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Climate Policy under Fat-Tailed Risk: An Application of *FUND*

David Anthoff[a] and Richard S.J. Tol[a,b,c]

Abstract: We apply four alternative decision criteria, two old ones and two new, to the question of the appropriate level of greenhouse gas emission reduction. In all cases, we consider a uniform carbon tax that is applied to all emissions from all sectors and all countries; and that increases over time with the discount rate. For a one per cent pure rate of the time preference and a rate of risk aversion of one, the tax that maximises expected net present welfare equals \$120/tC in 2010. However, we also find evidence that the uncertainty about welfare may well have fat tails so that the expectation exists only by virtue of the finite number of runs in our Monte Carlo analysis. This confirms Weitzman's Dismal Theorem. We therefore consider minimax regret as a decision criterion. As regret is defined on the positive real line, we in fact consider large percentiles instead of the ill-defined maximum. Depending on the percentile used, the recommended tax lies between \$100 and \$170/tC. Regret is a measure of the slope of the welfare function, while we are in fact concerned about the level of welfare. We therefore minimise the tail risk, defined as the expected welfare below a percentile of the probability density function without climate policy. Depending of the percentile used, the recommended tax lies between \$20 and \$330/tC. We also minimise the fatness of the tails, as measured by the p-value of the test of the hypothesis that recursive mean welfare is stationary in the number of Monte Carlo runs. We cannot reject the null hypothesis of non-stationary at the 5% confidence level, but come closest for an initial tax of \$50/tC. All four alternative decision criteria rapidly improve as modest taxes are introduced, but gradually deteriorate if the tax is too high. That implies that the appropriate tax is an interior solution. In stark contrast to some of the interpretations of the Dismal Theorem, we find that fat tails by no means justify arbitrarily large carbon taxes.

Key words: Climate change; integrated assessment; decision making under uncertainty; deep uncertainty; fat-tailed risk; dismal theorem

Corresponding Author: richard.tol@esri.ie

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[a] Economic and Social Research Institute, Dublin, Ireland
[b] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
[c] Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

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1. Introduction

Weitzman's Dismal Theorem (Weitzman 2009) challenged the quantitative economic analysis of climate policy: The uncertainty about the impacts of climate change would be so large that expected utility maximisation is either undefined or arbitrary. Unfortunately, Weitzman's is an impossibility theorem: It shows what cannot be done. It does not provide an alternative criterion that can be used to make decisions about climate change policy or indeed policy in any area that is characterised by fat-tailed risks. This paper attempts to fill this gap and suggest ways to use quantitative economic analysis to support climate change policy decisions.

(Weitzman 2009) was not the first economist to question the applicability of cost-benefit analysis (in the broad sense of the word) to climate change, but his paper is the most sophisticated. (van den Bergh 2004), for instance, qualitatively reiterates a number of objections to welfare maximisation as a guide to policy on a problem as uncertain, diffuse, and complex as climate change. (Nordhaus 2009) argues that Weitzman's result exposes the limitations of a constant relative risk aversion (CRRA) utility function (Geweke 2001) rather than the limitations of cost-benefit analysis of greenhouse gas emission reduction. (Tol 2003), on the other hand, cannot exclude the possibility of impacts so disastrous that they overwhelm the assumptions and approximations typically made in applied research on climate change. (Yohe 2003) argues that policy may overcome this. Particularly, Tol's disaster is a climate-change-induced collapse of a regional economy, which may be prevented by development policy and international transfers of money. (Tol and Yohe 2007) offer qualified support for this position.

Naively interpreted, the Dismal Theorem calls for an arbitrarily high carbon tax (Weitzman 2009). (Hennlock 2009), on the other hand, argues that fossil fuels are a necessary good, at least in the short run, and under such an interpretation immediate draconian climate policy would have disastrous implications for economic activity, including food production (Tol and Yohe 2006). The cure (immediate drastic emission reductions) may be worse than the disease (the impacts from climate change). It follows that the carbon tax should not be set at an arbitrarily high level because an extremely high carbon tax would itself be a disaster. Climate policy analysis should therefore strike a balance between two potential catastrophes.

(Raiffa 1968) argues that minimax regret is an appropriate alternative decision criterion if expected utility is undefined. (Froyn 2005;Loulou and Kanudia 1999) are the only ones to apply the minimax regret decision criterion to greenhouse gas emission abatement policies.[1] We follow their lead, but pay particular attention to the concepts of "worst case" and "maximum regret". This is not a trivial problem because outcomes are defined on the real line, while the number of numerical realisations from a model is necessarily bounded.

This paper is structured as follows. Section 2 discusses three alternative decision criteria for decision making with fat tails, and decision support using a numerical model. In Section 3, we present the numerical model used here. We use the model to illustrate the fat tails in Section 4. Section 5 shows the results of the decision analysis. Section 6 concludes.

