Insurance and Climate-Driven Extreme Events

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Abstract

We investigate how insurance affects agents' decisions when being faced by endogenous, climate-driven extreme events. This is not only important in order to understand how the possibility of insurance augments mitigation and saving decisions, but it also improves our understanding of how insurance should be provided. Since there are no studies as of now that rely on such an integrated approach, we extend the literature along two lines. Firstly, we develop a neoclassical growth framework with endogenous extreme events and an insurance sector. Secondly, we introduce a simulation method that allows us to explicitly take these extreme events into account and which yields additional numerical insights. In doing so we can fully characterize and quantify the impact of different insurance policies for mitigation and economic growth decisions.

Our analytical results and computational experiments show that i) transparency of the insurance sector is the decisive requisite for abatement activities, implying substantial policy opportunities; ii) a decentralized economy will under-invest in abatement without adequate policy interventions; iii) precautionary beliefs on the frequency of extreme events lead to more sustainability; iv) a social security system which prices insurance fairly is preferable to an insurance industry which provides insurance with an overhead.

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1 Introduction

During the past decades, both the frequency and the strength of natural disasters have substantially increased. The number of natural catastrophes quadrupled between 1970 and 2013, so did the economic losses associated with these events. Estimates suggest that, during the past decade, annually approximately 100,000 people died from natural catastrophes, 216,000 people were affected, with damage cost to society of USD 156 billion. These days, an event that qualifies in its extent as a natural catastrophe[1] happens on our planet on average every single day (Guha-Sapir, Hoyois and Below 2014). It then should not come as a surprise that the insurance industry plays a vital role when it comes to investment decisions and the way agents can smooth out the impact of disasters.

In this article we look at the interplay between natural disasters, climate change, decision-taking under uncertainty and the role of insurance. This comprehensive view is new to the literature. We extend the literature along two lines. Firstly, we study the interplay between stochastic endogenous extreme events in a neoclassical growth model with endogenous climate change. Secondly, we introduce an insurance sector that allows to smooth out those extreme events. In addition to these extensions, we study a calibrated model that is used to quantify the results of the analytical model and to further evaluate the role of the insurance industry.

To be more precise, our first extension is to model natural disasters as extreme events through a Poisson process, which is the natural approach towards understanding the role of uncertain extreme events. Our model here extends the previous works by Tsur and Zemel (1996), Tsur and Zemel (1998), Gjerde, Grepperud and Kverndokk (1999), De Zeeuw and Zemel (2012), Keller, Bolker and Bradford (2004), Tsur and Zemel (2008) and Zemel (2015), who analyze the impact of a single extreme event.[2] Normally, uncertainty in climate change models is analyzed via Brownian motions or sensitivity analysis, which is not useful to understand the economic impact of extreme events (Goodess, Hanson, Hulme and Osborn 2003). We show that the existence of extreme events modeled through a Poisson process leads to substantial changes from the results

[1] According to EM-DAT an event qualifies as a natural catastrophe if ten or more people are reported killed; or hundred people reported affected; or a declaration of a state of emergency or a call for international assistance happened.

[2] During the revision of this article, Bretschger and Vinogradova (2014) developed an AK growth model with a climate sector and Poisson-driven extreme events. The main difference to our model is their linearity assumption, which in turn allows the authors to obtain explicit results. Also, we allow for endogenous extreme events and insurance.

obtained in seminal climate policy assessment models (Nordhaus 2008). Overall, Poisson processes have seen surprisingly few applications in economic theory. The works by Waelde (1999) and Sennewald and Waelde (2006) were among the first continuous-time applications.

The other innovation to the literature is the inclusion of an insurance sector. Disaster insurance as provided by the major players in the insurance industry is the main market-based tool of reactive adaptation (Paavola and Adger 2006). This stands in contrast to e.g. the kind of adaptation mechanism as studied in Zemel (2015), which one may call preventive adaptation (Duus-Otterström and Jagers 2011).[3] Preventive adaptation is a means of reducing the actual impact of a disaster, while reactive adaptation tends to be come in the form of monetary transfers in the aftermath of a disaster. Our approach here of studying reactive adaptation is by studying the impact of an insurance sector through analyzing the role of different pricing and information strategies on the take-out of insurance policies and consumption, saving and abatement decisions. In particular, we model how full and partial information on the pricing mechanism affects the abatement decision of the agent. Since we assume that the agent can affect the state of the environment by appropriately deciding between consumption, saving and abatement, and since the state of the environment affects the frequency and strength of extreme events, the agent can affect the costs of insurance. It turns out that the insurance sector can implement a type of climate policy by signaling the consequences of climate change via insurance costs. This again is new to the literature, where climate policy tends to be solely based on government intervention.

One key assumption underlying our analysis is that climate change is endogenous to the decisions of the agent. We believe there exists ample evidence supporting this point of view that we do not need to motivate this assumption further. See for example the comprehensive studies by McCarthy et al. (2001) and Stern (2006). The evidence for extreme events being endogenous in terms of number and strength to changes in the climate however is less certain. We studied the climatology literature and the overall conclusion seems to be that in some regions extreme events increase in strength and numbers whereas in other regions they do not , see e.g. Walsh and Ryan (2000), Walsh (2004) or Henderson-Sellers et al.(1998). Also, in those regions where the strength of hurricanes increases the overall number of hurricanes seems to decrease (Webster, Holland and Curry 2005, Elsner, Kossin and Jagger 2008). Furthermore, climate change is going to lead to strong regional changes in the extreme weather conditions, with significant changes in

[3] For a discussion of different types of adaptation and the role that the government may take we refer the reader to Konrad, and Thum (2014).

the hot and cold days as well as wetter or drier areas (McCarthy et al. 2001, Stern 2006). Given this evidence, we pursue the following path. In the theoretical part we try to be as general as possible and assess the effects of endogenous changes in the number and strength of extreme events. In the computational part we only assess changes in the strength of events. Our damages are here calibrated to be in accordance with the standard integrated assessment literature with the main difference being that they come at uncertain points in time.

Our main results can be summarized as follows. We find that the transparency of the insurance sector is the decisive requisite for abatement activities, implying substantial policy opportunities. Essentially, if the insurance industry gives no information on the endogeneity of the insurance premium, then agents will only undertake mitigation actions for non-market- damages reasons. However, if the insurance industry provides full information on how the agents' actions impact climate change and thus the insurance premium, then the agents will integrate these feedbacks into their mitigation decisions. Another finding is that a decentralized economy will under-invest in mitigation without adequate policy interventions. This result is akin to the public good literature where agents, even if they know that extreme events are climate-driven, may not invest in mitigation actions because they perceive themselves to be too small to have an impact on climate change. Thus, this suggest substantial policy interventions at the aggregate level. We then study the impact of agents not having full information on the frequency of extreme events, and can thus have either optimistic or pessimistic beliefs. We find that pessimistic, or precautionary, beliefs on the frequency of extreme events leads to more sustainability. A further result is that a social security system which prices insurance fairly is preferable to an insurance industry which provides insurance with an overhead. This arises since agents prefer to insure fully in case insurance is provided fairly, which is welfare-improving.

The article is structured as follows. Section 2 introduces and solves the theoretical model. Section 3 gives the integrated assessment model with computational experiments. Finally, Section 4 concludes.

