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Sharing of Climate Risks across World Regions

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Summary

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Sharing of Climate Risks across World Regions[*]

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Abstract

Uncertainty is prevalent in the context of climate change impacts. Moreover, the distribution across the globe is not uniform. We analyze how climate risks could be reduced via an insurance scheme at the global scale across regions and quantify the potential welfare gains from such a scheme. Starting from the standard welfare analysis in Integrated Assessment Models (IAMs), which assumes no risk sharing across region, we introduce global risk sharing via a market for state-dependent Arrow-Debreu securities. We show that this allows equalizing *relative* consumption differences between states of the world across regions. We estimate that such risk sharing scheme of climate risks could lead to welfare gains reducing the global costs of climate change by up to one third, while the amount of transfers required is substantial. This provides arguments for considering risk sharing in IAMs, but also for potentially welfare increasing negotiations about sharing risks of climate change at the global level.

Keywords: Uncertainty, Risk Sharing, Insurance, Climate Change, Risk Aversion

JEL Classification: Q54, D81, D63

1   Introduction

Uncertainty is ubiquitous in the analysis of Climate Change. The risks associated in particular to impacts from climate change, including per se stochastic events such as extreme events but also long term trends that potentially include severe damages in the most vulnerable regions of the world, have lead to increasing concerns by policy

makers to not only mitigate climate change as such, but also to address issues of equity such as the compensation of the worst hit regions or countries. For instance, the "Warsaw international mechanism for loss and damage associated with climate change impacts"[1] initiated at the COP19 in 2013 aimed at creating an insurance scheme to provide compensations for developing countries being severely affected by ex-ante uncertain but climate change impacts. Therefore, the idea of insurance on a global scale against climate impacts could provide a way of mitigating the economic costs of global warming. While on a smaller scale the role of insurance, risk sharing, transfer schemes, and even microinsurance facing global warming are widely discussed (e.g., Mills (2005, 2009); MCII (2013)), this approach is quite different in that insurance or other risk transfer schemes based on the global scale contingent to certain impacts or extreme events cannot rely on a law of large numbers to achieve efficient risk sharing across agents. Rather, the idea of risk transfers can be established in cases where the impacts of global warming are not perfectly correlated across world regions. This gives rise to a global possibility to share risk efficiently in order to reduce the global risk exposure by a risk sharing mechanism, which is what we study in this paper.

In the literature on climate change impacts, the uncertainty about the future climate and associated socioeconomic impacts has received increasing attention in recent years. Still, in many integrated assessment models (IAMs), the effect of uncertainty is frequently found to be of minor importance confirming that uncertainty is a second order effect. The discussion of catastrophic, fat-tailed risk on the other hand found a much stronger effect (Weitzman, 2009). More recently, the role of risk aversion and appropriately parameterizing risk preferences has somewhat allowed to obtain more realistic estimates of the effect of uncertainty (Traeger, 2009; Ackerman et al., 2013; Cai et al., 2013; Crost and Traeger, 2014). However, their analysis has exclusively relied on globally aggregated models. If rather than a single representative agent multiple regions or countries are considered, the distribution of income, damages from climate change, and mitigation costs becomes relevant, notably assumptions about how the uncertainty is distributed and correlated across regions. Moreover, assumptions about how risk might or not be shared across regions are needed. Intuitively speaking, the question can be framed as whether risk aversion is considered at the global or regional level. This results in different evaluations based on whether the social planner exhibits different degrees of risk and inequity aversion, which is very plausible (Atkinson et al., 2009). Moreover, how risks are able to be shared across agents or countries, or risk transfers are allowed for, will affect the evaluation of climate change in disaggregated IAM models.

To illustrate this, consider the following two simple scenarios based on two countries of equal population size and two states of the world with equal probability. Table 1 shows the payoffs of two different situations:

In case A on the left of Table 1, the global total or average outcome is certain due to the symmetric and perfectly negatively correlated distribution, even though uncertainty is present in both countries. If the social planner considers the un-

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[1]http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf

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A	s_1	s_2	B	s_1	s_2
country 1	15	5	country 1	15	5
country 2	5	15	country 2	15	5

Table 1: Distribution of payoffs global certainty (left) and equality (right)

certainty at the global level, risk aversion should not affect his evaluation of this situation. That is the payoff will be independent of the degree of risk aversion. If on the other hand the risk is taken into account at the regional or country level, the resulting certainty equivalent will be lower in each region for higher degrees of risk aversion. Aggregating over both regions for an inequality neutral decision maker will therefore result in a lower level of welfare than in situation A. That is, how risk is considered in a disaggregated model affects the results, at least if different degrees for risk and inequality aversion are allowed for. The intuition behind this result is that in situation, there is room for welfare enhancing ex-ante risk sharing transfers. If inequality is lower than risk aversion (take zero for simplicity), his explains the difference between both aggregation rules. If risk is said to matter only at the global level, the risk disappears completely in case A since implicitly the social planner would evaluate the situation as if risk sharing is implemented. In case B on the right of Table 1 on the other hand, the correlation structure is such that no such risk sharing scheme is possible. In this case, therefore considering regional or only global risk would lead to the exact same welfare level and hence decision rules under uncertainty. Note that these differences are irrelevant for a decision maker with one single utility function considered across states of the world, regions, and time, such as (discounted) expected utility uilitarianism, see Fleurbaey and Zuber (2013) or Emmerling and Berger (2014).

In this paper, however, we introduce a market of contingent claims similar to an insurance but considering rather large geographical scales. This way, we explicitly implement a risk sharing scheme such that even in standard economic impact assessment models we can take into account risk sharing across macro regions. Our works is somewhat related to the numerical assessment in Schmidt et al. (2012), who introduce heterogeneity and uncertainty in a version of the DICE model using simple distributional assumptions and study risk sharing in this framework.

This paper is organized as follows: In section two we discuss the potential of risk sharing across regions in the context of climate change. Section three develops a model of a market for state-dependent securities as means to share risks from climate change across regions in a non-cooperative market equilibrium. The model is then implemented using a large scale IAM model in section four and appropriate welfare metrics are discussed to evaluate the welfare effects of the risk sharing scheme. Section five concludes.

