BASQUE CENTRE
FOR CLIMATE CHANGE
Klima Aldaketa Ikergai

Regional IAM: analysis of risk-adjusted costs and benefits of climate policies

Alexander Golub, Oleg Lugovoy, Anil Markandya

Ramon Arigoni Ortiz and James Wang

February 2013

BC3 WORKING PAPER SERIES

2013-06

The Basque Centre for Climate Change (BC3) is a Research Centre based in the Basque Country, which aims at contributing to long-term research on the causes and consequences of Climate Change in order to foster the creation of knowledge in this multidisciplinary science.

The BC3 promotes a highly-qualified team of researchers with the primary objective of achieving excellence in research, training and dissemination. The Scientific Plan of BC3 is led by the Scientific Director, Prof. Anil Markandya.

The core research avenues are:

- Adaptation to and the impacts of climate change
- Measures to mitigate the amount of climate change experienced
- International Dimensions of Climate Policy
- Developing and supporting research that informs climate policy in the Basque Country

See www.bc3research.org for further details.

The BC3 Working Paper Series is available on the internet at
http://www.bc3research.org/working_papers/view.html

Enquiries (Regarding the BC3 Working Paper Series):

Roger Fouquet

Email: roger.fouquet@bc3research.org

Regional IAM: analysis of risk-adjusted costs and benefits of climate policies[1]

Alexander Golub[a], Oleg Lugovoy[b], Anil Markandya[c],
Ramon Arigoni Ortiz[d] and James Wang[e]

Abstract: Across the full range of publications in the field of economics of climate change there is perhaps only one firm agreement: both costs and benefits of climate policy are highly uncertain. In an ideal world one would wait until a good deal of uncertainty is resolved and then make a final decision. Usually in the economic literature it would be interpreted as adopting a relatively weak policy now and adjusting it later. Unfortunately, in the context of path-dependency and irreversibility of climatic events there is no way to preserve a full flexibility for the future: near-term selection of an interim climate policy implies some irreversible consequences. Continued accumulation of GHG in the atmosphere makes some policy targets (expressed in temperature level or GHG ppm concentration) infeasible. The paper examines the application of real option analysis to calculate costs and benefits of an interim climate policy. In contrast to conventional CBA, the proposed methodology also accounts for lost and gained flexibility attributed to the adoption of an interim target.

Keywords: Climate policy; integrated impact assessment model; uncertainty; real option analysis
JEL Classification: Q54; C61

Cite as: Golub, A., O. Lugovoy, A. Markandya, R.A. Ortiz and J. Wang (2013) *Regional IAM: analysis of risk-adjusted costs and benefits of climate policies*. BC3 Working Paper Series 2013-06. Basque Centre for Climate Change (BC3). Bilbao, Spain.

---

[1] Acknowledgements: We would like to thank Jon Anda, Nat Keohane, Gernot Wagner, Ruben Lubowsky, participants of IEW 2008, 2010 and 2011; and participants of WEREC 2010 for their valuable comments and recommendations.

a – American University– Washington, DC – USA
b – EDF Environmental Defense Fund – Washington, DC – USA
c – BC^3 – Basque Centre for Climate Change – Bilbao – Spain
d – Ecometrika Estudos Econômicos em Sustentabilidade – Rio de Janeiro - Brazil
e – NOAA – National Oceanic and Atmospheric Administration – USA

1. Introduction

Across the full range of publications in the field of economics of climate change there is perhaps only one firm agreement: both costs and benefits of climate policies are highly uncertain. While scientists are calling for mitigation policies to limit global warming to within 2^0C, a temperature target that should prevent major irreversible changes in the climatic system, economists express concern that such an ambitious environmental goal could be prohibitively expensive. Current efforts to curb carbon emissions will generate some short- and mid-term costs while pushing benefits sometime into the distant future.

The expected value approach to the cost-benefit analysis of climate policy dominates the literature. A direct application of cost-benefit analysis suggests that the 2^oC target can be economically inefficient; a conclusion supported by most of integrated assessment models (IAM) with a wide range of plausible assumptions (e.g. Nordhaus, 2008). The only way to support a 2^0C policy is to modify exogenous parameters like lowering social rate of time preference (i.e. the rate at which society is willing to substitute present for future consumption – see for example Stern 2006 and 2009) or the inter-temporal substitution of consumption. But since the selected values for these parameters have a strong foundation, the application of a discount rate ten times lower than that suggested by the mainstream economic literature could not be considered as credible (e.g. Nordhaus, 2007).

Nevertheless, the use of IAMs could support a relatively tight policy target if they are properly adjusted to reflect the critical aspects of the underlying problem (see for example Webster et al. 2008). IAMs have played an important role to improve the understanding of economic growth in changing climatic conditions, including the trade-off between current and future consumption. But deterministic forward-looking versions of the models are not adequate tools to study uncertainties. By solving forward-looking optimization models, analysts should assess all future risks attributed to a selected policy. In this paper we apply a methodology for risk-adjusted costs and benefits of climate policies proposed in Anda *et al.* (2009) and Golub (2012).

In an ideal world one would wait until a good deal of uncertainty is resolved and then make a final decision. Decision makers will exercise a deferral option as long as possible in order to get the most reliable information resolving uncertainties (Pindyck, 2011). Usually, in the economic literature such delay represents adopting a relatively weak climate policy now and adjusting it later. That will prevent premature deployment of abatement technologies and will reduce some sunk cost on the mitigation side in case the climate policy should be corrected in the future. Flexibility on the abatement side would be secured at expense of lost flexibility on the “climatic” side. Unfortunately, in the context of path-dependency and irreversibility of climatic events there is no way to preserve a full flexibility for the future: near-term selection of an interim climate policy implies some irreversible consequences. Continued accumulation of GHG in the atmosphere makes some policy targets (expressed in temperature level or GHG ppm concentration) infeasible. This paper examines the application of real option analysis to calculate costs and benefits of interim climate policies. In contrast to conventional CBA, the proposed methodology also accounts for lost and gained flexibility attributed to the adoption of an interim target.

Most analysts perform a climate sensitivity test of key parameters by means of Monte Carlo simulations of deterministic models (e.g. Mastrandrea and Schneider, 2004; Ortiz *et al.*, 2011). Others introduce uncertainty of key parameters in stochastic versions of IAMs (e.g. Bahn *et al.*, 2008) but most often the central estimates of best-guess values are substituted by other uncertainty parameters (Nordhaus 2008), and then the deterministic version of IAMs is solved.

As an alternative we propose a method to address uncertainties in climate policy analysis based on Anda *et al.* (2009a, 2009b), which consists of the application of real option analysis (ROA) to estimate some important statistical properties (e.g. volatility, skeweness, kurtosis) of relevant and uncertain key parameters used in climate policy analysis, and then involves explicitly incorporating these into the deterministic run of an IAM as an approximation to a stochastic solution. The rationality behind this approach is based on few postulates:

- An “ideal” (in terms of CBA) climate policy exists and could be computed applying IAM if and only if all uncertainties are solved;
- It will take a significant time before a major fraction of uncertainties is solved;
- Irreversibility plays a significant role in climate policy;
- Irreversibility results in path-dependence (excessive accumulation of GHG in the atmosphere makes low-concentration stabilization targets impossible; some ecosystems could be lost forever *etc.*);

These postulates imply that an ability to adjust (i.e. flexibility) has an economic value, and lost flexibility constitutes an additional cost that is equal to the value of the lost flexibility. Thus, an initially selected climate policy will most likely deviate from an “ideal” policy all the way before a correction point when uncertainty is solved and, due to path dependence, a future climate policy will also deviate from “ideal”. In the absence of irreversibility, society would switch to an “ideal” policy and avoid additional cost in the future. However, due to path dependency, the “ideal” policy may not be achieved. Then the initially selected policy bears not only anticipated costs of its implementation but also correction costs. Correction costs are defined as the value of lost flexibility and we apply an option valuation approach to calculate the cost attributed to lost flexibility. Consideration of the value of lost flexibility in addition to anticipated costs constitutes the difference between the conventional approach and the methodology proposed in this paper. If correction costs are equal to zero, then we have a conventional formulation of a deterministic IAM and the traditional application of CBA. The difference is in an additional parameter, whose value is equal to the lost option value. In terms of IAM we add a penalty function. The value of this penalty function depends on the magnitude of uncertainty.

This method produces an IAM that is both practical and that incorporates the key uncertainties in its deterministic runs. In other words, the method consists of the calculation of risk-neutral costs and benefits associated with a climate policy based on the real options approach, and adding it up to the cost of the climate policy. We call this sum the "risk-adjusted" cost of climate policy.