2 The Theoretical Model

The setup of the model follows a Ramsey-type growth framework, where an infinitely-lived agent maximizes his uncertain stream of felicities $u(c(t), T(t))$, which is a function of consumption ($c(t) > 0$) and temperature ($T(t) > 0$), subject to consumption, abatement ($a(t) \geq 0$), insurance cover ($1-\gamma(t) \in [0,1]$), and the capital stock ($k(t) > 0$). Capital increases with production and is reduced by constant depreciation ($\delta_k > 0$), consumption, abatement, the size of the insurance premium $P(t)$, the percent of uninsured capital ($\gamma(t) \in [0,1]$), and uncertain extreme events. The extreme event is modeled as a Poisson process. When $q(t) = 0$ no shock occurs, whereas if $q(t) = 1$, then an extreme event reduces capital stock by $\gamma(t)\psi(T(t))k(t)$. The expected number of extreme events in any point in time is an endogenous, increasing function of temperature and given by $\lambda(T(t)) > 0$. The share of capital destroyed by an extreme event is given by the function $\psi(T(t)) \in (0,1)$, which too is increasing in temperature. When there is full insurance, thus $\gamma(t) = 0$, then the agent has full insurance coverage and will not be (financially) affected by the extreme event. Temperature is increased by productive activity and decreases due to a natural regeneration. In our model, abatement can reduce emissions, but it cannot affect temperature directly. One should therefore interpret abatement as an investment in greener technology. Our model can thus be viewed as an extension of the work by Gollier (1994) by allowing for abatement, as well as an endogenous number and size of extreme events and a climate change sector.

The agent thus solves the following problem:[4]

$$V(k_0, T_0) = \max_{\{c(t),\gamma(t),a(t)\}} E_{t_0}\left\{ \int_{t_0}^{\infty} u(c(t), T(t)) e^{-\rho(t-t_0)} dt \right\} \tag{1}$$

subject to

$$\begin{aligned} dk(t) &= \{f(k(t)) - c(t) - a(t) - (1-\gamma(t))P(t) - \delta_k k(t)\}dt - \gamma(t_-)\psi(T(t_-))k(t_-)dq(t), && (2)\\ dT(t) &= \{g(k(t), a(t)) - \delta_T T(t)\}dt, && (3)\\ &\quad \text{and} \quad k(0), T(0) \quad \text{given.} \end{aligned}$$

The interpretation of $T(t)$ as an argument in the utility function is that it represents a shorthand notation for $u(c(t), \lambda(T(t)))$ and means that the agent's utility is decreasing in the expected number of accidents. If $T(t)$ is interpreted as the stock of CO_2, then another interpretation is simply that it represents the amenity value for the environment or other non-market damages. We assume that capital follows a cádlág process, such that $k(t)$ is continuous from the right having left limits. The left limits are given by $\lim_{s\uparrow t} k(s) = k(t_-)$. Intuitively, if an extreme event occurs, then the size of the jump depends on the amount of capital just before the jump. In the subsequent part we skip this extra piece of notation but hope the reader keeps this in mind.

[4]We use subscripts to denote the first and double subscripts to denote the second derivate of functions with two arguments, while apostrophes for the derivatives of functions with one argument.

We assume the following functional forms.

Assumption 1: *The utility function* $u : \mathbb{R}^2_+ \to \mathbb{R}_+$ *is at least twice continuously differentiable, concave in both arguments, with* $u_c(c,T) > 0$*,* $u_T(c,T) < 0$*, and* $\lim_{c\to 0} u'(c) = \infty$.

Assumption 2: *The production function* $f : \mathbb{R}_+ \to \mathbb{R}_+$ *follows* $f(k) \geq 0$*,* $f(0) = 0$*,* $f_k > 0$*,* $f_{kk} < 0$*, with* $\lim_{k\to 0} f_k = \infty$*, and* $\lim_{k\to\infty} f_k = 0$.

Assumption 3: *The share of capital stock destroyed is* $\psi(T) \in (0,1)$*,* $\psi_T > 0$.

The assumptions on $\psi(T)$ come from the previous section.

Assumption 4: *The extreme event is modeled via a Poisson process. The endogenous, expected number of extreme events follows* $\lambda(T) > 0$*,* $\lambda'(T) > 0$.

Assumption 5: *Temperature increases concavely with capital* $g_k(k,a) > 0$*,* $g_{kk}(k,a) < 0$*, and decreases concavely with abatement activity* $g_a(k,a) < 0$*,* $g_{aa}(k,a) < 0$. These last assumptions on temperature accumulation are standard in the integrated assessment literature.

The Bellman equation of this control problem is given by

$$\rho V(k(t),T(t)) = \max_{\{c(t),a(t),\gamma(t)\}} \left\{ u(c(t),T(t)) + \frac{1}{dt} E_t dV(k(t),T(t)) \right\},$$

and $V(k(t),T(t))$ refers to the optimized utility functional. This equation suggests that the return of having $k(t)$ and $T(t)$, denoted in indirect utility terms, should at any point in time be equal to the instantaneous felicity as well as the expected change in the future indirect utility stream. Making use of the Change of Variable formula, which is the equivalent of Itô's Lemma but holds for Poisson processes, see Davis (1993), and taking the expectation we arrive at the following Hamiltonian- Bellman-Jacobian equation.

$$\begin{aligned}\rho V(k(t),T(t)) \quad = \quad & \max_{\{c(t),a(t),\gamma(t)\}} \Big\{ u(c(t),T(t)) + \big(g(k(t),a(t)) - \delta_T T(t)\big) V_T \\ & + \big(f(k(t)) - c(t) - a(t) - (1-\gamma(t))P(t) - \delta_k k(t)\big) V_k \\ & + \lambda(T(t)) \Big[V\big(k(t) - \gamma(t)\psi(T(t))k(t), T(t)\big) - V(k(t),T(t)) \Big] \Big\}.\end{aligned} \tag{4}$$

The part of the Bellman equation with the squared brackets includes the adjustment through extreme event. The term $V\big(k(t) - \gamma(t)\psi(T(t))k(t), T(t)\big) - V(k(t),T(t))$ describes the total cost of the extreme event, since it refers to the difference in indirect utility after a jump occurred minus the indirect utility without a jump. This difference is multiplied by $\lambda(T)$ to transform it in expected value terms.

The dynamic system after optimization is completely characterized by the following system of equations:

$$
\begin{aligned}
-\frac{u_{cc}}{u_c}dc &= \Bigg\{f_k - \delta_k + \frac{g_k}{g_a} - \rho + \frac{u_{cT}}{u_c}\big(g(k,a) - \delta_T T\big) \\
&\quad + \lambda(T)\bigg(\frac{u_{\tilde{c}}}{u_c}\big(1 - \gamma\psi(T)\big) - 1\bigg)\Bigg\}dt - \bigg\{\frac{u_{\tilde{c}}}{u_c} - 1\bigg\}dq(t), && (5)\\
\frac{g_{aa}}{g_a}da &= \Bigg\{g_a\frac{u_T}{u_c} - f_k + \delta_k - \delta_T - \frac{g_k}{g_a} - \frac{g_{ak}}{g_a}\bigg[f(k) - c - a - (1-\gamma)P - \delta_k k\bigg] \\
&\quad + \lambda_T\bigg[\frac{\tilde{V} - V}{V_T}\bigg] + \lambda(T)\bigg[\frac{\tilde{V}_T}{V_T} - \frac{\tilde{V}_k}{V_T}\gamma\psi_T k - \frac{u_{\tilde{c}}}{u_c}(1 - \gamma\psi(T))\bigg]\Bigg\}dt \\
&\quad + \bigg\{\frac{u_{\tilde{c}}}{u_c} - \frac{\tilde{V}_T}{V_T} - \frac{\tilde{g}_a}{g_a} + 1\bigg\}dq(t), && (6)\\
dk &= \{f(k) - c - a - (1-\gamma)P - \delta_k k\}dt - \gamma\psi(T)k\,dq(t), && (7)\\
dT &= \{g(k,a) - \delta_T T\}dt, && (8)\\
\frac{u_{\tilde{c}}}{u_c} &= \frac{P}{\lambda(T)\psi(T)k}, && (9)
\end{aligned}
$$

where $\tilde{x}$ refers to a variable after a jump occurred, and time subscripts are submitted for simplicity. We can interpret this system describing the way preferences and technical possibilities work together. Starting with equation (9) we know this defines the optimal level of insurance cover for the agent. If the premium is fair and therefore equal to the expected damages, then we obtain $\tilde{c} = c$ and no jump will occur since the agent will fully insure. This is a standard result in the insurance literature, attributable to Mossin (Mossin 1968). If there is an overhead on the premium, then $u_{\tilde{c}} > u_c$ which by concavity of the utility function implies consumption after an extreme event is lower than before an extreme event. The larger the overhead on the premium the bigger the jump of consumption.