2   Risk Sharing and Climate Change

The role of risk sharing is widely discussed in the context of e.g., extreme events where within a region, individual risky damages are able to be reduced via different types of insurance or risk sharing schemes. Basically, the law of large numbers allows to achieve a reduction of individual risks via an insuring party. Only if all risks were perfectly correlated, risk sharing cannot lead to a welfare improvement. Otherwise, however, all idiosyncratic risk could be in theory insured against (Ligon, 1998). In reality, there are however several obstacles to insure all idiosyncratic risks, namely transaction costs, limited liability, asymmetric information, and ambiguity. Notably ambiguity provides a serious hindrance to insurance in the context of climate change where the scientific uncertainty is hard to assess with probabilistic estimates (Kunreuther et al., 1993). As a result, insurance is far from covering all climate change damages. For instance, Mills (2005) estimates that globally, only around 20 per cent of all damages from natural disasters are insured.

Moreover, it has been argued that due to a lacking internationalization of insurance and financial markets, risks from climate change damages will not be shared efficiently across regions or agents (Gollier, 2006). That is, the scope of efficient risk sharing across macro regions must be considered as rather low. On the other hand, there is a large literature on risk sharing between countries that finds significant risk sharing of medium and long run risk in terms of macro consumption via international trade and financial markets (Obstfeld, 1994; Baxter, 2011). This way, a large share of the idiosyncratic macroeconomic risk is reduced via implicit mutually advantageous risk transfer between countries.

A substitute to insurance can be provided via implicit or explicit risk-sharing, which takes for instance the form of an indemnity financed by the taxpayers (Gollier, 2006). Examples include the public assistance to victims of natural disasters such as floods, or after terrorist attacks (such as the U.S. assistance after the WTC terrorist attacks through the 7 billion USD worth "September 11th Victim Compensation Fund". However, also more general campaigns to help to compensate, e.g., heavy losses of farmers or truckers as, e.g, in Spain or France can be considered as implicit risk sharing schemes.

In the context of the global problem of climate change, such a risk sharing scheme could be arranged in order to mitigate the idiosyncratic risk of climate damages (Schmidt et al., 2012). If the distribution of global damages across regions where to be unknown or sufficiently uncertain, the world as a whole could gain by committing to a risk sharing scheme where regions with lower damages or even positive impacts would compensate losers in the sense of high damage countries or regions. However, as soon as sufficient scientific knowledge is available to assess the regional distribution of climate change, these risks become uninsurable so that in this case information has a negative societal value (the so-called Hirshleifer (1971) effect). In this case, such a risk sharing scheme would need to be organized prior to the revelation of the information (Gollier, 2006).

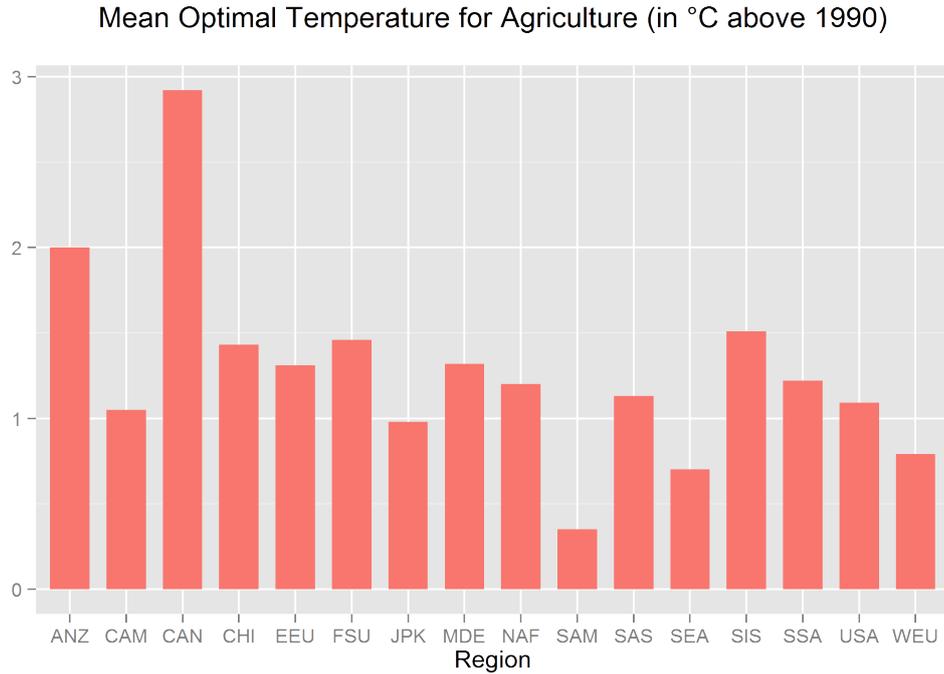To illustrate the potential of such a scheme, take for example the impacts of

Figure 1: Mean optimal temperature for Agriculture according to Ackerman and Munitz (2012)

climate change across the world. Figure 1 shows the estimated optimal temperatures for agriculture (in changes in degree Celsius compared to 1990). While on the global level, a very modest global warming of about one degree would lead to the optimal temperature in many regions, there is substantial regional variation: For several regions, including South America, (almost) no increase in the global mean temperature would be best for the agricultural sector while for colder regions such as Canada a higher temperature would be beneficial at least for productivity in agriculture. Given the large uncertainty about the climate sensitivity and other crucial parameters of the global climate, the actual change in global mean temperature is highly uncertain. Therefore, in theory, an explicit risk sharing scheme could consist in transfer pledges between different regions such that, e.g., if climate change is more severe than expected, relatively better off regions such as in this example Canada would compensate other regions and vice versa. This would result in less variation in consumption or welfare levels in different states of the world and under risk aversion, all regions would be better off by participating in such a risk sharing scheme.

Another example for such a risk sharing scheme can be seen in the prediction of extreme events across countries. For instance, Mendelsohn and Saher (2011) estimate the impacts from tropical cyclones and severe storms for the year 2100

using three different climate models. For the three different models, the estimates in different countries not only vary significantly, but also the ranking changes for many countries. his provides another example of how risk sharing or transfer schemes could reduce welfare costs of uncertain climate impacts, in this case extreme events.

