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JEL Classification: H21, Q51, Q54

Keywords: climate model uncertainty, climate scepticism, robust climate policies, max-min, min-max regret, ambiguity aversion, DICE integrated assessment model

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The Agnostic's Response to Climate Deniers: Price Carbon![*]

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Abstract

With the election of President Trump, climate deniers moved from the fringes to the centre of global policy making and need to be addressed in policy-making. An agnostic approach to policy, based on Pascal's wager, gives a key role to subjective prior probability beliefs about whether climate deniers are right. Policy makers that assign a 10% chance of climate deniers being correct set the global price on carbon to \$19.1 per ton of emitted CO2 in 2020. Given that a non-denialist scientist making use of the DICE integrated assessment model sets the price at \$21.1/tCO2, agnostics' reflection of remaining scientific uncertainty leaves climate policy essentially unchanged. The robustness of an ambitious climate policy also follows from using the max-min or the min-max regret principle. Letting the coefficient of relative ambiguity aversion vary from zero corresponding to expected utility analysis to infinity corresponding to the max-min principle, it is possible to show how policy makers deal with fundamental climate model uncertainty when they are prepared to assign prior probabilities to different views of the world being correct. Allowing for a wide range of sensitivity exercises including damage uncertainty, it turns out that pricing carbon is the robust response under rising climate scepticism.

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1. Introduction

There is widespread consensus among climate scientists and economists that carbon emissions should be priced at a price around $20 per ton of carbon to avoid global warming and the associated marginal economic costs (e.g., Nordhaus, 2014) but will be pushed up significantly if marginal damages rise with global warming and the rate of economic growth and uncertainty (e.g., Dietz and Stern, 2014; Rezai and van der Ploeg, 2016) or account is taken of the risk of tipping points (van der Ploeg, 2014; Cai et al., 2016; Lemoine and Traeger, 2016). Still, the message that pricing carbon curbs global warming is doubted by many people, business men, and politicians due to lack of scientific understanding of the inevitable processes underlying global warming, vested fossil fuel interests, or both. The many ways by which pricing carbon curbs global warming, viz. curbing demand for fossil fuel, switching from CO2-intensive coal to less CO2-intensive gas, encouraging renewable energy production and green R&D, stimulating insulation, carbon capture & sequestration, locking up coal, oil and gas in the crust of the earth, et cetera, may also not be fully understood, wilfully or not. Our objective is to take the views of climate deniers at face value and to investigate their effects on the derivation of optimal climate policy if this is based on their views as well as those of the views in the climate science community. We investigate what decision theory says about how to deal with different views on global warming and their costs. We thus adopt an agnostic approach to policy where the scientific uncertainty that climate deniers could be right after all is scientifically accounted for.[1]

In the seventeenth century, the French philosopher Blaise Pascal pioneered decision making under such fundamental uncertainty by asking if one should believe in (the Christian) God if one cannot prove His existence using scientific methods (Pascal, 1670). Pascal's recommendation for agnostics was assertive: believe in God, if you hold only the slightest prior belief that God could exist. The rationale is that the cost of wrongly believing in God is minimal or at least finite, but the cost of wrongly not believing is infinite (eternal damnation and burning in a Lake of Fire) and/or the benefit of rightly believing in God infinite (eternal bliss in Paradise). We use similar reasoning to argue that climate agnostics, who cannot fully discount the position that science has

[1] It is important to be clear about terminology: climate deniers are 100% certain that global warming has only natural causes whereas climate believers (or non-sceptic scientists) are 100% certain that anthropogenic carbon emissions contribute to global warming. Climate sceptics or agnostics attach a small positive probability that climate deniers are right or at least acknowledge the possibility that global warming is not caused by anthropogenic carbon emissions at all. In political debate, climate deniers are sometimes euphemistically referred to as "climate sceptics".

got it all wrong, should push for stringent climate policy nonetheless. We argue that acknowledgment of scientific uncertainty about our understanding of climate change in the pursuit of robust climate policies under both epistemological uncertainty about what the right climate model and what the right damage function are leads to only minimal downward revision of optimal mitigation efforts.

The appointment by President Trump of an outspoken climate sceptic at the top of the Environmental Protection Agency in the United States has thrown global climate policy in the ropes.[2] While genuine climate deniers are not swayed by doubt, prudent science must deal with the error that a model is falsely assumed to be correct. For this purpose, we draw on a variety of decision-theoretic approaches. The first one is expected-utility analysis with a subjective probability of climate deniers being correct. If such a climate policy does not differ very much from the one advocated by climate scientists, even with relatively high probabilities of climate deniers being right, an agnostic policy maker would pursue an ambitious climate policy nevertheless. The second one is the max-min approach, which delivers a robust climate policy by doing the best one can do under the worst possible model of the climate and of damages (Wald, 1945; Gilboa and Schmeidler, 1989).[3] Since the welfare losses from not fighting global warming when anthropogenic global warming is correct are relatively large (due to relatively high damages at 4 to 7 degrees Celsius) whilst those from fighting global warming when climate deniers are correct are relatively small (the welfare cost of distorting taxes on emissions *minus* the welfare gains from rebates), the max-min optimal policy is to price carbon. The third approach is the min-max-regret approach, which also delivers a robust climate policy by minimising the regret of pursuing the wrong policy under the worst possible outcome (Savage, 1954). The final approach is based on the more modern approach of relative ambiguity aversion, denoted by AA, and allows for a continuum between expected utility analysis where $AA = 0$ and max-min analysis where $AA \to \infty$ (Klibanoff et al., 2005).

[2] Only on March 9, 2017, Scott Pruitt, head of the US EPA, stated "[…] I think that measuring with precision human activity on the climate is something very challenging to do and there's tremendous disagreement about the degree of impact. So no, I would not agree that it's a primary contributor to the global warming that we see." The Trump administration's first budget proposal cuts funding for the EPA by 31%.

[3] Gilboa and Schmeidler (1989) give an axiomatic foundation of the max-min principle using the axiom of uncertainty aversion, the axiom of certainty independence (or the sure thing principle which weakens the classical independence axiom) as well as the usual axioms of transitivity, completeness, continuity and monotonicity.

We use a modular approach to optimal climate policy formulation (NAS, 2017; Rezai and van der Ploeg, 2017a). We have a common model of the economy, which for simplicity we take to be the DICE integrated assessment model (Nordhaus, 2008, 2013). We distinguish two models of the climate: one based on the carbon and temperature model of DICE and a modified one to capture the view of climate deniers. We also consider a sensitivity exercise where we distinguish two types of damage functions from global warming: the DICE damages with relatively flat marginal damages and a variant with more convex damages (e.g., Weitzman, 2010; Dietz and Stern, 2015). We then consider each of the four decision-theoretic approaches to see how climate policy is much affected by taking the view of climate deniers at face value.

