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Opposite ethical views converge under the threat of catastrophic climate change - preprint

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Abstract

Climate change is seen by economists as an issue of intertemporal consumption trade-off: consume all you want today and face climate damages in the future, or sacrifice consumption today to implement costly climate policies that will bring future benefits through avoided climate damages. If one assumes enduring technological progress, a controversial conclusion ensues: to reduce intergenerational inequalities, we should postpone climate policies and let future, richer generations pay. Growing evidence however suggests that the trade-off is more complex: abrupt, extreme, irreversible changes to the climate may cause discontinuities to socio-economic systems, possibly leading to a sharp decline of human population and consumption per capita. The most relevant trade-off would then be between present consumption and the size of future generations. In this paper we show that when accounting even for a very small risk of catastrophic climate change, it is optimal to pursue stringent climate policies to postpone the catastrophe. Our results conform with the well-known conclusion that tight carbon budgets are preferred when aversion towards inequalities between generations is low. However, by contrast with previous studies, we show that stringent policies are also optimal when inequality aversion is high. This is because a higher inequality aversion makes the scenario of a small and relatively poor population (obtained when mitigation is low) especially unattractive. The size of the optimal carbon budget decreases with the social preference for large populations, but this parameter plays almost no role at extreme levels of inequality aversion. Our result demonstrates that views from opposite sides of the ethical spectrum in terms of inequality aversion converge in terms of climate

policy recommendations, warranting immediate climate action. We identify ethically-robust climate policies as new spaces of compromise between contrasted ethical stances may emerge to set the ambition of climate policies.

Keywords: Climate change; Catastrophic risk; Equity; Population; Climate-economy model

JEL Classification: D63 ; Q01 ; Q54 ; Q56 ; Q5.

1 Introduction

The risk of abrupt and irreversible changes to the climate is one of the five reasons for concern identified by the IPCC [McCarthy et al., 2001, Smith et al., 2014]. Extreme climate events, climate tipping points [Lenton et al., 2008] - such as the shutoff of the Atlantic thermohaline circulation, the collapse of the West Antarctic ice sheet or the dieback of the Amazon rainforest - may have direct impacts like a catastrophic loss of biodiversity [Trisos et al., 2020]. Climate change may more generally favour the spread of vector-borne diseases [Rocklov and Dubrow, 2020]. Extreme climate events, such as droughts, may have indirect impacts too, for instance through increased migration and conflicts [Reuveny, 2007, Hsiang et al., 2013], triggering a ‘cycle of conflict and climate disaster’, as stated by the UN security council [UN, 2018]. Without appropriate policy responses, chain reactions could very well follow, possibly leading to general warfare, which would challenge the physical, political and social infrastructures of global society and possibly lead to its near collapse. Taking catastrophes into account has been a daunting task of economics [Dowlatabadi, 1999, Tol, 2003, Azar and Lindgren, 2003]. The discipline has traditionally mainly considered climate change as an issue of intertemporal consumption trade-off [Cline, 1992, Nordhaus, 1994]. In reality, the possible cascade of tipping points may represent an existential threat to civilization [Lenton et al., 2019] and may introduce an irreversible regime shift in the sense that post-catastrophe welfare is independent from pre-catastrophe actions [Cropper, 1976, Clarke and Reed, 1994], and could be very small. The possibility that social welfare may drop to very low levels can be interpreted as a reduction of the size of human population combined with a reduction of per capita consumption. The trade-off would then be not only between present and future consumption, but between present consumption and catastrophic risk reduction [Weitzman, 2009]. This trade-off has been little studied in the literature, with the exception of [Bommier et al., 2015] and [Martin and Pindyck, 2015].

Climate policy, and catastrophic risks in particular, raise very difficult ethical questions pertaining to how policies should be evaluated [Kolstad et al., 2014]. A tool to incorporate ethical views is the use of social welfare functions that may represent distributive judgements (on how goods or consumption should be distributed among individuals) and views about the value of total population (this is the population ethics problem). The issue of evaluating policies with varying population size [Broome, 2012] has been largely ignored in the literature, with the exception of [Adler and Treich, 2015], [Scovronick et al., 2017] and [Méjean et al., 2020]. This paper contributes to fill this gap by examining the issue of population ethics when there is a risk that population size may be affected by climate change. A key parameter to represent distributive judgements is the parameter of inequality aversion (η), also named elasticity of marginal utility of consumption in the economics literature: the larger the η , the more we want to equalize the distribution of consumption among individuals (see Methods). A key parameter we introduce to represent the value of total population is the social preference for large populations (β): the larger the β , the more we are willing to pay to increase population size (see Methods). Population ethics raises several paradoxes and impossibility results so that no consensus has emerged about the value of population. There are also debates about the correct value of inequality aversion, in particular in relation to social discounting [Kolstad et al., 2014, Dasgupta, 2008]. Given such ethical disagreements, can we find policy recommendations that are ethically robust, or can we at least find limited consensus when ethical views differ?

The paper is structured as follows. Section 2 presents the framework used to evaluate climate policies. The numerical analysis presented in section 3 shows that the preferred climate policy depends on the relative impact of ethical parameters on welfare. Section 4 concludes.

2 Methods

This paper builds on [Méjean et al., 2020], which examines the terms of the trade-off between present consumption and the existence of future generations when there is a risk of extinction due to climate change. Here, we extend that work by providing an extensive numerical analysis of the influence of ethical parameters on the optimal climate policy when accounting for the risk of catastrophic climate change. We evaluate the social welfare associated with 250 climate policies, corresponding to 250 carbon budgets. We follow two steps. Policies are first