On the other hand, there are obviously several limits to the actual implementation of such a risk sharing scheme. Firstly, impacts from climate change are expected to be realized over a long time horizon, due to the long permanence of CO_2 in the atmosphere but also due to irreversibility and threshold effects. Therefore, the transfers needed would need to be sustained over a long time horizon as well. Secondly, the involved amounts could be substantial due to the potentially high impacts from climate change. Thirdly, since already getting a global agreement to limit greenhouse gas emissions proves to be difficult, similar issues could be expected for such a risk sharing scheme. Even though the benefits of such a scheme could be possibly much easier justifiable, since they are in the self-interest of countries ex-ante. However, ex-post countries might well to decide to not comply with the scheme in case they had to pay the transfer. Fourth, the magnitude and variability of climate change impacts, the attribution problem, and finally the measurement of impacts provide a strong barrier to the implementation of such a system.

So while there are many reasons to believe that risk sharing across macro regions or countries is limited, why could it still matter? Disaggregated damage estimates can be interpreted as uncertain payoffs that typically are not perfectly correlated and thus exhibit scope for risk sharing. We consider three potential channels for such risk sharing in this context: macroeconomic risk sharing through international markets and financial diversification, through relocation of capital and/or labour, and through an international explicit transfer scheme. The first channel has been studied extensively in the macroeconomic literature (Obstfeld, 1994). Moreover, at least in standard CGE models, these mechanisms of implicit risk sharing are at least partly taken into account via prices and trade across sectors and countries and possibly relocation of production factors. The relocation of production factors and migration as way of ex post dealing with climate risks is a debated although contentious issue. The third channel of a transfer scheme is probably what is most closely related to our point in this paper. For instance international aid and disaster relief programs can be interpreted as sharing risk between countries or regions. Similarly, food aid has to some extent a similar characteristic.

Since disaggregated IAMs are typically not able to capture risk sharing (Ferranna, 2013), we allow for this possibility explicitly, which in theory encompasses all possible risk sharing mechanisms summarized into one instrument, while the interpretation is easiest in the case of an explicit risk-sharing scheme. To consider the full scope and in particular the possibility of an explicit transfer scheme, we develop an explicit market for insurance or risk sharing and integrate it into an IAM to study its effect. The results can then be though as combining both implicit and explicit risk sharing.

3 A model for risk sharing using state-dependent securities

We want to analyze the potential for risk sharing across regions in an integrated assessment model. From the first welfare theorem of economics, it follows that a market solution will implement the social optimal allocation under certain conditions, notable the existence of a set of complete markets. Therefore, by introducing a market for state-dependent securities based on the possible states of the world, we can find the socially optimal allocation of risk and thereafter study its distribution across regions and welfare implications.

Uncertainty in the model is introduced via a set of S finite states of the world and we denote the–possibly time-dependent–probability of each state of the world s as π_{st}. Based on the standard discounted expected utility criterion, we can write welfare under uncertainty of region or country n as

$$W_n = \sum_{t=0}^{T} P_{nt} \sum_{s=1}^{S} \pi_{st} U(c_{nt})(1+\delta)^{-t} \tag{1}$$

where δ denotes the pure rate of time preference, T the time horizon, P_{nt} the population in region or country n at time t and c_{nt} the level of per-capita consumption at date t and U the standard utility function.[2] While this framework using one single utility function is analytically very tractable, at least for the application, separating risk and fluctuation aversion is desirable to allow more realistic calibrations of preferences (Atkinson et al., 2009) and more meaningful comparative statics results. Hence we disentangle risk and fluctuation aversion in the spirit of Epstein and Zin (1989) to consider in particular the empirical observation that estimates for the degree of risk aversion are much higher than the level of fluctuation aversion.

In particular, this allows to risk aversion to take more reasonable magnitudes in typical integrated assessment models, that feature, e.g., the logarithm of consumption as utility function ($\eta = 1$). For instance, imagine a lottery where with 10% probability, you lose 10% of your consumption, as it might be the case for significant climate change damages in the future. For the case $\eta = 1$, this would imply that the representative agent would be indifferent between this lottery and a sure consumption loss of 1.05%.[3]To achieve a sizable risk premium, one need a much higher (but reasonable) degree of risk aversion. With $\eta = 8$, as proposed e.g., in the literature on the equity premium puzzle, the certainty equivalent increases to 1.5% and for $\eta = 20$ to 2.6%.

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[2]We assume that the utility function is identical across countries, which might be a strong assumption. Allowing for different degrees of risk aversion could be justifies on different preferences across world regions and cultures, which is an ongoing field of empirical research. Nevertheless, for calibrating the function used in the numerical part it would be difficult to estimate the utility function parameters, so that for the moment we leave this task for future research.

[3]Computed based on the definition of the certainty equivalent as $x = 1 - \left[p_L(1-10\%)^{1-\eta} + (1-p_L)1\right]^{\frac{1}{1-\eta}}$, which for CRRA utility functions is independent of the level of consumption at which it is evaluated.

Using power function specifications, let $U(x) = \frac{1}{1-\eta}x^{1-\eta}$ be the function capturing preferences over consumption smoothing and denote by V the vNM utility function capturing risk aversion: $V(x) = \frac{1}{1-\rho}x^{1-\rho}$. This allows us to rewrite the welfare function (1) of any region n as

$$W_n^{EZ} = \sum_{t=0}^{T} P_{nt} \frac{1}{1-\eta} \left(\left(\sum_{s=1}^{S} \pi_{st} c_{nst}^{1-\rho} \right)^{\frac{1-\eta}{1-\rho}} - 1 \right) (1+\delta)^{-t} \tag{2}$$

This welfare framework will be used also in the numerical application of the next section, while for the analytical part we introduce the market for contingent claims into a simple model of multiple regions N where each region maximizes welfare according to (2). We focus on two time periods which allows to simplify notation significantly and can easily extended by separating both time frames into sub-periods and introducing consequently markets at any point in time. For now we consider one single time-step T at which the true state of the world is revealed. That is, we have $\pi_{st} = \pi_s$ and that no learning occurs before period T. At some date t_0 before T, a contingent claims paying one dollar in any state $s \in S$ and zero otherwise are introduced and traded on a perfect market across regions. These state-dependent securities (Arrow-Debreu Securities) are traded on a competitive market among all regions. This market can be shown to yield the same allocation than a system of complete markets on state-dependent claims on commodities, see Arrow (1964).