2. Decision making with fat tails

Savage's minimax regret (Savage 1951) is the standard approach to decision making with fat tails (Raiffa, H. 68). It can be applied by using the following steps. First, think of the set of all possible policies to address the problem in question. In the case of climate change, each element of the policy set could be a specific carbon tax schedule. Second, for each state of the world find the policy that maximises welfare for that specific state of the world. Welfare here is defined as the conventional measure of net present value of population weighted average per capita consumption. Third, compare how each policy from the policy set compares to the welfare maximising policy in each state of the world in terms of welfare. The difference in welfare between the welfare maximising policy and the policy under consideration is called the regret from a specific policy for a specific state of the world. By definition, regret is positive; and there is at least one policy with zero regret. For each policy, one then finds the state of the world where the regret for this policy is highest. This is the maximum regret for a specific policy. The final decision rule states that one should pick the policy that has the lowest maximum regret.

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[1] Note that (Hof et al. 2010) do a cost-benefit analysis under worst-case assumptions, incorrectly referring to this as minimax regret.

In applied numerical analysis a number of issues arise. First, the policy set might consist of a continuum of policy choices. A carbon tax, for example, is a real number. Computational constraints put limits on how many specific policies, i.e. carbon taxes, one can analyse. In practise this problem is easily solved by approximating this with carbon taxes that increase in small discrete steps.

The second problem is that "maximum regret" is not properly defined in a numerical analysis. Strictly speaking, in a Monte Carlo analysis with N runs, the observed maximum regret is the regret at the $(1\text{-}1/N)^{\text{th}}$ percentile. Therefore, we replace "mini*max* regret" with "mini*percentile* regret" in practice, minimising the α^{th} percentile of regret. We do this for a range of αs. Confidence in estimates of large percentiles is low (Boos 1984;Weissman 1978), so we steer clear of the largest percentiles.

The third issue concerns the core of the decision criterion itself. The switch from welfare maximisation to regret minimisation is not innocuous. The regret decision criterion normalizes welfare of particular policy choices by "doing the best we can, given the circumstances". The difference between the welfare optimum in any particular state of the world and welfare for any other non-optimal policy in the same state of the world is less sensitive to parameter variations than the absolute welfare level itself. Regret is a measure of the slope of the welfare function along variations in policy. However, the minimax regret rule does not guarantee that welfare is above some acceptable absolute level. To paraphrase Churchill, sometimes it is not enough to do your best; you should do what it takes.

Let us consider two examples. In the first, welfare is CRRA in consumption and consumption may approach zero. In the second example, there is a floor to either welfare – as in (Weitzman 2009) – or consumption – e.g., through charity as in (Tol and Yohe 2007). In a disastrous state of the world, in the first example, welfare is large and negative while regret is large and positive. In the second example, welfare is large and negative but regret is small. Yet, the small progress made by policy in the disastrous scenario may be more important that the larger progress possible in less extreme scenarios.

Therefore, we propose two alternative decision rules. The first is straightforward. We are worried about the fat left tail of welfare. We should therefore minimise the risk in that tail. We define the tail as everything below the α^{th} percentile; and tail risk as

$$R_{\alpha_0} = \int_{-\infty}^{\alpha_0} W_t f(W_t) \mathrm{d}W_t \tag{1}$$

where R is the tail risk, α_0 is the cut-off point for what constitutes the tail of the welfare probability density function for the no policy scenario (t=0), W_t is net present welfare for a particular carbon tax profile t, and $f(W)$ is the probability density function of welfare. We do this for a range of cut-off points (α<0.5). Note that the tail risk coincides with expected welfare for α=1. As we only consider the left tail, we seek to minimise tail risk.

The third decision rule goes to the root of the problem. If fat tails are the problem, then one should choose policy such that the tail is thin or least-fat. This requires a definition of a fat tail. If the tail is fat, the mean would not converge to a constant value as the sample size increases, but vary instead. A probability density function is said to be stationary if it is constant over time, that is, if its moments converge. One typically tests for stationarity of the first moment (mean) only. Here, we are not interested in changes over time, but rather in changes over the sample size. We refer to this as Monte Carlo stationarity. We use the Augmented Dickey-Fuller test for stationarity, swapping time and sample size. That is, we estimate

$$\Delta\bar{W}_n = \delta\bar{W}_n + \gamma_1\Delta\bar{W}_{n-1} + \gamma_2\Delta\bar{W}_{n-2} + \ldots + \gamma_p\Delta\bar{W}_{n-p} + \varepsilon_t \tag{2a}$$

with

$$\bar{W}_n = \sum_{i=1}^{n} W ; \Delta\bar{W}_n = \bar{W}_n - \Delta\bar{W}_{n-1} \tag{2b}$$

where W_n is net present welfare in Monte Carlo run n. We test the hypothesis δ=0. We minimise the p-value of the ADF test, that is, reject the null hypothesis of non-stationarity as strongly as we can.

3. The model

We use the integrated assessment model *FUND* to assess climate policy under fat-tailed risk using the two proposed decision criteria. We compare the results to those for the “standard” minipercentile regret as well as to maximum expected utility. In many ways, *FUND* is a standard integrated assessment model (Guo et al. 2006;Tol 1997;Tol 1999;Tol 2006). It has simple representations of the demography, economy, energy, emissions, and emission reduction policies for 16 regions. It has simple representations of the cycles of greenhouse gases, radiative forcing, climate, and sea level rise. In other ways, though, *FUND* is unique. It is alone in the detail of its representation of the impacts of climate change. Impacts on agriculture, forestry, water use, energy use, the coastal zone, hurricanes, ecosystems, and health are all modelled separately—both in "physical" units and their monetary value (Tol 2002a;Tol 2002b). Moreover, *FUND* allows vulnerability to climate change impacts to be an explicit function of the level and rate of regional development (Tol 2005;Tol et al. 2007).