Rezai and van der Ploeg (2017b) deal with similar issues. The novelty of this paper is fourfold: (i) we allow for both climate model uncertainty and damage specification uncertainty and thus speak to the modular approach of NAS (2017); (ii) we allow for ambiguity aversion thereby nesting expected utility and max-min outcomes in a continuum; (iii) we allow for a continuous range of policy options rather than simply three or four discrete policy paths when deriving our max-min, min-max-regret and ambiguity-aversion optimal policy paths; and (iv) and we solve the problem in decentralised market equilibrium by maximising the decision-theoretic criterion subject to all the constraints of the market economy which allows us to use different discount rates and thus different welfare criteria for households and the policymaker.

The outline of this paper is as follows. Section 2 reviews Pascal's problem analytically and section 3 shows how it can be adapted to the problem of dealing with climate deniers. Section 4 gives numerical illustrations of how to calculate various socially optimal outcomes based on expected-utility, max-min and min-max-regret analysis using a calibrated integrated assessment model of the global economy. Section 5 shows how these approach can be nested using ambiguity-aversion analysis. Section 6 presents outcomes under various changes in assumptions to show the robustness of our claim that carbon should be priced even if taking account of the presence of climate deniers. Section 7 concludes.

2. Pascal's problem

Let us first consider Pascal's problem with the following table of costs of actions. Normalising so that the cost of not believing when God does not exist is zero, the cost of not believing in God when God does exist is eternal damnation with $b \to \infty$. Believing in God when God does exist leads to bliss in Paradise and thus $a \to \infty$. The cost of believing in God when God does not exist is the cost of conforming (e.g., not swimming on Sunday) so $c > 0$ is small and finite. Denote the probability that God does not exist by the constant $0 < \pi < 1$.

Table 1: Decision matrix for Pascal's problem

Pay-off	Belief in God	Do not believe in God
God exists	a	$-b$
God does not exist	$-c$	0
min pay-off	$\boldsymbol{-c}$	$-b$
max pay-off	$\boldsymbol{a}$	0

Key: The max-min and max-max policies lead one to believe in God with pay-offs $\boldsymbol{-c} > -b$ and $\boldsymbol{a} > 0$, respectively, irrespective of how close the probability that God does not exist, π, is to 1. The same outcome holds for expected-utility analysis.

The expected pay-off to believers, $(1-\pi)a - \pi c,$ thus exceeds the pay-off to non-believers, $-(1-\pi)b,$ if and only if the probability that God exists exceeds $0 < c/(a+b+c) < 1.$ Since $a \to \infty$ and $b \to \infty$ (strictly speaking, only one of these conditions is needed), the cut-off probability is infinitesimally close to zero. So unless one is an atheist and leaves no room for doubt at all, expected utility analysis drives a rational person to believe in God. Since clearly $c < b$, the penultimate row of Table 1 indicates that believing is also the pessimistic max-min policy. The bottom row of Table 1 indicates it is also the more optimistic max-max policy. If one believes in God and God does not exist, the regret is $a + c.$ If one does not believe in God but God does exist, the regret is $b.$ The min-max-regret policy is thus to believe in God provided that $a + c < b.$ Hence, although expected-utility, max-min and max-max analysis leads one to believe in God, min-max-regret policy only does this if the cost of Hell and Eternal Damnation dominates the benefit of Paradise plus the small cost of wrongly believing in God.

3. Decision theory: climate policy under fundamental model uncertainty

Table 2 takes a similar approach to the problem of formulating climate policy when climate deniers are taken seriously to Pascal's problem discussed in section 2. The first row corresponds to the view that anthropogenic warming exists, which is the view of (the vast majority of) climate scientists. The second row corresponds to the view that anthropogenic warming does not exist, which is the view of climate deniers. The actions for each of the two columns correspond to pricing carbon to internalise the damages from global warming (and rebating the revenue to the private sector) and to business as usual, respectively. Not taking action to fight climate change when the climate scientists are right leads to a rise in mean global temperatures of 4-7 degrees Celsius with large drops in economic activity, but taking action would have mitigated heating and welfare losses. Hence, we must have $a < b < 0$.

Table 2: Decision matrix for climate policy when deniers are taken seriously

Pay-off	Price carbon	Do not price carbon
Climate science	$-a$	$-b$
Climate deniers	$-c$	0
min pay-off	$\boldsymbol{-a}$	$-b$
max pay-off	$-c$	**0**

Taking climate action when climate deniers are right implies some welfare costs of unnecessarily distorting energy decisions, so $0 < c < a$ must hold. Using expected-utility analysis as before, it follows that global policy makers should take climate action if and only if the probability that climate scientists are correct exceeds $c/(b-a+c)$ or equivalent if the probability that climate deniers are correct is less than $(b-a)/(b-a+c).$ Since $b > a$ and $c > 0$, both these probabilities are between zero and one.

Assumption 1: *The regret of not taking climate action if climate scientists are right, $b - a > 0$, exceeds the regret of taking climate action if climate deniers are right, $c > 0$. Pricing carbon leads to a bigger welfare loss if climate scientists are right than if climate deniers are right, $a > c$.*

It is plausible to believe that this assumption holds and we will confirm that it is indeed the case for the DICE model in our numerical work in sections 4-6 below. Not conducting any climate policies when temperature rises substantially to say 4-7 degrees Celsius induces relatively big losses in economic output and welfare, whereas pricing carbon and rebating the revenue when anthropogenic global warming occurs leads to relatively small welfare loss triangles. It follows from the first part of assumption 1 that a sufficient condition for climate action to take place is that the probability of climate deniers being right is less than 50% (as $(b-a)/(b-a+c)$ is bigger than 50%). Since 97% of scientists and 58% of the general public in the USA say that human activity is a significant contributing factor in changing mean global temperature, one can safely assume this threshold for pricing carbon is met (Doran and Zimmerman, 2009). Furthermore, the max-min-regret policy is always to price carbon and to take action to fight global warming. The second part of assumption 1 states that when carbon is priced the welfare loss is higher without than with anthropogenic global warming, $a > c$. It follows that the max-min policy is to price carbon. Since similar results hold for expected-utility, min-max-regret and max-min analysis, the robust policy is to undertake to fight global warming by pricing carbon emissions either via a global carbon tax or via a competitive market for permission rights. This could be contrasted with the max-max policy (doing the best under the best possible outcome), which leads global policy makers always to not price carbon.