Denote by p_s the price of such a security yielding a pay-off of one unit at date T only if in state of the world s. Any country or region n decides on the quantity of such securities to be bought or sold at date t_0 which we denote by $q_{s,n}$. If this quantity is positive, the region has to pay the price for each claim at t_0 and will receive one dollar for each security held at date T in state s. If the quantity is negative, the region sells the claim and thus receives its market price and has the obligation to pay one Dollar per claim to the buyer of the claim if state s occurs.

Based on the level of consumption prior to the market for state-dependent securities, denoted as $c_{t,n}$ before the resolution of uncertainty and $c_{t,s,n}$ afterwards, the ex-post level of consumption for each region at date t_0 is now $c_{t_0,n} - \sum_{\sigma=1}^{S} p_\sigma q_{\sigma,n}$ while at date T it becomes $c_{T,s,n} + 1 \cdot q_{s,n}$.

The welfare in each region given by (1) will thus be directly affected at two periods: the trading period and when the payouts of the security are realized. Given that in the absence of the market, the allocation is already based on the optimization of (1), the equilibrium requires that marginal discounted expected utility is equalized over time within each region. Assuming that the introduced market is relatively small will thus not alter substantially the inter-temporal allocation of consumption within each region.[4] Hence, we can rewrite (1) focussing only on the time periods

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[4]The type of model under consideration here is basically a Ramsey type optimal growth model. Therefore, the Ramsey-rule dictates that marginal discounted consumption is equal at each point in time taken into consideration the interest rate. Since we don't assume trade nor international capital flows in our model, the national interest rates are given by the model.

that are going to be affected by the new market and write it as

$$W_n = e^{-\delta t_0} U\left(c_{t_0,n} - \sum_{s=1}^{S} p_s q_{s,n}\right) + e^{-\delta T} \sum_{s=1}^{S} \pi_s U\left(c_{T,s,n} + 1 \cdot q_{s,n}\right)$$

The market equilibrium of all s contingent claims dictates that each region n maximizes its welfare subject to the quantity of securities bought and sold for each state, and that the market clearing condition holds for each security or that the sum of bought and sold claims are equal to zero.

$$\begin{cases} \forall n : \quad max_{q_{s,n}} \left(e^{-\delta t_0} U\left(c_{t_0,n} - \sum_{s=1}^{S} p_s q_{s,n}\right) + e^{-\delta T} \sum_{s=1}^{S} \pi_s U\left(c_{T,s,n} + 1 \cdot q_{s,n}\right) \right) \\ s.t. \quad \forall s : \sum_{n=1}^{N} q_{s,n} = 0 \end{cases}$$

From this formulation of the problem, we can derive the first order conditions for each region and state of the world as

$$\forall n, s : e^{-\delta t_0} U'\left(c_{t_0,n} - \sum_{\sigma=1}^{S} p_\sigma q_{\sigma,n}\right)(-p_s) + e^{-\delta T} \pi_s U'\left(c_{T,s,n} + 1 \cdot q_{s,n}\right) = 0$$

or

$$\forall n, s : p_s = \pi_s e^{-\delta(T-t_0)} \frac{U'\left(c_{T,s,n} + 1 \cdot q_{s,n}\right)}{U'\left(c_{t_0,n} - \sum_{\sigma=1}^{S} p_\sigma q_{\sigma,n}\right)}.$$

Using again the recursive welfare specification as presented above in (2) with isoelastic function forms for disentangling intertemporal fluctuation aversion (η) and risk aversion (ρ), we obtain the following version of the first-order condition after some rearranging as

$$\forall n, s : p_s = \pi_s e^{-\delta(T-t_0)} \frac{\left[\sum_{\sigma=1}^{S} \pi_\sigma (c_{T,\sigma,n} + 1 \cdot q_{\sigma,n})\right]^{\frac{\rho-\eta}{1-\rho}} (c_{T,s,n} + 1 \cdot q_{s,n})^{-\rho}}{\left(c_{t_0,n} - \sum_{\sigma=1}^{S} p_\sigma q_{\sigma,n}\right)^{-\eta}}. \quad (3)$$

From this formulation, the factors driving asset prices can be inferred: the probability of a state influence the price of the respective state-dependent security while the discount factor reduces the price since the payoff is occuring in the future. To solve for the market equilibrium allocation, we have to solve a set of $(N+1)S$ equations of the NxS first-order conditions of the regions and in addition the S market-clearing conditions and solve for $N \times S$ quantities $q_{s,n}$ and S prices p_s.

For the case of a general utility function as in (2), we get that the marginal utilities are equalized across regions between any two states of the world. For applications, however, we are more interested in the isoelastic specification and the situation where preferences are disentangled. For this case, we obtain the following result:

Proposition 1. *With a poer utility specification and under risk aversion($\rho > 0$), **relative** differences in consumption are equalized across regions between any two states of the world $s_1, s_2 \in S$ at the equilibrium:*

$$\forall n \in N, s_1, s_2 \in S : \frac{(c_{T,s_2,n} + 1 \cdot q_{s_2,n})}{(c_{T,s_1,n} + 1 \cdot q_{s_1,n})} = RD_{s_2,s_1}$$

where RD_{s_2,s_1} represents the relative consumption difference in all countries in state s_2 compared to state s_1.