specified in terms of a savings rate, which is set at a constant value, 25.8%, for all scenarios [Golosov et al., 2014]. This is consistent with the observed world average gross savings rate [The World Bank, 2017, Dennig et al., 2015]. Policies are also specified in terms of carbon budgets, spanning 400-5800 GtCO₂ from 2015 to 2250 across scenarios. The 400 GtCO₂ budget is consistent with the objective of limiting warming to 1.5°C, while the 5800 GtCO₂ budget corresponds to warming above 6°C. We define the climate change related catastrophe in very simple economic terms as a drop in human population size (90% compared to the case without catastrophic climate change in the central scenario) combined with a drop in consumption per capita (after the catastrophe, consumption per capita is assumed to be constant, and is set at 1000 USD per capita per year in the central scenario). Each policy is first translated into a social outcome x using a climate-economy model linking the risk of catastrophe (or hazard rate) to temperature change. Social outcomes are defined in terms of consumption per capita c and hazard rate p over time. The catastrophe is defined as a drop in terms of human population size and consumption per capita. We assume that the catastrophic risk depends linearly on temperature, and on temperature only. We introduce parameter b as the marginal hazard rate (per annum per °C), which is the additional risk of a catastrophe occurring due to an increase in temperature of 1°C above a given temperature threshold (see below). Due to the catastrophic risk, the cumulative population over the whole horizon is unknown ex-ante. The generation size stream n depends on the policy, although it is common to all social outcomes before the catastrophe occurs. Generation t is of size n_t and enjoys consumption per capita c_t . Consumption is assumed to be equally distributed among individuals of the same generation. The cumulative size of the human population depends on the policy, as the generation size drops at date H . Date H depends on temperature via the hazard rate. After the catastrophe, generation size is \hat{n} (constant), and consumption per capita is \hat{c} (constant). Social outcomes, i.e., the streams of consumption and catastrophic risk over time, are then translated into social welfare using a social welfare function [Kolstad et al., 2014]. This function embodies ethical views in terms of inequality aversion and social preference for large populations. The chosen function treats all generations in a symmetric way, giving no *a priori* preference to the present [Ramsey, 1928, Stern, 2007]. Policies are then ranked according to social welfare. Below, we introduce in turn the social welfare function, the climate-economy model, the catastrophic risk, and its calibration.

2.1 Social welfare function

First consider sure social outcomes (i.e., without risk) with a bounded time horizon H (meaning that extinction occurs then for sure). We follow most of the existing literature and write welfare W as a generalized utilitarian form, which can be written as the product of average utility and a population weight N_H^β .

$$W_H = N_H^\beta \sum_{t=0}^H \frac{n_t}{N_H} \left[\frac{c_t^{1-\eta}}{1-\eta} - \frac{c^{1-\eta}}{1-\eta} \right] \quad (1)$$

where $N_H = \sum_{t=0}^H n_t$ is the total (cumulated) population that comes into existence in a given social outcome, and $\frac{c_t^{1-\eta}}{1-\eta} - \frac{c^{1-\eta}}{1-\eta}$ is the utility enjoyed by an individual of generation t . There is no pure time discounting, i.e., we treat generations in a symmetric way. The social welfare function embodies the preferences of a social planner through two ethical parameters.

Parameter η is the intergenerational inequality aversion coefficient. It determines the marginal utility of individual consumption. A more inequality averse social welfare function means that the social planner is willing to sacrifice more to equalize consumption levels across generations. Indeed, increasing consumption by \$1 brings a social value of $c^{-\eta}$. A person with consumption $2c$ has a relative priority for consumption increase of $2^{-\eta}$ compared to a person with consumption c . Or equivalently, taking \$1 from the person with consumption $2c$ while giving only $\$2^{-\eta}$ to the person with consumption c would leave social welfare unchanged. This means that the larger the η , the larger the loss we accept when making transfers to equalize income across individuals. This is the so-called leaky-bucket experiment [Okun, 2015]. We test a wide range for this parameter, from 1 to 4, similar to the range of inequality aversion values reviewed in the latest IPCC assessment report [Kolstad et al., 2014].

Parameter β is the social preference for large populations. For a population with equal consumption, a crucial parameter is the elasticity of substitution between population and consumption, that is how much average consumption must increase to compensate for a drop in population size. The larger the β , the more we are willing to sacrifice in terms of consumption to increase population size. The social welfare function embeds well-known views of utilitarianism when population size varies. Total (or classical) utilitarianism values the total sum of utilities ($\beta = 1$). Average utilitarianism values average utility ($\beta = 0$). We vary β between 0 and 1, spanning

cases between total and average utilitarian views.

The social welfare function also includes a consumption per capita threshold, \underline{c} . In the case of total utilitarianism ($\beta = 1$), it is the critical level of consumption, i.e., the level of consumption such that, if enjoyed by an additional individual, total welfare is left unchanged when that individual is added to the population. When $\beta < 1$ however, the critical level is not constant and depends on population size and average utility. Here, the consumption per capita threshold is calibrated on an extreme poverty consumption level (1000 USD per capita per year).

Now consider a risky social prospect. At each time step, three possible events may occur (conditional on humanity not being extinct and on the world not having switched to a catastrophic state): (i) humanity goes extinct, with probability p_{ex} , which is unrelated to climate change ; (ii) the catastrophe occurs and there is a switch to an exogenous path of consumption per capita and population (\hat{c}, \hat{n}) , with probability $p_c(t)$ (the hazard rate at date t); (iii) the world continues as before, with probability $1 - (p_{ex} + p_c)$. The probability of not becoming extinct and not having switched to a catastrophic state at the beginning of period H is: $P_{\geq H} = \prod_{t=0}^{H-1} (1 - (p_{ex} + p_c))$. After the catastrophe, the world exists for τ additional periods with probability $p_{ex} \cdot (1 - p_{ex})^{\tau-1}$.

For each time horizon H , we write the contribution to expected total welfare of the event that humanity may go extinct, $W_{ex,H}$, and the contribution to expected total welfare of the event that the catastrophe may occur, $W_{c,H}$. Expected total welfare, W , is then written as the sum of those for all possible time horizons:

$$W_{ex,H} = P_{\geq H} \cdot p_{ex} \cdot N_H^{\beta-1} \sum_{t=0}^H n_t \cdot u(c_t) \quad (2)$$

$$W_{c,H} = P_{\geq H} \cdot p_c(H) \sum_{\tau=1}^{\infty} p_{ex} (1 - p_{ex})^{\tau-1} \left[(N_H + \tau \hat{n})^{\beta-1} \left[\sum_{t=0}^H n_t \cdot u(c_t) + \tau \hat{n} \cdot u(\hat{c}) \right] \right] \quad (3)$$

$$W = \sum_{H=0}^{\infty} [W_{ex,H} + W_{c,H}] \quad (4)$$

The above welfare function is used to evaluate the social outcomes computed by the climate-economy model.