Result 1: *Given assumption 1 and a choice of only two actions, namely to price or not to price carbon, the max-min and min-max-regret policies are to price carbon. Under expected utility analysis, a sufficient condition for policy makers to price carbon is that the probability of climate deniers holding the correct view is less than 50%. The max-max policy is to do nothing.*

Modern decision theory also allows for ambiguity aversion (Klibanoff et al., 2005). Effectively, policy makers thus have an aversion to not knowing what the right climate model is. This approach accounts for irreducible uncertainty and puts a premium on playing it safe when venturing into domains where different models give different outcomes (Millner et al, 2013). As in the following sections 4-6, we assume that policy p can take on a continuum of values instead of only two values ('to price or not to price carbon'). It is perhaps easiest to think of p as the initial carbon price which henceforth grows at the same rate as world GDP (cf. Golosov et al., 2014; van den Bijgaart et al., 2016; Rezai and van der Ploeg, 2016), but in later sections we allow the price of carbon *p* to be time-varying. Formally, if *AA* > 0 denotes the coefficient of relative ambiguity aversion, $W_S(p)$ denotes the welfare criterion if climate scientists are right and $W_D(p)$ denotes the welfare criterion if the climate deniers are right, the agnostic policy maker with ambiguity aversion chooses policies *p* to maximise the expected value of $\left((1-\pi)W_S(p)^{1-AA}+\pi W_D(p)^{1-AA}-1\right)/(1-AA)$ if $AA\neq 1$ and $(1-\pi)\ln\left(W_S(p)\right)+\pi\ln\left(W_D(p)\right)$ if $AA=1$. This formulation nests both the expected welfare approach (with *AA* = 0) and the extremely cautious max-min approach (with *AA* = ∞). The first-order optimality condition is $\mathrm{E}\left[(1-\pi)W_S\,'(p)W_S(p)^{-AA}+\pi W_D\,'(p)W_D(p)^{-AA}\right]=0$ or

$$\mathrm{E}\left[(1-\pi^*)W_S\,'(p)+\pi^* W_D\,'(p)\right]=0,\ \text{where}\ 0\leq\pi^*\equiv\pi/\left(\pi+(1-\pi)\left(W_D(p)/W_S(p)\right)^{AA}\right)\leq 1.$$

Allowing for ambiguity aversion is thus equivalent to maximising expected welfare provided one change π for the ambiguity-adjusted probability π^*. As $W_D(p)>W_S(p)$ under assumption 1, we see that π^* increases in π. Ambiguity aversion (*AA* > 0) implies that $\pi^*<\pi$ and that π^* decreases in *AA*. Furthermore, as $W_S\,'(p)>0$ and $W_D\,'(p)<0,$ we see that π^* increases in the price of carbon *p*. We thus get $\pi^*=\pi^*(\pi,AA,p)$ with $\pi^*_\pi>0, \pi^*_{AA}<0$ and $\pi^*_p>0.$ The optimality condition for maximising expected welfare gives $p=p(\pi^*)$ with $p_{\pi^*}<0.$ Hence, solving for the optimal price of carbon we get $p=p(\pi,AA)$ with $p_\pi<0$ and $p_{AA}>0.$

Result 2: *Accounting for ambiguity aversion in policy making introduces caution and requires downward adjustment of the probability that climate deniers are right. The adjustment is larger if ambiguity aversion is large or the costs of global warming assessed by climate scientists are high. Climate action is thus more ambitious if the subjective probability that climate deniers are right is low and relative ambiguity aversion is high.*

So far, armchair arguments have led to results 1 and 2. To get a more realistic analysis, we use one commonly used integrated assessment models of climate change and the economy to put some numbers to these results and to obtain options for robust climate policy where the policy actions *p* are now just a continuous stream of time-varying carbon prices starting from the present.

4. Pricing carbon under conflicting views of global warming

To implement the two opposing views of the climate-economy interaction - one in which human emissions contribute to climate change and one in which the climate follows exogenous projections of committed warming - we adapt and extend the most commonly used integrated assessment model DICE as presented in Nordhaus (2014) and describe our adaptation and chosen parameter values in the Appendix. The "scientific" view corresponds to the DICE-2013R version of the DICE. Strictly speaking, the International Panel on Climate Change allows for a very small probability that deniers are right but we will call the "science" view the one which says that all anthropogenic carbon emissions contribute to global warming. The "denier" model corresponds to a variant of DICE-2013R where (future) anthropogenic emissions do not enter the atmosphere and the climate evolves independently of the economy, responding to exogenous and past emissions already in the system. Hence, peak mean temperature is only 1.3°C.

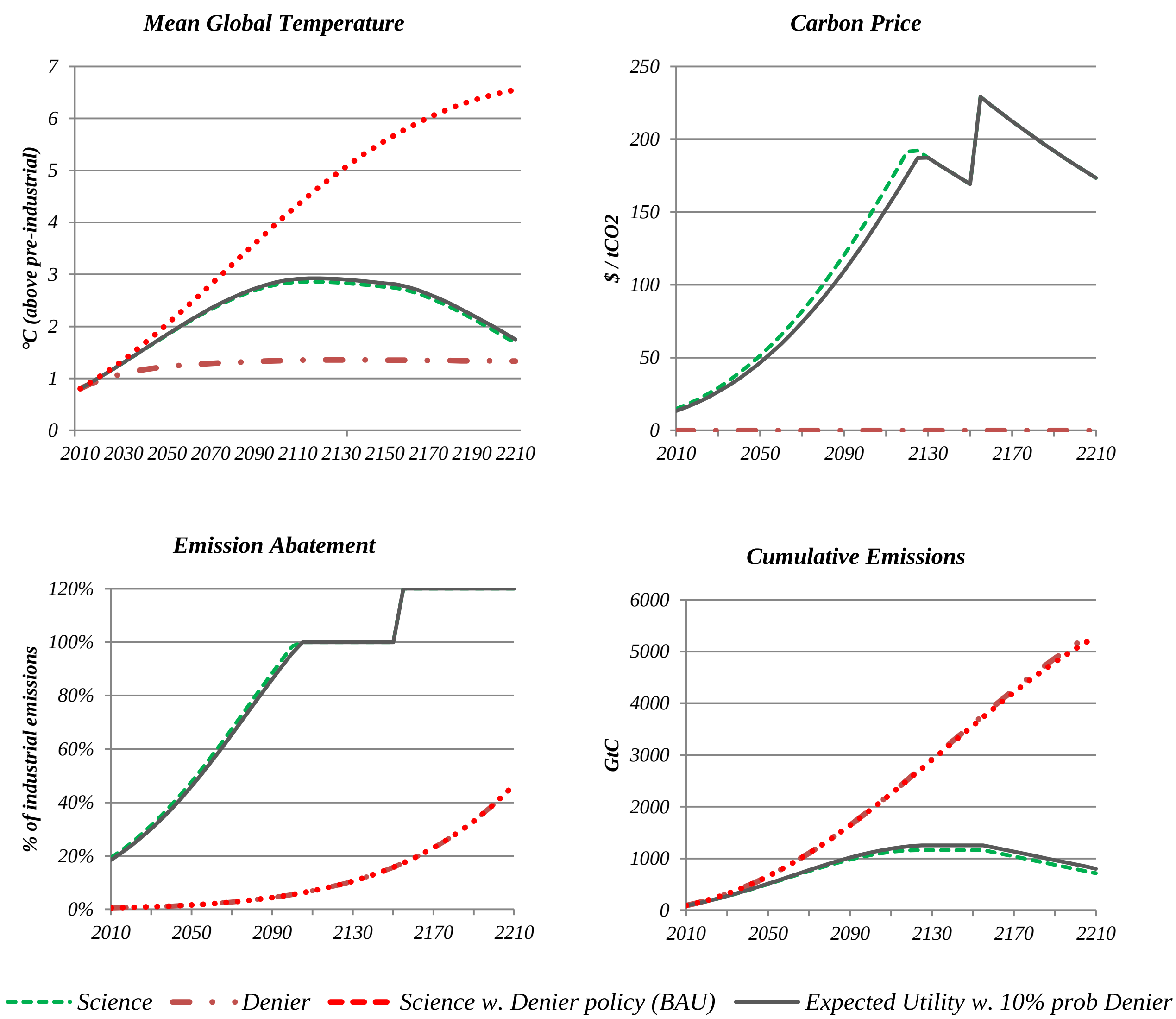
To start off, we assume that the two rival views only differ in their view of the causes of global warming. Both views use in our exercise the same model of economic growth, consumption and energy use and also the same damages from global warming, namely the ones of DICE. Although climate deniers might differ in their degree of impatience and their willingness to make sacrifices for future generations, we assume first that climate deniers and climate scientists employ the same social rate of impatience and relative intergenerational inequality aversion and thus the same social discount rate as climate scientists. Given these benchmark assumptions, we let agnostic policy makers choose climate policy under this form of "climate model" uncertainty. For simplicity we ignore "statistical" uncertainties in any particular model.

