achieve consensus to adopt new public policies, then identifying such politically feasible policies is of practical relevance. Future work should identify the intersection of policies that are both politically feasible and robust to alternative definitions of allocative efficiency.

Because WTP for policies varies with the state of the economy, the timing of new policy adoption potentially represents a new source of endogenous risk. Whereas we assume agents cannot foresee any policy change, Pastor and Veronesi (2012) model this source of risk, and Pástor and Veronesi (2013) and Kelly, Pástor and Veronesi (2016) show the importance of government policy uncertainty for asset pricing. Their work does not model the interplay of disagreeing constituencies in determining the timing of policy adoption. Combining the two approaches could provide a useful model of government policy dynamics in a heterogeneous and democratic society.

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# A Proofs

## Proof of Proposition 1.

Note that  $\tau_{comp} \geq \tau_{min}$  and  $\tau_{max} \geq \tau_{uncond}$  follow directly from the respective definitions. We now show that  $\tau_{uncomp} \geq \tau_{comp}$ . In what follows we replace  $(1 - \tau)C$  with the argument  $\tau$  in the various value functions to simplify notation. We also omit the parameter argument  $\Omega$ , and write  $\hat{V}(\cdot)$  to distinguish the value function incorporating the modified structural parameters  $\hat{\Omega}$ . Assume without loss of generality that  $\sum_a^N x_i = 1$ .

Using the constraints in the definition of  $\tau_{comp}$  in Equation (8):

$$\begin{aligned}
 x_a \hat{V}_a(\hat{X}, \tau_{comp}) + \dots + x_N \hat{V}_N(\hat{X}, \tau_{comp}) &\geq x_a V_a(X, 0) + \dots + x_N V_N(X, 0) \\
 &= V(X, 0) \\
 &= \hat{V}(X, \tau_{uncomp}) \\
 &= x_a \hat{V}_a(X, \tau_{uncomp}) + \dots + x_N \hat{V}_N(X, \tau_{uncomp}) \\
 &\geq x_a \hat{V}_a(\hat{X}, \tau_{uncomp}) + \dots + x_N \hat{V}_N(\hat{X}, \tau_{uncomp}).
 \end{aligned}
 \tag{A1}$$

The second line follows from the definition of the value function; the third line follows from the definition of the uncompensated tax rate  $\tau_{uncomp}$ ; the fourth line follows from the definition of the value function; the fifth line follows from Pareto efficiency, because it is feasible to choose the allocation corresponding to  $\hat{X}$  in state  $X$ . The final line in inequality (A1) and the monotonicity of individual payoff functions  $\hat{V}_i(\hat{x}, \tau)$  in  $\tau$  implies that  $\tau_{uncomp} \geq \tau_{comp}$ .

Pareto efficient allocations and monotonicity of the value functions implies the planner's strategies are unique in  $X$ . When  $\tau_{max} > \tau_{min}$ ,  $X \neq \hat{X}$ , implying that the final inequality in (A1) is strict and  $\tau_{uncomp} > \tau_{comp}$ . ■

**Proof of Proposition 4.** Equivalence follows from the first order conditions for compensated WTP. Recall that agent preferences are homothetic, as shown in Proposition 8 of Duffie and Epstein (1992b), which implies an agent’s utility becomes arbitrarily small as his consumption share approaches zero. Existence and uniqueness follow because  $\frac{1}{\alpha}\hat{H}_a(\hat{x})$  is monotonically increasing in  $\hat{x}$ , whereas  $\frac{1}{\alpha}\hat{H}_b(\hat{x})$  is monotonically decreasing in  $\hat{x}$ . ■

## B Two period exchange economy

Consider a model with two time periods, where the aggregate endowment is  $0 < C_0 < \infty$  in period  $t = 0$ , with uncertain growth  $\frac{C_1}{C_0} \in \{\Delta_L, \Delta_H\}$  in period  $t = 1$ , for  $0 < \Delta_L < \Delta_H < \infty$ . All agents have expected log utility and time discount factor  $\beta$ , but may be assign different probabilities  $\pi_i$  to the low growth state  $\Delta_L$ , where subscript  $i$  indexes the agent (or type). We consider two model variants: one with homogeneous beliefs, and another with two agents who disagree.

### B.1 Homogeneous beliefs

Suppose all agents have identical beliefs about the probability of  $\Delta_L$ , for which we write  $\pi$ , dropping the unnecessary subscript. The representative agent has lifetime expected utility, or value function,

$$V(C_0; \Omega) = \log(C_0) + \beta [\pi \log(C_0 \Delta_L) + (1 - \pi) \log(C_0 \Delta_H)]. \quad (\text{B1})$$

The structural endowment growth parameters are  $\Omega = \{\Delta_L, \Delta_H, \pi\}$ .

The following lemma summarizes WTP for the specific disaster reduction policies, per Definition 4 and Definition 5, with homogeneous beliefs.

**Lemma 1** *In the two period economy with homogeneous beliefs, WTP for Reduce Severity and Eliminate Disasters is identical, and is equal to*

$$\tau = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi}{1+\beta}} \quad (\text{B2})$$

**Proof.** For either  $\hat{\Omega} = \{\Delta_H, \Delta_H, \pi\}$  (Reduce Severity) or  $\hat{\Omega} = \{\Delta_L, \Delta_H, 0\}$  (Eliminate Disasters), the value function reduces to

$$V(C_0; \hat{\Omega}) = (1 + \beta) \log((1 - \tau)C_0) + \beta \log(\Delta_H).$$

WTP  $\tau$  satisfies Equation (1), so

$$\begin{aligned} (1 + \beta) \log(1 - \tau) &= \beta\pi \log(\Delta_L) - \beta\pi \log(\Delta_H), \\ \Rightarrow \tau &= 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi}{1+\beta}}. \end{aligned}$$

■

## B.2 Heterogeneous beliefs

Suppose there are two types of agent, indexed  $i \in \{a, b\}$ , with different beliefs about the probability of low growth in period 1:  $\pi_a \neq \pi_b$ . We solve for the competitive, complete markets equilibrium in the usual way, via the planner's problem. The solution can be separated into two parts. First compute the consumption allocation for a single period, contingent on aggregate consumption  $C$ , agent a Pareto share  $x \in (0, 1)$ , and agent b Pareto share  $1 - x$ :

$$\max_{C_a + C_b = C} x \log(C_a) + (1 - x) \log(C_b). \quad (\text{B3})$$

The solution is

$$C_a(x, C) = xC, \quad (\text{B4})$$

$$C_b(x, C) = (1 - x)C. \quad (\text{B5})$$

Write agent a's initial, period 0 Pareto share  $x_0 \in (0, 1)$ .<sup>15</sup> With heterogeneous beliefs, the Pareto share in period 1 is stochastic. We will take agent b's beliefs as the reference measure, and use change of measure,  $\eta_{1,s}$  for  $s \in \{L, H\}$ :

$$\eta_{1,L} = \frac{\pi_a}{\pi_b}, \quad \eta_{1,H} = \frac{1 - \pi_a}{1 - \pi_b}. \quad (\text{B6})$$

This implies that agent a has state-contingent period 1 Pareto share

$$x_{1,L} = \frac{x_0 \eta_{1,L}}{1 - x_0 + x_0 \eta_{1,L}}, \quad (\text{B7})$$

$$x_{1,H} = \frac{x_0 \eta_{1,H}}{1 - x_0 + x_0 \eta_{1,H}}. \quad (\text{B8})$$

Above, the numerator adjusts the Pareto weight for agent a's relative perception of the state's likelihood, and the denominator is simply a normalization so that period 1 weights sum to unity, retaining their interpretation as Pareto shares.

Combining the stochastic Pareto share with the consumption allocation rule, the agents have value functions

$$V_a(C_0, x_0; \Omega) = \log(x_0 C_0) + \beta [\pi_a \log(x_{1,L} C_0 \Delta_L) + (1 - \pi_a) \log(x_{1,H} C_0 \Delta_H)], \quad (\text{B9})$$

$$\begin{aligned} V_b(C_0, x_0; \Omega) &= \log((1 - x_0) C_0) \\ &+ \beta [\pi_b \log((1 - x_{1,L}) C_0 \Delta_L) + (1 - \pi_b) \log((1 - x_{1,H}) C_0 \Delta_H)], \end{aligned} \quad (\text{B10})$$

where structural parameters are  $\Omega = \{\Delta_L, \Delta_H, \pi_a, \pi_b\}$ .

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<sup>15</sup>Normalizing initial Pareto weights to sum to 1 is without loss of generality.

The representative agent value function can be written in the form given by Equation (4):

$$V(C_0, x_0; \Omega) = x_0 V_a(C_0, x_0; \Omega) + (1 - x_0) V_b(C_0, x_0; \Omega). \quad (\text{B11})$$

The following lemmas summarize individual WTP, defined in Definition 3, for the specific disaster reduction policies, defined in Definition 4 and Definition 5. Note that WTP with heterogeneous agents is contingent on  $x_0$ , but we write, e.g.,  $\tau_a$  for  $\tau_a(x_0)$  to simplify notation.

**Lemma 2 (WTP for Reduce Severity)** *Individual WTP for Reduce Severity is, for agents  $a$  and  $b$  respectively,*

$$\tau_a = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta \pi_a}{1+\beta}}, \quad (\text{B12})$$

$$\tau_b = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta \pi_b}{1+\beta}}. \quad (\text{B13})$$

**Proof.** For Reduce Severity,  $\tau_a$  satisfies

$$0 = V_a(C_0, x_0; \{\Delta_L, \Delta_H, \pi_a, \pi_b\}) - V_a((1 - \tau_a)C_0, x_0; \{\Delta_H, \Delta_H, \pi_a, \pi_b\}),$$

$$0 = \beta [\pi_a \log(\Delta_L) + (1 - \pi_a) \log(\Delta_H)] - (1 + \beta) \log(1 - \tau_a) - \beta \log(\Delta_H),$$

$$\log(1 - \tau_a) = \frac{\beta \pi_a}{1 + \beta} [\log(\Delta_L) - \log(\Delta_H)],$$

$$\Rightarrow \tau_a = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta \pi_a}{1+\beta}}.$$

Derivation of  $\tau_b$  is analogous. ■

**Lemma 3 (WTP for Eliminate Disasters)** *Individual WTP for Eliminate Disasters is, for agents*

$a$  and  $b$  respectively,

$$\tau_a = 1 - \left( \frac{x_{1,H}}{x_0} \right)^{\frac{\beta}{1+\beta}} \left( \frac{x_{1,L}}{x_{1,H}} \right)^{\frac{\beta\pi_a}{1+\beta}} \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi_a}{1+\beta}}, \quad (\text{B14})$$

$$\tau_b = 1 - \left( \frac{1-x_{1,H}}{1-x_0} \right)^{\frac{\beta}{1+\beta}} \left( \frac{1-x_{1,L}}{1-x_{1,H}} \right)^{\frac{\beta\pi_b}{1+\beta}} \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi_b}{1+\beta}}. \quad (\text{B15})$$

**Proof.** For Eliminate Disasters, note that implementation of the policy implies  $\pi_a = \pi_b = 0$  and also  $x_{1,H} = x_0$ , since agreement that the disaster won't occur eliminates Pareto weight dynamics. Therefore  $\tau_a$  satisfies

$$\begin{aligned} 0 &= V_a(C_0, x_0; \{\Delta_L, \Delta_H, \pi_a, \pi_b\}) - V_a((1-\tau_a)C_0, x_0; \{\Delta_L, \Delta_H, 0, 0\}), \\ 0 &= \beta [\pi_a \log(x_{1,L}\Delta_L) + (1-\pi_a) \log(x_{1,H}\Delta_H)] - (1+\beta) \log(1-\tau_a) - \beta \log(x_0\Delta_H), \\ \log(1-\tau_a) &= \frac{\beta}{1+\beta} [\log(x_{1,H}) - \log(x_0) + \pi_a (\log(x_{1,L}) - \log(x_{1,H}) + \log(\Delta_L) - \log(\Delta_H))], \\ \Rightarrow \tau_a &= 1 - \left( \frac{x_{1,H}}{x_0} \right)^{\frac{\beta}{1+\beta}} \left( \frac{x_{1,L}}{x_{1,H}} \right)^{\frac{\beta\pi_a}{1+\beta}} \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi_a}{1+\beta}}. \end{aligned}$$

Derivation of  $\tau_b$  is analogous. ■

Based on the formulas for individual WTP, Proposition 2 shows that both individual and societal WTP is lower for Eliminate Disagreement than for Reduce Severity.

### Proof of Proposition 2.

Recall that the period 1 Pareto weights are

$$\begin{aligned} x_{1,L} &= \frac{x_0\pi_a}{x_0\pi_a + (1-x_0)\pi_b}, \\ x_{1,H} &= \frac{x_0(1-\pi_a)}{x_0(1-\pi_a) + (1-x_0)(1-\pi_b)}. \end{aligned}$$

Equation (12) holds iff

$$\left( \frac{x_{1,H}}{x_0} \right)^{\frac{\beta}{1+\beta}} \left( \frac{x_{1,L}}{x_{1,H}} \right)^{\frac{\beta\pi_a}{1+\beta}} > 1,$$

or equivalently

$$\left( \frac{1 - \pi_a}{x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b)} \right)^{1 - \pi_a} \left( \frac{\pi_a}{x_0\pi_a + (1 - x_0)\pi_b} \right)^{\pi_a} > 1. \quad (\text{B16})$$

Differentiating the above expression in logs w.r.t.  $x_0$  yields

$$\begin{aligned} & \frac{\partial}{\partial x_0} [(1 - \pi_a) (\log(1 - \pi_a) - \log(x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b))) \\ & + \pi_a (\log(\pi_a) - \log(x_0\pi_a + (1 - x_0)\pi_b))] \\ & = - \frac{(1 - x_0)(\pi_a - \pi_b)^2}{[x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b)][x_0\pi_a + (1 - x_0)\pi_b]} \leq 0, \end{aligned}$$

with strict inequality for  $x_0 < 1$ . Therefore there is no interior extremum, and the term approaches its minimum as  $x_0 \rightarrow 1$ . This in turn implies  $[\tau_a | \text{Eliminate Disagreement}]$  approaches its maximum as  $x_0 \rightarrow 1$ , for  $\pi_a, \pi_b$  given.

