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Discounting in the Context of Climate Change Economics:

The Policy Implications of Uncertainty and Global Asymmetries

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Abstract: This paper considers the debate on discounting in the context of climate change economics. It identifies and reviews three different frameworks: discounting under certainty in a single world, discounting under uncertainty in a single world, and discounting in an asymmetric world. A single world approach assumes that the world is composed of homogeneous individuals and goods while an asymmetric world approach takes into consideration differences in income distribution and preferences among people, and heterogeneity among goods. The paper links these conceptual frameworks with policy debates. It concludes that structural uncertainty and the importance of recognizing global asymmetries reveal the limitations of standard inter-temporal welfare optimization frameworks to assess climate change policies. While the issue of uncertainty has received wide attention in the literature and policy debates, global asymmetries have been somewhat neglected, a gap that this paper aims at contributing to correcting.

I. INTRODUCTION

The economics of climate change is often framed as a choice between two possible scenarios. In one scenario we can choose to live in a world where we do nothing now to mitigate climate change, but in the future will have to suffer income losses from the damages of warming. In the other scenario, we can choose to live in a world where those future income losses are avoided, but at the expense of taking costly action starting now or very soon to mitigate climate change, which implies cuts in GDP growth in the short-run. In this second scenario, avoided future losses from climate change are benefits while current incomes foregone to receive those future benefits are costs.

This is how cost-benefit analysis of climate change is typically described. Such an analysis relates climate change to trade-offs across generations. Why across generations? Because climate change is seen as a very long-term challenge. The relationship between emissions, concentrations of greenhouse gases in the atmosphere, the radiative (or warming) effect of those concentrations, and finally the impact of the radiative effect on climate patterns are complex and develop typically over long periods of time. Emissions of greenhouse gases that drive warming are almost irreversible. Emissions at the outset of the Industrial Revolution are still with us. Substantial amounts — up to a third — of today's emissions will stay in the atmosphere for centuries. Thus even if we were to stop all emissions now, past emissions would persist in the atmosphere and would affect climate well into the next century and beyond.

There are two important implications of considering climate change as a very long-term issue. The first is that the choice of the discount rate used to make comparisons of income losses across time is critical to assess the trade-offs between the nearer-term costs of mitigation and the longer term losses from warming. Given that discounting takes place over many years, even relatively small differences in the discount rate can have a very large impact on this assessment. There is some debate on whether the estimates of income losses from mitigation and warming are reasonable[1], but the effect of the discount rates on the cost-benefit analysis of climate change typically—although not always, as argued by Arrow, 2007, for example—overwhelms the effect of differences in loss estimates.

The second implication of the long-term analysis of climate change is high uncertainty. The relevant timeframe is measured in many decades, sometimes centuries. We only need to have in mind how the world was in 1908 to realize how much can change over the course of a century. The long-term nature of climate change, coupled with the complexity of climate systems, implies that while we know that the earth is warming, we do not know how fast and how far the implications from this warming will be with certainty. Catastrophic outcomes that can change the world in fundamental ways—like a new ice age or increases in sea levels by twenty meters—while unlikely in the short run, are not impossible within a timeframe of one to two centuries. This implies, in turn, that a deterministic setting may be incomplete for analyzing climate change. Thus, it is worthwhile to explicitly consider risk and uncertainty when determining the amount of income losses and the value of the discount rate, and what this implies in terms of the rationale and timing for mitigation.

[1] Almost everybody agrees that the long-term losses from warming typically underestimate damages from climate change once natural assets that are not captured by national accounts—like the existence value for certain species or ecosystems—are factored in.

But this simplified and ultra-stylized single world analysis is grossly incomplete as a framework to analyze the challenge of climate change. The world is not composed of a single individual or a group of identical individuals. The world is not composed of a single goods or a basket of identical goods either. It is important to take into account asymmetries that exist in the world and thus the impact of climate change on income distributions.

Income distributions intersect with climate change at two levels: first, in terms of the *causes* of climate change (emissions of greenhouse gases) and second, in terms of the *effects* of climate change.

In terms of *causes* of climate change, asymmetries in contributions to the current stocks of greenhouse gases are intimately linked to differences across countries in the accumulation of global income over time. There is no direct correspondence between rich countries today and historical heavy emitters, in part because some heavily industrialized countries have fallen back economically (like the transition economies). But today's richest countries have the overwhelming responsibility for the accumulated stocks of greenhouse gases in the atmosphere. If we look at today's emissions—that is, flows rather than stocks—rich countries remain important emitters, but a few large developing countries are also starting to contribute significantly. There is a third group of countries that have not contributed much, either historically or now, and they have the lowest shares of today's world income.

Emission paths into the future will also have important income distribution implications. The losses of income that are predicted if mitigation is taken up will fall on some people more than others. For example, strong mitigation measures may hurt economies that are heavily dependent on fossil fuels. Within countries, many people that work in or are dependent on emission-intensive activities may be economically displaced. Of course, these future income distributional issues linked with emissions can be managed in principle, namely with transfers.

In terms of the *effects* of climate change, the distributional implications will be much more difficult to manage. While temperature has been increasing since the Industrial Revolution, global warming is only now starting to affect climate patterns. If we exclude extreme consequences of warming, such as the catastrophic events that are likely to leave every country and virtually every person worse off, climate change affects different regions and different groups of people differently. Some regions in the North may even benefit from warmer temperatures and increased rainfall. But the effects in tropical regions are and will be overwhelmingly negative. The poorest countries and people are suffering the most in terms of the effects of climate change, and this pattern is likely to persist in the future. If this pattern does persist, climate change will drive income divergence and deepen global inequalities.

This paper reexamines the debate on discounting considering three successive aspects, building on and complementing related efforts, such as Heal, 2008, to bring together and summarize what has been a rich and often heated debate. Section II takes the single-world perspective and describes how the Ramsey model of "consumption smoothing" determines the discount rate. As is well known, the discount rate in this simplified deterministic setting depends on preference-related parameters and the rate of growth of the global economy. Section III reviews extensions to the discussion on the discount rate to a stochastic setting, incorporating uncertainty in the model, but still under a single-world framework. Under this approach, the discount rate is not uniquely determined if we account for risk while the analysis unravels if we take a further step of incorporating structural uncertainty. Section IV discusses discounting in the economics of climate change when we go beyond a single world approach to an asymmetric world where heterogeneity in preferences, income distribution and consumption goods are taken into consideration. Section V links the review of the theoretical discussion with policy debates. Section VI presents the conclusions.

II. DISCOUNTING UNDER CERTAINTY IN A SINGLE WORLD

There is a long-running debate in economics on how to determine an appropriate social discount rate. Both ethical judgments and empirical information that assess preference parameters from observed behavior are used—sometimes in combination. Under strong assumptions and simplifications[2], it is possible to express a global social discount rate through the expression below.

$$\boxed{r = \rho + \eta . g} \qquad (1)$$

[2] These strong assumptions include: the overall objective is assumed to be to maximize a social welfare function which is expressed as the integral across all households and all time of the utility of households; the utility is additively separable across time; the only determinant of utility is consumption at each instant; there is one representative household and the utility function is unchanging over time; utility is assumed to take a constant-elasticity-of-substitution functional form.

This is the Ramsey formula for the social discount rate (r is the social discount rate and it is used to discount consumption; ρ is the pure time preference rate, and it is used to discount utility; η is the elasticity of marginal utility of consumption, measuring the relative curvature of the utility function—how quickly utility drops as consumption increases; g is the growth rate of consumption per capita).