Figure 1 plots the temperature profiles for both views of the climate.[4] The dashed green line with temperature peaking at 3.4°C corresponds to the science view where decision makers price carbon at \$21.1/tCO2 in 2020 to avoid excessive climate change. Under the deniers' view global

[4] Mitigation is limited to 100% of emissions for 150 years and to 120% from then onwards in DICE. These upper bounds for the carbon price are the reason for the non-monotonic price curve in Figure 1. As soon as mitigation reaches its upper bound, the carbon price follows the exogenous (falling) cost of the backstop.

temperature is unrelated to human emissions and peaks at 1.3°C regardless of policy as can be seen from the dashed-dotted red line. To avoid unnecessary regulation, it is optimal to avoid any carbon price if policy makers hold the view that anthropogenic global warming does not exist.[5]

Figure 1: Temperature, carbon prices, and emissions (abated and cumulated) in the science and denier's models under either policy. Optimal climate policy (green dashed) limits peak global warming (PW) to 3.4°C in the science (DICE) model. Climate deniers (red dot-dashed) hold the view that temperature is independent of policy and thus fossil fuel is phased out only due to its limited availability. This policy of no carbon prices and relative in-action translates into 7°C PW if the science view on anthropogenic global warming is right (red dotted). Expected-utility analysis giving a 10% probability that climate deniers are right (black solid) leads to a carbon price almost identical to the science case.



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[5] Despite a zero carbon price, emission abatement under the climate deniers' view is positive and driven by the endogenous Hotelling rent as total availability of fossil fuels is limited in DICE.

We also consider scenarios where one type of policy (price carbon or don't price carbon) is implemented in the other type of climate view (science or denier). In the science/don't price carbon case (red dotted), the absence of a carbon price leads to rapidly rising temperature, peaking at 7°C – see the solid red line. This is commonly called "business as usual" or BAU. In the denier/price carbon case (not plotted), human carbon emissions fall but temperature is unchanged due to the decoupling of temperature and emissions.

Table 3 summarises the four scenarios in terms of global welfare gains, which we define in % of current world GDP relative to BAU, and is our benchmark numerical analogue of Table 2. The first row assumes that the science view is correct. Wrongly not pricing carbon when climate scientists are right as in business as usual involves unfettered growth in emissions, temperature peaking at 7°C and consequently severe damages to the world economy. However, if carbon is priced, temperature is stabilised and welfare is increased by 17% of current world GDP relative to business as usual. The second row assumes that climate deniers are right. Temperature increases to 1.3°C regardless of policy and the economic future under business as usual is much brighter than what doomsayer scientists think. The benefit of removing severe climate change damage amounts to 41% of world GDP. In a climate denier's world, wrongly and unnecessarily pricing carbon and rebating the revenues introduces efficiency losses and a drag on economic growth equivalent to a drop in 7% of world GDP.

Table 3: Welfare gains under climate model uncertainty

(% initial world GDP, relative to BAU under the science view)

Climate view	Price carbon	Don't price carbon
Science	17%	0%
Denier	34%	41%
min welfare	**17%**	0%
max regret	**7%**	17%

Key: Pricing carbon increase welfare by 17% if scientists are correct but lowers welfare by 7% if deniers are right. The welfare under carbon pricing is lower if climate scientists are right (17%) than if climate deniers are right (34%).

If one follows Pascal and adopts the expected-welfare approach with only these two policies, it is optimal to price carbon if and only if the probability that climate deniers are right is less than 70% and not to price carbon otherwise.[6] Agnostic policy makers who maximise welfare under the worst possible outcomes (the max-min decision criterion), also choose to price carbon, because the resulting efficiency losses are much lower than the deleterious effects of future severe climate change (in a 7°C world). The same logic and climate policy applies if policy makers minimise maximum regret, since the regret of not pricing carbon when climate scientists turn out to be right (17% of world GDP) exceeds the regret of pricing carbon when climate deniers turn out to be right (7% of world GDP). Both max-min and min-max-regret policies are the classical policy responses to model uncertainty. They maximise welfare or minimise regret under the worst possible view of global warming and compel policy maker to price carbon even when taking climate deniers seriously.

So far we have only considered either-or choice (for one either believes in God or doesn't), but the modern expected-welfare approach allows for a continuous range of policy options. We find that maximising expected welfare with a 10% probability that climate deniers hold the correct view of the world (solid black lines in Figure 1) does not alter the purely science-based optimal climate policy much: the price of carbon falls from \$21.1 to \$19.1/tCO2 and expected peak warming rises by a mere 0.1°C. Expected-utility outcomes for further levels of π are reported in Table 4.