To illustrate our methodology we use the DICER model (Ortiz *et al.* 2011; 2010; 2009) an IAM designed to be an instrument for the analysis of uncertainties in climate policy, which is based on the structure of the DICE2007[2] model. Our objective is to compare the results obtained with a deterministic run of DICER considering an optimal climate policy, one in which a social planner maximizes the global economic welfare and determines that GHG abatement is undertaken in those regions where it is cheapest to abate and to the level that marginal abatement cost equals marginal damage costs[3], with results obtained with another deterministic run of DICER in which the parameters of the damage and abatement cost functions incorporate uncertainty. We focus on the analysis of an interim policy target that takes into account future correction cost. We believe that DICER better accounts for irreversibility on the climatic side (more realistic assumption about response of the climatic system taking into account an updated description of non-CO2 radioactive forcing) than DICE or other IAMs. At the same time, the model is conservative since it assumes a horizontal asymptote for damage function way below the one assumed in DICE and most of other IAMs.

---

[2] We thank Prof. Williams Nordhaus at Yale University for making the DICE2007 model´s code public for other researchers.

[3] The latest version of DICER does not consider eventual compensation transfers among regions due to some regions bearing greater abatement costs than others, regardless of the damages observed in each region. The optimal policy scenario is thus politically unrealistic, and should be seen as a benchmark to measure the economic efficiency of alternative climate policies.

The paper is organized as follows: section 2 details the proposed methodology for incorporating the observed uncertainty of parameters of damage and abatement cost functions within DICER; section 3 briefly describes the damage and abatement cost functions of the DICER model; section 4 presents our results; and conclusions and discussion are in section 5.

2. Application of real option to value flexibility

Irreversibility of climatic change or at least much lower rate of reversibility compared to the sunk economic cost of a policy is a key problem when assessing climate policies. It may take decades to recover the economic losses attributed to excessively restrictive carbon regulation but it may take centuries to recover the economic losses attributed to climate change and some of such losses may never be recovered.

If one can quantify risk and express it in units of output or in utility units, we can assign an additional cost function to each development strategy. Adjusted costs and benefits will then be presented in a risk free metrics. Note: in this framework there is no absolute irreversibility. In other words, we do not allow for a catastrophic damage as well as for a catastrophic burden on the economy imposed by a given climate policy. Risk can be significant but manageable.

For some special case it is possible to propose a simple formula for risk quantification. The substitution of the Neumann-Morgenstern Utility Function (NMUF) for the constant relative risk aversion (CRRA) function that is the most common utility function in IAMs, allows a simple approximation:

$$\max\{U(C) = -e^{-rC}\} \cong \max\{\bar{C} - \frac{r}{2}\sigma_C^2\}, \quad (1)$$

where C denotes consumption, r stands for absolute risk aversion, $\bar{C}$ is the expected consumption and σ_C^2 denotes variance of consumption. In other words, instead of maximizing NMUF one could maximize the mean-variance utility function (M-VUF) for cases where the magnitude of the risk is not too large. Despite the obvious attraction of applying the M-VUF that offers a direct metrics for risk, there is two other important drawbacks. First, this approach requires constant (absolute) risk aversion to be independent of the level of consumption. Second, and most importantly, consumption is assumed to be normally distributed. The second condition makes the application of M-VUF in IAMs very problematic: consumption exhibits a skewed right distribution with long left tail. In other words, equation (1) will understate the risk associated with climate damage. M-VUF could also be a substitute for a quadratic utility function. Application of a quadratic function allows log-normal distribution for the underlying asset (say damage or avoided losses in consumption) but nevertheless M-VUF is defined over the first moments of the underling asset's distribution[4]. As demonstrated in Anda *et al.*, (2009a), skewedness and kurtosis are extremely important in the quantification of riskiness of climate policy.

The losses are uncertain and the distribution of these losses is far from normal. Details are in Anda *et al.*, (2009a) where the paper highlights the trade-off between expected values on one hand and tail and variance on the other. In this particular example, the expected costs of the policy "outweighs" expected benefits. Hence a conventional cost-benefit analysis would reject this policy. However, the presence of a fat tail in the benefits distribution suggests potential high damages if the policy is rejected.

Anda *et al.* (2009) presented a numerical example that demonstrates that with relatively low yet significant probability, the damage may reach double-digit figures: there is a 10% probability that

---

[4] A quadratic utility function also suffers for boundedness problems which make it less suitable for the analysis of large risks.

the irreversible damage process results in costs of more than 5.7% of the gross world product, while there is a 90% probability that the cost of a policy is less than 4.4% of the GWP. Therefore, the choice is between higher costs versus higher risk. The expected value approach masks this trade-off. Since the distributions of costs and benefits are so different, the expected values may be not sufficient to make a decision and there is the need for an additional indicator that quantifies the trade-offs between risks.

Options on flexibility

In the general case, we keep risk-attributed costs of development and utility separately. We calculate risk-adjusted costs, and then we solve the deterministic forward-looking model. In order to fix costs on the level of expected values the regulator pays a premium upfront.

Let both anticipated benefits and costs equal to their expected values. Then correction costs on the benefit side equals to zero, if actual damage is less than the expected value. The regulator could slightly "untighten" the emission target in order to save on abatement costs in the future. Correction costs are positive if actual damage exceeds its expected value. The expected correction costs (ECC) are:

$$\mathrm{ECC} = \sum \mathrm{p_i} \max\{0, \mathrm{D_i} - \overline{\mathrm{D}}\} ,$$

where p_i is the probability of an outcome D_i and $\overline{\mathrm{D}}$ is the expected damage. Correction costs, as defined above, equal to an option value of call on adaptation services. If the response of the climatic system to an anthropogenic impact would appear higher than expected, then an actual adaptation cost (plus irrecoverable damage) D will be consistently higher than its expected level $\overline{\mathrm{D}}$. Assume that in order to hedge these costs the regulator can buy at-the-money call option on adaptation. Holding this option the regulator will call for "adaptation services" if actual damage exceeds its expected value. The regulator may consider any other value for anticipated damage (for example, its median, or damage in 90th percentile), then the selected value for anticipated costs will be the trigger price.

The value of this option is a value of risk associated with the selected policy. Then instead of a value of damage we consider an expected damage and price of the option on adaptation services. This will make the selected emission target appear more expensive in terms of potential losses. Higher uncertainties on the climate side will drive the price of that option higher. The same strategy could be applied to the abatement cost of the selected climate policy. The regulator includes in the calculation the price of at-the-money call option on adaptation services, or, in other words, the regulator adds a lost value of a call option on the climate asset.

Flexibility and preservation of "climate asset"

Valuation of the lost flexibility is perhaps the easiest way to explain the option approach to the valuation of the risk-adjusted costs of climate policy. The worsening of climate implies the deterioration of the climate asset that could be expressed in a permanent loss of productivity. Suppose that by selecting the emission target E_0 the regulator avoids future damage. In other words the regulator keeps the climate asset in good condition and has an option to continue the enforcement of a harmless emission trajectory. The benefits of this policy will be observed in the future and the regulator would be able to solve a new optimization model and determine the optimal use of the climate asset, but at this time the regulator just keeps the climate asset untouched and the only quantifiable benefit of this policy is the expected value of avoided damage plus the option value to continue this policy and avoid a damage greater than expected. The future benefits of the saved flexibility have an option value. Partial losses of this flexibility result in partial losses of option value. The regulator has a "multiple choice" to select an emission target and this target is associated with losses in option value. This value could be added to the expected value of damage. The option value is calculated as at-the-money option. Both spot and strike price are equal to the expected value of damage.

The costs of climate policy are also uncertain, and then the same logic could be applied to the calculation of risk-adjusted abatement cost. Then the total risk-adjusted cost of climate policy includes four components:

- Expected damage;
- Expected abatement cost
- At-the-money call option on "adaptation services";
- At-the-money call option on abatement.

Since the decision on climate policy is assumed irreversible, the regulator loses both options in time period zero when selecting an optimal policy. Two ATM options represent correction cost that we can call a penalty function.

Modifying IAM

This penalty function (or premium paid for preservation of a selected level of flexibility) is equal to the price of at-the-money call option. In case of the damage calculation, it is a call on adaptation services. In the case of abatement it is a call on carbon credits. Since forward-looking models are one-time optimization problems (i.e. all decisions are taken in time zero), the regulator will purchase these options and strike simultaneously.

$$max \sum_{t=0}^{T}\{U(E_t) - Z(E_t) - D(Q_t) - R_Z(Z_t,\sigma_Z) - R_D(D_t,\sigma_D)\}\delta^{-t} \qquad (2)$$

s.t.

$$Q_t = f(E_0, \dots E_t)$$

Where $U(E_t)$ stands for utility in year t with respect to emission E_t; $Z(E_t)$ denotes for abatement cost (the first derivative is negative); Q represents environmental quality, which is a function of previous emissions; δ denotes the discount rate; i.e. risk-free interest rate that is equal to the risk-free long-term economic growth determined by marginal productivity. In this model discount is exogenous (in fact it should be endogenous since environmental deterioration may permanently reduce productivity – we ignore it here). R_z and R_D are at-the-money options. Value of these options reflects adjustment cost and plays a role of a "penalty" function. We define this penalty function as an expected value of excessed damage relative to expected one and excessed abatement cost relative to expected. Then according to Golub, (2012) the penalty function equals to at-the-money option value.