Proof. Write out the first-order conditions (3) for one country and two different states of the world s_1 and s_2. Combining the two conditions and noting that the denominator and first term in the numerator are independent of the state of the world considered, one obtains

$$\frac{p_{s_2}}{p_{s_1}} = \frac{\pi_{s_2}}{\pi_{s_1}} \left(\frac{c_{T,s_2,n} + 1 \cdot q_{s_2,n}}{c_{T,s_1,n} + 1 \cdot q_{s_1,n}} \right)^{-\rho}.$$

Comparing this condition across different countries[5], it follows that relative differences across states of the world, which is just the term in the parenthesis, are going to be equalized at the equilibrium. Rearranging the equation yields for the relative differences $RD_{s_2,s_1} = \left(\frac{p_{s_1}/\pi_{s_1}}{p_{s_2}/\pi_{s_2}} \right)^{1/\rho}$ which is independent of n and thus equalized across regions at equilibrium. Only for $\rho = 0$, the relative differences do not matter anymore as utility is not affected by the uncertainty in the distribution of consumption and relative consumption can be different across regions. $\square$

The reason for this result is that with power utility functions, relative differences in consumption are independent of the level of consumption and the degree of risk aversion. The outcome also equals the optimal allocation of risk across regions from the first welfare theorem. Consider as an example the impacts from climate change, which are typically expressed in percentage terms of consumption. Optimal risk sharing through the market for state-contingent claims introduced here will lead to the equalization of relative damages across countries or regions. The advantage of the market mechanism is, however, that the implicit transfers needed ex-ante can be calculated and hence the implications for welfare and political feasibility of the risk sharing scheme.

3.1 Market frictions and transaction costs

So far, we considered the market to be perfectly competitive without transaction costs and other imperfections. However, in the context of such security market, market frictions or transaction costs could be significant and stem from various sources. The explicit and implicit costs of international transfers, political costs, etc. could provide a serious limitation to the functioning of such an insurance scheme. To include this possibility in the model, we consider a bid-ask spread between the

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[5]We assumed so far that the degree of risk aversion are equal across countries. We maintain this assumption since in order to implement such a model, estimates of risk preferences across countries or regions are hardly available as of today. However, the model can easily be adjusted featuring different degrees of relative risk aversion across countries ρ_n. For this case we can along the line of the proof, it is not the relative difference that is equalized across countries but rather the term $RD_{s_2,s_1}^{\rho_n}$. That is, as the degree of risk aversion of a particular country ρ_n increases, relative differences between states in this country will tend towards one, since this country would for constant risk aversion of all other countries buy more insurance.

prices of the assets paid for by the buying country and the value received by the selling country. We denote by p_s the price of the security paid for by the buying region whereas the writing counterpart receives only $p_s(1\text{-}\tau)$ where τ stands for the relative spread. This modification changes our problem and one can rewrite the first order condition as in (3) now as

$$p_s\left\{1 - \mathbb{1}_{q_{s,n}\leq 0}\tau)\right\} = \pi_s e^{-\delta(T-t_0)}\frac{\left[\sum_{\sigma=1}^{S}\pi_\sigma(c_{T,\sigma,n} + 1\cdot q_{\sigma,n})\right]^{\frac{\rho-\eta}{1-\rho}}(c_{T,s,n} + 1\cdot q_{s,n})^{-\rho}}{(c_{t_0,n} + T_{t0,n} - \sum_{\sigma=1}^{S}p_\sigma\left\{1 - \mathbb{1}_{q_{\sigma,n}\leq 0}\tau)\right\}q_{\sigma,n})^{-\eta}}$$

where $\mathbb{1}_{q_{\sigma,n}\leq 0}$ denotes the indicator function which is equal to one if $q_{\sigma,n} \leq 0$ and zero otherwise. The sum of the transaction costs $\sum_{n=1}^{N}\sum_{\sigma=1}^{S}\tau p_\sigma\left\{\mathbb{1}_{q_{\sigma,n}\leq 0}\right\}(-q_{\sigma,n})$ needs to be in a lump-sum fashion be redistributed across regions through the term $T_{t0,n}$.[6] It is important to note that the result of Proposition 1 does not hold necessarily anymore once we consider the spread. However, as long as all regions buy or sell in all states of the world so that $q_{s,n}$ bears the same sign for all s for any n, the result still holds and relative consumption differences are equalized. In this case the indicator function cancels out when computing the ratio across prices and therefore the result still holds.

3.2 Contingent claims used as saving device

If the market for state-contingent claims is introduced in a model without international capital flows or national saving possibilities, the new assets will also be potentially used as to trade diference in regional or national interest rates and consumption smoothing within regions by simultaneously buying or selling assets for all states of the world rather than from the pure insurance motif. While introducing an international capital market into the models might be a solution, this poses several problems. Firstly, global financial markets are far from perfect, notably interest rates differ substantially between regions, even if inflation and risk premia difference are considered. Moreover, a frictionless capital market would imply significant lending and borrowing streams over a long time horizon. Typically,countries with a high growth prospect such as China would borrow against the future whereas countries with a more flat growth path would be willing to lend today. Therefore, and in order to assess the real effect of the insurance market, we need to abstract from claims that are bought or sold merely as a savings or lending technology.

In order to separate the savings motif from the insurance one, we simply consider that savings would be equal across states of the world if there was no risk (which is what we observe in the numerical model below). Therefore, by computing the difference between the assets bought or sold in one state of the world minus the quantity bought or sold in another state of the world gives the amount of asset that would be traded if insurance against climate risks was the sole motif to trade the AD securities. To do so, we compute a net-trade in the state-contingent assets such

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[6]Another way of dealing with the costs would be consider them as sunk and a dead weight loss and set $T_{t0,n} = 0$.

that the trade in one state $\sigma \in S$ (e.g., where no impacts from climate change occur) equals to zero for all regions. Moreover, we want the central result of Proposition 1 still to hold, which implies that we will compute the net trade of claims of a region n for state of the world s as

$$NetTrade(n, s) \equiv \frac{q_{sn}}{RD_{s,\sigma}} - q_{\sigma\Sigma n}$$

which still satisfies the market clearing condition, the equalization of relative differences between states across regions, and implies that in state σ no asset will be traded. The results show that the interpretation makes sense economically.[7]