2.2 Climate-economy model

The climate economy model RESPONSE [Ambrosi et al., 2003, Dumas et al., 2012, Pottier et al., 2015] belongs to the tradition of cost-benefit analysis integrated assessment models [Nordhaus, 1994, Hope et al., 1993, Tol, 1997], combining a simple representation of the economy and a climate module. The economic module is a Solow-like growth model with capital accumulation and exogenous population. It includes climate mitigation costs and a climate damage function that is chosen to be equivalent to that of the DICE model. The main equations of the economic module are presented in the appendix (section A). The climate module describes the evolution of global temperature increase and radiative forcing as a function of emissions. The temperature increase feeds back on the economy through the damage function. We model the climate catastrophe as an abrupt event that occurs over the course of a decade. This is a harsh simplification, as the processes involved would be gradual, with feedbacks between institutions, consumption, mortality and fertility, and would probably take decades to unfold. We consider that after the catastrophe occurs, the course of events is inevitably set and cannot be acted upon [Cropper, 1976, Clarke and Reed, 1994]. Whether such a catastrophic chain of events would actually lead to a sharp decline of human population size and consumption per capita is controversial and may be considered as highly unlikely. Given the large uncertainty surrounding the probability of such events, we attempt at covering a wide range of possible values for that parameter (as described below).

2.3 Catastrophic risk

We assume that the hazard rate p_t at date t depends on the temperature increase T only, and not on wealth or adaptive capacity. We therefore disregard any factor, social or natural, that may mitigate the effect of climate change on the risk of a catastrophe occurring. More precisely, we model the hazard rate $p_c(t)$ as a linear function of temperature increase T , above a temperature threshold T_0 . The hazard rate at date t , $p_c(t)$, is truly $p_c(T)$, a function of temperature increase T at date t . We assume that this function is valid in a range of temperature increase spanning from 1 °C to 10 °C, which includes the values of temperature increase presented in the analysis. Given the very nature of the risk considered, there is no available data about its realization from which the parameters of the hazard rate function could be inferred. The calibration can thus only be illustrative and tentative. The calibration does not rely on the frequentist approach to

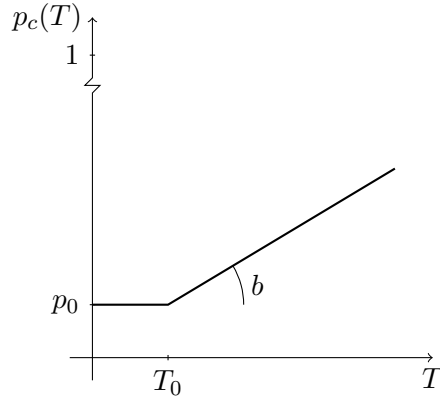


Figure 1: Catastrophic risk (hazard rate p_c) as a function of temperature increase T . $p_c(T)$ is the hazard rate as a function of temperature increase T , p_0 is the minimum hazard rate, set at 10^{-3} per annum, T is the temperature increase compared to pre-industrial levels ($^{\circ}\text{C}$), T_0 is the temperature increase above which the hazard rate starts and rising with temperature, set at 1°C , b is the marginal hazard rate per $^{\circ}\text{C}$ above T_0 .

probability but on the Bayesian or subjective approach, where the probability reflects informed though subjective beliefs about the links between events. The first step is to calibrate the exogenous risk of extinction p_{ex} , which is unrelated to climate change. We build on the Stern Review [Stern, 2007] which treats generations in a symmetric way, yet uses a non-zero time discount rate, set at 10^{-3} per annum to account for the possible extinction of humanity. We follow the argument and set p_{ex} at 10^{-3} per annum. Although the calibration of the marginal hazard rate (b) is impossible due to the inherent lack of data, we attempt at providing a range by considering values that cannot be reasonably excluded, building on the evidence provided in the literature. To get a sense of the orders of magnitude at stake, we refer to estimates of the probability of triggering tipping point events from the literature [Lontzek et al., 2015]. Based on these estimates, we find that $b = 10^{-3}$ per annum per $^{\circ}\text{C}$ approximately corresponds to triggering one tipping point event. We thus choose 10^{-3} per annum per $^{\circ}\text{C}$ as the maximum value of b . We also find that $b = 10^{-5}$ and $b = 10^{-7}$ per annum per $^{\circ}\text{C}$ correspond to triggering two and three tipping point events in the same year, respectively. We choose 10^{-7} per annum per $^{\circ}\text{C}$ as the minimum value of b . Another way to think about the minimum value for b is to consider that the risk that an increase of temperature of 1°C above T_0 would cause a drop in population size and consumption per capita would be at the minimum a few orders of magnitude below p_{ex} (set at 10^{-3} per annum). With $b = 10^{-7}$ per annum per $^{\circ}\text{C}$, the probability that there is no climate change related catastrophe after a hundred years at a sustained temperature increase of 10°C becomes 0.90471, instead of 0.90479 for $b = 0$. This shows that in this case, b would have little impact on the hazard rate. This minimum value is therefore appropriately

small. To sum up, we test values for b from 10^{-7} to 10^{-3} per annum per $^{\circ}\text{C}$ and assume $T_0 = 1^{\circ}\text{C}$. In addition to these values, we test the case where there is no risk of catastrophic climate change ($b = 0$).

2.4 Parameter ranges

The numerical analysis presented below will explore the following parameter ranges.