3. The DICER model

The DICER model, its structure and equations, have been described in detail in Ortiz *et al.*, (2010) and Ortiz *et al.*, (2011). In this paper we focus on the damage and abatement cost functions used in the current deterministic version of DICER, which represent the main differences between DICER and other IAMs.

The damage function used in DICER assumes that economic (tangible and intangible) damages are dependent on global mean temperature change and limited to a maximum potential GDP loss (damage cap). Another assumption is that the damages of climate change are likely to be larger for poor and tropical countries than for rich and larger countries in mid-latitude. The damage curves are derived from estimates of the climate change-related impacts for eight regions of the world. The studies from which we obtained region-specific damage estimates include Tol (2002, 2005), Pearce *et al.* (1996), Mendelsohn *et al.* (1998), Nordhaus and Boyer (2000).

In order to accommodate the negative damage of (or economic benefit from) climate change in some regions in the northern hemisphere we initially assumed a specific functional form for the damage functions: translated parabola, suggested in Roughgarden and Schneider (1999). However, attempts to calibrate DICER using region-specific translated-parabola damage functions were not successful because of the non-monotonic feature of some of our damage functions; i.e. for regions where some benefits of climate change are expected for a small benefits increase in average atmospheric temperature our damage functions are decreasing between zero (no climate change) and 1°C. In order to overcome such a limitation we assumed “zero damage” for the temperature range where our damage functions predicted negative damages. Given the relatively small benefits from climate change over this interval we believe that the errors in ignoring them will not qualitatively affect the results in this model. We also note that the model overestimates the costs of mitigation at low temperature increases because it does not account for ancillary benefits from those reductions in GHGs. Thus, overestimating the costs of making small reductions in temperature increase is cancelled out to some extent by overestimating the damages caused by these increases. Equation 1 shows our final functional form[5] adopted in our damage functions while Figure 1 shows the curves.

$$D_{r,t} = CAP_r - \frac{CAP_r}{1+\left(a_r\cdot\left(\Delta T^*_{r,t}+c_r\right)^2+d_r\right)} \qquad (3)$$

Where:

$D_{r,t}$	The damage function in region (r) as a fraction of the region´s output;
CAP_r	The highest percentage of GDP allowed as climate change damage;
$T0_r$	The temperature at which the climate damage starts to become positive in region (r);
a_r, c_r, d_r	Region-specific parameters of the damage function;
t	Time (decades from 2008-2017; 2018-2027; …);
$\Delta T^*_{r,t}$	Global temperature growth adjusted to regional damage pattern:

$$\Delta T^*_{r,t} = \begin{cases} 0, & \Delta T_t \le T0_r \\ \Delta T_t, & \Delta T_t > T0_r \end{cases}$$

For computational purposes $\Delta T^*_{r,t}$ is approximated with the functional form:

$$\Delta T^*_{r,t} \approx \frac{1}{2}(T0_r + \Delta T_t) + \frac{1}{2}\sqrt{(T0_r - \Delta T_t)^2 + \delta}$$

Where

δ	Small positive constant ($\delta = 0.001$);
ΔT_t	Global temperature increase observed at period (t).

---

[5] The final functional form was suggested by an anonymous participant at a discussion forum of GAMS´ users and modelers.

The abatement cost curves used in DICER follow the ones suggested by Nordhaus (2008), and assumes that the abatement costs are proportional to global output and to a polynomial function of the emissions-reduction rate. These functions have the form $P_r = a_r.\%GHG^{2.8}$, where P_r is the abatement cost in terms of percentage of GDP; $\%GHG$ is the reduction in emissions and a_r is the region-specific parameter (backstop technology price). These are similar to those used in RICE2010 (Nordhaus, 2010). However, by checking some of the latest available literature on the cost of abatement from the Energy Modeling Forum (EMF22 – Clarke *et al.*, 2009) we decided to re-calibrate the parameters of the marginal abatement cost functions (MACs) used in the RICE2010 model in order to reflect the average abatement costs given in EMF22. In summary, our aim was to choose the MACs – functional form and parameters – that best represent the available data on abatement costs. The calibration involved using higher backstop technology prices, about 50% higher than those used in the RICE2010 model. Our MACs have the form shown in Figure 2.

Figure 1: Damage functions in DICER

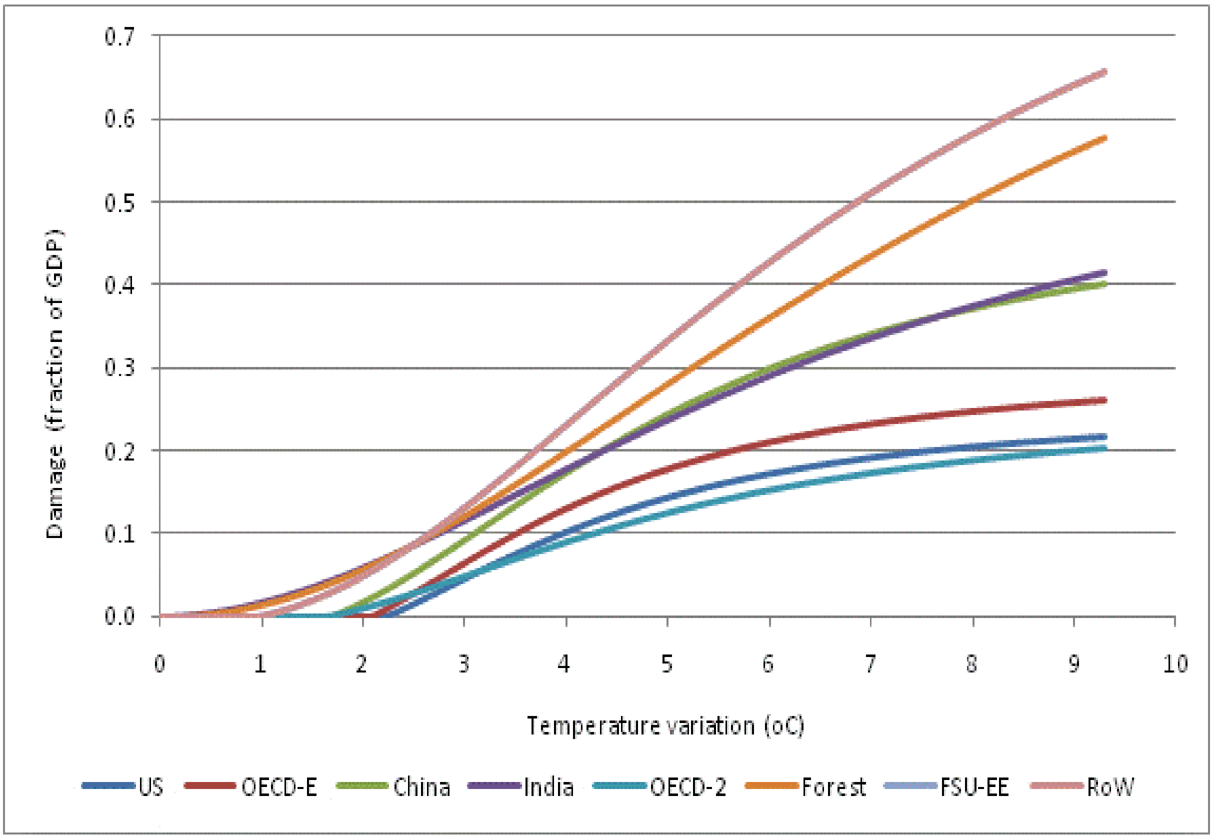
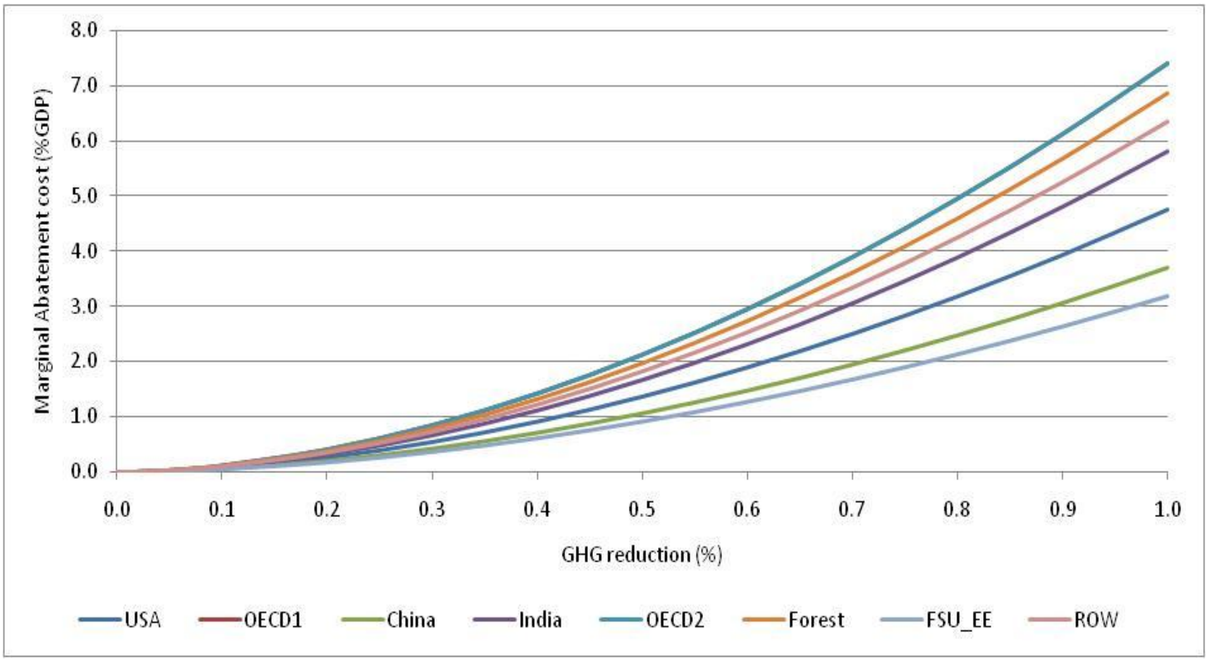