Equation (5) refers to the optimal consumption choice of the agent. The part in the first curly brackets explains the way the agent chooses during periods in which no extreme event occurs. This term is a standard Ramsey-Keynes component, where the agent will choose to increase consumption if the benefits of producing more outweigh the costs of capital depreciation, time preference, and it also involves a valuation of how changes in temperature affect future marginal utilities. We obtain a new result about precautionary savings, which is summarized in the following proposition.

Proposition 1 *Given the control system* (1) *to* (3) *we find that the anticipation of extreme events may either lead to precautionary savings or precautionary consumption. Given an indemnity contract with a fixed overhead* $\phi > 1$ *we find positive precautionary savings if* $\gamma\psi > (\phi - 1)/\phi$.

To understand this result we have to investigate the term $\lambda(T)\big(\frac{u_{\tilde{c}}}{u_c}\big(1-\gamma\psi(T)\big)-1\big)$, which is new to the literature. If we assume that the currently exogenously given insurance premium sufficiently exceeds the expected damage, then we know that if an extreme event occurs, consumption will decrease and therefore $u_{\tilde{c}} > u_c$. Hence, if the jump is large enough, then this term will have a positive effect on consumption growth. We call this precautionary consumption. Since the agent knows that in the future his consumption might be reduced through an extreme event, he prefers to increase his current consumption in order to fall back to some average level later. However, this term need not always be positive. If insurance cover is low and the percent of capital stock which gets destroyed large, then the overall term might turn negative, leading to a reduction in consumption in favor of either abatement activity, insurance or precautionary capital accumulation. It therefore becomes clear that the theoretical model leaves us with an insurance puzzle: Whether the agent increases or decreases his future consumption will depend on the relative strength of the precautionary consumption versus the precautionary savings effect. The last term in the curly brackets refers to the adjustment in case an extreme event occurs. Since the ratio $u_{\tilde{c}}/u_c \geq 1$ we know that the jump in case an extreme event occurs will be negative. Indeed, the size of the jump can be found for the case of an interior solution in $\gamma \in (0,1)$, constant-relative risk aversion (CRRA) utility and a standard insurance contract with an overhead on an otherwise fair premium. In that case we know from equation (9) that $u_{\tilde{c}}/u_c = \phi$, where $\phi > 1$ gives the overhead. Thus the jump in consumption will be determined by the level of consumption before the jump, the size of the overhead and the intertemporal elasticity of substitution (IES). It will be given by $\tilde{c} = \phi^{-1/\sigma}c$, where $\sigma > 0$ is the IES. We can easily calculate that $\frac{d\tilde{c}}{d\sigma} > 0$ (taking given the effect of σ on c), implying a stronger consumption smoothing the larger the intertemporal elasticity of substitution. This also allows us to obtain a condition for the precautionary consumption versus savings decision. Given the previous assumptions, precautionary consumption is positive if $\gamma\psi < (\phi-1)/\phi$, whereas precautionary savings are positive otherwise. Clearly, the more capital gets destroyed the more incentive will be for precautionary savings. On the converse, the larger the overhead the more likely is precautionary consumption.[5] One would, therefore, expect more precautionary consumption if the agent insures less.

Equation (6) gives optimal abatement. The terms in the first line are the standard ones describing trade-offs between abatement versus capital for their relative effectiveness on temperature, capital accumulation and future costs. The first term in the second line describes the cost of a marginal increase in the expected number of extreme events on the future stream of utilities.

[5] Since $\gamma\psi < 1$ is bounded by $\psi < 1$ for $\gamma \to 1$ whereas $(\phi-1)/\phi \to 1$ for increasing ϕ.

The larger the marginal impact of temperature on the expected number of extreme events and the higher the costs of an extreme event in terms of utility foregone, the stronger will the agent increase abatement. The second term in the second line gives the amount of precautionary abatement. Precautionary abatement is positive if, in case of an extreme event, we expect a lot of capital to be destroyed and if the impact of changes in temperature on the percent of capital which gets destroyed is very large. Precautionary abatement can be negative though, too. This will be the case if precautionary consumption is very big. This trade-off obviously comes from the capital constraint. The third line of equation (6) gives the impact on abatement in case of an extreme event. Abatement growth itself will respond to an extreme event with either an upward or a downward jump. It will jump upwards if consumption falls significantly after a jump, but it will decline if the marginal impact of temperature on indirect utility after a jump is much higher than before a jump.

In general, this system is not fully analytically tractable[6] but it allows us to look at specific, important cases which would normally not have been observed or taken into account. These cases provide us with tractable benchmarks which we shall also later use in the computational experiments.[7]

2.1 The insurance industry

Our intention now is to introduce the insurance industry in this framework. We start with the strong assumption that the insurance company behaves like a risk-neutral firm in a perfectly competitive market. This has two major implications. Firstly, we do not account for a possible default of the insurance sector. Though this is a viable threat for small insurance companies, we do not believe that this is likely to occur for the global insurance sector. If the premia are chosen with a certain foresight that reflects the actual expected number and size of extreme events, then the probability of a global default of the insurance industry is likely to be small. Furthermore, it is standard in the insurance industry that certain portfolios which smaller insurance companies deem too risky are transferred to reinsurance companies that can control these excess risks much

[6] A special case of this model has been studied in Bretschger and Vinogradova (2014). There the authors study the model without insurance, with an AK technology and flow pollution.

[7] In general it is not our objective to solve for the dynamics of these systems. However, it can be shown that a steady state exists (in the certainty case). Solving for the dynamics around steady state will however give conditions which do not help us in interpreting the results.

better. Secondly, with this assumption we abstract from the possibility that the insurance sector accumulates capital which it can invest in a capital market.[8] Abstracting from these points allows us to derive more clear-cut results for the role that the actual premium plays in agents' decisions. The implications of the insurance industry in our model could therefore be described as follows.[9] The agent will be able to obtain insurance but in his decisions of insurance he will not include the possibility of default in the insurance industry (since the probability of default is zero). If the insurance industry is able to receive more capital during certain periods than it has to pay out, then this capital will not be invested in the capital market but stays perfectly liquid in order to pay for future claims later. With this in mind we can turn to the problem of the insurance sector.

The expected insurance claims at any point in time are $\lambda(T(t))\psi(T(t))k(t)(1-\gamma(t))$, whereas the insurance premia obtained are $(1-\gamma(t))P(t)$. There may exist transaction costs or operational costs, represented by a mark–up $\phi > 0$ on the insurance claims. The expected profits are therefore

$$E(\Pi(t)) = (1-\gamma(t))P(t) - (1+\phi)\lambda(T(t))\psi(T(t))k(t)(1-\gamma(t)).$$

The zero-profit condition then implies $P(t) = (1+\phi)\lambda(T(t))\psi(T(t))k(t)$, where $(1+\phi)$ represents overhead charges on the premium. If the transaction costs or operational costs are negligible, then the premium will be equal to the expected costs from an extreme event for a fair insurance contract.

