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"Attitudes Toward Catastrophe"

Christoph M. Rheinberger and Nicolas Treich

Toulouse School of Economics

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Christoph M. Rheinberger and Nicolas Treich*

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Abstract

In light of climate change and other global threats, policy commentators sometimes urge that society should be more concerned about catastrophes. This paper reflects on what society's attitude toward low-probability, high-impact events is, or should be. We first argue that catastrophe risk can be conceived of as a spread in the distribution of losses. Based on this conception, we review studies from decision sciences, psychology, and behavioral economics that elicit people's attitudes toward various social risks. We find more evidence against than in favor of catastrophe aversion—the preference for a mean-preserving contraction of the loss distribution—and discuss a number of possible behavioral explanations. Next, we turn to social choice theory and examine how various social welfare functions handle catastrophe risk. We explain why catastrophe aversion may be in conflict with equity concerns and other-regarding preferences. Finally, we discuss current approaches to evaluate and regulate catastrophe risk.

*CMR: Toulouse School of Economics (LERNA), email: rheinberger.cm@gmail.com. NT: Toulouse School of Economics (LERNA-INRA), email: ntreich@toulouse.inra.fr. The research in this paper was funded by the Foundation for an Industrial Safety Culture (FonCSI), in the context of the SAF€RA ERA-NET. We acknowledge valuable comments by Matthew Adler, James Hammitt, Kerry Krutilla, Eric Marsden, Chris Olivola, Olga Špačková, and Jonathan Wiener.

1 Introduction

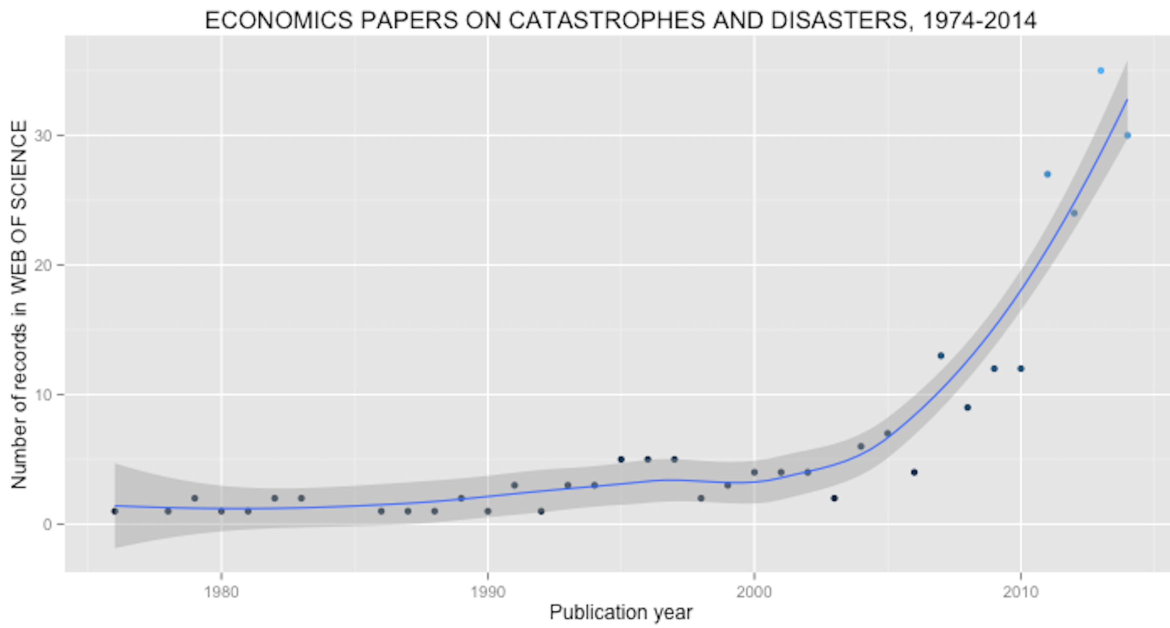
Catastrophes have always been a prominent theme in environmental and resource economics. Debates about doomsday models (Solow 1972), resource exhaustion (Dasgupta and Heal 1974), and the irreversibility effect (Arrow and Fisher 1974) have had a lasting effect on the discipline. More recently, man-made environmental threats like ozone layer depletion and climate change have attracted a lot of attention and technological 'remedies' to alleviate these threats—geo-engineering for instance—present their own catastrophic potential. In response, the behavioral and social sciences are witnessing an upsurge of interest in catastrophic and even existential risks (Posner 2004; Diamond 2005; Sunstein 2007; Bostrom and Cirkovic 2008; Taleb 2010; Barro and Ursua 2012, Wiener 2015).

In this paper we present and discuss a conceptual framework that—or so we believe—is useful for environmental economists because it enables us to think systematically about catastrophes. A straightforward way to gauge the rising interest in economics is to count papers published in leading journals that contain keywords related to catastrophes and disasters. Figure 1 displays the results of such a bibliometric analysis, demonstrating the effective upsurge of interest since the early 2000s.[1]

In recent years, economists have devoted special attention to the modeling of climate catastrophes. The following are some important contributions. In his dismal theorem, Weitzman (2009) is concerned with the implications of structural uncertainty for the economics of low-probability, high-impact catastrophes. He provocatively argues that cost-benefit analysis (CBA) cannot be used to assess "fat-tailed" risks. Millner (2013) scrutinizes the implications of the dismal theorem and proposes an alternative framework in which the contribution of catastrophes to welfare loss is dampened. Pindyck and Wang (2013) use a general equilibrium model of production, capital accumulation, and household preferences to assess how much society should spend on reducing the probability and impact of a climate catastrophe.

[1] Key words and journals included in the bibliometric analysis appear in the Appendix. Note that our analysis includes all kinds of catastrophic events including natural disasters and climate change, but also warfare and financial crises.

Figure 1: Economists' growing interest in catastrophes and disasters



Notes: Bibliometric search of the WEB OF SCIENCE™ with the key words <catastrophe>, <catastrophes>, <catastrophic>, <disaster>, <disasters>, or <disastrous>; hits are articles published in selected economics journals between 1974 and 2014.

Barro (2015) shows that optimal investment in climate change mitigation increases with both social risk aversion and the probability and size of catastrophes. Most recently, Martin and Pindyck (2015) analyze the limits of CBA to deal with multiple catastrophe risks.

What do all of the above contributions to climate economics have in common? Starting from the premise of a representative agent who seeks to maximize expected utility over uncertain consumption paths, they model catastrophe risk in essentially the same fashion. As Weitzman (2009: 9) puts it: "The basic idea is that a society trading off a decreased probability of its own catastrophic demise against the cost of lowering the probability of that catastrophe is facing a decision problem conceptually analogous to how a person might make a tradeoff between decreased consumption as against a lower probability of that person's own individually catastrophic end." Since economists deal with catastrophe risks just like they deal with ordinary consumption risks, they also presume that society *should be* catastrophe averse in the very same way the representative agent is risk averse with regard to aggregated consumption. The sanctity of the representative agent in climate-economic models is highlighted by the discussion of Weitzman's dismal theorem, which has centered on the limitations of the proposed constant relative risk aversion (CRRA) utility function (Nordhaus 2011; Pindyck 2011; Millner 2013; Arrow and Priebsch 2014; Horowitz and Lange 2014).

In this paper we introduce an alternative framework, which conceptualizes catastrophes as social risks that have a small likelihood of many people dying (or, more generally, facing a loss) together. The key aspect here is the *coincidence* of many deaths, because the social planner in our framework cares about the total number of fatalities in each state of the world. In other words, our focus is on population risk. We characterize the catastrophic potential of a risk by the spread in the distribution of fatalities within the threatened population. Our main objective then is to explore conceivable attitudes toward catastrophe risks. We focus on threats to life and limb mostly because the expected number of lives saved is the prevailing benefit measure of policies designed to avoid climate catastrophes, or nuclear accidents, or terrorist attacks. The expectancy criterion fails, however, to account for society's desire to avoid catastrophes. Let us illustrate this claim by the following example.

The U.S. President and Vice President do not travel together, in order to avoid a "decapitation strike", i.e. the possibility of the simultaneous deaths of the commander-in-chief and his second-in-command. On the other hand, it seems reasonable to presume that, when traveling with his family, the President should take the same plane to reduce the prospect of bereavement. In a seminal paper on the value of life, Schelling (1968: 156) noted that: "If a family of four *must* fly, and has a choice among four aircraft, of which it is known that one is defective but not known which one, it should be possible to persuade them to fly together. The prospects of each individual's survival are the same, no matter how they divide themselves among the aircraft, but the prospects for bereavement are nearly eliminated through the correlation of their prospects. Society's interest, in support of the family's interest, should be to see that they are permitted and encouraged to take the same plane together."

A related thought experiment, but in the environmental context and involving many more lives, has been put forward by Sunstein (2007: 135): "[C]onsider three stylized environmental problems, creating three quite different sorts of risks: The first problem creates a 999,999 in a million chance that no one will die, and a one in a million chance that 200 million people will die. The second problem creates a 50% chance that no one will die and a 50% chance that 400 people will die. The third problem creates a 100% chance that 200 people will die. Suppose that the government can eliminate all three problems at a specified cost." Although in all of the three problems the expected loss amounts to 200 lives, Sunstein suggests to prioritize the most catastrophic problem. In particular, he argues that the social cost of losing 200 million people (about two-thirds of the U.S. population) is much higher than a million times the social cost of losing 200 people and, therefore, warrants a modified version of cost-benefit analysis (CBA) that weights catastrophic losses. He also worries that the first problem may in fact receive the lowest priority in many decision-making contexts, and concludes that to "the extent that many people show little concern about global warming, part of the explanation may well lie in the fact that human beings often neglect low-probability, high-harm risks" (Sunstein 2007: 138).

The above examples illustrate that, depending on the context, one may or may not prefer the situation that gives rise to the possibility of simultaneous deaths. This prompts two important questions: How do we behave in the face of a looming catastrophe? And how should we behave in order to optimally protect ourselves against catastrophes? In the remainder of the paper, we collect insights from decision theory, behavioral economics, psychology, social choice, political economy, and risk management studies to reflect upon these questions. We proceed as follows. In Section 2 we provide a formal definition of what we mean by catastrophe risk. We make use of this definition to introduce different attitudes toward catastrophe that express preferences over the frequency and size of adverse outcomes. In Section 3 we present a review and discussion of empirical studies that explore how people make decisions in the face of catastrophes. Section 4 provides a summary of the social choice approach to evaluate risky social situations. Against this theoretical background, in Section 5 we look at what regulators actually do when they manage catastrophe risks. Section 6 summarizes the main points of our analysis.

2 Definition of Catastrophe Risk

The term *catastrophe* has a different meaning for different people. This is true both in general and in economics. For the sake of clarity, we start with a precise definition of what we mean by catastrophe risk. The definition is consequentialist, focusing solely on the number of fatalities. It characterizes catastrophes as a "bunching of fatalities", without specifying whether the bunching arises from a common cause, or among an identified group of people, or at the same time, or in the same place (Lathrop 1982). In our framework, individuals are identical so that the identity of victims and survivors does not matter. Our definition does not attempt a sharp distinction between catastrophic and common risks. Instead, we consider all possible distributions of fatalities pertaining to one risky situation and propose a criterion to rank the distributions in terms of how relatively catastrophic they are. More precisely, we compare social risks based on the spread in the distribution of fatalities, and thus keep the expected number of fatalities constant across the compared situations.

Consider a population of $i = 1, ..., N$ individuals, each of whom faces the probability of dying $p_i \in [0, 1]$ due to a particular cause. The risk of death is modeled as a Bernoulli random variable $\tilde{x}_i$ which takes on the value 1 if individual i dies, and 0 otherwise. We are interested in the distribution of fatalities across the population at risk: $\tilde{d} := \sum_{i=1}^{N} \tilde{x}_i$. We define a *more catastrophic* distribution of fatalities—that is a more catastrophic risk—based on the notion of second-order stochastic dominance (Rothschild and Stiglitz 1970).[2]

Definition 1. A distribution of fatalities $\tilde{d}$ is more catastrophic than another distribution $\tilde{d}'$ if, for any concave function $f(\cdot)$, $\mathsf{E}[f(\tilde{d})] = \sum_{k=0}^{N} \pi_k f(k) \leq \mathsf{E}[f(\tilde{d}')] = \sum_{k=0}^{N} \pi'_k f(k)$, where

[2] We note that our definition of catastrophe risk is similar to Fishburn and Sarin's (1991) definition of ex post risk equity.