Figure 2: Marginal abatement cost curves



Note: Estimated by the authors using RICE2010 MACs but assuming higher costs of backstop technologies; %GHG reduction (horizontal axis); the abatement cost is given as %GDP (vertical axis).

4 Uncertainties and climate policy: Numerical Experiments using DICER

Calibration

In order to calculate the value of at-the-money option we apply the Black-Sholes option pricing formula that we can easily approximate. The value of at-the-money call option is equal to 0.4σ , where σ denotes standard deviation (see Anda *et al.*, 2009 for details). Experiments with DICE demonstrate that the standard deviation of damage is a linear function of the level of damage and we found the same results for abatement cost, which is a linear function of expected cost. These results hold for different emissions pathways. The linear function for volatility is valid as long as the second derivative of damage function is positive (i.e. function is convex). If a damage function has non-monotonic second derivative, then linear the relation does not hold. When the damage function does have a convex form the new damage function can be written as:

$$\tilde{D} = \overline{D}\left(1 + 0.4 v_D(T)\right)$$

where $\overline{D}$ stands for the expected damage.

In the DICE model the damage function is limited and can't exceed 100% of output. For relatively low temperature increase, variability of damage stays constant. However, when temperature increases reach double-digits and damage is getting close to its limit, variability declines. In DICER upper limits on damage are much tighter. Therefore the coefficient of variability declines right away. For higher temperature increases the relative option value is less than for a low temperature increase. For instance, EU region damage function is capped at 10% of output and approaches this limit at around an increase of 10ºC in temperature. The volatility of the damage function converges to zero at that point and so does the option value. Then we apply a simplified approximation of at-the-money Black-Sholes $R_{D,t} = 0.4\sigma_D D_t$ and the same for abatement cost, keeping in mind that sigma is not a constant. In the optimization criteria (2) all option values are discounted back to time zero. Numerical experiments with DICER's damage function revealed that volatility is a declining function of temperature. We can simplify (2) based on this property just assuming that variance is a function of temperature increase.

Given the above reasoning t the risk-adjusted cost has a form: $\tilde{Z} = \overline{Z}(1 + 0.4v_Z)$ and expected damage: $\tilde{D} = \overline{D}(1 + 0.4v_D(T))$ where $\overline{Z}$ denotes the present value of total expected cost and $\overline{D}$ stands for the present value of total expected damage over the optimization period. Now a numerical solution is as easy as a solution of forward-looking deterministic model. The last complication relates to the non-linearity of the abatement cost and damage functions. In a case of permanent shocks the expected value is higher than median as long as damage and costs are convex functions. More numerical experiments are needed to check how adequate would be the substitution (central estimate for expected value). For numerical experiments with DICER we applied the algorithm described below.

Experimenting with DICER we noticed that the volatility of damage and abatement costs is stable across different emission scenarios. This allowed us to apply a closed-form expression for Black-Sholes formula:

- First we run Monte-Carlo simulation and estimated the moments of the distribution of costs and damages;
- Since moments of the distribution depend on the state of the climatic system we ran a Monte-Carlo for each damage and cost function for different temperature levels;
- Approximation of the at-the-money Black-Sholes option price is a linear function of the underlying asset. Hence a new component could be added to the abatement cost and damage functions. This is an elegant way to apply at-the-money option pricing formula to options with a centrally symmetric monetization;
- In order to address monetization at the expected damage and expected cost we simply multiply costs and damages by a correction coefficient that reflects the volatility of the underlying parameters i.e $\tilde{Z} = \overline{Z}(1 + 0.4v_Z)$ and $\tilde{D} = \overline{D}(1 + 0.4v_D(T))$. Since there is a difference between expected damage and it's central estimate we apply an additional correction to express expected damage as a function of the state of climatic system.

In order to calculate the adjustment coefficients we conducted a Monte-Carlo simulation for damage and cost functions. This was performed for different temperature levels and as we pointed before, volatility was found different for different temperatures. Based on that fitted a non-linear function to express volatility as a function of temperature.

For all regions volatility is well approximated as a power function. See two examples below for OECD and China (figure 3):

Vol = volatA * T^volatB

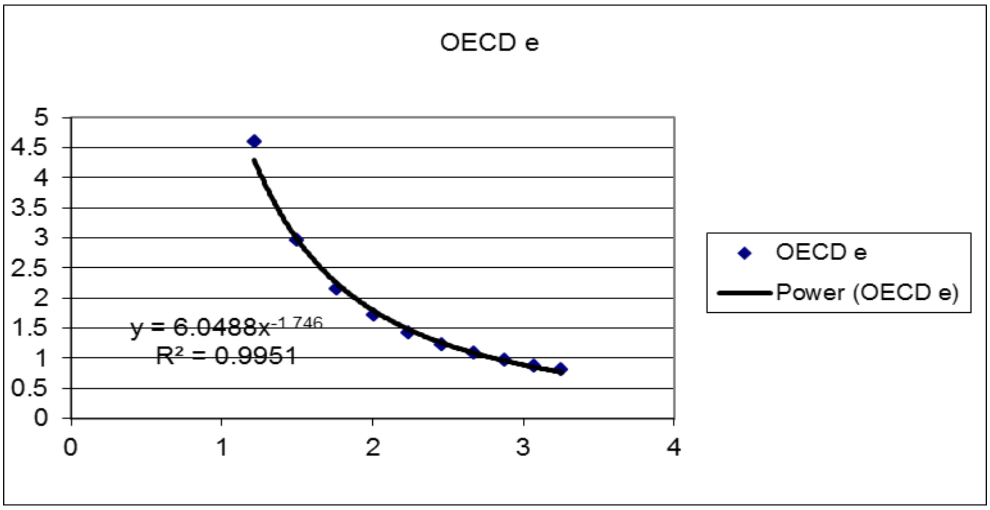
Where Vol stands for volatility of damage;

T denotes the global temperature increase;

volatA and volatB are constants.

Coefficients volatA and volatB depend on the shape of the damage functions and are different for different regions.