[8] One could argue that the insurance industry, and especially re-insurance companies, are non-negligible players on the world capital market. As such, they could play both an active role in driving the capital market and in mitigation (Mills 2012). However, allowing for a positive profit would raise questions like: To whom belongs this capital? Are these companies then risk-neutral or do they reflect the preferences of their owners? Is their mitigation action a complement or a substitute to the public's mitigation action? This would obviously give rise to similarly strong assumptions. Finally, a representative insurance company would have to withdraw capital from the capital market in equal amount to the losses from an extreme event, which thus would be equivalent to no insurance at all. One could therefore not study a complete general equilibrium setup with a agent framework. We are willing to give up a small amount of completeness in order to be able to clearly compare to previous results while still keeping a good degree of analytical tractability.

[9] Whether or not the insurance industry can continue to provide coverage when faced with continuous climate change is subject to discussion, e.g. Tol (1998) suggests that there may be significant obstacles, whereas e.g. Konrad et al. (2014) are more supportive. We shall avoid this discussion here and simply do as if the insurance industry has superior and sufficient knowledge of the climate change risks.

2.2 The case of naive insurance

In this section we assume that there is no overhead[10] on the insurance premium such that $\phi = 0$. In this case we obtain the following result.

Result 1 *The optimal control problem given by equations* (1) *to* (3) *leads us to conclude that transparency of the insurance industry is decisive for abatement decisions and thus sustainability.*

More specifically, given the dynamic system (5) to (9) we obtain that any risk-averse agent will choose full insurance, thus $\gamma(t) = 0$ (Mossin 1968). This implies that our dynamic system reduces to

$$\begin{aligned}
-\frac{u_{cc}}{u_c}\dot{c} &= f_k - \rho - \delta_k + \frac{g_k}{g_a} + \frac{u_{cT}}{u_c}\dot{T}, &(10)\\
-\frac{g_{aa}}{g_a}\dot{a} &= -g_a\frac{u_T}{u_c} - \delta_k + \delta_T + f_k + \frac{g_k}{g_a} + \frac{g_{ak}}{g_a}\dot{k}, &(11)\\
\dot{k} &= f(k) - c - a - \lambda(T)\psi(T)k - \delta_k k, &(12)\\
\dot{T} &= g(k,a) - \delta_T T. &(13)
\end{aligned}$$

Under a fair insurance premium the only effect which the extreme event might have is that the agent behaves as if he has a capital stock which is reduced by the expected damage of extreme events (his payment to the insurance industry). Not surprisingly, his consumption and abatement decisions are not affected by any precautionary decision process. Most interestingly, since the agent takes the evolution of the insurance premium as given, he will not take the impact of his decisions on the expected number and size of extreme events into account. We interpret this case as that of a *naive insurance*, and it is here where the role of the insurance industry becomes dominant. If the insurance industry is not transparent enough and does not inform the agent of his influence on the evolution of the insurance premium, then this should have drastic consequences for climate change. Since the agent does not control for the effect of temperature on the premium, one would expect that temperature increases drastically in the naive insurance case, which should lead to large reductions in future capital stocks. We shall confirm this in a subsequent section via computational experiments.

Corollary 1 One could very well imagine that this case corresponds to the way a small agent in a decentralized setup would act who believes that his decisions have no influence on the evolution

[10] We investigate the implication of an overhead in the next section.

of the premium. Possible changes in the premium would not figure in his abatement decisions. The only reason for undertaking abatement in this case would be the mitigation of non-market damages in the utility.

As we have seen, transparent pricing of insurance contracts may play a significant role for the evolution of climatic and economic variables. Of course, if the insurance industry feels that future environmental and economic conditions are important, then it could improve upon this situation. Apart from setting the size of the premium and thereby influencing the decisions of the agent, the insurance company can inform the agent about the evolution of the premium given his production choices. We shall analyze this case now.

2.3 The case of an internalized insurance premium

Imagine that the agent knows that he will get a fair premium and will therefore take up full insurance. Furthermore assume that the insurance company transparently communicates to the agent how their economic decisions impact the premium which they have to pay. Then the agent will incorporate the changing costs of the insurance premium into his decision taking.

Result 2 *Under a fair and internalized insurance premium the agent will fully incorporate the future climate change costs of his decisions.*

The problem then writes as follows:

$$V(k_0, T_0) = \max_{\{c(t), a(t)\}} \int_{t_0}^{\infty} u(c(t), T(t)) e^{-\rho(t-t_0)} dt \tag{14}$$

subject to

$$\begin{aligned} \dot{k}(t) &= f(k(t)) - c(t) - a(t) - \lambda(T(t))\psi(T(t))k(t) - \delta_k k(t), & (15) \\ \dot{T}(t) &= g(k(t), a(t)) - \delta_T T(t). & (16) \end{aligned}$$

A rather surprising observation is that this is equivalent to a standard integrated assessment model like DICE by Nordhaus (1991). The DICE model is therefore similar to our model if we have a fair premium and thus full insurance plus a agent who takes the evolution of this premium into account. One could rephrase this slightly. Assuming one wishes to use the DICE model to analyze extreme events without altering its structure. Then we can conclude that the model will produce acceptable results only under full insurance and the internalization of the evolution of the premium.

Writing the Hamiltonian from the above equations leads to

$$\mathcal{H} = u(c,T) + \mu\big[f(k) - c - a - \lambda(T)\psi(T)k - \delta_k\big] + \xi\big[g(k,a) - \delta_T T\big]. \tag{17}$$

We can derive the following system of equations which characterize the dynamics:

$$\begin{aligned}
\dot{c} &= c\sigma(c)\left[f_k - \lambda(T)\psi(T) - \rho + \frac{g_k}{g_a} - \delta_k + \frac{u_{cT}}{u_c}\dot{T}\right], && (18)\\
\dot{a} &= a\theta(a)\left[f_k - \lambda(T)\psi(T) - \delta_k + \delta_T + \frac{g_k}{g_a}\right. && (19)\\
&\quad \left. -\frac{u_T}{u_c}g_a + g_a\big(\lambda_T\psi(T) + \lambda(T)\psi_T\big)k + \frac{g_{ak}}{g_a}\dot{k}\right], && (20)\\
\dot{k} &= f(k) - c - a - \lambda(T)\psi(T)k - \delta_k k, && (21)\\
\dot{T} &= g(k,a) - \delta_T T, && (22)
\end{aligned}$$

where we define $\sigma(c) = -u_c/(cu_{cc})$ and $\theta(a) = -g_a/(ag_{aa})$. Two new effects can be singled out. Firstly, the direct effect of the premium's size. If $\lambda(T)\psi(T)$ is large, meaning that many events happen and they destroy a significant part of the capital stock, then this term may lead to a decrease in consumption and abatement growth. Both may be optimally reduced since stronger damage leads to a lower global capital stock which does not allow to continue consumption and abatement at the previous levels. The other new term only affects abatement and it relates to the direct impact of abatement on the change in the expected value of an extreme event through a change in temperature. The larger the marginal effect of abatement on temperature or the larger the effect of temperature on the expected costs of the extreme event, the more will be invested by the agent into reducing temperature. This term does not show up in the accumulation for consumption since consumption affects temperature or the expected costs of extreme events only indirectly. In the computational experiments we shall study the magnitude of this result in a properly calibrated model.