π_k and π'_k denote the probabilities of observing $k = 0, 1, ..., N$ deaths.

By Definition 1, $\tilde{d}$ is a mean-preserving spread (MPS) of $\tilde{d}'$ and therefore second-order stochastically dominated by $\tilde{d}'$. Accordingly, we define three distinct attitudes toward catastrophe risk.

Definition 2. Catastrophe aversion is a preference for the less catastrophic distribution $\tilde{d}'$ or, equivalently, for a mean-preserving contraction in the distribution of fatalities. Catastrophe acceptance is the reversed preference for the more catastrophic distribution $\tilde{d}$ or, equivalently, in favor of a MPS in the distribution of fatalities. Catastrophe neutrality implies indifference between $\tilde{d}$ and $\tilde{d}'$.

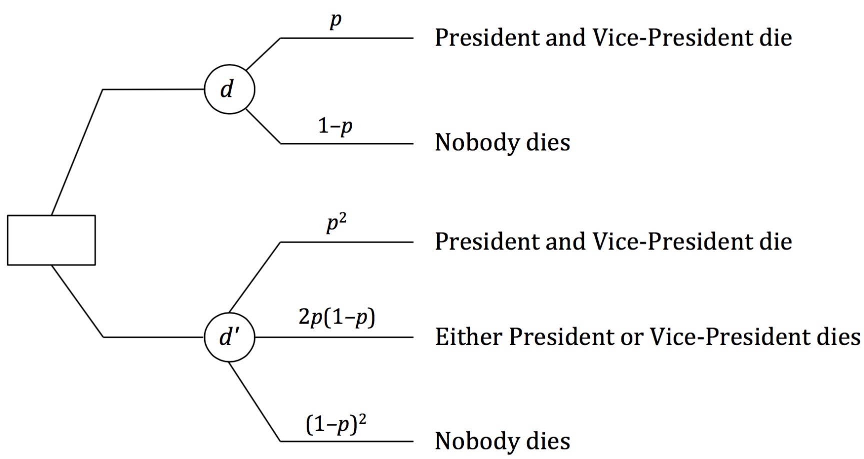
Definition 2 is consistent with Keeney's (1980a) seminal work on catastrophe avoidance.[3] In fact, our definition is more general as Keeney only considered binary distributions in which one outcome is zero fatalities.

Let us now revisit the Presidential travel example to illustrate what we mean by a more catastrophic distribution.

Example 1. Assume the U.S. President and Vice President need to attend the same ceremony to which they travel either together or separately. Let us presume that the likelihood of a plane crash, and therefore the probability of dying, is p. There are but two admissible distributions of deaths: if they travel together, either both stay alive or both die (with a chance $\pi_2 = p$); in case they travel separately, there is some chance $\pi'_1 = 2p(1-p)$ that one of them dies in a plane crash, and a very small chance $\pi'_2 = p^2$ that both die in two different plane crashes. Moreover, chances are higher that no one dies if they travel together $\pi_0 = 1 - p > \pi'_0 = (1-p)^2$. Figure 2 shows the two admissible distributions of deaths as probability trees. Catastrophe averse (accepting) preferences imply that one prefers the two leaders to travel separately (together).

[3]Keeney was not the first to allude to society's fear of catastrophic events. In the 1970s, nuclear engineers started to argue that society's apparent acceptance of daily hazards and its concern for possibly catastrophic hazards suggests catastrophe aversion. The argument was based on the idea that a consistent relationship exists between the severity and frequency of fatal accidents that would somehow reflect social attitudes toward risk (Starr 1969).

Figure 2: Presidential travel example



Let us clarify the difference between the MPS definition of catastrophe risk and an alternative definition based on the mean-variance rule of modern portfolio theory. The latter definition implies that catastrophe aversion is equivalent to preferring the less variable of two distributions with identical expected loss in terms of the number of fatalities: $\tilde{d}' \succ \tilde{d}$ if $\mathsf{E}[\tilde{d}] = \mathsf{E}[\tilde{d}']$ and $\mathsf{var}[\tilde{d}] > \mathsf{var}[\tilde{d}']$. It is immediate that a more catastrophic distribution in the sense of a MPS must have a greater variance. The converse is not true, however. This is because the variance induces a complete ordering, while a MPS gives rise to a partial ordering only. The MPS criterion is therefore stronger than the increasing variance criterion.

An important point to raise is that catastrophe aversion implies, but is not implied by, preferences for minimizing the maximum probable loss. While at odds with common justifications for catastrophe aversion (Peterson 2002), this non-equivalence reflects an intuitive principle: what matters to a catastrophe averse decision maker when comparing two distributions of fatalities is not only the likelihood of the worst possible outcome, but also that of the second worst, third worst, etc.[4] Our conception of catastrophe aversion can be directly applied to address questions such as: "How should a single accident that takes N lives be weighted relative to N accidents, each of which takes a single life?" (Slovic et al.

[4]In risky situations involving only two individuals, minimax, minimal variance, and catastrophe averse preferences are strictly equivalent (Bernard et al. 2015).

1984: 464). Indeed, within our framework the question is formally interpreted as a decision between the sum of N i.i.d. Bernoulli random variables, i.e. $\sum_{i=1}^{N} \tilde{x}_i$, versus N times one single Bernoulli random variable, i.e. $N\tilde{x}_i$. According to Definition 1, the latter distribution is more catastrophic than the former, and preferences are determined by the decision maker's attitude toward catastrophe risk.

3 Catastrophe Risk and Empirical Social Choices

We now turn to the available evidence on attitudes toward catastrophe risk. Below, we provide a summary of empirical studies that put subjects in the shoes of a social planner and ask them to make risky choices affecting other people.

3.1 Risky Social Choices involving Lives

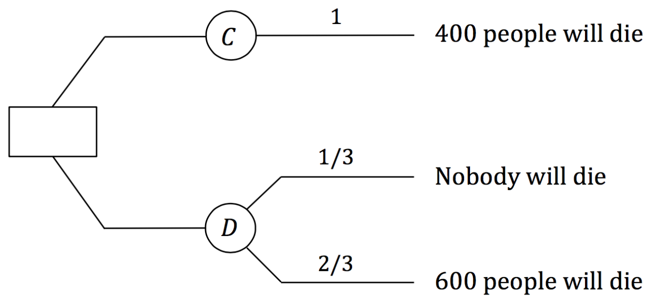
We start with evidence arising from survey studies in which subjects evaluate risky social situations involving human lives. Let us stress a number of limitations beforehand. First and foremost, these studies are hypothetical by necessity. Decisions involving possibly many fatalities cannot be incentivized in the same way that economic experiments typically are. Second, the perspective of a social planner is unusual for most people and their decisions are thus prone to various heuristics and biases as explored in the psychometric risk literature. Third, subjects are typically asked to consider the problem in isolation and to ignore the social cost of their decisions. In light of these limitations, we agree with the reader that the generalizability of these survey studies is limited. Nonetheless, they provide a good starting point. The general picture that emerges from our summary is striking and perhaps, surprising as most studies summarized in Table 1 provide evidence in favor of catastrophe accepting attitudes.

We proceed by reviewing various types of risky social choices that have been used to elicit subjects' attitudes toward catastrophe risk. We emphasize that most problems involve

Table 1: Empirical studies on risky social situations involving life and death prospects

Author(s)	**Year**	**Method**	**Number of People at Risk**	**Evidence**
Tversky and Kahneman	1981	Standard gamble	200-600 deaths	mixed results, framing effect
Hammerton et al.	1982	Standard gamble	100 deaths	catastrophe aversion
Fischhoff	1983	Standard gamble	100-100,000 deaths	catastrophe acceptance
Slovic et al.	1984	Standard gamble	170-300 deaths	catastrophe acceptance
Keller and Sarin	1989	Standard gamble	10-100 deaths	catastrophe acceptance
Keller and Sarin	1989	Paired gamble	10-100 deaths	catastrophe acceptance
Hubert et al.	1991	Paired gamble	10-1,000 deaths	catastrophe aversion
Jones-Lee and Loomes	1995	Ranking choices	25-30 deaths	catastrophe acceptance
Fetherstonehaugh et al.	1997	Ranking choices	5,000-20,000 deaths	catastrophe acceptance
Druckman	2001	Standard gamble	200-600 deaths	mixed results, framing effect
Itaoka et al.	2006	Discrete choice experiment	4,000-20,000 deaths	catastrophe aversion
Abrahamsson and Johansson	2006	Paired gamble	up to 1,000 deaths	catastrophe acceptance
Slovic	2007	Ranking choices	100 deaths	catastrophe acceptance
Sunstein	2007	Ranking choices	2,000-200 million deaths	catastrophe acceptance
Olivola and Sagara	2009	Paired gamble	200-600 deaths	catastrophe acceptance
Rheinberger	2010	Paired gamble	up to 100 deaths	catastrophe acceptance
Rheinberger	2010	Discrete choice experiment	1-6 deaths per year	catastrophe acceptance
Carlsson et al.	2012	Ranking choices	up to 200 deaths	catastrophe acceptance among public
Carlsson et al.	2012	Ranking choices	up to 200 deaths	mixed results among experts

Figure 3: Risky social decision problem: standard gamble



"life or death" prospects to fewer than 1,000 individuals. The term "catastrophe" is thus used in the technical sense of Definition 1, rather than in the colloquial sense of an apocalyptic threat.

Standard gambles. Probably the most famous risky social choice problem is Tversky and Kahneman's (1981) Asian disease problem, which can be illustrated as standard gamble as in Figure 3. As the original problem was designed to detect preference reversals, there exists a loss framing and a gain framing (in square brackets):

> *Imagine that the U.S. is preparing for the outbreak of an unusual Asian disease, which is expected to kill 600 people. Two alternative programs to combat the disease have been proposed. Assume that the exact scientific estimate of the consequences of the programs are as follows: If Program C [A] is adopted, 400 [200] people will die [be saved]. If Program D [B] is adopted, there is 1/3 probability that nobody [600 people] will die [be saved], and 2/3 probability that 600 people [no people] will die [be saved]. Which of the two programs would you favor?*

Tversky and Kahneman found strong evidence against catastrophe aversion when the framing emphasized the number of deaths (78% of subject preferred program D to C) and strong evidence for catastrophe aversion when the framing emphasized the number of lives saved (72% of subjects preferred program A to B).

Dozens of replication studies have confirmed that people are consistently more risk seeking (averse) in the loss (gain) domain (Kuehberger 1998). In a noteworthy study, Olivola and Sagara (2009) manipulated responses to the Asian disease problem by showing subjects differently shaped distributions of mortality-causing events beforehand. The results suggest that distributions of event-related death tolls which people observe in their daily lives govern the evaluation of lifesaving interventions and risk preferences concerning them.

Another important study on risky social choices was devised by Fischhoff (1983). Presuming that the natural way of framing such decision problems is to emphasize the loss of life, he explored preferences over catastrophe risk by varying both the loss of lives and the corresponding probability in a systematic way. A large majority of subjects (70% and more) chose the probabilistic option across all of Fischhoff's treatments, providing strong evidence for catastrophe accepting preferences. In a similar vein, Slovic et al. (1984) asked several hundred students whether they would rather reduce the frequency of single-fatality accidents or of large-scale accidents involving 300 deaths. More than 70% of their subjects preferred reducing the frequency of single-fatality accidents, even though reducing the frequency of large-scale accidents implied a 10%-reduction in the expected number of fatalities.

