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Building Risk into the Mitigation/Adaptation Decisions simulated by Integrated Assessment Models

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Abstract

This paper proposes an operationally simple and easily generalizable methodology to incorporate climate change damage uncertainty into Integrated Assessment Models (IAMs). First uncertainty is transformed into a risk measure by extracting damage distribution means and variances from an ensemble of socio economic and climate change scenarios. Then a risk premium is computed under different degrees of risk aversion, quantifying what society would be willing to pay to insure against the uncertainty of the damages. Our estimates show that the premium for the risk is a potentially significant addition to the "standard average damage", but highly sensitive to the attitudes toward risk. In the last research phase, the risk premium is incorporated into the climate change damage function of a widely used IAM which shows, consequently, a substantial increase in both mitigation and adaptation efforts, reflecting a more precautionary attitude by the social planner. Interestingly, adaptation is stimulated more than mitigation in the first half of this century, while the situation reverses afterwards.

Keywords Risk · Uncertainty · Climate change damages · Adaptation · Mitigation

JEL Classification Q2 · Q3 · D8 · D9 · D62

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1 Introduction

The estimated costs of climate impacts are highly uncertain, and indeed uncertainty is the key concept in climate change discussion. Different sources of uncertainty are defined in the literature. In addition to "epistemic uncertainty", deriving from the still incomplete knowledge of natural and social phenomena, "aleatory uncertainty", is also present, deriving from the irreducible randomness of those phenomena (on the distinction between epistemic and aleatory uncertainty see: Kaplan and Garrick 1981; Halsnæs et al. 2007; Aven 2010; North 2010; Garrick 2010; Kunreuther et al. 2014). In climate disciplines both forms of uncertainty characterize a "cascade" that begins with the description of the functioning of the climate system, followed by the environmental system reactions, leading to uncertainties related to the final economic assessment of climate change consequences and the social and economic responses. In formal terms, this uncertainty originates from a situation in which the distribution of probabilities to characterize the phenomena under scrutiny are not known.[1] This is the concept of Knightian uncertainty (Knight 1921). Furthermore, socio-economic assessments of climate change impacts are influenced by multiple knowledge frames characterized by multiplicity of perceptions regarding the main problems at stake and the goals that should be achieved. This results in "ambiguity", that is a situation in which more priors on different distributions of subjective (i.e. formed starting from unknown, uncertain) probabilities are possible.

The pervasive role of uncertainty in the climate change discussion partly explains the difficulties in communicating results from science transparently (see for instance Aven and Renn 2015 on the definition/communication of uncertainty in the 2013–2014 IPCC Fifth Assessment Report, AR5). It might also explain the criticism on the validity and robustness of the prescriptions emerging from the main tools used for impact evaluations such as Integrated Assessment models (IAMs).[2]

The integrated assessment modelling literature proposes a multiplicity of approaches to characterize uncertainty. A common practice is to develop multi-scenario analyses and/or use "ensembles" of models, climate Global Circulation Models (GCMs), impact/process models, and economic models to capture at any time future (aleatory) and epistemic uncertainty.[3] Equally diffused is the performance of sensitivity analyses on models' behavioural parameters[4] and/or the development of stochastic IAMs to deal with randomness. Stochastic IAMs are used to verify which abatement prescriptions are consistent with different preferences and risk management criteria. In a number of cases, the welfare performances of the maximization of expected utility, are compared with alternative criteria of robust decision making (see e.g.: Hall et al. 2012; Kunreuther et al. 2014; Drouet et al. 2015).

An alternative approach represents uncertainty in terms of risk and then optimizes expected utility or expected damage functions as set out by von Neumann and Morgenstern (1944). This requires characterizing the probabilities involved in the decision making process. Uncertain situations where probabilities are unknown or not perfectly known are

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[1] Uncertainty about objective probabilities does not prevent agents from forming subjective probabilities.

[2] In-depth review of IAMs' limitations are beyond the scope of the paper, we point the interested reader to Stern (2013) and Pindyck (2013) as just two paramount examples in this vein.

[3] Exercises like EMF (https://emf.stanford.edu/), ISI-MIP (https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip) and AgMIP (http://www.agmip.org/) well illustrate this approach.

[4] See Anderson et al. (2014) for a discussion and new approaches on sensitivity tests.

thus translated into "risky" situations, with known probabilities. In the Knightian sense this would mean transforming "genuine uncertainty" into "uncertainty risk" (Knight 1921). Risk aversion, i.e. agents´ attitudes while facing combinations of outcomes and probabilities, is then embedded in the "shape", or parameterization, of the utility functions. Several studies have applied this approach in the context of climate change to study the effect of catastrophic risk and tipping points (Gjerde et al. 1999; Keller et al. 2004; Lemoine and Traeger 2012; Cai et al. 2013), showing that more ambitious mitigation policies can indeed represent hedging strategies.

In a similar vein, Millner et al. (2013) use a modified version of the Nordhaus DICE 2007 model to evaluate the relative welfare performance of an abatement policy that stabilizes CO_2 concentrations at twice their preindustrial level over a business as usual policy under different degrees of risk and ambiguity aversion. Ambiguity stems from the different published estimates of the probability distribution for climate sensitivity. Their paper draws on the increasingly sophisticated ambiguity literature, which springs from the view that our entire state of knowledge in a given area cannot be represented by a unique combination of subjective and objective probability distributions over states of the world (Ellsberg 1961; Gilboa et al. 2008, 2009). The ambiguity framework has been developed to represent preferences in a way that separates tastes from beliefs by Klibanoff et al. (2005, 2009). Millner et al. (2013) separate risk aversion and ambiguity aversion and introduces learning, using an ambiguity function to represent different probability models for climate sensitivity. Concavity of this function ensures ´ambiguity aversion´ in a similar way that concavity of the utility function ensures risk aversion. The main outcome of the study is that introducing ambiguity aversion increases the welfare gain of an abatement policy especially when damages are convex in temperature in a way comparable to risk aversion embedded in the elasticity of marginal utility, where utility is a function of income. The general conclusion is that neglecting ambiguity aversion might drastically understate the welfare benefits of abatement.

In this paper we also transform uncertainty into a risk to analyse how building risk into an IAM affects mitigation and adaptation decisions. Our study is similar to Millner et al. (2013), though we do not separate risk from ambiguity aversion, as we believe it is too difficult to separate them in an operational context. Moreover, we do not consider the effect of learning. Our study has three main aims.

First, it suggests a general empirical methodology to transform uncertainty about climate change damages, including those deriving from the scientific ambiguity, into risk. Specifically, we develop "risk premium adjusted" damage functions by embedding more climatic parameters than just climate sensitivity and uncertainty into probability density functions.

Second, taking these probabilities as given, we compute the "climate change risk premium" associated with different degrees of risk aversions. Our 'risk premium' represents what risk averse agents would be willing to pay to insure against an uncertain event.

Third, the paper develops a practical example of implementing risk premiums, interpreted as a "damage mark-up", in the damage function of a well-established IAM, the WITCH model[5] (Bosetti et al. 2006) developed to include adaptation choices as in Agrawala et al. (2011) and Bosello et al. (2013). The WITCH model, whose damage functions remain fully deterministic, is used to assess how the inclusion of a risk premium,

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[5] http://www.witchmodel.org.

would affect both the decision to mitigate and to adapt under different level of risk aversion. This is a novelty compared to Millner et al. (2013) and to the bulk of the literature in the field, which focusses mostly on mitigation with little emphasis on adaptation (partial exceptions are Felgenhauer and de Bruin 2009, Bosello and De Cian 2014). The strategic feature of the equilibrium described in the WITCH model makes it also possible to compare cooperative and non-cooperative outcomes.

Overall our methodology offers three main advantages: (a) it is conceptually simple to implement even though it requires some computational capacity (b) it allows attitudes to aversion to risk to be reflected in a transparent way (c) it is easily generalizable to the many IAMs building upon the "DICE/RICE" frame. This last feature enables convenient model sensitivity analyses to test the robustness of our results to different model set-ups.

Before developing our analysis, it is worth mentioning two important contributions related to our approach. The first, is the idea that mitigation policies cannot be viewed as hedging strategies, conjectured by Nordhaus (2008) and demonstrated empirically by Dietz et al. (2015). From an examination of a large number of uncertainty sources affecting consumption profiles in the DICE Integrated Assessment Model (IAM), Dietz et al. (2015) confirm Nordhaus's observation that the dominant one relates to future technological progress. It is stronger than the uncertainty stemming from climate sensitivity and damage function. In this context, mitigation "does not hedge"; indeed the authors show that it can even increase future risk. Within the framework of the Consumption Based Capital Asset Pricing (CCAPM) model of Lucas (1978) which they use as theoretical underpinning, this means that benefits from mitigation policies should be discounted with a risk-adjusted rate higher than the risk free one.[6] As the authors note, however, the CCAPM model does not capture "many dimensions of the real world, in particular the existence of structural uncertainties and fat tails" Dietz et al. (2015, p. 34). Furthermore, the model indicates that the Net Present Value of investments in mitigation today will anyway be higher under these uncertainties (although they will be discounted at a higher rate). Accordingly, we think that our "risk premium approach" is still justified.

The second is Weitzman's (2009a, b) dismal theorem. This shows how the presence of very high-damage, low-probability climatic events can increase the willingness to pay to avoid them, and thus to abate, virtually to an infinite level. This narrative has been key in shifting the attention from expected to catastrophic risk, advocating for the internalization of the precautionary approach into the mitigation policy discourse. Even though we do not include catastrophic events, our findings strongly support precaution, thus strengthening Weitzman conclusions.

The remainder of the paper is organized as follows. Section 2 explains the approach and proposes a method by which the premium to be included in IAMs can be calculated. Section 3 describes the IAM model used in this study, and describes the implementation of risk-adjusted damage functions for three levels of risk aversion into the model. Section 4 compares the results of the policy response with and without risk premium. Section 5 concludes.

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[6] The risk adjusted rate is given by r where $r = r_f + \beta\pi$, where r_f is the risk free discount rate, β is the elasticity of net benefit of the investment with respect to a change in aggregate consumption and π is the systematic risk premium. A value of $\beta > 1$, that is what authors find in relation to mitigation policies, implies an increase in the discount rate to be applied.

2 Modelling Climate Change Impacts as a Risk Premium: A Theoretical Framework

2.1 Risk Premium: Conceptual Issues

The basic idea of a risk premium is very simple: people are willing to pay a certain amount to reduce the riskiness of a given act, both when it is one that has on average a benefit to them or a cost. When faced with a prospect of winning €10,000 if a "fair" coin comes down heads and nothing if it comes down tails the expected return that most people can easily compute is €5000. Yet if offered a choice between a certain return of €5000 and tossing a coin in this manner most will choose the certain €5000 (especially if the figures are a matter of their way of life). Indeed most people will take a little less than €5000 rather than play the game. If the minimum they would accept with certainty is €4500 then €500 is defined as the risk premium associated with that game. Similarly, when faced with a potential loss of €10,000 with probability of half and no loss with a probability of a half, people might pay an insurance company a premium of, say, €500 to be guaranteed an outcome of €5000 irrespective of which state of the world prevails. The insurance company then has an expected pay out of €0 but it makes an expected profit of €500 on the premium and both sides are happy. This €500 is the risk premium associated with the uncertain event and the true cost of the event is not €5000 but €5500.

