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Anil Markandya, BC3
Enrica De Cian,CMCC and FEEM
Laurent Drouet, CMCC and FEEM
Josué M. Polanco-Martìnez, BC3
Francesco Bosello, CMCC and FEEM

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Keywords: Risk, Uncertainty, Climate, Adaptation, Mitigation

JEL Classification: Q2, Q3, D8, D9, D62

The research leading to these results has received funding from the European Community's Seventh Framework Programme under Grant Agreement No.308337 (BASE) and No° 298436 (DYNAMIC).

Address for correspondence:
Enrica De Cian
Fondazione Eni Enrico Mattei
Isola di San Giorgio Maggiore
30124 Venice
Italy
E-mail: enrica.decian@feem.it

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1. Introduction

The estimated costs of climate impacts are highly uncertain. In addition to the irreducible randomness of natural and social phenomena, the so-called “aleatory uncertainty”, there are many other sources deriving from an incomplete knowledge of these phenomena, called “epistemic uncertainty”. These can be divided into (Refsgaard et al., 2013) uncertainties on input data, model uncertainty, and context uncertainty, i.e. when the boundaries of the systems to be modelled, for instance future climate and regulatory conditions, are not explicitly included in the modelling study. Finally, there is frequently a simultaneous presence of multiple knowledge frames, reflecting varying perceptions different persons may have of what the main problems are, what is at stake, or which goals should be achieved. These can cause “ambiguity”. Assessing climate change impacts, and consequently analysing adequate policies, is thus subject to an “uncertainty cascade”, which starts from what is embedded in emission scenarios generated by global and regional climate models and their statistical downscaling processes, passes through to the scenario originating from environmental impact models, and finally ends up with the scenario related to socio-economic responses.

Accounting for this uncertainty is thus a key issue in the Integrated Assessment (IA) of climate change, which uses different strategies to do so. These go from the practice of using ensembles of General Circulation Models (GCMs), to impact models or even multi-model environmental and economic impact assessments to capture the model uncertainty[1], to performing sensitivity analyses on models’ behavioural parameters[2], and finally to developing stochastic IA models to deal with randomness.

Defining uncertainty boundaries is not only important *per se*, but also, and most obviously, in determining how decisions can be affected by this uncertainty. In this regard, the IA literature proposes again a multiplicity of approaches. One is to use expected utility or expected damage functions to embed uncertainty directly in the decision-making process. This methodology is typically applied to studying the effect of catastrophic risk and tipping points (Kverndokk 1999, Keller et al. 2004, Lemoine and Trager 2012, Cai et al. 2013). Alternatively, different specifications of damage functions are tested to verify the robustness of climate policy prescriptions. In this vein Sterner and Persson (2008) show that explicitly accounting for the increase in the relative price of environmental goods induced by their depletion, raises the estimated damage of climate change. Moore and Diaz (2015) find a similar result, but by

[1] 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/) are good representatives of this approach.
[2] See Anderson et al (2014) for a discussion and new approaches on sensitivity tests.

assuming that climatic changes affect the rate of growth rather than the level of GDP. In both cases more mitigation is justified.

A further methodology consists of specifying stochastic damage functions in IA models and then verifying which abatement prescriptions are consistent with different preferences and risk management criteria (Kunreuter et al., 2013; Drouet et al., 2015)

The bulk of this literature, however, focuses on mitigation choices, while little has been done on adaptation (partial exceptions are Felgenhauer and de Bruin 2009, Bosello et al., 2014). Furthermore, these approaches tend to consider a “specific” risk and to implement not easily generalizable *ad hoc* methodologies.

The idea behind this paper is to develop a more general framework to account for uncertainty, reflecting different degrees of risk aversion as well as uncertainty in climate change damages, into a deterministic, integrated assessment model (the WITCH model by Bosetti et al, (2006), developed to include adaptation choices as in Agrawala et al. (2010). The concept underpinning the analysis it that of defining a risk premium which allows us to estimate a ”damage mark-up” that varies with the degrees of aversion to risk. Such damage ‘add-ons’, would then affect the assessment of adaptation options, and their interaction with mitigation. Using such a risk premium offers some advantages: (a) it is relatively simple to model and (b) it allows public attitudes of aversion to risk uncertainty to be reflected in a transparent way.

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 or even in assessments of adaptation options at the project level 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 in the model. Section 4 compares the results of the policy response with and without risk premium. Section 5 concludes.

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 event, irrespective of whether 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 €5,000. Yet if offered a choice between a certain return of €5000 and tossing a coin in this manner most will choose the certain €5,000 (especially if the figures are an issue affecting their way of life). Indeed, most people will take a little less than €5,000 rather than play the game. If the minimum they would accept with certainty is €4,500 then €500 is defined as the risk premium associated with that game. Similarly, when faced with a potential loss of €10,000 with a 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 €5,000. irrespective of what state of the world prevails. The insurance company then has an expected payout 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 €5,000 but €5,500. In the case of climate impacts a similar argument can be made. In Figure 1, expected damages from (say) flooding are plotted against temperature.

The average damages are shown by the bold black line in Figure 1, while the damages with the risk premium are shown by the bold red line. The higher line represents the real damages, when risk is accounted for. In this context both adaptation and mitigation should be carried out to reduce that line. This can be done in a number of ways, which include measures to reduce the expected part of damages or through measures that reduce the risk premium associated with the damages. The latter could be achieved, for example, through public insurance schemes or through actions that reduce the uncertainty associated with the event in the first place, e.g. by undertaking research on the different steps, from temperature increase to the physical impacts and the monetary damages.