How does discounting relate to the economic analysis of climate change? While the specific way in which discounting affects the outcomes of many of the models used in cost-benefit analysis is complex, in general high social discount rates favor a "ramp-up" approach to mitigation, while low discount rates favor more immediate large-scale action.

In the context of the single-world analysis under certainty, the issue is one of "consumption smoothing," and the debate is centered on the choices for the preference-related parameters of the discount rate: the rate of pure time preference (ρ) and the elasticity of marginal utility with respect to consumption (η). Table 1 provides a summary of choices of values by some of the leading authors, and some of the criticisms that have been weighed against these choices.

The rate of pure time preference, ρ, has several possible interpretations. From an individual's perspective, ρ measures "impatience". Since people in general prefer deriving utility today rather than tomorrow, it is usually assumed that the rate of pure time preference is positive. The higher the value of ρ, the more we discount the future.

The inter-temporal allocation seen from an individual's perspective has only limited relevance for the cost-benefit analysis of climate change. The more relevant interpretation of ρ is from an inter-generational perspective. ρ measures how we weight the utility (or welfare) of future generations compared to the utility of present generations. Thus, it is called the social discount rate and has an ethical meaning.

A positive ρ means that the utility (or welfare) of future generations are valued less or "discounted" compared to the utility of present generations. The higher the value of ρ, the more we discount future generations' welfare. A zero ρ means that the welfare of future generations is treated equally to the one of present generations. This principle of universalizability, meaning all generations should be treated alike, is proposed by some economists such as Pigou, 1932; Ramsey, 1928; Harrod, 1948; Koopmans, 1965; Solow, 1974; and Stern, 2007, to argue for a low ρ close to zero. Stern's value of 0.1% is derived from the probability of human extinction given some catastrophic event. However, other authors like Arrow, 1995; Nordhaus, 2007, argue that the implications of a close-to-zero rate of pure time preference in standard savings and investment models is inconsistent with plausible and observed savings behavior[3].

The elasticity of marginal utility of consumption η measures the percentage change in marginal utility (or marginal well-being) derived from a one percentage change in consumption. In the

[3]The classical utilitarianism, a moral foundation of neo-classical economics of climate change, attaches equal weight to changes in present and future welfare. However, Brown, 1998, criticizes the standard neo-classical approach to climate change assumes utilitarianism as unsatisfactory. He recommends replacing utilitarianism with a stewardship argument which refers to a responsibility to take care of something one does not own. Environmental stewardship is an ethic that embodies cooperative planning and management of environmental resources to avoid long term depletion of natural resources. Howarth, 2007, uses the concept of "sustainability" to argue that the present society holds a moral obligation to pass on a world of undiminished life opportunities to members of future generations. His "sustainability" argument is closely related to the stewardship ethics in Brown, 1998.

generalized conditions of the Ramsey equation, 1/ η, measures the inter-temporal elasticity of substitution while its reciprocal, η, also measures the coefficient of relative risk aversion.

The interpretation of η is difficult, since it can represent three concepts of aversion at once. First, η can be interpreted as a measure of *personal risk aversion* towards future consumption fluctuations. Second, η can be interpreted as a measure of *aversion towards inter-generational inequality*. Third, η can also be interpreted as a measure of *aversion towards intra-generational inequality* (i.e. inequality across space).

Values for the coefficient of relative risk aversion η are commonly taken to be somewhere between 1 and 4. Stern, 2007, chooses a value of 1. As Nordhaus, 2007, points out, in calibrating a growth model, the pure time preference rate ρ and the elasticity of marginal utility of consumption η cannot be chosen independently because r and g are given, so the values of ρ and η are interdependent. A low η implies a relatively high ρ, and a high η implies a relatively low ρ, if the Ramsey formula is used to calibrate using observed interest and growth rates. For example, if r is 10 percent and the growth rate g is assumed to be 3 percent, then if we choose a low value of η— let's say of 1—this implies a high value of ρ at 7 percent. If we choose a high η—let's say of 3—this implies a low value of ρ at 1 percent. However, some authors question the validity of these calibrations—and moreover note that Nordhaus, 2007, still only has one equation to determine the value of two parameters, so at least one parameter must be chosen outside the empirical calibration framework.

III. DISCOUNTING UNDER UNCERTAINTY IN A SINGLE WORLD

There are a wide range of uncertainties involved in almost every link of climate change modeling and policy analysis. These uncertainties can be categorized into two groups: one group concerns the future course of climate change, and the other group concerns the effect of available policies on actual emissions. The first group includes uncertainties on baseline emission projections, how emissions accumulate via the carbon cycle into atmospheric concentrations, how and when atmospheric concentrations translate into global mean temperature changes, how global mean temperature changes decompose into regional temperature and climate changes, among others. The lack of knowledge in the scientific understanding of climate change leads to a variety of different damage estimates. The standard damage approach has also been questioned. For example, Gerlagh and van der Zwann, 2001, argue that most of the damages caused by climate change should be evaluated as a decrease in the quality and quantity of environmental functions, which could be much higher than a reduction in the flow of (man-made) consumption goods.

The second group includes uncertainties on how adaptation and mitigation policies can affect emissions (especially at a regional level), how policy induced GHG emission reductions are translated into utility changes, how future regional utility changes are aggregated and discounted.

This section will look at how uncertainty in the path of consumption per capita g could affect the selection of discount rate in the economics of climate change. There are two issues to tackle under a framework of uncertainty. The first discusses discounting *under risk*, that is, when the parameters describing the probabilistic behavior of the growth rate of consumption per capita g are assumed to be known with certainty. The second looks at the consequences of *structural* *uncertainty* on discounting when the parameters describing the probabilistic distribution of g are, themselves, unknown.

a. Discounting Under Risk

In a framework of risk there is no single "rate of interest" in the economy, because the remuneration rate of assets depends on how risky they are.

Weitzman, 1998, and 1999, suggest that uncertainty reflected in future discount rates will result in a declining certainty-equivalent social discount rate over time and it may be essential to incorporate such a declining certainty-equivalent discount rate into any cost-benefit analysis of long-term environmental projects. According to Weitzman, 1998, interest rates under uncertainty do not aggregate arithmetically into a certainty-equivalent interest rate. Instead we should average the probabilistic discount factors, not the likely future discount rates. If there is a subjective probability p_i that the future discount rate r_i is the correct rate to use, then the effective discount rate for time t will be:

$$r(t) = -\frac{\log \sum p_i e^{-r_i t}}{t}. \qquad (2)$$

This effective discount rate declines monotonically over time from the expected interest rate $r(0) = \sum p_i r_i$ to an asymptotic limit of $r(\infty) = \min\{r_i\}$.

Table 2 uses a numerical example to show that this averaging process produces discount rates that decline with time. We assume 10 potential future discount rate scenarios, and each scenario has an equal probability: $p_1 = p_2 = \ldots = p_{10} = 0.1$. The numerical example shows that the discount rate for the current year will be 5.46 percent, but it slides fast with time. For the period 10 years from the present, the certainty-equivalent discount rate drops to 5.09 percent; for the period 50 years from the present, the certainty-equivalent discount rate lowers to 3.75 percent, and for the period 100 years from now, the discount rate declines further to 2.84 percent and then to 2.08 percent for the period 200 years from the present.