It is important to emphasize again the role of information. Since the agent can internalize his impact on the premium in case the insurance policy is set in a transparent way, then we would certainly expect a lower insurance premium over time than it would be the case of a naive insurance policy. One could question whether there can exist a market equilibrium with a fully transparent insurance policy, or whether a naive insurance policy is superior from an insurance company's perspective. The first observation here is that, in order to avoid default, both a naive insurance policy and a fully transparent insurance policy will be based upon the same premium. The only difference is that in the latter case the agent is told how he may impact the premium himself. However, over time, an economy faced with a transparent premium will evolve to have a different premium compared to an economy with a naive policy because a transparent policy induces agents to take their impact on the premium into account.

As a second point we would argue that an insurance company does have incentives to set a transparent policy. Let us, just for the purpose of illustration, marginally re-write the profit function of an insurance company. Neglecting mark-ups, we may define the profits a naive insurance and those of a fully transparent insurance, assuming that the insurance company itself is not fully informed about the risks that it faces in the future. Let us thus assume that the insurance companies believe that with probability q they are faced with a low expected number of extreme events (λ_L), while with probability $1 - q$ they face a high expected number of events (λ_H). Furthermore, let us assume that the insurance company knows that these probabilities are endogenous to climate change, such that $q(T)$, with $q_T > 0$. In this case, an insurance industry with a fully transparent insurance policy will, over time, be faced with lower probabilities of high extreme events, because agents incorporate their impact on the premium and hence undertake more mitigation actions. Hence, the uncertainty of being faced with potentially higher damages diminishes with more insurance companies that provide transparent policies. Thus, while in theory it is entirely possible that a naive insurance co-exists with a fully transparent insurance, from the perspective of the insurance industry itself, a fully transparent policy tends to be preferable due to the reduced future risks that it is likely to bring.

In effect, insurance companies around the world have already picked up upon this effect. As Mills (2009) has described in his review of insurance industries' responses to climate change, for most insurance industries climate change ranks among the top threats, if not the top threat, that the industry faces. The response of the insurance industry to this threat took many forms, among which climate-risk disclosure was one of the main ones. Insurance companies now work much closer together with policy makers and with the general public in order to fully inform them about potential mitigation and adaptation possibilities, and how this affects their premia (Mills 2009). In addition, they undertake actions that lead to risk-reducing behavior, for example in terms of Pay-as-you-drive insurance schemes (Lifsher 2008), or more general where insurance policies reward greener behavior with lower premia (Mills 2009).

3 Computational Experiments

The analytical model gives first insights into the dynamics of an economy which is exposed to extreme events. To show how these events affect consumption, investment and abatement, this section reports results from computational experiments.

Computational experiments require fully specified functions and parameters. To keep the analysis comparable with the literature, these functions and parameters are taken from well-known integrated assessment models, whenever reasonable and available. Moreover, we develop a technique to solve the model numerically. It is a top–down technique based on non–linear optimization. We use time–consistent forward iterations to approximate an infinite time-horizon. Details are given below.

3.1 Specifications

Instantaneous utility of the risk averse agent is assumed logarithmic in current consumption. We neglect direct impacts of climate change on utility, hence $u(c(t)) = \ln(c(t))$. We assume away non-market damages to be able to show more clearly the role of the insurance premium. The climate sub–model takes current carbon dioxide emissions $e(t)$ as input from the economic model and translates these into atmospheric carbon concentration perturbations, $A(t)$. Atmospheric carbon is measured in ppmv (parts per million) relative to the pre–industrial level (280 ppmv). We short-cut the link between emissions and climate change induced damages for computational reasons. Economic damages directly relate to $A(t)$, leaving out the temperature-perturbation module of climate sub-models. A similar sub–model to map $e(t)$ on $A(t)$ is used in Nordhaus' DICE 2007 version. Joos et al. (1999) have shown that this proxy works quite well. The climate sub–model is sufficiently non–linear to mimic the results of larger climate models like those used in the IPCC scenarios.

Carbon emissions arise in fixed proportions to production of $y(t)$. However, emissions can be abated, for example by substituting solar energy for oil. Abatement activities are summarized through $m(t) \in [0, 1]$ which gives the share of abated emissions in total emissions.

Production of $y(t)$ is Cobb–Douglas type with labor and capital as inputs. Output elasticity of capital is assumed 0.3. Labor is exogenously given and price–inelastically supplied. Production is spent on consumption, investment, insurance and abatement, with abatement costs $a(t) =$

$.3m(t)^2y(t)$. Completely decarbonising the economy ($m(t) = 1$) would take thirty percent of GDP in addition to current energy spending. Capital accumulates according to

$$K(t+1) = \big(1 - \gamma(t)\Psi(A(t)\big)dq(t))(1 - \delta_K)K(t) + i(t)$$

where

$$\Psi(A(t)) = 0.001 + \min\left\{1, \frac{\Delta A(t)^2}{\Omega_K}\right\}. \tag{23}$$

The share of uninsured in total capital is $\gamma \in [0,1]$, which is a decision variable for the agent. We term this the insurance cover. The arrival rate of extreme events is fixed such that one extreme event is expected every ten years. We assume that this probability does not depend on the current climate. Thus, in our simulations extreme events do not occur with higher frequencies, but instead only with a higher intensity that is driven by climate change. Parameter Ω_K is calibrated such that the expected value of damages due to extreme events accounts for a loss of 3 per cent in total output at double pre–industrial carbon concentration (equivalent to a rise in temperature of 2.5 C).[11] The discount rate on instantaneous utility ρ is assumed 0.03, and capital depreciation is $\delta_k = .05$.

Simulations are carried out with GAMS/CONOPT3. Time is taken as discrete with a five year time–step. We establish a complete stochastic event tree for ten periods, resulting in 512 different scenarios which the agent takes into consideration. This is the full–fledged stochastic part of the numerical model. To avoid end-of-time horizon effects, we concatenate the stochastic model with its deterministic counterpart for another 30 periods. The deterministic counterpart is based on expected values for damages. It is linked to the stochastic version by taking the expected capital and carbon stocks in the final stochastic period as initial stocks to the deterministic model. In sum, the agent looks 200 years ahead when making his decisions; 50 years are modeled fully stochastic.

To proxy the fully stochastic model, we employ an envelope–technique by exploiting the time consistency of optimal decisions. This works as follows: we start in $t = 0$ where $k(0)$ and $A(0)$ are given. The agent maximizes her expected utility by choosing $c(t)$, $i(t)$, $\gamma(t)$ and $m(t)$ state-contingent on the unfolding scenario of observed extreme events. Only $c(1)$, $i(1)$, $\gamma(1)$ and $m(1)$ are determined irreversibly in period $t = 0$. All other decisions are state–contingent, depending on the course of events. After the agent made her decisions, nature decides whether an extreme

[11] This is equivalent to a twenty per cent capital damage in case of an extreme event. Since the expected number of events is .5, and the output elasticity .3, this ends up with an expected loss of three per cent.

event occurs $(dq = 1)$ or not $(dq = 0)$. In period $t = 1$ we then have two different initial states. We proceed by re-running the complete model for every initial state. This procedure continues for ten periods, i.e. we unfold 512 scenarios.

To cope with the curse of dimensionality, we consider only ten periods in full stochastic dimensionality. Sensitivity analysis shows that the combination of concatenated stochastic–deterministic model jointly with the forward recursion procedure gives excellent results.

The scenarios are sampled such that the agent observing these scenarios would conclude from statistical inference that he faces a Poisson process with the given arrival rate $\lambda = .5$.[12]

We run computational experiments to get quantitative answers for the following questions: What is the implication of uncertainty and insurance for policy decisions? What happens if the agent holds false beliefs about the risk of extreme events? Who should provide insurance?