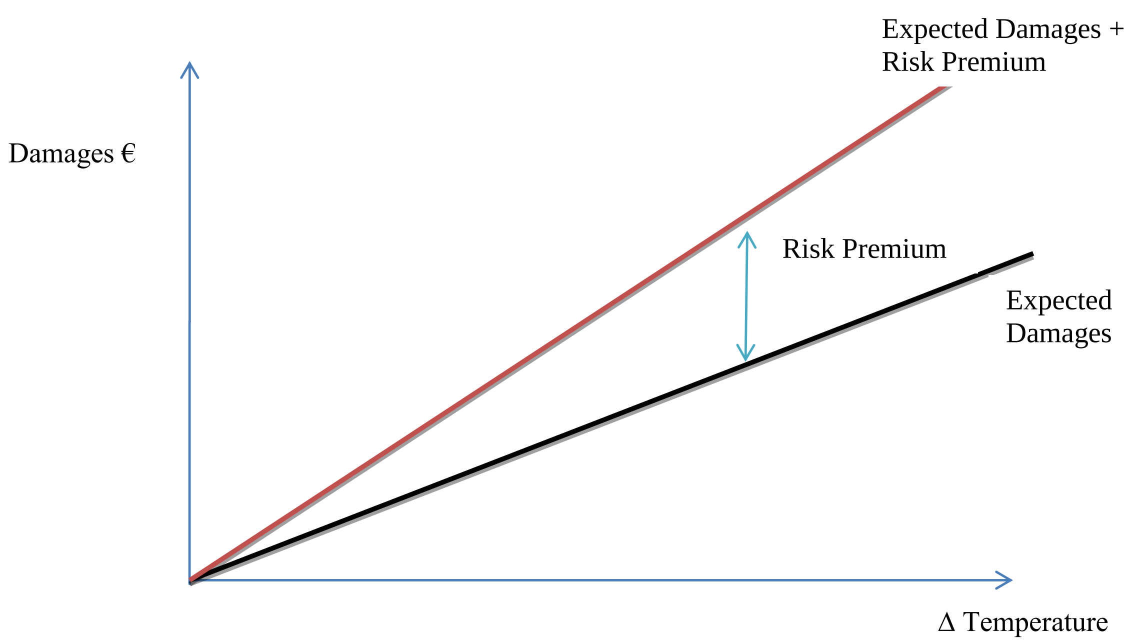

Figure 1: Premium for Risk in Climate Cost Estimation

The use of this framework has been questioned, especially by psychologists who argue that 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 risk assessment, however, we are seeking a social representation of risk aversion in a single direction (i.e. that of possible losses), and so at least 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).

2.2 Measuring the Risk Premium

Several approaches can be used to estimate risk premiums[3]. The conjoint choice method asks people, and one major line of research has used this empirical approach (Green et al. 2001). An alternative, more theoretical method is based on the expected utility framework. Here we follow the latter and apply methods used to study consumer choices in the presence of risk aversion in other realms in the area of assessing climate change damage[4]. 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.

Let us now consider a society with uncertain income *x* which derives a utility *U(x)*, where *U(x)* is the individual's Von Neumann-Morgenstern utility function. Income *x* is uncertain and the probability of different outcomes is described by 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:

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

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

[4] Applications of the theory for understanding 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, Markandya and Nickell (1993).

The certainty equivalent x^* is smaller than 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. Accordingly:

$$U(x^*) = U(E(x) - r) = U(\mu - r) \quad (2)$$

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

$$E(U) = \int U(x)\, f(x)\, dx = U(E(x) - r) = U(x^*) \quad (3)$$

In the specific context of this study, uncertain future climate change impacts are the source of income uncertainty. To compute the uncertainty equivalent, we first need 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.[5] Rabl and Spadaro (1999), for instance, note that if the final number (damages) is the outcome of a process such 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 can then be represented by the "standard" family of functions:

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

η, which can be interpreted as the coefficient of relative risk aversion (but see more on that below), has generally been estimated to take values of between 1 and 2, but possibly even as high as 10 (Kaplow, 2005). Note that when η is equal to 1, the above function reduces (by L'Hôpital's Rule) to:

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

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

In order to show how equation (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 $f(x;\mu,\sigma)$ we get the 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:

$$\begin{aligned} E(U) &= \int_0^\infty \frac{x^{1-\eta} - 1}{1-\eta} \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} dx = \\ &= \frac{1}{1-\eta} \int_0^\infty x^{1-\eta} \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} dx - \frac{1}{1-\eta} = \frac{E(x^{1-\eta}) - 1}{1-\eta} \end{aligned} \tag{8}$$

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:

$$U(x) = \ln x \tag{10}$$

Accordingly equation (3) boils down to:

$$\ln x^* = \mu \tag{11}$$

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

$$x^* = e^\mu \tag{12}$$

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

$$\bar{x} = e^{\mu+\sigma^2/2} \tag{13}$$

For example with μ=10 and σ=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 a 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%.

The next section introduces first the IA model 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 equation (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[6] (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). WITCH also features an adaptation module (see Agrawala et al. 2010, 2011) that aggregates 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 forms 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. A forward-looking social planner in each macro-region maximizes his inter-temporal welfare by optimally choosing investments in final good energy technologies, energy R&D[7], and adaptation, subject to the budget constraint. The resulting Nash equilibrium is a constrained optimum, which does not internalise the environmental and technology externalities globally, but only within the boundary of each given region. In the second case, a world

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

[7] For more insights on the treatment of technical change in the WITCH model see Bosetti et al. (2009), De Cian et al. (2012).