Weitzman, 1999, concludes in the limit, as t goes to infinity, the discount rate converges to the lowest possible interest rate. Our numerical example also shows that the certainty-equivalent discount rate continues dropping to 1.46 percent for the period 500 years from the present, 1.23 percent for the period 1000 years from the present, 1.12 percent for the period 2000 years from the present, and 1.05 percent for the period 5000 years from the present which is very close to the "lowest possible" interest rate (1 percent in this example).

Weitzman, 2001, argues that even if each individual's discount rate is certain and held constant over time, the certainty-equivalent social discount rate will follow a Gamma distribution and decline over time because of the wide spread differences of opinion on what interest rate to use to discount over time.

Gollier, 2004, challenges the findings of Weitzman, 2001. He shows the certainty-equivalent discount rate could increase over time when you face far distant future uncertainties and the discount rate will converge to the largest possible rate as t goes to infinity. Gollier, 2004, suggests the divergence of results is due to the two different arbitrary criteria used to rank investment projects. Gollier, 2004, ranks projects using their expected net future value while Weitzman, 2001, ranks projects according to their expected net present value.

Hepburn and Groom, 2007, demonstrate that both Gollier, 2004, and Weitzman, 2001, can be right. On the one hand, the certainty-equivalent social discount rate declines as in Weitzman, 2001, irrespective of the criteria employed in the cost-benefit analysis (whether investment projects are ranked according to their expected net present value or according to their expected net future value). On the other hand, as the evaluation date of the investment projects moves further into the future, the certainty-equivalent discount rate at a particular point in time will increase as in Gollier, 2004.

Weitzman, 2007a, goes one step further and models two distinct interest rates by making the growth rate of consumption per capita g a random variable, normally distributed with mean μ and standard deviation σ (both known with certainty). He argues that all the uncertainty is captured in the path of g. Such an uncertainty will lead to a lower social discount rate than the one derived from the simple deterministic Ramsey model.

$$g \sim N(\mu, \sigma) \qquad (3)$$

The expected marginal utility (EMU) of one additional sure unit of consumption derived from the model looks like:

$$EMU = e^{-\rho - \eta\mu + \frac{1}{2}\eta^2\sigma^2} \tag{4}$$

Therefore, the (risk-free) interest rate is given by the stochastic Ramsey formula:

$$r^f = \rho + \eta\mu - \frac{1}{2}\eta^2\sigma^2 \tag{5}$$

Thus, uncertainty will *always* bring the risk-free rate down compared with the interest rate under the deterministic Ramsey formula (if one assumes that g in the determinist setting equals the mean μ in this probabilistic setting) because of the negative term, $-\frac{1}{2}\eta^2\sigma^2$. The higher the uncertainty (measured as a higher σ), the more the risk-free interest rate comes down.

But, as noted, with uncertainty riskier assets have interest rates that differ from the risk-free interest rate. For example, the remuneration of equity (riskier) assets is:

$$r^e = \rho + \eta\mu - \frac{1}{2}\eta^2\sigma^2 + \eta\sigma^2 \tag{6}$$

Thus, equity holders require an additional remuneration for holding risky assets, captured by the term $\eta\sigma^2$, which is a measure of the equity risk premium. In comparison with the deterministic Ramsey formula, re-writing the equity interest rate as:

$$r^e = \rho + \eta\mu + \eta\left(1 - \frac{\eta}{2}\right)\sigma^2 \tag{7}$$

shows that for values of η lower than 2 the equity interest rate will always be higher than the deterministic Ramsey interest rate.

What rate, then to use? In a more general framework, the rate of return on a composite asset e^{-rt} may be calculated as the sum of the risk-free rate of return $e^{-r^f t}$ and a risk premium, $\beta(e^{-r^e t} - e^{-r^f t})$, that depends on β, which stands for the "quantity of risk" in the capital asset pricing models, measuring the correlation between the returns to the asset and the equity market returns.

$$e^{-rt} = e^{-r^f t} + \beta(e^{-r^e t} - e^{-r^f t}) \tag{8}$$

Thus, the interest rates used to discount an investment in assets with risk "in-between" the risk-free rate and the (risky) equity rate are a (log) weighted average of the risk-free and risky interest rates:

$$r(t) = -\frac{\log\left[\beta e^{-r^e t} + (1-\beta)e^{-r^f t}\right]}{t}, \tag{9}$$

If β is zero, then there is no risk so the discount rate becomes the risk-free rate r^f, and if β is one, then the asset is as risky as equity, so the discount rate becomes r^e.

The expression can be re-arranged and expressed as:

$$r(t) = r^f - \frac{\log\left\lfloor \beta\left(e^{-\eta\sigma^2 t} - 1\right) + 1 \right\rfloor}{t} \tag{10}$$

The above expression shows that the discount rate is an additive function of the risk-free interest rate and a time-variant term that depends on β, η, σ and t. Thus, there is no "unique" interest rate to use for discounting, as the deterministic model suggests.

Gollier, 2002, treats uncertainty over the growth rate of consumption per capita, g, in a different way. He expresses the discount rate as a sum of three components: the rate of pure time preference (ρ), the pure wealth effect (defined as the expected change in consumption times the absolute coefficient of risk aversion), and the prudence effect (defined as a function of the variance of change in consumption, the absolute coefficient of risk aversion and the coefficient of absolute prudence).

$$r = \rho + E(\Delta c) \cdot \left(-\frac{u''(c)}{u'(c)}\right) - \frac{1}{2} Var(\Delta c)\left(-\frac{u''(c)}{u'(c)}\right)\left(-\frac{u'''(c)}{u''(c)}\right) \tag{11}$$

The first term in the above equation of the discount rate r is the rate of pure time preference ρ; the second term is the pure wealth effect which is positive if consumption is expected to grow (i.e. $E(\Delta c) > 0$) and individuals are risk averse to consumption fluctuations over time (i.e. $-\frac{u''(c)}{u'(c)}>0$); the third term is the prudence effect which captures how uncertainty over g could affect the discount rate *r*. The third term will have an unambiguous negative impact on *r* if individuals exhibit absolute risk aversion (i.e. $-\frac{u''(c)}{u'(c)}$>0) **and** absolute prudence[4] (i.e. $-\frac{u'''(c)}{u''(c)}$>0). In Gollier's approach, the wealth effect and the prudence effect act in opposition to one another in determining the discount rate.

Both Gollier, 2002, and Weitzman, 2007a, argue for a lower discount rate due to uncertainty over consumption growth rate *g* but they provide different reasoning behind such a decline in the discount rate.

To recall, in Weitzman, 2007a, the risk-free discount rate (6):

$$r^f = \rho + \eta\mu - \frac{1}{2}\eta^2\sigma^2,$$

In Gollier, 2002, if we assume $\frac{\Delta c}{c} = g$ ~ N (μ, σ), Gollier's expression for the discount rate (11) becomes:

$$r = \rho + \eta\mu - \frac{1}{2}\sigma^2(\eta)(-\frac{u'''(c)}{u''(c)} \cdot c) \qquad (12)$$

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[4] The Kimball's coefficient of absolute prudence is defined as $-\frac{u'''(c)}{u''(c)}$, and the Arrow-Pratt coefficient of absolute risk aversion is defined as $-\frac{u''(c)}{u'(c)}$. Positive prudence is defined as $-\frac{u'''(c)}{u''(c)} > 0$.

Therefore, Weitzman, 2007a, shows that uncertainty will *always* bring the risk-free discount rate down compared with the interest rate under the deterministic Ramsey formula because the third component $-\frac{1}{2}\eta^2\sigma^2$ is unambiguously negative. But according to Gollier, 2002, decreasing absolute risk aversion[5] is a sufficient condition for uncertainty to bring down the discount rate.