At  $x_0 = 1$ , we have

$$[\tau_a | \text{Eliminate Disagreement}, x_0 = 1] = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi_a}{1+\beta}} = [\tau_a | \text{Reduce Severity}].$$

Since  $[\tau_a | \text{Eliminate Disagreement}]$  is strictly below its maximum value for any  $x_0 < 1$ , whereas  $[\tau_a | \text{Reduce Severity}]$  is constant for all  $x_0$ , Equation (12) holds for any  $x_0 \in [0, 1)$ .

The equivalent condition for Equation (13) to hold is

$$\left( \frac{1 - \pi_b}{x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b)} \right)^{1 - \pi_b} \left( \frac{\pi_b}{x_0\pi_a + (1 - x_0)\pi_b} \right)^{\pi_b} > 1. \quad (\text{B17})$$

The derivative of the above condition, in logs, w.r.t.  $x_0$  is

$$\begin{aligned} & \frac{\partial}{\partial x_0} [(1 - \pi_b) (\log(1 - \pi_b) - \log(x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b))) \\ & + \pi_b (\log(\pi_b) - \log(x_0\pi_a + (1 - x_0)\pi_b))] \\ & = \left( \frac{x_0(\pi_a - \pi_b)^2}{[x_0(1 - \pi_a) + (1 - x_0)(1 - \pi_b)][x_0\pi_a + (1 - x_0)\pi_b]} \right) \geq 0, \end{aligned}$$

with strict inequality for  $x_0 > 0$ . Therefore the left hand side of Equation (B17) limits to its minimum as  $x_0 \rightarrow 0$ , which implies  $[\tau_b|\text{Eliminate Disagreement}]$  limits to its maximum as  $x_0 \rightarrow 0$ .

At  $x_0 = 0$  we have

$$[\tau_b|\text{Eliminate Disagreement}, x_0 = 0] = 1 - \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta\pi_b}{1+\beta}} = [\tau_b|\text{Reduce Severity}].$$

Since  $[\tau_b|\text{Eliminate Disagreement}]$  is strictly below its maximum value for any  $x_0 > 0$ , whereas  $[\tau_b|\text{Reduce Severity}]$  is constant for all  $x_0$ , Equation (13) holds for any  $x_0 \in (0, 1]$ .

Therefore each agent strictly prefers Reduce Severity to Eliminate Disagreement for  $x_0 \in (0, 1)$ .

To see that the inequalities for social WTP measures  $\tau_{comp}$  and  $\tau_{uncomp}$  also hold, note that results for individual WTP imply as a corollary that

$$\begin{aligned} V_a(C_0, x_0; \hat{\Omega}_{\text{EliminateDisasters}}) &< V_a(C_0, x_0; \hat{\Omega}_{\text{ReduceSeverity}}), \\ V_b(C_0, x_0; \hat{\Omega}_{\text{EliminateDisasters}}) &< V_b(C_0, x_0; \hat{\Omega}_{\text{ReduceSeverity}}), \end{aligned}$$

for any  $C_0 > 0$  and  $x_0 \in (0, 1)$ , since the value functions are strictly increasing in their first argument. Results for  $\tau_{comp}$  and  $\tau_{uncomp}$  follow naturally from their respective defi-

nitions.

■

Note that the fundamental reduction in risk is identical for both experiments: in each case, the aggregate endowment growth is  $\Delta_H$  with certainty in period 1.

### **B.3 Mapping: Heterogeneous Beliefs to Homogeneous Beliefs**

In this section we find a homogeneous agent economy that is observationally equivalent to the heterogeneous agent economy in terms of certain aggregate characteristics. We allow the heterogeneous economy parameters and initial Pareto weight to take arbitrary values on their natural domains, and solve for a mapping from those parameter values to the homogeneous economy parameter values. The purpose of the mapping is to compare WTP for some policy in the heterogeneous economy to WTP for the same policy in an equivalent homogeneous economy.

It is generally impossible that the two economies should be observationally equivalent along all conceivable dimensions, so the choice of characteristics to match necessarily involves discretion. We assume that the aggregate consumption endowment is observable and important to match, such that parameters  $C_0$ ,  $\Delta_L$ , and  $\Delta_H$  are identical in the two economies. This leaves only mappings to  $\beta$  and  $\pi$  in the homogeneous economy.

Recall that we assume complete financial markets throughout, which requires two non-redundant financial assets in our two state example. We take the usual approach, defining a stock paying aggregate consumption as a dividend, with the second asset a riskless bond. We choose parameters  $\beta$  and  $\pi$  in the homogeneous economy such that the price-dividend ratio of the stock, and the riskless rate, match those of the heterogeneous economy. We match these characteristics because they are observable, important financial market indicators, and because the mapping is easy to solve for in closed form.

In the homogeneous economy, the stochastic discount factor is

$$\frac{\beta C_0}{C_1}.$$

Therefore the ex-dividend price of the stock is

$$\mathbb{E} \left[ C_1 \frac{\beta C_0}{C_1} \right] = \beta C_0,$$

and the gross riskless rate is

$$\left( \mathbb{E} \left[ \frac{\beta C_0}{C_1} \right] \right)^{-1} = (\beta C_0)^{-1} \left( \frac{\pi}{\Delta_L} + \frac{1 - \pi}{\Delta_H} \right)^{-1}.$$

In the heterogeneous beliefs economy, frictionless complete markets imply that agents a and b agree on state prices, so stochastic discount factors are equivalent up to a change of measure. Under agent b's measure, the stochastic discount factor is

$$\frac{\beta C_{b,0}}{C_{b,1}} = \frac{\beta C_0 (1 - x_0 + x_0 \eta_1)}{C_1}.$$

The stock price is the same as in the homogeneous beliefs economy,

$$\mathbb{E} \left[ C_1 \frac{\beta C_0 (1 - x_0 + x_0 \eta_1)}{C_1} \right] = \beta C_0,$$

recalling that  $\eta_1$  is a Martingale under b's measure.

Therefore, if we set the price-dividend ratio in the homogeneous economy to match that of the heterogeneous beliefs economy,  $\beta$  must be the same in each economy.

In the heterogeneous economy the riskless rate is

$$\begin{aligned} & \left( \mathbb{E} \left[ \frac{\beta C_0 (1 - x_0 + x_0 \eta_1)}{C_1} \right] \right)^{-1} \\ &= (\beta C_0)^{-1} \left( \frac{\pi_b (1 - x_0) + \pi_a x_0}{\Delta_L} + \frac{(1 - \pi_b)(1 - x_0) + (1 - \pi_a)x_0}{\Delta_H} \right)^{-1}. \end{aligned}$$

Setting the riskless rate equal in the homogeneous and heterogeneous economies implies

$$\pi = \pi_a x_0 + \pi_b (1 - x_0),$$

so the homogeneous economy disaster probability is the Pareto-weighted average of the heterogeneous economy disaster probabilities.

Having mapped the heterogeneous economy parameters into a homogeneous economy, Proposition 3 summarizes how disagreement effects WTP.

**Proof.** Lemma 1 shows  $[\tau|\text{ED}] = [\tau|\text{RS}]$ . Proposition 2 shows  $[\tau_{comp}|\text{RS}] > [\tau_{comp}|\text{ED}]$  and  $[\tau_{uncomp}|\text{RS}] > [\tau_{uncomp}|\text{ED}]$ . And Proposition 1 with  $\pi_a \neq \pi_b$  implies  $[\tau_{uncomp}|\text{RS}] > [\tau_{comp}|\text{RS}]$ . It only remains to show

$$[\tau|\text{RS}] = [\tau_{uncomp}|\text{RS}]. \quad (\text{B18})$$

For Reduce Severity with heterogeneous agents,  $\tau_{uncomp}$  solves

$$\begin{aligned} 0 &= V(C_0, x_0; \{\Delta_L, \Delta_H, \pi_a, \pi_b\}) - V((1 - \tau_{uncond})C_0, x_0; \{\Delta_H, \Delta_H, \pi_a, \pi_b\}), \\ 0 &= \beta(x_0\pi_a + (1 - x_0)\pi_b) [\log(\Delta_L) - \log(\Delta_H)] - (1 + \beta) \log(1 - \tau_{uncomp}), \\ \Rightarrow \tau_{uncomp} &= \left( \frac{\Delta_L}{\Delta_H} \right)^{\frac{\beta(x_0\pi_a + (1-x_0)\pi_b)}{1+\beta}}. \end{aligned}$$

Since  $\pi = x_0\pi_a + (1 - x_0)\pi_b$  in the matched homogeneous beliefs economy,  $[\tau|\text{RS}] = [\tau_{uncomp}|\text{RS}]$ . ■

## C Baseline calibration: analysis and discussion

This appendix provides some additional analysis and discussion of the baseline calibration, with parameter values given in the second column (labeled Disagreement) of Table 1. We focus on the effects of parameter values governing beliefs about, and realizations of, disasters.

As discussed in the main text, optimistic and pessimistic beliefs regarding disaster arrival rate  $\lambda$  are calibrated to the average 25th percentile and 75th percentile GDP growth forecasts in the Survey of Professional Forecasters (SPF). Beliefs about other financial and economic statistics remain within a reasonable range. To illustrate, Table C1 shows financial and macroeconomic statistics for economies where one agent dominates, and his beliefs are correct. The equity premium, stock return volatility, and investment-capital ratio change only moderately. The real interest rate varies more, but well within historical norms. Skewness and kurtosis are more affected, but the forward-looking disaster risk to which these moments are highly sensitive is difficult to estimate, so the range seems plausible.

Volatility of GDP growth is large in our model relative to the data, but this is unrelated to disagreement. We follow the approach of Pindyck and Wang (2013), who select Brownian volatility parameter  $\sigma = 13.55\%$  in order to match stock market volatility, which implies (with jump risk) GDP volatility over 14% annualized, versus around 2% empirically. Our agents agree on  $\sigma$ , so GDP volatility stays about the same with disagreement.

As usual with any parsimonious model there is a trade-off: either we can match the higher moments of equity returns and the first GDP growth moment, or we can match the higher GDP growth moments and only the equity risk premium. Several papers confront this issue using similar models without disagreement. Pindyck and Wang (2013) take the first approach, whereas Barro (2009) and Barro and Jin (2011)

take the second approach.<sup>16</sup> A natural question is whether our main results regarding disagreement carry over to a Barro-type calibration. Appendix D shows that they do, qualitatively, and that in magnitude reductions in WTP due to disagreement are larger than in our baseline calibration. Appendix D also discusses the SPF GDP forecasts in more detail, including disagreement regarding the most negative GDP growth outcomes.

## C.1 GDP growth disagreement versus stock return disagreement

Given that arrival rate  $\lambda$  governs stock market crash risk, a relevant question regarding our baseline calibration (Table 1 in the paper) is whether directly targeting disagreement about stock market crash risk would lead to very different results. Robert Shiller’s survey of institutional and individual investors includes questions about perceived stock market crash risk in the US. Specifically, respondents are asked to assess the probability of a one-day US stock market crash, within the next six months, that is as bad or worse than the -12.82% crash of October 28, 1929. Individual survey responses or summary measures of disagreement are not publicly available. However Goetzmann, Kim and Shiller (2016) report a mean crash probability of 19.4% and a median crash probability of 10.0% from 1989-2015 survey data. They note that such probabilities are far higher than the frequency in the data, which is approximately 1% for the history of the Dow Jones Industrial Average, or 1.7% for the 1929 to 1988 sub-period minimally containing the two disasters satisfying their crash criterion.

In our calibration, the optimist perceives the six-month probability of such a severe crash as 0.92%, whereas the pessimist believes the probability is 1.62%. So our agents have beliefs in a range consistent with historical experience, but both are optimistic relative to the Shiller survey respondents. Summary survey statistics in Goetzmann, Kim and Shiller (2016) also indicate very dispersed individual survey responses.<sup>17</sup> So

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<sup>16</sup>A third approach is to introduce leverage in dividends, as in Abel (1999).

<sup>17</sup>In their Table 2, compare, e.g., summary statistics for individual responses  $\pi(i, t)$  to averages of responses received in a month  $\pi(t - 30, t - 1)$ . Dispersion between third quartile and first quartile prob-

our calibration likely understates disagreement about stock market crash risk.

In summary, our calibration of disasters to match historical stock market moments, and of disagreement about the probability of disasters based on GDP growth forecasts, is on the conservative side. Had we instead calibrated our model along the lines of the survey data in Goetzmann, Kim and Shiller (2016), we would have obtained a much stronger impact of disagreement on WTP. Indeed, we obtain a quantitatively large impact with less disagreement.

## C.2 Selection of true arrival rate $\lambda_c$ for baseline calibration

In the heterogeneous beliefs setting, selection of the true and unobserved arrival rate  $\lambda_c$ , which governs realizations of disasters in the model, involves considerations that don't arise without disagreement. To clarify, this section presents an example.  $\lambda_c$  governs model-implied moments under the true measure through two channels: directly, through the frequency of disasters, and indirectly, by altering the dynamics of the wealth share. Figure C1 shows the simulated probability density for the optimist wealth share under three values of  $\lambda_c$ : below our baseline value (top panel,  $\lambda_c = 0.61$ ), at our baseline value (middle panel,  $\lambda_c = 0.7$ ), and above our baseline value (bottom,  $\lambda_c = 0.79$ ).<sup>18</sup> All other parameters are unchanged from our baseline calibration. Approximately identical distributions at 500 year and 1000 year horizons illustrate stationarity in all cases. However the optimist has most of the wealth on average in the top panel (smaller  $\lambda_c$ ), whereas the pessimist has most of the wealth on average in the bottom panel (larger  $\lambda_c$ ). Our baseline parameter value, in the middle, has an approximately symmetrical wealth distribution centered around 50%.