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:

$$U(t,n) = \sum_t L(t,n) \frac{\frac{C(t,n)}{L(t,n)}^{1-\eta} - 1}{1-\eta} df(t) \tag{14}$$

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

$$df(t) = \prod_{t'=0}^{t} (1+\rho(t')) \tag{15}$$

The WITCH default value of the η is 1.5 and the pure rate of time preference ρ is 1%. Following the discussion in section 2, a possible issue arises on which value of η to use for the computation of the risk premium. The parameter η in equation (14) serves two purposes. Following the standard approach of optimal growth models under certainty and perfect foresight (Nordhaus, 2014), it represents the inverse of intertemporal elasticity of substitution of consumption over time[8]. However, the parameter also reflects risk attitudes. Accordingly, two possibilities are at hand. The first is to use the same value of η in equation (15) and in the risk premium computation process described by equations (1) to (13). The second is to use different values of η in (1) to (13) and to keep in the WITCH utility function the value of η equal to 1.5, if we assume 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 η = 1.5 and we use this calibration to test different risk premium-corrected damage functions calculated using equations (1)-(13) under different values of risk aversion, namely η = 1, 1.5, and 2[9].

[8] In social welfare literature this parameter typically takes a value of around 1.3 (Layard, Mayraz and Nickell, 2007)

[9] However, we perform some sensitivity tests (available upon request) showing 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, if we assume that η=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 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

We then analyze the implications of including a risk premium in the two model setup:

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. Given the non-cooperative nature of these scenarios, abatement effort results very close to a no mitigation policy case. They can thus be interpreted as 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” scenarios.

The socio-economic reference case for the WITCH model is that of the Shared Social Economic Pathway 2 (SSP2), (O’ Neill et al. 2015). 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 profiles as well as intermediate economic growth, providing at least some resources to address adaptation needs[10]. In its standard setup 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 first need to estimate the distribution of regional damages to quantify μ and σ in equations (8), (12) and (13). This has been done by using a simple emulator of the global climate model simulations that comprise the CMIP5 ensemble archive to extract the “geophysical uncertainties” determining temperature profiles associated with a given carbon budget (Taylor et al. 2012). Emulation has been performed by using a Bayesian inversion technique based on a Monte Carlo Markov chain. This has been coupled with a set of 802 emission pathways for the next century, extracted from the IPCC AR5 scenario database to capture uncertainty about climate policy implementation (e.g. different delay of action, technology availability, level of cooperation and climate targets).

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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. 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 $\rho=0$.

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

More precisely, the procedure has been as follows:

1. We calibrated a simple climate model 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, aerosol factors, initial conditions, etc.
2. We then derived emission profiles until 2100 by using 802 scenarios from the AR5 database
3. We generated a distribution of temperature for each emission profile.
4. We applied WITCH's damage function (Bosetti et al. 2006, Bosello and De Cian 2014) to the temperature distributions to generate related distributions of regional damages
5. We fitted for the year 2100 regional damage distributions with a log-normal distribution and computed the mean log and standard deviation log of the damages. The fit, based on the Akaike Information Criteria (AIC)[11]. is found to be good (see Appendix).
6. Finally, the parameters of the log-normal distribution (mean log and standard-deviation log) are 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 details 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

[11] The Akaike information criterion (AIC) is a measure of the relative quality of statistical models for a given set of data.

details are in the Appendix which provides results for all the regions as well as for values of η equal to 1, and 1.5).

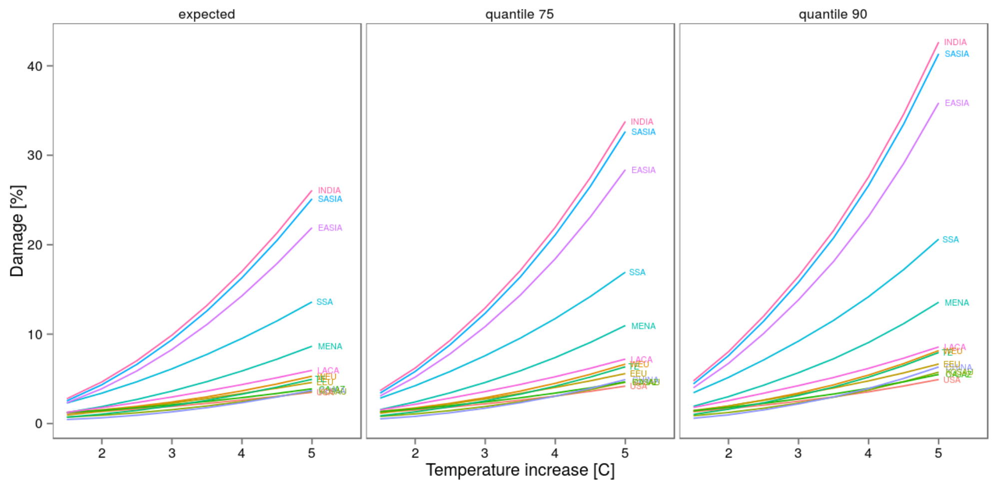

Figure 2: Damage measured as % loss in regional Gross Domestic Product (GDP) as a function of temperature. Expected values and 75th and 90th quintile