Table 4: Peak warming and carbon prices under different priors that deniers are correct

	Prior that deniers hold correct view										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Peak Warming	3.3 °C	3.5 °C	3.6 °C	3.8 °C	3.9 °C	4.2 °C	4.5 °C	4.8 °C	5.4 °C	6.3 °C	7.0 °C
Carbon Price (2020, per tCO2)	\$ 21.1	\$ 19.1	\$ 17.1	\$ 15.0	\$ 12.9	\$ 10.8	\$ 8.7	\$ 6.6	\$ 4.4	\$ 2.2	\$ 0.0

Key: Peak warming levels increase from 3.3°C to 7°C and carbon prices (in 2020) decrease from \$21.1 to \$0 per tCO2 as the prior that deniers are correct, π, rises from 0% to 100%.

[6] As discussed in section 3, the key difference is that Pascal's argument requires either infinite welfare in Paradise or infinite negative welfare if in hell whereas in the climate context these welfare effects are finite. If π is the subjective probability that deniers are correct, expected welfare when carbon is priced yields higher expected welfare than not pricing carbon if $0.17\ (1-\pi) + 0.34\ \pi > 0.41\ \pi$ or $\pi < 70\%$.

Peak warming rises non-linearly from 3.3°C to 7.0°C as the probability that science has it wrong rises from 0% to 100%. Not surprisingly, the optimal carbon price under expected-utility analysis falls linearly in the probability from the optimal carbon price ignoring climate uncertainty, \$21.1/tCO2, to the price under business as usual, \$0/tCO2.

If we take 3% for the climate specialists and 42% for the general public, as suggested in Doran and Zimmerman (2009), the carbon taxes are \$20.5 and \$12.5 per ton of emitted CO2 and peak warming levels are 3.4°C and 4°C, respectively.

5. Ambiguity aversion: nesting expected-utility and max-min analysis

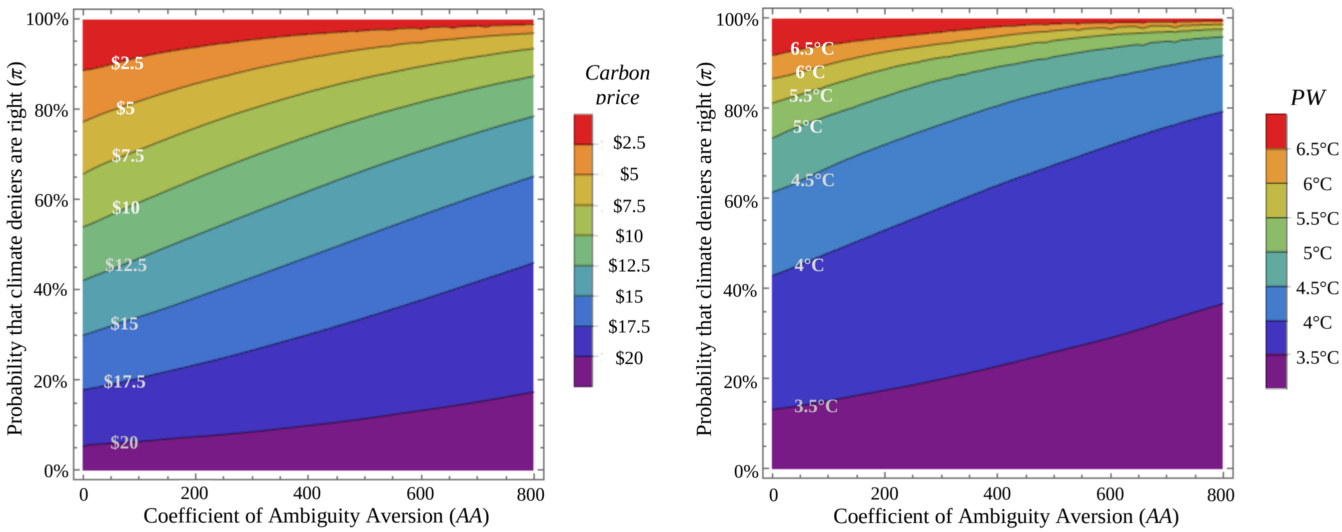
How would ambiguity aversion impact agnostic climate policy? From Result 2 we know that in the case of climate change ambiguity aversion induces caution and increases the carbon price for any given π. Figure 2 shows iso-carbon-price and iso-peak-warming curves for combinations of the subjective prior probability that climate deniers are right, π (vertical axis) and the coefficient of relative ambiguity aversion, *AA* (horizontal axis). In the left panel the carbon price in 2020 decreases from \$21.1 to \$0/tCO2 and in the right panel peak warming increases from 3.4°C to 7°C as the probability that climate deniers are right increases from zero to one (vertical axis).

The degree of ambiguity aversion (*AA*) rises from 0 to 800 on the horizontal axis. With *AA* = 0, the findings correspond to the expected-utility case discussed above. As *AA* increases, climate policy becomes more ambitious: carbon price and peak warming levels fall. This can be seen in Figure 2 as iso-price and iso-peak-warming curves are upward sloping.

Holding fixed the probability that deniers are right, π, increases in ambiguity aversion *AA* lead to regions with higher carbon prices and lower peak warming levels. For example, the optimal carbon price is \$15/tCO2 if there is no ambiguity aversion (*AA* = 0) and the probability that climate deniers are right is as high as π = 30%. Following the \$15/tCO2 iso-price curve to *AA* = 800 yields a probability of two thirds (π = 66%). A significantly higher probability of climate change being a hoax is needed (i.e., two third instead of one third) to support the same \$15 price on CO2 if decision makers are strongly averse to ambiguity.

Figure 2: Priors, ambiguity aversion and peak warming

(a) Carbon price in 2020 ($/tCO2) ***(b) Peak global warming (°C)***



Key: (a) the carbon price in 2020 and (b) peak warming as a function of ambiguity aversion (horizontal axis) and the probability that climate deniers are right (vertical axis). Values for *AA* = 0 correspond to those of Table 2. As *AA* increases, policymakers are more cautious and climate policy is more ambitious: carbon prices increase and peak warming levels fall.

Similarly, if *AA* = 0, peak warming increases by more than 0.5°C only for priors that deniers are right greater than a third. If *AA* = 800, this cut-off for the prior rises to 70%. Aversion to ambiguity, about what the right climate model is, thus biases priors toward the non-sceptic scientist and encourages more ambitious climate policy. This effect is small for low *AA*, but large for high *AA*. Even if policy makers assign a 50% (90%) chance to climate deniers being right, allowing for a high degree of robustness (more than for expected-utility but less than for max-min policy) biases this chance down to 20% if *AA* = 800 (2000). This implies a price of carbon of $17.1/tCO2 in 2020 and peak global warming of 3.6°C. Also, a higher probability of climate deniers being right requires higher ambiguity aversion to keep the carbon price in 2020 constant.