Based upon the theoretical model we single out three broad scenario types.

- *Stochastic* means that the agent can not insure at all, hence he is fully exposed to extreme weather events. He anticipates his influence on the future climate and related damages.
- *Perfect Insurance* occurs for a fair insurance premium, i.e. the premium equals expected damages from extreme events. In this case, a risk averse agent transfer all risks to the insurance company. He takes into account that he endogenously determines the insurance premium through non–abated emissions. This is similar to a deterministic case with fully internalized climate change like in the DICE or MERGE models. We take this scenario as reference.
- *Naive Insurance* refers to the scenario where the agent insures against extreme weather events but – in contrast to the perfect insurance scenario – takes climate change and the insurance premium as given. The insurance premium is fair.

In principle, we compare a stochastic economy (Stochastic) with an economy where climate damages unfold smoothly and deterministically (Perfect Insurance). Evidently, the variance of the stochastic paths tends to infinity over time due to the Poisson process. Reporting single paths or a small selection of paths therefore makes no sense as one might have picked up very unlikely

[12] A scenario is a sequence $dq(t), t = 1, ...$ of 0, 1, indicating the number of extreme events in t. We do not consider the case where more than one extreme event occurs.

paths with either many or very few events. We avoid this problem by considering the expected realizations at date t of each variable.

The basic results refer to the Stochastic and Perfect Insurance scenarios. Recall that the agent in the Stochastic scenario fully bears the risk of extreme events. In Perfect Insurance, he can – and indeed does – transfer all risk to the insurance company, which charges the expected damages as the premium.

Table 1 shows the impact of extreme events. In fact, the effects are quite small, in particular for the first periods. This is due to the small intensity at low carbon stocks and a low degree of risk aversion. The natural and man-made capital stocks behave in the expected way: atmospheric carbon stocks (natural capital) are lower in Stochastic than in Perfect Insurance. Man-made capital is lower too, implying that the agent substitutes physical capital by natural capital when exposed to the risk of extreme events.

The precautionary saving motive dominates precautionary consumption. Only in the first period, we observe a tiny precautionary consumption effect, which is too small to be discriminated from numerical imprecision of the applied solver settings.

The individual stochastic paths differ significantly as time unfolds. In Table 2 we report the worst, best and expected case for consumption. The worst case occurs for one extreme event every five years, the best case if no extreme events occur. In 2040, consumption in the worst case is -6.3 % relative to expected consumption and $+7.7\%$ for the best case.

As we suggested above, results may be different if the insurance industry does not inform the agent about the relationship between the premium and climate change. This corresponds to our naive insurance scenario. It is equivalent to a non-transparent or non-internalized insurance policy, and it is furthermore equivalent to a competitive economy where a small agent considers himself sufficiently small not to bear any impact on the insurance price. Since the agent is not informed about the endogenous evolution of the premium, no abatement will be undertaken.[13] Since the agent does not take his impact on the insurance premium into account, it leads to large initial increases in investment allowing for high consumption in the subsequent periods, followed by a fast worsening of the climate feedback. In our simulation, these increases in temperature lead to a large damages due to extreme events. After around 40 years this implies large destructions of capital stock, leading to a non-sustainable evolution of consumption. In

[13]The only mitigation that an agent would undertake would be due to non-market damages, which are however excluded in this simulation.

terms of welfare, the naive insurer does the worst of all.

3.2 Are precautionary beliefs welfare-improving?

Information on how the agent can influence the impact of extreme events, and hence the evolution of the insurance premium, is one of the key determinants of an optimal path of the main economic and environmental variables.

Information about the impact of extreme events comprises both the expected number (λ) and the size (ψ) of extreme events. In this subsection we assume that the agent knows the size of the extreme events and how they are climate change impacts these. However, he does not necessarily know the true λ. We then ask what would be the effect of under- or overestimating this key parameter? Underestimation of λ could reflect an optimistic attitude since the agent assumes that things are not as bad as they seem. Overestimation of λ reflects a pessimistic, more precautionary attitude. Both cases then reflect false-beliefs about λ.

The *False Beliefs* scenario that we are going to study then refers to the Stochastic scenario with the agent holding wrong beliefs about the probabilities of extreme events. To outline the idea of measuring welfare implications of false beliefs, i.e. expectation errors, recall that we simulate an event tree for a finite time horizon T. This time horizon spans $S = 2^{T-1}$ scenarios, where each scenario s is a sequence of 1 and 0, indicating whether an extreme event occurred or not. For example $s = (0, 0, 1, 0, \dots)$ is a scenario, where the first extreme event occurs in period three. Scenario s occurs with probability $p_\lambda(s)$, which depends on λ and the number of extreme events in s.

The agent can choose an optimal consumption plan from a finite and bounded set $\mathcal{C}$. The feasible set of consumption plans, $\mathcal{C}$, depends on technology, the climate system parameters, and the initial stocks of capital and atmospheric carbon. The generic element $c(t, s)$ of a consumption plan is consumption in period t if scenario s unfolds. The sequence of consumption streams in s is denoted by $\mathbf{c}(s)$. Let $w(\mathbf{c}(s))$ denote the discounted value of the consumption stream along scenario s. Hence the planner solves

$$V(\lambda) = \max_{c\in\mathcal{C}} \sum_s p_\lambda(s) w(\mathbf{c}(s)). \tag{24}$$

We consider now a setting where the agent assumes either λ^O, λ^* or λ^P, with $\lambda^O < \lambda^* < \lambda^P$. In the first case he is an optimist, in the second a realist, and in the third a pessimist.

Let us begin with the realist, i.e. $\lambda = \lambda^*$. Expected welfare is

$$V(\lambda^*) = \max_{c \in \mathcal{C}} \sum_s p_{\lambda^*}(s) w(\mathbf{c}(s)) = \sum_s p_{\lambda^*}(s) w(\mathbf{c}^*(s)),$$

where $\mathbf{c}^*(s)$ solves (24) for $\lambda = \lambda^*$.

Now assume that once the agent has committed to $\mathbf{c}^*(s)$, he learns that the true λ is λ^O or λ^P. What are the welfare implications of this information, given that he cannot revise his consumption plan? Table 4, second column, shows the expected welfare for each of these cases. Given the numerical results, we find that changing the belief from realist to optimist increases the perceived expected welfare. This is in line with intuition, since any decrease in the probability of extreme events should increase expected welfare for a given consumption plan.

The more interesting case occurs if the realist is right about λ. The optimist solves

$$V(\lambda^O) = \max_{c \in \mathcal{C}} \sum_s p_{\lambda^O}(s) w(\mathbf{c}(s)) = \sum_s p_{\lambda^O}(s) w(\mathbf{c}^O(s)).$$

However, his true expected welfare is

$$\sum_s p_{\lambda^*}(s) w(\mathbf{c}^O(s)) < \sum_s p_{\lambda^*}(s) w(\mathbf{c}^*(s)).$$

The same applies for the pessimist,

$$\sum_s p_{\lambda^*}(s) w(\mathbf{c}^P(s)) < \sum_s p_{\lambda^*}(s) w(\mathbf{c}^*(s)).$$

Table 4, third column, shows that these inequalities hold for our simulations. We are mostly interested in the relative position of the choice variables and indirect utilities.[14] More detailed result for this case are given in Table 5, which shows the results for expected instantaneous utility, consumption, capital and atmospheric carbon. If the agent under-estimates the expected number of extreme events, he will abate less carbon emissions, leading to significant increases in temperature. The scenario with precautionary beliefs, or an over-expectation of extreme events ($\lambda = 0.75$) behaves exactly the opposite way: high abatement activity and low overall temperature changes.