In the case of climate impacts a similar argument can be made. In Fig. 1 money damages are plotted against loss of utility associated with those damages. Owing to risk aversion the disutility function is convex in damages. With temperature T_1 the monetary damage is $D(T_1)$ and the corresponding utility is $UL(DT_1))$. With a higher temperature T_2 the monetary damage is $D(T_2)$ and the corresponding utility is $UL(DT_2))$. The utility loss associated with the expected damage from these outcomes is UL(E(D)), corresponding to losing E(D) with certainty. This is lower than the expected utility loss with that set of outcomes, given by E(UL(D)). The Damage Certainty Equivalent CE(D) is thus larger than the expected damage E(D(T))). The difference is the risk premium CE(D(T)), that should be added on top of the expected damage.

The use of this framework has been questioned, especially by psychologists who argue risk aversion cannot be represented in such a simple way. In particular, individuals have asymmetric attitudes to losses and gains and they are likely to value the risk of potential losses more than potential gains (Kahneman 2011). Furthermore, the evaluation of losses and gains varies according to what people consider to be their reference point. These important findings are the central propositions of prospect theory, which of course is not in question. For the purposes of this assessment of risk, however, we are seeking a social representation of risk aversion in a single direction (i.e. that of possible losses) and so the first issue does not apply, making it more justifiable to use a consistent representation that reflects those losses. Furthermore, we would argue that a social representation, which we are aiming to evaluate, can be based on principles that choose to exclude those aspects of individual decision-making considered to be excessively irrational. Some behavioural economics findings of how choices are made fall into that category (Shiller 2000; Thaler and Sunstein 2008).

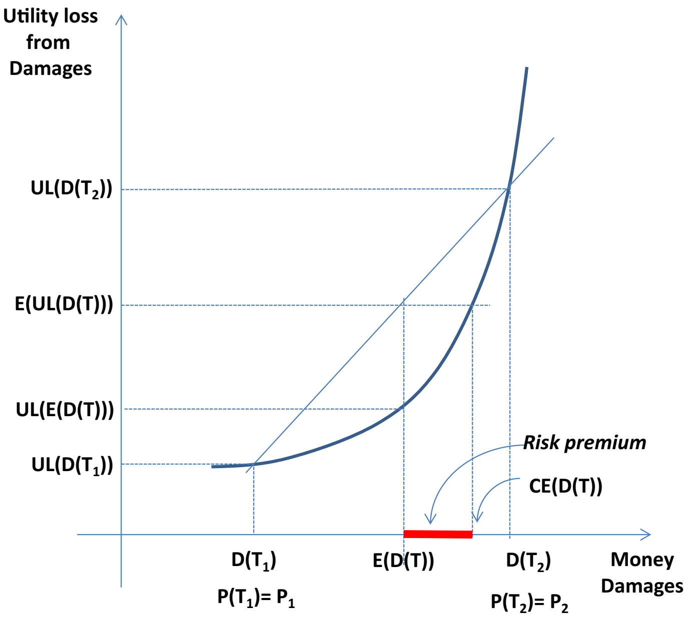

Fig. 1 Stylized representation of premium for risk in climate cost estimation Source: authors' elaboration. There are two possible states of the world/temperature: T_1 associated to low and T_2 associated to high damages, with probability P_1 and P_2 respectively. Due to risk aversion the dis-utility function is convex in damages. The utility loss associated to the expected damage UL(E(D(T))) (corresponding to loosing E(D(T)) with certainty) is lower than the expected utility loss E(UL(D(T))). The Damage Certainty Equivalent CE(D(T)) is thus larger than the expected damage E(D(T)). The difference, is the risk premium

2.2 Measuring the Risk Premium

Several approaches can be used to estimate risk premiums.[7] The conjoint choice method asks people, and one major line of research has used this empirical approach (Green et al. 2001). Developing case studies to obtain empirical data suitable for calibrating risk premium in the context of adaptation and mitigation is certainly an interesting research topic that is left for future research.

An alternative, more theoretical, method is based upon the expected utility framework which is rather common to study consumer choices in the presence of risk aversion in many different domains.[8]

Consider an economy with uncertain income x which yields a utility $U(x)$, where $U(x)$ is the Von Neumann-Morgenstern utility function. We can think of it as representing the

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[7] See Kousky et al. (2011) for a review of the different methodologies to measure risk premium to be included in the social cost of carbon.

[8] Applications of the theory to understand investments decisions in finance are commonplace. See for example, Levy (1994) and Blake (1996) as well as the excellent notes of Professor Norstad. http://www.norstad.org/finance/util.pdf. An application to environmental decision-making is Krupnick et al. (1993). Note that we are using the concept of expected utility to elicit the risk premium but we are not applying the expected utility framework in the full sense of the CCAPM model, which we regard as inappropriate for this kind of analysis.

social planner's view of utility as a function of aggregate income. This income x is uncertain and the probability of different outcomes is described the density function $f(x)$. In this context we can define the certainty equivalent to the uncertain outcome described by the expected utility $E(U)$ as the certain outcome x^* that gives the same utility as the uncertain prospect:

$$U(x) = E(U) = \int U(x) f(x)\, dx \tag{1}$$

The certainty equivalent x^* can differ from the expected or average value of x, which is given by: $E(x) = \int x f(x)\, dx = \mu$. The difference, $E(x) - x * \equiv \mu$ - x^*, represents the risk premium, r, which is the amount people are willing to pay in order to avoid the uncertain outcome. It is positive, zero or negative, under risk aversion, risk love and risk neutrality respectively. Accordingly:

$$U(x) = U(E(x) - r) = U(\mu - r) \tag{2}$$

Exploiting the concept of certainty equivalent in (1), (2) immediately gives the possibility to estimate the risk premium r by solving the equation:

$$E(U) = \int U(x) f(x)\, dx = U(E(x) - r) = U(x) \tag{3}$$

In the specific context of this study, uncertain future climate change impacts are the source of income uncertainty. To compute the uncertainty equivalent, we need first to assign a functional form to the distribution of x that we conveniently assume to be lognormal. This, in fact, can be justified if the linkages from temperature to physical impacts and from physical impacts to losses is multiplicative.[9] Rabl and Spadaro (1999) for instance note that if the final number (damages) is the outcome of a process as the one described above and if the variable at each step has an independent distribution with a given geometric mean, then, by an application of the Central Limit Theorem, the final distribution has a log-normal form. In this case, the geometric mean of the log of the final figure is the sum of the logarithms of the individual means and the standard deviation of the final figure is the sum of the squares of the geometric standard deviations of each process that gives rise to the final product.

The utility function of x, has frequently been represented in the literature by a "standard" family of power functions:

$$U(x) = \frac{x^{1-\eta} - 1}{1 - \eta} \tag{4}$$

η, which can be interpreted as the coefficient of relative risk aversion (see more on that below), has been generally estimated to take values of between 0.5 and 2, but possibly even

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[9] In practice all the links in the chain from temperature to damages may be multiplicative. Certainly the relationship between temperature and economic damages is, but if the others were not, the use of the log normal will be more of an approximation.

as high as 12 (Bliss and Panigirtzoglou 2004, Kaplow 2005, Millner et al. 2013).[10] Note that when η is equal to 1 the above function reduces (by L'Hôpital's Rule) to:

$$U(x) = \underset{\eta\to 1}{1} \frac{x^{1-\eta}-1}{1-\eta} = \ln x \tag{5}$$

Functional form (4) is very extensively used in the risk literature; it allows for a wide range of attitudes to risk aversion and is analytically tractable. In order to show how Eq. (2) turns out in the specific case when the frequency distribution of x is lognormal and the utility function takes the form (4) we present the functions below. The expression for expected utility $E(U)$ is given by:

$$E(U) = U(x)\, f(x, \mu, \sigma)\; dx \tag{6}$$

With $f(x;\mu,\sigma)$ lognormal distribution density function:

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \tag{7}$$

In the specific case of constant relative risk aversion coefficient utility function, with risk aversion coefficient η different from one, the expected utility is:

$$x^{1-\eta} \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} dx - \frac{1}{1-\eta} = \frac{E(x^{1-\eta})-1}{1-\eta} \tag{8}$$

Then (4) and (8) allow through (3) the immediate computation of x* and thus of r.

In the case of relative risk aversion coefficient η equal to one:

$$E(U) = \ln x \cdot f(x;\mu,\sigma)\; dx = \mu \tag{9}$$

While, as said, the utility of x is represented by Eq. (5).

Accordingly, Eq. (3) boils down to:

$$\ln x = \mu \tag{10}$$

Giving the certainty equivalent x^* as a function of μ:

$$x = e^{\mu} \tag{11}$$

Similarly $\bar{x}$, the expected value of x, is given by

$$\bar{x} = e^{\mu+\sigma^2/2} \tag{12}$$

For example with $\mu = 10$ and $\sigma = 1$ we obtain directly from the above that: $x^* = 22{,}026$ and $\bar{x} = 36{,}316$, yielding a value of the risk premium r of 14,110. In other words, for the case where the individual or social group faces a distribution of future income with a mean of 36,316 and a log normal distribution of those returns as specified here, the risk premium is 14,110, or 38.8%.

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[10] The literature on risk aversion indicates that the coefficient of relative risk aversion may increase with the size of the income loss or gain (Arrow 1965; Holt and Laury 2002). In this respect an alternative utility function (the exponential function) may be more appropriate. This takes the form: $U(x) = \frac{-\exp^{-\gamma x}}{\gamma}$. In this case the coefficient of relative risk aversion is given by γx. Studies show, however that for variations in x that are small relative to total x (which in our case is GDP) a constant relative risk aversion function is a reasonable approximation.

The next section introduces first the IAM used for the empirical assessment and then explains how the mean and standard deviations of regional damages have been computed in order to estimate the risk premium as given in Eq. (3).

3 Correcting Damages from Climate Change Impacts with a Risk Premium: A Numerical Application Using the WITCH Model

3.1 The Modelling Framework

WITCH[11] (Bosetti et al. 2006) is a hard-linked Integrated Assessment model based upon a Ramsey optimal growth economic engine with a breakdown of the energy sector into different uses and technologies. The economic system is fully integrated with a simple climate module that translates carbon emissions produced from the use of fossil fuels to radiative forcing and temperature increase. Regional reduced-form damage functions link the global temperature increase above pre-industrial levels to changes in regional gross domestic product (GDP).[12] WITCH also features an adaptation module (see Agrawala et al. 2011) aggregating the possible adaptive responses into specific adaptive capacity-building, anticipatory adaptation, and reactive adaptation. The different forms of adaptation expenditure reduce climate change damages, but need to compete, under a limited budget, with other form of investments/expenditures (e.g. in R&D, in physical capital and in mitigation/clean technologies). The model equilibrium can be solved either as the solution of a non-cooperative game or as a global cooperation among the model's thirteen geopolitical blocks. In the first case, agents behave strategically. The resulting Nash equilibrium is a constrained optimum, in which forward-looking regional planners maximize inter-temporal welfare by optimally choosing investments in final good, energy technologies, energy R&D (for more insights on the treatment of technical change in the WITCH model see Bosetti et al. (2006), and adaptation, subject to the budget constraint without internalising global environmental and technology externalities. In the second case, a world decision maker fully internalizes all the externalities, maximizing a global utility function represented by a weighted sum of regional utilities.

The utility function of the representative regional agent exhibits a constant elasticity of marginal utility of per capita consumption η:

$$U(t,n) = \sum L(t,n)\frac{\frac{C(t,n)}{L(t,n)}^{1-\eta} - 1}{1-\eta} df(t) \tag{13}$$

r(t) is the utility discount factor that relates to the pure rate of time preference ρ as follows:

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[11] The WITCH model outcomes are amply referenced in the Fifth Assessment Report of the IPCC (Clarke et al. 2014) and in many model inter-comparison exercises (Bosetti et al. 2015, Lessmann, et al. 2015, Tavoni et al 2014) placing WITCH among the established models in the integrated assessment community. For detailed information on the WITCH model we address the interest reader to: http://www.witchmodel.org/.