The symmetrical wealth distribution corresponding to our baseline calibration seems

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abilities is 20% for individuals, versus 6.8% when monthly responses are first averaged. Note that this measure of individual belief dispersion is not directly comparable to the SPF GDP growth dispersion measure, where quartiles are first computed within a survey period and then averaged over time.

<sup>18</sup>To illustrate, we pick two symmetric points above and below our baseline that satisfy the parametric restrictions that make our model stationary.

intrinsically appealing. It also implies moments that are, overall, closer to the data than for the alternative values of  $\lambda_c$ , as illustrated by Table C2. Note that some moments, such as the interest rate, aren't directly affected by  $\lambda_c$ : for a given wealth share, investor beliefs determine the market clearing interest rate. In such cases, the choice of  $\lambda_c$  still has an indirect effect, because it affects the stationary wealth distribution. In other cases, such as stock return kurtosis,  $\lambda_c$  shows up directly in how frequently disasters are realized. Table C2 also shows that, although  $\lambda_c$  is important, our baseline calibration's model-implied moments aren't extremely sensitive to small changes in its value.

## **D Alternative calibration based on extreme declines in GDP**

In the main text, we calibrate a stationary equilibrium with disagreement about the likelihood of disasters and recursive preferences showing, among other things, that (i) WTP for policies to eliminate or reduce disasters with disagreement is lower than in an economy with agreement and identical unconditional moments, and (ii) given disagreement, the "Eliminate Disasters" policy has lower WTP than the "Reduce Severity" policy. In this section, we show that our results are robust to an alternative calibration focused on the most extreme disasters in GDP observed in long horizon international data.

Very rare GDP and consumption disasters are documented and analyzed in Barro and Ursua (2008); Barro (2009); Barro and Jin (2011), among other works. These studies focus on truly extreme 9.5% or greater GDP losses. After comparing estimates from these studies with available survey data, we conclude that there is substantial disagreement about such disaster risk. Our analysis has some intrinsic value because it shows how the conclusions of such studies change with the addition of disagreement. It also shows that our baseline calibration is far from extreme in terms of the magnitude of disagreement's impact on WTP estimates. A calibration focusing on perceptions of the most extreme disasters, rather than on more common and moderate disasters, implies WTP is more

sensitive to disagreement, not less.

## D.1 Historical and survey evidence

Based on international GDP and consumption growth data beginning in 1870, Barro and Ursua (2008) estimate a roughly 3.5% annual probability of disasters with cumulative declines of 10% of GDP or worse. They argue that, accounting for leverage, this accords with an equity premium of over 7%. While they note some ways in which the US is exceptional, especially with regard to consumption growth, there were 5 GDP disasters in the US during the 20th century when GDP declined by 10% or more. Hence, rare GDP disaster risk is advanced as a candidate explanation for the high US equity premium.

How does this assessment compare to data from the SPF? In the survey, forecasters are not specifically asked about such extreme disaster risk. However, from 1981, they are asked the probability, during the following quarter, that annual-average real GNP (through 1991) or real GDP (after 1991) growth falls into certain ranges. The most pessimistic range available from 1981 is -2% or worse. This provides an upper bound on perceived US disaster risk among survey participants beginning in 1981. Table D1 shows summary statistics for  $PRGDP < -2\%$ . With a mean forecast probability of only 2.6% for even a -2% drop, the SPF participants are on average quite optimistic relative to Barro and Ursua (2008). This is in sharp contrast to Robert Shiller's stock market survey results, where survey participants are an order of magnitude more pessimistic than direct empirical estimates support. In fact, in the SPF survey there is always at least one forecaster who gives disasters no chance at all in the coming quarter.

On average, the most pessimistic SPF forecaster assigns 11.1% probability to a -2% GDP drop, so there is significant dispersion in forecasts. Figure D1 shows that this is mostly attributable to a few periods — for example while the 2008 financial crisis is unfolding — in which there is a very high forecast probability of a GDP drop, even by the average forecaster. For most of the sample, the chance of a disaster is forecasted to be

near zero on average. Only the Q1 1983 recession and the Q1 2008 recession saw realized -2% annual average real GDP declines, so the low forecast probabilities are empirically justifiable - although it appears forecasters recognized these severe recessions after their onset. Recall that the prediction is for annual average over annual average declines, so disagreement may be about the depth and persistence of a downturn after its onset.

To summarize, Barro and Ursua (2008) offer empirical support for extreme disaster risk with sample average probability of around 3.5% annually. However SPF data suggests mean perceived risk of only 2.6%, even for mild disasters. The lower bound forecast — the optimistic forecast — is zero. The upper bound is around 11% (unconditionally) based on the SPF data.

## D.2 Calibration based on Barro (2009) and Barro and Jin (2011)

Given evidence of disagreement about extreme GDP disasters, we consider a calibration of our model to such disasters. Barro and Jin (2011) provide detailed justification that Pareto distribution truncated at -9.5% (e.g., capturing disasters worse than a 9.5% GDP loss) provides a good approximation to the left tail of GDP. The equivalent distribution of  $Z$  in our framework has density

$$\bar{f}(Z) = \frac{\gamma Z^{\gamma-1}}{\bar{Z}^\gamma - \underline{Z}^\gamma}, \quad 0 \leq \underline{Z} \leq Z \leq \bar{Z} \leq 1, \quad (\text{D1})$$

and  $n$ th moment

$$\mathbb{E}[Z^n] = \frac{\gamma}{\gamma + n} \frac{\bar{Z}^{\gamma+n} - \underline{Z}^{\gamma+n}}{\bar{Z}^\gamma - \underline{Z}^\gamma}, \quad (\text{D2})$$

with  $\bar{Z} = 0.905$  and  $\underline{Z} = 0$  except for the Reduce Severity experiment. Barro and Jin (2011) use historical mean arrival rate 3.83%, which we adopt as our true arrival rate  $\lambda_c$ . They estimate Pareto distribution parameter  $\gamma = 6.86$ , assume normally distributed GDP growth volatility  $\sigma = 2\%$ , and estimate relative risk aversion of 4.33 to match an unlevered equity premium of 5%. The remaining parameters are less important to de-

termination of the equity premium in their setting, so they are not formally estimated. Barro (2009) provides a calibrated example with similar GDP disasters in an endowment economy. We use his subjective discount parameter  $\beta = 5.2$ , and jointly choose  $\theta$  and  $\delta$  to match the 2% output growth rate in his endowment economy and the consumption/investment ratio from Pindyck and Wang (2013), taking  $A = 11.3$  from their paper as given. Barro (2009) assumes an elasticity of intertemporal substitution of 2; we diverge slightly and choose EIS of 1.5. Given the other parameters, a stationary equilibrium with optimists and pessimists is more likely to obtain with the lower EIS: see Figure 1 in Borovička (2016) for an illustration.

Based on our survey data, the optimist should perceive  $\lambda_a$  close to zero, but it is necessary that both our agents assign positive probability to disasters: otherwise we cannot define a change of measure between the two agents' beliefs. We set  $\lambda_a = 0.38\%$ , one tenth of the true probability  $\lambda_c$ . The pessimist's beliefs are more difficult to pin down, since we have survey data only for drops worse than -2%, not -9.5%. We choose  $\lambda_b = 7\%$ , which is consistent with our survey data, and which places the true measure at about the midpoint of the optimist and the pessimist. The second column of Table D2 summarizes the "Barro" model calibration without disagreement, and the third column gives parameter values adding disagreement to that economy.

Before proceeding to our results with disagreement, we note some characteristics of the Barro calibration without disagreement. In the model of Barro and Jin (2011) and in our model without disagreement, higher moments of GDP growth and stock returns are jointly governed by parameters  $\sigma$ ,  $\lambda$ ,  $\gamma$ , and bounds  $\bar{Z}$  and  $\underline{Z}$ . Since the previously cited papers provide detailed analysis of higher GDP growth moments we do not go into them here. We report selected summary statistics in the first column of Table D3, including higher moments of equity returns. Note the annualized unlevered equity return volatility that is a bit low (5%), and the extreme negative skewness (-806%) and kurtosis (10632%). These figures, which assume no disagreement, are not driven by

our production economy setting: this is simply the trade-off that higher GDP growth moments and higher equity moments cannot be matched simultaneously in this variety of model. Skewness and kurtosis are standardized by volatility in the usual way, so their magnitudes would attenuate if volatility were higher.

Adding disagreement to the Barro calibration, Figure D2 shows there is a stationary wealth distribution such that both agents survive, but the optimist has most of the wealth on average.<sup>19</sup> The third column of Table D3, labeled “Disagreement,” reports unconditional moments calculated based on this stationary distribution. Because the optimist has most of the wealth on average, the unconditional equity premium in our model with disagreement is only 1%. Even if we raise  $\lambda_c$  so that the pessimist’s probability of disasters coincides with the true one, the optimist will still have over half the wealth on average, and the equity premium remains below 5% despite disasters more frequent than the data supports. Essentially, the intuition from Borovička (2016), where an irrational optimist can survive or even dominate the economy given recursive preferences, carries over to our setting with disagreement about disasters.<sup>20</sup> This presents a challenge to the rare disasters explanation of the high equity premium: our survey evidence suggests that even professional forecasters are quite sanguine about disaster risk, and provided such optimists trade, their perceptions should have a large impact on average equity returns.

Finally, we show the implications of disagreement for WTP to reduce or eliminate disasters in the Barro setting. We repeat our two main experiments: Reduce Severity, and Eliminate Disasters, summarized in Table D4.<sup>21</sup> As in Section 4, we fit model parameters

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<sup>19</sup>We attribute the bi-modal distribution at 50 years to the rarity of disasters, since there will be many simulated paths for which no jumps occur within 50 years. The 50 year density is simply for illustration, and is not used in any calculations. We initialize  $x_0$  uniformly on  $(0, 1)$ , and use a normal kernel density estimator.

<sup>20</sup>In Borovička (2016), disagreement is about the growth rate, equivalent to our parameter  $\delta$ .

<sup>21</sup>Since this is a robustness exercise, we consider only our two main experiments, Reduce Severity and Eliminate Disasters. In principle, the other two remaining experiments could be also done for this alternative calibration. However, comparable parameter values are not obvious for experiments Controversial Good and Controversial Bad, so we omit them in this analysis.

without disagreement to reproduce the unconditional moments implied by our model with disagreement (last columns of Tables D2 and D3), and use the fitted model as a reference point for WTP without disagreement. We also calculate WTP for the Barro calibration without disagreement. All results for WTP are summarized in Table D5.

Overall the story is similar to the one for our baseline calibration in the paper, except that disagreement has a larger effect here. In the economies with agreement, WTP to reduce or eliminate disasters is either 35% or 43%, depending on whether the Barro calibration or the fitted model parameters are used.<sup>22</sup> With disagreement, compensated WTP  $\tau_{comp}$  is just 10% for Reduce Severity, and only 5.5% for Eliminate Disasters. We reiterate that it is the relative declines that are most interesting to us, e.g., the over three-fold reduction in WTP for Reduce Severity and the over six-fold reduction for Eliminate Disagreement. The drop in WTP is enormous, even if speculative opportunities are preserved, as in the Reduce Severity experiment. We conclude that the relative reductions in WTP reported in the main text are probably conservative.

## E Robustness to alternative preference parameters

In our baseline numerical analysis in Section 4, our results for WTP correspond to those in Proposition 3 in many respects, although the dynamic model is quite different from the two period model underpinning the proposition. However there is one major difference in the results from our calibrated dynamic model: the matched homogeneous economy has much higher WTP for Reduce Severity than the heterogeneous economy, even if we measure uncompensated WTP in the heterogeneous economy. In the two period model, which assumes log utility, Reduce Severity is valued equally with or without disagreement when measured by uncompensated WTP.

Experimentation suggests that the preference specification in the dynamic model is

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<sup>22</sup>Our WTP differs from that reported in Barro (2009) because we use the estimated disaster distribution and risk aversion parameters from Barro and Jin (2011), rather than the calibrated values from Barro (2009).

the most important factor driving this difference in results, and that the EIS is particularly important. This appendix provides supplemental evidence on how preferences affect the ordering of WTP, and the magnitude of WTP more generally.

We begin by examining sensitivity to risk aversion,  $1 - \alpha$ , with a focus on higher risk aversion that would be implied by alternative calibration criteria. Overall we find that WTP is not especially sensitive to risk aversion.

We then examine sensitivity to the EIS,  $\frac{1}{1-\rho}$ , which proves more important for WTP. The choice of  $EIS > 1$ ,  $EIS = 1$ , or  $EIS < 1$  is important in many economic models, as it determines whether agents increase investment or consumption in response to changes in the market opportunities, e.g., an increase in the interest rate.

## E.1 Robustness: risk-aversion and volatility

In our baseline calibration in Table 1, we choose a high value of  $\sigma$ , the Brownian volatility, in order to match the high stock return volatility in the data. This, coupled with disaster risk, allows us to match the equity premium with risk aversion around 3, specifically,  $1 - \alpha = 3.07$ . An alternative approach might choose a lower value of  $\sigma$ , to more closely approximate consumption volatility in the data, but this would require a higher risk aversion to match the equity premium. While our estimates of WTP should not be directly affected by  $\sigma$ , they could be sensitive to  $\alpha$ . What is the impact on WTP if we take this alternative calibration approach?

To answer this question, we consider two alternative calibrations, which incrementally reduce  $\sigma$ , increase risk-aversion (reduce  $\alpha$ ), and increase  $\lambda_c$ . The first two items are aimed at keeping the equity premium about the same, while shifting its source in terms of parameters. This captures the essence of the calibration tradeoff, i.e., that the equity premium can be matched either through high volatility or high risk aversion. The last item tries to keep about the same stationary wealth distribution as in the baseline calibration, which is also relevant for approximately matching the unconditional equity

premium.<sup>23</sup> We leave other parameters the same as our baseline calibration, in Table 1.