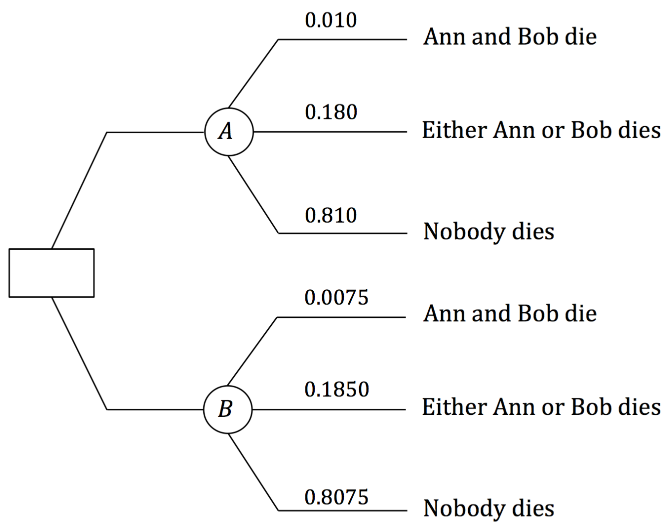
The only standard-gamble study that found some support for catastrophe averse preferences asked subjects whether society should rather sacrifice one (anonymous) individual in exchange for the survival of a group of 99 individuals, or accept that each of the 100 individuals faces a 1/100 probability to die (Hammerton et al. 1982).[5] One hundred of the 118 subjects approved of the sacrifice. Later replications by Keller and Sarin (1988) did, however, not confirm the original result (42 out of 53 subjects preferred the gamble).

Paired gambles. In this type of decision problem, subjects choose between two risky options. Keller and Sarin (1988) framed paired-gamble problems in the following way:

> *There are 100 islanders who are susceptible to a specific fatal disease which has recently appeared on the mainland. [...] All susceptible people must be injected with the serum within 24 hours, or each will have a 15% chance of contracting the disease and eventually dying. There is no time to acquire more serum. There are only 3000 milligrams of the serum available. As the public health officer, it is your job to choose between the following options: A) Give the same low dose of 30 milligrams of serum to all 100 susceptible islanders. 50 of those susceptible are northerners, 50 are southerners. Each susceptible person will have an independent 10% chance*

[5]Individuals' risk of dying was described as independent so that there was only a tiny probability (10^{-20}) of 100 deaths, but a significant probability (0.264) of observing two or more deaths.

Figure 4: Risky social decision problem: paired gamble



> *of dying. The expected number of deaths is 10; B) Divide up the available serum among the 50 northerners who are susceptible to the disease. Thus, these people will receive a higher 60 milligram dose. Each of the 50 will now have an independent 5% chance of dying. Since the 50 susceptible southerners will receive none of the serum, each will still have a 15% chance of dying by contracting this disease. The expected number of deaths is 10.*

All but one of the 53 subjects chose option A, which is a MPS of option B. In Figure 4 we divide the population at risk by 50 to illustrate that the problem is one of either splitting a scarce resource among two individuals so that common fates become more likely (option A), or of favoring one individual over the other so that there is more likelihood of only one fatality (option B). Keller and Sarin used several paired gambles of this type, all pointing to catastrophe accepting preferences. Hubert et al. (1991) used a different paired-gamble method. In their study, a sample of 22 high-ranking French public administrators indicated the probabilities that would make them indifferent to either 100-fatalities or 1,000-fatalities accidents and a 1/10 chance of a 10-fatalities accident. The results indicate strong catastrophe aversion. Yet the findings have to be interpreted with caution as they rely on a sample of subjects who are responsible for local safety and may therefore consider additional decision constraints.

Two recent studies by Abrahamsson and Johansson (2006) and by Rheinberger (2010) extend the paired-gamble approach, using the gamble-tradeoff method (Wakker and Deneffe 1986). The gamble-tradeoff method is a chained utility elicitation protocol, which requires subjects to equalize two risky gambles by stating an indifference value. The stated value is then used as reference value in the next elicitation step so that one ends up with a sequence of outcomes that are equally spaced in utility units. Based on the assumption of a CRRA-disutility function over the number of lives lost, $f(d) = d^\gamma$, the two studies estimate the subject-specific coefficient of relative risk aversion $\hat{\gamma}$. In both studies, the majority of subjects made choices implying catastrophe accepting preferences; i.e., $\hat{\gamma} < 1$.

Discrete choices. A straightforward extension of paired gambles is to vary the frequency and severity of accidents systematically in a series of different combinations of scenarios from which subjects choose the preferred one. The result is a discrete choice experiment (DCE) with options that may be phrased as alternative safety policies. Itaoka et al. (2006) conducted such a DCE to examine the influence of risk characteristics involved in fossil fuel and nuclear power generation, on willingness to pay for the reduction of mortality risks. The attributes to describe nuclear risks included the probability of a catastrophic accident and the corresponding expected loss of lives. The authors found evidence of catastrophe aversion, meaning that subjects focused on the conditional loss from a nuclear accident, not its probability. In contrast, Rheinberger (2010) found no indication of catastrophe aversion in a DCE that was specifically designed to examine the tradeoff between the number of road fatalities and the frequency of accidents. In a random utility framework, he estimated a structural model of preferences over catastrophe risk, assuming CRRA-type risk preferences. The estimated coefficient of relative risk aversion is well below unity ($\hat{\gamma} = 0.84$), suggesting that subjects put distinctly more weight on the frequency of accidents than on the number of deaths.

Ordinal choices. The functional choice of the CRRA-disutility function can be related to a fundamental psychophysical principle known as Weber's law. This principle states that people react with diminishing sensitivity to steady increments in a stimulus. In an influential study, Fetherstonehaugh et al. (1997) applied the principle to lifesaving interventions and found that subjects were largely insensitive to the number of lives saved against a background of increasing numbers of lives at risk. Fetherstonehaugh and co-authors suggest a form of "psychophysical numbing" to explain the inability to appreciate losses of life as they become more catastrophic. In economic terms this insensitivity implies that the marginal utility of saving an additional life decreases and may even become negative (Västfjäll et al. 2015).

In a different set up, Jones-Lee and Loomes (1995) studied the perceived transportation safety in London's Underground railway system. Two hundred and twenty-two subjects assessed the following statement on an ordinal ranking scale ranging from <strongly disagree> to <strongly agree>:

> *25-30 deaths in a single Underground accident is worse than 25-30 deaths in separate Underground accidents.*

Only 20% of the subjects agreed that the single accident was worse, while 67% thought separate accidents were worse. Having expressed their preferences over different transportation risks, subjects were then asked to assume that a specific safety budget had to be allocated to reducing fatalities either from large-scale accidents or from small-scale ones. A minority of 23% preferred investing in the reduction of catastrophic accidents. Carlsson et al. (2012) did a similar study on traffic safety in Sweden, surveying both members of the general public and public administrators, and found that the expressed risk preferences were more nuanced. While members of the general public preferred the avoidance of frequent single-fatality accidents over the avoidance of infrequent large-scale ones, there was no clear preference among public administrators. Roughly 40% of them preferred avoiding either large-scale or small-scale accidents, while the remaining 20% said they had no preference for either one of the prospects.

We conclude that the findings from empirical social choice studies involving multiple-fatality risks are somewhat blurry. Nevertheless, they suggest that the majority of study participants—mostly Americans or Europeans—do not want regulators to adopt catastrophe averse policies when it comes to risks to life and limb.

3.2 Risky Social Choices involving Financial Stakes

So far, we have looked at studies that elicit preferences over risks involving human lives. We will now summarize the key findings of lab experiments that explore other-regarding preferences in risky choices over financial gambles. Of course, preferences revealed in such gambles are different from those involving human lives, as is the decision context. So while these studies are not informative about attitudes toward catastrophe risk in the narrow sense, they are properly incentivized and may therefore reveal dimensions of social risk attitudes that cannot be elicited by hypothetical choices.

Existing studies focus on three issues: ex ante fairness, ex post outcomes, and attitudes toward social risks and in particular toward the correlation between one subject's prospects and the prospects of the other subjects. Evidence on correlation attitudes is relevant because it tells us whether or not subjects prefer to win/lose simultaneously.

Lotteries. One way to study correlation attitudes in risky choices is by means of lottery tasks in which social context plays a role. Several such studies have recently been conducted. Rohde and Rohde (2011) analyze how individuals' decisions under risk depend on risks that others face in the same environment. Their results suggest that people prefer risks in the *gain* domain to be independent rather than correlated. Friedl et al. (2014) look at the take-up of insurance for correlated and uncorrelated risk and find that the average willingness-to-pay for insurance is significantly higher for the latter type of risk. This suggests that people prefer risks in the *loss* domain to be correlated rather than independent. Linde and Sonnemans (2012) and Lahno and Serra-Garcia (2015) zoom in on peer effects in risky choices and find that risk attitudes are affected by concerns for relative payoff: subjects are more risk averse in situations in which they can earn at the most as much as their peers than they are in situations in which they will earn at least as much. Harrison et al. (2013) explore yet another aspect of social risk. They elicit individual and group risk attitudes using multiple price lists and find them to be highly correlated.

Dictator games. Konow (2000), Krawczyk and Le Lec (2010), Brock et al. (2013), and López-Vargas (2014) present evidence from probabilistic Dictator games.[6] A significant share of subjects in all of these studies exhibit preferences for ex ante equal chances, highlighting that fairness and equity preferences matter in risky choices. Brock et al. (2013) note, however, that preferences based exclusively on ex ante or ex post comparisons cannot generate the empirical patterns they observe. Even with regard to attitudes toward social risks there is no clear evidence that individuals avoid negatively correlated risks more often than positively correlated risks. Ex post fairness in outcomes would predict that people strictly prefer positively correlated gambles. López-Vargas (2014) finds that subjects take substantially more risk when outcomes are fairly distributed ex post, but experiments by Brennan et al. (2008) and Bolton and Ockenfels (2010) do not support this result.

Public goods games. Milinski et al. (2008) initiated a wave of experiments that explored the conditions under which people cooperate to avoid catastrophic outcomes. In their experiment, six players are endowed with €40. The game stretches over ten periods, in each of which players decide how much they want to contribute to the avoidance of a climate catastrophe. Players have no means to communicate and therefore cannot coordinate. The "catastrophe" is averted with certainty if at least €120 are raised at the end of the game. In that case, each player receives the amount of money he or she has left. Otherwise, players face the collective risk $p = 0.9$ of losing everything, which implies perfectly correlated financial risks. There exist two symmetric pure strategy equilibriums: players contribute €0 in every period, yielding an expected payoff of €4 to each player; or players contribute €2 in every period, yielding everyone a certain payoff of €20. Only half of the ten participating groups reached the efficient equilibrium. Replications by Tavoni et al. (2011) and Barrett and Dan-

[6] In these games, two players face a coin-flip risk between prospects $\mathcal{A}$ and $\mathcal{B}$. For example, both prospects may pay either \$5 or \$50 but outcomes are positively or negatively correlated. Using obvious notations, we have: $\mathcal{A}: \frac{1}{2}(5,5) \oplus \frac{1}{2}(50,50)$ vs $\mathcal{B}: \frac{1}{2}(5,50) \oplus \frac{1}{2}(50,5)$. If player 1 dislikes both unequal outcomes and risk, she will prefer prospect $\mathcal{A}$ over prospect $\mathcal{B}$ although she faces the same personal risk under both prospects.

nenberg (2012) found that communication between the players dramatically increased the success in raising the target amount.

In terms of attitudes toward catastrophe risks, the results of public goods games are more difficult to interpret than those of lotteries or dictator games, for the measurement of risk preferences is confounded by the strategic nature of the game—the avoidance of the catastrophe is also the efficient equilibrium.

3.3 Behavioral Explanations

Several behavioral factors might explain the patterns emerging from the empirical studies reviewed above. In this section we briefly visit some of them. Note that we are not suggesting that the presented explanations are either exhaustive or mutually exclusive.