[12] The WITCH model thus, sharing this feature with a whole stock of IAMs, uses reduced form climate change damage functions. I.e. all the complexities of impact assessments are compacted in few parameters. This simplification is particularly useful for the present exercises. For more discussion on the pros and cons of reduced form damage functions see Bosello (2014).

$$df(t) = \prod_{t'=0}^{t} (1 + \rho(t')) \tag{14}$$

The WITCH default value of the η is 1.5 and the pure rate of time preference ρ is 1%.

Following the discussion in Sect. 2, a possible issue arises on which value of η to use for the computation of the risk premium. The parameter η in Eq. (13) serves two purposes. Following the standard approach of optimal growth models under certainty and perfect foresight, it represents the inverse of intertemporal elasticity of substitution of consumption over time. In the social welfare literature this parameter typically takes a value of around 1.3 (Layard et al. 2008). However, the parameter also reflects risk attitudes. Accordingly, two possibilities are at hand: using the same value of η in Eq. (15) and in the risk premium computation process described by Eqs. (1) to (13). Alternatively, using different values of η in (1) to (13) and keeping in the WITCH utility function the value of η equal to 1.5, assuming that the inverse of intertemporal elasticity of substitution of consumption over time and aversion to risk may diverge. Here we follow the latter approach. In the WITCH utility function we fix $\eta = 1.5$ and we use this calibration to test different risk premium-corrected damage functions calculated using Eqs. (1)-(13) under different values of risk aversion, namely $\eta = 1$, 1.5, and 2.[13]

We then analyze the implications of including a risk premium in the two models set up:

(1) Global cooperation: where the model is solved by maximizing a global social welfare functions. We name this set of scenarios “Global cooperation”.
(2) Regional fragmented action: the model is solved as a non-cooperative Nash game. This can thus be interpreted as a sort of baseline scenarios with no additional internationally agreed climate policy measured relative to 2005, which is the base year of the model. We name this set of scenarios “Regional action”.

The social economic reference case for the WITCH model is that of the Shared Social Economic Pathway 2 (SSP2) (O’Neill et al. 2012). Its narrative corresponds to a world evolving along the trends typical of recent decades with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. SSP2 is thus conceived as a scenario posing intermediate challenges to both mitigation and adaptation as it features intermediate emission

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[13] We also performed some sensitivity tests (see supplementary Appendix Table 4) showing, in general, a relatively small effect of forcing the two values to be the same. The sensitivity analysis also shows that for some values of η in the WITCH utility function, the model cannot find an equilibrium. Specifically, assuming $\eta = 2$, optimization for high-damage regions, such as Sub Saharan Africa, can be solved only if the pure rate of time preference ρ is adjusted downward. The economic intuition is the following: the case $\eta = 2$ corresponds to a situation of high relative risk aversion and low willingness to substitute consumption inter-temporally. In this case future damages are high, as they incorporate a large premium for the risk, and representative agents in the model would have a stronger preference to consume everything today. Thus, from the Ramsey equation, an increase in η reduces the growth rate of consumption, and, in our simulations, the reduction is “too much” to find a feasible intertemporal optimum. The resulting lower sensitivity of consumption growth to the gap between the interest rate and the pure rate of time preference can be compensated by reducing the pure rate of time preference ρ. Gollier (2002) shows how uncertainty in future consumption modifies the Ramsey equation in a similar way. The pure rate of time preference would be lower in order to induce precautionary savings. In the context of the debate on climate change discounting, Gollier (2008) and Dasgupta (2008) have also suggested a parameter combination of $\eta = 2$ and $\rho = 0$.

profiles as well as intermediate economic growth providing at least some resources to address adaptation needs[14]. In its standard set up the WITCH reduced-form climate module foresees for the SSP2 a temperature increase of 4 °C by the end of the century.

3.2 Risk-adjusted Damage Functions in the WITCH Model

To compute the risk premium of climate change damages, we need first to estimate the distribution of regional damages to quantify μ and σ in Eqs. (8), (12) and (13).

More precisely, the procedure was as follows:

1. A simple climate model was calibrated based on Urban and Keller (2010) to emulate CMIP5 ensemble of climate simulations and underlying uncertainty arising from 14 geophysical parameters, including climate sensitivity (CS), ocean heat exchange, etc., determining temperature profiles associated with a given carbon budget (Taylor et al. 2012. Emulation has been performed using a Bayesian inversion technique based on a Monte Carlo Markov chain.
2. Emissions profiles were derived until 2100 using 802 scenarios from the AR5 database to capture uncertainty about the climate policy implementation (e.g. different delay of action, technology availability, level of cooperation and climate targets).
3. A distribution of temperature was generated for each emissions profile.
4. The WITCH's damage function (Bosetti et al. 2006, Bosello and De Cian 2014) were applied to the temperature distributions to generate related distributions of regional damages
5. Regional damage distributions were fitted for 2100 with a log-normal distribution and computed the mean log and standard deviation log of the damages. The fit was verified by means of the Akaike Information Criteria (AIC)
6. Finally, the parameters of the log-normal distribution (mean log and standard-deviation log) were related to the expected temperature increase.

Figure 2 depicts the result of this process presenting in three panels the expected, the 75th and the 90th quantiles of the regional damage distributions respectively, expressed as percentage of GDP loss, as functions of the temperature increase (for more detail see the Appendix). Figure 3 shows the damage curves with and without the risk premium for a value of η equal to 2 for the two regions with the lowest and highest risk premium across the WITCH 13 model regions (full detail are in the Appendix which provides results for all the regions as well as for values of η equal to 1, and 1.5).

The calculations show that the risk premium adds around 90–110% to the "non-risk adjusted" damage estimate, irrespective of the temperature increase for a value of η equal to 2 and around 1–10% for a value of η equal to 1, depending on the region considered. For a value of η equal to 1.5 the increase in damage ranges between 1 and 19%. Thus the choice of the coefficient of risk aversion is critical. Furthermore, it is also evident that damages are non-linear in η. A sort of threshold is value of 1.5, beyond which damages increase steeply.

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[14] The quantitative characterization on the evolution of main social economic variables in the scenario (namely GDP and population) have been extracted from: https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about.

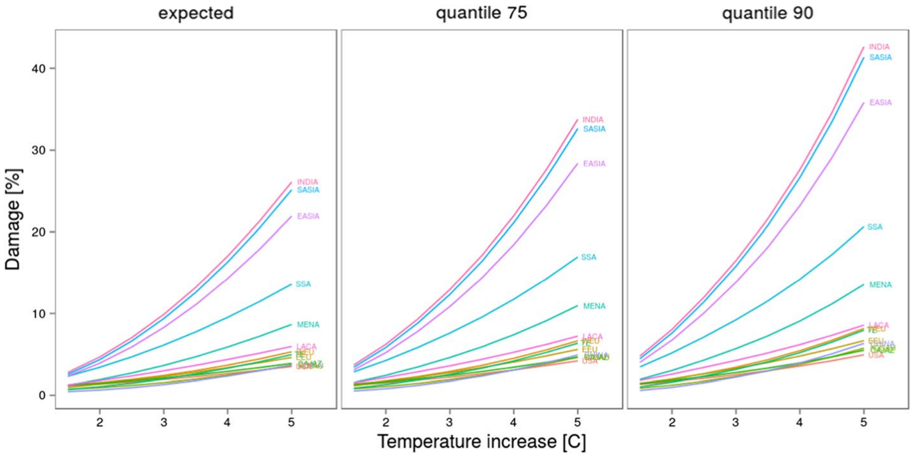

Fig. 2 Climate change damage measured as percentage loss in regional Gross Domestic Product (GDP) as a function of temperature. Expected values, 75th and 90th quintile

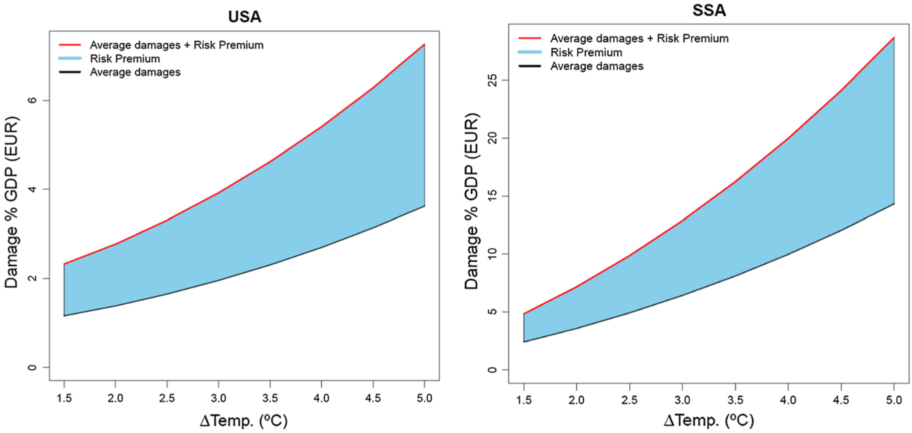

Fig. 3 Calibrated regional damage functions in selected regions with (upper red line) and without (lower blue line) the risk premium. Risk aversion equal to 2 ($\eta = 2$)

4 Results

4.1 Implications of the risk Premium on the Optimal Balance Between Mitigation and Adaptation

From the discussion on risk premium in Sect. 2, it can be reasonably accepted that in the case of climate change, as in other situations involving risk, the damage people really react to when faced with a range of possible outcomes is greater (potentially much greater) than the average damage. A key result of our analysis is how risk-adjusted damages can influence climate policy action, and especially the optimal

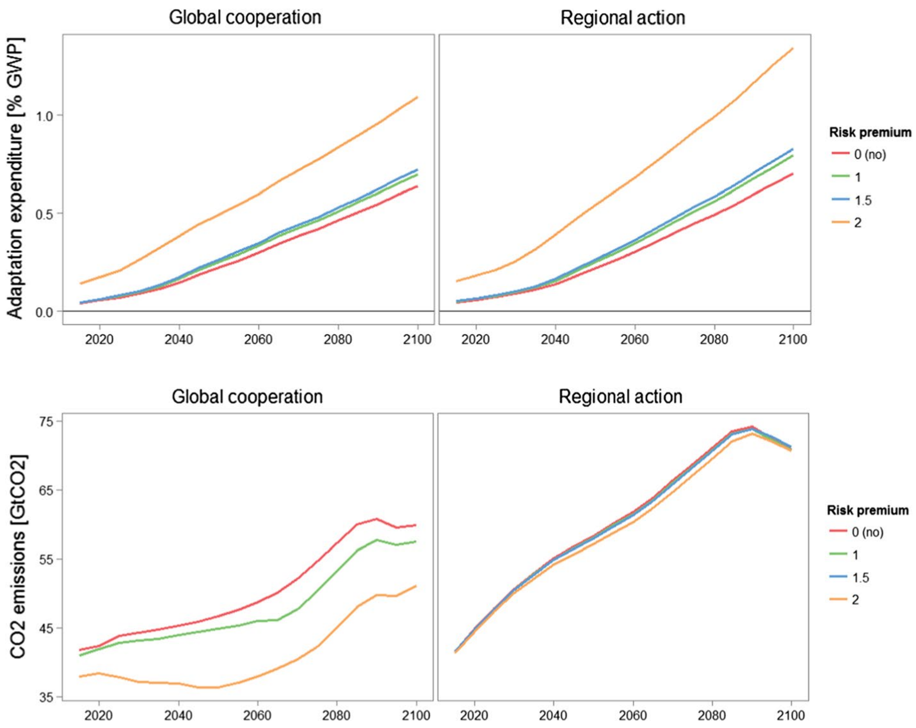

Fig. 4 Global adaptation expenditure (Upper Panel) and CO2 emissions (Lower Panel). Scenarios with global cooperation (Left Hand Panel) and regional action (Right Hand Panel)

mitigation-adaptation mix. As a first result, we find both mitigation and adaptation levels increase in order to reduce potential damages.