Our baseline calibration has  $1 - \alpha = 3.07$ ,  $\sigma = 0.1355$ , and  $\lambda_c = 0.70$ , which we can call relatively low risk aversion. Our intermediate risk aversion case has  $1 - \alpha = 5$ ,  $\sigma = 0.1$ , and  $\lambda_c = 0.785$ , with unconditional moments in Table E1, and Pareto weight and wealth distributions in Figure E1. Our high risk aversion case has  $1 - \alpha = 7$ ,  $\sigma = 0.07$ , and  $\lambda_c = 0.91$ , with unconditional moments in Table E2, and Pareto weight and wealth distributions in Figure E2.

Table E3 includes WTP for Reduce Severity and Eliminate Disasters for each of the three parameter sets: low (baseline), intermediate, and high risk aversion. For purposes of comparing WTP, matched homogeneous economies are fitted on a pair-wise basis for each case.

In all three cases, the ordering of WTP remains the same: WTP is highest in the matched homogeneous economy, with disagreement it is higher for Reduce Severity than for Eliminate Disasters, and for each experiment,  $\tau_{comp} > \tau_{min}$ . The maximum magnitude of the reduction in WTP, which comes from comparing  $\tau$  without disagreement to  $\tau_{min}$  for Eliminate Disasters, is similar in all three cases: around 20% in absolute terms. Overall, WTP is higher with high risk aversion, which is to be expected. There are a number of changes in how measures of WTP relate to each other: for example, in the high risk aversion case, the difference in WTP between Reduce Severity and Eliminate Disasters is not so large as in the low risk aversion calibration, perhaps because purely speculative trade is less valued with higher risk aversion.

In broad strokes, WTP is affected by the same mechanisms with higher risk aversion, and magnitudes are not especially sensitive to the choice of risk aversion.

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<sup>23</sup>See related discussion in Appendix C.2, and in Borovička (2016), in which preference parameters are related to survival results and accuracy of beliefs.

## E.2 Robustness: elasticity of intertemporal substitution (EIS)

EIS is known to be an important parameter in dynamic models generally, and when assessing WTP for reduction in aggregate risk specifically; see, e.g., Bansal, Kiku and Yaron (2010). Along some dimensions, model response to a given stimulus may change in sign around  $EIS = 1$ , where income and substitution effects offset. In Table 5 of their paper, Pindyck and Wang (2013) present robustness statistics for the effect of EIS on WTP for disaster reduction, in a model equivalent to ours, but without disagreement. Their WTP results are not especially sensitive to EIS, and we follow them in using  $EIS = 1.5$  in our baseline calibration. However the effects of EIS on WTP could change in a model with agents who disagree.

To understand how EIS affects WTP with disagreement, we consider two alternative calibrations, which incrementally reduce  $\rho$  and EIS ( $\frac{1}{1-\rho}$ ). We also adjust  $\lambda_c$  slightly to achieve a stationary distribution with the modified parameters, similar to our approach in Section E.1. We leave other parameters the same as our baseline calibration, in Table 1.

The relatively low EIS case has  $\rho = -1/3$  ( $EIS = 0.75$ ) and  $\lambda_c = 0.65$ , with unconditional moments in Table E4, and Pareto weight and wealth distributions in Figure E3. The intermediate EIS case has  $\rho = -0.05$  ( $EIS = 0.95$ ) and  $\lambda_c = 0.65$ , with unconditional moments in Table E5, and Pareto weight and wealth distributions in Figure E4. Our baseline calibration has relatively high  $\rho = 1/3$  ( $EIS = 1.5$ ) and  $\lambda_c = 0.70$ . Importantly, the low and high scenarios are on either side of  $EIS = 1$ .

Table E6 reports WTP for each value of EIS. Overall WTP is increasing in EIS, consistent with Pindyck and Wang (2013). Per Corollary 1, for a given policy we always have  $\tau_{uncomp} > \tau_{comp} > \tau_{min}$ . Furthermore the magnitude of the difference between  $\tau_{uncomp}$  and  $\tau_{comp}$  is consistently quite small for all EIS, whereas the difference between  $\tau_{comp}$  and  $\tau_{min}$  is larger but also of consistent magnitude for all EIS. In the economy with disagreement, Reduce Severity has higher WTP than Eliminate Disasters, regardless of how WTP is measured. The spread between WTP for the two policies remains similar, falling

slightly as EIS is reduced from our baseline calibration.

The most interesting effect of lowering EIS is in how WTP in the heterogeneous economy relates to WTP in the homogeneous economy. Abbreviating Reduce Severity as RS, recall that in our two period model with log utility, we show  $[\tau|RS] = [\tau_{uncomp}|RS]$ : the matched homogeneous economy has the same WTP for RS as the heterogeneous economy under the uncompensated WTP measure. Log utility implies  $EIS = 1$ . In Table E6, our dynamic model has  $[\tau|RS] > [\tau_{uncomp}|RS]$  for  $EIS = 1.5$ , but  $[\tau|RS] < [\tau_{uncomp}|RS]$  by a small margin when  $EIS = 0.75$ . For  $EIS \approx 1$ , the dynamic model implies  $[\tau|RS] > [\tau_{uncomp}|RS]$ , but also by a small margin. It seems that EIS is important for how WTP in the heterogeneous economy relates to WTP in the homogeneous economy, particularly when issues of Pareto improvement and loss of speculative opportunities have been stripped away.

A number of factors recommend  $EIS > 1$ . For example, Baker, Hollifield and Osambela (2016) chooses  $EIS > 1$  to match empirical investment dynamics: when there is a positive growth shock, investment as a fraction of output tends to increase. This occurs in the model only when the optimist prefers a higher investment-capital ratio  $i$  to the pessimist, which is the case for  $EIS > 1$ . High EIS is also important in the long run risk framework of Bansal and Yaron (2004). Table E6 shows that EIS is also an important consideration in our analysis of WTP.

## F Policy effects on growth via investment

In our production setting, we incorporate, and can quantify, the endogenous impact on growth of a disaster reduction policy. Recall that the expected growth of capital and output is

$$i_t - \frac{1}{2}\theta i_t^2 - [\delta + \lambda_j(1 - \mathbb{E}[Z])],$$

where  $j$  indexes beliefs. Let us focus on the econometrician's measure, with  $j = c$ , for the purpose of computing illustrative statistics.

Disaster-reducing policies affect expected growth through two channels. The first channel is exogenous: the policies reduce  $\lambda_c(1 - \mathbb{E}[Z])$ , whether by reducing  $\lambda_c$  or increasing  $\mathbb{E}[Z]$ . This channel would be present in an endowment economy also. The second channel is endogenous: the equilibrium investment-capital ratio,  $i_t$ , responds to the reduction in disaster risk. In our setting with  $EIS > 1$ ,  $i_t$  increases due to the policy, further increasing expected output growth by the amount of change in  $i_t - \frac{1}{2}\theta i_t^2$ . This channel would be absent in an endowment economy.

Table F1 illustrates the magnitude of each channel's effect. The relative increase in  $i_t$  due to policy adoption is about 22% for Reduce Severity or 18% for Eliminate Disasters.<sup>24</sup> Expected output growth increases an additional  $\frac{1}{3}\%$  or more from the endogenous investment response. Reducing risk has a significant impact on investment in our production economy.

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<sup>24</sup>The increase is slightly larger for Reduce Severity because perceived speculative gains increase investment relative to the case without disagreement, as in Eliminate Disasters. See Baker, Hollifield and Osambela (2016) for discussion of the mechanism.

	Parameter	Disagreement	No Disagreement
Subjective discount rate (%)	$\beta$	4.98	4.73
Risk aversion	$1 - \alpha$	3.07	2.85
Elasticity of intertemporal substitution	$1/(1 - \rho)$	1.50	1.50
Volatility of output growth (%)	$\sigma$	13.55	13.50
Output-capital ratio (%)	$A$	11.30	11.30
Adjustment cost	$\theta$	12.03	11.98
Disaster distribution	$\gamma$	23.17	23.16
Depreciation drift (%)	$\delta$	-2.32	-2.56
Mean arrival rate of jumps (a)	$\lambda_a$	0.44	0.76
Mean arrival rate of jumps (b)	$\lambda_b$	0.79	0.76
Mean arrival rate of jumps (c)	$\lambda_c$	0.70	0.76

**Table 1: Parameter values.** The table reports the baseline parameter values used in our numerical examples. Agents a and b agree on all parameter values except the mean arrival rate of jumps  $\lambda$ .

	Data	Disagreement	No Disagreement
Equity premium	6.60	6.11	6.11
Stock return volatility	14.53	14.51	14.51
Stock return skewness	-11.56	-11.99	-11.99
Stock return excess kurtosis	13.74	14.28	14.28
Interest rate	0.80	0.95	0.95
Output-capital ratio	11.30	11.30	11.30
Investment-capital ratio	2.94	3.15	3.15
Output growth rate	2.00	1.97	1.97
Optimist growth forecast	3.03	3.03	1.97
Pessimist growth forecast	1.62	1.62	1.97
Growth forecast dispersion	1.41	1.41	0.00

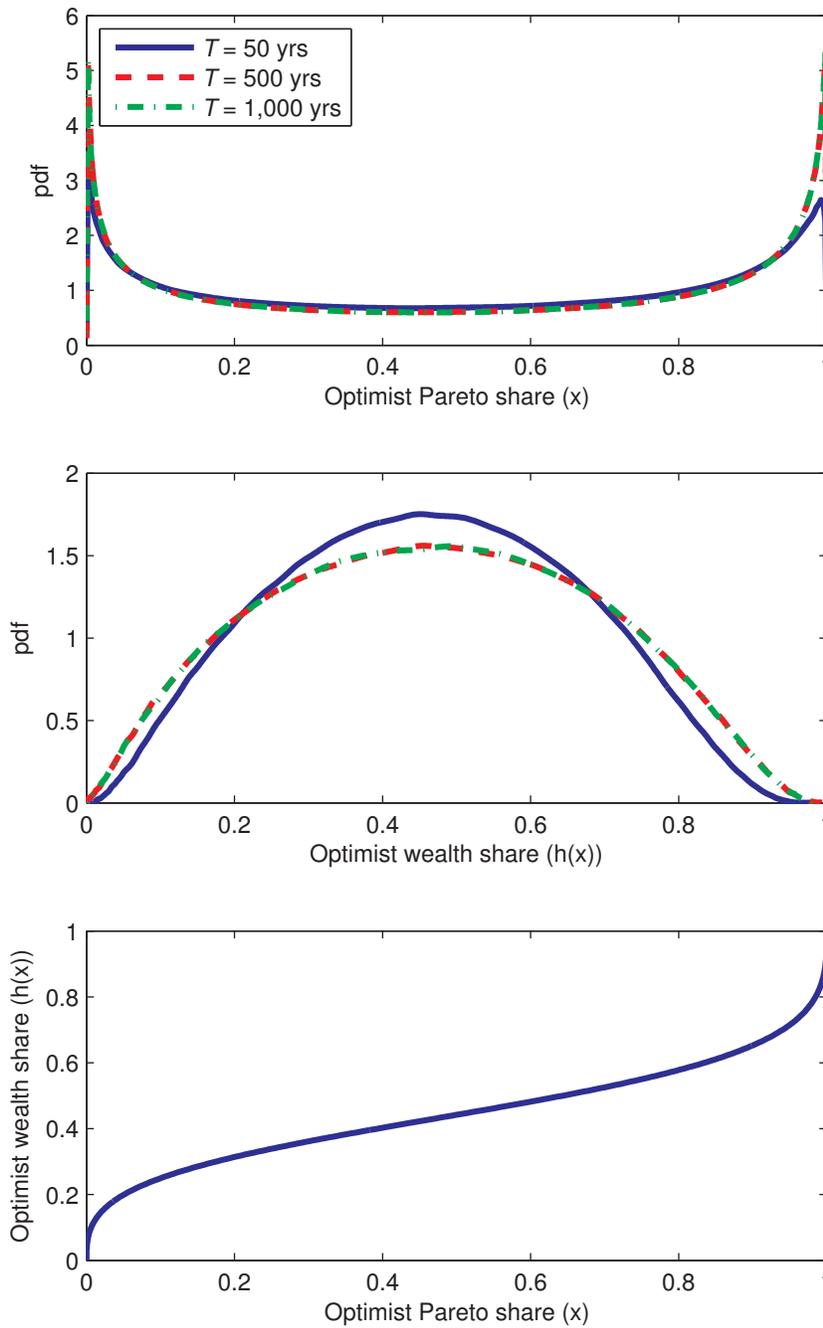
**Table 2: Unconditional moments.** The table reports unconditional moments from the data, the model with disagreement, and the reference model without disagreement. All values are percent.