4 Implementation in an IAM

In the following we implement the market into a numerical integrated assessment model, namely the World Induced Technical Change Hybrid model (WITCH)[8] to derive the potential, implications, and costs of such a risk sharing device. Regarding the source of uncertainties, we consider the possibility of climate impacts occurring or not with equal probability. This simple example at least provides a broad estimation of the order of magnitudes in the climate change literature regarding the climate sensitivity and impacts from global warming. While being simplistic, this allows at least to gauge the order of magnitude of the potential of climate risk sharing at the macro level. That is, we consider damages of climate change that are unknown in that only in the future will the damages be either as predicted as by the best-guess estimate of the model's damage function (state s_1) or turn out to be negligible (state s_2). We are then interested in both how much of the uncertainty in the future is going to be mitigated by the additional markets, and in the volume of the market at present that would be required to implement such a scheme in order to assess its economic and political feasibility. We consider the period of 2015-2045 the trading period in which the securities are traded and after learning the actual distribution of damages in 2050, the corresponding time period 2050-2080 where the payouts are realized.[9]

The following graph shows the impacts from climate change expressed as damages in per cent of GDP lost estimated for the year 2050, which vary between 1 and 6 per

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[7]An alternative, though less appealing, would be to simply compute the differences across states to determine the insurance motif, i.e., reporting the net trade on claims of a region n for state of the world s subtracted the trade in one state $\sigma \in S$ as $NetTrade(n, s) \equiv q_{sn} - q_{\sigma n}$. The resulting net trades would however violate the central equilibrium condition which is why we prefer the way described in the text. While an appropriate market solution taking both quantities and prices as final outcomes would be preferable, we tried several ways to separate savings from the risk trade, but in the numerical model did not succeed in reasonable outcomes. Taking into account savings explicitly would solve the problem but introduce many issues on its own due to the fact that a perfect international capital market cannot be considered as realistically in these models.

[8]www.witchmodel.org

[9]The time step of the WITCH model is five years, and the time horizon is until the year 2150. The insurance scheme considered here thus spans over roughly half of a century, while it could be extended to longer time horizon introducing multiple resolutions of uncertainty.

cent across regions (red bars). When risk sharing is allowed for through the market for state-contingent claims, regional differences in consumption between the damage and no-damage states of the world are equalized across regions at about three per cent (blue bars), as predicted by Proposition 1.
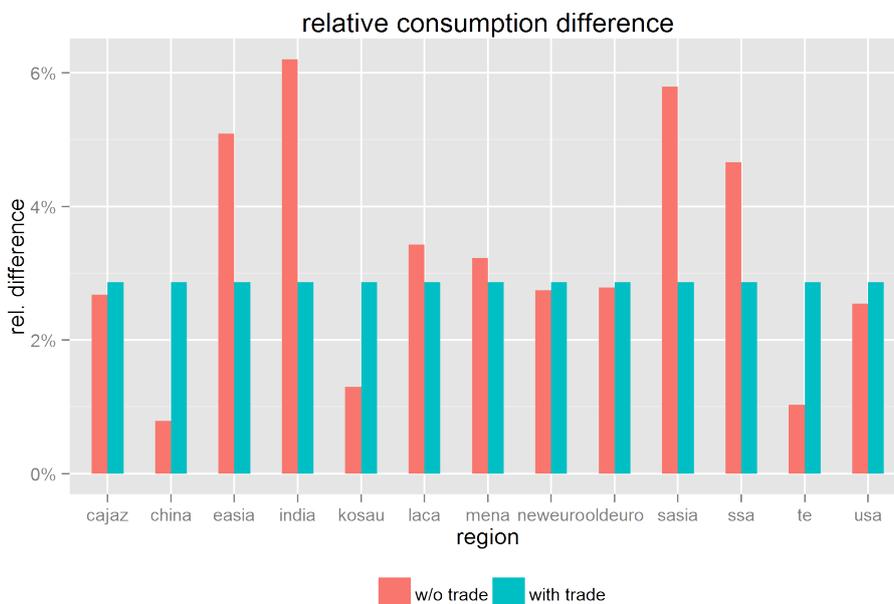
Based on the equilibrium outcome of the market for the state-contingent claims, we get the regional distribution of trade in these securities. As it can be seen from the following figure, the regions buying insurance against relatively high damages are mainly East and South Asia, India, and Sub-Saharan Africa, which all are characterized by relatively higher climate damages as predicted. The regions offering this type of insurance would be mainly China, South Korea, South Africa, and Australia ("kosau"), the transition economics("te"), and the USA. These regions are expecting to suffer lower damages from climate change than the global average and therefore prefer to sell the insurance at given market prices.

Trade on Net claims on state s1 (with damages) [Bln. USD]
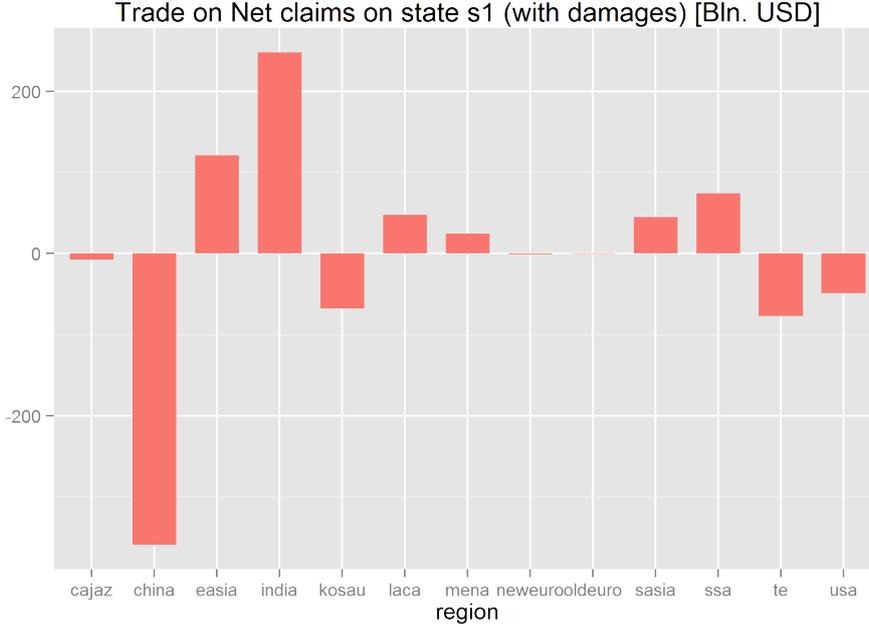
The resulting prices for the contingent claims and market volume are reported in the following table, where we consider two different degrees of relative risk aversion $\rho = 1.5 = \eta$, that where the two preference dimensions coincide, and $\rho = 10$ while maintaining a value of $\eta = 1.5$ for the inverse of the inter-temporal elasticity of substitution.