Figure 4, shows higher expenditure in adaptation (top panel) and lower emissions (lower panel) in both the cooperative and non-cooperative scenarios. In the non-cooperative case, however, the free riding incentive is strong. Therefore emission reduction, albeit positive is negligible. This has an interesting implication for adaptation. While the risk-premium-corrected emission reduction is very low under regional action, where damages remain high, adaptation, which is used as damage reducing strategy, turns out to be greater than in the global cooperation case. Adaptation, differently from mitigation, is a private appropriable good at the scale of our decision makers which are macro regions, and thus it is not affected by the free riding curse.

The emissions profile are clearly not consistent with global temperature stabilization at 2 °C by the end of the century. For example after 2050, even with $\eta = 2$, emissions are increasing. This outcome is driven by how the WITCH damage function has been modified. It essentially incorporates risk as a higher deterministic damage. Hence, neither irreversible nor catastrophic damages affect the decision maker.

Table 1 Relative and total contribution to percentage damage reduction due to mitigation and adaptation in 2050 and 2100 (Global Cooperation: a global social welfare function is optimized)

		Adaptation action only	Mitigation action only	Mitigation and adaptation
2050	$\eta = 0$	20.5	5.9	21.9 (of which: 84% due to adaptation and 16% to mitigation)
	$\eta = 2$	28.7	14.0	30.0 (of which: 80% due to adaptation and 20% to mitigation)
2100	$\eta = 0$	41.6	18.9	45.0 (of which: 86% due to adaptation and 14% to mitigation)
	$\eta = 2$	45.7	26.6	51.0 (of which: 70% due to adaptation and 30% to mitigation)

Table 2 Cumulated discounted mitigation and adaptation expenditure under different risk attitudes (low risk aversion, $\eta = 0$, high risk aversion, $\eta = 2$) (Global Cooperation: a global social welfare function is optimized)

	2005–2050		2050–2100		2005–2100	
	$\eta = 0$	$\eta = 2$	$\eta = 0$	$\eta = 2$	$\eta = 0$	$\eta = 2$
Adaptation expenditure (2005USD Tn.)	5.4	13.8	50.8	89.3	56.3	103.1
Dis-investment in fossil resources (2005USD Tn.)*	3.6	4.6	4.1	7.4	7.7	12.0
Investment in fossil resources with CCS (2005USD Tn.)	0.0	3.3	0.0	6.1	0.0	9.3
Investment in renewable sources (2005USD Tn.)	7.6	10.4	3.6	6.5	11.2	18.1
Total mitigation expenditure (2005USD Tn.)	11.2	18.2	7.7	20.0	18.9	38.3
% change in adaptation expenditure moving from $\eta = 0$ to $\eta = 2$	155.6		75.8		83.1	
% change in mitigation expenditure moving from $\eta = 0$ to $\eta = 2$	63.1		158.7		108.6	

*Values represent lower investment and thus should appear with a minus sign, however in the table they are positive being accounted as positive mitigation investment

Table 1 reports the relative contribution of mitigation and adaptation to damage reduction under global cooperation.[15] By the end of the century, the two policies together reduce the damage by roughly 51% and 45% with and without the correction for the risk premium respectively, showing agents to be more conservative in the former setting. Interestingly, while adaptation remains the preferred strategy to reduce the damages, in relative terms accounting for risk increases the contribution of mitigation relatively more. Taking 2100 as reference and $\eta = 2$, the share of damage reduction due to mitigation doubles, while that of adaptation shrinks by the 23%.

A similar outcome applies if expenditures in mitigation and adaptation are considered. Now, both increase as the risk correction fosters either mitigation or adaptation, but while the expenditure on the former more than doubles (+108%) over the century, that on the latter expands by +83% (Table 2). It is also interesting to note that in the first half of the century expenditure on adaptation increases more than that on mitigation while in the second half of the century the situation reverses. This is an effect on how damages are modified by the risk premium, which acts as a shifting factor of present and future damages, even though more accentuated in the last part of the century. This initially tends to advantage

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[15] This computation is scarcely meaningful in a non-cooperative set up as almost all of the climate policy relies upon adaptation.

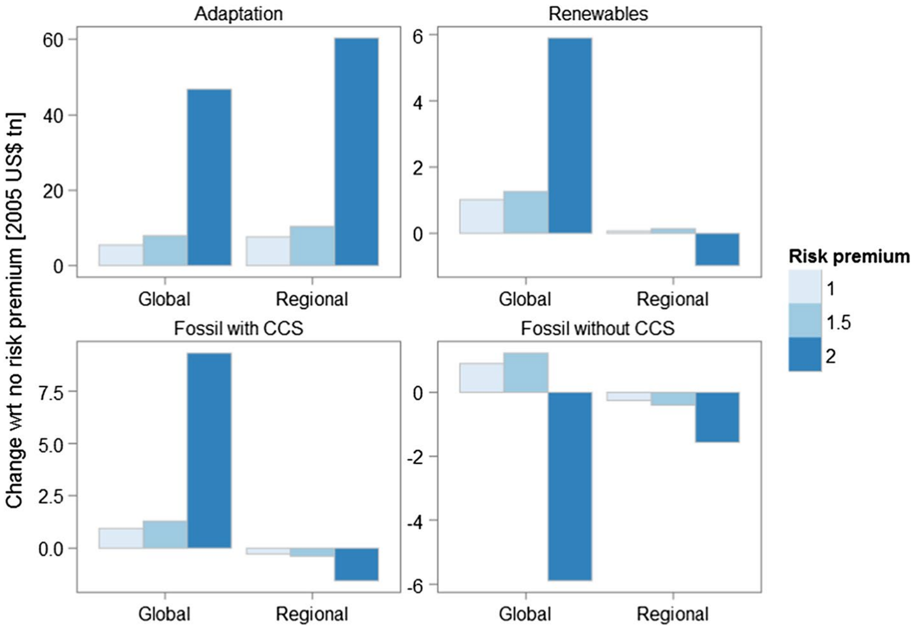

Fig. 5 Global adaptation expenditure and mitigation investments. Cumulative values (2005–2100) in the cases with risk premium relative to the scenarios without risk premium in 2005USD Trillion. Scenarios with global cooperation and regional action

adaptation that is more quickly effective than mitigation to deal with current damage. In the longer term mitigation becomes more cost effective. The result is consistent with previous analysis of adaptation-mitigation trade-offs without uncertainty (Bosello et al. 2010, 2013).

The overall emission reduction is achieved through a combination of increased investments in renewables and fossil-fuel based energy equipped with Carbon Capture and Storage (CCS) and through reduced investments in fossil-fuel based energy. In the Regional action case ("Regional" in Fig. 5) reduction in energy demand is the main mitigation strategy as shown by a general decline in investment in all energy sources, either fossil or non-fossil based. As a consequence, the average annual change in adaptation expenditure is globally greater under regional action than under global cooperation.

4.2 Regional Results

Regional results for the 13 regions (list in Table 5 in the Appendix) follow the trends highlighted at the global level, but they provide some additional pieces of information.

As risk premium-corrected damages are higher (Fig. 6), emission reduction increases (Fig. 7). Under a global cooperation scenario this occurs in all the regions. The efficient (marginal abatement cost equalizing) internalization of the environmental externality imposes a higher emission reduction on India and South Asia, which also experience higher damages, immediately followed by Economies in Transitions given their relatively lower abatement costs. Under regional action some regions (Western Europe, Korea South Africa Australia, Canada Japan, New Zealand and partially Sub Saharan Africa) mitigate