Howarth, 2009, finds similar result as Weitzman, 2007a, and Gollier, 2002, that uncertainty may justify the use of low discount rates in cost-benefit analysis. But he focused on the uncertainty involved in the future benefits provided by public goods (environmental quality in the model). Howarth, 2009, agrees with Sandmo, 1972, that the discount rate for public investment under uncertainty should be based on the market rate of return on a private sector investment in an appropriately defined similar risk class. But Howarth, 2009, argues that the risk margin contained in the public sector's discount rate should correspond to a consumption risk premium only instead of an investment risk premium, and his model shows that the main part of the gap between the returns on risky and risk-free assets is explained entirely by the investment risk premium. Thus Howarth, 2009, concludes that the expected benefits of environmental policies should be discounted at a rate that is close to the risk-free rate of return, even if the public environmental policies have high degrees of risk.

[5] Decreasing absolute risk aversion will guarantee that growth uncertainty affects the discount rate negatively. Decreasing absolute risk aversion is defined as that its marginal absolute risk aversion is negative, i.e. $d(-\frac{u''(c)}{u'(c)})/dc < 0$ which implies $-\frac{u'''(c)}{u''(c)} > -\frac{u''(c)}{u'(c)} > 0$. The empirical evidence on decreasing absolute risk aversion is mixed.

b. Discounting Under Structural Uncertainty[6]

A further complication on determining the certainty-equivalent social discount rate is that if the parameters that describe the probabilistic distribution of the random variable are unknown (for example, the mean and standard deviation, μ and σ, of the consumption growth g become unknown). We can estimate μ and σ either from past observations or from a simulation. But the limited information and/or uncertainty will lead to that as if g is distributed following a t-student distribution. This type of analysis is relevant, for instance, when there is a small (non-zero) probability of a major catastrophic event. Intuitively, this means that the probability distribution of g has a fat left tail.

The implication of explicitly recognizing the uncertainty of g is that in this case, due to the fat tail of the t-student distribution, the expected marginal utility of an additional sure unit of consumption is unbounded:

$$EMU \to \infty .$$

The structural uncertainty, represented by explicitly incorporating our ignorance about the true values of the parameters in the distribution of growth rate *g,* completely overwhelms the discounting debate—regardless of whether we are under a deterministic or a stochastic setting.

[6] This section draws mainly on Weitzman, 2007a.

The interpretation is that the conventional "consumption smoothing" analysis developed using marginal reasoning is no longer meaningful. The more reasonable argument for immediate actions, according to Weitzman, 2007a, has to move towards justifications for catastrophe insurance as the rationale for making resource allocations today to "thin" the tails of the distribution of growth *g* to avoid extreme outcomes in the future.

There have been some theoretical proposals from economists to deal with such uncertainties. Gjerde et al., 1999, introduce uncertainty of whether a climate catastrophe will occur or not to the model by applying a hazard rate function. The simulation results show that even if we do not believe in climate catastrophes, a high abatement is called for due to continuous climate-feedback effects.

Chichilnisky, 2000, introduces a new decision criterion to represent how people rationalize the problem of making decisions in situations involving catastrophic risks. The criteria are composed of two terms: one term that takes into account the maximization of expected utility; a second term that represents people's desire to avoid a catastrophe. Both parts are present, and both turn out to be important in making decisions under catastrophic risks.

Weitzman, 2007b, has developed a model of asset returns (also applicable to climate change) where people form their expectations based on a Bayesian estimation from a small sample. And the best available estimate of the true probability distribution has fat tails. Because people are assumed to be risk-averse, the attempt to avoid the small possibility of infinite losses dominates policy decisions. Weitzman, 2008, argues it may be irrelevant to estimate the most likely level of climate damages; instead, what really counts is the worst-case scenario, i.e. how bad and how likely the worst extremes of the possible outcomes are. He summarizes the theorem as follows: "in principle, what might be called the catastrophe-insurance aspect of such a fat-tailed unlimited-exposure situation, which can never be fully learned away, can dominate the social-discounting aspect, the pure-risk aspect, and the consumption-smoothing aspect".

IV. DISCOUNTING IN AN ASYMMETRIC WORLD

The discussion on the determination of discounting so far has not considered the implications of asymmetries (heterogeneity) in preferences, the distribution of income, or other factors. The simpler models assume that the world could be represented by just one individual or a group of identical individuals at each point in time, consuming one goods or a basket of identical goods. But in reality, the world is not composed of a single individual or a group of identical individuals, and the impacts of climate change on different countries and communities will be very diverse. Thus, it is important to take inter-generational and intra-generational inequality into account and see how factoring in the asymmetries that exist in the world may affect the determination of global social discount rate. In reality, the world is not composed of homogeneous goods either. Environmental goods is different from other consumption goods in that some environmental goods/natural resources have finite stock and are exhaustible while other consumption goods can be produced and restocked. In this section, we will explore how the relaxation of homogeneity assumption in the simple Ramsey growth model will change the discount rate used in the economics of climate change.

a. Accounting for Inter-Generational Inequality

Inter-generational inequality raises the confusion whether a higher or a lower discount rate should be used in the economics of climate change.

On the one hand, impacts of climate change on future generations raise very firm questions of ethics. It has been argued that inter-generational inequality concerns should be incorporated into climate risk assessments by applying a lower "ethical" rate of pure time preference ρ to evaluate benefits received by future generations, so as to not trivialize these benefits relative to current costs. Pigou, 1932; Ramsey, 1928; Harrod, 1948; Koopmans, 1965; Solow, 1974; and Stern, 2007a, all argue for a low ρ close to zero.

On the other hand, the concern about inter-generational inequality will argue for a higher η and a higher discount rate r. Given positive economic growth, future generations are going to be better off (with more to consume) than present generations. A high η indicates a high degree of aversion towards inter-generational inequality. The intuition is that with a high η, and with a positive growth rate of consumption per capita, the relatively-poor present generations care more about inter-generational inequality caused by redistributing income across time from the present poor to the future rich. The higher the η, the faster marginal utility diminishes, and the consumption becomes worth more to the present poor relative to the future rich.

In other words, if the present poor are concerned about inter-generational inequality and want to avoid the income redistribution from the present poor to the future rich, a higher η should be chosen. In other words, if we are to smooth inter-generational consumption, larger values of η should be admitted. According to the Ramsey formula, a higher η leads to a higher discount rate r. The implication is that if future generations are going to be better off (with more to consume) than present generations, then our willingness to sacrifice on their behalf is certainly reduced.

But a third parameter in the Ramsey formula—the growth rate of consumption per capita *"g"*—is often omitted from discussion of inter-generational inequality issues of climate change. We argue that a different approach should be used to measure the growth rate g so as to capture how much better off future generations are going to be than present generations (in other words, how big inter-generational inequality is). This will lead to a lower discount rate used in the economics of climate change.

In the simple Ramsey growth model, g represents the reduced-form representation of "technology". In a model without technological change where growth comes only from capital accumulation with decreasing returns to capital, the steady state growth rate is zero. From the Ramsey formula, we see that a low pure time preference rate ρ and/or a low elasticity of marginal utility of consumption η do not necessarily imply a low discount rate r. The growth rate of consumption per capita g can be a reason for discounting. If future technology improvements increase the standard of living of future generations, then our willingness to sacrifice on their behalf is certainly reduced. The higher g implies that it would require a greater discount rate to justify depriving ourselves of consumption. Similarly if consumption were falling over time the discount rate would be negative. When we simulate the future global growth rate with the threat of climate change, the potential growth rate of consumption per capita g will be lower than has been suggested in the literature. Thus, it could also lead to a lower discount rate.