<i>parameter</i>	<i>description</i>	<i>range</i>
X	CO ₂ budget	[400 , 5800] GtCO ₂
η	inequality aversion parameter	[1.0 , 4.0]
β	population parameter	[0 , 1]
b	marginal hazard rate	[0 , 10^{-3}] per annum per $^{\circ}\text{C}$
\hat{n}	post-catastrophe population	[0 , 10] billion
\hat{c}	post-catastrophe per capita consumption	[500 , 1000] USD per year

Table 1: Parameter ranges

3 The role of inequality aversion and the preference for large populations

In this section we present the numerical analysis on how the preferred climate policy depends on the relative impact of ethical parameters on welfare. We compare the cases with and without accounting for a risk of catastrophic climate change, and explore wide parameter ranges, as summarised in Table 1. Each figure shows the preferred carbon budget (i.e., the carbon budget that gives the highest welfare in the range of carbon budgets considered) for each pair of ethical parameters (η, β) .

3.1 The case without a risk of catastrophe

When the risk of catastrophe related to climate change is not accounted for (marginal hazard rate $b = 0$), large carbon budgets are optimal if the social planner is averse to inequalities

across generations (high η). This is a standard result in the economics literature¹: as future generations are assumed to be richer thanks to technological progress, a high aversion towards inequalities across generations means postponing climate policy (i.e., choosing larger carbon budgets) to spare the present, poorer generation [Dasgupta, 2008]. This is illustrated in Figure 2, where carbon budgets leading to warming of at least 3°C are preferred for an inequality aversion $\eta \geq 1.7$ (darker colors represent cases where a larger carbon budget results in higher welfare, and is thus the preferred option).

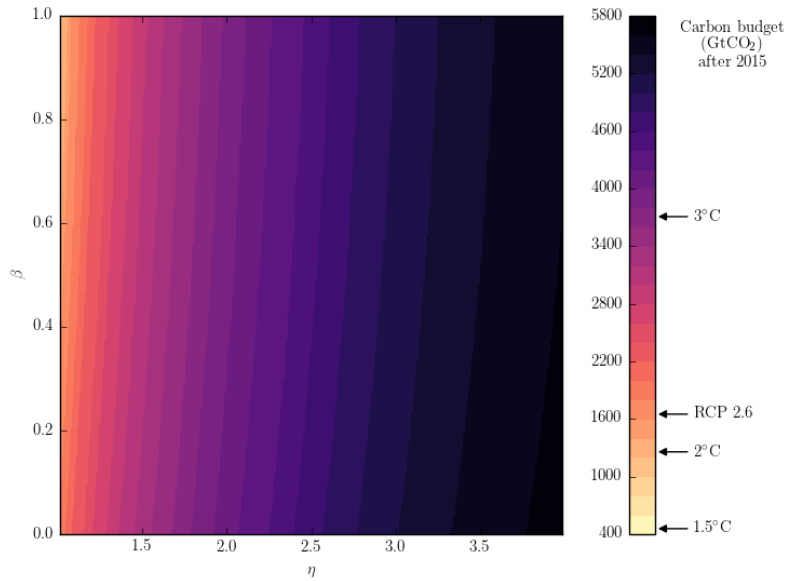


Figure 2: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for an exogenous hazard rate ($b = 0$)

3.2 Accounting for the risk of catastrophic climate change

This result changes dramatically when accounting for a risk of catastrophe which depends on temperature increase. In the central scenario presented in Figure 3, the post-catastrophe per capita consumption (\hat{c}) is set at 1000 USD per year, and the post-catastrophe population (\hat{n}) is set at 1 billion individuals. In that case, even with a very small risk (e.g., $b = 10^{-7}$ per annum per °C), it is optimal to achieve tighter carbon budgets than in the case without catastrophic risk. This result holds for all combinations of inequality aversion (η) and preference for large populations (β), although to various degrees. For instance in the case ($\eta = 2.5, \beta = 0.5$), with

¹However, this relies on analysis that ignores intragenerational inequalities and the fact that the most vulnerable populations will be severely hit by climate change. The role of inequality aversion is substantially altered when this is taken into account [Budolfson et al., 2017]

a very small catastrophic risk ($b = 10^{-7}$ per annum per $^{\circ}\text{C}$), the optimal carbon budget is 40% lower than in the case without risk (from 4600 GtCO₂ without risk, to 2800 GtCO₂ with risk). With a stronger preference for large populations (larger β), it is optimal to implement a tighter carbon budget. This is shown on Figure 3, where for a given inequality aversion (say $\eta = 3$), increasing β from 0 to 1 (i.e., giving a stronger preference to large populations by switching from the average utilitarian to the total utilitarian case) reduces the optimal carbon budget by almost 70% from 5000 GtCO₂ (corresponding to a stabilization above 3 $^{\circ}\text{C}$) to less than 1600 GtCO₂, thus bringing the temperature increase close to the 2 $^{\circ}\text{C}$ objective. This result is intuitive, as a tighter carbon budget delays the catastrophe due to climate change, which leads to a larger cumulative number of individuals across generations.

The impact of inequality aversion (η) on the optimal carbon budget is very different than in the case without catastrophic risk. When accounting for a risk of catastrophe due to climate change, the standard result that high inequality aversion leads to postponing climate policy to spare the present, poorer generation does not hold. Instead, the results show that when accounting for an endogenous risk of climate catastrophe, both cases of high and low inequality aversion command tight carbon budgets (Figure 3). This is because with a low inequality aversion, the benefit of preserving a large and on average richer population makes mitigation attractive, whereas a high inequality aversion makes the scenario of a short-lived and relatively poor population particularly unattractive. For instance, with a strong preference for large populations ($\beta = 1$), both low inequality aversion ($\eta < 1.5$) and high inequality aversion ($\eta > 3$) command carbon budgets which may limit global warming to 2 $^{\circ}\text{C}$ (Figure 3).

3.3 Influence of the level of risk

This pattern remains as we consider higher risks of catastrophe due to climate change (from 10^{-7} to 10^{-5} per annum per $^{\circ}\text{C}$). However, in those cases, tight carbon budgets are optimal for a wider range of ethical views: the results show a larger number of combinations of inequality aversion (η) and preference for large populations (β) for which tight carbon budgets are warranted (Figure 4). For even higher risks of catastrophic climate change (b set at 10^{-4} and 10^{-3} per annum per $^{\circ}\text{C}$), the most stringent carbon budget (400 GtCO₂) is optimal for all social preferences on population size and inequality aversion across generations. Such a carbon budget is compatible with limiting global warming to 1.5 $^{\circ}\text{C}$ above the pre-industrial level.