Risk perception and emotions. Subjects in the above studies evaluated risky social situations in their context. It is well-known that this context is shaped by the attention that society gives to various threats (Kasperson et al. 1988) and that catastrophes are produced and consumed by society in the sense that some risks receive much more attention than others (Zeckhauser 1996). Dread, outrage and other negative feelings determine how risks are perceived (Slovic 1987; Slovic et al. 2000). It is therefore of little surprise that Itaoka et al. (2006) found strong evidence for catastrophe aversion in choices that involved a catastrophic nuclear accident, a rare hazard over which the individual has little control, while Rheinberger (2010) found catastrophe acceptance in choices over road accidents, an everyday hazard over which the individual has significant control. These findings coincide with the risk-as-feelings hypothesis (Loewenstein et al. 2001), which contends that people evaluate risks both at a cognitive level (i.e., based on the probability and desirability of the associated consequences) and an emotional level (i.e., based on feelings), but that emotional reactions to risks can diverge from cognitive evaluations of the same risks as their determinants differ.

Ambiguity aversion. It has been suggested that the dread dimension of some risks is cognitively related to the ambiguity dimension of rare events (Hsu et al. 2005). If one does not know the probabilities of outcomes, it seems natural to focus on worst-case consequences (Ellsberg 1961). While the prospects in the studies reviewed above are all described in terms of objective probabilities, a mental association between the small likelihood of a catastrophe and the attitude toward ambiguous probabilities seems possible. However, experimental studies have found ambiguity-seeking behavior to prevail in the loss domain and for unlikely events (Wakker 2010; Kocher et al. 2015). Hence, it is not clear at all whether one would find ambiguity aversion or rather ambiguity seeking when analyzing attitudes toward climate change and other environmental catastrophes—just as the studies reviewed above found more evidence for catastrophe acceptance than for catastrophe aversion.

Inequity aversion. One such reaction that pervades through the evaluation of life and death prospects is that people dislike "dooming" some individuals. That is, they are ex post inequity averse. In this respect the study by Keller and Sarin (1988) is particularly insightful. Subjects were asked not only about their preferred option but also about the fairer option, and the answers they received were almost perfectly correlated, suggesting that people chose what they deemed morally defensible. Their preferences seem to be linked to anticipated feelings such as guilt, remorse and regret, that might diminish the decision maker's utility after the realization of the risk (Battigalli and Dufwenberger 2007; Ellingsen et al. 2010).

Salience and immediacy effects. Subjects' evaluations of social risks are likely to be affected by salience and immediacy effects. Risks that subjects have never experienced before (as is likely for low-probability, large-loss events) are assessed differently from those just experienced or from those witnessed frequently. For instance, Huang et al. (2013) found that, after the Fukushima accident, people living close to a nuclear power plant in China perceived the risk of a nuclear accident as being much higher, and the acceptability of that risk as being much lower. The salience hypothesis is consistent with a process-level model of magnitude evaluation, based on memory sampling and relative judgment that does not rely on stable value representations to explain attitudes toward catastrophe risks (Olivola and Sagara 2009). Alternatively, the salience hypothesis is also consistent with context-dependent choice models that presume decision makers are risk seeking when a prospect's upside is more salient, and risk averse when its downside is more salient (Bordalo et al. 2012).

Probability weighting. It is well documented that people weight probabilities when faced with gambles over money stakes. For example, Bruhin et al. (2010) analyzed almost 18,000 decisions over gambles involving real monetary gains and losses and found that roughly 80% of their 448 subjects exhibited significant deviations from linear probability weighting. Although probabilities were known to subjects of the reviewed empirical choice studies, there is little reason to believe that probability weighting would not affect the choices made. First, subjects may distort given probabilities when making choices due to decision weighting (as in prospect theory). Second they may not believe in the announced probabilities and may replace them by subjective probabilities. The commonly observed pattern of probability weighting is best modeled by an inverse S-shaped function (Prelec 1998), and there is some evidence suggesting that the same pattern also applies to life and death prospects (Rheinberger 2010). If that were the case, the empirical evidence should tend to favor catastrophe aversion since small probabilities are typically inflated. This suggests that probability weighting either does not apply in choices over life and death prospects, or—more probable to us—is dominated by other psychological factors.

Psychophysical numbing. The psychophysical numbing hypothesis (Fetherstonehaugh et al. 1997) is a direct explanation for why people do not exhibit catastrophe averse preferences in life and death prospects. Reasons invoked for the diminished sensitivity to the value of life include: (i) people's inability to emotionally appreciate the loss of lives in absolute numbers (Slovic 2007); (ii) a form of motivation crowding-out in which knowing the number of lives one cannot save reduces the utility of helping (Västfjäll et al. 2015); and (iii) the disparity in the valuation of identified versus statistical victims (Jenni and Loewenstein 1997; Small and Loewenstein 2003). All of these reasons may actually explain why the social disutility derived from an accident in which 1,000 people die might be less than 10 times the social disutility from another accident claiming 100 lives.

Framing effects. The empirical evidence on attitudes toward catastrophe risk is subject to various framing effects (see Kuehberger et al. 1999). The Asian disease problem illustrates that one important effect relates to whether consequences are framed as lives *lost* or *saved*. Interestingly, when Druckman (2001) modified the original problem to:

> *If Program C is adopted, 400 people will die and 200 people will be saved. If Program D is adopted, there is 1/3 probability that nobody will die and 600 people will be saved, and 2/3 probability that 600 people will die and no people will be saved. Which of the two programs would you favor?*

43% of subjects chose the catastrophe averse option C, which is approximately mid-way between the results he found for the gain framing (68.1%) and the loss framing (22.8%). Other framing effects are known to play a role in decisions under risk, and perhaps even more so in risky social situations. Stewart et al. (2003) show that the set of available options has a large effect on choices under risk. This suggests that many people value prospects relative to one another, which gets support from the psychophysical numbing hypothesis. Accountability has also been shown to affect preferences over life and death prospects. For example, subjects in Rheinberger (2010) declared in debriefing questions that the social planner should be held accountable for multiple small-scale accidents, while rare large-scale accidents were rationalized as random acts.

In sum, the results of empirical social choice studies are consistent with various effects found in psychometric risk research. However, it is not clear which of the effects are predominant in explaining the observed attitudes toward catastrophe risks.

4 Catastrophe Risk and Social Choice Theory

The above summary of empirical social choice studies suggests a number of behavioral motives that might affect society's attitudes toward catastrophe. In this section, we turn our attention to normative models and explain how various risk attitudes can be grounded in social choice theory. The social choice approach is most popular among philosophers and economists. It typically puts forward a set of axioms and explores their logical implications. This immediately raises a thorny question: Who decides about the axioms that society ought to adopt? The intuition of philosophers and economists might be poor guidance for collective decision making. Relying instead on real choices such as those made in ballots does not seem very useful either, since existing policies and political institutions tell us little about the desirability of specific axioms. Experimental economics could be useful here, but experimental outcomes are often plagued by the self-serving bias, and it is difficult to properly measure social fairness concerns in the lab (Johansson-Stenman and Konow 2010). One could rely on stated preferences instead, but applying ethical theories is often complex, and it is unclear how one should elicit lay people's opinions about the desirability of technical axioms in any informative way. Balancing these issues, we decided simply to present the most important axioms pertaining to catastrophe risks, and to leave it to the reader to judge their appeal for policymaking.

4.1 Social Welfare Functions

Social choice theory and cognate disciplines have a long-standing interest in attitudes toward risk. In his aggregation theorem, Harsanyi (1955) proposed that the social planner should maximize the sum of individual utilities as if individuals would maximize expected utility under a veil of ignorance (i.e., without knowing their identity). Utilitarianism has, however, been widely contested, for it is indifferent to both ex ante and ex post inequalities in the distribution of outcomes.[7] A number of alternative social welfare functions (SWFs) have been proposed to capture concerns for the worse-off in the evaluation of risky social situations (Bovens and Fleurbaey 2012). In the context of mortality risk, Adler et al. (2014) examined the most popular SWFs with respect to sensitivity to wealth and baseline risk, equal value of risk reduction, preference for risk equity and catastrophe aversion, and compared them to welfare assessments based on the standard CBA framework. Below, we illustrate some of

[7] Prominent criticism includes that of Diamond (1967), Sen (1970), Myerson (1981), Broome (1984), Epstein and Segal (1992), Ben-Porath et al. (1997), and Fleurbaey (2010).

these results using the canonical example of Diamond (1967).

Example 2. Consider three risky social situations $\mathcal{S} = \mathcal{A}, \mathcal{B}, \mathcal{C}$, in which individuals $i = 1, 2$ face the risk of dying. They face two equiprobable states $j = \text{head}, \text{tail}$ (where j is determined by a coin toss). The state-dependent individual utilities u_{ij} associated with each situation are represented by the following outcome matrices:

$$\mathcal{A}: \begin{array}{c} \\ {\scriptstyle j=\text{head}} \\ {\scriptstyle j=\text{tail}} \end{array} \begin{array}{c} {\scriptstyle i=1 \quad i=2} \\ \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} \end{array} \quad \text{vs.} \quad \mathcal{B}: \begin{array}{c} \\ {\scriptstyle j=\text{head}} \\ {\scriptstyle j=\text{tail}} \end{array} \begin{array}{c} {\scriptstyle i=1 \quad i=2} \\ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{array} \quad \text{vs.} \quad \mathcal{C}: \begin{array}{c} \\ {\scriptstyle j=\text{head}} \\ {\scriptstyle j=\text{tail}} \end{array} \begin{array}{c} {\scriptstyle i=1 \quad i=2} \\ \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix} \end{array}.$$

Situation $\mathcal{A}$ implies the most catastrophic risk, while situations $\mathcal{B}$ and $\mathcal{C}$ induce the same distribution of fatalities. Situation $\mathcal{B}$ is ex post unequal as in each state one individual dies while the other one stays alive. Situation $\mathcal{C}$ is ex ante and ex post unequal as individual 2 is going to die and individual 1 stays alive no matter whether the coin lands on head or tail.

Example 2 highlights the apparent conflicts between fairness considerations and social risk assessment in general (Fishburn and Sarin 1991; 1994; Gajdos et al. 2010) and between catastrophe avoidance and risk equity concerns (Keeney 1980a; 1980b; Fishburn 1984; Bommier and Zuber 2008) in particular. Lichtenstein et al. (1990: 99) conclude that “one can achieve only one of the apparently laudable but inconsistent goals of fatality minimization, risk equity, and catastrophe avoidance”. How do common SWFs handle these conflicting goals?

- Utilitarian SWF: $W_U(\mathcal{S}) = \sum_{i=1}^{N} \sum_{j=1}^{M} p_j u_{ij}$ for persons $i = 1, ..., N$, states $j = 1, ..., M$, and statewise utility u_{ij}. Applied to Example 2 we have $W_U(\mathcal{A}) = W_U(\mathcal{B}) = W_U(\mathcal{C}) = 1$, demonstrating that the utilitarian SWF is catastrophe and inequity neutral.
- Ex ante prioritarian SWFs: $W_{EAP}(\mathcal{S}) = \sum_{i=1}^{N} \varphi \left(\sum_{j=1}^{M} p_j u_{ij} \right)$ for persons $i = 1, ..., N$, states $j = 1, ..., M$, statewise utility u_{ij}, and a strictly concave function φ. Applied to Example 2 we have $W_{EAP}(\mathcal{A}) = W_{EAP}(\mathcal{B}) = 2\varphi(1/2) > W_{EAP}(\mathcal{C}) = \varphi(1) + \varphi(0)$, demonstrating

that ex ante prioritarian SWFs are catastrophe neutral, but exhibit ex ante inequity aversion.

- Ex post prioritarian SWFs: $W_{EPP}(\mathcal{S}) = \sum_{j=1}^{M} p_j \sum_{i=1}^{N} \varphi(u_{ij})$ for persons $i = 1, ..., N$, states $j = 1, ..., M$, statewise utility u_{ij}, and a strictly concave function φ. Applied to Example 2 we have $W_{EPP}(\mathcal{A}) = W_{EPP}(\mathcal{B}) = W_{EPP}(\mathcal{C}) = \varphi(1) + \varphi(0)$, showing that ex post prioritarian SWFs result in the same preferential order as utilitarianism.