It is also worthwhile to note that the infinite horizon agent framework, pioneered by Ramsey, 1928, is only one way to analyze inter-temporal or inter-generational choice. One new direction in the economics of climate change is to use another type of inter-temporal framework, overlapping generation (OLG) models. Instead of assuming an infinitely-lived representative agent, OLG models assume a succession of generations to allow for easy modeling of agent heterogeneity. In each period there are young agents (born this period) and elder agents (born last period). OLG models are thus intrinsically dynamic and can derive rich economic behavior. OLG models have been widely used in the field of public finance to study the impacts of taxation and government debt on the distribution of income between generations.

As environmental policy questions often touch on inter-generational distribution, it is argued that OLG models may provide a superior framework than infinitely-lived representative agent models to characterize the behavior of decision-makers. Howarth, 1998, studies an OLG climate model and finds that the discount rate is contingent on policies that define the distribution of income between generations. Gerlagh and van der Zwaan, 2001, use an OLG model to allow for a more flexible relationship between the discounting rate and economic growth. Various factors can result in changes in the discount rate over time, such as local or global demographic changes (for example, the expected modification in life expectancy of local or global population), or a modification of the regime designed to prevent excess exploitations of the environment (for example, the possibility of establishing an environmental trust fund).

b. Accounting for Intra-Generational Inequality

Apart from *inter-generational* inequality, several extensions will capture *intra-generational* inequality (or more generally, heterogeneity) in the discounting analysis of climate change. All these extensions will argue for a lower discount rate. Among these extensions, two extensions capture heterogeneity in the rate of pure time preference ρ, while another two extensions capture modifications in the elasticity of marginal utility of consumption η. An alternative methodology to capture heterogeneity in the growth rate of consumption per capita also suggests a lower discount rate.

Heterogeneity in the rate of pure time preference ρ

Given that people have different rates of pure time preference ρ, Gollier and Zeckhauser, 2005, provide a model that captures heterogeneous time preferences and analyze the effect of such heterogeneity on the aggregate discount rate. In their model, the rate of pure time preference is heterogeneous across the population (i.e. the rate of pure time preference ρ_i is individual specific). Wealthier individuals are more patient and tend to have a lower rate of pure time preference ρ_i.

Gollier and Zeckhauser, 2005, aim to find the collective rate of pure time preference $\rho(t)$ at time t for the representative agent whose behavior duplicates the behavior of the whole population[7].

[7] It is a common practice in macroeconomics to use a representative agent to represent the whole group although aggregation of individuals' heterogeneous behavior is always a concern. In the classic case with homogeneous time

The collective rate of pure time preference $\rho(t)$ is a weighted mean of the members' individual rates of pure time preference ρ_i. Each member's weight is proportional to his/her degree of absolute risk aversion for composition fluctuations $-\frac{u_i''(c(t))}{u_i'(c(t))}$.

The collective rate of pure time preference $\rho(t)$ is:

$$\rho(t) = \frac{\sum \rho_i * (-\frac{u_i''(c(t))}{u_i'(c(t))})}{\sum (-\frac{u_i''(c(t))}{u_i'(c(t))})}. \qquad (13)$$

It is important to notice that the weights $-\frac{u_i''(c(t))}{u_i'(c(t))}$ in the above equation are a function of time t. Thus, even if the individual rate of pure time preference ρ_i is constant over time, the representative agent's rate of pure time preference is time-varying. Furthermore, this aggregation rule implies that the collective rate of pure time preference $\rho(t)$ is decreasing with respect to the time horizon when wealthier consumers are less risk averse to consumption fluctuations, a common assumption (with a smaller $-\frac{u_i''(c(t))}{u_i'(c(t))}$).

Gollier and Zeckhauser, 2005, thus conclude that the representative agent will have a declining discount rate when individuals have decreasing risk aversion preferences even though all members of a group have a constant discount rate.

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preference, the collective rate of pure time preference for the representative agent is not a function of time t. But with heterogeneous time preferences, time enters as an additional factor.

Li and Lofgren, 2000, apply the social-choice approach and look at a similar model where two different rates of pure time preference exist in the society. One is held by utilitarians, and the other held by conservationists. Utilitarians' rate of pure time preference is higher than conservationists'. Li and Lofgren, 2000, show that a declining ρ is consistent with a rule whereby current (future) generations must always take into account the well-being of future (current) generations.

Modifications to the elasticity of marginal utility of consumption η

Intra-generational inequality issues can also be captured using the elasticity of marginal utility of consumption η. For example, Dasgupta, 2007, interprets the parameter η as a measure of aversion towards consumption inequality among people. According to Dasgupta, 2007, not only inter-generational inequality matters in discounting but also does intra-generational inequality. Climate change is predicted to inflict far more damage to the tropics (the poor world) than to the temperate zone (the rich world). If present generations are concerned about intra-generational inequality, a higher η should be used. As climate change will have a disproportionate negative impact on the world's poor (whose marginal utility is high because η is implicitly large) urgent action is needed to avoid the increase in inequality between the poor and the rich. In this case, a higher η will lower the discount rate, which is not captured in the simple Ramsey model. Dasgupta, 2007, recommends increasing η to 3 to increase aversion towards intra-generational inequality.

Atkinson and Brandolini, 2006, argue that η shouldn't be a constant. Instead η should first rise as income rises, then fall. The reason is that a low or zero elasticity η indicates our interest in redistributing income below a poverty line. But we would or should not be interested in redistributing income amongst the rich.

A more straightforward way to tackle intra-generational inequalities across income groups (individuals or regions) is to write a group-specific utility function of consumption c_i at each point in time. We then add utility across groups in that generation and integrate utility over time.

Suppose c_i is consumption per capita for group i, and the group-specific discount factor λ_i can be expressed as:

$$\lambda_i = u'(c_i)e^{-\rho t} \tag{14}$$

The aggregate discount factor λ can be expressed as:

$$\lambda = \sum_{i=1}^{N} \alpha_i u'(c_i)e^{-\rho t} \tag{15}$$

where N is the number of income groups or regions and α_i describes how a unit increment in aggregate consumption is distributed across groups.

If the increment is distributed equally across groups, the aggregate discount factor λ becomes:

$$\lambda = \sum_{i=1}^{N} (1/N) u'(c_i) e^{-\rho t} \qquad (16)$$

If we look at the above equation of λ as an expected welfare function for utility taking the functional form of *u'*, we can use the Atkinson theorem[8] to analyze how an enlarging intra-generational inequality will affect the aggregate discount factor λ and then the discount rate *r*.

Atkinson, 1970, establishes a well-known theorem covering the passage from inequality to welfare. He proves that if a decision-maker is income-seeking and inequality-averse, Lorenz-dominance is a necessary and sufficient condition to detect welfare superiority in the dominating distribution, provided that the dominating distribution has the same or higher mean than that of the dominated distribution.