	value ($\rho = \eta = 1.5$)	value ($\rho = 10$)
p_{s_1}	0.43\$	0.48\$
p_{s_2}	0.41\$	0.36\$
$\frac{1}{2}\sum_{s=1}^{S} p_s \sum_{n=1}^{N} |q_{s,n}|$	240 bln USD p.a.	270 bln USD p.a.
$\frac{1}{2}\frac{\sum_{s=1}^{S} p_s \sum_{n=1}^{N} |q_{s,n}|}{\sum_{n=1}^{N} c_{t_0,n}}$	0.18% of GDP	0.21% of GDP

The state-dependent securities for the "bad" state s_1 where consumption is lower due to climate damages are more expensive at equilibrium as expected and the difference increases in the degree of risk aversion as insurance becomes more costly, even though the allocation is identical due to the equalization result which holds or any value $\rho > 0$. With regard to the volume of trade of the market, it is around 250 bln. USD per year or about 0.20% of global GDP from 2015 onwards. While being a substantial amount, one can compare it e.g., to the 359 billion USD of total climate finance flows that have been recorded for 2012 (CPI, 2013). While the order of magnitude seems reasonable, it is important to point out that this amount only deals with the distribution of climate risk while leaving the impacts unchanged, either through mitigation or adaptation. Therefore, this volume certainly would require significant financial flows and pledges among regions or countries additionally to investments in adaptation or mitigation actions.

Asset prices of contingent claims
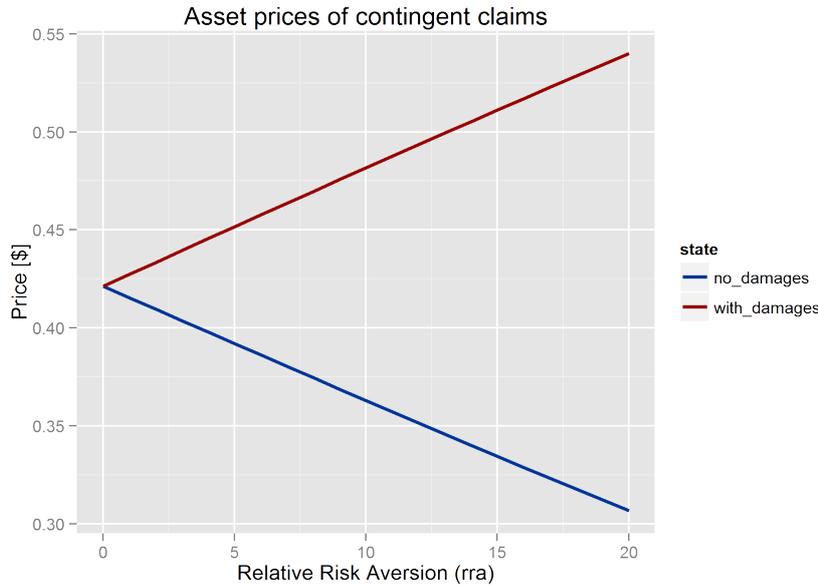
So far we assumed no transaction or other costs of the traded securities. However, it seem reasonable that (significant) costs could be expected for the risk sharing market mechanism, based on the administration, political concerns, and details of the implementation. We implemented an imperfect market modeling a bid-ask spread of $\tau = 10\%$ between the buyer's and seller's price of the AD securities which takes into account these costs. The costs are then refunded to the regions in a lump-sum fashion. In this case, small differences in future consumption across states remain while the general results do hold qualitatively.

4.1 Welfare evaluation

By construction, the trade in these securities is improving inter-temporal welfare in each region or at least leaving it unchanged, while the relative gains will vary across regions. For a global welfare analysis of the risk sharing scheme, on the other hand, we need to aggregate welfare globally and compare the situation with and without trade. In order to compute these welfare changes, we use the "certainty, equity, and balanced growth equivalent" (CEBGE) developed by Mirrlees and Stern (1972), that has been used in a similar context recently in Anthoff and Tol (2009) and Schmidt et al. (2012). The CEBGE is computed as the level of per-capita consumption that, if equally distributed across regions and identical in all states of the world, and growing at a constant rate g everywhere, resulted in the same welfare as the actual distribution over time, regions, and states of the world.

That is, we compute global welfare based on a Utilitarian social welfare function[10] as $W^{EZ} = \sum_{n=1}^{N} W_n^{EZ}$ where W_n^{EZ} is regional inter-temporal welfare given by (2). Then, the CEBGE can be computed for any constant growth rate g by inverting

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[10]Whether utilitarian weights or other weights including Negishi weights are used in aggregation does not alter the results shown below significantly.

the definition of welfare and solving for the level of consumption in the first period given the equal distribution and constant growth assumptions. One thus gets the following formula

$$CEBGE = \left[\frac{W^{EZ}(1-\eta) + \sum_{t=0}^{T} P_t(1+\delta)^{-t}}{\sum_{t=0}^{T} P_t\left((1+g)^{t(1-\eta)}\right)(1+\delta)^{-t}}\right]^{\frac{1}{1-\eta}} \qquad (4)$$

similar as in Anthoff and Tol (2009) where P_t denotes the global population at time t.[11] This measure of welfare depends on the degrees of risk, and inequality aversion only through the value of welfare W^{EZ} since across regions and states of nature, consumption is by definition equalized. However, it depends on the balanced growth rate g assumed. However, when one is interested in relative comparisons, the dependence on the growth rate cancels out such that relative gains or welfare are independent of the growth rate assumed[12], which makes it a suitable measure for generalized welfare comparisons (Anthoff and Tol, 2009).