Figure 3. Volatility as a function of global temperature



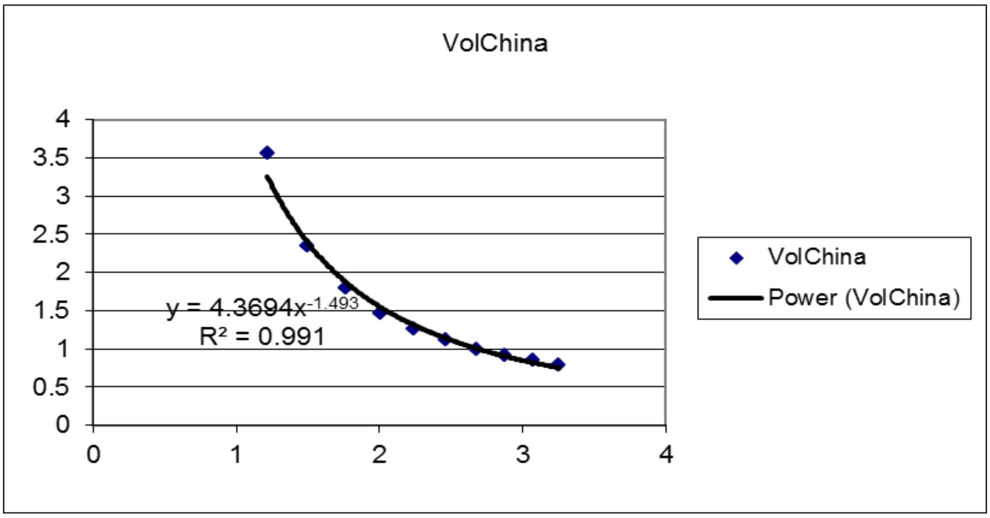
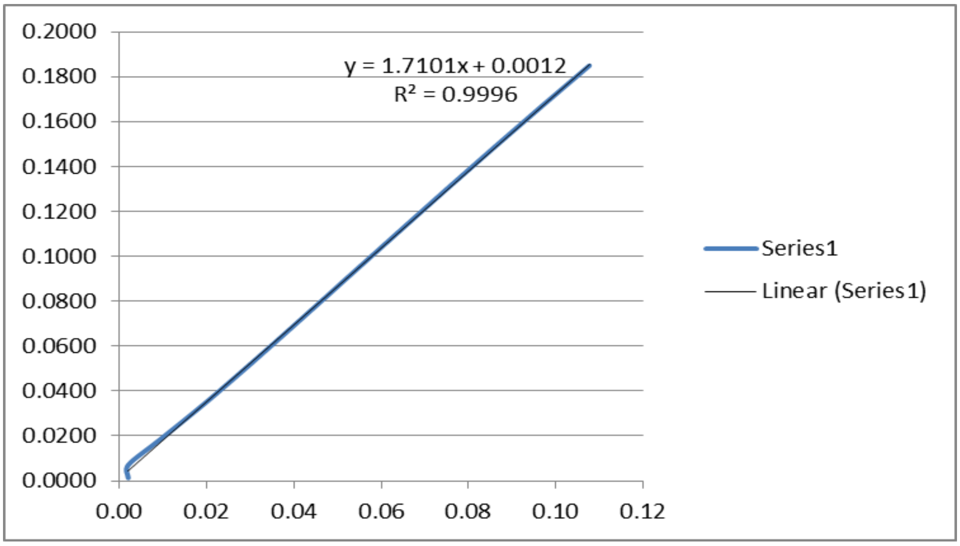


Figure 3 demonstrates how volatility of damage depends on the temperature level. Declining volatility is explained by the presence of a horizontal asymptote for damage function. A higher temperate means less relative uncertainty since we are approaching the upper bound for the damage.

We also adjusted central value of damage and cost assuming that the mean value is a linear function of central estimate. Next we estimated the correction coefficient for central value. We concluded that expected damage can be expressed as a linear function of its central value. Example for US is shown below.

Figure 4 Expected damage and its central value



Note: (OX is central value of economic damage and OY is its expected value)
I.e. expected damage =McentralA*[central value] +McentralB

The adjustment coefficients for damage are described in Table 1.

Table 1: Volatility of damage function and mean correction parameters

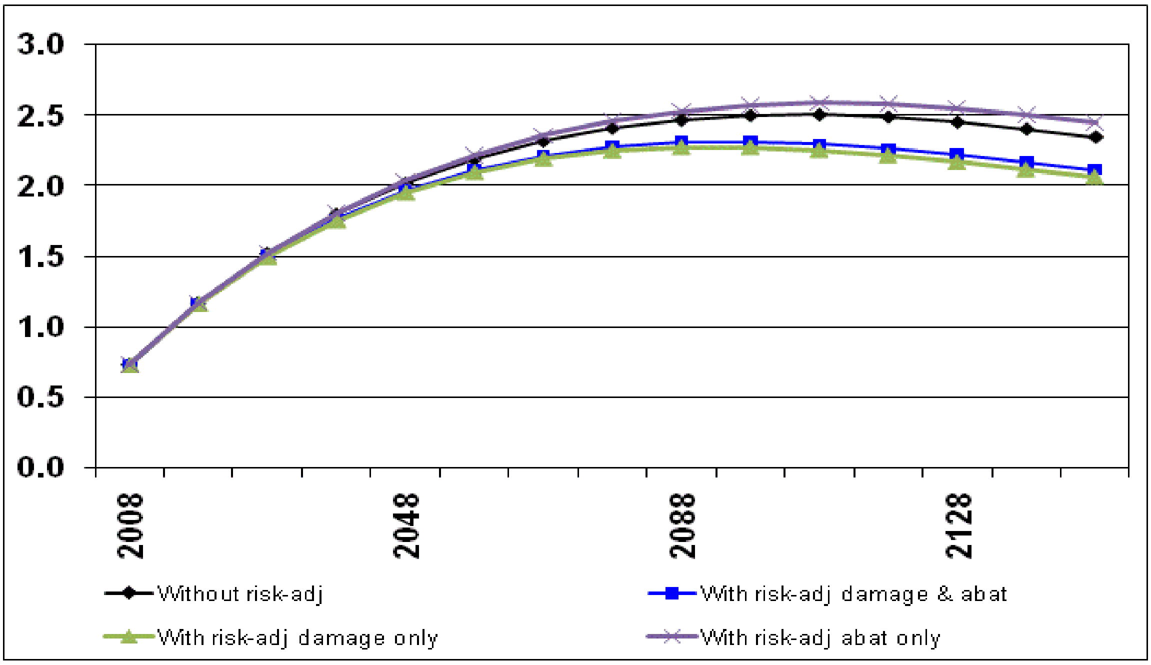
Region	volatA	volatB	McentralA	McentralB
USA	4.5696	-1.443	1.7	0
OECD1	6.0488	-1.746	0.77	0.03
CHINA	4.3694	-1.493	0.93	0.025
INDIA	0.775	-0.161	1.5	0
OECD2	4.0776	-1.459	1.023	0.012
FOREST	1.054	-0.208	1.82	0
FSU_EE	7.3682	-1.453	1.16	0.023
RoW	1.875	-0.718	1.71	0

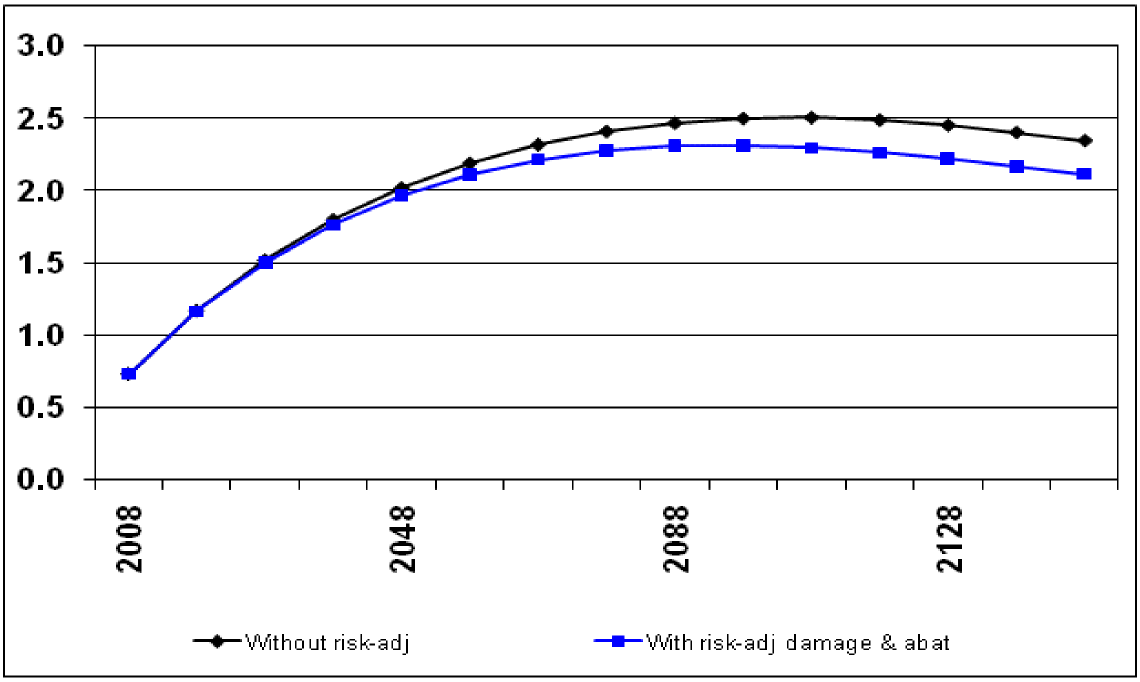
The volatility for cost functions is 0.25 regardless of abatement level. Then the correction coefficient for the cost functions is 1.1. With those values we ran the model with adjustments specified above and computed a unique optimal solution with respect to savings and abatement.