As *AA* approaches infinity, peak warming falls to 3.4°C regardless of prior probabilities about whether climate scientists or deniers are right and converges to the max-min policy. Aversion to ambiguity about scientific uncertainty lowers willingness to tolerate increases in global warming. Policy makers that cannot specify probabilities about whether climate scientists or deniers are right should probably aim for the max-min policy (cf. Gilboa and Schmeidler, 1989).

6. Robustness

The results of sections 4 and 5 build on the published version of DICE-2013R. Here, we explore the robustness of our results by varying three important determinants of the climate policy: damages, income growth and discount rates. Figure 3 presents these scenarios for the 'science' view and Table 5 summarises the effects on peak warming and the carbon price for different prior probabilities that climate deniers are correct.

Figure 3: Robustness of climate policy (the 'science' view) to more convex damages, lower growth rates, and differential discount rates

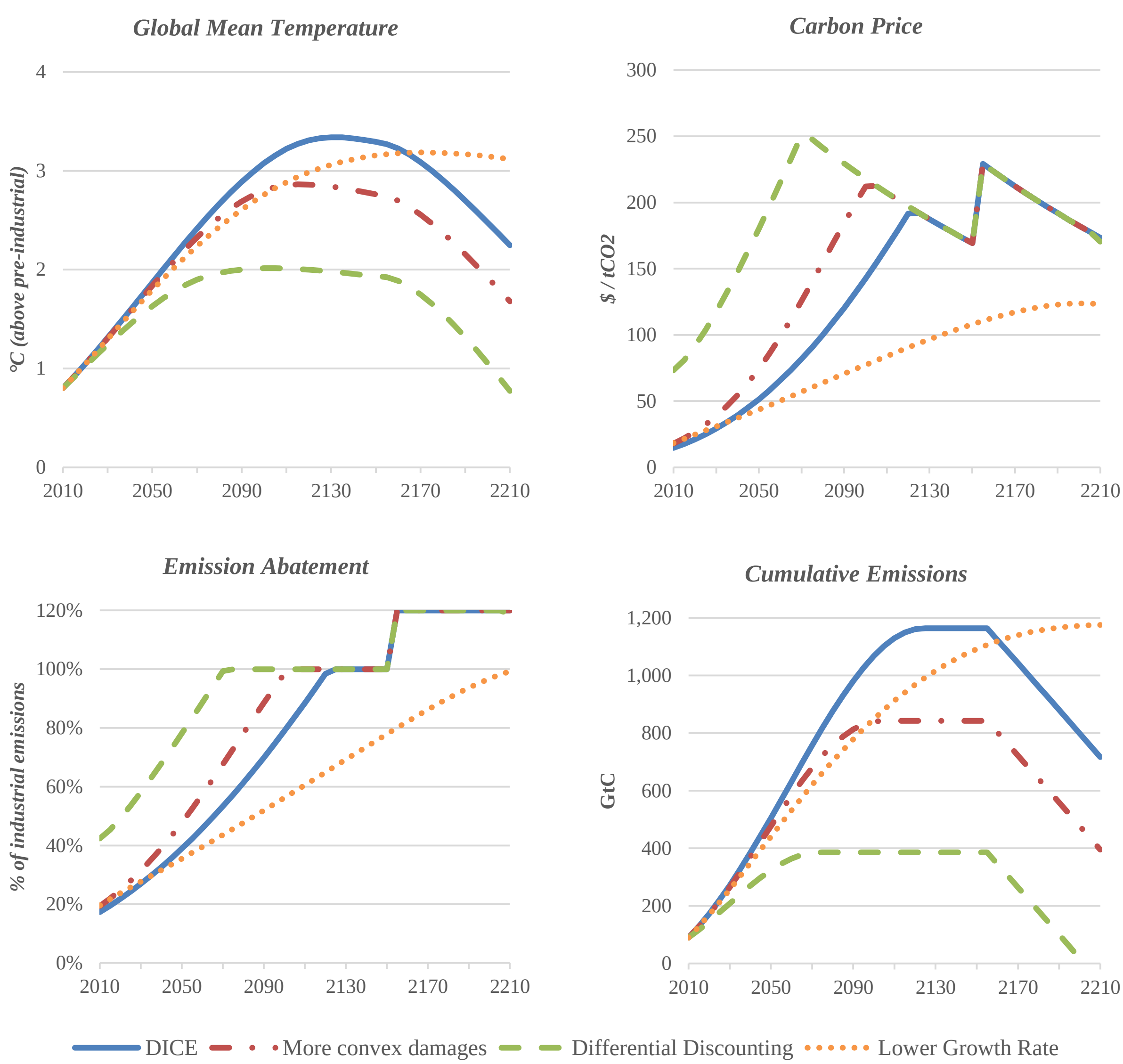


Table 5: Robustness of climate policy to more convex damages, lower growth rates and differential discount rates

		Prior that Deniers are Right			
		0%	10%	50%	100%
DICE-2013R	Peak Warming	3.3°C	3.5°C	4.2°C	7.0°C
	Carbon Price	21.1 $/tCO2	19.1 $/tCO2	10.8 $/tCO2	0.0 $/tCO2
More Convex Damage	Peak Warming	2.9°C	2.9°C	3.3°C	6.6°C
	Carbon Price	26.7 $/tCO2	24.7 $/tCO2	16.2 $/tCO2	0.1 $/tCO2
Lower Growth	Peak Warming	3.2°C	3.3°C	3.9°C	5.3°C
	Carbon Price	24.7 $/tCO2	22.3 $/tCO2	12.6 $/tCO2	0.0 $/tCO2
Differential Discounting	Peak Warming	2.0°C	2.1°C	2.6°C	7.0°C
	Carbon Price	91.3 $/tCO2	83.7 $/tCO2	51.1 $/tCO2	0.0 $/tCO2

6.1. More convex damages from global warming

DICE-2013R uses the damage specification of Nordhaus (2008) which aggregates micro estimates of the costs of global warming to macroeconomic costs of 1.7% of world GDP when global warming reaches 2.5°C. Weitzman (2010) and Dietz and Stern (2015) argue that damages rise more rapidly at higher levels of global mean temperature than suggested by Nordhaus (2008), but empirical studies on the costs of global warming at higher temperatures are not available. Following this reasoning, Ackerman and Stanton (2012) recalibrate damages to fit the additional points of 50% damage at 6°C and 99% damage at 12.5°C.[7]

Having more convex damages increases the marginal cost of climate change which makes climate policy more ambitious. Consequently, peak warming falls to 2.9°C and the carbon price in 2020 increases to 26.7$/tCO2 in Figure 3 (dot-dashed red lines) and Table 5.