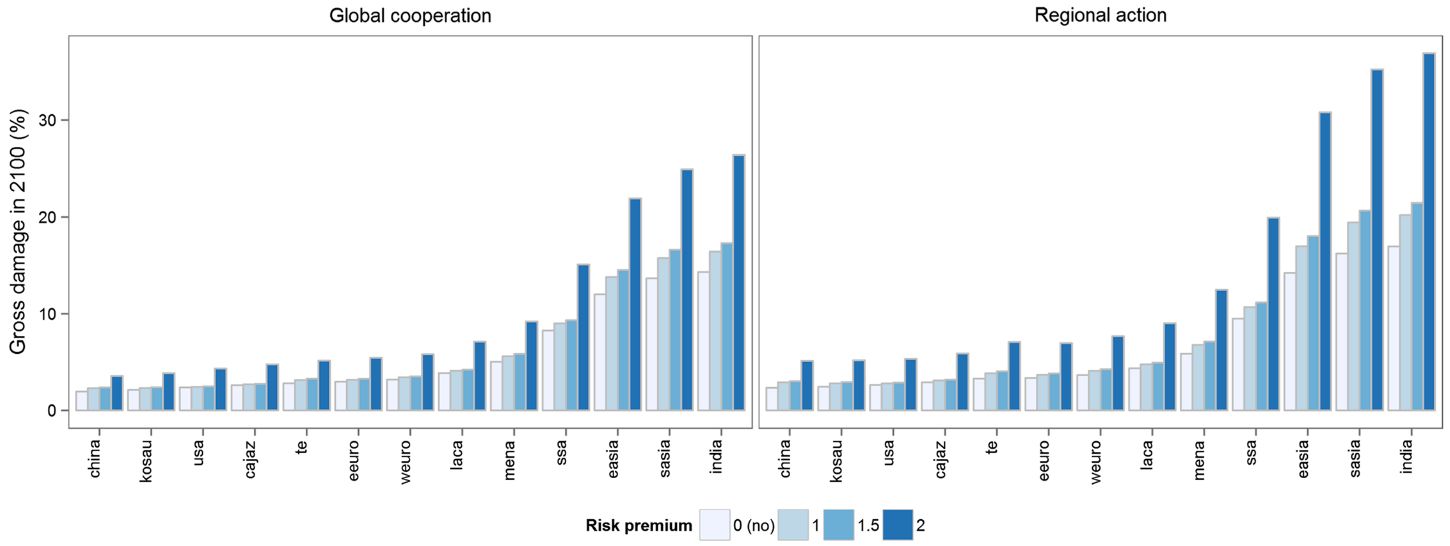

Fig. 6 Regional damages in 2100 for different risk attitudes

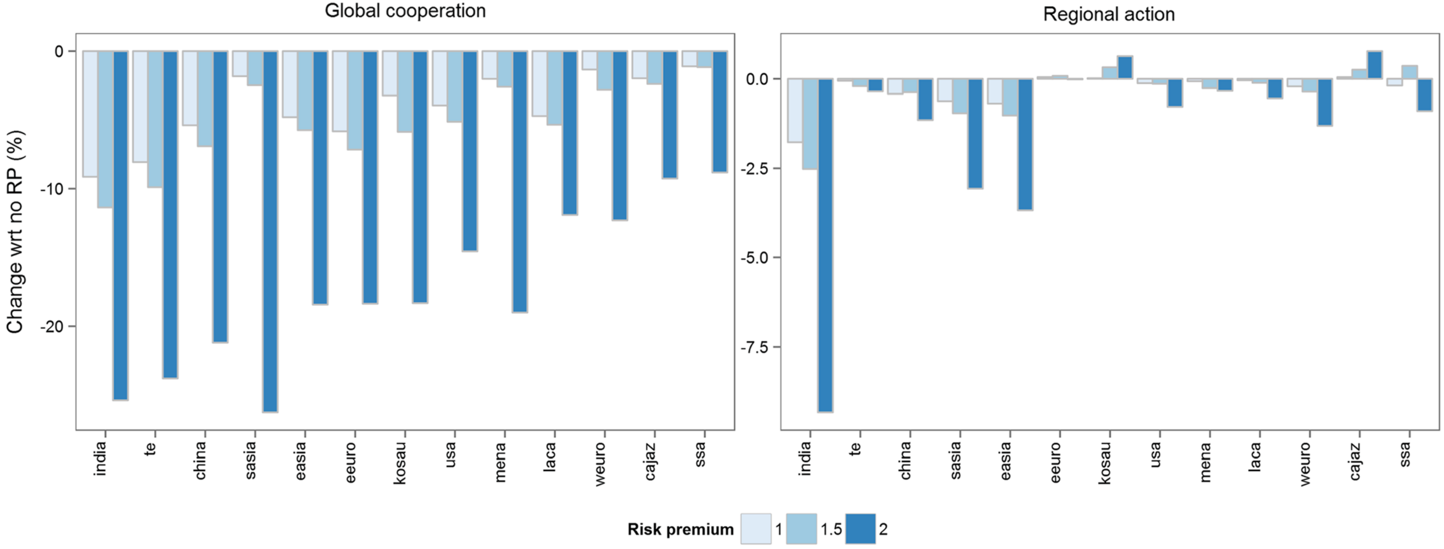

Fig. 7 Percentage reduction in regional cumulative CO2 emissions in 2005–2100

Table 3 Global cooperation (a global social welfare function is optimized): Cumulated discounted (2005–2100) mitigation and adaptation expenditure under different risk attitudes (low risk aversion, $\eta = 0$, high risk aversion, $\eta = 2$), by region

		USA	Weur	Eeur	Kosau	Cajaz	TE	MENA	SSA	SASIA	China	EASIA	LACA	India
Adaptation expenditure (2005 USD Tn)	$\eta = 0$	5.05	8.37	0.63	1.62	2.13	1.05	4.19	11.64	2.64	4.27	2.97	3.76	7.94
	$\eta = 2$	10.91	16.47	1.28	3.31	4.48	2.23	7.29	19.47	4.07	8.44	4.85	7.26	13.00
% change. in Ad. Expenditure		116.1	96.8	103.4	105.0	110.3	111.9	73.8	67.4	54.0	97.5	63.1	93.1	63.8
Dis investment in fossil sources (2005 USD Tn.)	$\eta = 0$	2.03	0.40	0.15	0.44	0.15	1.24	0.23	−0.71	−.06	3.08	0.12	−.06	0.70
Inv. in CCs (2005 USD Tn.)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inv. in renewables (2005 USD Tn.)		−.94	0.25	0.21	0.48	−.20	1.31	0.80	−.01	0.03	5.65	0.23	0.29	3.08
Dis investment in fossil sources (2005 USD Tn.)	$\eta = 2$	1.95	0.41	0.12	0.08	0.36	1.16	2.21	0.25	0.47	3.07	0.74	1.32	−.14
Inv in CCs (2005 USD Tn.)		0.00	0.60	0.00	0.10	0.21	0.87	2.50	0.97	0.97	0.00	1.06	1.98	0.10
Inv in renewables. (2005 USD Tn.)		1.06	0.22	0.34	0.72	−.05	1.84	1.17	0.00	0.05	8.14	0.71	0.43	3.44
Total Mitigation Exp. (2005 USD Tn.)	$\eta = 0$	1.09	0.65	0.36	0.92	−.05	2.55	1.03	−.72	−.03	8.73	0.35	0.23	3.78
	$\eta = 2$	3.02	1.23	0.46	0.90	0.52	3.87	5.89	1.22	1.49	11.20	2.51	3.74	3.40
% change in Mitigation. Expenditure		177.4	88.8	27.9	−2.9	na*	51.5	470.4	na*	na*	28.3	613.6	1520.0	−0.0

* For these region the total mitigation expenditure under $\eta = 0$ turn out to be negative. Mitigation expenditure is computed as the difference in energy investments with respect to the regional action case which represents the no mitigation scenario. A negative value thus means that the region is investing less in renewables or using more fossil fuel sources under global cooperation than under regional action. Accordingly when with $\eta = 2$ renewable investment increases

less. In these cases, the incentive to free ride, strengthened by the additional abatement from other areas, overcomes the incentive to reduce emissions deriving from the higher risk premium corrected own damages.

In relative terms, mitigation expenditure tends to increases more than adaptation expenditure, even though in absolute terms the second is larger (Table 3). The larger percentage increase in mitigation expenditure occurs in Latin and Central America, East Asia, Middle East and North Africa. There are also two regions, India and Korea-South Africa-Australia, where the risk premium correction decreases the expenditure in mitigation. This does not mean, however, that emissions increase. In fact, what changes is the mix of mitigation strategies which can deliver more abatement even though with a lower net investment in de-carbonization. In both regions, risk premium increases the investment in renewables and carbon capture and sequestration, but also more expenditure (lower disinvestment) in fossil fuels. Regions adapting more are the USA, Korea, South Africa and Australia, Economies in transitions and the Easter Europe.

5 Conclusions

The role of uncertainty is paramount in the climate change debate. In addressing it this paper has three aims. One, more methodological, is to propose an operationally simple and easily generalizable way to transform climate change damage uncertainty into risk, a more manageable analytical and quantitative context. The second, is to compute the risk premium associated with uncertain climate change damages accounting for climatic and social economic uncertainty and different degrees of risk aversion. The third, is to analyse the optimal climate policy (mitigation and adaptation) mix using an Integrated Assessment Model (IAM) whose damage function has been modified to incorporate the risk premium.

Uncertainty is transformed into a risk-premium damage-correction region-specific factor by extracting damage distribution means and variances from an ensemble combination of socio economic and climate change scenarios. The risk premium quantifies what risk averse agents would be willing to pay to insure themselves against the risks associated with the damages. It can thus be considered an add-on to the standard "average or expected damage". Our computations highlight that this addition can double the "non-risk adjusted" damage when the risk aversion coefficient, η, equals 2. They also show that the choice of η is critical, as the correction decreases sharply with values below 1.5.

Once the risk premium is incorporated in the climate change damage function of the integrated assessment model WITCH, simulations show a substantive increase in both mitigation and adaptation reflecting a more conservative attitude by the regional planners. Interestingly, driven by the different time effectiveness of the two strategies (short-term for adaptation and long-term for mitigation) adaptation is stimulated more than mitigation in the first half of the century, while the situation reverses afterwards. Furthermore, in relative terms, the risk premium correction fosters more mitigation, which doubles, than it does adaptation, which rises by about 80%.

Relevant differences can be identified across the global cooperation and the regional action cases. In the former, mitigation is achieved with important investment in renewables and CCS and disinvesting in fossil energy sources, while in the latter, basically by slightly reducing energy use. Accordingly, adaptation expenditure is higher in the regional action than in the global cooperation case.

The analysis by region also emphasizes that while including risk premium under global cooperation increases abatement in all regions, under regional action, some, characterized either by low emissions or low damages may abate less. In these areas the free riding incentive prevails over the stimulus to abate more in response to the higher risk-premium corrected domestic damage.

The policy implications from our results are quite straightforward. The perceived threats from climate change, using a "standard" coefficient of risk aversion, double the average damages and would call for a doubling of the mitigation and adaptation effort. This is not quite as far as the "dismal theorem" by Weitzman would suggest we should go, but it is anyway a strong incentive to incorporate the precautionary principle in climate change policies and a further support to GHG stabilization. At the same time, embedding risk aversion is not per se sufficient to spur more mitigation in all the regions. Only global cooperation grants this outcome. This casts some doubts that a fragmented climate regime or a totally bottom-up approach can deliver the mitigation required to avoid irreversible and potentially catastrophic climatic events. The Paris process thus needs to urgently move toward an internationally coordinated and binding climate change action. A possible way to facilitate the process is the diffusion of "carbon markets". Notwithstanding all criticisms, at the moment these are the only mechanisms allowing to achieve emission reduction efficiently. It would thus be of primary interest to support the introduction and diffusion of such systems that eventually could be linked into a global mechanism.

This work opens interesting lines of research that need to be addressed in the future. First, being based upon a reduced-form climate change damage function, our analysis is restricted to the uncertainty generated by climate models and emission scenarios. Therefore it does not include perhaps the most important source of uncertainty, that relating to how climate variables lead to physical impacts and how those translate into socioeconomic impacts. The addition of this dimension is likely to deeply influence the determination of the risk premium. Secondly, given its crucial role, further work is needed to get a better estimates of the appropriate value of the coefficient of relative risk aversion in the specific context of climate change policy decisions. As the paper has shown a critical value for this parameter is 1.5. It would be very interesting to elicit this value using stated preference methods. This may also allow, and this is a third development, to better capture the role of thresholds, tipping points and irreversibility that our current approach, still based upon a "smooth" description of climate change damages, cannot consider properly.

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Appendix

We ran the SSP2 with and without adjustment in the ηcoefficient in the model and results show that the adjustment to set it equal to the coefficient of risk aversion does not have a big impact when the non–cooperative solution is implemented (Table 4). The same applies when we make small changes to the pure rate of time preference (ρ) (See Tables 4, 5, 6, 7, 8, 9, Fig. 8).

The sensitivity analysis also shows that for some values of η in the WITCH utility function, the model cannot find an equilibrium. Specifically, assuming $\eta = 2$, optimization for high-damage regions, such as Sub Saharan Africa, can be solved only if the pure

Table 4 Change in total adaptation expenditure and CO2 emissions in three time slices relative to the case with no risk premium. Regional action (non-cooperative Nash game), scenarios SSP2

Risk Premium	η; ρ	Emissions			Adaptation costs		
		2005–2030	2030–2050	2050–2100	2005–2030	2030–2050	2050–2100
1	1.5; 1%	1295.05	1111.65	3400.54	1.36	4.49	60.58
1	1; 1%	1330.27	1124.11	3380.82	1.62	5.44	66.36
2	1.5; 1%	1287.09	1096.16	3353.97	3.89	10.4	104.64
2	2; 0.00001%	1260.69	1071.77	3368.06	3.41	8.97	96.74

rate of time preference ρ is adjusted downward. The economic intuition is the following: the case η = 2 corresponds to a situation of high relative risk aversion and low willingness to substitute consumption inter-temporally. In this case future damages are high, as they incorporate a large premium for the risk, and representative agents in the model would have a stronger preference to consume everything today. Thus, from the Ramsey equation, an increase in η reduces the growth rate of consumption, and, in our simulations, the reduction is "too much" to find a feasible intertemporal optimum. The resulting lower sensitivity of consumption growth to the gap between the interest rate and the pure rate of time preference can be compensated by reducing the pure rate of time preference ρ. Gollier (2002) shows how uncertainty in future consumption modifies the Ramsey equation in a similar way. The pure rate of time preference would be lower in order to induce precautionary savings. In the context of the debate on climate change discounting, Gollier (2008) and Dasgupta (2008) have also suggested a parameter combination of η = 2 and ρ = 0.