This paper uses version 3.6 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 3.6 of *FUND* corresponds to version 1.6 (Tol et al. 1999;Tol 2001;Tol 2002c) except for the impact module described in (Link and Tol 2004;Narita et al. 2009a;Narita et al. 2010;Tol 2002a;Tol 2002b) and carbon cycle feedbacks taken from (Tol 2009). A full list of papers, the source code, and the technical documentation for the model can be found online at http://www.fund-model.org/.

The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 3000 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs.[2] The centuries after the 21st are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2300.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of

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[2] The period of 1950–2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The scenario for the period 2010–2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). The 2000–2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100–3000 extrapolated.

the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and storms. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by a five-box model (Hammitt et al. 1992;Maier-Reimer and Hasselmann 1987), extended with a dynamic biosphere (Tol 2009): If it gets sufficiently warm, terrestrial vegetations, currently a sink of carbon dioxide, turns into a source of emissions. The model also contains sulphur emissions (Tol 2006).

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is as in the IPCC (Ramaswamy et al. 2001). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperatures follow from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of

500 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996).

The climate impact module (Tol 2002a;Tol 2002b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, unmanaged ecosystems, and tropical and extra tropical storms. The last two are new additions (Narita et al. 2008;Narita et al. 2009b). Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b).

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (Cline 1992). The value of emigration is set to be 3 times the per capita income (Tol 1995), the value of immigration is 40 per cent of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (Tol 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

Welfare of a particular state of the world is defined as the sum over time of population weighted utility of world average per capita consumption, discounted at a pure rate of time preference of 1% per year. Utility is defined as the natural logarithm of per capita consumption. In both choices we follow the standard utilitarian assumption commonly used in economic analysis of climate change policy.

All parameters in the model (almost 900) are uncertain and assume a probability density function. These PDFs are occasionally derived from meta-analyses of published estimates, but more often based on “expert guesses”. The PDFs are assumed to be independent of one another. However, in those cases where there is a known relationship between parameters, we model that relationship and assume a PDF for the hyperparameters. For instance, the climate sensitivity and the rate of energy dissipation in the ocean are related and jointly constrained by the observed warming. Instead of assuming a correlation between the parameters, we have that the rate of energy dissipation is an uncertain function of the climate sensitivity (itself an uncertain parameter) and the observed warming.

Unlike *DICE* (Nordhaus 2008) and *PAGE* (Hope 2008), *FUND* does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realisations are catastrophic. The fat tails found in the Monte Carlo analyses in *FUND* are a result, rather than an assumption.

4. Fat tails in a numerical model

We run the model 10,000 times[3] in a Monte Carlo analysis. Figure 1 shows the probability density function (PDF) of the net present welfare, assuming a 1% pure rate of time preference and a rate of risk aversion of unity. The PDF is clearly not a Normal distribution. There is a plateau in the middle, with two tails. The left hand tail, which contains the bad outcomes, drops linearly at first and then turns to become fat – at least graphically.

Figure 1 also shows that the PDF is very noisy. The 10,000 realisations were put in 400 bins. One would expect a relatively smooth curve, particularly in the middle of the distribution. Instead, Figure 1 shows that there is little confidence in the estimates of the number of realisations per bin.

This is confirmed by Figure 3. Figure 3 shows the estimate of the expected value of the net present welfare for the first 1000 realisations in the Monte Carlo analysis, the first 1001 realisations, the first 1002 realisations, and so on. The recursive mean drifts up and down, even with 9,000 or more realisations. The augmented Dickey-Fuller test reveals the same. The hypothesis $\delta=0$ in Equation (2) has a p-value of 0.104 – that is, there is a 10.4% probability of obtaining the realisations of the recursive mean welfare if the underlying process is non-stationary. Normally, this means non-rejection of the null hypothesis, so that we have to work with the assumption that the mean is Monte Carlo non-stationary. Hence, the left tail is fat. *FUND* displays the behaviour predicted by Weitzman.

Figure 1 further shows the PDF of net present welfare for two policy scenarios. In the first scenario, a carbon tax of $50/tC is levied on all greenhouse gases in all regions in 2010. After 2010, the carbon tax increases with the interest rate. This continues until the radiative forcing is stabilised, after which the carbon tax falls with

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[3] Recall that the law of large numbers is independent of the dimensionality or complexity of the data generating process.

one-tenth of the interest rate.[4] In the second policy scenario, the initial carbon tax is \$500/tC. Figure 2 shows the difference in the PDFs.

An initial carbon tax of \$50/tC, rising with the interest rate until radiative forcing is stabilized, would shift the PDF of net present welfare to the right. This is most clearly seen in Figure 2: the chance of low welfare decreases, and the chance of high welfare increases. Figure 1 reveals that the worrisomely fat left tail is largely cut off.

Raising the initial carbon tax to \$500/tC does not have a clear impact in Figure 1. Figure 2, however, shows that a high carbon tax thins the right tail: There is a smaller chance of large welfare. The carbon tax is sufficiently high to prevent rapid economic growth. A high initial carbon tax also thickens the left tail. While a modest carbon tax reduces the probability of low welfare as climate change and its impacts are less pronounced, a high carbon tax increases the probability of low welfare as the costs of emission reduction escalate and substantially slow down economic growth. Even though *FUND* corroborates the Dismal Theorem, it does not advocate an arbitrarily high carbon tax. Put differently, these results reveal that there is dangerous climate change as well as dangerous climate policy.