[14]The differences in the simulation results are small due to our chosen parameters. Other parameters may readily increase the differences. The results should not be viewed as a full-fletched empirically-relevant simulation, but more as an indication of the overall direction of the effects.

Clearly, when looking at expected consumption from a discounted utilitarian perspective, it might be advisable to place more emphasis on consumption now and simply give fewer weight to the climate system. Indeed, this could be one of the main reasons for questioning the use of the discounted utilitarian criterion in climate analysis altogether. Our results show that optimists abate less than realists, hence they create the highest atmospheric carbon levels. At the same time, however, optimists also invest more into the physical capital stock, such that the consequences on consumption are negative for the first periods. Our numerical experiment show that for the first decade, consumption is lowest with an optimist. This pays back with higher consumption levels later. The pessimist behaves the other way around. Early investments go down, which allows for higher consumption at the beginning, but not later.

Overall, our findings indicate that the beliefs that one holds have an impact on the welfare that will be realized in the future. In particular, if we believe that agents learn over time the real probabilities of events, then obviously ex post the realized welfare will be evaluated at the correct beliefs. Hence, realists will have the highest levels of ex post welfare, followed by pessimists and then optimists. Thus, given that we have an incomplete knowledge of the true probabilities that are underlying extreme events, it may be advisable, from a realized welfare perspective in the future, to err on the pessimistic side, since this is at least likely to lead to a higher realized welfare than if one were to have optimistic beliefs.

3.3 What is the role of transparency in the insurance sector?

One way to understand the role of the insurance industry in environmental and economic policy is to investigate the importance of transparency. A fully transparent insurance policy is equivalent to the perfect insurance scenario, whereas an opaque policy would be depicted by the naive insurance case. As already discussed above, both scenarios differ heavily in terms of realized welfare, climate impact and consumption. It cannot be emphasized too much that the insight into how oneself affects the premium is vital for sustainable consumption and global welfare. This opens up a potential role for regulatory efforts toward stronger information revelation and mandatory insurance.

If the insurance industry reveals its pricing mechanism, then the agent can incorporate this into his decision process.[15] As a welcomed side–effect, this tightens competition in the insurance

[15] In a decentralized version one would assume that agents who are aware of their impact on the insurance would

market such that overheads will decrease and policy uptakes increase. As we show later under the analysis of partial insurance, this is likely to increase global welfare.

In addition, regulatory efforts directed toward a reduction of asymmetric information could improve the climate–change–signaling character of insurance premia. For example, insurance companies generally dispose over detailed information about expected extreme events and disaster hot spots. It is however hardly possible to obtain any data from the insurance sector due to the fear of competitive pressure. It is exactly here where policy regulations can provide the greatest benefits.

3.4 Who should provide the insurance?

For many regions, the occurrence of extreme events has significant impacts on people's welfare and quality of life. Access to insurance can be seen as one of the major means to make those people less vulnerable. At the same time one must remember that the insurance industry is not driven by considerations of charity but by profit maximization and shareholder value, like any other industry. It is thus important to question as to who should provide insurance in case of disasters which protrude through the whole society.

Many insurance companies work locally, in small units. Under those circumstances one would expect higher overhead charges on the premia. Furthermore, the risk which the smaller insurance companies can not bear are sold to the reinsurance industry, which again implies additional overhead costs. Re-insurance can pool risks at a global level, hence minimizes the risk of default. But these shifting of portfolios between the insurance intermediaries tends to make insurance quite expensive. The re-insurance industry is highly concentrated, therefore it may exercise significant market power. Other designs like some type of social security system where the government aims at full insurance could potentially be more welfare-improving.

We investigate this hypothesis by analyzing the effects of overheads on the insurance premium which lead to unfair premia and therefore to partial insurance. If an insurance policy which provides insurance at a fair premium provides higher welfare than one which is supplied at an unfair premium, then this would indeed rise some questions about market power and regulation. We look at several policies. Perfect Insurance, which implies full insurance at any time serves as a benchmark again. Mark Ups range from 12.5 to 17 %. Rates above 17 % are prohibitive, that

act in a cooperative way, through e.g. voting, in order to reduce climate change.

is the planer decides not to insure at all. This is equivalent to the Stochastic scenario, where no insurance is available.

We compare the results of the simulations between the Perfect Insurance and the Stochastic scenario. The *Partial Insurance* scenario refers to the scenario where the agent insures against extreme weather events but – in contrast to the perfect insurance scenario – a mark-up is charged on the premium. Obviously, the fair-priced insurance leads to the highest global welfare. Table 6 shows the results.

Under a small overhead (below 12.5%), we notice that the agent insures himself fully after only a few periods.[16] This however implies that he has to pay more than the expected costs of the extreme events. Whether or not this implies a lower global welfare depends on what precisely determines the overhead. If this overhead arises due to transaction costs, search-and-matching costs, or similar reasons, then it represents a loss to society and one should pursue an insurance policy or government intervention that reduces this overhead cost. While the government may not necessarily be better informed about the risks than the insurance industry (Konrad et al. 2014), it could nevertheless try to regulate the insurance industry or finance research on risk reduction such that this overhead is reduced.[17]

If the overhead arises because the insurance sector is not sufficiently competitive, then the question should be as to what the insurance industry does with this profit. While our assumption of perfect competition above has been chosen in order to be able to specifically focus on the role of the premium, it is clear that the insurance industry is a rather large player on the capital markets (Mills 2009). Hence, it would also be worthwhile to investigate the role of the insurance sector in this case. There is evidence that some insurance companies undertake mitigation actions through their investments on the capital markets (Mills 2012).[18] How this impacts the mitigation actions of the agents and what this implies for the take-out of insurance and the relation to agents' mitigation actions should be interesting future research.

[16] See Gollier (1994) for the theoretical argument.

[17] Regulation of the insurance industry has to be done with care. For example, some US insurance companies have left left the coastal market (Mills 2007, Titus 2008, Stiles and Hulst 2013).

[18] For example, Mills (2009) has noted the following (p.342): "Fortis has offered financing for fuel-efficient cars coupled with discounted insurance; KBC offers preferential terms on green home-improvement loans. AXA has bundled insurance and financing for solar panels and home improvements. Fortis, HSB, ING and AIG have provided commercial financing or credit support for large-scale energy-efficiency, renewable-energy and other types of carbon-saving projects."

4 Conclusion

This paper investigates the role of uncertainty and the insurance industry in the economics of endogenous extreme events. Our theoretical growth model, where extreme events are endogenously determined but an agent can insure himself against these events, yields several important and new results. Firstly, we find a role for precautionary savings but also for precautionary consumption. Which of the two prevails over the other critically depends on the percent of capital insured as well as how much of the capital the agent expects to lose. Secondly, we notice that standard integrated assessment models like the DICE model (Nordhaus 2008) correspond to our model in case of full insurance and if the agent is fully aware about the impact of emissions on the insurance premium. This is an important result since this allows us to define a benchmark and thus allows for comparability to other results, and it also suggests the limitations of the DICE or MERGE model (Manne, Mendelsohn and Richels 1995) in dealing with extreme events or catastrophes. Thirdly, we find a significant role for transparent pricing of insurance contracts. The more transparent the insurance industry, or the more information it leaks as to how it sets its premia, the more sustainable will the economic and environmental system be. The reason for this is that agents can then incorporate the impact of their economic choices on the evolution of the insurance premia, which tends to induce more mitigation actions and subsequently reduced premia over time.

We then develop a calibrated Computable General Equilibrium Model based on our theoretical model in order to quantify the analytical results. This model is calibrated with key data from 2005, and it uses similar functional forms and parameters as the DICE (Nordhaus 2008) and MERGE models (Manne et al. 1995). In addition, we introduce endogenous, Poisson-driven shocks and an insurance sector.