This result of welfare ranking of different distribution is important because it is independent of the exact functional form of the welfare function. The result only requires that the welfare/utility function increases in income/consumption and that the welfare/utility function is concave (inequality averse). In simpler words, the Atkinson theorem concludes that an enlarging unequal distribution will lower the welfare if the welfare/utility function increases in income/consumption and is concave. If the welfare/utility function decreases in

[8] The Atkinson theorem says if the following three conditions are satisfied: a) the Lorenz Curve of distribution Y dominates the Lorenz Curve of distribution X; b) the distributions have an equal mean income or the Y mean is greater than the X mean income; c) the decision-maker is income-seeking and inequality-averse (i.e. the welfare function has positive first derivative and negative second derivative with respect to individual incomes); then welfare is higher in Y than in X.

income/consumption and is convex, the Atkinson theorem concludes the opposite: an enlarging inequality will increase welfare instead.

Applying the Atkinson theorem to the above aggregate discount factor equation to compare two discount factors λ and λ^{new} with different consumption profiles c_i and c_i^{new} within a generation, we obtain:

$$\lambda = \sum_{i=1}^{N} (1/N) u'(c_i) e^{-\rho t} \tag{17}$$

$$\lambda^{new} = \sum_{i=1}^{N} (1/N) u'(c_i^{new}) e^{-\rho t} \tag{18}$$

Assume c_i^{new} is more unequal than c_i, if $u'(c_i)$ decreases in c_i and is convex[9], Atkinson's theorem will conclude that $\lambda^{new} > \lambda$ and the corresponding discount rate $r^{new} < r$. Thus an enlarging intra-generational inequality leads to a lower discount rate and justifies an urgent action to tackle global warming.

Population-weighted growth rate of consumption per capita g

In reality, the growth rate of consumption per capita g is heterogeneous across regions and countries. When calculating the global growth rate of consumption per capital, researchers usually use the conventional per capita GDP-weighted growth rate to capture heterogeneity in g

[9] $u'(c_i)$ decreases in c_i and is convex as long as the utility function $u(c_i)$ increases in c_i and is concave. All isoelastic utility functions considered in the note satisfy this condition.

across areas. The GDP-weighted growth rates are often cited due to their ready availability in all databases. This method is appropriate for monitoring regional or global GDP growth. But the GDP-weighted growth rates could be inappropriate for other purposes. For example, in the context of Africa, where South Africa and Nigeria account for 50 percent of the total regional output, the GDP-weighted growth of the African region reflects mainly the growth performances of these two countries. Therefore, some researchers prefer the "population-weighted" GDP growth rates, which they argue representative of the growth experienced by a typical African (Collier and O'Connell, 2005).

Thus, when calculating the global discount rate in climate change, instead of using the conventional GDP-weighted growth rate of consumption per capita *g*, an alternative methodology is to measure the growth rate of consumption per capita *g* using population as weights. By doing so, we probably will see a higher global growth rate of consumption per capita in recent years (mainly due to the high economic growth rates of populous China and India). On the other hand, it also implies that the future negative effect of global warming on the growth of those fast-growing populous developing economies will reduce the overall global growth rate even more if we use the methodology of "population-weighted" growth rates of consumption per capita.

c. Accounting for Relative Price Change in Environmental Goods

Most previous cost-benefit analyses model the economy producing and consuming one representative goods. Thus, while estimating damages caused by climate change, these models ignore the negative climate-related impacts on the quality and quantity of environmental goods. How will the distinction between environmental goods and all other consumption goods change the cost-benefit analyses of climate change? How will such a distinction affect the discount rate?

Intuitively, over time, as environmental goods become scarcer, the relative price of environmental goods will be higher. Sterner and Persson, 2007, argue when we conduct the cost-benefit analysis of climate change, we will not only discount the future damages; we will also re-price the future damages by incorporating the rising relative price of environmental goods. In other words, we should value future environmental damages in real future prices and then discount to today's value. The re-pricing effect will counteract the discounting effect and thus will amplify climate-related damages compared to the conventional models with only homogenous goods in the utility function.

Hoel and Sterner, 2007, show the distinction of environmental goods from other consumption goods also affects the discount rate itself. They study a two sector model (the environmental goods sector and the all-other-goods sector) with different growth rates g_e and g_c. In this two-sector model with the possible substitution between environmental goods and other consumption goods, the endogenous discount rate r becomes a function of ρ, η and the other four parameters, γ (the share of consumption expenditure on environmental goods), σ (the inter-temporal elasticity of substitution between environmental goods and other consumptions goods), g_c and g_e.

$$r(t) = \rho + [(1-\gamma(t))\eta + \gamma(t)(1/\sigma)]g_c + [\gamma(t)(\eta - 1/\sigma)]g_e \qquad (19)$$

In the above equation, $\gamma(t)$ describes the allocation of consumption expenditure on environmental goods. $\gamma(t)$ is endogenous and time-variant because two sectors grow at different rates (it is reasonable to assume $g_c > g_e$), and as time passes, environmental goods become relatively scarcer, and the relative price of environmental goods goes up. Rational utility-maximizing agents will constantly adjust their consumption bundle and substitute expensive environmental goods with relatively cheaper consumption goods. The fact that $\gamma(t)$ is endogenous and time-variant leads to that the discount rate $r(t)$ is endogenous and time-variant even though we assume constant g_c and g_e. The equation (19) could yield a lower or higher discount rate than equation (1). If we assume $g_c > g_e$, then the discount rate in this two-sector model will be lower than the one yielded from the Ramsey formula if $\eta\sigma < 1$, and higher if if $\eta\sigma > 1$. If the inter-temporal elasticity of substitution between environmental goods and other consumption goods is very low (i.e. small σ), it is possible to have a time-variant discount rate considerably lower than the conventional discount rate.

The re-pricing effect p is described as

$$p = (1/\sigma)(g_c - g_e) \tag{20}$$

The combined effect of discounting and re-pricing is thus simply

$$R(t) = r(t) - p \tag{21}$$

After taking into account the re-pricing effect, the combined effect *R(t)* will be lower than *r(t)* as long as $g_c > g_e$. The lower *R(t)* will amplify the damages estimates caused by climate change. This combined effect in some cases could be even negative.

V. Linking Theoretical Discussion to Policy Debates

a. Discounting and Climate Policy Debate

The theoretical discussion of discounting is critical to climate change policy because climate change is a very long-run issue. In a standard inter-temporal welfare smoothing problem, comparing different policies involves discounting all the future flows (of both costs and benefits) for each policy and sum them up over time to get the total present value of costs and benefits. The choice of a discount rate is critical because the flows to be discounted have a long time horizon in the case of climate change. One important variable policymakers use to decide on mitigation strategies is the social cost of carbon (SCC) which is the value of the climate change impacts from 1 tonne of carbon emitted, aggregated over time and discounted back to the present day. It can be interpreted as the marginal global damage costs of carbon emissions.

While the specific way in which discounting affects the outcomes of different climate policies is complex, in general high social discount rates result in a lower SCC estimate and favor a "ramp-up" approach to mitigation, while low discount rates result in a higher SCC estimate and favor more immediate large-scale action.

For example, low discount rates (with its preferred parameter values ρ = 0.1%, η =*1*, and g = 1.3%, Stern's discount rate is r=1.4%) used in Stern, 2007, leads to a social cost of carbon in the baseline scenario of $310 per tonne of carbon in 2005, with a strong policy implication that immediate deep cuts in emissions are justified.

The results of Stern, 2007, are all based on a single integrated assessment model, PAGE2002 developed by Hope, 2006a. However, Hope, 2006b, also using PAGE2002 but picking ρ = 1-3%, η =*1*, finds that the mean SCC emitted in 2001 is only $43 per tonne of carbon under both a business-as-usual scenario, and under a scenario aimed at stabilizing CO_2 concentrations at 550 ppm, which implies the SCC estimate is not sensitive to the path of emissions. Clearly, the SCC estimate is sensitive to a number of scientific and economic inputs to the model including the choice of the discount rate. When using ρ = 0.1% in the same PAGE model, Hope, 2006b, finds the SCC estimate goes up from $43 per tonne of carbon to $365 per tonne of carbon.