Figure 3 shows the recursive mean welfare as a function of the sample size for the two policy scenarios. The mean does not converge at a constant, but is considerably less volatile. For an initial carbon tax of \$50/tC, the *p*-value of the ADF test is 0.062 – lower than without climate policy, but the null hypothesis of non-stationarity is rejected at the 10% level only. For an initial carbon tax of \$500/tC, the *p*-value is 0.075. A high tax increases the non-stationarity of the recursive mean, and thus the fatness of the tail. This again shows that a very high carbon tax makes matters worse rather than better.

These results are indicative and illustrative. The next section puts these tentative findings on a firmer footing.

5. Robust taxes for greenhouse gas emissions

We repeated the Monte Carlo analysis, with 10,000 runs, for initial carbon taxes between \$0/tC and \$500/tC, in steps of \$10/tC. This took 84 hours on an i7 2.67GHz processor with 4 GB RAM. The Monte Carlo analysis formed the outer loop, and the

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[4] The rate of the decline of the carbon tax was set by trail and error; the chosen rate ensures that greenhouse gas concentrations do not increase.

carbon taxes formed the parallelised inner loop so that the parameter realisations across the policy scenarios were identical.

Figure 4 shows expected welfare as a function of the initial carbon tax.[5] Expected welfare rapidly rises with modest carbon taxes, but it turns and gently slopes down if carbon taxes are too high. The expected welfare maximising, initial carbon tax is $120/tC. The shape of the objective function shown in Figure 4 makes clear that adopting a tax that is too stringent is less costly than adopting a tax that is too lenient.

Figure 4 also shows selected percentiles of the PDF of regret.[6] The same pattern emerges as for the mean. A modest carbon tax sharply cuts regret, but very high carbon taxes cause slightly more regret. The minimedian regret tax is $100/tC. The minipercentile (75) regret tax is also $100/tC. This increases to $140/tC for the 90th percentile; and to $170/tC for the 95th, 99th and 99.5th. For the 99.9th percentile, the minipercentile regret tax falls to $100/tC. Figure 4 reveals that the confidence in estimate of the 99.9%ile (the hundredth-smallest realisation) is not great. For each percentile, we find evidence that very high carbon taxes thicken the left tail. Comparing the taxes across the percentiles suggests that choosing a higher percentile does not necessarily imply a higher carbon, which again underlines the risks of a climate policy that is overly stringent. That said, the asymmetry of the objective functions suggests that it is better to err on the conservative side.

Figure 5 shows the tail risk as a function of the initial carbon tax. As in Figure 4, we show the 50th, 75th, 90th, 95th, 99th, 99.5th and 99.9th percentile. As above, the decision criterion improves rapidly in value for modest taxes, and deteriorates gently if the tax is greater than the recommended one. The risk in the "whole tail" – that is, everything below the median of the no policy distribution – is minimum for an initial carbon tax of $150/tC. The minimum tail risk tax is lower for a narrower definition of the tail: $110/tC for the 75th and 90th percentile. This is because the costs of emission reduction shift the welfare distribution to the right. The minimum tail risk tax increases again, to $120/tC, if the tail is confined to the 95th percentile. If we consider

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[5] Note that we numerically derive the entire objective function instead of finding its optimum through successive approximations of the objective function; we do this for the four alternative decision criteria considered in this paper.

[6] Recall that the definition of regret requires that the optimum tax be found for each state of the world, that is 10,000 times in our case. We saved the value of the objective function for each state of the world and each tax. This is possible as we defined policy such that it can be characterised by a single number (the initial tax) and as discretised that initial tax.

only the tip of the tail (99%ile), the tax is much higher: $330/tC. However, the very tip of the tail behaves differently again. The risk above the 99.5%ile is essentially flat for a tax greater than $100/tC. The risk above the 99.9%ile is zero (in our numerical analysis) for an initial tax of $20/tC or greater.

The minimum tail risk decision criterion, while intuitive – "chop off the worrisome tail" – does not provide clear guidance because the definition of the tail is ambiguous, but more importantly because climate policy would redistribute risks within the tail.

Figure 6 displays the *p*-value for the test for non-stationarity of the recursive mean of net present value as a function of the initial carbon tax. As above, a modest tax rapidly thins the tail but the tail slowly grows thicker again as the tax gets too high. The *p*-value is minimum for an initial tax of $110/tC. However, the *p*-value is still 0.064, which indicates that we cannot reject the hypothesis that the recursive mean is Monte Carlo non-stationary. However, it is as close we can get to a thin tail.

6. Discussion and conclusion

In this paper, we seek to find the policy implications of Weitzman's Dismal Theorem. Superficially, the Dismal Theorem calls for a climate policy that is arbitrarily stringent, or a carbon tax that is arbitrarily high. We show that this interpretation is incorrect. The risks of climate change fall rapidly as climate policy gets more stringent; but the risks of climate policy increase slowly too and eventually overtake the risks of inaction.