Experiment		$\lambda_a$	$\lambda_b$	Z
1: Reduce Severity	Before	0.44	0.79	$\gamma = 23.2$
	After	0.44	0.79	$\underline{Z} = 0.999$
2: Eliminate Disasters	Before	0.44	0.79	$\gamma = 23.2$
	After	0	0	N.A.
3: Controversial Good	Before	0.444	0.79	$\gamma = 23.2$
	After	0.01	0.2	$\gamma = 23.2$
4: Controversial Bad	Before	0.1	0.1	Z=0.99
	After	0.11	0.4	Z=0.99

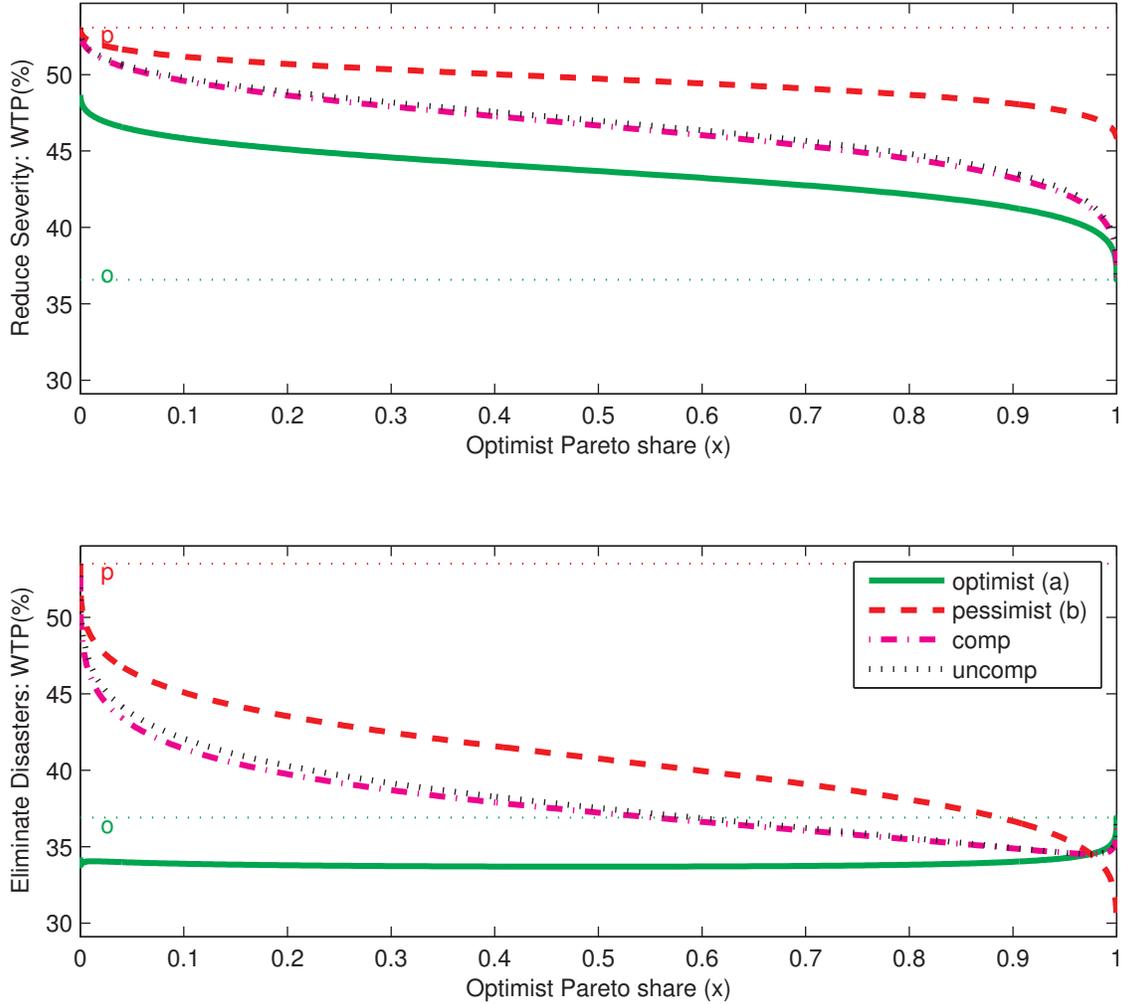
**Table 3:** Summary of experimental parameter changes. All other parameter values correspond to Table 1.

	1: Reduce Severity	2: Eliminate Dis.	3: Controversial Good
$\tau$ : no disagreement	55.29	55.74	55.18/49.94
$\mathbb{E}[\tau_a]$	43.35	33.98	50.46
$\mathbb{E}[\tau_b]$	49.50	40.54	51.78
$\mathbb{E}[\tau_{min}]$	43.35	33.82	47.85
$\mathbb{E}[\tau_{uncomp}]$	46.36	38.38	49.37
$\mathbb{E}[\tau_{comp}]$	46.11	38.07	49.04
$\mathbb{E}[transfer]$	2.10	6.88	2.64

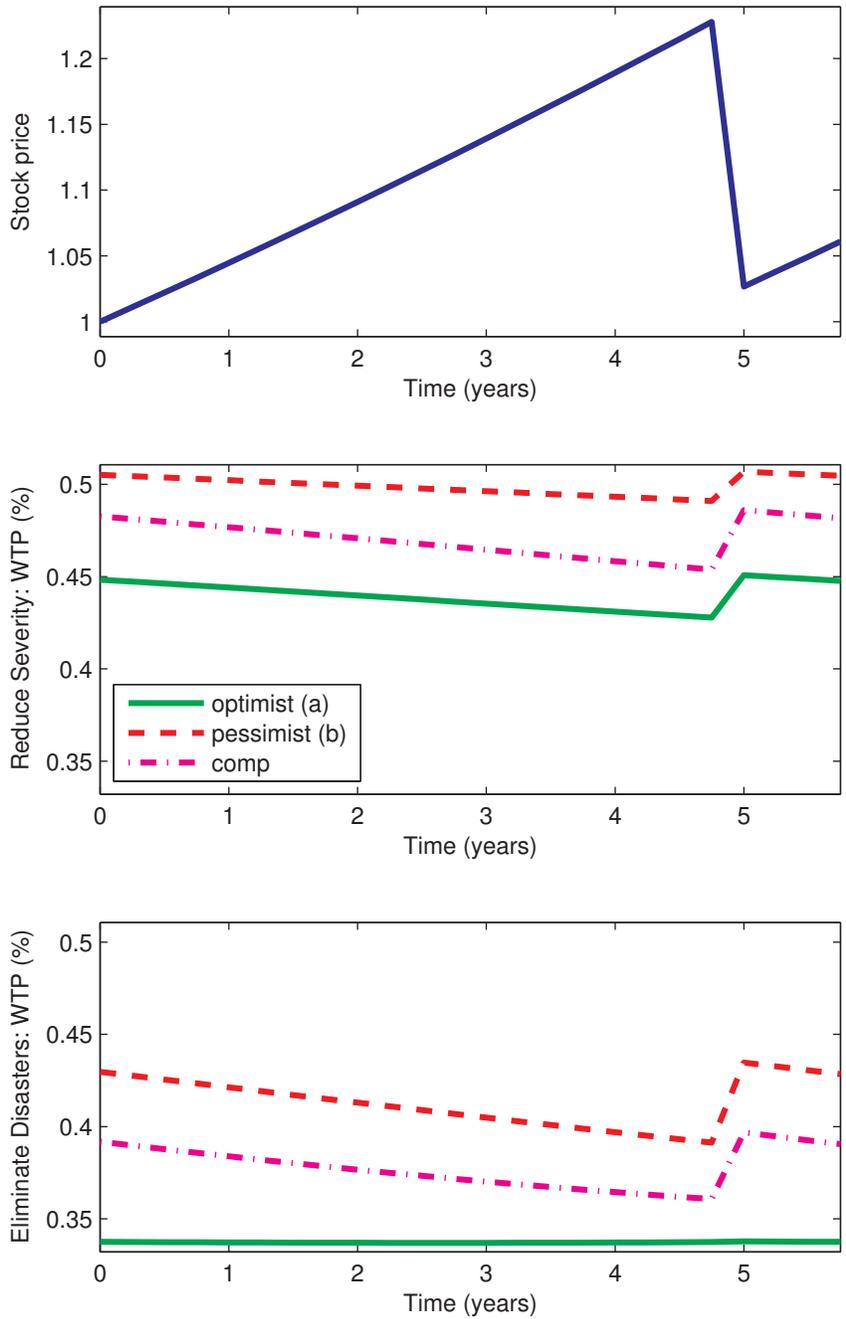
**Table 4: Unconditional WTP.** The table reports unconditional expected WTP for the first three experiments, for each agent individually, and for each of our three forms of aggregation. The expected transfer from optimist (a) to the pessimist (b), associated with  $\tau_{comp}$ , is also shown. The first row shows constant WTP in the equivalent economy without disagreement. Since Controversial Good involves disagreement regarding the policy's effectiveness, WTP without disagreement is reported under both the optimist's perception ( $\hat{\lambda}_a = 0.01$ ) and the pessimist's perception of the policy ( $\hat{\lambda}_b = 0.2$ ), respectively. All values are percent.



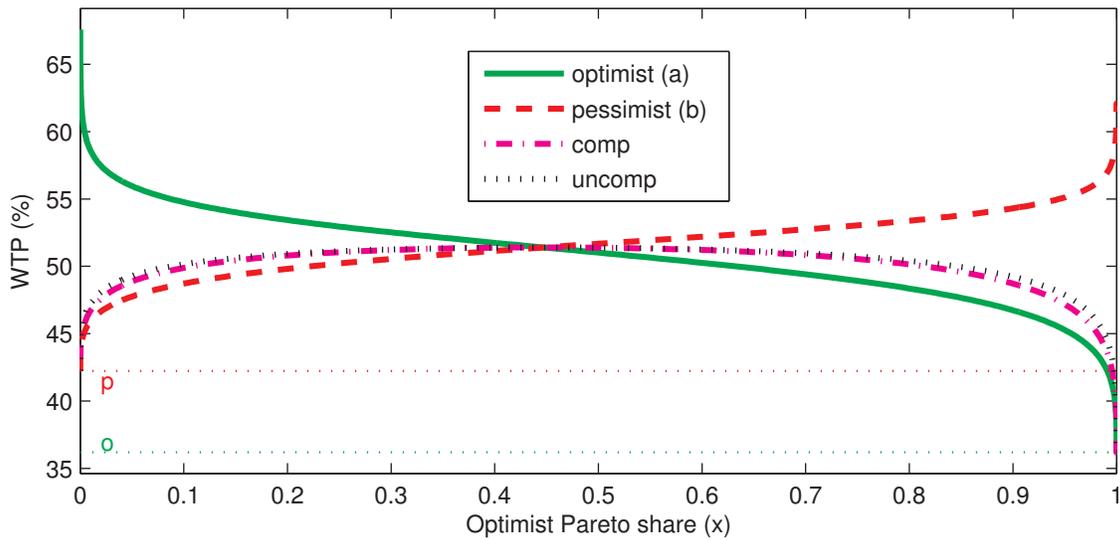
**Figure 1: State variable distribution.** The figure shows that the main state variable, the optimist's Pareto share  $x$ , has a non-degenerate stationary distribution. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with a starting value  $x_0 = 0.5$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. Looking at the pdf of the optimist's wealth share  $h(x)$ , shown in the middle panel, illustrates the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail. The bottom panel shows the relation between  $x$  and  $h(x)$ , effectively a rescaling.



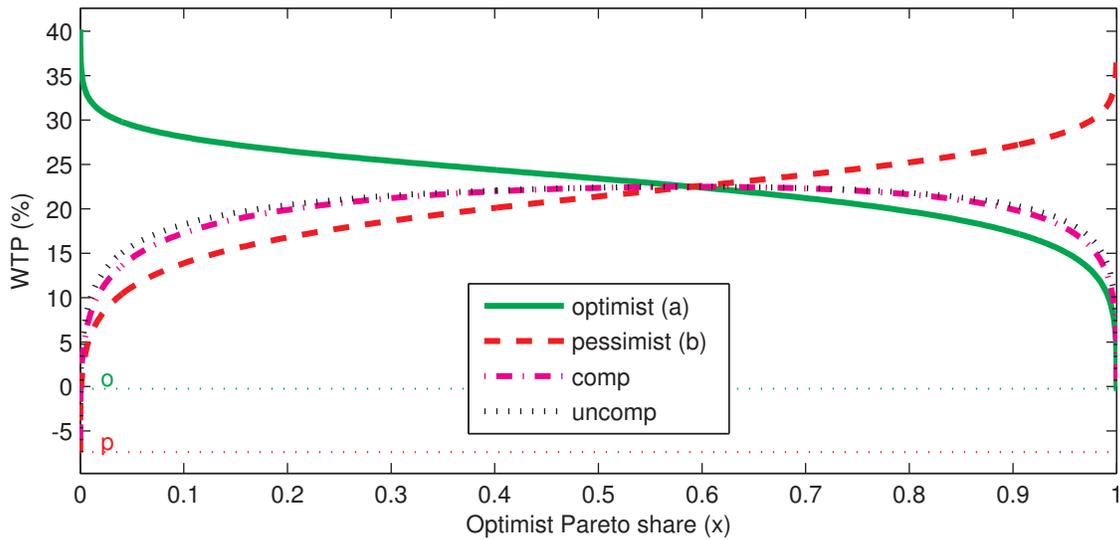
**Figure 2: WTP for Reduce Severity vs. Eliminate Disasters.** The figure shows willingness to pay for a proposal ensuring that disasters destroy less than 0.1% of the capital stock (Reduce Severity), or for a policy that eliminates disasters entirely (Eliminate Disasters). Parameters prior to the policy change are given in Table 1. Agents disagree regarding the probability of a disaster occurring at all, but agree on the distribution of disasters given one occurs. The green solid line is  $\tau_a$ , the red dashed line is  $\tau_b$ , the magenta dot-dash line is  $\tau_{comp}$ , and the black dotted line is  $\tau_{uncomp}$ . Dotted horizontal lines also indicate homogeneous economy WTP for each agent.



**Figure 3: Example path for Reduce Severity vs. Eliminate Disasters.** Willingness to pay will vary over time and with economic outcomes. The figure shows a hypothetical 6-year path of the economy, where a very rare sequence of events - four consecutive disasters of average size - occurs at the start of the 5th year. The magnitude of the disaster is illustrated by the fall in stock price at top. The middle and bottom panels show the paths of WTP for Reduce Severity and Eliminate Disasters, respectively. The green solid line is  $\tau_a$ , the red dashed line is  $\tau_b$ , and the magenta dot-dash line is  $\tau_{comp}$ .



**Figure 4: Controversial Good.** The figure shows willingness to pay for a proposal that will reduce the likelihood of disasters. Parameters prior to the policy change are given in Table 1. If the policy is implemented then the optimistic agent believes  $\lambda_a = 0.01$  and the pessimistic agent believes  $\lambda_b = 0.2$ . The green solid line is  $\tau_a$ , the red dashed line is  $\tau_b$ , the magenta dot-dash line is  $\tau_{comp}$ , and the black dotted line is  $\tau_{uncomp}$ . Dotted horizontal lines also indicate homogeneous economy WTP for each agent.