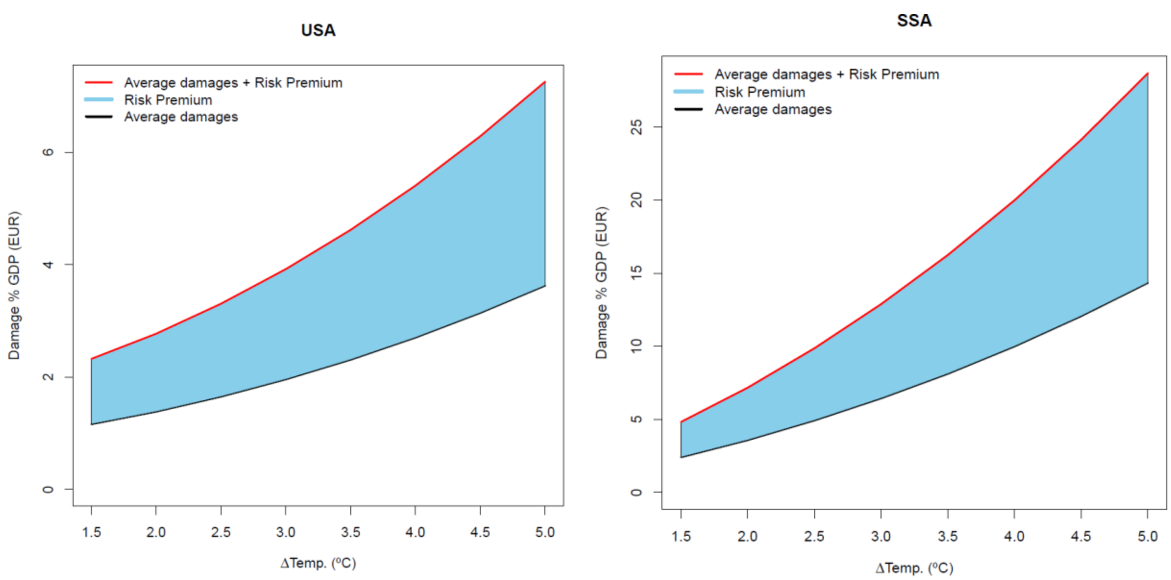

Figure 3: Calibrated regional damage functions in selected regions with and without the risk premium. Risk aversion equal to 2 (η= 2).

The calculations show that the risk premium is significant. It 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 the value of 1.5, beyond which damages steeply increase.

4. Results

4. 1. Implications of the risk premium on the optimal balance between mitigation and adaptation

From the discussion on risk premium in section 2 it can be concluded 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. The key is to understand how risk-adjusted damages can influence climate policy action, and especially the optimal mitigation-adaptation mix. As a first result, we find that both mitigation and adaptation levels increase in order to reduce potential damages.

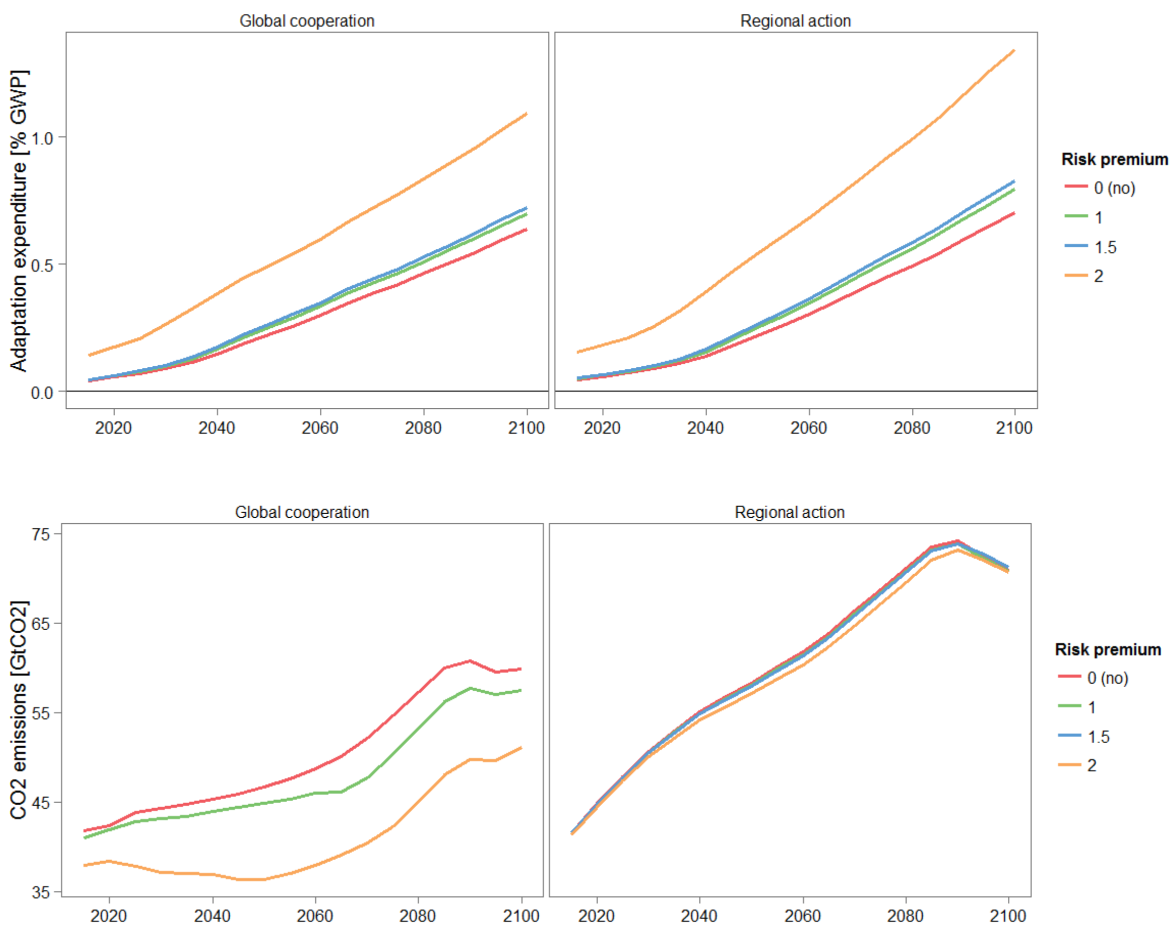

Figure 4 shows higher expenditure in adaptation (top panel), and lower emissions (lower panel) in both the cooperative and non-cooperative scenarios. In the non-cooperative case, however, the free riding incentive is strong. Therefore emission reduction, albeit positive, is negligible. This has an interesting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