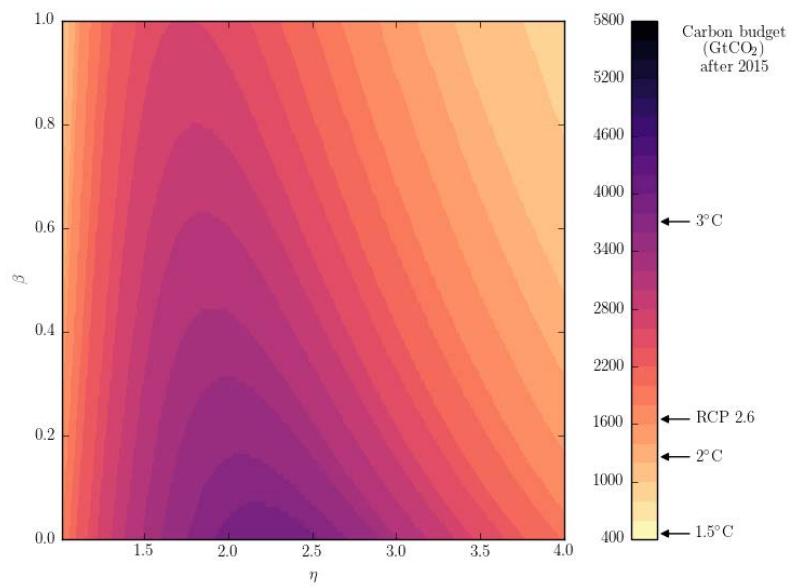
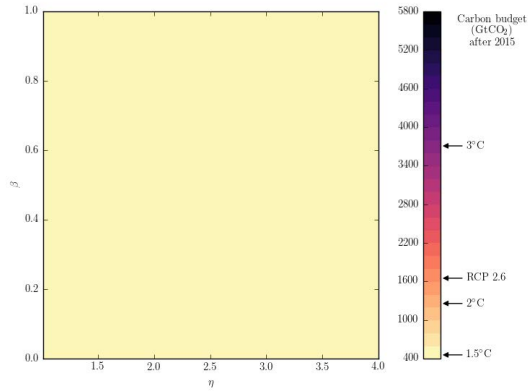
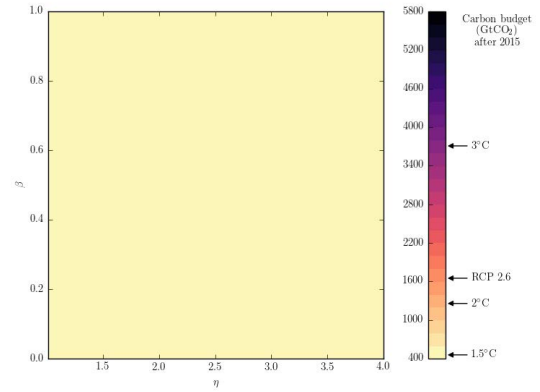


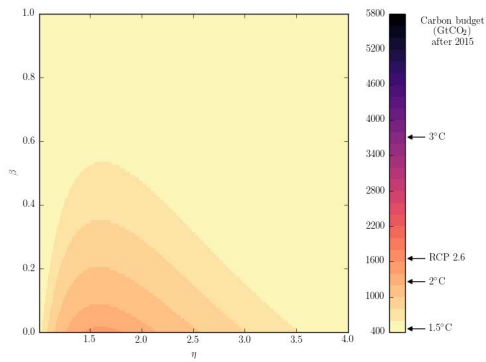
Figure 3: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for a hazard rate that depends on temperature ($b = 10^{-7}$ per annum per °C, $\hat{c} = 1000$ USD per capita, $\hat{n} = 1$ billion)



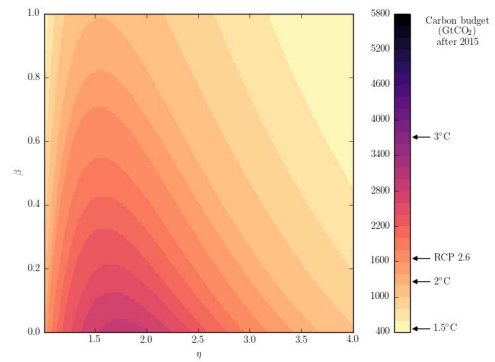
(a) $b = 10^{-3}$ per annum per °C



(b) $b = 10^{-4}$ per annum per °C



(c) $b = 10^{-5}$ per annum per °C



(d) $b = 10^{-6}$ per annum per °C

Figure 4: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for a range of values of the marginal hazard rate (b), with ($\hat{c} = 1000$ USD per capita, $\hat{n} = 1$ billion)

3.4 The case of extinction

Allowing for the possibility of extinction (i.e., assuming $\hat{n} = 0$) does not qualitatively change the influence of the ethical parameters on the preferred policy, as the shape of the results remains the same (Figure 5). In particular, the case of total utilitarianism ($\beta = 1$) gives strictly identical results in the case of extinction compared to the case of a drop in population size and consumption per capita (labelled ‘existential catastrophe’ in the figure). This is due to the fact that in the central case presented here, post-catastrophe consumption (\hat{c}) is set to be equal to the threshold per capita consumption (\underline{c}). Therefore $u(\hat{c}) = 0$, which means that adding or removing individuals who consume \hat{c} does not change aggregate welfare in the case of total utilitarianism. The result is different for lower values of β . In the case of average utilitarianism ($\beta = 0$), it appears that the possibility of extinction leads to prefer larger carbon budgets, compared with the case of a catastrophe causing a drop in population size and consumption per capita (darker points on the $\beta = 0$ line on Figure 5). In other words, assuming that more people survive the catastrophe warrants more ambitious climate policies in the case of average utilitarianism. This is due to the fact that the catastrophe leads to a world with many future poor. As $\hat{c} = \underline{c}$, the consumption of the surviving individuals is too low to contribute to aggregate welfare, while the fact that they are many (1 billion) reduces average welfare. Therefore, for low values of β , a low level of post-catastrophe consumption is more threatening than extinction from a welfare point of view, and warrants more abatement for a given set of ethical parameters (η, β).