**Figure 5: Controversial Bad.** The figure shows willingness to pay for a proposal that will increase the likelihood of disasters. Parameters prior to the policy change are given in Table 1, but agents initially agree on the frequency of minor disasters, as summarized in Table 3. If the policy is implemented, then both agents agree the frequency of disasters will increase, but they disagree as to how much. The green solid line is  $\tau_a$ , the red dashed line is  $\tau_b$ , the magenta dot-dash line is  $\tau_{comp}$ , and the black dotted line is  $\tau_{uncomp}$ . Dotted horizontal lines also indicate homogeneous economy WTP for each agent.

	Data	Pessimistic (agent b)	Optimistic (agent a)
Equity premium	6.60	6.67	6.22
Stock return volatility	14.53	14.59	14.15
Stock return skewness	-11.56	-12.20	-7.57
Stock return excess kurtosis	13.74	14.43	9.24
Interest rate	0.80	0.35	1.83
Investment-capital ratio	2.94	2.82	3.20
Output growth rate	2.00	1.41	3.06

**Table C1: Equilibrium outcomes under agreement.** The table reports the equilibrium outcomes in homogeneous beliefs economies in which all investors have either pessimistic or optimistic beliefs. Expectations are taken under the beliefs of the representative investor for each case. Parameter values are under Disagreement in Table 1. All values are percent.

	Data	$\lambda_c = 0.6148$	$\lambda_c = 0.7$	$\lambda_c = 0.7852$
Equity premium	6.60	5.65	6.11	6.57
Stock return volatility	14.53	14.34	14.50	14.61
Stock return skewness	-11.56	-10.26	-11.93	-13.15
Stock return excess kurtosis	13.74	12.35	14.18	15.50
Interest rate	0.80	1.32	0.94	0.64
Investment-capital ratio	2.94	3.21	3.14	3.02
Output growth rate	2.00	2.02	1.97	1.89

**Table C2: Unconditional moments: varying  $\lambda_c$ .** The table reports unconditional moments from the data (see Pindyck and Wang (2013)), and from the baseline model calibration with varying arrival rate under the true measure  $\lambda_c$ . All other model parameters are given in the Disagreement column of Table 1. All values are percent.

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Unconditional mean	
Number of respondents	34.1
Min	0
Max	11.1
Mean	2.6
Median	2.3
25th percentile	1.3
75th percentile	3.0

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**Table D1: Survey of Professional Forecasters: PRGDP < -2%.** Summary statistics, Q3 1981 through Q1 2017, of forecast probability of annual average over annual average real GDP growth less than -2%. Statistics combine earlier GNP estimates with later (after 1991) GDP estimates. All values are in percent, except number of respondents.

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	Parameter	No Dis: Barro	Disagreement	No Dis: Fitted
Subjective discount rate (%)	$\beta$	5.20	5.20	4.93
Risk aversion	$1 - \alpha$	4.33	4.33	1.28
Elasticity intertemp. sub.	$1/(1 - \rho)$	1.50	1.50	1.50
Vol. of output growth (%)	$\sigma$	2.00	2.00	1.94
Output-capital ratio (%)	$A$	11.30	11.30	11.30
Adjustment cost	$\theta$	13.88	13.88	13.85
Disaster distribution	$\gamma$	6.86	6.86	6.90
Depreciation drift (%)	$\delta$	-0.46	-0.46	-1.44
Arrival rate (a, %)	$\lambda_a$	3.83	0.38	8.53
Arrival rate (b, %)	$\lambda_b$	3.83	7.00	8.53
Arrival rate (c, %)	$\lambda_c$	3.83	3.83	8.53

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**Table D2: Parameter values.** The table reports the baseline parameter values used in our numerical examples for the “Barro” type of calibration. Agents a and b agree on all parameter values except the mean arrival rate of jumps  $\lambda$ .

	Data	No Dis: Barro	Disagreement	No Dis: Fitted
Equity premium	6.60	4.99	1.02	1.02
Stock return volatility	14.53	4.98	6.19	6.19
Stock return skewness	-11.56	-806.61	-649.63	-649.63
Stock return excess kurtosis	13.74	10632.01	6058.53	6058.53
Interest rate	0.80	1.96	5.52	5.52
Output-capital ratio	11.30	11.30	11.30	11.30
Investment-capital ratio	2.94	2.94	3.30	3.30
Output growth rate	2.00	1.99	2.20	2.20
Optimist growth forecast	3.03	1.99	2.92	2.20
Pessimist growth forecast	1.62	1.99	1.53	2.20
Growth forecast dispersion	1.41	0.00	1.39	0.00

**Table D3: Unconditional moments.** The table reports unconditional moments from the data, the model with disagreement, and the reference models without disagreement, using parameter values from Table D2. All values are percent.

Experiment		$\lambda_a$	$\lambda_b$	$Z$
1: Reduce Severity	Before	0.38%	7%	$\gamma = 6.86, \underline{Z} = 0, \bar{Z} = 0.905$
	After	0.38%	7%	$\gamma = 6.86, \underline{Z} = 0.999, \bar{Z} = 1$
2: Eliminate Disasters	Before	0.38%	7%	$\gamma = 6.86, \underline{Z} = 0, \bar{Z} = 0.905$
	After	0	0	N.A.

**Table D4:** Summary of experimental parameter changes. All other parameter values correspond to Table D2.

	1: Reduce Severity	2: Eliminate Dis.
$\tau$ : agreement, Barro	34.92	34.95
$\tau$ : agreement, fitted	43.31	43.38
$\mathbb{E}[\tau_a]$	8.31	4.21
$\mathbb{E}[\tau_b]$	17.80	8.10
$\mathbb{E}[\tau_{min}]$	8.31	4.00
$\mathbb{E}[\tau_{uncomp}]$	10.50	5.71
$\mathbb{E}[\tau_{comp}]$	10.09	5.51
$\mathbb{E}[transfer]$	7.22	4.06

**Table D5: Unconditional WTP.** The table reproduces WTP for the Reduce Severity and Eliminate Disasters experiments, but using the Barro calibration. The first row shows constant WTP in the equivalent economy without disagreement using Barro’s parameters, the second shows homogeneous economy results with fitted parameters. Parameter values are in Table D2. All values are percent.

	Data	Disagreement	No Disagreement
Equity premium (%)	6.600	5.757	5.757
Stock return volatility (%)	14.526	11.395	11.395
Stock return skewness	-11.560	-26.479	-26.479
Stock return excess kurtosis	13.740	39.475	39.475
Interest rate (%)	0.800	0.961	0.961
Output-capital ratio (%)	11.300	11.300	11.300
Investment-capital ratio (%)	2.940	3.126	3.126
Output growth rate (%)	2.000	1.610	1.610
Optimist growth forecast (%)	3.030	3.019	1.610
Pessimist growth forecast (%)	1.620	1.610	1.610
Growth forecast dispersion (%)	1.410	1.410	0.000

**Table E1: Unconditional moments:**  $1 - \alpha = 5$ ,  $\sigma = 0.1$ ,  $\lambda_c = 0.785$ . The table reports unconditional moments from the data, the model with disagreement, and the reference model without disagreement. All values are percent.

	Data	Disagreement	No Disagreement
Equity premium (%)	6.600	4.672	4.672
Stock return volatility (%)	14.526	9.151	9.151
Stock return skewness	-11.560	-59.175	-59.175
Stock return excess kurtosis	13.740	111.160	111.160
Interest rate (%)	0.800	1.467	1.467
Output-capital ratio (%)	11.300	11.300	11.300
Investment-capital ratio (%)	2.940	3.202	3.202
Output growth rate (%)	2.000	1.142	1.142
Optimist growth forecast (%)	3.030	3.065	1.142
Pessimist growth forecast (%)	1.620	1.657	1.142
Growth forecast dispersion (%)	1.410	1.410	0.000

**Table E2: Unconditional moments:**  $1 - \alpha = 7$ ,  $\sigma = 0.07$ ,  $\lambda_c = 0.91$ . The table reports unconditional moments from the data, the model with disagreement, and the reference model without disagreement. All values are percent.

	1: Reduce Severity	2: Eliminate Dis.	
$\tau$ : no disagreement	55.29	55.74	
$\mathbb{E}[\tau_a]$	43.35	33.98	
$\mathbb{E}[\tau_b]$	49.50	40.54	
$\mathbb{E}[\tau_{min}]$	43.35	33.82	(A)
$\mathbb{E}[\tau_{uncomp}]$	46.36	38.38	
$\mathbb{E}[\tau_{comp}]$	46.11	38.07	
$\mathbb{E}[transfer]$	2.10	6.88	
$\tau$ : no disagreement (%)	62.11	62.56	
$\mathbb{E}[\tau_a]$ (%)	47.09	41.83	
$\mathbb{E}[\tau_b]$ (%)	50.99	45.44	
$\mathbb{E}[\tau_{min}]$ (%)	47.09	41.83	(B)
$\mathbb{E}[\tau_{uncomp}]$ (%)	48.93	43.79	
$\mathbb{E}[\tau_{comp}]$ (%)	48.76	43.64	
$\mathbb{E}[transfer]$ (%)	8.85	7.47	
$\tau$ : no disagreement (%)	70.40	70.84	
$\mathbb{E}[\tau_a]$ (%)	52.25	48.62	
$\mathbb{E}[\tau_b]$ (%)	55.34	51.35	
$\mathbb{E}[\tau_{min}]$ (%)	52.25	48.62	(C)
$\mathbb{E}[\tau_{uncomp}]$ (%)	53.58	49.99	
$\mathbb{E}[\tau_{comp}]$ (%)	53.44	49.87	
$\mathbb{E}[transfer]$ (%)	9.75	8.85	

**Table E3: Unconditional WTP: modified risk aversion.** The table reports unconditional expected WTP for the first two experiments, with parameters modified from our baseline calibration. Panel (A) matches the baseline calibration. Panel (B) is an intermediate risk aversion case with  $1 - \alpha = 5$ ,  $\sigma = 0.1$ , and  $\lambda_c = 0.785$ . Panel (C) is a high risk aversion case with  $1 - \alpha = 7$ ,  $\sigma = 0.07$ , and  $\lambda_c = 0.91$ . WTP is calculated for each agent individually, and for each of our three forms of aggregation. The expected transfer from optimist to the pessimist, associated with  $\tau_{comp}$ , is also shown. The first row shows constant WTP in the equivalent economy without disagreement, which is fitted to match unconditional moments of each calibration on a pair-wise basis.

	Data	Disagreement	No Disagreement
Equity premium (%)	6.600	6.361	6.361
Stock return volatility (%)	14.526	14.306	14.306
Stock return skewness	-11.560	-9.882	-9.882
Stock return excess kurtosis	13.740	11.857	11.857
Interest rate (%)	0.800	0.742	0.742
Output-capital ratio (%)	11.300	11.300	11.300
Investment-capital ratio (%)	2.940	3.284	3.284
Output growth rate (%)	2.000	2.265	2.265
Optimist growth forecast (%)	3.030	3.115	2.265
Pessimist growth forecast (%)	1.620	1.706	2.265
Growth forecast dispersion (%)	1.410	1.410	0.000

**Table E4: Unconditional moments:**  $\frac{1}{1-\rho} = 0.75$ ,  $\lambda_c = 0.65$ . The table reports unconditional moments from the data, the model with disagreement, and the reference model without disagreement. All values are percent.

	Data	Disagreement	No Disagreement
Equity premium (%)	6.600	6.205	6.205
Stock return volatility (%)	14.526	14.347	14.347
Stock return skewness	-11.560	-10.342	-10.342
Stock return excess kurtosis	13.740	12.435	12.435
Interest rate (%)	0.800	0.982	0.982
Output-capital ratio (%)	11.300	11.300	11.300
Investment-capital ratio (%)	2.940	3.208	3.208
Output growth rate (%)	2.000	2.220	2.220
Optimist growth forecast (%)	3.030	3.070	2.220
Pessimist growth forecast (%)	1.620	1.661	2.220
Growth forecast dispersion (%)	1.410	1.410	0.000

**Table E5: Unconditional moments:**  $\frac{1}{1-\rho} = 0.95$ ,  $\lambda_c = 0.65$ . The table reports unconditional moments from the data, the model with disagreement, and the reference model without disagreement. All values are percent.