The Intergovernmental Panel on Climate Change (IPCC), 2007, notes that peer-reviewed estimates of SCC in 2005 have an average value of $43 per tonne of carbon. However, the range around this mean is large. In a survey of 100 estimates, the values ran from -$10 per tonne of carbon up to $350 per tonne of carbon.

Nordhaus, 2008, takes the DICE-2007 model and applies a different discount rate (ρ at 3% per year and declining slowly to about 1% per year in 300 years, η =*2,* and g is calibrated) and calculates the estimate of SCC is $25 per tonne of carbon in 2005, less than 10 percent of $310 per tonne of carbon as in Stern, 2007. But when he applies Stern's discount rate to the same model, the estimate of SCC shoot up. Therefore Nordhaus, 2008, argues that strong results in Stern, 2007, are caused by the extremely low discount rate used in the study, and concludes that no immediate deep emission cut policy is justified.

Mityakov, 2007, finds the low discount rates used in Stern 2007 raise the damage estimate by a factor of 8 to 16 (depending upon which baseline discount rate is used.) Weitzman, 2007, uses a "trio of twos" of ρ = 2%, η =2, and g = 2%, which gives r=6%, and calculates the present discounted value of a given climate-related damage 100 years away is only one hundredth of the present discounted value at Stern's discount rate of 1.4%. That is a difference of two orders.

b. Policy Implications of Uncertainty

Uncertainty plays a crucial role in how we approach policy interventions concerning climate change.

A first policy implication of uncertainty may be that it is important to allow for flexibility in climate policy making, including targets and strategies, whenever necessary and appropriate. Climate policies need to be sensitive and responsive to new information and progress made on further research on climate change science, economic modelling and policy analysis. As IPCC, 2007, puts it, the challenge for policymakers is not to find the best climate policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information. The implication is that in practice, when designing and implementing climate policies, it may be wise to keep many options open from both the analytical the policy perspective.

A second policy implication is to emphasize the robustness and sensitivity check in climate policy modeling analysis. In practice, it may be worthwhile to check alternative scenarios and alternative climate change models. Instead of using a single discount rate, different discount rates can be applied depending on the period of time and the path.

Third, public policy can play an important role in dealing with climate uncertainty in terms of promoting research on and awareness of climate change. Uncertainty implies opportunities for learning. Governments are probably best positioned to educate people about the urgency to stabilize the climate and to promote research on climate change science and economics through research grants and endowments. Especially, technological progress to reduce the cost of mitigation (for example, technologies to sequester carbon or reduce incoming solar radiation) could be explored and made possible with the support of public funding.

Lastly, besides direct policy measures to cut emissions, it is also important for policymakers to devote efforts to adaptation. As both adaptation and mitigation efforts are continuously re-evaluated in the light of new information and findings, adopting a composite policy involving both adaptation *and* mitigation may be more effective. Creating an environment in which economic development can take place is seemed as another form of insurance since it will enable people who are currently vulnerable to the climate change to diversify their economic activities and thereby become more robust and sustainable in the face of climate challenges.

In the case of potentially catastrophic but highly uncertain climate change, if policymakers focus on the catastrophic uncertainty involved in climate change, the policy implication is quite clear. Given structural uncertainties, the conventional "consumption smoothing" analysis developed using marginal reasoning is no longer meaningful. The combination of unknown structural uncertainty (probability distribution) and potentially catastrophic outcomes provides a motivation for precautionary policy in climate change, which implies making resource allocations today to "thin" the tails of the distribution of consumption growth rate to avoid extreme outcomes in the future. This catastrophe insurance argument is the same logic as the one motivating individuals to purchase earthquake or flood insurance.

Thus, in spite of the concern that immediate and deep carbon emissions may slow the economy down, catastrophe insurance arguments provide an alternative framework (similar to using a very low discount rate in measuring the benefits of climate change mitigation policies) for policymakers to take immediate actions today to avoid a potentially much larger, albeit uncertain, loss of income from some future catastrophic climate event[10]. The greater are uncertainties, the greater is the risk of waiting. As Quiggin, 2008, concludes that "the more uncertain we are about the outcomes, the more certain we should be about the need to take action that reduces the rate of climate change."

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[10] Summers and Zeckhauser, 2008, argue that, given the opportunity of learning, greater uncertainties about damages could increase or decrease the optimal level of current mitigation activities. They do not allow for infinitely negative outcomes. Thus, unlike Weitzman, 2007, they will accept a finite probability of a complete disaster before sacrificing nearly everything. The critical argument for lesser action is that we can wait, and then decide what to do. The critical argument for greater action is that if damages are uncertain and they turn out to be high, significant reductions will be required. Given the increasing marginal costs of reductions, if we wait until later period, this will be very costly; thus immediate action should be enhanced.

To policymakers facing such deep structural uncertainties, an alternative to the cost-benefit analysis is the cost-effectiveness analysis, as uncertainty is largely missing in the current generation of cost-benefit analysis. Tol and Yohe, 2006, summarize the economics of climate change show "irrefutably that delay cannot be a least cost approach to achieving any climate policy target. Period." Economics supports immediate action as long as climate change poses as a threat, and society is willing to make big sacrifice to eliminate such those catastrophic risks[11]. Such a case for urgent action has little to do with how big or small estimates of damages calculated in the cost-benefit analysis are.

Then, what policy target to set? Ackerman et al., 2008, suggest setting the climate policy target in terms of allowable increases in temperature and carbon emission levels. In this case, as maximum safe targets are established, discounting and uncertainty become less of a concern because under maximum safe targets, mitigation and adaptation efforts are usually required much sooner. Even though there will remain debates on intensity of immediate action and the appropriate mix of immediate action, economics can contribute to help design strategies for achieving climate stabilization (meeting maximum safe targets) in a cost-effective manner.

c. Policy Implications of Asymmetries

There are important asymmetries that policymakers need to keep in mind when making and implementing climate policies. On the one hand, asymmetries in contributions to the current stocks of greenhouse gases argue for the principle of "common but differentiated responsibility"

[11] Barro, 2006, finds the welfare cost of disaster risk is large – society would be willing to lower real GDP by about 20% each year to eliminate all disaster risk.

to tackle climate change. On the other hand, climate change affects different regions and different groups of people differently (except for catastrophic climate events that are likely to leave every country and virtually every person worse off). Near-term climate warming may be welcomed and valued positively in cold rich countries, while the climate effects in tropical regions are and will be overwhelmingly negative.

There exist asymmetric views of posterity, valuation of environmental goods and aversion to losses among individuals linked with income distribution. Thus, the urge to act, the weight given to the future, the tolerance for risk, and other factors that determine how strongly and quickly we want to start addressing climate change will probably vary depending on people's place of residence and income level.

The asymmetries studied in this paper reveal that comparing costs and benefits across time or space using a single discount rate should be considered carefully. The conventional climate change policymaking based on a single constant global discount rate ignores important asymmetries in preferences, distribution of income, regional economic growth prospects and exhaustibility of consumption goods. These asymmetries suggest to policymakers a lower discount rate, a higher estimate of SCC and make climate policies more likely to pass a cost-benefit analysis[12].