Table 5 WITCH model regions

1	USA
2	WEU: Western Europe (excluding the EEU)
3	European Economic Union (EEU)
4	KOSAU: South Korea, South Africa, Australia
5	CAJAZ: Canada, Japan, New Zealand
6	TE: Transition Economies
7	MENA: Middle East and North Africa
8	SSA: Sub-Saharan Africa
9	SASIA: South Asia (excluding India)
10	CHINA
11	EASIA: East Asia (excluding China)
12	LACA: Latin America and the Caribbean
13	INDIA

For a detailed description of the WITCH model see http://www.witchmodel.org. Note that different regional aggregations are available

Table 6 Data on damage distribution as a function of temperature change

Expected temperature	Region	Log-normal distribution				
		dist_meanlog	dist_sdlog	Expected damage	Damage (75th quantile)	Damage (90th quantile)
1.50	USA	−4.46	0.11	1.16	1.25	1.33
1.50	WEU	−4.38	0.12	1.25	1.36	1.46
1.50	EEU	−4.65	0.28	0.96	1.16	1.38
1.50	KOSAU	−4.93	0.15	0.73	0.80	0.88
1.50	CAJAZ	−4.39	0.12	1.24	1.34	1.44
1.50	TE	−4.94	0.28	0.72	0.86	1.02
1.50	MENA	−4.40	0.35	1.23	1.56	1.93
1.50	SSA	−3.77	0.32	2.30	2.84	3.45
1.50	SASIA	−3.67	0.44	2.54	3.40	4.44
1.50	CHINA	−5.39	0.21	0.46	0.52	0.60
1.50	EASIA	−3.76	0.43	2.32	3.09	4.00
1.50	LACA	−4.37	0.28	1.26	1.52	1.80
1.50	INDIA	−3.59	0.42	2.77	3.69	4.77
2.00	USA	−4.29	0.15	1.37	1.52	1.67
2.00	WEU	−4.17	0.19	1.54	1.75	1.97
2.00	EEU	−4.30	0.29	1.36	1.65	1.97
2.00	KOSAU	−4.68	0.22	0.93	1.08	1.24
2.00	CAJAZ	−4.21	0.16	1.48	1.65	1.82
2.00	TE	−4.56	0.33	1.05	1.31	1.60
2.00	MENA	−3.96	0.36	1.90	2.42	3.01
2.00	SSA	−3.38	0.33	3.40	4.24	5.16
2.00	SASIA	−3.14	0.44	4.34	5.83	7.59
2.00	CHINA	−5.04	0.32	0.65	0.80	0.97
2.00	EASIA	−3.24	0.43	3.90	5.20	6.73
2.00	LACA	−4.03	0.29	1.78	2.16	2.57
2.00	INDIA	−3.07	0.43	4.66	6.21	8.04
2.50	USA	−4.12	0.18	1.63	1.84	2.06
2.50	WEU	−3.95	0.24	1.93	2.27	2.62
2.50	EEU	−4.02	0.29	1.80	2.19	2.61
2.50	KOSAU	−4.42	0.28	1.21	1.45	1.72
2.50	CAJAZ	−4.04	0.19	1.77	2.01	2.26
2.50	TE	−4.22	0.35	1.48	1.87	2.32
2.50	MENA	−3.61	0.36	2.70	3.44	4.28
2.50	SSA	−3.06	0.33	4.68	5.83	7.11
2.50	SASIA	−2.72	0.43	6.62	8.83	11.44
2.50	CHINA	−4.67	0.38	0.94	1.21	1.52
2.50	EASIA	−2.83	0.42	5.89	7.80	10.06

Table 6 (continued)

Expected temperature	Region	Log-normal distribution				
		dist_meanlog	dist_sdlog	Expected damage	Damage (75th quantile)	Damage (90th quantile)
2.50	LACA	−3.75	0.29	2.35	2.85	3.39
2.50	INDIA	−2.65	0.42	7.03	9.31	12.00
3.00	USA	−3.95	0.20	1.92	2.20	2.50
3.00	WEU	−3.73	0.27	2.41	2.90	3.41
3.00	EEU	−3.78	0.28	2.28	2.76	3.27
3.00	KOSAU	−4.17	0.30	1.55	1.90	2.29
3.00	CAJAZ	−3.86	0.21	2.10	2.42	2.75
3.00	TE	−3.92	0.36	1.99	2.53	3.15
3.00	MENA	−3.32	0.35	3.63	4.60	5.69
3.00	SSA	−2.79	0.32	6.12	7.59	9.22
3.00	SASIA	−2.37	0.41	9.37	12.34	15.80
3.00	CHINA	−4.34	0.40	1.31	1.72	2.20
3.00	EASIA	−2.49	0.40	8.28	10.85	13.84
3.00	LACA	−3.52	0.28	2.97	3.58	4.24
3.00	INDIA	−2.31	0.40	9.88	12.94	16.49
3.50	USA	−3.79	0.22	2.26	2.61	2.98
3.50	WEU	−3.51	0.29	2.99	3.63	4.33
3.50	EEU	−3.58	0.27	2.80	3.37	3.98
3.50	KOSAU	−3.93	0.32	1.97	2.44	2.95
3.50	CAJAZ	−3.70	0.22	2.48	2.88	3.30
3.50	TE	−3.65	0.35	2.60	3.29	4.08
3.50	MENA	−3.06	0.34	4.69	5.90	7.25
3.50	SSA	−2.56	0.31	7.74	9.55	11.53
3.50	SASIA	−2.07	0.39	12.60	16.39	20.77
3.50	CHINA	−4.03	0.40	1.78	2.33	2.98
3.50	EASIA	−2.20	0.38	11.08	14.35	18.13
3.50	LACA	−3.31	0.27	3.64	4.37	5.15
3.50	INDIA	−2.02	0.38	13.21	17.10	21.58
4.00	USA	−3.64	0.23	2.63	3.08	3.55
4.00	WEU	−3.31	0.31	3.66	4.50	5.42
4.00	EEU	−3.39	0.27	3.36	4.04	4.77
4.00	KOSAU	−3.71	0.33	2.45	3.07	3.75
4.00	CAJAZ	−3.54	0.24	2.90	3.41	3.94
4.00	TE	−3.41	0.36	3.29	4.18	5.19
4.00	MENA	−2.83	0.34	5.88	7.39	9.07
4.00	SSA	−2.35	0.31	9.52	11.74	14.19
4.00	SASIA	−1.81	0.38	16.30	21.11	26.63

Table 6 (continued)

Expected temperature	Region	Log-normal distribution				
		dist_meanlog	dist_sdlog	Expected damage	Damage (75th quantile)	Damage (90th quantile)
4.00	CHINA	−3.76	0.41	2.33	3.07	3.92
4.00	EASIA	−1.95	0.38	14.28	18.43	23.18
4.00	LACA	−3.13	0.27	4.36	5.24	6.17
4.00	INDIA	−1.77	0.38	17.02	21.95	27.59
4.50	USA	−3.49	0.25	3.05	3.61	4.20
4.50	WEU	−3.12	0.32	4.43	5.51	6.70
4.50	EEU	−3.23	0.28	3.96	4.78	5.67
4.50	KOSAU	−3.50	0.35	3.01	3.80	4.68
4.50	CAJAZ	−3.39	0.26	3.37	4.00	4.67
4.50	TE	−3.20	0.36	4.08	5.20	6.48
4.50	MENA	−2.63	0.34	7.20	9.07	11.17
4.50	SSA	−2.16	0.32	11.48	14.20	17.21
4.50	SASIA	−1.59	0.38	20.48	26.52	33.48
4.50	CHINA	−3.51	0.41	2.98	3.93	5.05
4.50	EASIA	−1.72	0.38	17.89	23.10	29.08
4.50	LACA	−2.97	0.28	5.13	6.18	7.31
4.50	INDIA	−1.55	0.38	21.31	27.50	34.60
5.00	USA	−3.35	0.27	3.50	4.19	4.93
5.00	WEU	−2.94	0.34	5.29	6.64	8.16
5.00	EEU	−3.08	0.29	4.60	5.59	6.66
5.00	KOSAU	−3.32	0.36	3.63	4.62	5.74
5.00	CAJAZ	−3.25	0.27	3.88	4.66	5.49
5.00	TE	−3.01	0.37	4.95	6.35	7.94
5.00	MENA	−2.45	0.35	8.65	10.96	13.56
5.00	SSA	−2.00	0.32	13.60	16.93	20.62
5.00	SASIA	−1.38	0.39	25.13	32.66	41.34
5.00	CHINA	−3.29	0.42	3.71	4.91	6.32
5.00	EASIA	−1.52	0.38	21.90	28.39	35.86
5.00	LACA	−2.82	0.28	5.95	7.21	8.57
5.00	INDIA	−1.34	0.38	26.08	33.79	42.65

Table 7 Risk-premium adjusted damages for $\eta = 1$

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
1.50	USA	1.16	0.01	1.17
1.50	WEU	1.25	0.01	1.27
1.50	EEU	0.96	0.04	1.04
1.50	KOSAU	0.73	0.01	0.74
1.50	CAJAZ	1.24	0.01	1.26
1.50	TE	0.72	0.03	0.77
1.50	MENA	1.23	0.08	1.39
1.50	SSA	2.30	0.12	2.53
1.50	SASIA	2.54	0.25	3.04
1.50	CHINA	0.46	0.01	0.48
1.50	EASIA	2.32	0.22	2.76
1.50	LACA	1.26	0.05	1.36
1.50	INDIA	2.77	0.26	3.29
2.00	USA	1.37	0.02	1.40
2.00	WEU	1.54	0.03	1.60
2.00	EEU	1.36	0.06	1.48
2.00	KOSAU	0.93	0.02	0.98
2.00	CAJAZ	1.48	0.02	1.52
2.00	TE	1.05	0.06	1.17
2.00	MENA	1.90	0.13	2.15
2.00	SSA	3.40	0.19	3.77
2.00	SASIA	4.34	0.43	5.21
2.00	CHINA	0.65	0.03	0.72
2.00	EASIA	3.90	0.37	4.64
2.00	LACA	1.78	0.07	1.93
2.00	INDIA	4.66	0.44	5.54
2.50	USA	1.63	0.03	1.68
2.50	WEU	1.93	0.06	2.04
2.50	EEU	1.80	0.08	1.95
2.50	KOSAU	1.21	0.05	1.30
2.50	CAJAZ	1.77	0.03	1.83
2.50	TE	1.48	0.10	1.67
2.50	MENA	2.70	0.18	3.06
2.50	SSA	4.68	0.26	5.19
2.50	SASIA	6.62	0.63	7.88
2.50	CHINA	0.94	0.07	1.08
2.50	EASIA	5.89	0.54	6.96

Table 7 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
2.50	LACA	2.35	0.10	2.55
2.50	INDIA	7.03	0.64	8.31
3.00	USA	1.92	0.04	2.00
3.00	WEU	2.41	0.09	2.59
3.00	EEU	2.28	0.09	2.46
3.00	KOSAU	1.55	0.07	1.70
3.00	CAJAZ	2.10	0.05	2.19
3.00	TE	1.99	0.13	2.25
3.00	MENA	3.63	0.23	4.09
3.00	SSA	6.12	0.32	6.76
3.00	SASIA	9.37	0.81	11.00
3.00	CHINA	1.31	0.11	1.53
3.00	EASIA	8.28	0.69	9.66
3.00	LACA	2.97	0.12	3.20
3.00	INDIA	9.88	0.82	11.52
3.50	USA	2.26	0.05	2.36
3.50	WEU	2.99	0.13	3.24
3.50	EEU	2.80	0.11	3.01
3.50	KOSAU	1.97	0.10	2.17
3.50	CAJAZ	2.48	0.06	2.60
3.50	TE	2.60	0.17	2.93
3.50	MENA	4.69	0.28	5.25
3.50	SSA	7.74	0.39	8.51
3.50	SASIA	12.60	1.00	14.59
3.50	CHINA	1.78	0.15	2.08
3.50	EASIA	11.08	0.85	12.77
3.50	LACA	3.64	0.14	3.91
3.50	INDIA	13.21	1.01	15.22
4.00	USA	2.63	0.07	2.78
4.00	WEU	3.66	0.18	4.01
4.00	EEU	3.36	0.13	3.62
4.00	KOSAU	2.45	0.14	2.73
4.00	CAJAZ	2.90	0.08	3.07
4.00	TE	3.29	0.21	3.72
4.00	MENA	5.88	0.35	6.57
4.00	SSA	9.52	0.47	10.47
4.00	SASIA	16.30	1.24	18.78