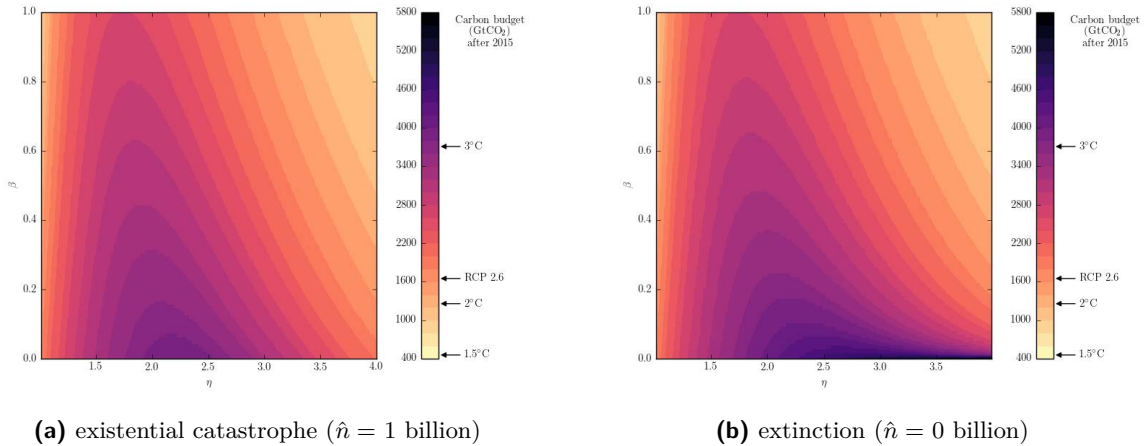


Figure 5: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) in the case of extinction ($\hat{n} = 0$) vs. the case of a drop in consumption and population size (central case: $b = 10^{-7}$ per °C per annum, $\hat{c} = 1000$ USD per capita, $\hat{n} = 1$ billion)

3.5 The influence of post-catastrophe consumption and population size

A lower or higher level of post-catastrophe consumption does not qualitatively change the influence of the social preference for large populations and of inequality aversion on the optimal climate policy (Figure 6). For a given set of ethical parameters (η , β), the optimal carbon budget is smaller for a lower consumption level after the catastrophe (\hat{c}), which conforms with intuition. This is also the case for total utilitarianism: adding individuals with a level of consumption below \underline{c} reduces aggregate welfare, hence the preference for more stringent climate policies to postpone the catastrophe. Conversely, the optimal carbon budget is larger for a higher consumption level after the catastrophe ($\hat{c} > \underline{c}$).

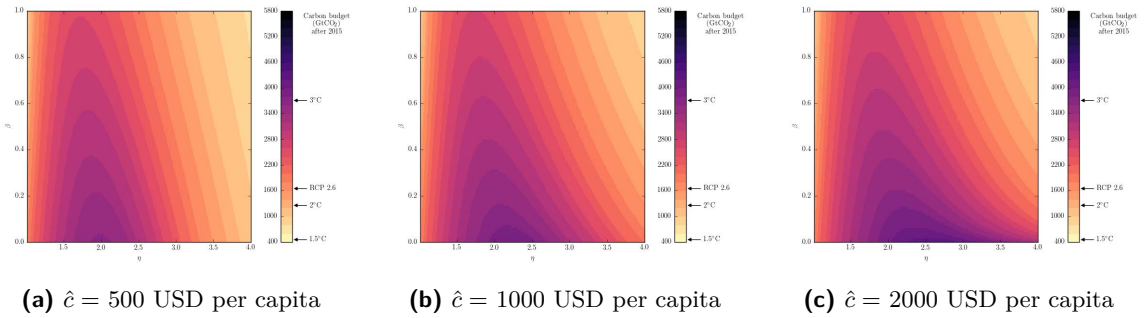


Figure 6: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for $b = 10^{-7}$ per annum per $^{\circ}\text{C}$ and $\hat{n} = 1$ billion individuals, in the central case ($\hat{c} = 1000$ USD per capita) vs. a case with lower post-catastrophe consumption ($\hat{c} = 500$ USD per capita) vs. a case with higher post-catastrophe consumption ($\hat{c} = 2000$ USD per capita)

As in the central case shown on Figure 4, for a given pair (η , β), the optimal climate policy is more stringent as the catastrophic risk increases (Figure 7 shows the case $\hat{c} = 500$ USD per capita). The same qualitative result is obtained in the case $\hat{c} = 2000$ USD per capita.

Finally, maintaining population size at the level reached before the catastrophe (i.e., 10 billion individuals) also gives similar qualitative results (Figures 8 and 9). A larger post-catastrophe population size warrants more stringent climate policy for a given (η , β), for the opposite reasons as in the case of extinction (section 3.4).