The above results demonstrate that common SWFs are catastrophe neutral; i.e., they do not distinguish between situations $\mathcal{A}$ and $\mathcal{B}$. Environmental economists should raise an eyebrow here, because policy evaluation is typically based on a utilitarian SWF, implying that popular integrated assessment models of climate change (e.g., DICE, RICE, FUND, PAGE) are catastrophe neutral! So let us turn to recent SWF approaches that do allow for social attitudes toward catastrophe to be captured.

- Ex post transformed SWFs: $W_{EPT}(\mathcal{S}) = \sum_{j=1}^{M} p_j \phi\left(\left(\sum_{i=1}^{N} \varphi(u_{ij})\right)/N\right)$ for persons $i = 1, ..., N$, states $j = 1, ..., M$, statewise utility u_{ij}, and a strictly concave function φ. The transformation function ϕ may be linear, concave, or convex. Applied to Example 2 we obtain $W_{EPT}(\mathcal{A}) = 0.5\phi(\varphi(1)) + 0.5\phi(\varphi(0))$ and $W_{EPT}(\mathcal{B}) = W_{EPT}(\mathcal{C}) = \phi(0.5\varphi(1) + 0.5\varphi(0))$, so that preferences are catastrophe accepting (averse) if and only if ϕ is convex (concave). One noteworthy transformation is the equally distributed equivalent (EDE) proposed by Fleurbaey (2010), which is obtained by setting $\phi = \varphi^{-1}$ (where ϕ is convex by the concavity of φ). When applied to Example 2, the EDE results in catastrophe accepting attitudes toward social risk and neutrality toward ex ante inequity.

- Catastrophe sensitive (CS) SWFs: $W_{CS}(\mathcal{S}) \sum_{j=1}^{M} \frac{1}{\varepsilon}(1 - \prod_{i=1}^{N}(1 - \varepsilon u_{ij}))$ for persons $i = 1, ..., N$, states $j = 1, ..., M$, statewise utility u_{ij}, and the constraint $\varepsilon u_{ij} < 1$. When applying the CS-SWF proposed by Bommier and Zuber (2008) to Example 2, we obtain $W_{CS}(\mathcal{A}) = 1 - 0.5\varepsilon$ and $W_{CS}(\mathcal{B}) = W_{CS}(\mathcal{C}) = 1$. Consequently, attitudes are averse (accepting) toward catastrophe risk if and only if ε is positive (negative), while they are always neutral toward ex ante inequity.

The above examples allow several conclusions to be drawn. First, ex ante approaches are always catastrophe neutral. Indeed, all that matters under ex ante approaches is individual expected utility. Therefore, the comparison of the realized levels of individual utility is irrelevant for welfare assessments. Consequently, ex ante approaches do not care whether people reach simultaneously high or low utility levels in a specific state. In contrast, ex post approaches can be catastrophe sensitive. Typically, a social planner who dislikes ex post inequity will prefer situation $\mathcal{A}$ over situations $\mathcal{B}$ and $\mathcal{C}$, as only in the first situation are utility levels equal across states. For that reason, the ex post inequity averse planner is also said to exhibit common-fate preferences (Schelling 1968).

Not all ex post approaches are catastrophe sensitive, however. As W_{EPT} and W_{CS} illustrate, the key property that induces sensitivity to the possibility of catastrophe is non-separability. Many scholars deem non-separability a problematic property because it implies that the level of utilities of individuals who are unaffected by a particular policy might still matter for the evaluation of that policy. We finally stress that ex post approaches violate the Pareto principle and have the additional drawback of neutrality toward ex ante inequity.[8] We conclude that allowing for catastrophe sensitive preferences comes at the cost of abandoning other normatively desirable goals. This conclusion takes us all the way back to the seminal result of Keeney (1980a), which states that there is always a conflict between ex ante and ex post risk equity.[9] While Keeney's result tells us nothing about which attitude the decision maker should exhibit toward catastrophe risk, it highlights the trade-off that the decision maker faces if he or she is averse to ex ante risk inequity and to catastrophic outcomes.

[8] See Fleurbaey (2010: 658) and Bovens and Fleurbaey (2012: 242-243) for a response to these objections.

[9] One important limitation of Keeney's theorem is that it assumes individual risks to be statistically independent. It is possible to relax the independence assumption whenever a risk transfer from the more exposed to the less exposed person does not decrease the statistical correlation between their risks (Bernard et al. 2015).

4.2 Some Implications for Risk Management

What are the implications for risk management of using one or the other SWF? Here, we begin to theoretically explore how the social planner's attitudes toward catastrophe can affect the level of the collective risk management effort. Consider a society composed of $i = 1, ..., N$ homogenous individuals all endowed with initial wealth w. Let the per capita cost of effort e to manage a certain risk be $c(e) > 0$, and the per capita loss due to the realization of this risk be $l(e) > 0$. This loss is interpreted as the individual's utility loss induced by death or injury, plus any monetary damage associated with the realization of the risk. Effort reduces the size of damage ($l'(e) < 0$), but is costly ($c'(e) > 0$). Moreover, effort is increasingly more costly ($c''(e) > 0$) and increasingly less effective ($l''(e) \geq 0$). Hence, agents face a classical self-insurance problem.

Using the notation introduced in Section 2, each individual's risk is represented by a Bernoulli random variable $\tilde{x}_i$. This variable takes on the value 1 if the risk materializes, and 0 otherwise. As a result, individual i derives the (random) utility $w - c(e) - \tilde{x}_i l(e)$ from the self-insurance effort e. We are interested in the planner's attitude toward the aggregate risk $\tilde{d} := \sum_{i=1}^{N} \tilde{x}_i$. We first study the optimal social level of effort under a utilitarian SWF. The utilitarian social planner maximizes the (unweighted) sum of utilities, namely $Nw - Nc(e) - \mathsf{E}[\tilde{d}]l(e)$, which yields the optimal effort e^* that solves the first order condition:

$$-Nc'(e^*) - \mathsf{E}[\tilde{d}]l'(e^*) = 0.$$

Observe that the optimal effort does not depend on how catastrophic the risk is, since it depends only on the aggregate risk $\mathsf{E}[\tilde{d}]$. In other words, the utilitarian social planner cares only about the expected size of damage (namely, the expected number of fatalities or injuries), but not about its distribution.

Let us now turn to a more general class of SWFs, which can display catastrophe accepting or catastrophe averse preferences. Following the discussion in Section 4.1, we use an ex post transformed SWF.[10] In this case, the social planner maximizes

$$\mathsf{E}\left[\phi\left(w - c(e) - \frac{\tilde{d}l(e)}{N}\right)\right],$$

where ϕ convex (concave) means catastrophe acceptance (aversion). The maximand is in general non-separable in individual utilities and can therefore be sensitive to higher order moments of the aggregate risk $\tilde{d}$. Note also that catastrophe accepting preferences may lead to a non-concave maximand if ϕ is sufficiently convex. We ignore this (possibly interesting) complication here and assume that the maximization problem is "well behaved".

Standard comparative statics techniques can thus be applied. The social planner obviously shows more self-insurance effort if he or she has a marginal incentive to increase effort compared to the utilitarian effort e^*. Formally, this holds whenever:

$$\mathsf{E}\left[\left(-c'(e^*) - \frac{\tilde{d}l'(e^*)}{N}\right)\phi'\left(w - c(e^*) - \frac{\tilde{d}l(e^*)}{N}\right)\right] \geq 0,$$

which is, by the first order condition under utilitarianism, equal to $\mathsf{cov}[(-c'(e^*) - \frac{\tilde{d}l'(e^*)}{N}), \phi'(w - c(e^*) - \frac{\tilde{d}l(e^*)}{N})] \geq 0$. The term $(-c'(e^*) - \frac{dl'(e^*)}{N})$ always increases in d, while the term $\phi'(w - c(e^*) - \frac{dl(e^*)}{N})$ increases in d if and only if ϕ' is decreasing. This is enough to sign the covariance term, implying the intuitive result that the collective effort in risk reduction increases (decreases) when the social planner is catastrophe averse (accepting). Our result does, however, not imply that the effort increases when the risk becomes more catastrophic. For that we would need to show that the function $\left[\left(-c'(e^*) - \frac{dl(e^*)}{N}\right)\phi'\left(w - c(e^*) - \frac{dl(e^*)}{N}\right)\right]$ is concave in d, which depends on the third derivative of ϕ. This remark underlines the richness of the conceptual problem of including attitudes toward catastrophe into optimal risk management.

The above model is simplistic, of course. The technology of risk reduction is basic self-insurance. Alternatively, or additionally, one could consider self-protection and risk-

[10]For the sake of simplicity, we assume W_{EPT} with $\varphi(x) = x$.

sharing instruments. One could also introduce individual risk averse preferences, or other forms of catastrophe sensitive SWFs. Finally, one could consider heterogeneous agents in a multi-period model. All of these extensions are left for future research.

5 Regulatory Approaches to Catastrophe Risk

The question of how catastrophe risks should be regulated is not new, of course. Rising concerns about large-scale chemical pollution and resource depletion in the 1960s and 1970s largely contributed to the development of the environmental movement. Environmentalists have mostly focused on activities that may have catastrophic consequences. As early as 1975, the U.S. Nuclear Regulatory Commission stated (USNRC 1975: 12): "The public appears to accept more readily a much greater social impact from many small accidents than it does from the more severe, less frequent occurrences that have a smaller societal impact." More recently, the introduction of the precautionary principle into European law and several international treaties reflect growing concerns over potentially catastrophic environmental risks and the view that policy making in relation to such risks carries with it a special moral responsibility (Jonas 1984).

In this section we explore the apparent links between regulatory practice, political issues, and people's beliefs and attitudes toward catastrophe. We first summarize the use of CBA for assessing health and safety policies. We then discuss alternative risk assessment metrics that are currently used to manage large-scale environmental and industrial risks. Finally, we take a look at the political economy of risk regulation and the impact that looming catastrophes have on it.

5.1 Standard Cost-Benefit Analysis

The standard economic approach to evaluate health and safety policies is CBA. So, how does CBA handle catastrophe risk? Standard CBA quantifies mortality risks in monetary units by multiplying the expected number of fatalities by the value of statistical life (VSL), i.e., $\mathsf{E}[\tilde{d}] \times$ VSL.[11] Accordingly, policy-induced changes in risk have a monetary value that is proportional to a VSL figure (e.g., the U.S. Environmental Protection Agency is currently using a value of about \$8 million per statistical life). Since our definition of catastrophe aversion remains $\mathsf{E}[\tilde{d}]$ constant, standard CBA is clearly catastrophe neutral. As an illustration, consider the monetized benefit of eliminating mortality risk in situations $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$ of Example 2. Remember that as exactly one individual will die in each of the three situations, the value of a risk-eliminating policy in each situation is just equal to the VSL. There is no premium whatsoever for eliminating the most catastrophic risk associated with situation $\mathcal{A}$.

It has been argued, however, that we should employ context-specific VSL values (Sunstein 2004). Taken to the extreme, this idea would imply the collection of individuals' WTP for each specific mortality risk reduction under scrutiny. The outcome of the CBA exercise would hinge on individual probability changes induced by each project. To illustrate this, consider again Example 2. When comparing situations $\mathcal{A}$ and $\mathcal{B}$, ex ante individual probabilities of dying are equal to 1/2 in both situations. As the risks faced by the two individuals are identical, there is no reason to justify different values for a risk elimination project. Yet, when we compare situations $\mathcal{A}$ and $\mathcal{C}$, we find that ex ante individual probabilities differ because in situation $\mathcal{C}$ one individual is sure to die while the other one bears no risk at all. One can easily imagine that the former individual's WTP to eliminate the certainty of his or her own death is infinite. More generally, policy assessments based on CBA are sensitive to how heterogeneity in individual risks affects the aggregate WTP for implementing a risk-reducing project (Pratt and Zeckhauser 1996). Previous work has shown that the effect depends, among other things, on whether information concerns heterogeneity in baseline risk or in changes in risk (Armantier and Treich 2004), and whether the valuation is based on compensating or equivalent variation (Hammitt and Treich 2007).