A more careful interpretation of the Dismal Theorem is that expected welfare maximisation is not applicable to a problem like climate change. If it were, our model would recommend a carbon tax on all greenhouse gas emissions from all sectors and all countries of $120/tC in 2010, and rising with the interest rate thereafter.

Minimax regret is the standard decision criterion under deep uncertainty. In this case, regret is defined on the non-negative real line; and the maximum is undefined. We therefore minimise selective percentiles of the regret distribution. For all percentiles considered, the minipercentile regret tax lies strictly between $100/tC and $170/tC – that is, the carbon tax can be too high as well as too low. The tax initially increases as more extreme percentiles are considered, but appears to bend back for the highest percentiles.

Minimax regret and minipercentile regret taxes are the best one can do given the circumstances. However, sometimes one needs to do what it takes. We therefore introduce two alternative decision criteria. The first is to minimise the risk in the tail of the distribution of welfare without policy. Intuitively, we chop off the worrisome tail. We again find interior solutions only (between \$20 and \$330/tC), rejecting the notion of an arbitrarily high tax. However, this criterion does not provide clear guidance as the definition of the "tail" is arbitrary and climate policy not only thins the tail but redistributes probability mass within the tail as well.

Fat-tailed distributions have moments that vary with the sample size in a Monte Carlo analysis. We therefore introduce a new decision criterion – the tax that maximises the probability of rejecting the null hypothesis of Monte Carlo non-stationarity of the recursive mean. Once more, there is an interior solution, and a unique one at that: \$50/tC. Moderate carbon taxes thin the tails, but overly stringent climate policy thickens the tails again. We find that while there is a tax that minimises the thickness of the tail, there is no tax that rejected the hypothesis of a thick tail with 95% confidence.

In sum, our numerical experiments corroborate the Dismal Theorem, showing that the left tail of the welfare distribution is thick with and without climate policy. Furthermore, we provide guidance on the appropriate level of a carbon tax, argue against the notion the appropriate level of the carbon tax is arbitrary, and strongly reject the notion that the carbon tax should be arbitrarily high. We find that there is dangerous climate change as well as dangerous climate policy; and that the appropriate carbon tax is bounded from below as well as from above. Our model suggests a range of \$20-330/tC.

The results come with a number of caveats. The policy implications should be treated as indicative only until the analysis here is replicated with additional scenarios, with alternative specifications of the welfare function and its parameters, and with other models. The analysis should also be repeated with additional policy instruments, particularly income transfers (which may be used to prevent economic collapse) and geoengineering (which may be used to prevent climate change). Furthermore, we disregard learning. All these matters are deferred to future research.

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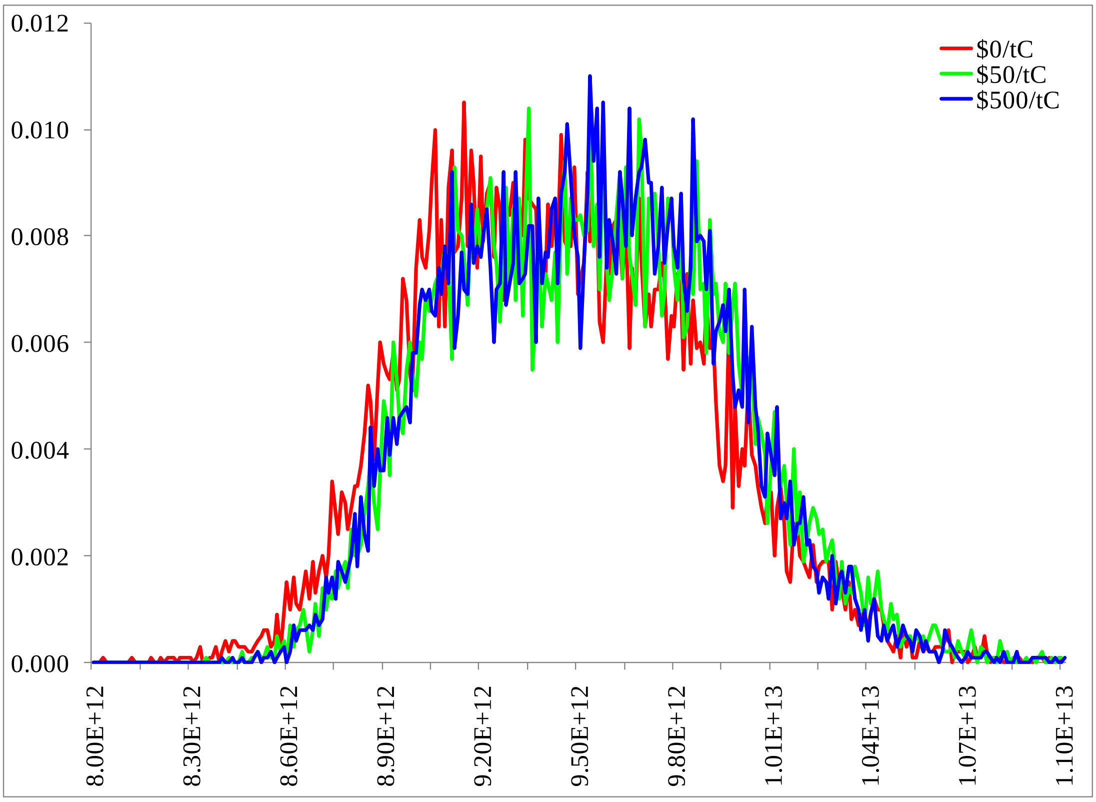

Figure 1. The probability density function of the net present value of global welfare for the case without climate policy, and with an initial carbon tax of $50/tC and $500/tC.