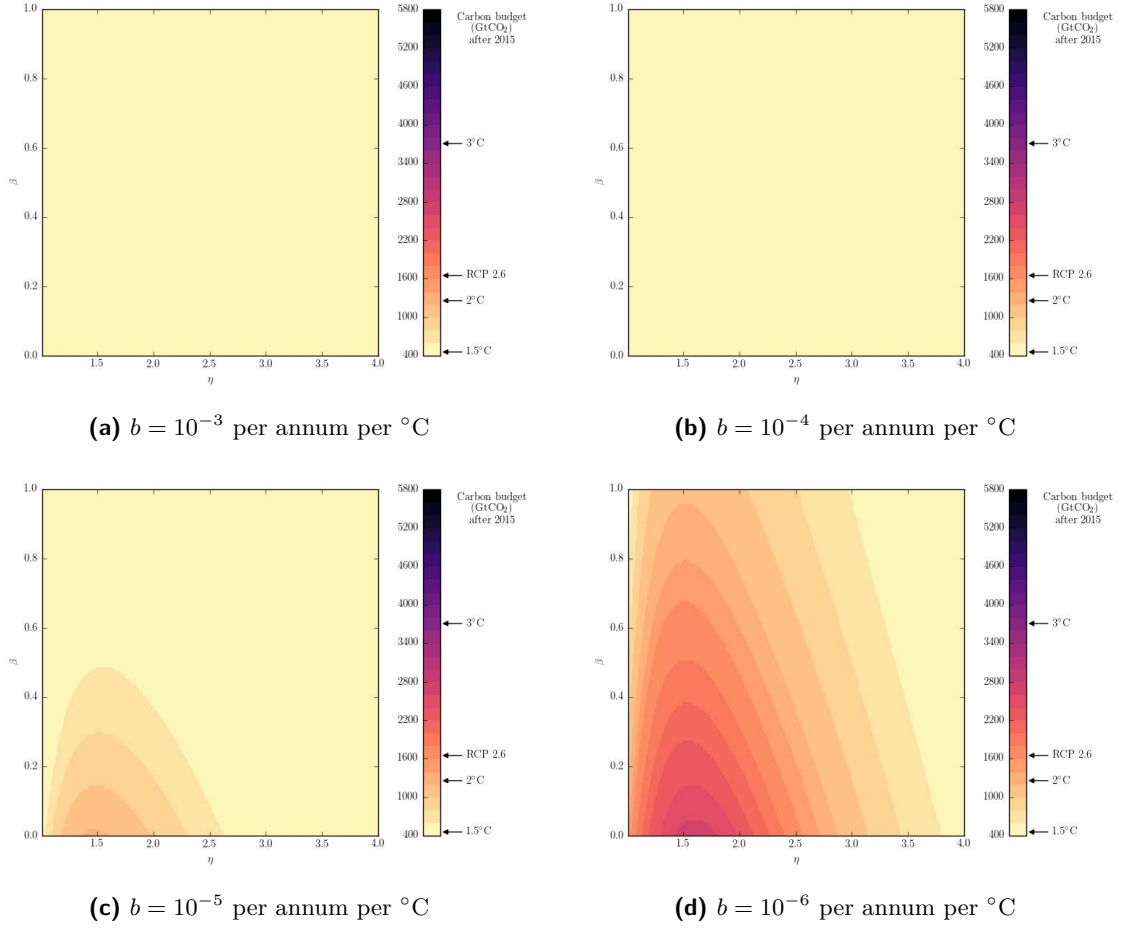


Figure 7: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for a range of values of the marginal hazard rate (b), $\hat{c} = 500$ USD per capita, $\hat{n} = 1$ billion individuals

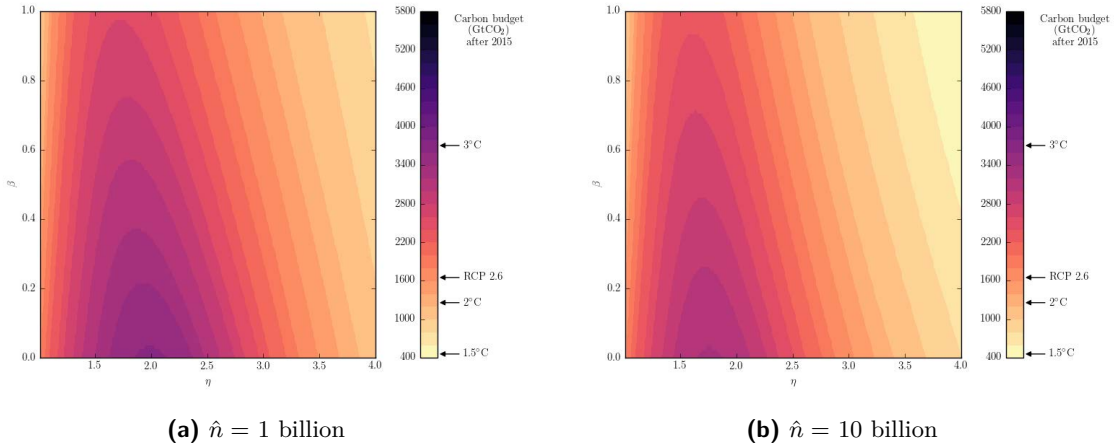


Figure 8: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for $b = 10^{-7}$ per annum per °C and $\hat{c} = 500$ USD per capita, in the central case ($\hat{n} = 1$ billion) vs. a case with higher post-catastrophe population ($\hat{n} = 10$ billion)