In the following table, we report the values of the certainty, equity, and balanced growth equivalent level of consumption in 2005 in US-$. First we consider the baseline without impacts from climate change and risk sharing/trade. Second, we consider the situation where damages occur with certainty. For the stochastic version of the model, we then consider the cases with stochastic impacts with and without trade and finally including a bid-ask spread of 10% for the contingent claims.

CC trade	impacts	CEBGE (ρ=1.5)	CEBGE (ρ=10)
no	never	3004.7$	3004.7$
no	yes (always)	2870.8$ (-4.5%)	2870.8$ (-4.5%)
no	yes (in s_1)	2936.6$(-2.27%)	2929.2$(-2.51%)
yes	yes (in s_1)	2962.4$ (-1.40%)	2959.9$ (-1.50%)
with 10% bid-ask spread	yes (in s_1)	2962.4$ (-1.40%)	2959.9$ (-1.50%)

First of all, from the first two columns one can infer that climate change damages in total imply a welfare loss in terms of consumption of around 4.5%. This welfare loss of certain climate change impacts is obviously independent of the degree of risk aversion and the solution with risk sharing will be in between the baseline with and without impacts. With impacts being stochastic as described and no risk sharing available, expected welfare losses are around 2.5% and higher for higher levels of risk aversion, even though the difference is relatively minor. Now when allowing trade in the state-contingent securities, we ask how much of the the welfare loss due to the expected damages could be reduced via the global insurance scheme. From the fourth row in the table, we see that the trading scheme leads to a welfare loss

[11]For the case of logarithmic utility or $\eta = 1$, the formula instead becomes $CEBGE = exp\left(\frac{W^{EZ} - \sum_{t=0}^{T} P_t ln(1+g)^t(1+\delta)^{-t}}{\sum_{t=0}^{T} P_t(1+\delta)^{-t}}\right)$

[12]We assume a balanced growth rate of $g = 1.5\%$ in this paper when reporting the value of the CEBGE.

compared to the baseline without impacts of $1.4 - 1.5\%$. That is, due to the risk sharing induced by trade in the state-dependent securities, the welfare loss is reduced by almost one percentage point of GDP, or, in relative terms, by over one third. To be precise, the welfare loss is reduced by 38% for $\rho = 1.5$ and 40% for a degree of risk aversion of 20 over the welfare loss without risk sharing. Finally, introducing the bid-ask spread does not alter the results, which is somewhat surprising, but can be explained by the fact that due to the redistribution of the transaction costs towards the regions the obtained welfare is (almost) unchanged.

Compared to the total cost of damages over no climate change impacts, this means that around one third of the welfare costs of climate change are avoided through the risk based trading resulting in transfers to the most severely affected regions in case the damages materialize. These results suggest that while climate impacts still significantly reduce welfare, implementing an efficient risk sharing scheme across regions could lead to a reduction of welfare costs by up to one third. While climate damages are the same as without risk sharing, the welfare cost could at least in theory and involving substantial amounts of transfers be significantly reduced. The results have to be considered with caution, though. While the proposed transfer scheme is indeed incentive compatible, the large time scale involved poses a serious problem of contract enforcement and renegotiation issues that could arise. Moreover, indexing such transfer schemes to observable and verifiable outcomes of certain physical characteristics or socioeconomic impacts is important and introduces an important obstacle to its implementation.

Nevertheless, the results suggest two main implications for modeling and policy. Firstly, the potential of risk sharing due to regional heterogeneity does seem to provide at least a potential to reduce welfare costs due to uncertainty for instance about climate change impacts. Some of the risk sharing mechanisms can be explicitly captured, e.g., in CGE models considering price effects of mobility of production factors across sectors and (less frequent) countries. In many integrated assessment models used for long-term climate change simulations, on the other hand, limitations in granularity typically do not allow to take this consideration and therefore risk sharing is completely absent. Thus, this way of allowing for risk sharing allows to capture the potential of risk sharing in these models. Secondly, the results can be interpreted as a justification of sharing climate risk even at a broad macro level across regions or countries. Given the deep uncertainties in the field of climate change, this potential should at least be acknowledged, even though it is clear that only a fraction of it will most likely be realized or implemented in the end. Still, it can provide arguments for negotiations of compensations for losses from climate change to reduce the full exposure to climate impacts at least economically via various forms of risk sharing.

5 Conclusion

We showed that the substantial uncertainties in the field of climate change along with regional heterogeneity provides a scope for risk sharing at the global level across

regions or countries. Whereas insurance or risk sharing has been studied extensively on a more micro level to mitigate risks e.g., from extreme weather events or other impacts, risk sharing is also conceivable on the macro level via different channels. Most long-term integrated assessment models, however, do by construction not allow for risk sharing across regions. We therefore explicitly allow for this possibility introducing a market for contingent claims as risk sharing mechanism in such a model. We show that this allows to equalize relative consumption differences between states across regions leading to potential welfare gains reducing the welfare costs of climate change. Our estimates based on a perfectly competitive market suggest that up to one third of total welfare costs from climate impacts could be mitigated via such an insurance scheme, which can be considered as an upper bound estimate to the potential welfare gain.

In particular, such a insurance scheme would require substantial amounts of financial flows which we estimate around 250 billion USD per year or about 0.2% or global GDP. How such an insurance scheme could work is not trivial, but risk sharing at the global scale can comprise relocation of capital and labor (migration), international trade, financial markets, and–potentially most relevant in this context– and explicit risk transfer scheme between nations. While risk sharing does not reduce the total impacts from climate change and therefore can only be considered an additional policy option, the results suggest that indeed compensating particularly hard hit countries from climate change impacts could reduce the global welfare loss due to climate change while ex-ante benefiting all participating countries. This provides a rationale for institutions such as the "Warsaw international mechanism for loss and damage associated with climate change impacts". Moreover, whereas the public good nature of climate change makes global cooperation hard to achieve, it could be substantially less challenging to achieve global welfare gains from insuring against idiosyncratic uncertain climate impacts. The sharing of climate risk is thus a relevant feature not only for economic modeling of climate change under uncertainty, but also for policies dealing with insurance and compensations in this context.

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