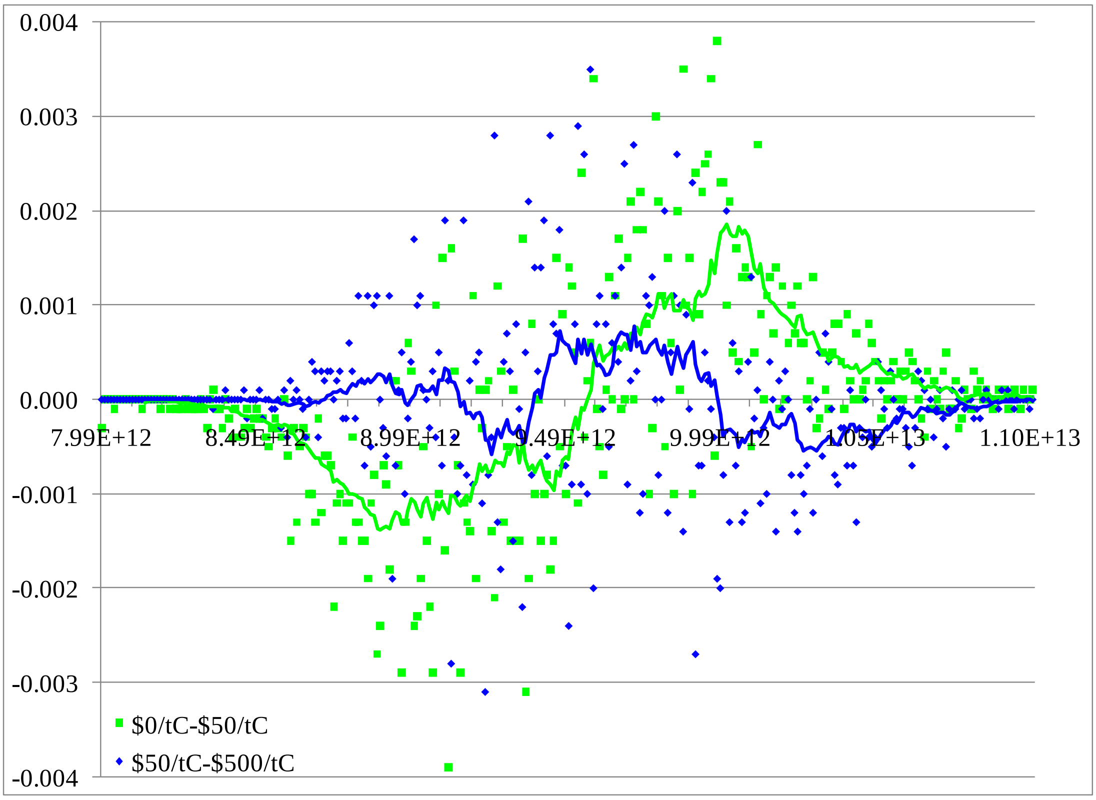

Figure 2. The difference in the probability density function between no climate policy and an initial carbon tax of $50/tC, and between a $50/tC and a $500/tC carbon tax.