Table 7 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
4.00	CHINA	2.33	0.20	2.73
4.00	EASIA	14.28	1.06	16.40
4.00	LACA	4.36	0.16	4.69
4.00	INDIA	17.02	1.25	19.53
4.50	USA	3.05	0.10	3.24
4.50	WEU	4.43	0.24	4.90
4.50	EEU	3.96	0.16	4.28
4.50	KOSAU	3.01	0.19	3.38
4.50	CAJAZ	3.37	0.11	3.59
4.50	TE	4.08	0.28	4.63
4.50	MENA	7.20	0.44	8.07
4.50	SSA	11.48	0.59	12.65
4.50	SASIA	20.48	1.56	23.61
4.50	CHINA	2.98	0.26	3.50
4.50	EASIA	17.89	1.33	20.55
4.50	LACA	5.13	0.20	5.53
4.50	INDIA	21.31	1.58	24.47
5.00	USA	3.50	0.13	3.75
5.00	WEU	5.29	0.31	5.91
5.00	EEU	4.60	0.20	4.99
5.00	KOSAU	3.63	0.24	4.11
5.00	CAJAZ	3.88	0.14	4.17
5.00	TE	4.95	0.35	5.65
5.00	MENA	8.65	0.55	9.75
5.00	SSA	13.60	0.74	15.07
5.00	SASIA	25.13	1.97	29.07
5.00	CHINA	3.71	0.34	4.38
5.00	EASIA	21.90	1.68	25.27
5.00	LACA	5.95	0.25	6.44
5.00	INDIA	26.08	1.99	30.07

Table 8 Risk-premium adjusted damages for $\eta = 1.5$

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
1.50	USA	1.155	0.015	1.177
1.50	WEU	1.248	0.019	1.276
1.50	EEU	0.960	0.076	1.075
1.50	KOSAU	0.725	0.016	0.749
1.50	CAJAZ	1.238	0.018	1.264
1.50	TE	0.715	0.056	0.799
1.50	MENA	1.230	0.152	1.460
1.50	SSA	2.295	0.231	2.645
1.50	SASIA	2.538	0.483	3.273
1.50	CHINA	0.455	0.020	0.485
1.50	EASIA	2.318	0.419	2.956
1.50	LACA	1.260	0.099	1.409
1.50	INDIA	2.770	0.498	3.529
2.00	USA	1.370	0.032	1.418
2.00	WEU	1.540	0.056	1.624
2.00	EEU	1.360	0.113	1.531
2.00	KOSAU	0.930	0.046	1.000
2.00	CAJAZ	1.480	0.038	1.537
2.00	TE	1.050	0.114	1.222
2.00	MENA	1.900	0.245	2.272
2.00	SSA	3.400	0.361	3.946
2.00	SASIA	4.340	0.829	5.603
2.00	CHINA	0.650	0.065	0.748
2.00	EASIA	3.900	0.708	4.978
2.00	LACA	1.780	0.145	1.999
2.00	INDIA	4.660	0.844	5.944
2.50	USA	1.625	0.055	1.708
2.50	WEU	1.928	0.112	2.096
2.50	EEU	1.800	0.150	2.026
2.50	KOSAU	1.205	0.091	1.343
2.50	CAJAZ	1.768	0.064	1.865
2.50	TE	1.475	0.185	1.756
2.50	MENA	2.700	0.350	3.230
2.50	SSA	4.675	0.500	5.432
2.50	SASIA	6.618	1.208	8.456
2.50	CHINA	0.935	0.135	1.140
2.50	EASIA	5.888	1.030	7.455
2.50	LACA	2.350	0.191	2.639

Table 8 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
2.50	INDIA	7.030	1.225	8.894
3.00	USA	1.920	0.080	2.041
3.00	WEU	2.410	0.178	2.679
3.00	EEU	2.280	0.181	2.553
3.00	KOSAU	1.550	0.144	1.767
3.00	CAJAZ	2.100	0.094	2.241
3.00	TE	1.990	0.254	2.375
3.00	MENA	3.630	0.446	4.307
3.00	SSA	6.120	0.627	7.068
3.00	SASIA	9.370	1.561	11.743
3.00	CHINA	1.310	0.213	1.634
3.00	EASIA	8.280	1.331	10.303
3.00	LACA	2.970	0.230	3.317
3.00	INDIA	9.880	1.578	12.279
3.50	USA	2.255	0.108	2.417
3.50	WEU	2.988	0.250	3.365
3.50	EEU	2.800	0.210	3.117
3.50	KOSAU	1.965	0.199	2.266
3.50	CAJAZ	2.478	0.125	2.666
3.50	TE	2.595	0.324	3.085
3.50	MENA	4.690	0.541	5.509
3.50	SSA	7.735	0.752	8.873
3.50	SASIA	12.598	1.918	15.510
3.50	CHINA	1.775	0.289	2.215
3.50	EASIA	11.078	1.637	13.562
3.50	LACA	3.640	0.268	4.045
3.50	INDIA	13.210	1.941	16.156
4.00	USA	2.630	0.144	2.848
4.00	WEU	3.660	0.345	4.181
4.00	EEU	3.360	0.252	3.741
4.00	KOSAU	2.450	0.270	2.859
4.00	CAJAZ	2.900	0.166	3.151
4.00	TE	3.290	0.416	3.920
4.00	MENA	5.880	0.672	6.898
4.00	SSA	9.520	0.923	10.915
4.00	SASIA	16.300	2.394	19.936
4.00	CHINA	2.330	0.386	2.917
4.00	EASIA	14.280	2.043	17.381

Table 8 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
4.00	LACA	4.360	0.321	4.845
4.00	INDIA	17.020	2.421	20.694
4.50	USA	3.045	0.192	3.334
4.50	WEU	4.428	0.464	5.130
4.50	EEU	3.960	0.309	4.427
4.50	KOSAU	3.005	0.360	3.551
4.50	CAJAZ	3.368	0.220	3.699
4.50	TE	4.075	0.533	4.884
4.50	MENA	7.200	0.846	8.481
4.50	SSA	11.475	1.149	13.212
4.50	SASIA	20.478	3.016	25.058
4.50	CHINA	2.975	0.506	3.745
4.50	EASIA	17.888	2.573	21.792
4.50	LACA	5.130	0.393	5.722
4.50	INDIA	21.310	3.051	25.940
5.00	USA	3.500	0.249	3.876
5.00	WEU	5.290	0.605	6.205
5.00	EEU	4.600	0.382	5.178
5.00	KOSAU	3.630	0.465	4.336
5.00	CAJAZ	3.880	0.284	4.309
5.00	TE	4.950	0.675	5.974
5.00	MENA	8.650	1.067	10.267
5.00	SSA	13.600	1.434	15.769
5.00	SASIA	25.130	3.797	30.897
5.00	CHINA	3.710	0.644	4.690
5.00	EASIA	21.900	3.246	26.828
5.00	LACA	5.950	0.482	6.677
5.00	INDIA	26.080	3.845	31.918

Table 9 Risk-premium adjusted damages for η = 2

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
1.50	USA	1.16	1.15	2.31
1.50	WEU	1.25	1.24	2.50
1.50	EEU	0.96	0.99	1.99
1.50	KOSAU	0.73	0.73	1.46
1.50	CAJAZ	1.24	1.23	2.48
1.50	TE	0.72	0.74	1.48
1.50	MENA	1.23	1.30	2.60
1.50	SSA	2.30	2.39	4.80
1.50	SASIA	2.54	2.76	5.55
1.50	CHINA	0.46	0.46	0.93
1.50	EASIA	2.32	2.51	5.05
1.50	LACA	1.26	1.30	2.61
1.50	INDIA	2.77	3.00	6.03
2.00	USA	1.37	1.37	2.76
2.00	WEU	1.54	1.55	3.12
2.00	EEU	1.36	1.40	2.82
2.00	KOSAU	0.93	0.94	1.90
2.00	CAJAZ	1.48	1.48	2.98
2.00	TE	1.05	1.10	2.21
2.00	MENA	1.90	2.01	4.03
2.00	SSA	3.40	3.55	7.14
2.00	SASIA	4.34	4.73	9.50
2.00	CHINA	0.65	0.68	1.36
2.00	EASIA	3.90	4.23	8.50
2.00	LACA	1.78	1.84	3.69
2.00	INDIA	4.66	5.05	10.15
2.50	USA	1.63	1.64	3.29
2.50	WEU	1.93	1.96	3.95
2.50	EEU	1.80	1.86	3.73
2.50	KOSAU	1.21	1.24	2.49
2.50	CAJAZ	1.77	1.78	3.58
2.50	TE	1.48	1.56	3.13
2.50	MENA	2.70	2.85	5.73
2.50	SSA	4.68	4.88	9.82
2.50	SASIA	6.62	7.18	14.43
2.50	CHINA	0.94	1.00	2.00
2.50	EASIA	5.89	6.36	12.79
2.50	LACA	2.35	2.42	4.87
2.50	INDIA	7.03	7.60	15.26
3.00	USA	1.92	1.94	3.90
3.00	WEU	2.41	2.48	4.98
3.00	EEU	2.28	2.35	4.72
3.00	KOSAU	1.55	1.61	3.23
3.00	CAJAZ	2.10	2.13	4.27

Table 9 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
3.00	TE	1.99	2.10	4.22
3.00	MENA	3.63	3.82	7.68
3.00	SSA	6.12	6.38	12.82
3.00	SASIA	9.37	10.08	20.27
3.00	CHINA	1.31	1.41	2.83
3.00	EASIA	8.28	8.89	17.86
3.00	LACA	2.97	3.06	6.14
3.00	INDIA	9.88	10.60	21.30
3.50	USA	2.26	2.29	4.60
3.50	WEU	2.99	3.08	6.20
3.50	EEU	2.80	2.88	5.79
3.50	KOSAU	1.97	2.05	4.11
3.50	CAJAZ	2.48	2.52	5.06
3.50	TE	2.60	2.74	5.50
3.50	MENA	4.69	4.92	9.89
3.50	SSA	7.74	8.04	16.16
3.50	SASIA	12.60	13.46	27.05
3.50	CHINA	1.78	1.91	3.83
3.50	EASIA	11.08	11.81	23.74
3.50	LACA	3.64	3.74	7.52
3.50	INDIA	13.21	14.08	28.29
4.00	USA	2.63	2.68	5.38
4.00	WEU	3.66	3.80	7.64
4.00	EEU	3.36	3.45	6.94
4.00	KOSAU	2.45	2.56	5.15
4.00	CAJAZ	2.90	2.95	5.94
4.00	TE	3.29	3.47	6.97
4.00	MENA	5.88	6.17	12.39
4.00	SSA	9.52	9.89	19.89
4.00	SASIA	16.30	17.37	34.91
4.00	CHINA	2.33	2.51	5.04
4.00	EASIA	14.28	15.19	30.53
4.00	LACA	4.36	4.48	9.00
4.00	INDIA	17.02	18.10	36.37
4.50	USA	3.05	3.11	6.25
4.50	WEU	4.43	4.62	9.29
4.50	EEU	3.96	4.08	8.20
4.50	KOSAU	3.01	3.16	6.35
4.50	CAJAZ	3.37	3.44	6.92
4.50	TE	4.08	4.31	8.66
4.50	MENA	7.20	7.56	15.20
4.50	SSA	11.48	11.95	24.01
4.50	SASIA	20.48	21.83	43.87
4.50	CHINA	2.98	3.21	6.45