[11] The term "value of statistical life" is somewhat controversial (Cameron 2010) and U.K. regulators therefore use the term "value of prevented fatality" (VPF) instead. In any case, the metric refers to an individual's marginal rate of substitution between income and mortality risk.

In practice, there are at least two other motives that may justify the representation of catastrophe attitudes in CBA. The first one relates to the perception of risk. It is conceivable that people are willing to pay a premium when it comes to avoiding or reducing catastrophe risks, either because of the small probabilities and large uncertainties associated with such events (Viscusi 1998, Treich 2010), or because of the horror of widespread deaths as invoked in popular movies. In his book *Catastrophe: Risk and Response*, Posner (2004) attempts to estimate the monetary benefit of preventing human extinction in the year 2100. Assuming a VSL of $28 million and a future population of 12 billion people, he arrives at a tentative figure of $336 quadrillion. Posner maintains an inflated VSL value precisely to reflect the horror of extinction. Others have argued that even this 27-digit figure is much too small to capture the economic value of human extinction (see Bostrom 2013).

The second motive for including catastrophe attitudes into CBA relates to other-regarding preferences. Remember Schelling's quote in the introductory section, which mentions the prospect of bereavement associated with the possibility of surviving relatives. People may anticipate tremendous suffering from an inequality that arises after the materialization of the risk. As we have seen, there is experimental evidence supporting the notion of ex post inequity aversion. This is not to be confounded with altruistic motives as studied in the VSL literature (Bergstrom 1982; Jones-Lee 1992). The latter are ex ante concerns and hence cannot be sensitive to the possibility of a catastrophe. Nonetheless, there is evidence that other-regarding preferences play a significant role in empirical VSL studies (Hammitt and Haninger 2010; Gerking et al. 2014), and this leaves open the question of the specific effect of catastrophe risk.

5.2 Alternative Approaches

Aside from CBA, two other quantitative criteria are frequently used in environmental and technical risk assessments: individual risk criteria (IRC) and societal risk criteria (SRC).[12] As

[12] Adler (2005) provides an extensive discussion and critique of different environmental risk assessment approaches.

their labels suggest, the two criteria relate to different dimensions of risk. IRC are concerned with the distribution of risk across individuals. Known in law as *de minimis* standards, they place an upper limit on the "tolerable" or "acceptable" risk of death to individuals and thereby promote equity in the distribution of risk. SRC, on the other hand, are concerned with aggregate risk across groups of people. They place limits on the "tolerable" frequency of adverse outcomes (e.g., fatal accidents) of a specific size. Depending on how the tolerability criterion is defined, SRC may promote catastrophe aversion or acceptance in decisions over risky social situations. In the following, we briefly review two ways of implementing SRC in regulatory frameworks.

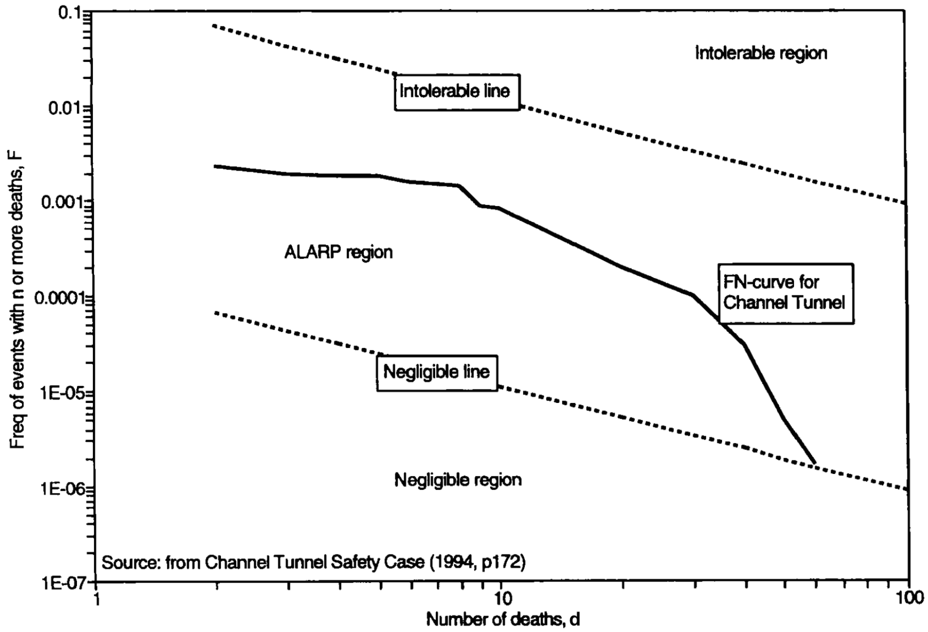
FN criterion. The most common way to implement SRC is by means of so-called Frequency-Number (FN) diagrams that plot the number of fatalities d against the cumulative frequency of events $F(d)$ that cause d or more deaths, and by a FN-criterion line $C(d)$ that specifies which risks are deemed tolerable.[13] When plotted in double-logarithmic scales as in Figure 5, risk tolerability is determined by the (negative of the) slope factor γ of a straight FN-criterion line. A slope factor $\gamma > 1$ implies catastrophe averse preferences on behalf of the regulator.[14] Evans and Verlander (1997) demonstrate that adhering to the FN-criterion is equivalent to a minimax decision rule in which the regulator chooses the policy option j that fulfills: $\min_j \max_d \left\{ \frac{F_j(d) d^\gamma}{C(d)} \right\}$.

Expected disutility criterion. An alternative SRC can be established based on the tenets of expected utility theory. Consider a catastrophe averse society and adopt the CRRA-disutility function over the number of lives lost, $f(d) = d^\gamma$, to model catastrophe aversion. An accident of uncertain size $\tilde{d}$ is evaluated by the expected disutility $\mathsf{E}\left[f(\tilde{d})\right] = \sum_{k=0}^{N} \pi_k d^\gamma$, where π_k is the probability that the event causes exactly k deaths. While a priori unknown, this probability can be approximated by the normalized frequency of size-k events; i.e., $\pi_k \approx f(k)/f$, where f is the overall frequency of events that cause deaths (Evans and

[13]FN-criteria are used in various European countries (see Rheinberger 2010; Bedford 2013).

[14]A catastrophe accepting regulator would, of course, adopt a slope criterion $\gamma < 1$.

Figure 5: Example of an FN-diagram, source: Evans and Verlander (1997)



Verlander 1997).[15] $\mathsf{E}\left[f(\tilde{d})\right]$ is compared against some tolerability threshold Ψ set by the regulator. Risk is deemed intolerable if $\mathsf{E}\left[f(\tilde{d})\right] > \Psi$.[16] If the disutility function is assumed to be quadratic, a risk-as-variance definition can be invoked (Stallen et al. 1996). In that case, uncertainty over the distribution of fatalities is regarded as a major cause of catastrophe aversion and this concern can be directly incorporated as a function of the spread of the distribution: social risk is deemed intolerable if $\mathsf{E}\left[\tilde{d}\right] + \kappa\sigma\left[\tilde{d}\right] > \Psi$, where $\kappa > 1$ is an aversion factor that accounts for the spread in the distribution of fatalities as measured by its standard deviation $\sigma\left[\tilde{d}\right]$.

Regulatory frameworks that have adopted one of the above SRC pursue a two-step approach. They first assess the tolerability of risk before and after the implementation of one or more policies. In the second step, they discard policy options that do not satisfy the tolerability criterion and perform the cost-benefit assessment only for the remaining policy

[15] Bedford (2013) argues that the approximation is mistaken for rare events (involving large n) and therefore difficult to defend in settings such as climate catastrophes. Instead, he proposes a two-parameter disutility function that extends the above approach to account for uncertainty in π_k.

[16] Bohnenblust and Slovic (1998) propose to marry the expected disutility criterion with standard CBA by multiplying for each policy option the expectation over the weighted number of deaths $\mathsf{E}\left[f(\tilde{d})\right]$ rather than the expected number of deaths $\mathsf{E}\left[\tilde{d}\right]$ by the VSL, obtaining a money measure of the disutility of lives lost.

options (Pate-Cornell 2002). The major problem we see with intolerability criteria and similar decision standards is that they are not well grounded theoretically. Yet, in the absence of a theoretical foundation, how can such standards form a robust and comprehensive basis for regulatory decisions?

5.3 The Political Economy of Catastrophe Risk Regulation

Why is it that some risks receive a lot of attention both from policymakers and the general public, while others go almost undetected despite their potentially catastrophic nature? Consistent with the Social Amplification of Risk perspective (Kasperson et al. 1988) we suggest that several politico-economic factors may help to explain why and how society decides to emphasize one risk, but not another. Due to limited space we can discuss only a few factors that are of particular relevance for understanding social attitudes toward catastrophe risk.

Perception. In *The Law of Fear: Beyond the Precautionary Principle*, Sunstein (2005) forcefully argues that developed countries invest too much in the prevention of low-probability, high-impact risks. Sunstein's core argument combines insights from psychology and political economy: the public tends to overestimate the probability of dreaded events, and policymakers respond to the public's fears and anxieties in a populist manner.[17] Breyer (1993) had made a similar point before, alluding to the excessive congressional reaction to popularized risks—toxic waste in this case—as the "vicious circle of risk regulation". Wiener (2015) adds that catastrophe risks are prone to what he calls the "unavailability" heuristic: uncommon risks are not available to human perception since they are, by definition, rare events.[18] It is therefore not contradictory that people overestimate low risks like plane crashes or tornados (Slovic et al. 2000), but underestimate or ignore rare risks altogether (Klinke and Renn 2002). This might explain Posner's (2004) observation that policymakers respond to catas-

[17] The issue of whose perceptions should ultimately count in public policy is analyzed in Portney (1992), Pollack (1998), Johansson-Stenman (2008), and Salanie and Treich (2009) among others.

[18] Wiener notes that blockbuster movies like *Deep Impact* or *The Day After Tomorrow* do little to alleviate the unavailability heuristic since the public tends to perceive such movies as what they are: good entertainment.

trophe risks far less than to other, more common risks. The summarized arguments suggest a complex pattern of policymakers' responses to catastrophe risk, which might well depend on a number of other factors directly linked to the public's perception.

Responsibility. Another crucial factor for understanding the regulation of risks is the question of responsibility. In a world that encounters evermore man-made risks, we forge our own destiny (Giddens 1999). Two questions come to the fore: Who is to determine which risks society accepts and which ones it does not? And who is to blame in the event of a catastrophe? It seems natural that government has a particular responsibility in overseeing activities that involve the risk of potentially many fatalities. It does so by enforcing safety standards and by intervening if those standards are not complied with. Firms engaged in hazardous activities are another social entity involved in the regulation of risks. Through regulatory guidelines they are required to operate so that the residual risk of accident is *as low as reasonably practicable* (Pate-Cornell 2002). While firms are generally liable for their activities, they may not be sufficiently capitalized to pay the compensations associated with a big accident. Limited liability in turn reduces a firm's incentive to invest in the prevention of accidents. Government may hence require firms to buy insurance coverage. This "surrogate regulation" restores some incentives for prevention by encouraging firms to undertake loss reduction measures and by monitoring their operations (Freeman and Kunreuther 1997).

Both the legal system and insurance offer possibilities to successfully manage large risks. Yet we need to keep in mind that extreme events may be large enough to harm or even destroy institutions. For example, it is unlikely that the court system would be operating after a large asteroid collision or that the Maldives could fully insure against the sinking of their islands. Anticipating the dysfunction of institutions in the aftermath of a catastrophe undermines their effectiveness in managing catastrophe risks (Wiener 2015).