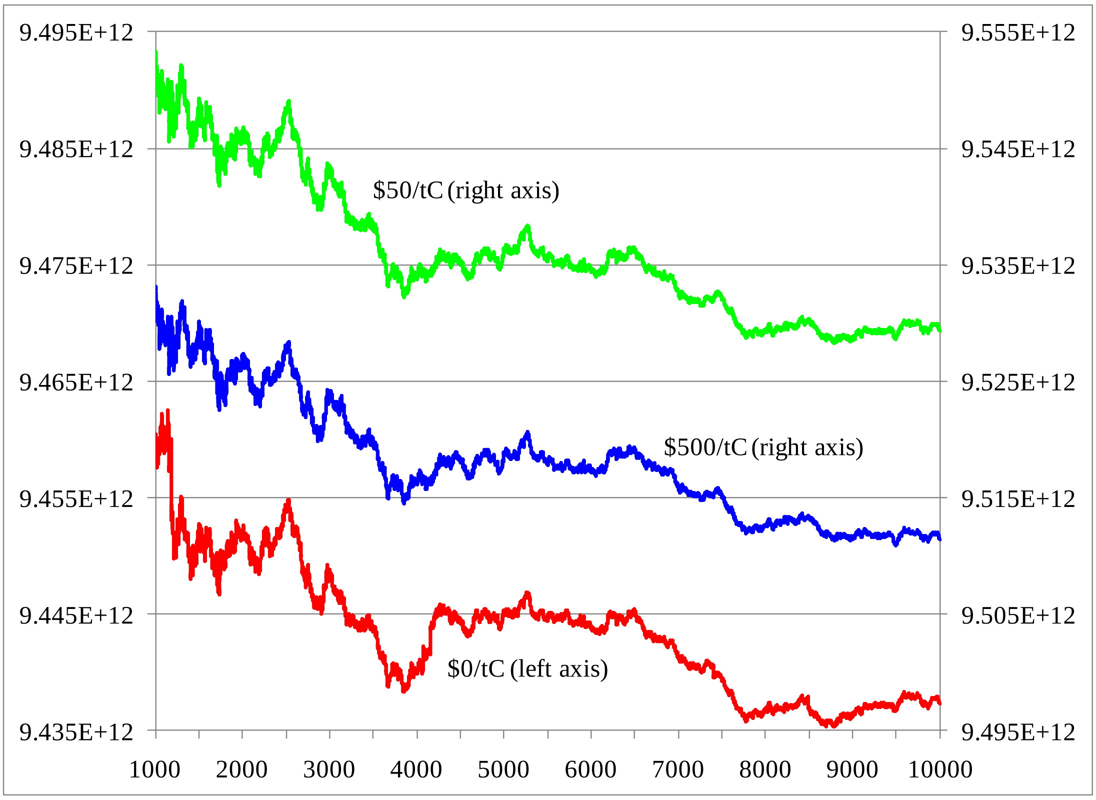

Figure 3. The expected value of the net present value of global welfare as a function of the Monte Carlo sample size for the case without climate policy, and with an initial carbon tax of $50/tC and $500/tC.

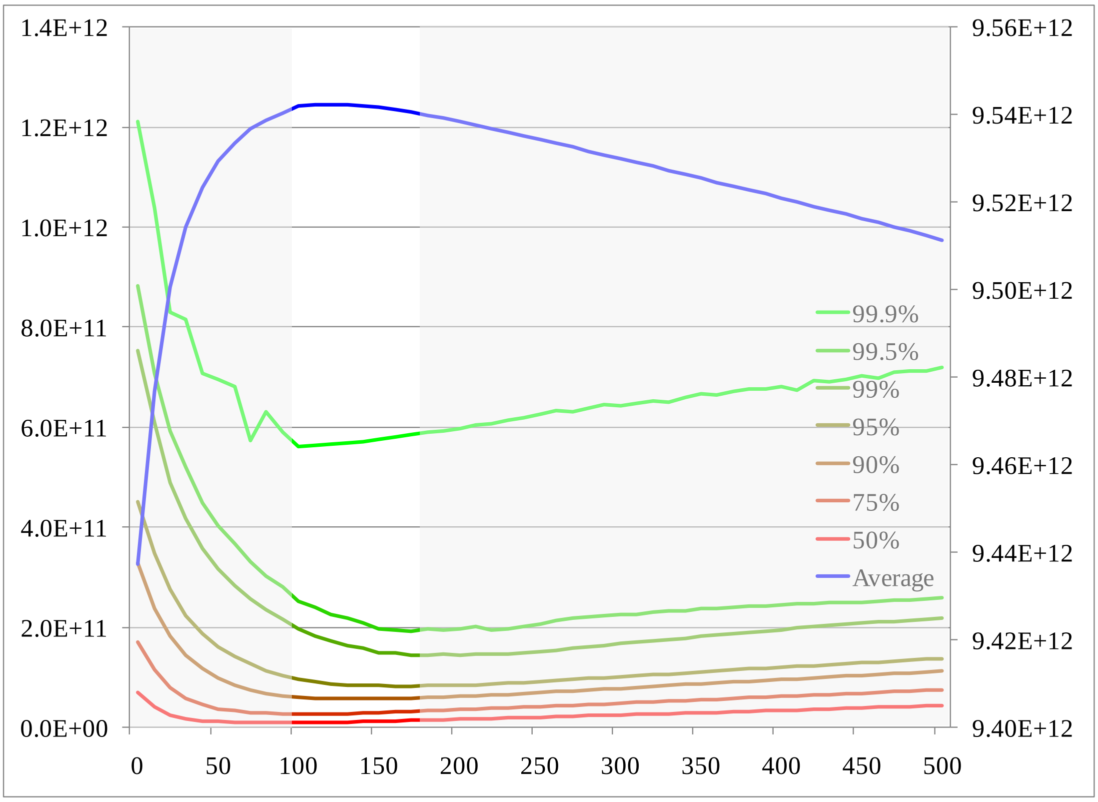

Figure 4. The expected net present value of global welfare (right axis) and selected percentiles of the regret distribution (left axis) as a function of the initial carbon tax. The unshaded area comprises minipercentile regret taxes.