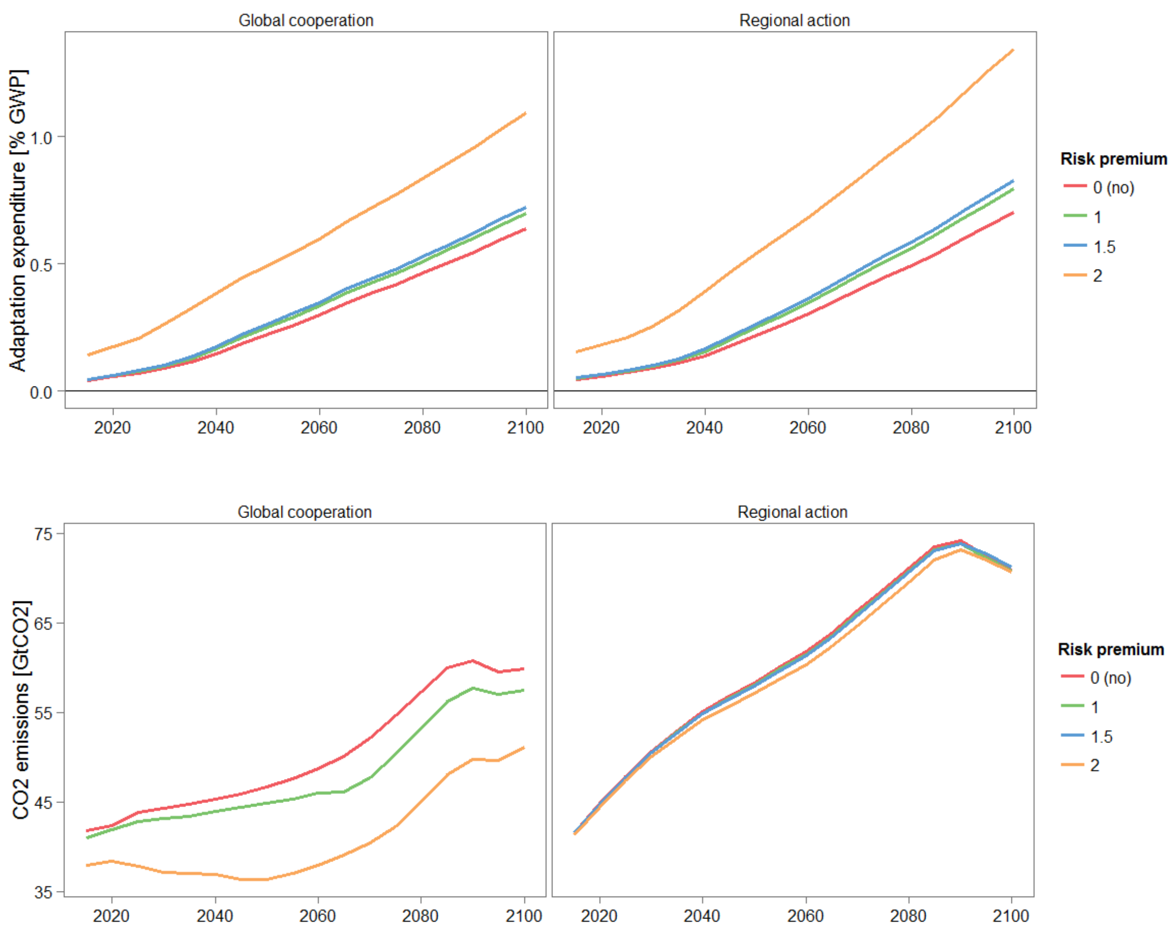

Figure 4: Global adaptation expenditure (Upper Panel) and CO2 emissions (Lower Panel). Scenarios with global cooperation (Left Hand Panel) and regional action (Right Hand Panel).

All in all, however, the emissions profile is clearly not consistent with global temperature stabilization at 2°C by the end of the century. For example, after 2050, even with η = 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 are biting the decision-maker.

As damages are higher with than without a risk premium, the effect of higher engagement in climate action does not automatically translate into lower residual damages as a percentage of global world product (GWP). Risk-premium adjusted damages are higher, amounting by the end of the century to roughly 5% and 6% of GWP under global cooperation and regional action, respectively against the 3% and 3.5% of GWP highlighted in the standard damage case (Figure 5).

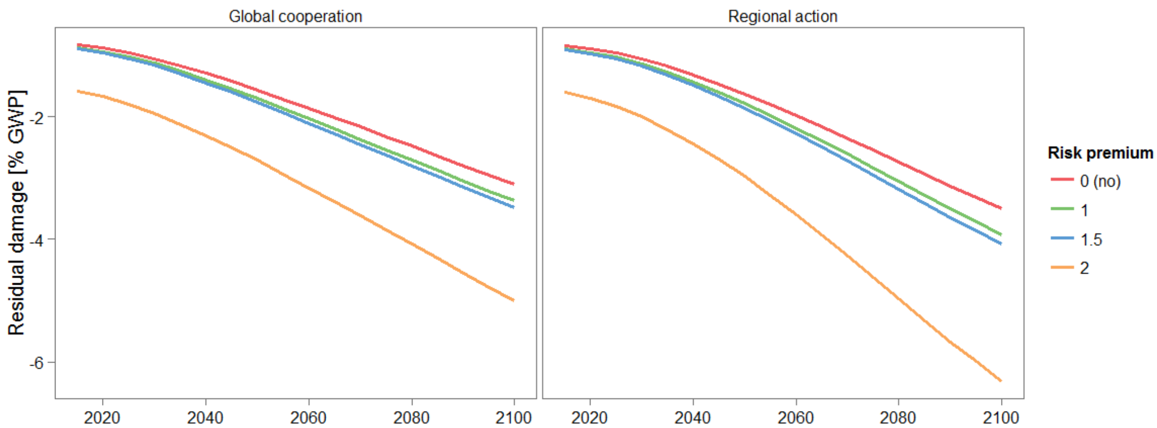

Figure 5. Risk-premium adjusted global residual damage curves. Global cooperation (Left Panel) and regional action (Right Panel)