Table 6 reports the welfare effects of climate action (and inaction) for the science and denier world views. The more convex damage function increases the damages from climate change at high levels of temperature. This increases the cost of not pricing carbon significantly from 17% to 189%

[7] The damage function (defined as % of potential output loss in temperature increase T_t) is $1-Z(T_t)=1-(1+\zeta_1 T_t^{\zeta_2}+\zeta_3 T_t^{\zeta_4})^{-1}$ in DICE-07 with ζ_1 = 0.00284, ζ_2 = 2, and ζ_3= ζ_4 = 0. The recalibration by Ackerman and Stanton (2012) changes these parameter to ζ_1 = 0.00245, ζ_2 = 2, ζ_3 = 5.021 x 10^{-6}, and ζ_4 = 6.76. For temperature increases below 2.5°C this recalibration yields lower damages of at most 0.1% of GDP. DICE2013R uses the damage function $\tilde{Z}(T_t)=0.00267 T_t^2$ which fits the specification of DICE-07 closely: for T_t < 5°C the difference is less than 0.1 % of GDP.

of initial world GDP (compared to the baseline calibration of section 4). More ambitious climate policy increases the cost of inefficient legislation in the denier's world from 7% to 12% of GDP. The regret of not taking climate action when the scientists turn out to be right is boosted from 17% to 189% of world GDP whilst the regret of taking climate action when the deniers turn out to be right increases from 7% to a mere 12% of world GDP. More convex damages thus increase the case for taking climate action based on max-min or min-max-regret policies. More convex damages also induce the ambiguity averse policy maker to be more cautious and use more aggressive climate policy with positive π, as reported in Table 5. Allowing for a 50-50 chance that climate change is not man-made increases peak warming by a mere 0.4°C to 3.3°C.

Table 6: Welfare gains (% initial world GDP) under convex damages

Climate view	Price carbon	Don't price carbon
Science	189%	0%
Denier	204%	216%
min welfare	**189%**	0%
max regret	**12%**	189%

6.2. Lower TFP growth

Relative affluence of future generations is a key determinant of climate policy. The richer future generations are, given the social discount rate, ρ, and the degree of intergenerational inequality aversion, *IIA*, the less justifiable the sacrifice of climate policy imposed on current generations. Here, we cut the trend rate of future total factor productivity growth in half. Lower income growth lowers the interest applied to discount future climate damage and thus increases the intiial optimal carbon price to 24.7\$/tCO2 (which is slightly higher than in the scenario with more convex damages). However, this higher level of carbon pricing does not translate in significantly lower peak warming levels, because the lower income growth also lowers the growth trajectory of the carbon price as shown in Figure 3.

Lower growth in the economy lowers cumulative carbon emissions and the threat of climate change. With peak warming delayed by four decades to 2170, the present discounted value of inaction falls to 11% as can be seen from Table 7. Less stringent climate policy, however, also lowers the cost of policy in the denier's view of the world to 5% of GDP. More importantly, the robust max-min and min-max-regret policies that follow from Table 7 again point towards pricing carbon.

Table 7: Welfare gains (% initial world GDP) under lower TFP growth

Climate view	Price carbon	Don't price carbon
Science	11%	0%
Denier	33%	38%
min welfare	**11%**	0%
max regret	**5%**	11%

6.3. Different discount rates for private agents and policy makers

Much of the debate around the Stern Review centered on the role of social discounting of future welfare. Stern (2006) prominently echoed Ramsey (1928) arguing that it is unethical to discount future welfare and that market rates of interest are not a good guide to social discount rates. Nordhaus (2008) leads the opposition to this view by arguing that these ethical parameters are not really ethical but need to be chosen such that simulated interest rates match those observable in the market. Following von Below (2012), Schmitt (2014), Belfiori (2017) and Barrage (2016), we sidestep this debate by allowing differential discounting for private agents and policy makers. The former discount in the spirit of Nordhaus, calibrated to reflect market interest rates, while the latter are free to follow ethical considerations, in our model following Stern's view. To do so, we lower the *social* discount rate, ρ, from 1.5% to 0.1% per year and decreasing the degree of intergenerational inequality aversion, *IIA*, which equals the inverse of the intertemporal elasticity of substitution, from 1.45 to 1. The saving decisions of private agents thus continue to employ ρ = 1.5% per year and *IIA* = 1.45, the values used in DICE-2013R.[8] With a trend growth rate of 2% per year, the interest rate applied to private decisions is by the Keynes-Ramsey rule 1.5 + 1.45 x 2 = 4.4% per year but the interest rate applied to social decisions is 0.1 + 1 x 2 = 2.1% per year. So the difference between interest rates employed by the private sector and policy makers is 2.3% per year and this difference increases as economic growth slows along the growth path.

[8] We model the private and social decisions as a Stackelberg game with the government as the leader and private agents as followers. We assume that the government can commit to future policies. With differential discount rates, our equilibrium will be time inconsistent and future policy makers would like to deviate.

A lower discount rate increases the weight placed on the welfare future generations and strengthens climate policy. Peak warming falls to 2.0°C and the carbon price increases to as much as 91.3 $/tCO2 (see long dashed, green lines in Figure 3 and Table 5). Placing higher welfare weight on the future also increases the cost of inaction under BAU. Table 8 recalculates Table 3 for the case of differential discounting. If policy makers do the best under the worst possible view of the world, they price carbon as 968% exceeds 0% of world GDP. If they minimise the maximum regret from conducting the wrong policy, they also price carbon as the regret from pricing carbon if deniers turn out to be right, 160% of world GDP, is less than the regret from not pricing carbon if the scientists turn out to be right, 968% of world GDP. The case for pricing carbon, and ambitiously, is thus starkly enhanced.

Table 8: Welfare gains (% initial world GDP) under differential discounting

Climate view	Price carbon	Don’t price carbon
Science	968%	0%
Denier	991%	1151%
min welfare	**968%**	0%
max regret	**160%**	968%

6.4. Multiple types of model uncertainty: damage and growth uncertainty combined

So far we have only studied the risks stemming from damage and growth uncertainty separately. In reality, integrated assessment models of climate and the economy have been criticised severely (Pindyck, 2017) and it is a big improvement if it is recognised that policy makers need to face a multitude of known (and unknown) unknowns simultaneously (e.g., Heal and Millner, 2014; Rezai and van der Ploeg, 2017b; Brock and Sargent, 2017; Berger and Marinacci, 2017). Following the modular approach to formulating the problem of optimal climate formulation (cf., NAS, 2017; Rezai and van der Ploeg, 2017a), one could think of different damage models for the effect of temperature on aggregate production (additive versus multiplicative, more or less convex, etc.), different climate models for the stock of carbon in the atmosphere and global mean temperature (2-box, 3-box or 4- box models, including lags in temperature response or not, including positive feedback loops or not, etc.), different economic models (endogenous or exogenous growth, the global economy versus a multitude of countries, etc.) and different models of ethics and preferences (low or high discount rates, low of high willingness to sacrifice consumption for future generations). In this section we outline for purely illustrative purposes how climate policy robust to uncertain growth rates and damages from climate change could be derived.