	1: Reduce Severity	2: Eliminate Dis.
$\tau$ : no disagreement (%)	41.82	42.13
$\mathbb{E}[\tau_a]$ (%)	38.12	30.72
$\mathbb{E}[\tau_b]$ (%)	45.72	39.62
$\mathbb{E}[\tau_{min}]$ (%)	38.12	30.28 (A)
$\mathbb{E}[\tau_{uncomp}]$ (%)	42.74	37.74
$\mathbb{E}[\tau_{comp}]$ (%)	42.45	37.30
$\mathbb{E}[transfer]$ (%)	7.41	7.31
$\tau$ : no disagreement (%)	44.40	44.75
$\mathbb{E}[\tau_a]$ (%)	38.79	31.59
$\mathbb{E}[\tau_b]$ (%)	45.79	37.79
$\mathbb{E}[\tau_{min}]$ (%)	38.79	31.05 (B)
$\mathbb{E}[\tau_{uncomp}]$ (%)	42.19	36.09
$\mathbb{E}[\tau_{comp}]$ (%)	41.91	35.75
$\mathbb{E}[transfer]$ (%)	7.67	6.27
$\tau$ : no disagreement	55.29	55.74
$\mathbb{E}[\tau_a]$	43.35	33.98
$\mathbb{E}[\tau_b]$	49.50	40.54
$\mathbb{E}[\tau_{min}]$	43.35	33.82 (C)
$\mathbb{E}[\tau_{uncomp}]$	46.36	38.38
$\mathbb{E}[\tau_{comp}]$	46.11	38.07
$\mathbb{E}[transfer]$	2.10	6.88

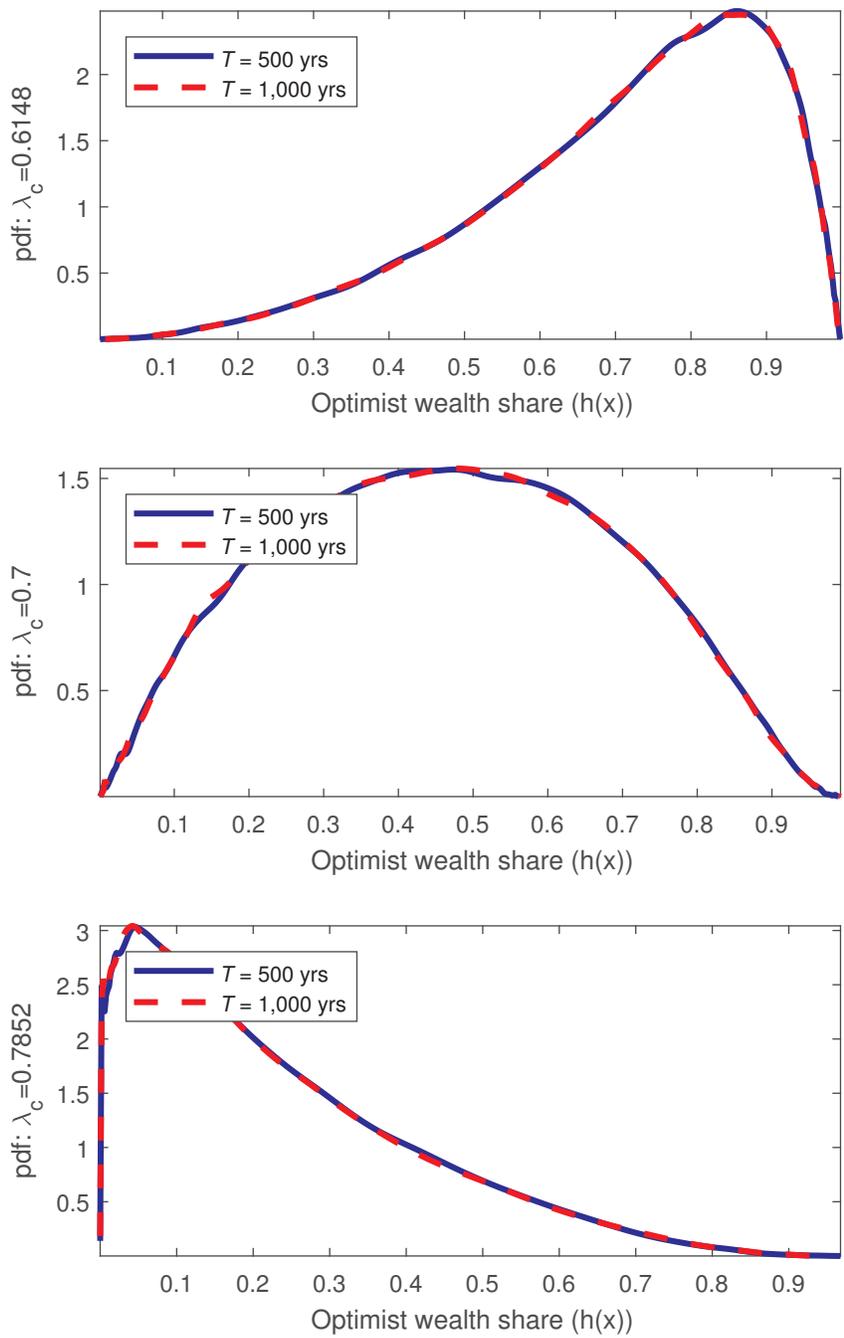
**Table E6: Unconditional WTP: modified EIS.** The table reports unconditional expected WTP for the first two experiments, with parameters modified from our baseline calibration. Panel (A) is a low elasticity of intertemporal substitution (EIS) case, with  $\frac{1}{1-\rho} = 0.75$  and  $\lambda_c = 0.65$ . Panel (B) is an intermediate EIS case, with  $\frac{1}{1-\rho} = 0.95$  and  $\lambda_c = 0.65$ . Panel (C) matches the baseline calibration. WTP is calculated for each agent individually, and for each of our three forms of aggregation. The expected transfer from optimist to the pessimist, associated with  $\tau_{comp}$ , is also shown. The first row shows constant WTP in the equivalent economy without disagreement, which is fitted to match unconditional moments of each calibration on a pair-wise basis.

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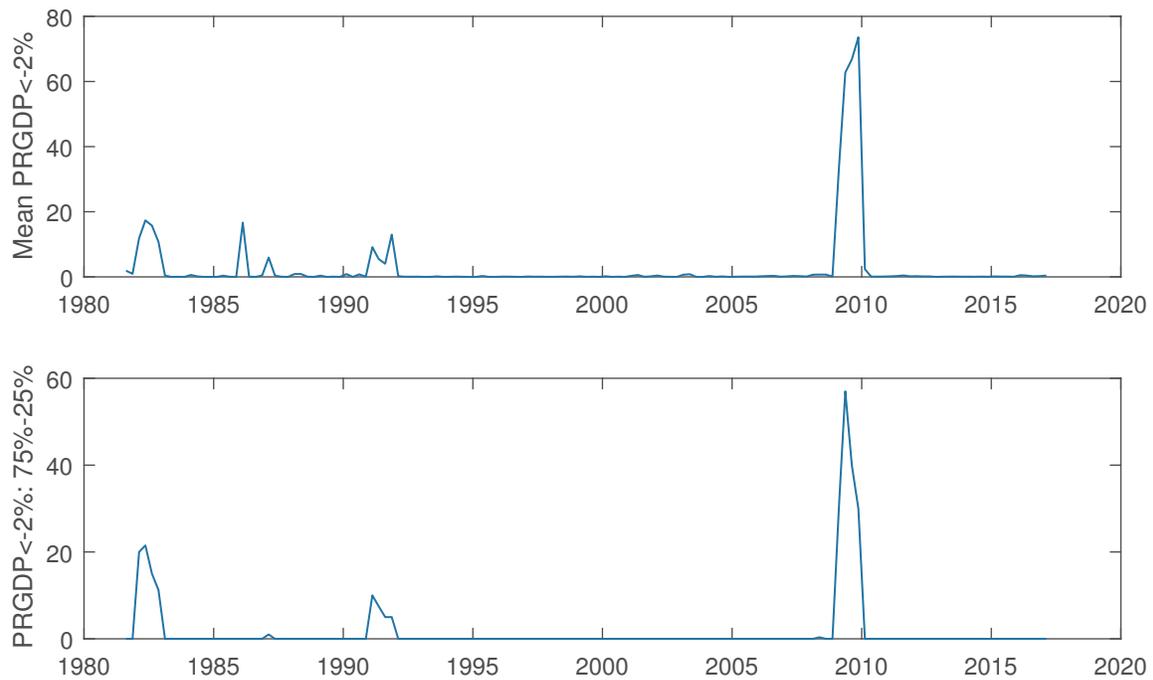
	Baseline	Reduce Severity	Eliminate Dis.
Investment-capital ratio, $i$ (%)	3.146	3.867	3.725
Expected output growth (%)	1.974	5.252	5.211
Total growth increase due to policy (%)	0.000	3.278	3.237
Growth due to policy via $i$ (%)	0.000	0.417	0.340

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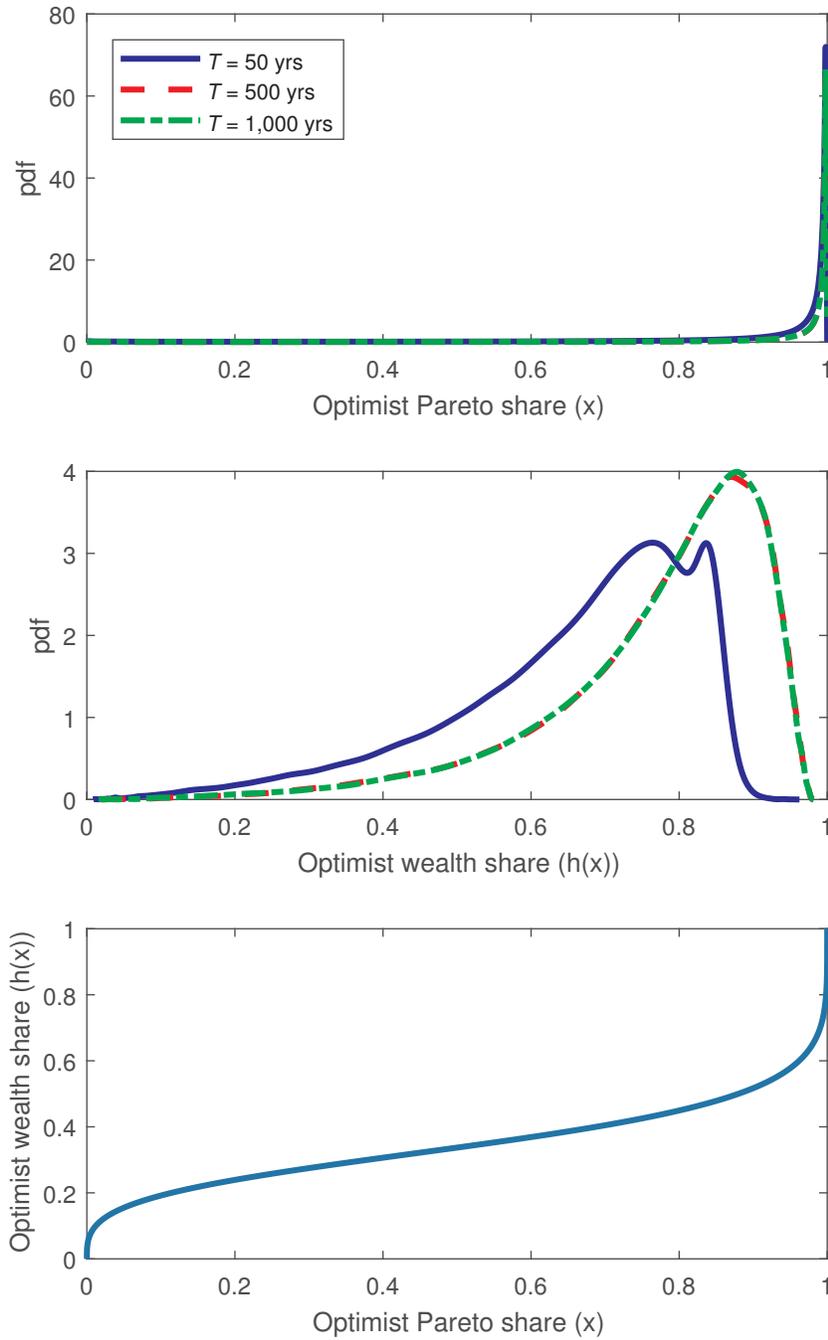
**Table F1: Expected growth and investment.** The table reports unconditional expected values of output growth and the investment-capital ratio  $i_t$  taken under the econometrician's measure.



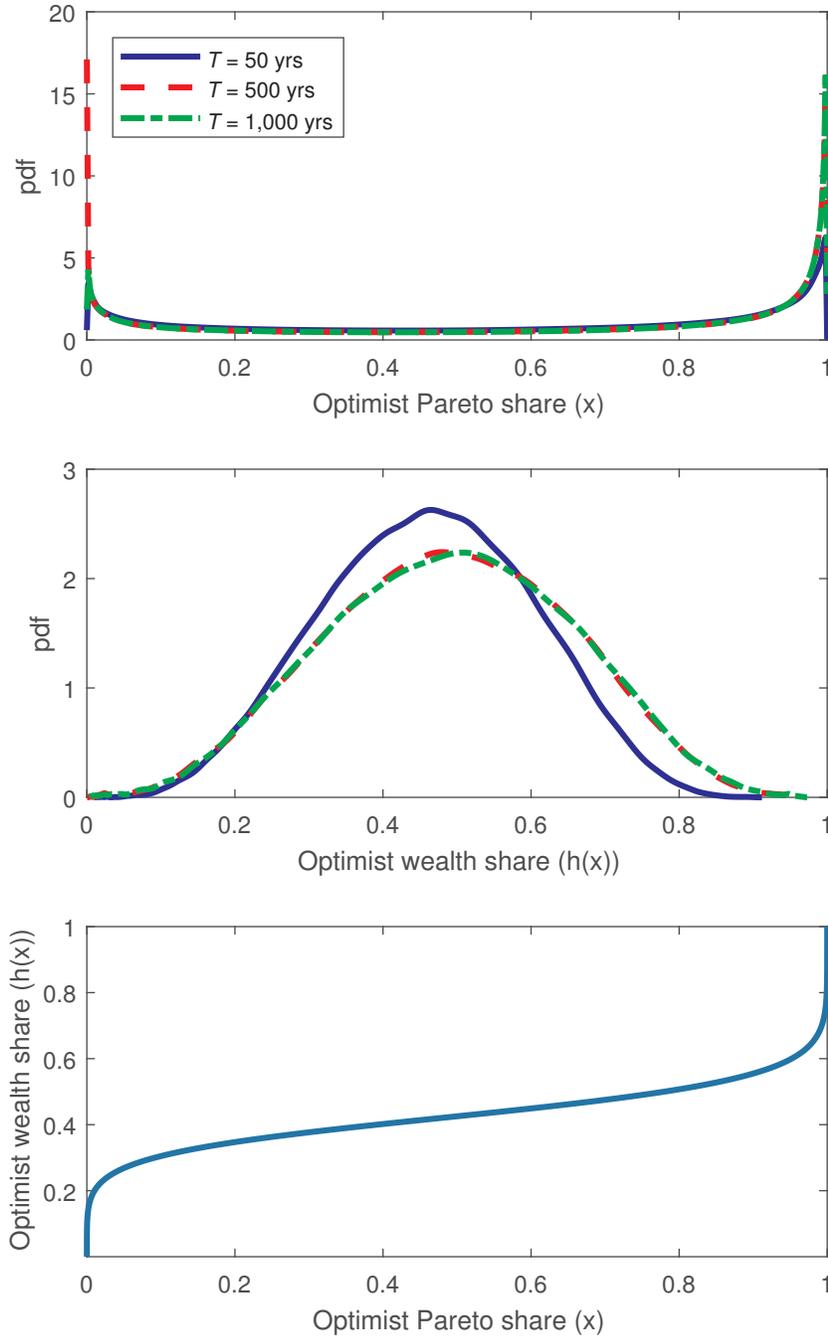
**Figure C1: Wealth distribution, varying  $\lambda_c$ .** All other parameter values are listed under Disagreement in Table 1.