[12] Guo et al., 2006, test six declining discount rate schemes using the same integrated assessment model and find all the declining discount rate schemes (due to asymmetries) will produce an increase in the estimates of SCC but with a wide range.

Various intra-generational asymmetries discussed in the paper argue for a lower discount rate because climate change will have a disproportionate negative impact on the poor. If policymakers are concerned about intra-generational inequality, a lower discount rate should be used also to avoid enlarging income disparities. A higher aversion to intra-temporal inequality will lower the discount rate.

Policymakers concerned about inter-generational inequality probably would apply a lower “ethical” rate of pure time preference in climate risk assessments to evaluate benefits received by future generations, so as to not trivialize these benefits relative to current costs. In another case, if the consumption growth rate per capita actually would fall over time with the threat of climate change, it could lead to a lower discount rate. Especially if we project global consumption growth rates using population weights instead of GDP weights, the future negative effects of global warming on the growth of fast-growing populous developing economies will reduce the overall global growth rate even more compared to the GDP-weighted methodology. This could lead to an even lower discount rate and a stronger policy implication for immediate actions on climate change.

The OLG framework provides policymakers an alternative angle to account for the inter-generational asymmetry in their policymaking. The possibility of a more flexible relationship between the discount rate and economic growth implies various factors that may affect economic growth could also lead to a time-variant discount rate (often declining over time). Thus, incorporating those factors (local or global demographic changes or any environmental policy modifications) to climate policymaking will capture the inter-generational asymmetry.

Climate policymakers should also take into account the difference between environmental goods and other consumptions goods when evaluating different policy options. Re-pricing the future damages using the rising relative price of environmental goods could counteract the discounting effect and amplify climate damage estimates, which will thus suggest a much more urgent need for mitigation and adaptation.

VI. CONCLUSION

The paper has reexamined the debate on discounting in the context of climate change, using three main frameworks: a "single world" approach, where people within and across generations are homogeneous (in two settings—deterministic and stochastic) and an "asymmetric world" approach, where differences in income distribution, preferences among people, regional economic growth prospects and exhaustibility of consumption goods are taken into account.

In the context of a single world framework, without uncertainty, the discount rate depends essentially on two factors, which can either drive the rate upwards or downwards. The first factor relates to how much we value the welfare of future generations. If we value the welfare of future generations as much as the welfare of present generations—this component of the discount rate should essentially be very close to zero. Not everybody agrees, but the case from a human development perspective gives it a very strong support. The second factor is related to how much the welfare of people changes as their income changes. Is a one percent increase in income worth the same—proportionally—to a rich as to a poor person? If so, this implies that this second component of the discount rate is low (close to one). Together with the first factor being zero, this implies a low discount rate. If, instead, we consider that increments in income should be worth less to the rich than to the poor then this second factor should be higher and in turn, the discount rate would go up.

However, in this deterministic single world scenario, the derivation of the discount rate does not take into account uncertainty in its application to climate change. The analysis of discounting under uncertainty forces us to recognize that there is no single discount rate in the same way that there is no single "rate of interest" in the economy. Because of the huge uncertainty surrounding climate changes and the limited knowledge we currently have about such an uncertainty, the impact of uncertainty might completely overwhelm any effect the discount rates have on the economics of climate change.

The debate on discounting is extended further if instead of considering the world as a single and homogeneous place we incorporate asymmetries in preferences, income distributions, growth prospects and exhaustibility of consumption goods. These incorporations could lead to a lower discount rate. For example, if we simulate the future global population-weighted growth rate with the threat of climate change, the potential growth rate will be lower and so will be the discount rate. If we consider heterogeneity in the rate of pure time preference, various authors have shown that the discount rate will be reduced. The representative agent will have a declining discount rate when individuals have decreasing risk aversion preferences even though all members of a group have a constant discount rate. Heterogeneity in the elasticity of marginal utility of consumption also suggests a lower discount rate. Taking into account the relative price increase in environmental goods will amplify climate-related damages and could lead to a lower discount rate as well.

Reviewing a wider range of perspectives on discounting in our paper suggests the limitations of framing the policy problem as a standard inter-temporal welfare optimization problem.

There is a claim that the uncertainties surrounding climate change are so deep that they overwhelm the debate on what numerical value one should use for the discount rate. As a result, insurance arguments may provide a more relevant framework of climate change analysis, where people are willing to pay today to avoid a potentially much larger, albeit uncertain, loss of income from some future catastrophic climate event.

The issue of uncertainty has received wide attention in the literature and policy debates. Global asymmetries have been somewhat overlooked. This paper highlights the relevance of asymmetries, given that the world is not a homogeneous place. It would be important to advance our understanding of the implications of asymmetries for climate change policy, in the same way that this has been done at least to some extent when it comes to uncertainty.

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Table 1: Discounting in the context of climate change

<table>
<tr><th>Author</th><th>ρ</th><th>Criticism</th><th>η</th><th>Criticism</th></tr>
<tr><td>Nordhaus (1994)</td><td>3%</td><td>ρ of 3% is unconscionable (Delong 2006)</td><td>1</td><td rowspan="3">η is too low to yield reasonable saving rates (Dasgupta 2007)</td></tr>
<tr><td>Cline (1992)</td><td>0- stewardship argument</td><td rowspan="3">ρ is too small to yield reasonable saving rates (Arrow 1995; Weitzman 2007)
ρ and η are not independent and given η=1, ρ has to be higher to be consistent with Ramsey optimal growth model (Nordhaus 2006)
ρ also needs to be higher to match observed market data (Nordhaus 2006)
ρ is too low relative to revealed aversion to risk in insurance data (Gollier 2006)</td><td>1.5</td></tr>
<tr><td>Stern (2006)</td><td>0.1%, standard utilitarian view and hazard rate argument</td><td>1</td></tr>
<tr><td>Dasgupta (2007)</td><td>0</td><td>[2,4], inequality aversion and risk aversion argument</td><td>Dasgupta's analysis on η omits technical progress which could imply much lower saving rates. (Delong 2006; Dietz 2007)</td></tr>
</table>

Source: Own elaboration.

Table 2: Numerical example of Weitzman's declining certainty-equivalent discount rate

Table 1: Numerical example of Weitzman's declining certainty-equivalent discount rate									
Interest rate scenarios	discount factors in period t								
	1	10	50	100	200	500	1000	2000	5000
1%	0.99	0.90	0.61	0.37	0.14	0.01	0.00	0.00	0.00
2%	0.98	0.82	0.37	0.14	0.02	0.00	0.00	0.00	0.00
3%	0.97	0.74	0.22	0.05	0.00	0.00	0.00	0.00	0.00
4%	0.96	0.67	0.14	0.02	0.00	0.00	0.00	0.00	0.00
5%	0.95	0.61	0.08	0.01	0.00	0.00	0.00	0.00	0.00
6%	0.94	0.55	0.05	0.00	0.00	0.00	0.00	0.00	0.00
7%	0.93	0.50	0.03	0.00	0.00	0.00	0.00	0.00	0.00
8%	0.92	0.45	0.02	0.00	0.00	0.00	0.00	0.00	0.00
9%	0.91	0.41	0.01	0.00	0.00	0.00	0.00	0.00	0.00
10%	0.90	0.37	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Certainty-equivalent discount factor	0.95	0.60	0.15	0.06	0.02	0.00	0.00	0.00	0.00
Certainty-equivalent discount rate	5.46%	5.09%	3.75%	2.84%	2.08%	1.46%	1.23%	1.12%	1.05 %

Source: Own calculations.