Free-riding and group interest. Global risks raise issues similar to the problem of the commons, but on a bigger scale. The challenge of international negotiations on climate change or nuclear energy programs provides ample illustration. Typically, various interest groups have stakes in risk regulation and therefore seek to influence the regulator. The influence of particular groups often depends on the characteristics of the risk. One key criterion for the regulators' response to catastrophic threats is how regulatory costs and benefits are shared. Consider a policy intervention that seeks to reduce air pollution. The corresponding cost is borne by all taxpayers, but the benefits go primarily to people living in large cities. It is unclear how the relative group size affects policymaking: if the group of people exposed to air pollution is large, the policy enjoys more political support; at the same time, there are stronger incentives to free-ride in collective action settings (Olson 1971). The more catastrophic a risk is, the larger these incentives are, because more people are potentially affected, albeit with a smaller individual probability.

Regulatory costs might be borne by a specific industry that contributes to generating the potential catastrophe in the first place, as in the case of GHG emissions. Yet it is well known that the causative principle triggers strong political opposition and the influence and visibility of various lobby groups matters a lot for "pricing" catastrophe avoidance. Regulatory capture—the fact that a firm or industry may gain control over the agency meant to regulate it—is a significant problem in government decision-making (Laffont and Tirole 1991), especially when it comes to hazardous activities.[19] Interest groups exert pressure on politicians and/or policymakers who are concerned about their reputation (Kuran and Sunstein 1999). They typically do so with the help of the media, which have an important role in shaping the public's perception of risks that may (or may not) have the potential for a catastrophe. This may explain why not all catastrophes receive the same level of public attention (Eisensee and Strömberg 2007).

[19] In the aftermath of the Fukushima accident, von Hippel (2011) commented in a *New York Times* op-ed: "Nuclear power is a textbook example of the problem of 'regulatory capture' [...which] can be countered only by vigorous public scrutiny and Congressional oversight [...]."

6 Conclusions

The current paper has presented a framework to think systematically about catastrophes—the big ones that are going to increase both in frequency and size as ever more people live on our planet, and the *very* big ones that threaten the existence of humanity. We have argued that standard economic approaches to assess environmental, health, and safety risks do not account for important dimensions such as the sheer size of a catastrophe or the disutility of bereavement. Other approaches can be conceived of. We have formally defined the notions of catastrophe aversion and acceptance, respectively. Evaluations based on these notions capture different ex post attitudes toward social risk. Our review of existing empirical choice studies suggests that, in many contexts, people tend to be catastrophe accepting.

It is hard to say which motives drive catastrophe accepting attitudes. We have discussed several behavioral phenomena that may explain the observed empirical patterns. Perhaps the most important one is inequity aversion. Since a more catastrophic situation is generally also more equitable ex post, there is a clear link between catastrophe and equity. Maximal ex post equity is attained in the extreme case wherein either nobody or everybody dies.

We end up with a somewhat dissatisfactory reply to the two questions posed in the introduction. It is not clear whether we are, nor whether we should be, catastrophe averse. In future research, it may be interesting to study how the context systematically shapes our attitudes toward catastrophe risk. It may also be useful to identify the political forces (e.g., populism, responsibility, lobbying) that may induce or hinder regulatory action in regard of a looming catastrophe. On the normative side, we see a need to characterize optimal risk policies in economic models under catastrophe sensitive preferences. Our discussion has revealed that various disciplines including decision theory, behavioral economics, psychology, social choice and risk management have different perspectives on these issues. This calls for more integrated research on the management of catastrophe risks.

References

Abrahamsson, M., Johansson, H., 2006. Risk preferences regarding multiple fatalities and some implications for societal risk decision making-an empirical study. Journal of Risk Research 9 (7), 703–715.

Adler, M. D., 2005. Against "individual risk": A sympathetic critique of risk assessment. University of Pennsylvania Law Review 153 (4), 1121–1250.

Adler, M. D., Hammitt, J. K., Treich, N., 2014. The social value of mortality risk reduction: Vsl versus the social welfare function approach. Journal of Health Economics 35, 82–93.

Armantier, O., Treich, N., 2004. Social willingness to pay, mortality risks and contingent valuation. Journal of Risk and Uncertainty 29 (1), 7–19.

Arrow, K. J., Fisher, A. C., 1974. Environmental preservation, uncertainty, and irreversibility. Quarterly Journal of Economics 88 (2), 312–319.

Arrow, K. J., Priebsch, M., 2014. Bliss, catastrophe, and rational policy. Environmental and Resource Economics 58 (4), 491–509.

Barrett, S., Dannenberg, A., 2012. Climate negotiations under scientific uncertainty. Proceedings of the National Academy of Sciences 109 (43), 17372–17376.

Barro, R. J., 2015. Environmental protection, rare disasters and discount rates. Economica 82, 1–23.

Barro, R. J., Ursua, J., 2012. Rare macroeconomic disasters. Annual Review of Economics 4, 83–109.

Battigalli, P., Dufwenberg, M., 2007. Guilt in games. American Economic Review 97 (2), 170–176.

Bedford, T., 2013. Decision making for group risk reduction: Dealing with epistemic uncertainty. Risk Analysis 33 (10), 1884–1898.

Ben-Porath, E., Gilboa, I., Schmeidler, D., 1997. On the measurement of inequality under uncertainty. Journal of Economic Theory 75 (1), 194–204.

Bergstrom, T. C., 1982. When is a man's life worth more than his human capital? In: Jones-Lee, M. (Ed.), The Value of Life and Safety. No. 3–26. North-Holland, Amsterdam.

Bernard, C., Rheinberger, C. M., Treich, N., 2015. Catastrophe aversion and risk equity under dependent risks, mimeo, Toulouse School of Economics.

Bohnenblust, H., Slovic, P., 1998. Integrating technical analysis and public values in risk-based decision making. Reliability Engineering & System Safety 59 (1), 151–159.

Bolton, G. E., Ockenfels, A., 2010. Betrayal aversion: Evidence from Brazil, China, Oman, Switzerland, Turkey, and the United States: Comment. American Economic Review 100 (1), 628–633.

Bommier, A., Zuber, S., 2008. Can preferences for catastrophe avoidance reconcile social discounting with intergenerational equity? Social Choice and Welfare 31, 415–434.

Bordalo, P., Gennaioli, N., Shleifer, A., 2012. Salience theory of choice under risk. Quarterly Journal of Economics 127 (3), 1243–1285.

Bostrom, N., 2013. Existential risk prevention as global priority. Global Policy 4 (1), 15–31.

Bostrom, N., Cirkovic, M. M., 2008. Global catastrophic risks. Oxford University Press, Oxford.

Bovens, L., Fleurbaey, M., 2012. Evaluating life or death prospects. Economics and Philosophy 28 (2), 217–249.

Brennan, G., González, L. G., Güth, W., Levati, M. V., 2008. Attitudes toward private and collective risk in individual and strategic choice situations. Journal of Economic Behavior and Organization 67 (1), 253–262.

Breyer, S., 1993. Breaking the Vicious Circle: Toward Effective Risk Regulation. Harvard University Press, Cambridge, MA.

Brock, J. M., Lange, A., Ozbay, E. Y., 2013. Dictating the risk: Experimental evidence on giving in risky environments. American Economic Review 103 (1), 415–437.

Broome, J., 1984. Uncertainty and fairness. Economic Journal 94 (375), 624–632.

Bruhin, A., Fehr-Duda, H., Epper, T., 2010. Risk and rationality: Uncovering heterogeneity in probability distortion. Econometrica 78 (4), 1375–1412.

Cameron, T. A., 2010. Euthanizing the value of a statistical life. Review of Environmental Economics and Policy 4 (2), 161–178.

Carlsson, F., Daruvala, D., Jaldell, H., 2012. Do administrators have the same priorities for risk reductions as the general public? Journal of Risk and Uncertainty 45 (1), 79–95.

Dasgupta, P., Heal, G., 1974. The optimal depletion of exhaustible resources. Review of Economic Studies 41, 3–28.

Diamond, J., 2005. Collapse: How societies choose to fail or succeed. Penguin, New York, NY.

Diamond, P. A., 1967. Cardinal welfare, individualistic ethics, and interpersonal comparison of utility: Comment. Journal of Political Economy 75 (5), 765–766.

Druckman, J. N., 2001. Evaluating framing effects. Journal of Economic Psychology 22 (1), 91–101.

Eisensee, T., Strömberg, D., 2007. News droughts, news floods, and us disaster relief. Quarterly Journal of Economics 122 (2), 693–728.

Ellingsen, T., Johannesson, M., Tjøtta, S., Torsvik, G., 2010. Testing guilt aversion. Games and Economic Behavior 68 (1), 95–107.

Ellsberg, D., 1961. Risk, ambiguity, and the savage axioms. Quarterly Journal of Economics 75, 643–669.

Epstein, L. G., Segal, U., 1992. Quadratic social welfare functions. Journal of Political Economy 100 (4), 691–712.

Evans, A., Verlander, N., 1997. What is wrong with criterion fn-lines for judging the tolerability of risk? Risk Analysis 17 (2), 157–168.

Fetherstonhaugh, D., Slovic, P., Johnson, S. M., Friedrich, J., 1997. Insensitivity to the value of human life: A study of psychophysical numbing. Journal of Risk and Uncertainty 14 (3), 283–300.

Fischhoff, B., 1983. Predicting frames. Journal of Experimental Psychology: Learning, Memory, and Cognition 9 (1), 103–116.

Fishburn, P. C., 1984. Equity axioms for public risks. Operations Research 32 (4), 901–908.

Fishburn, P. C., Sarin, R. K., 1991. Dispersive equity and social risk. Management Science 37 (7), 751–769.

Fishburn, P. C., Sarin, R. K., 1994. Fairness and social risk I: unaggregated analyses. Management Science 40 (9), 1174–1188.

Fleurbaey, M., 2010. Assessing risky social situations. Journal of Political Economy 118 (4), 649–680.

Freeman, P. K., Kunreuther, H., 1997. Managing environmental risk through insurance. Studies in risk and uncertainty. Kluwer Academic Publishers, Norwell, MA.

Friedl, A., De Miranda, K. L., Schmidt, U., 2014. Insurance demand and social comparison: An experimental analysis. Journal of Risk and Uncertainty 48 (2), 97–109.

Gajdos, T., Weymark, J. A., Zoli, C., 2010. Shared destinies and the measurement of social risk equity. Annals of Operations Research 176 (1), 409–424.

Gerking, S., Dickie, M., Veronesi, M., 2014. Valuation of human health: An integrated model of willingness to pay for mortality and morbidity risk reductions. Journal of Environmental Economics and Management 68 (1), 20–45.

Giddens, A., 1999. Risk and responsibility. The Modern Law Review 62 (1), 1–10.

Hammerton, M., Jones-Lee, M., Abbott, V., 1982. Equity and public risk: Some empirical results. Operations Research 30 (1), 203–207.

Hammitt, J., Haninger, K., 2010. Valuing fatal risks to children and adults: Effects of disease, latency, and risk aversion. Journal of Risk and Uncertainty 40, 57–83.

Hammitt, J. K., Treich, N., 2007. Statistical vs. identified lives in benefit-cost analysis. Journal of Risk and Uncertainty 35 (1), 45–66.

Harrison, G. W., Lau, M. I., Rutström, E. E., Tarazona-Gómez, M., 2013. Preferences over social risk. Oxford Economic Papers 65, 25–64.

Harsanyi, J., 1955. Cardinal welfare, individualistic ethics and interpersonal comparisons of utility. Journal of Political Economy 63 (4), 309–321.

Horowitz, J., Lange, A., 2014. Cost–benefit analysis under uncertainty—a note on weitzman's dismal theorem. Energy Economics 42, 201–203.

Hsu, M., Bhatt, M., Adolphs, R., Tranel, D., Camerer, C. F., 2005. Neural systems responding to degrees of uncertainty in human decision-making. Science 310 (5754), 1680–1683.

Huang, L., Zhou, Y., Han, Y., Hammitt, J. K., Bi, J., Liu, Y., 2013. Effect of the fukushima nuclear accident on the risk perception of residents near a nuclear power plant in china. Proceedings of the National Academy of Sciences 110 (49), 19742–19747.