Table 1 reports the relative contribution of mitigation and adaptation to damage reduction under global cooperation[12]. By the end of the century, the two policies together reduce the damage by roughly 51% and 45%, respectively with and without the correction for the risk premium, 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 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. That 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 adaptation that is

[12] This computation is scarcely meaningful in a non-cooperative setup, as almost all of the climate policy relies upon adaptation.

more quickly effective than mitigation to deal with current damage. In the longer term mitigation becomes more cost effective. The result is consistent with (Bosello et al. 2010, Bosello et al. 2013)

Table 1. Relative and total contribution to % damage reduction of mitigation and adaptation in 2050 and 2100 (Global Cooperation)

		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 (Global Cooperation)

	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
% ch. in adaptation expenditure moving from $\eta = 0$ to $\eta = 2$	155.6		75.8		83.1	
% ch. 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

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 Figure 6) reduction in energy demand is the main mitigation strategy, as shown by a general decline in investment in all energy sources, whether 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.

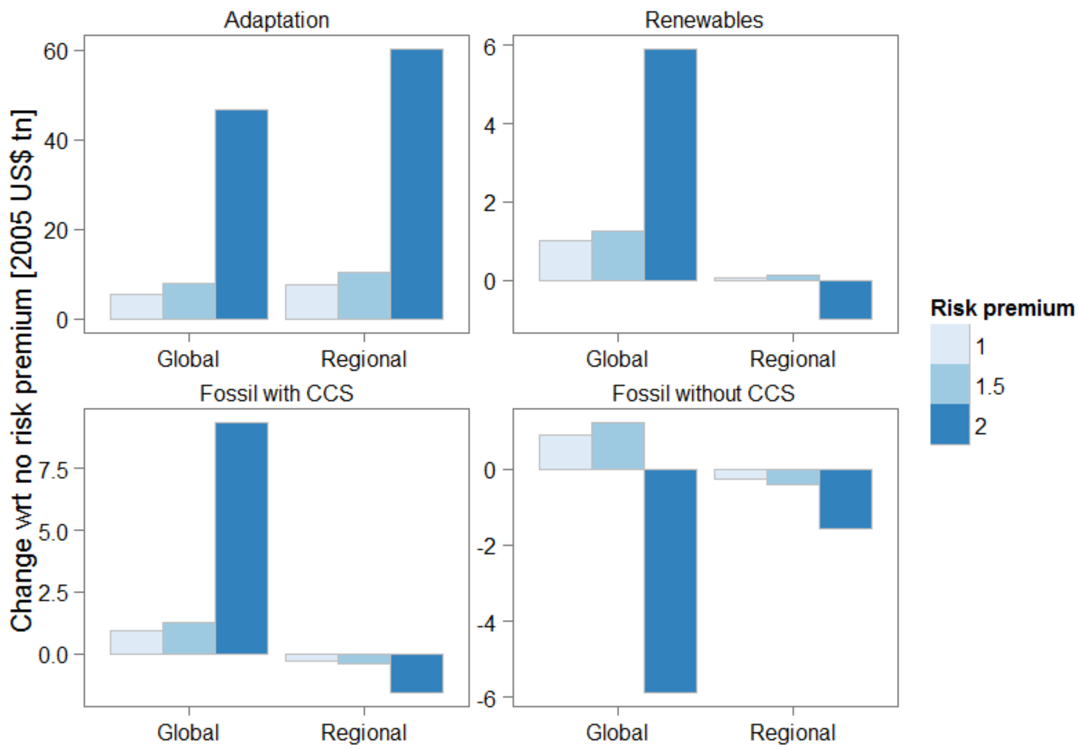

Figure 6: Global adaptation expenditure and mitigation investments. Cumulative values (2005-2100) in the cases with risk premium relative to the scenarios without risk premium in 2005USD Tn. Scenarios with Global cooperation and regional action.

4.2 Regional results

Regional results follow the trends highlighted at the global level, but they provide some additional pieces of information.

As risk premium-corrected damages are higher (Figure 7), emission reduction increases (Figure 8). 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 Transition Economies, 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 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.

In relative terms, mitigation expenditure tends to increase 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, and South Africa and 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 dis-investment) in fossil fuels. Regions adapting to a greater extent are the USA, Korea, South Africa and Australia, Transition Economies and Eastern Europe.