Table 9 (continued)

Expected temperature	Region	Expected Damage	Risk Premium	Damage With Risk
4.50	EASIA	17.89	19.03	38.25
4.50	LACA	5.13	5.28	10.61
4.50	INDIA	21.31	22.67	45.56
5.00	USA	3.50	3.59	7.22
5.00	WEU	5.29	5.55	11.15
5.00	EEU	4.60	4.75	9.54
5.00	KOSAU	3.63	3.83	7.70
5.00	CAJAZ	3.88	3.99	8.01
5.00	TE	4.95	5.25	10.55
5.00	MENA	8.65	9.11	18.31
5.00	SSA	13.60	14.20	28.53
5.00	SASIA	25.13	26.84	53.94
5.00	CHINA	3.71	4.01	8.05
5.00	EASIA	21.90	23.36	46.94
5.00	LACA	5.95	6.13	12.33
5.00	INDIA	26.08	27.80	55.88

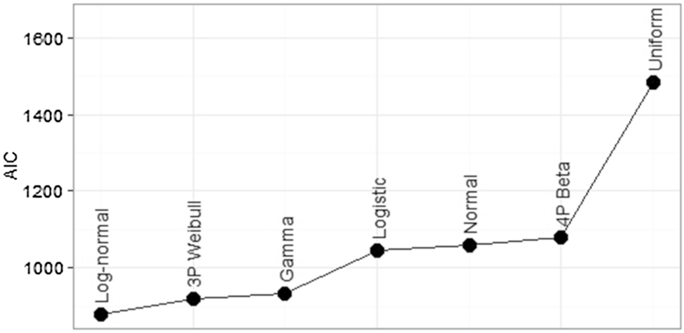

Fig. 8 Akaike Information Criteria (AIC) of the fitting of damages with different distribution (the lower the better)

References

Agrawala S, Bosello F, Carraro C, De Cian E, Lanzi E, De Bruin K, Dellink R (2011) "PLAN or REACT? Analisys of adaptation costs and benefits Using Integrated Assessment Models. Clim Change Econ 2(3):1–36

Anderson B, Borgonovo E, Galeotti M, Roson R (2014) Uncertainty in integrated assessment modelling: can global sensitivity analysis be of help. Risk Anal 34:271–293

Arrow KJ (1965) Aspects in the theory of risk bearing. Academic Bookstores, Helsinki

Aven T (2010) On the need for restricting the probabilistic analysis in risk assessments to variability. Risk Anal 30(3):354–360

Aven T, Renn O (2015) An evaluation of the treatment of risk and uncertainties in the IPCC reports on climate change. Risk Anal 35(4):701–712

Blake D (1996) Efficiency, risk aversion and portfolio insurance: an analysis of financial asset portfolios held by investors in the United Kingdom. Econ J 106:1175–1192

Bliss RR, Panigirtzoglou N (2004) Option implied risk aversion parameters. J Financ, LIX, pp 407–444

Bosello F (2014) The role of economic modelling for climate change mitigation and adaptation strategies. In: Markandya A, Galarraga I, Sainz de Murieta E (eds) Routledge handbook of the economics of climate change adaptation. Routledge, Oxon and New York

Bosello F, Carraro C, De Cian E (2010) Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. Clim Change Econ 1(2):71–92

Bosello F, Carraro C, De Cian E (2013) Can adaptation help mitigation? an integrated approach to post-2012 climate policy. Environ Dev Econ 18:270–290

Bosello F, De Cian E (2014) Documentation on the development of damage functions and adaptation module in the WITCH model. http://www.witchmodel.org/pag/publications.html

Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M (2006) WITCH: A World Induced Technical Change Hybrid Model. Energ J Special Issue. Hybrid modeling of energy-environment policies: reconciling bottom-up and top-down, pp 13–38

Bosetti V, Marangoni G, Borgonovo E, Diaz Anadon L, Barron R, McJeon H, Politis S, Friley P (2015) Sensitivity to energy technology costs: a multi-model comparison analysis. Energ Policy. https://doi.org/10.1016/j.enpol.2014.12.012

Cai Y, Judd KL, Lontzek TS (2013) The social cost of stochastic and irreversible climate change. NBER 18704

Dasgupta P (2008) Discounting Climate Change. J Risk Uncertainty 37:141–169

Dietz S, Gollier C and Kessler L (2015) The Climate Beta. Centre for Climate Change Economics and Policy Working Paper No. 215

Drouet L, Bosetti V, Tavoni M (2015) Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. Nature Climate Change 5:937–940

Ellsberg D (1961) Risk, ambiguity and the savage axioms. Quart. J. of Ec. 75(4):643–669

Felgenhauer T, de Bruin KC (2009) Optimal paths of climate change mitigation and adaptation under certainty and uncertainty. Int J Global Warming 1:66–88

Garrick BJ (2010) Interval analysis versus probabilistic analysis. Risk Anal 30(3):369–370

Gilboa I, Postlewaite AW, Schmeidler D (2008) Probability and uncertainty in economic modeling. J Econ Perspect 22(3):173–188

Gilboa I, Postlewaite A, Schmeidler D (2009) Is it always rational to satisfy Savage's axioms? Econ Philos 25(3):285–296

Gjerde J, Grepperud S, Kverndokk S (1999) Optimal climate policy under the possibility of a catastrophe. Res En Ec 21(3–4):289–317

Gollier C (2002) Time horizon and the discount rate. J Econ Theory 107:463–473

Gollier C (2008) Discounting with fat-tailed economic growth. J Risk Uncertainty 37:171–186

Green PE, Krieger AM, Wind Y (2001) Thirty years of conjoint analysis: reflections and prospects. Interfaces 200131(3 Supplement):S56–S73

Hall JW, Lempert RJ, Keller K, Hackbarth A, Mijere C, Mcinerney DJ (2012) Robust climate policies under uncertainty : a comparison of robust decision making and info-gap methods. Risk Anal 32(10):1657–1672

Halsnæs K, Shukla P, Ahuja D, Akumu G, Beale R, Edmonds J, Gollier C, Grübler A, Ha Duong M, Markandya A, McFarland A, Nikitina Sugiyama ET, Villavicencio A, Zou J (2007) Framing issues. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Holt CA, Laury SK (2002) Risk Aversion and Incentive Effects. Am Econ Rev 92(5):1644–1655

Kahneman D (2011) Thinking fast and slow. Penguin Books, London

Kaplan S, Garrick BJ (1981) On the quantitative definition of risk. Risk Anal 1(1):11–27

Kaplow L (2005) The Value of a statistical life and the coefficient of relative risk aversion. J Risk Uncertainty 31(1):23–34

Keller K, Bolker BM, Bradford DF (2004) Uncertain climate thresholds and optimal economic growth. J Environ Econ Manag 48:723–741

Klibanoff P, Marinacci M, Mukerji S (2005) A smooth model of decision making under ambiguity. Econometrica 73(6):1849–1892

Klibanoff P, Marinacci M, Mukerji S (2009) Recursive smooth ambiguity preferences. J Econ Theory 144(3):930–976

Knight FH (1921) Risk, uncertainty, and profit. Hart, Schaffner & Marx; Houghton Mifflin Company, Boston

Kousky C, Kopp RE, Cooke RM (2011) Risk premia and the social cost of carbon: a review. Econ Open-Access Open-Assess E-J 5(2011-21):1

Krupnick AJ, Markandya A, Nickell E (1993) The external costs of nuclear power: ex ante damages and lay risks. Am J Agr Econ 75:1273–1279

Kunreuther H, Gupta S, Bosetti V, Cooke R, Dutt V, Ha-Duong M, Held H, Llanes-Regueiro J, Patt A, Shittu E, Weber E (2014) Integrated risk and uncertainty assessment of climate change response policies. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC (eds) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Layard R, Mayraz G, Nickell S (2008) The marginal utility of income. J Public Econ 8–9(92):1846–1857

Lemoine DM, Traeger C (2012) Tipping points and ambiguity in the economics of climate change. NBER 18230

Lessmann K, Kornek U, Bosetti V, Dellink R, Emmerling J, Eyckmans J, Nagashima M, Weikard H-P, Yang Z (2015) The stability and effectiveness of climate coalitions: a comparative analysis of multiple integrated assessment models. Environ Resource Econ 1:1. https://doi.org/10.1007/s10640-015-9886-0

Levy H (1994) Absolute and relative risk aversion: an experimental study. J Risk Uncertainty 8:289–307

Lucas RE (1978) Asset prices in an exchange economy. Econometrica 46:1429–1445

Millner A, Dietz S, Heal G (2013) Scientific Ambiguity and Climate Policy. Environ Resource Econ 55:21–46

Nordhaus WD (2008) A Question of balance: weighing the options on global warming policies. Yale University Press, Yale

North WD (2010) Probability theory and consistent reasoning. Risk Anal 30(3):377–380

O'Neill BC, Carter TR, Ebi KL, Edmonds J, Hallegatte S, Kemp-Benedict E, Kriegler E, Mearns L, Moss R, Riahi K, van Ruijven B, van Vuuren D (2012). Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research, Boulder, CO, November 2–4, 2011. http://www.isp.ucar.edu/socio-economic-pathways

Pindyck R (2013) Climate change policy: what do the models tell us? J Econlit 51(3):860–872

Rabl A, Spadaro JV (1999) Environmental damages and costs: an analysis of uncertainties. Environ Int 25(1):29–46

Shiller R (2000) Irrational exuberance. Princeton University Press, Princeton

Stern N (2013) The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. J Econ Lit 51(3):838–859

Tavoni M, Kriegler E, Riahi K, van Vuuren DP, Aboumahboub T, Bowen A, Calvin K, Campiglio E, Kober T, Jewell J, Luderer G, Marangoni G, McCollum D, van Sluisveld M, Zimmer A, van der Zwaan B (2014) Post-2020 climate agreements in the major economies assessed in the light of global models. Nat Clim Change. https://doi.org/10.1038/nclimate2475

Taylor K, Stouffer R, Meehl G (2012) An overview of CMIP5 and the experiment design. Bull Am Meteor Soc 93:485–498

Thaler RH, Sunstein CR (2008) Nudge: improving decisions about health, wealth and happiness. Yale University Press, New Haven

Urban NM, Keller K (2010) Probabilistic hindcasts and projections of the coupled climate, carbon cycle and Atlantic meridional overturning circulation system: a Bayesian fusion of century-scale observations with a simple model. Tellus A 62(5):737–750

von Neumann J, Morgenstern O (1944) Theory of Games and Economic Behavior. Princeton University Press, Princeton

Weitzman M (2009a) Additive damages, fat-tailed climate dynamics, and uncertain discounting. economics: the open-access. Open-Assess E-J 3:2009–2039

Weitzman M (2009b) On modeling and interpreting the economics of catastrophic climate change. Rev Econ Stat 91:1–19