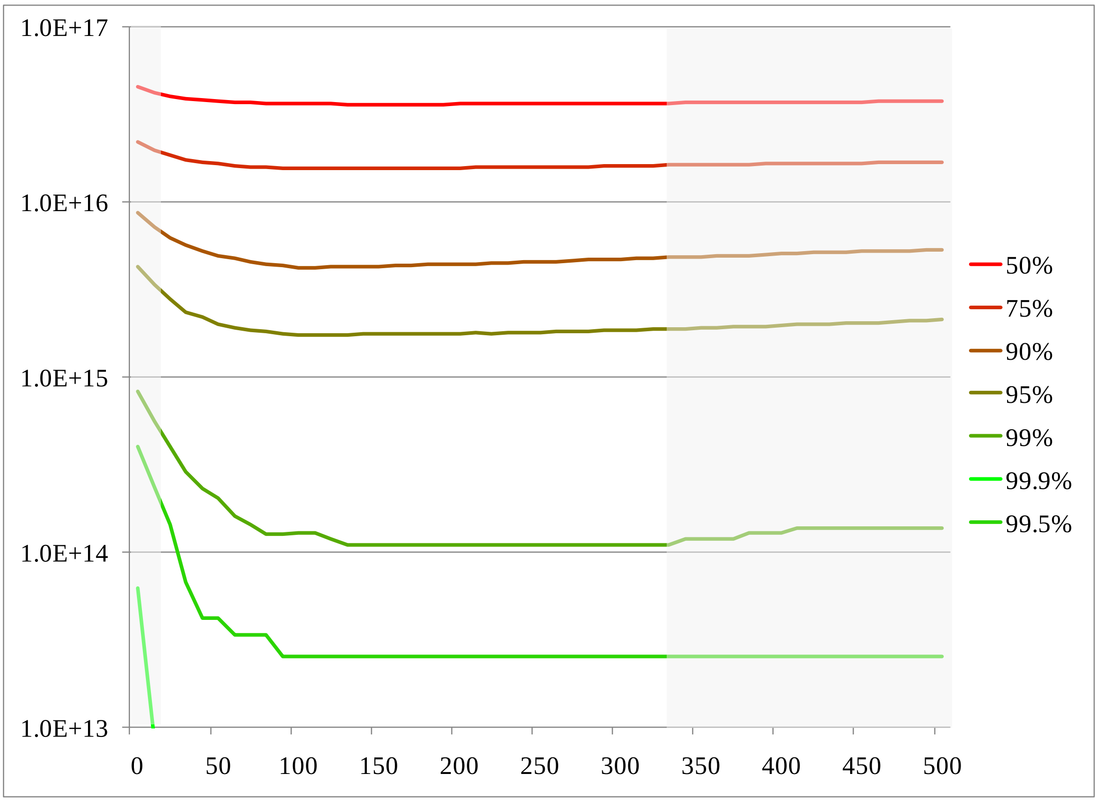

Figure 5. The tail risk of the net present value of global welfare for selected definitions of the tail as a function of the initial carbon tax. The unshaded area comprises minimum tail risk taxes.

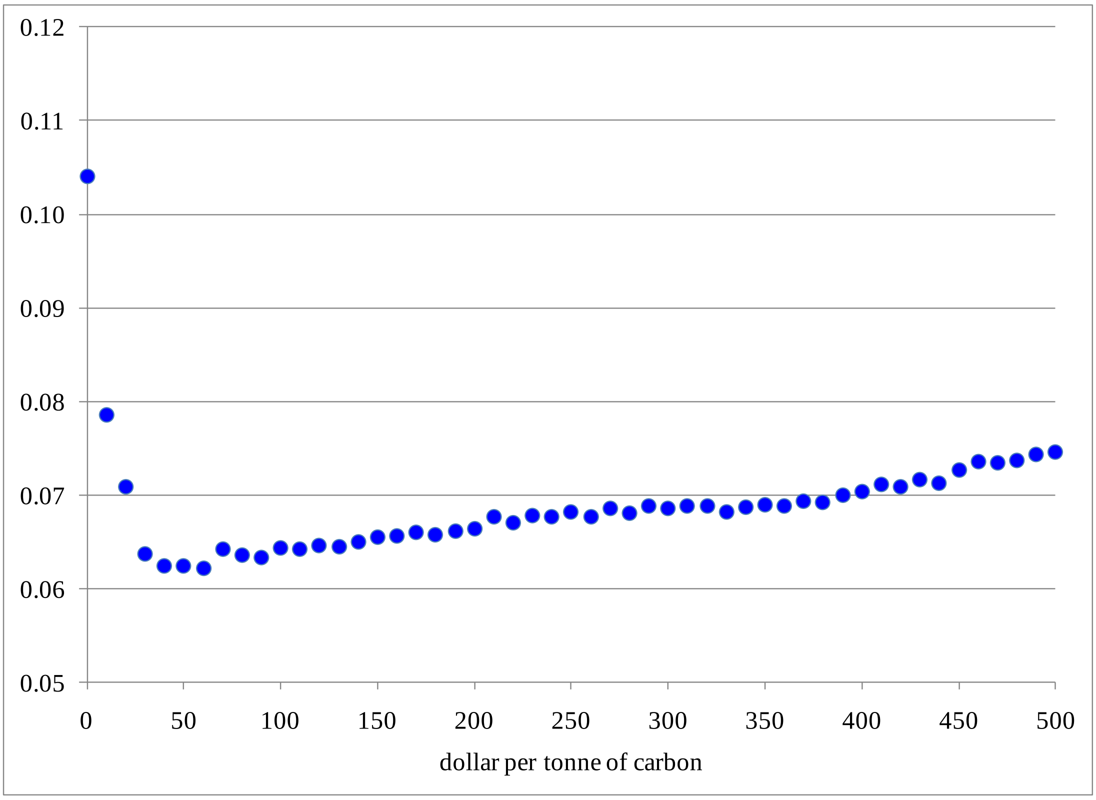

Figure 6. The probability of rejecting the null hypothesis that the recursive mean of the net present value of global welfare is Monte-Carlo-stationary as a function of the initial carbon tax.

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