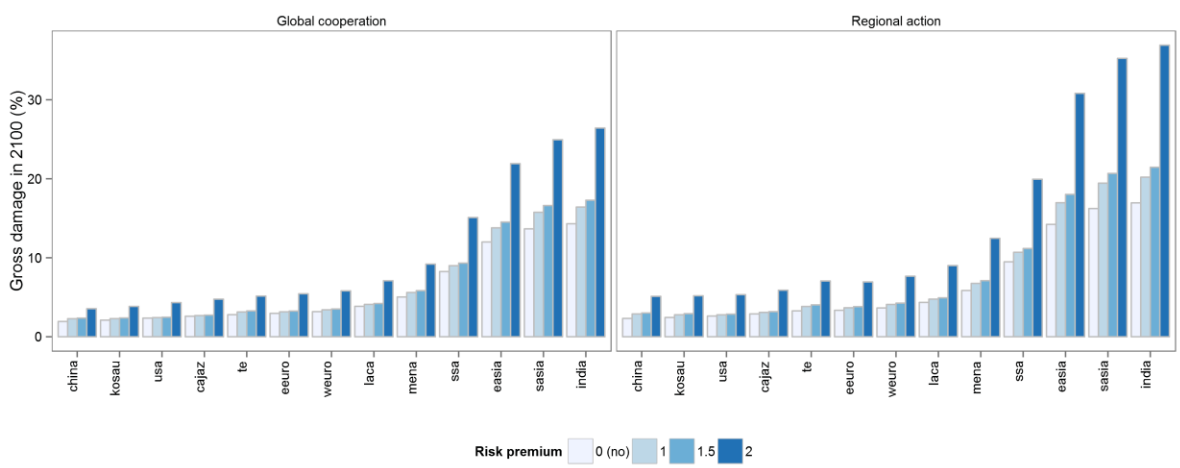

Figure 7. Regional damages in 2100 for different risk attitudes.

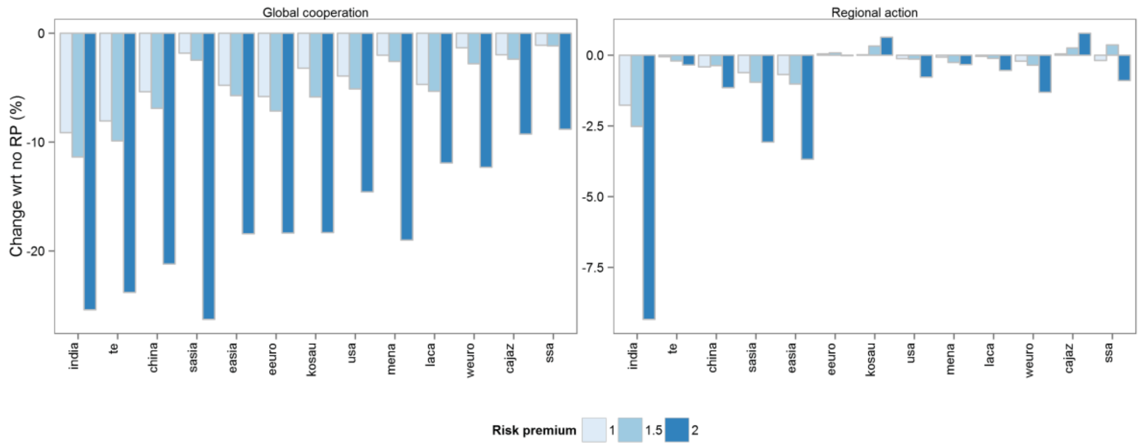

Figure 8: Percentage of reduction in regional cumulative CO2 emissions in 2005-2100.

Table 3. Global cooperation: Cumulative discounted (2005-2100) mitigation and adaptation expenditure under different risk attitudes, 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
%ch. 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	-0,06	3,08	0,12	-0,06	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 ren. (2005 USD Tn)		-0,94	0,25	0,21	0,48	-0,20	1,31	0,80	-0,01	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	-0,14
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 ren. (2005 USD Tn)		1,06	0,22	0,34	0,72	-0,05	1,84	1,17	0,00	0,05	8,14	0,71	0,43	3,44
Total Mit. Exp. (2005 USD Tn)	$\eta = 0$	1,09	0,65	0,36	0,92	-0,05	2,55	1,03	-0,72	-0,03	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
%ch in Mit. Expenditure		177,4	88,8	27,9	-2,9	na*	51,5	470,4	na*	na*	28,3	613,6	1520,0	-10,0

* For these regions the total mitigation expenditure under $\eta = 0$ turns 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.

5. Conclusions

The role of uncertainty is paramount in the climate change debate. This paper proposes an operationally simple and easily generalizable methodology to incorporate climate change damage uncertainty into Integrated Assessment Models (IAMs), and uses that to revisit the optimal strategic decisions on how much to adapt or mitigate.

Uncertainty is first transformed into a risk-premium damage-correction region-specific factor by extracting damage distribution means and variances from a combination of socio-economic and climate change scenarios. According to the consolidated expected utility framework, the risk premium quantifies what society would be willing to pay to insure itself against the risks associated with the damages. It can thus be considered an add-up to the standard "average damage". Our computations highlight that this addition can be significant, roughly doubling 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 climate change damage function incorporates the risk premium into an IAM (in this paper we have used the AD-Witch integrated assessment model), model runs 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. Over the century, even though adaptation remains the main strategy for addressing climate change (absorbing an almost triple expenditure volume compared to mitigation), the risk premium correction fosters more mitigation, which doubles, than adaptation, which rises by about 80%.

Relevant differences can be identified between the cases of global cooperation and regional action. In the former, mitigation is achieved with important investments in renewables and CCS and disinvestments 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.

This work opens interesting lines of research that need to be addressed in future work. First, being based upon a reduced-form 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 socio-economic 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 better estimates of the appropriate value of the coefficient of relative risk aversion in the specific context of decisions on climate change policy. As the paper has shown, a critical value for this parameter is 1.5. It would be very interesting to elicit this value by using stated preference methods. This may also make it possible (and this is a third development) to capture the role of thresholds, tipping points and irreversibility, which our current approach, still based upon a "smooth" description of climate change damages, cannot consider properly.