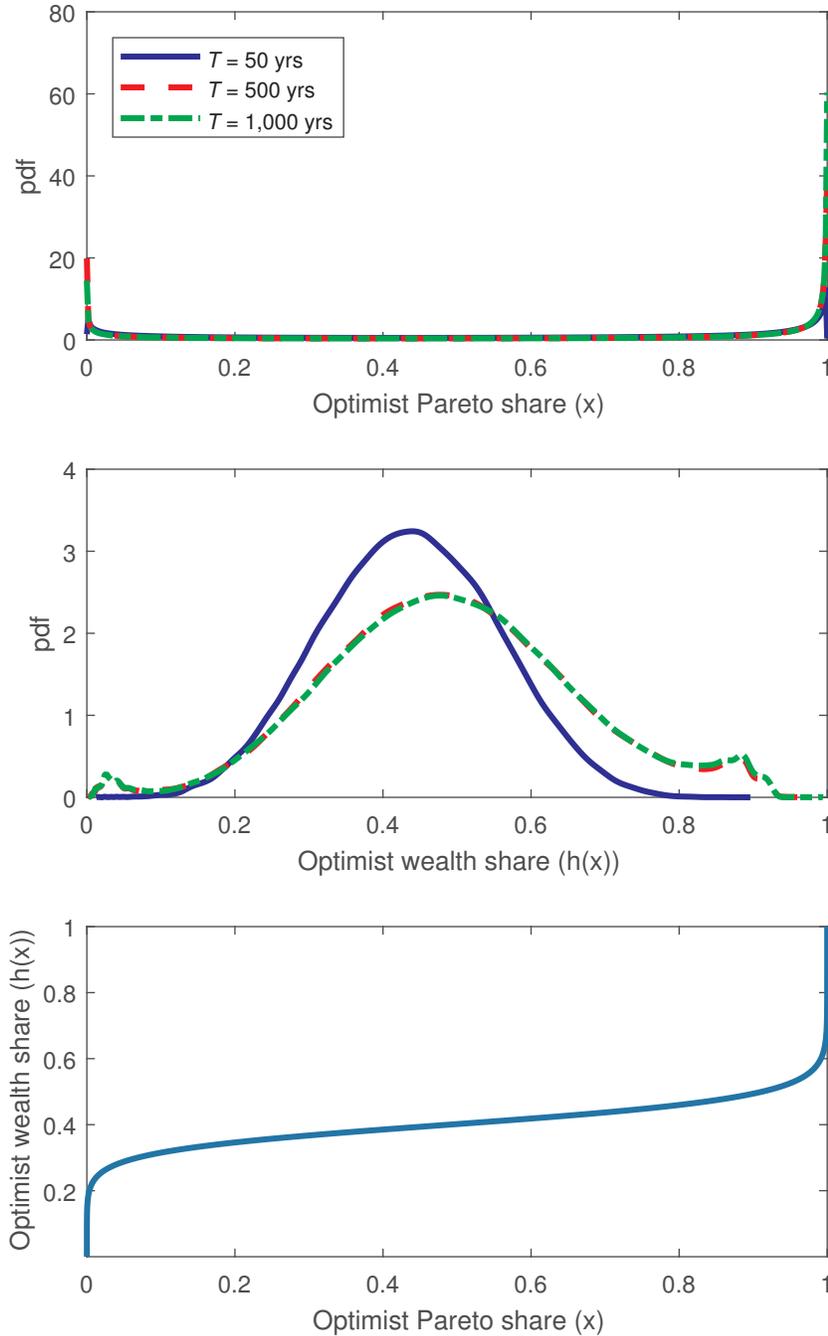
**Figure D1: Survey of Professional Forecasters: PRGDP < -2%.** The top panel shows the mean forecast. The bottom panel shows dispersion between the 25th percentile and 75th percentile forecasts.



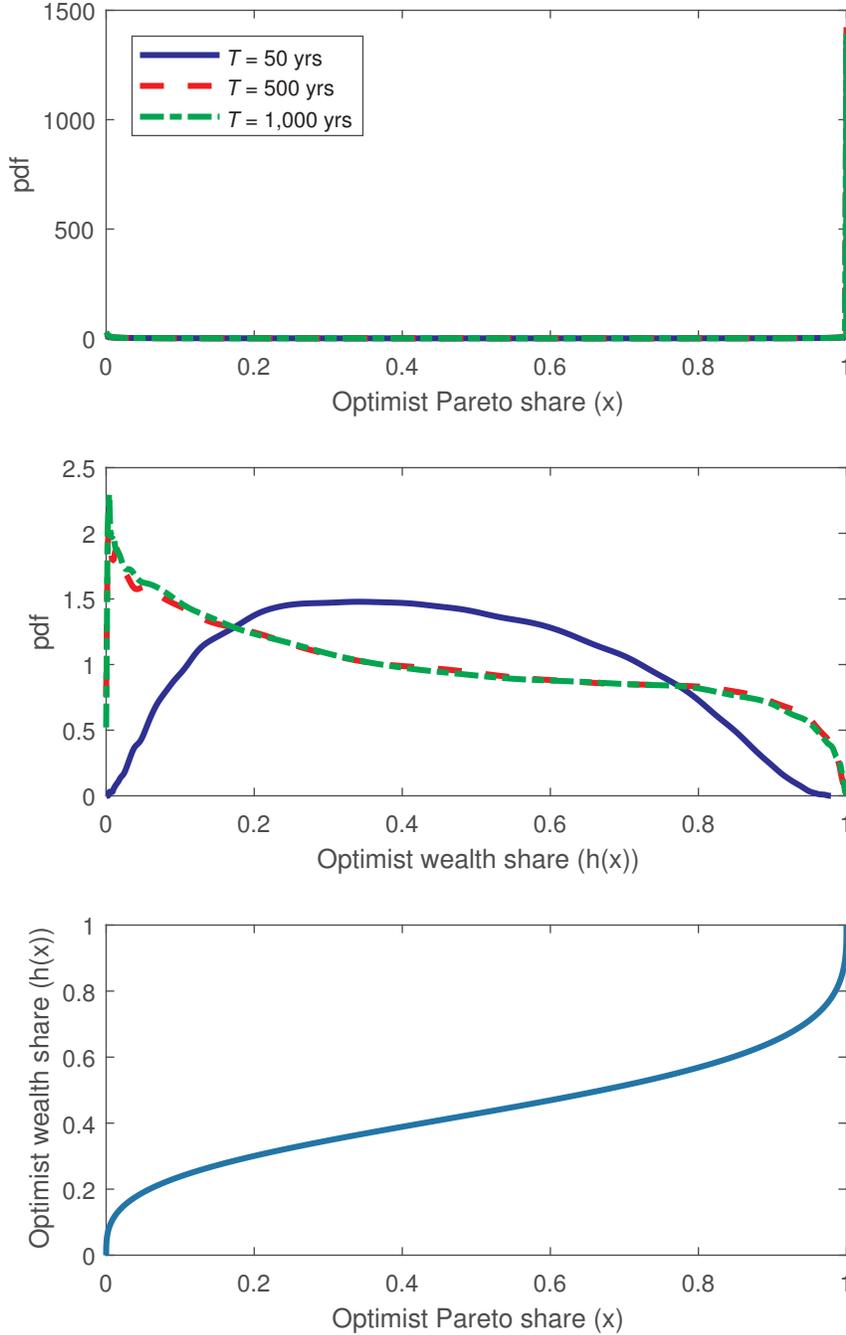
**Figure D2: State variable distribution.** The figure shows that the main state variable, the optimist’s Pareto share  $x$ , has a non-degenerate stationary distribution. Parameter values are under Disagreement in Table D2. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with  $x_0$  initialized uniformly on  $(0, 1)$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. The optimist’s wealth distribution, a rescaling of  $x$ , shows the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail.



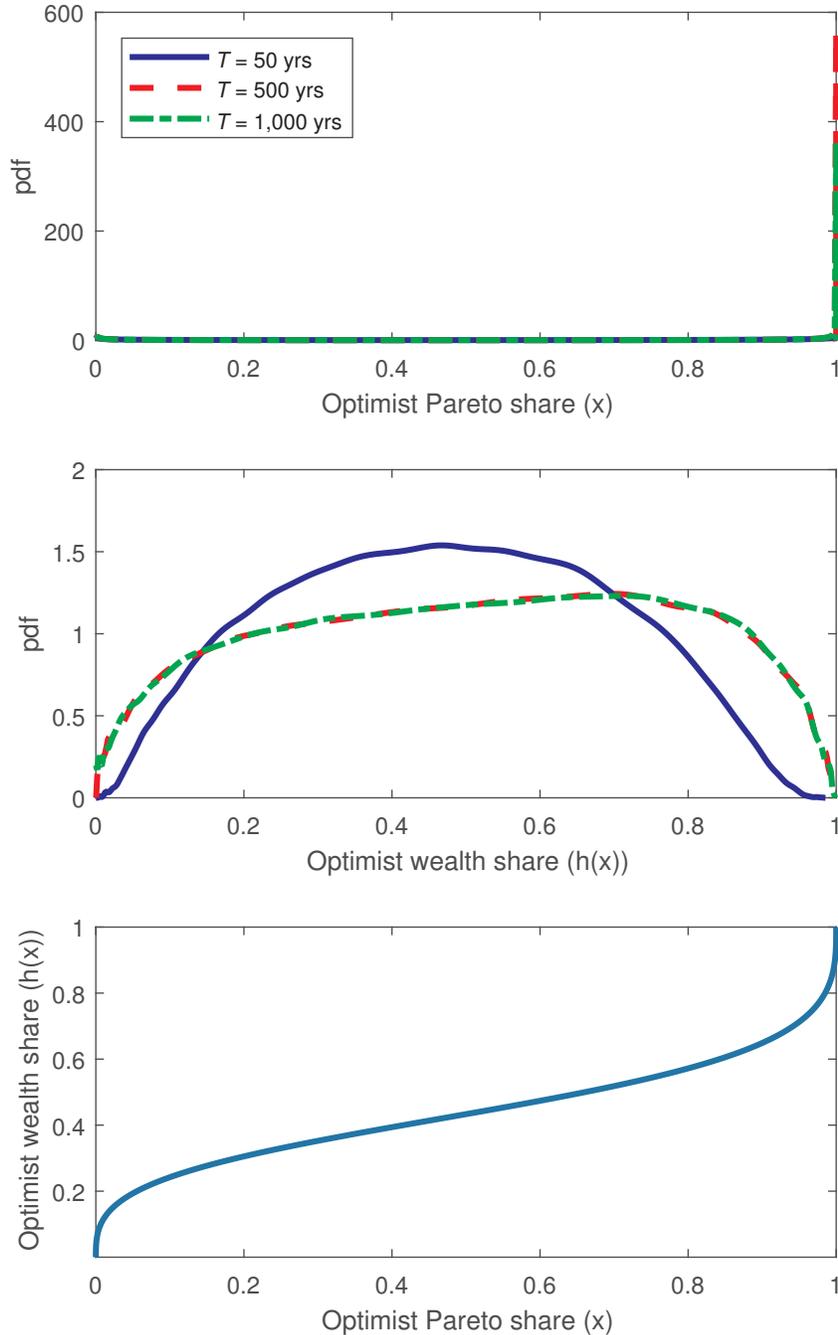
**Figure E1: State variable distribution:**  $1 - \alpha = 5$ ,  $\sigma = 0.1$ ,  $\lambda_c = 0.785$ . The figure shows that the main state variable, the optimist's Pareto share  $x$ , has a non-degenerate stationary distribution. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with a starting value  $x_0 = 0.5$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. Looking at the pdf of the optimist's wealth share  $h(x)$ , shown in the middle panel, illustrates the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail. The bottom panel shows the relation between  $x$  and  $h(x)$ , effectively a rescaling.



**Figure E2: State variable distribution:**  $1 - \alpha = 7$ ,  $\sigma = 0.07$ ,  $\lambda_c = 0.91$ . The figure shows that the main state variable, the optimist's Pareto share  $x$ , has a non-degenerate stationary distribution. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with a starting value  $x_0 = 0.5$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. Looking at the pdf of the optimist's wealth share  $h(x)$ , shown in the middle panel, illustrates the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail. The bottom panel shows the relation between  $x$  and  $h(x)$ , effectively a rescaling.



**Figure E3: State variable distribution:**  $\frac{1}{1-\rho} = 0.75$ ,  $\lambda_c = 0.65$ . The figure shows that the main state variable, the optimist's Pareto share  $x$ , has a non-degenerate stationary distribution. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with a starting value  $x_0 = 0.5$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. Looking at the pdf of the optimist's wealth share  $h(x)$ , shown in the middle panel, illustrates the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail. The bottom panel shows the relation between  $x$  and  $h(x)$ , effectively a rescaling.



**Figure E4: State variable distribution:**  $\frac{1}{1-\rho} = 0.95$ ,  $\lambda_c = 0.65$ . The figure shows that the main state variable, the optimist's Pareto share  $x$ , has a non-degenerate stationary distribution. Results are generated by Monte Carlo simulation of 1,000,000 paths of 1,000 years each, with a starting value  $x_0 = 0.5$ . Nearly identical distributions at 500 and 1,000 year horizons indicate stationarity. Looking at the pdf of the optimist's wealth share  $h(x)$ , shown in the middle panel, illustrates the density near the boundaries  $x = 0$  and  $x = 1$  in greater detail. The bottom panel shows the relation between  $x$  and  $h(x)$ , effectively a rescaling.