Hubert, P., Barny, M., Moatti, J., 1991. Elicitation of decision-makers' preferences for management of major hazards. Risk Analysis 11 (2), 199–206.

Itaoka, K., Saito, A., Krupnick, A., Adamowicz, W., Taniguchi, T., 2006. The effect of risk characteristics on the willingness to pay for mortality risk reductions from electric power generation. Environmental and Resource Economics 33 (3), 371–398.

Jenni, K., Loewenstein, G., 1997. Explaining the identifiable victim effect. Journal of Risk and Uncertainty 14 (3), 235–257.

Johansson-Stenman, O., 2008. Mad cows, terrorism and junk food: Should public policy reflect perceived or objective risks? Journal of Health Economics 27, 234–248.

Johansson-Stenman, O., Konow, J., 2010. Fair air: distributive justice and environmental economics. Environmental and Resource Economics 46 (2), 147–166.

Jonas, H., 1984. The imperative of responsibility: In search of an ethics for the technological age. University of Chicago Press, Chicago, MI.

Jones-Lee, M. W., 1992. Paternalistic altruism and the value of statistical life. Economic Journal 102 (410), 80–90.

Jones-Lee, M. W., Loomes, G., 1995. Scale and context effects in the valuation of transport safety. Journal of Risk and Uncertainty 11 (3), 183–203.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X., Ratick, S., 1988. The social amplification of risk - a conceptual-framework. Risk Analysis 8 (2), 177–187.

Keeney, R. L., 1980a. Equity and public risk. Operations Research 28 (3), 527–534.

Keeney, R. L., 1980b. Utility-functions for equity and public risk. Management Science 26 (4), 345–353.

Keller, L. R., Sarin, R. K., 1988. Equity in social risk: Some empirical observations. Risk Analysis 8 (1), 135–146.

Klinke, A., Renn, O., 2002. A new approach to risk evaluation and management: Risk-based, precaution-based, and discourse-based strategies. Risk Analysis 22 (6), 1071–1094.

Kocher, M. G., Lahno, A. M., Trautmann, S. T., 2015. Ambiguity aversion is the exception. CESifo Working Paper Series No. 5261.

Konow, J., 2000. Fair shares: Accountability and cognitive dissonance in allocation decisions. American Economic Review 90 (4), 1072–1091.

Krawczyk, M., Le Lec, F., 2010. 'Give me a chance!' An experiment in social decision under risk. Experimental Economics 13 (4), 500–511.

Kuehberger, A., 1998. The influence of framing on risky decisions: A meta-analysis. Organizational Behavior and Human Decision Processes 75 (1), 23–55.

Kuehberger, A., Schulte-Mecklenbeck, M., Perner, J., 1999. The effects of framing, reflection, probability, and payoff on risk preference in choice tasks. Organizational Behavior and Human Decision Processes 78 (3), 204–231.

Kuran, T., Sunstein, C. R., 1999. Availability cascades and risk regulation. Stanford Law Review 51 (4), 683–768.

Laffont, J.-J., Tirole, J., 1991. The politics of government decision-making: A theory of regulatory capture. Quarterly Journal of Economics 106 (4), 1089–1127.

Lahno, A. M., Serra-Garcia, M., 2015. Peer effects in risk taking: Envy or conformity? Journal of Risk and Uncertainty 50 (1), 73–95.

Lathrop, J. W., 1982. Evaluating technological risk: prescriptive and descriptive perspectives. In: Kunreuther, H. C., Ley, E. V. (Eds.), The Risk Analysis Controversy—An Institutional Perspective. Springer, Berlin.

Lichtenstein, S., Gregory, R., Slovic, P., Wagenaar, W. A., 1990. When lives are in your hands: Dilemmas of the societal decision maker. In: Hogarth, R. M. (Ed.), Insights in Decision Making: A Tribute to Hillel J. Einhorn. University of Chicago Press, Chicago, pp. 91–106.

Linde, J., Sonnemans, J., 2012. Social comparison and risky choices. Journal of Risk and Uncertainty 44 (1), 45–72.

Loewenstein, G. F., Weber, E. U., Hsee, C. K., Welch, N., 2001. Risk as feelings. Psychological Bulletin 127 (2), 267–286.

López-Vargas, K., 2014. Risk attitudes and fairness: Theory and experiment, working paper.

Martin, I. W., Pindyck, R. S., 2015. Averting catastrophes: the strange economics of scylla and charybdis. American Economic Review 105 (10), 2947–2985.

Milinski, M., Sommerfeld, R. D., Krambeck, H.-J., Reed, F. A., Marotzke, J., 2008. The collective-risk social dilemma and the prevention of simulated dangerous climate change. Proceedings of the National Academy of Sciences 105 (7), 2291–2294.

Millner, A., 2013. On welfare frameworks and catastrophic climate risks. Journal of Environmental Economics and Management 65 (2), 310–325.

Myerson, R. B., 1981. Utilitarianism, egalitarianism, and the timing effect in social choice problems. Econometrica 49 (4), 883–897.

Nordhaus, W. D., 2011. The economics of tail events with an application to climate change. Review of Environmental Economics and Policy 5 (2), 240–257.

Olivola, C. Y., Sagara, N., 2009. Distributions of observed death tolls govern sensitivity to human fatalities. Proceedings of the National Academy of Sciences 106 (52), 22151–22156.

Olson, M., 1971. The Logic of collective action—Public goods and the theory of groups, 2nd Edition. Harvard University Press, Cambridge, MA.

Pate-Cornell, M., 2002. Risk and uncertainty analysis in government safety decisions. Risk Analysis 22 (3), 633–646.

Peterson, M., 2002. The limits of catastrophe aversion. Risk Analysis 22 (3), 527–538.

Pindyck, R. S., 2011. Fat tails, thin tails, and climate change policy. Review of Environmental Economics and Policy 5 (2), 258–274.

Pindyck, R. S., Wang, N., 2013. The economic and policy consequences of catastrophes. American Economic Journal: Economic Policy 5 (4), 306–39.

Pollak, R. A., 1998. Imagined risks and cost-benefit analysis. American Economic Review 88 (2), 376–380.

Portney, P. R., 1992. Trouble in happyville. Journal of Policy Analysis and Management 11 (1), 131–132.

Posner, R. A., 2004. Catastrophe: risk and response. Oxford University Press.

Pratt, J. W., Zeckhauser, R. J., 1996. Willingness to pay and the distribution of risk and wealth. Journal of Political Economy 104 (4), 747–763.

Prelec, D., 1998. The probability weighting function. Econometrica 66 (3), 497–527.

Rheinberger, C. M., 2010. Experimental evidence against the paradigm of mortality risk aversion. Risk Analysis 30 (4), 590–604.

Rohde, I. M., Rohde, K. I., 2011. Risk attitudes in a social context. Journal of Risk and Uncertainty 43 (3), 205–225.

Rothschild, M., Stiglitz, J. E., 1970. Increasing risk: I. a definition. Journal of Economic Theory 2 (3), 225–243.

Salanié, F., Treich, N., 2009. Regulation in happyville. The Economic Journal 119 (537), 665–679.

Schelling, T., 1968. The life you save may be your own. In: Chase, S. (Ed.), Problems in Public Expenditure Analysis. Brookings, Washington, DC, pp. 143–144.

Sen, A., 1970. Interpersonal aggregation and partial comparability. Econometrica 38 (3), 393–409.

Slovic, P., 1987. Perception of risk. Science 236, 280–284.

Slovic, P., 2007. ‘if I look at the mass I will never act’: Psychic numbing and genocide. Judgment and Decision Making 2 (2), 79–95.

Slovic, P., Fischhoff, B., Lichtenstein, S., 2000. Facts and fears: Understanding perceived risk. In: Slovic, P. (Ed.), The Perception of Risk. Earthscan, London, pp. 137–154.

Slovic, P., Lichtenstein, S., Fischhoff, B., 1984. Modeling the societal impact of fatal accidents. Management Science 30 (4), 464–474.

Small, D. A., Loewenstein, G., 2003. Helping a victim or helping the victim: Altruism and identifiability. Journal of Risk and Uncertainty 26 (1), 5–16.

Solow, R. M., 1972. Notes on "“doomsday models”". Proceedings of the National Academy of Sciences of the United States of America 69 (12), 3832–3833.

Stallen, P. J. M., Geerts, R., Vrijling, H. K., 1996. Three conceptions of quantified societal risk. Risk Analysis 16 (5), 635–644.

Starr, C., 1969. Social benefit versus technological risk. Science 165, 1232–1238.

Stewart, N., Chater, N., Stott, H. P., Reimers, S., 2003. Prospect relativity: How choice options influence decision under risk. Journal of Experimental Psychology: General 132 (1), 23–46.

Sunstein, C. R., 2004. Valuing life: A plea for disaggregation. Duke Law Journal 54 (2), 385–445.

Sunstein, C. R., 2005. Laws of fear: Beyond the precautionary principle. Cambridge University Press, Cambridge, MA.

Sunstein, C. R., 2007. Worst-case scenarios. Harvard University Press.

Taleb, N. N., 2010. The black swan: The impact of the highly improbable fragility. Random House, New York.

Tavoni, A., Dannenberg, A., Kallis, G., Löschel, A., 2011. Inequality, communication, and the avoidance of disastrous climate change in a public goods game. Proceedings of the National Academy of Sciences 108 (29), 11825–11829.

Treich, N., 2010. The value of a statistical life under ambiguity aversion. Journal of Environmental Economics and Management 59 (1), 15–26.

Tversky, A., Kahneman, D., 1981. The framing of decisions and the psychology of choice. Science 211 (4481), 453–458.

Västfjäll, D., Slovic, P., Mayorga, M., 2015. Pseudoinefficacy: Negative feelings from children who cannot be helped reduce warm glow for children who can be helped. Frontiers in Psychology 6, 616.

Viscusi, W. K., 1998. Rational Risk Policy. Oxford University Press, New York, NY.

Von Hippel, F. N., 2011. It could happen here. New York Times March 24, A31.

Wakker, P., Deneffe, D., 1996. Eliciting von neumann-morgenstern utilities when probabilities are distorted or unknown. Management Science 42 (8), 1131–1150.

Wakker, P. P., 2010. Prospect theory: For risk and ambiguity. Cambridge University Press.

Weitzman, M. L., 2009. On modeling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics 91 (1), 1–19.

Wiener, J., 2015. The tragedy of the uncommons. Global Policy, forthcoming.

Zeckhauser, R., 1996. The economics of catastrophes. Journal of Risk and Uncertainty 12 (2-3), 113–140.

Appendix

The bibliometric analysis depicted in Figure 1 is based on a query of the Web of Science™. The query words `catastrophe`, `catastrophes`, `catastrophic`, `disaster`, `disasters`, and `disastrous` were used to search through abstracts, titles and key words of articles published between 1974 and 2014 in the following list of economics journals: *American Economic Journal: Applied Economics*, *American Economic Journal: Economic Policy*, *American Economic Journal: Macroeconomics*, *American Economic Journal: Microeconomics*, *American Economic Review*, *Econometrica*, *Economic Journal*, *European Economic Review*, *Games and Economic Behavior*, *International Economic Review*, *Journal of Econometrics*, *Journal of Economic Theory*, *Journal of Finance*, *Journal of Financial Economics*, *Journal of International Economics*, *Journal of Labor Economics*, *Journal of Monetary Economics*, *Journal of Political Economy*, *Journal of Public Economics*, *Journal of the European Economic Association*, *Rand Journal of Economics*, *Review of Economics and Statistics*, *Review of Economic Studies*, *Quantitative Economics*, *Quarterly Journal of Economics*, *Theoretical Economics*, *American Journal of Agricultural Economics*, *Ecological Economics*, *Energy Economics*, *Environmental and Development Economics*, *Environmental and Resource Economics*, *Journal of Agricultural and Resource Economics*, *Journal of Environmental Management and Economics*, *Land Economics*, *Review of Environmental Economics and Policy.*