References

Agrawala, S., Bosello F., C. Carraro , E. De Cian, E. Lanzi, K. De Bruin, R. Dellink 2010. "PLAN or REACT? Analysis of adaptation costs and benefits Using Integrated Assessment Models", OECD Environment Working Papers, No. 23, OECD Publishing. doi: 10.1787/5km975m3d5hb-en

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

Anderson, B., Borgonovo, E., Galeotti, M. and R. Roson. 2014. "Uncertainty in Integrated Assessment Modelling: Can Global Sensitivity Analysis Be of Help?" Risk Analysis 34, 271-293

Blake, D. 1996. Efficiency, Risk Aversion and Portfolio Insurance: an Analysis of Financial Asset Portfolios Held by Investors in the United Kingdom. The Economic Journal, 106: 1175-1192.

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

Bosello, F., De Cian, E. and L. Ferranna. 2014. "Catastrophic risk, precautionary abatement and adaptation transfers", FEEM Note di Lavoro 214.108

Bosello, F., Carraro, C., De Cian, E. 2013. "Can Adaptation can help mitigation: an integrated approach to post-2012 climate policy", Environment and Development Economics, 18: 270–290

Bosello, F., Carraro, C., De Cian, E. 2010. "Climate policy and the optimal balance between mitigation, adaptation and unavoided damage', Climate Change Economics 1(2): 71–92., 18: 270–290

Bosetti, V., Carraro C., Galeotti M., Massetti E., Tavoni M. 2006. WITCH: A World Induced Technical Change Hybrid Model. The Energy Journal Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.

Dasgupta, P. 2008. Discounting Climate Change. Journal of Risk and Uncertainty, 37: 141–169.

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

Felgenhauer, T and K. C. de Bruin, 2009. Optimal Paths of Climate Change Mitigation and Adaptation under Certainty and Uncertainty. International Journal of Global Warming 1.

Gjerde, J. Grepperud, S., Kverndokk, S. 1999. "Optimal climate policy under the possibility of a catastrophe", Resource & Energy Economics 21(3-4), 289-317

Gollier, C. 2002. Time Horizon and the Discount Rate. Journal of Economic Theory, 107: 463–473.

Gollier, C. 2008. Discounting with Fat-Tailed Economic Growth. Journal of Risk and Uncertainty, 37: 171–186.

Green, P. E., Krieger A. M., Wind Y. 2001. Thirty Years of Conjoint Analysis: Reflections and

Prospects, Interfaces 200131:3 Supplement, S56-S73.

Kahneman, D. 2011. Thinking Fast and Slow. London: Penguin Books.

Kaplow, L. 2005. The Value of a Statistical Life and the Coefficient of Relative Risk Aversion. The Journal of Risk and Uncertainty, 31:1, 23-34.

Krupnick, A.J., Markandya, A., Nickell, E. 1993. The External Costs of Nuclear Power: Ex Ante Damages and Lay Risks. American Journal of Agricultural Economics, 75: 1273-1279.

Layard, R. Mayraz, G and Nickell, S. 2008. The marginal utility of income. Journal of Public Economics, Volume 92, Issues 8–9, 1846–1857.

Levy, H. 1994. Absolute and Relative Risk Aversion: An Experimental Study. Journal of Risk and Uncertainty, 8: 289-307.

Meinshausen, M.; Meinshausen, N.; Hare, W.; Raper, S. C. B.; Frieler, K.; Knutti, R.; Frame, D. J. & Allen, M. R., 2009. Greenhouse-gas emission targets for limiting global warming to 2C Nature, 458, 1158-1162

Moore, F.C. and D.B. Diaz 2015. "Temperature impacts on economic growth warrant stringent mitigation policy", Nature Climate Chang, 5, 127–131

O'Neill, B.C., Carter, T.R., Ebi, K.L., 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. Available at: http://www.isp.ucar.edu/socio-economic-pathways.

Rabl, A., Spadaro J.V. 1999. Environmental damages and costs: an analysis of uncertainties. Environmental International, 25(1): 29–46.

Refsgaard, J.C., K. Arnbjerg-Nielsen, M. Drews, K. Halsnæs, E. Jeppesen, H. Madsen , A. Markandya , J. E. Olesen, J. R. Porter, J. H. Christensen 2013. The role of uncertainty in climate change adaptation strategies—A Danish water management example. Mitigation and Adaptation Strategies, 18 (3): 337-359.

Shiller, R. 2000. Irrational Exuberance. Princeton: Princeton University Press.

Thaler, R.H. and Sunstein, C.R. 2008, Nudge: Improving Decisions about Health, Wealth and Happiness. New Haven: Yale University Press.

Urban, N.M. and 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.

Appendix

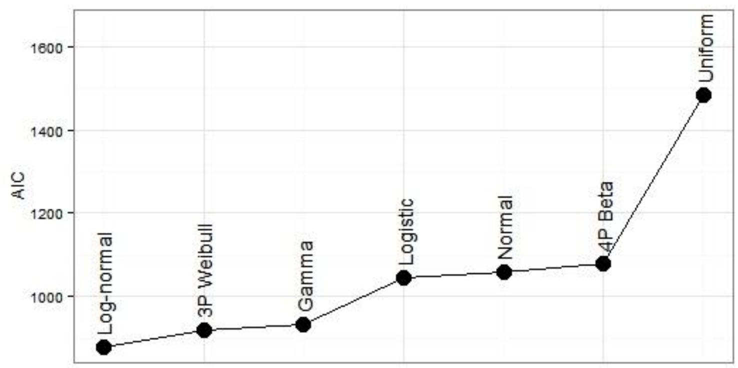

Figure A1: Akaike Information Criteria (AIC) of the fitting of damages with different distribution (the lower the better)

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

Table A1. WITCH model regions

Table A2. Data on Damage Distribution as a Function of Temperature Change

Expected temperature	Region	dist_meanlog (Log-normal distribution)	dist_sdlog (Log-normal distribution)	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
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
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 A3. 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
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
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 A4. Risk-premium adjusted damages for η = 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
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
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 A5. 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
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
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

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