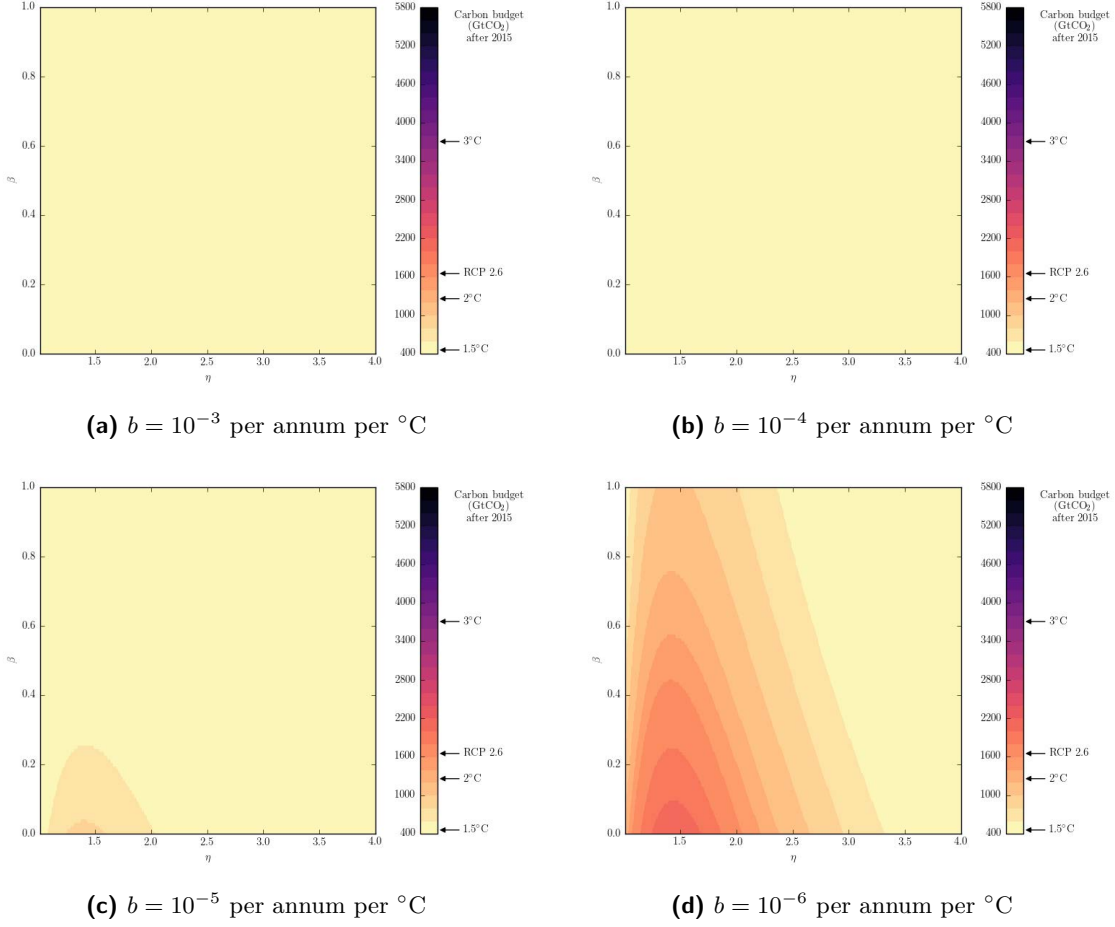


Figure 9: Optimal climate budget as a function of the social preference for large populations (β) and the inequality aversion coefficient (η) for a range of values of the marginal hazard rate (b), $\hat{c} = 500$ USD per capita, $\hat{n} = 10$ billion individuals

4 Conclusion

In this paper, we show that the possibility that climate change may induce a sharp decline in human population size and per capita consumption, as unlikely as it may be, changes the terms of the trade-off to solve the climate puzzle. A catastrophic risk as small as 10^{-7} per annum per °C above 1°C commands much tighter carbon budgets than in the case where that risk is not accounted for. The size of the optimal carbon budget decreases with the social preference for large populations, but this parameter plays almost no role at extreme levels of inequality aversion. Further, the results show an unexpected ethical consensus on the ambition of climate change: when accounting for an endogenous risk of climate catastrophe, both cases of high and low inequality aversion command tight carbon budgets. With a low inequality aversion, the benefit of preserving a large and on average richer population makes mitigation attractive,

while with a high inequality aversion, the scenario of a short-lived and relatively poor population particularly unattractive. We also show that a catastrophic risk of 10^{-4} per annum per $^{\circ}\text{C}$ above 1°C commands strong, immediate action to limit global temperature increase to 1.5°C for the whole range of ethical values considered. This result is robust to the level of post-catastrophe consumption per capita and population size explored in the sensitivity analysis. Accounting for the risk of catastrophe due to climate change reveals new spaces of compromise between opposing ethical stances to set the ambition of climate policies. Coalitions could therefore arise between opposite sides of the ethical spectrum in terms of inequality aversion.

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A Economic equations of the RESPONSE model

The main equation of economic module of the climate-economy model RESPONSE [Dumas et al., 2012] are presented below.

Production function

The economy produces a unique good Y_t from capital K_t and labour L_t . The production function is a traditional Cobb-Douglas. Population L_t is an exogenous variable (before the catastrophe or extinction occurs). Total factor productivity A_t is exogenous.

$$Y_t = A_t \cdot K_t^\alpha \cdot L_t^{1-\alpha} \quad (\text{A-1})$$

Emissions

Emissions E_t are endogenous. They are a by-product of production. Their level depends on output Y_t , on the carbon intensity of production σ_t , and on abatement a_t . The carbon intensity of production is expected to decline over time through exogenous technical change.

$$E_t = \sigma_t \cdot (1 - a_t) \cdot Y_t \quad (\text{A-2})$$

The climate module is described through a three reservoirs linear carbon-cycle model, similar to that used in the DICE model.

Non-catastrophic damages

Damages D depend on the atmospheric temperature increase T_t . Damages are expressed as a share of output Y_t . Damages are assumed to be a quadratic function of temperature change.

$$D(T_t) = \kappa \cdot T_t^2 \quad (\text{A-3})$$

Abatement costs

Abatement costs C_a depend on the abatement level at t a_t , and possibly on past abatement a_{t-1} , if inertia is accounted for. Abatement costs are expressed as a share of output Y_t . Note that abatement a_t is expressed as a fraction of emissions.

$$C_a(a_t, a_{t-1}) = PT_t \cdot \left(a_t \cdot \zeta + (BK - \zeta) \cdot \frac{a_t^\nu}{\nu} + \xi^2 \cdot (a_t - a_{t-1})^2 \right) \quad (\text{A-4})$$

Capital accumulation

We consider a continuum of identical households, who derive instantaneous utility from consumption of a composite good. C_t is the aggregate consumption, and capital K_t evolves endogenously according to the following equation:

$$K_{t+1} = (1 - \delta) \cdot K_t + Y_t \cdot [1 - C_a(a_t, a_{t-1}) - D(T_t)] - C_t \quad (\text{A-5})$$

The main variables and parameters of the model are summarised in table A.

<i>name</i>	<i>description</i>
t	time
A_t	exogenous productivity factor
C_t	aggregate consumption
α	share of capital in revenues
δ	depreciation rate of capital
D	damages (share of output Y_t)
C_a	abatement costs (share of output Y_t)
T_t	atmospheric temperature increase
PT_t	exogenous technical progress (abatement technologies)
BK	backstop price
ζ	marginal cost of abatement when abatement is null
$\frac{a_t^\nu}{\nu}$	absolute level of abatement
ξ	inertia parameter
κ	damage parameter
ν	power coefficient of the abatement cost function

Table A: Selected variables and parameters