We firstly asked how relevant uncertainty is for the policy maker's decisions. We find that if one constructs an average path from a large set of Poisson-driven uncertain paths, then the difference between the resulting average stochastic path and the full insurance path when the premium is internalized stems fully from the uncertainty. This, therefore, allows for a quantification of the impact of uncertainty in terms of many measures like consumption-equivalent variation, like ex-post welfare or a comparison based on various sustainability criteria.

We then take a look at the role of transparency in the insurance sector. We observe drastic differences in the evolution of the premium in case the insurance industry provides full information, in comparison to when the policy maker does not internalize his decisions on the evolution of the premium. If the premium is not internalized, then abatement effort is negligible, climate change will take drastic forms and consumption can even drop below current levels, which would violate any sustainability criterion. We suggest that transparency is the major determinant of the economic and environmental system, opening the possibility for important regulative possibilities.

We find that false beliefs accentuate the problems of the discounted utilitarian criterion in the analysis of climate change. The highest realized welfare is obtained when the agent underestimates the amount of disasters, which leads to strong climate change, high current consumption but an unsustainable consumption in the future. On the contrary, an over-estimation of the frequency of disasters leads to high abatement, little climate change and high consumption in the future. One would wonder whether our initial question, namely if precautionary beliefs are welfare-improving, should not be re-phrased into the old question: Whose welfare should we take care of?

Our final contribution is in approaching the question of whether insurance of extreme events that affect a potentially significant proportion of the population should be left to the private sector. Our conclusion is that if the private sector demands an overhead due to market power or dis–economies of scale which a social insurance system may not demand due to possible advantages in risk pooling and without the need for the various insurance intermediaries, then a social insurance system may be preferred from a welfarist point of view.

In terms of future research, we believe that the most useful improvements in this field will be in the insurance sector. Allowing for the default of the insurance industry will be a good extension, although it is questionable whether this will lead to qualitative changes in the results. In case of default, the insurance industry will most likely keep a certain cushion of capital which it will call upon in case of multiple consecutive events. We should therefore expect a slightly higher premium in the first periods, which implies an overhead on the premium, and our results from the unfair insurance premium should apply.

More interesting will be if one allows the insurance industry to undertake investments in the capital market. This will however require an overhead on the premium such that the insurance industry can gather capital which it can invest in the capital market. It will also imply stochastic capital markets and therefore uncertain returns to capital, implying further uncertainties in the agent's budget constraint. And finally, one will have to deal with the allocation of the excess profits of the insurance industry. Most importantly, one would have to move away from the agent framework to a multi-agent one which will be difficult from an analytical point of view and will not allow the comparison with the standard results in the literature.

The last remark obviously directly suggests that one of the most important extensions of this work will be a regional approach like the RICE model but with a global insurance industry. One can then study how risk gets transferred from more risky to less risky regions and from higher income regions to lower income ones.

Finally, we have hinted at the possibility that a social insurance system might be welfare-improving in comparison to a private insurance industry. For example, one could look at this from a paternalistic point of view, or a redistributive one, and finally from the problems of market failure. Indeed, one could think about a social insurance system which might be able to internalize the externality of today's emissions imposed on future generations in the insurance premia now, which would somewhat adhere to the polluter pays principle.

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Scenario	Year						
	2015	2020	2025	2030	2035	2040	2045
	Atmospheric carbon in ppmv relative to pre-industrial levels (2010 = 140)						
Stochastic	142.609	147.222	152.730	158.555	164.394	170.084	175.539
Perfect	142.644	147.347	152.987	158.979	165.008	170.903	176.573
Naive	143.036	148.614	155.657	163.463	171.599	179.8	187.902
	Capital Stock						
Stochastic	301.918	430.512	517.640	570.574	599.464	612.704	616.267
Perfect	304.265	436.203	526.768	582.761	614.158	629.344	634.355
Naive	321.589	495.723	636.316	740.556	814.559	865.772	900.594
	Consumption						
Stochastic	140.463	162.042	175.157	182.734	186.801	188.692	
Perfect	140.456	162.438	175.964	183.921	188.315	190.480	
Naive	128.032	156.016	174.028	185.114	191.595	195.067	
	Abatement						
Stochastic	0.062	0.075	0.084	0.090	0.094	0.097	
Perfect	0.057	0.069	0.077	0.083	0.086	0.089	
Naive	0	0	0	0	0	0	
	Expected Instantaneous Utility						Expected Utility (2010-45)
Stochastic	4.945	5.088	5.165	5.208	5.229	5.239	103.389
Perfect	4.945	5.090	5.170	5.215	5.238	5.250	103.484
Naive	4.852	5.050	5.159	5.221	5.255	5.273	102.959

Table 1: Key results for the scenarios Stochastic and Perfect Insurance

	Consumption		
Year	Worst case	Expected	Best case
2015	138.91	140.46	142.02
2020	158.23	162.04	165.98
2025	168.93	175.16	181.83
2030	174.27	182.73	192.17
2035	176.42	186.80	198.86
2040	176.73	188.69	203.14

Table 2: Consumption in Stochastic: Best case, expected consumption and worst case

Scenario	Year					
	2015	2020	2025	2030	2035	2040
	Insurance premium					
Perfect Insurance	3.77	5.48	6.85	7.89	8.68	9.28
Naive Insurance	4.02	6.43	8.71	10.79	12.70	14.44

Table 3: Results for Perfect Insurance and Naive Insurance

Scenario	$V = p(s)u(c^*(s))$	$V = p^*(s)u(c(s))$
Realist ($p(s) = p^*, \lambda^* = .50$)	159.724	159.724
Optimist($p(s) = p^O, \lambda^O = .25$)	159.995	159.722
Pessimist ($p(s) = p^P, \lambda^P = .75$)	159.465	159.723

Table 4: False beliefs: Implications on expected welfare

Scenario	Year					
	2015	2020	2025	2030	2035	2040
	Instantaneous expected utility					
Realist	4.9449	5.0877	5.1654	5.2075	5.2294	5.2393
Optimist	4.9389	5.0870	5.168	5.2123	5.2354	5.2459
Pessimist	4.9485	5.0868	5.1618	5.2024	5.2234	5.2331
	Consumption					
Realist	140.4629	162.0420	175.1565	182.7343	186.8012	188.6924
Optimist	139.6264	161.9253	175.6227	183.6154	187.9371	189.9487
Pessimist	140.9667	161.9051	174.5391	181.8000	185.6906	187.5138
	Capital					
Realist	301.9177	430.5116	517.6397	570.5743	599.4639	612.704
Optimist	309.2969	446.334	540.4839	598.3711	630.2574	644.9186
Pessimist	296.0695	418.3858	500.6189	550.3608	577.5412	590.1935
	Atmospheric carbon					
Realist	142.6092	147.2223	152.7298	158.5553	164.3942	170.0838
Optimist	142.7915	147.7970	153.8363	160.2743	166.7630	173.1097
Pessimist	142.4595	146.7633	151.8637	157.2317	162.5950	167.8123

Table 5: False beliefs: optimists underestimate λ, pessimists overestimates it

Year	Cover (in % of losses insured)				
	12.5	12.75	12.8	15	17
2015	0.449	0.380	0.338	0	0
2020	0.559	0.503	0.470	0.011	0
2025	0.622	0.575	0.546	0.147	0
2030	0.666	0.623	0.598	0.244	0
2035	0.697	0.659	0.637	0.316	0.03
2040	0.722	0.687	0.666	0.372	0.089

Table 6: Insurance covers for different mark ups