Results

The application of risk-adjusted damage and abatement costs changes the optimal solution. While in deterministic scenarios the optimal temperature reaches about 2.5C by the end of this century, with risk-adjusted cost and damage the maximum increase is about 2.25C. If we apply risk adjustments to damage only, then the maximum increase of optimal temperature is even lower. If risk adjustment were applied to abatement cost only, then temperature is slightly higher than in deterministic case (see figure 4 below):

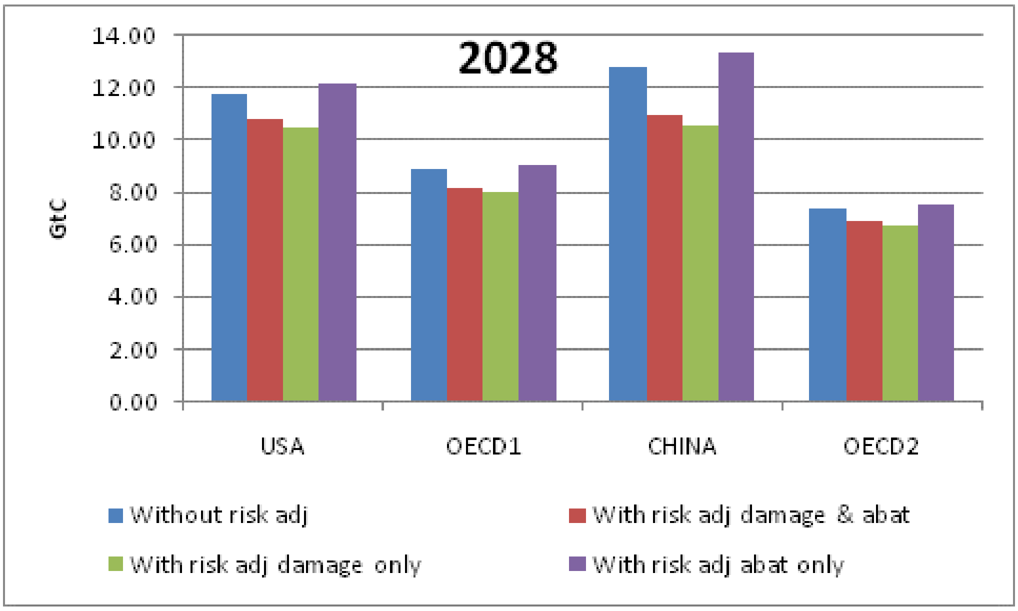
Figure 3: Risk-adjusted atmospheric temperature (C^o) – optimal scenario





These results could be explained since in the neighbourhood of the deterministic trajectory damage demonstrates relatively higher volatility than cost. Due to heterogeneous abatement cost, additional emission reduction in risk-adjusted solution is distributed across region unevenly.

Figure 4: Risk-adjusted emissions per region – 2028 (GtC) – optimal scenario



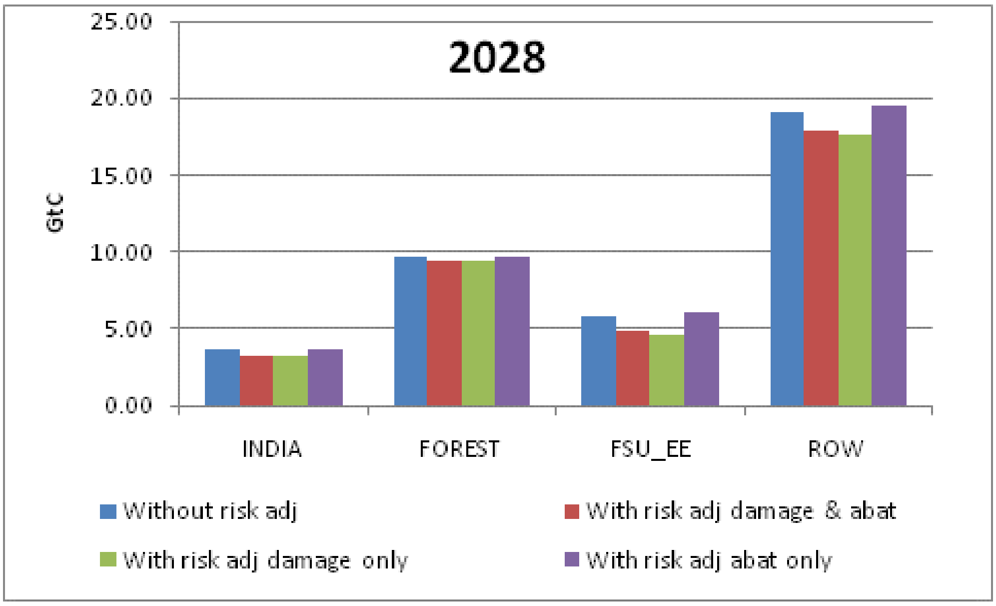
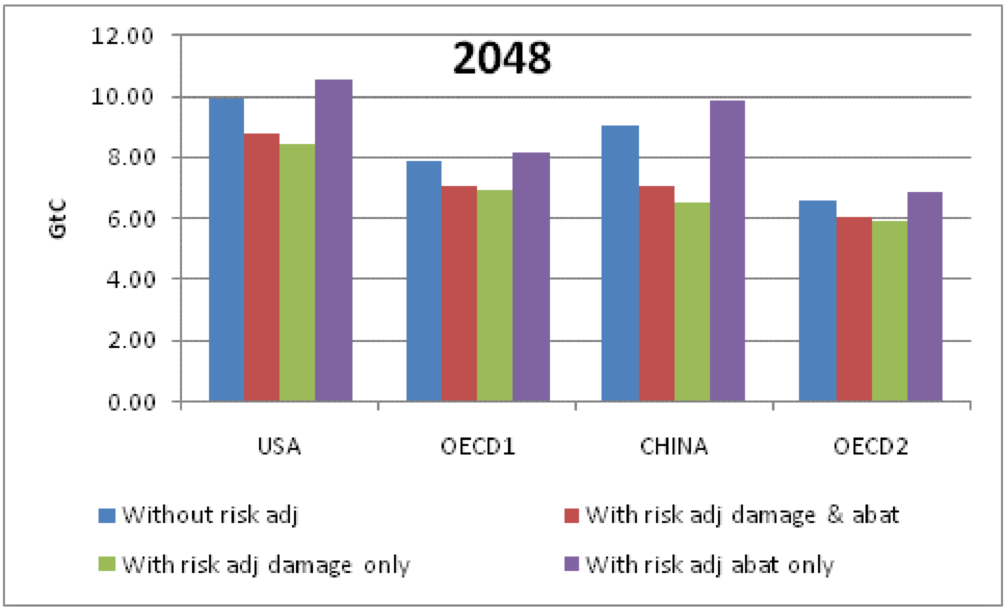
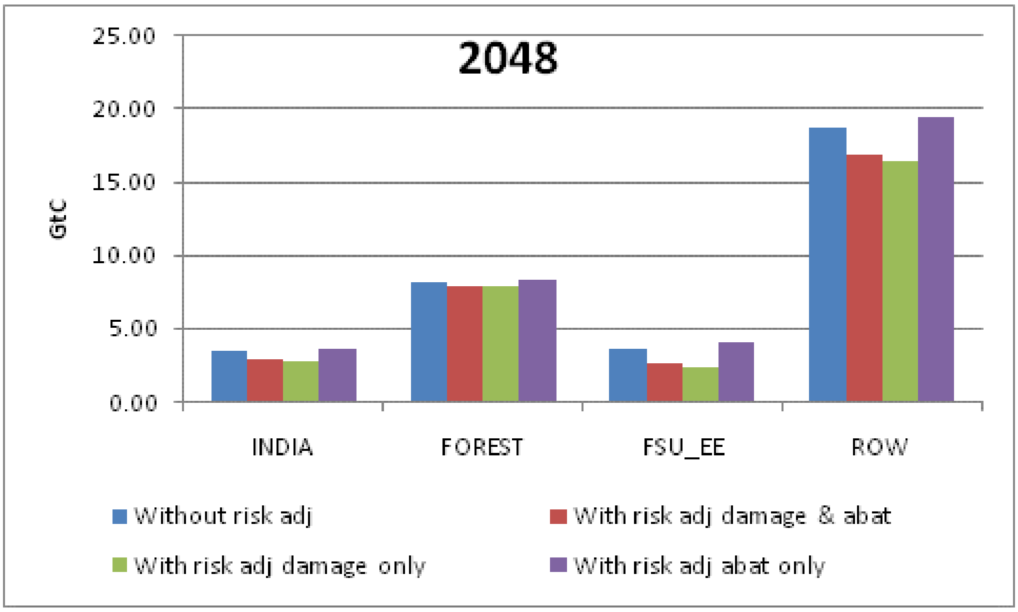


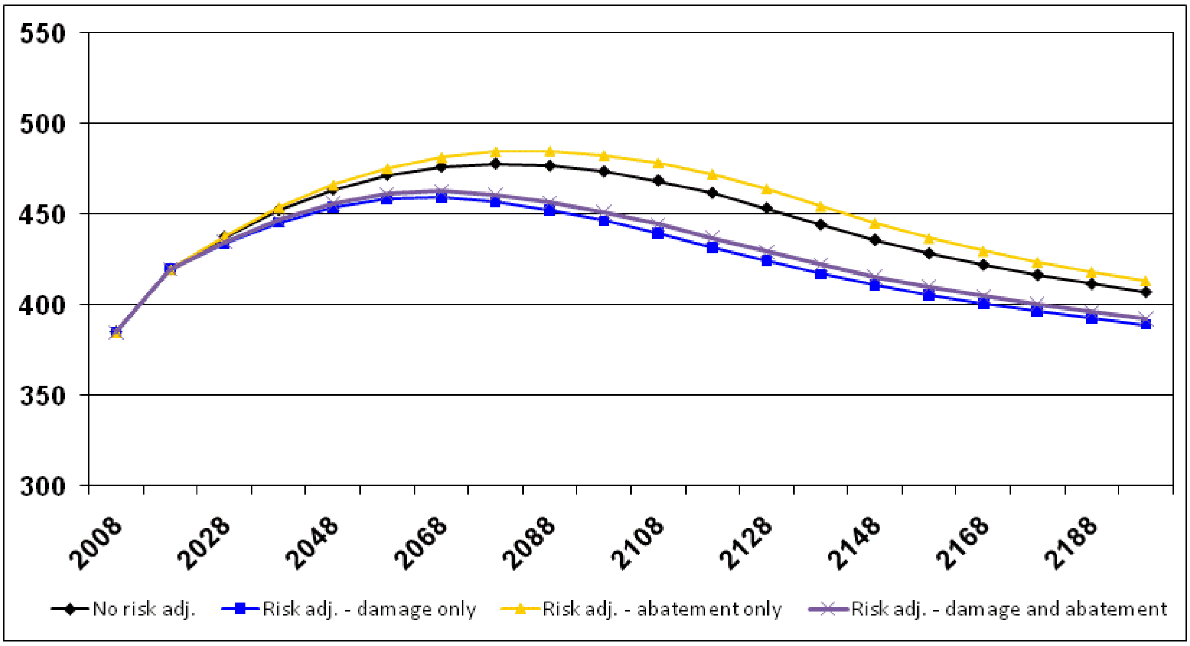
Figure 5: Risk-adjusted Emissions per region – 2048 (GtC) – optimal scenario





China exhibits the highest reduction while forest and India are least affected. Balancing risks on damage and on abatement cost side China should take most aggressive cuts over next 40 years.

Figure 6: Risk-adjusted CO_2 Concentration (ppm) – optimal scenario



In either scenarios the optimal concentration exceeds 450 ppm. As for the temperature, it is still uncertain. However, the magnitude of uncertainty is significantly lower for the risk adjusted scenario.

Figure 7: Distribution of atmospheric temperature – 2048 (°C)

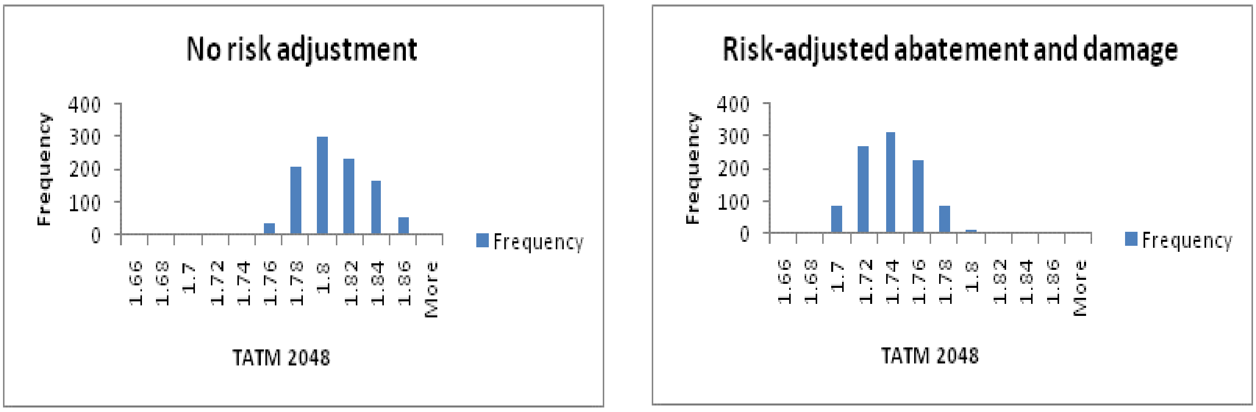
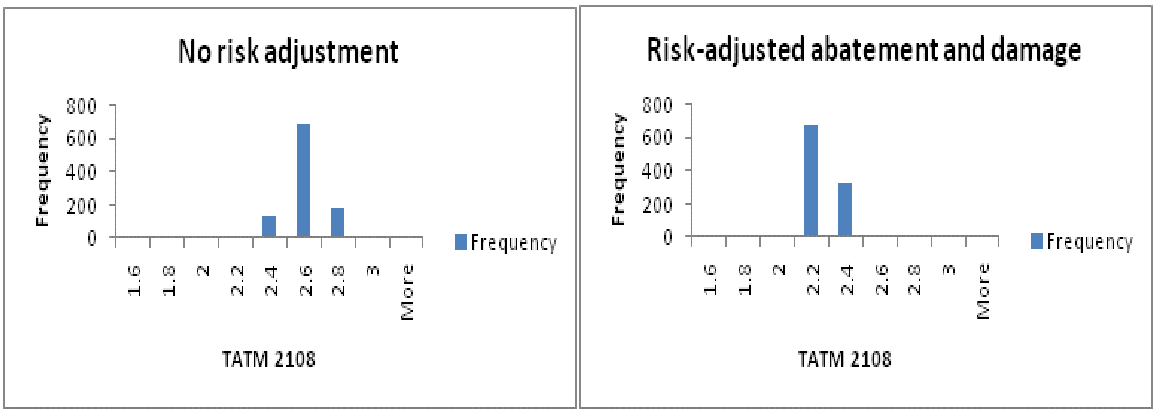


Figure 8: Distribution of atmospheric temperature – 2108 (°C)



It is easy to see that optimization with risk-adjusted parameters reduces uncertainties on climate change and, most importantly, significantly reducing a tail risk.

5 Conclusions and discussion

Numerical experiments with the model demonstrate that even adopting very optimistic assumptions regarding resilience of society to climate change in the long run the model requires a more aggressive GHG reduction policy over next 100 years.

Even without the assumption about a possible catastrophic event near-term GHG reduction appears as a reasonable policy response to climate change. Coordinated actions by all nations are needed even prior to signing a comprehensive global agreement.

Adding uncertainty this reduction pathway should be even more profound. Global climatic system is a common good. Cost effective solution assumes no exemptions: all countries should cut emission reduction below BAU. First stop emission growth and then begin with absolute reduction.

With uncertainties in place, near-term climate policy appears as a risk management policy. The model allows calculation of risk adjusted shadow price of carbon. This shadow price could be a benchmark for emerging national climate policies, i.e. proxy for a carbon tax of equilibrium allowances price at regional (like EU) carbon market.

Application of real options methodology allows us to calculate a risk adjusted shadow price of carbon adding value of lost flexibility to expected value of externalities associated with carbon emission. In the paper we applied a relatively simple formula to calculate lost value of flexibility. Application of more precise formula for option valuation may suggest even deeper cut in emission. Nevertheless, even most aggressive climate policy does not guaranty elimination of risk attributed to climatic change.

Accounting for risk results in a more drastic abatement scenario relative to the scenario we get without accounting for risk. Participation of all countries is critical. Thus a new global agreement should create and adequate incentives and enforcement for all nations. The model helps us to understand optimal global policy target but is silent on the issue how this target could be implemented.

References

Anda, J.; A. Golub and E.Strukova (2009a), "Economics of climate change under uncertainty: benefits of flexibility", *Energy Policy*, 37(4).

Anda, J.; A. Golub and E.Strukova (2009b), "Trade-offs between expectations and uncertainties: applying real options methodology to climate policy analysis", in A. Golub and A. Markandya (eds) Modeling Environment – improving technological innovations under uncertainty, London: Routledge.

Bahn, O.; A. Haurie; and R. Malhame (2008), "A Stochastic Control Model for Optimal Timing of Climate Policy", *Automatica*, 44, p. 1545-1558.

Bosetti, V.; E. Massetti and M. Tavoni (2007), "The WITCH Model: structure, baseline and solutions", Nota di Lavoro, 10.2007, FEEM – Fundazione Eni Enrico Mattei, available online at http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm

Bosetti, V.; C. Carraro and M. Galeotti (2006), "The Dynamics of Carbon and Energy Intensity in a Model of Endogenous Technical Change", *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Buchner, B.; C. Carraro; I. Cersosimo and C. Marchiori (2005), "Back to Kyoto? US participation and the linkage between R&D and climate cooperation", in A.Haurie and L.Viguier (eds.), *The Coupling of Climate and Economic Dynamics*, Amsterdam: Springer.

Crassous, R.; J-C Hourcade and O.Sassi (2006), "Endogenous Structural Change and Climate Targets Modelling Experiments with Imaclim-R", *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Dowlatabadi, H (1998), "Sensitivity of climate change mitigation estimates to assumptions about technical change", *Energy Economics*, 20(5), p.473-493.

Edenhofer, O.; K.Lessmann and N.Bauer (2006), "Mitigation Strategies and Costs of Climate Protection: the effects of ETC in the hybrid model MIND", *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Edwards, N.; H.Grepin; A.Haurie and L.Viguier (2005), "Linking Climate and Economic Dynamics", In *The Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment*, eds. Alain Haurie and Laurent Viguier, Amsterdam: Springer.

Gerlagh, R. (2006), ITC in a Global-Climate Model with CCS: the value of induced technical change for climate stabilization". *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Gollier, C. and M.L. Weitzman (2009), "How Should the Distant Future be Discounted When Discount Rates are Uncertain?" available online at http://idei.fr/doc/by/gollier/discounting_long_term.pdf

Golub, A., "Climate policy and uncertainty: alpha-precautionary principle versus real options analysis". 2012. Golub, The Environmental Law Reporter, Volume 42, N 8.

Hedenus, F.; C.Azar and K.Lindgren (2006), "Induced Technological Change in a Limited Foresight Optimization Model". *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Hope, C. (2006), "The Marginal Impact of CO_2 from PAGE2002: an integrated assessment model incorporating the IPCC´s five reasons of concern", *The Integrated Assessment Journal*, 6(1), p.19-56.

MAGICC (2007), “Model for the Assessment of Greenhouse-gas Induced Climate Change”, available online at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html.

Manne, A.; R. Mendelsohn and R. Richels (1995), “MERGE: A model for evaluating regional and global effects of GHG reduction policies”, *Energy Policy*, 23(1), p.17-34.

Mastrandea, M.D. and S.H. Schneider (2004), "Probabilistic Integrated Assessment of Dangerous Climate Change", *Science*, 304, p.571-575.

Masui, T.; T.Hanaoka; S.Hikita and M. Kainuma (2006), “Assessment of CO_2 Reductions and Economic Impacts Considering Energy-Saving Investments”. *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Nordhaus, W.D. (2009), “New Estimates of Efficient Approaches to the Control of Global Warming”, Cowles Foundation Discussion Paper, 1716, August 2009.

Nordhaus, W.D. (2008), A Question of Balance: weighting the options on global warming policies. New haven: Yale University press,

Nordhaus, W.D. (2007), *The Challenge of Global Warming: Economic Models and Environmental Policy*, available online at http://nordhaus.econ.yale.edu/dice_mss_072407_all.pdf, last visited 29/10/2008.

Nordhaus, W.D. (1994), Managing the Global Commons: The Economics of Climate Change, Cambridge: MIT Press.

Nordhaus, W.D. and J. Boyer (2000), *Warming the World: Economic Models of Global Warming*, Cambridge, MA: MIT Press.

Nordhaus, W.D. and Z. Yang (1996), “A Regional Dynamic General-Equilibrium Model of Alternative Climate Change Strategies”. *American Economic Review*, 886, p.741-765.

Ortiz, R.A.; A. Golub; O. Lugovoy; A. Markandya and J. Wang (2011), "DICER: a tool for analyzing climate policies ", *Energy Economics*, 33, p.S41-S49.

Ortiz, R.A.; A. Golub; O. Lugovoy; A. Markandya and J. Wang (2010), "The DICER model: methodological issues and initial results", *BC^3 Working Paper Series*, 2010-11, available online at http://www.bc3research.org/working_papers/view.html.

Ortiz, R.A. and A. Markandya (2009), "Integrated Impact Assessment Models of Climate Change: a literature review", *BC^3 Working Paper Series*, 2009-06, available online at http://www.bc3research.org/working_papers/view.html.

Paltsev *et al.* (2007), “Assessment of US cap-and-trade proposals”, MIT Joint Program of on the Science and Policy of Global Change, Report 146, available online at http://mit.edu/globalchange/www/MITJPSPGC_Rpt146.pdf

Plambeck, E.L.; C. Hope and J. Anderson (1997), “The PAGE95 model: integrating the science and economics of global warming”, *Energy Economics*, 19, p.77-101.

Popp, D. (2006), “Comparison of Climate Policies in the ENTICE-BR Model”, *Energy Journal*, Endogenous Technological Changes and the Economics of Atmospheric Stabilization Special Issue, 2006.

Pindyck, R. (2011), “Fat Tails, Thin Tails, and Climate Change Policy”, *Rev Environ Econ Policy, 5 (2): 258-274*

Roughgarden, T. and S.H. Schneider (1999), “Climate change policy: quantifying uncertainties for damages and optimal carbon taxes”, *Energy Policy*, 27, p.415-429.

Stanton, E.A.; F. Ackerman and S. Kartha (2008), “Inside Integrated Assessment Models: four issues in climate economics”, *Stockholm Environment Institute Working Paper*, WP-US-0801.

Tol, R.S.J. (1997), “On the optimal control of carbon dioxide emissions: an application of FUND”, *Environmental Modeling and Assessment*, 2, p.151-163.

Tol, R.S.J. (1996), “The Damage Costs of Climate Change Towards a Dynamic Representation”, *Ecological Economics*, 19, p.67-90.

Toth, F.L (2005), “Coupling Climate and Economic Dynamics: recent achievements and unresolved problems”, In *The Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment,* eds. Alain Haurie and Laurent Viguier, Amsterdam: Springer.

Wang, S. and P. Nijkamp (2007), “Impact Assessment of Clean Development Mechanisms in a General Spatial Equilibrium Context”, in: Cooper, R., K. Donaghy and G. Hewings (eds) *Globalization and Regional Economic Modelling*, Springer, Berlin.

BC3 WORKING PAPER SERIES

Basque Centre for Climate Change (BC3), Bilbao, Spain

The BC3 Working Paper Series is available on the internet at the following address:

http://www.bc3research.org/lits_publications.html

http://ideas.repec.org/s/bcc/wpaper.html

BC3 Working Papers available:

2012-08	Roger Fouquet: *Economics of Energy and Climate Change: Origins, Developments and Growth*
2012-09	Maria-Angeles Diez, Iker Etxano, Eneko Garmendia: *Evaluating Governance and Participatory Processes in Natura 2000: Lessons Learned and Guidance for Future Prospects*
2012-10	Iker Etxano, Eneko Garmendia, Unai Pascual. David Hoyos, Maria-Angeles Diez, José A. Cadiñanos, Pedro J. Lozano: *Towards a Participatory Integrated Assessment Approach for Planning and Managing Natura 2000 Network Sites*
2012-11	Luis M. Abadie and José M. Chamorro: *Valuation of Wind Energy Projects: A Real Options Approach*
2012-12	Helen Ding and Paulo A.L.D. Nunes: *Modeling the Links between Biodiversity, Ecosystem Services and Human Wellbeing in the context of Climate Change: Results from an Econometric Analysis on the European Forest Ecosystems*
2012-13	Helen Ding, Anil Markandya and Paulo A.L.D. Nunes: *The Economic Impacts of Biodiversity Policy for Improving the Climate Regulating Services Provided by EU Natura 2000 Habitats*
2012-14	Martin-Ortega, J. E. Ojea, C. Roux. *Payments for Water Ecosystem Services in Latin America: Evidence from Reported Experience.*
2013-01	Samuel Bobbino, Héctor Galván and Mikel González-Eguino: *Budget-Neutral Financing to Unlock Energy Savings Potential: An Analysis of the ESCO Model in Barcelona*
2013-02	Agustin del Prado, Karlos Mas, Guillermo Pardo, Patricia Gallejones: *Development of a new modelling framework to estimate the C footprint from Basque dairy farms*
2013-03	Roger Fouquet: *Long Run Demand for Energy Services: the Role of Economic and Technological Development*
2013-04	David Heres, Steffen Kallbekken and Ibon Galarraga: *Understanding Public Support for Externality-Correcting Taxes and Subsidies: A Lab Experiment*
2013-05	Ibon Galarraga, Luis María Abadie and Alberto Ansuategi: *Economic Efficiency, Environmental Effectiveness and Political Feasibility of Energy Efficiency Rebates: the Case of the Spanish Energy Efficiency "Renove" Plan.*
2013-06	Alexander Golub, Oleg Lugovoy, Anil Markandya, Ramon Arigoni Ortiz and James Wang: *Regional IAM: Analysis of Risk-Adjusted Costs and Benefits of Climate Policies*