Table 9 presents an extended version of the table format presented in previous sections. Each row corresponds to a state of the world in which damages are either high (as in section 6.1) or low (as in DICE2013R), expected future annual growth is either high (2%) or low (1%) and climate change can be real according to the view of the scientists or non-existent according to the view of the climate deniers. Each column represents a policy optimal for the corresponding state of the world (again, damages and growth being high or low). The last column gives the case of “laissez-faire” in which carbon is not priced. Entries in Table 9 are aggregate welfare expressed as a percentage of initial world GDP (averaged across all scenarios).

Table 9: Welfare losses in % initial average world GDP (relative regret) and robust policy in the presence of damage and growth uncertainty

		climate policies				
state of the world		high growth low damage	high growth high damage	low growth low damage	low growth high damage	Don’t price carbon
high growth low damage	Science	10520% (0%)	10519% (1%)	10518% (2%)	10520% (1%)	10504% (17%)
	Denier	10537% (8%)	10532% (13%)	10540% (5%)	10537% (8%)	10545% (0%)
high growth high damage	Science	10517% (2%)	10519% (0%)	10501% (18%)	10515% (4%)	10329% (189%)
	Denier	10537% (8%)	10533% (13%)	10541% (5%)	10538% (8%)	10546% (0%)
low growth low damage	Science	9693% (2%)	9690% (4%)	9694% (0%)	9694% (1%)	9683% (12%)
	Denier	9710% (12%)	9704% (17%)	9716% (6%)	9711% (11%)	9722% (0%)
low growth high damage	Science	9692% (1%)	9691% (2%)	9691% (2%)	9693% (0%)	9628% (65%)
	Denier	9711% (12%)	9705% (17%)	9716% (6%)	9712% (11%)	9723% (0%)
min welfare		9692%	9690%	9691%	**9693%**	9628%
max welfare		10537%	10533%	10541%	10538%	**10546%**
max regret		(12%)	(17%)	(18%)	**(11%)**	(189%)
max regret (excl. denier)		**(2%)**	(4%)	(18%)	(4%)	(189%)

Welfare under the science view is highest if the corresponding policy is implemented (i.e. in the table’s main diagonal, so 10520% for high growth and low damage, 10519% for high growth and high damage, et cetera). Under the denier view, welfare is maximised if carbon is not priced (i.e. in the table's final column). Numbers in brackets give regret for each model across all possible policies, relative to that state's optimal policy.

In selecting the maximum among the worst possible outcome associated with each policy option, max-min policy is the most *prudent* of the criteria we are considering. In our case, this worst outcome is the case of low growth and high damages and thus the max-min policy is the low-growth and high-damage policy. Max-max policy is the *optimistic* counterpart to max-min policy in evaluating a policy under its best outcome. Welfare is then maximised in the case of no climate change and no climate policy, since here there are neither the cost of climate change nor of its policy. The max-max policy is thus not to price carbon at all.

The numbers in brackets in Table 9 give the regrets of conducting the wrong policies for each view of the world (again in percent of initial average GDP). If we include the possibility that climate change is not induced by humans, maximum regrets of each policy is dominated by the extremes of implementing climate policy needlessly and erroneously not implementing climate policy. A policy with some but not too much climate policy (low-growth high-damage) minimises regret in the numerical example of Table 9. Climate policy becomes more ambitious if one excludes the possibility that climate change is fake. In this case, the baseline policy of DICE (high-growth low-damages) minimises regret as it balances the costs of overdoing climate policy if damages and growth are low and the costs of unambitious policy when damages are high and expected future growth is strong.

The analysis of Table 9 can also be carried out for the case where policy makers are not concerned about welfare but about peak warming levels. Policy makers are then interested in minimising peak warming in the hottest possible state of the world for each policy. As can be seen in Table 10, peak warming levels increase if economic growth is high and the policy implemented has either low growth or damages. If policy makers strive to limit peak warming to the lowest level in the hottest possible outcome, they implement the most ambitious climate policy available (i.e., high-growth high-damage) corresponding to peak warming of 2.9°C.

Table 10: Peak warming under damage and growth uncertainty

state of the world		policies: high growth low damage	high growth high damage	low growth low damage	low growth high damage	Don't price carbon
high growth low damage	Science	3.3°C	2.9°C	4.4°C	3.5°C	7.0°C
	Denier	1.4°C	1.4°C	1.4°C	1.4°C	1.4°C
high growth high damage	Science	3.3°C	2.9°C	4.4°C	3.5°C	6.7°C
	Denier	1.4°C	1.4°C	1.4°C	1.4°C	1.4°C
low growth low damage	Science	2.8°C	2.5°C	3.2°C	2.8°C	5.3°C
	Denier	1.4°C	1.4°C	1.4°C	1.4°C	1.4°C
low growth high damage	Science	2.8°C	2.5°C	3.2°C	2.8°C	5.2°C
	Denier	1.4°C	1.4°C	1.4°C	1.4°C	1.4°C
max peak warming		3.3°C	**2.9°C**	4.4°C	3.5°C	7.0°C

7. Conclusion

We conclude from our study of robust climate policies that the cost of avoiding the most harmful aspects of climate change is small compared with the cost of inaction, so robust policies such as doing the best under the worst possible outcomes or minimising the maximum regret call for pricing carbon to substantially curb global warming. Even for less cautious policies with finite but substantial degrees of ambiguity aversion towards climate model uncertainty and subjective prior probabilities that climate deniers are right as high as 20%, the price of carbon is close to the non-sceptic, scientifically optimal one. In fact, even if the subjective probability of climate deniers being right were 50%, possibly due to the odious influence of the coal and shale gas lobbies, peak warming would increase by less than 1°C and the end of the fossil fuel era would be delayed by only 30 years relative to the rational science-based view. This delay shortens as the prior probability that deniers are right falls or aversion to ambiguity, about whether scientists or deniers are right, increases. Agnostic decision makers might not want to make an assessment of the prior distribution of the different views of the climate as it is fundamentally unknown. In that case, the max-min solution and thus the science-based policy are appropriate. This is more strongly so if marginal damages rise steeply with global warming or if policy makers place more weight on the future than private agents do.

We focus on the uncertainty about whether anthropogenic global warming exists or not, but there are many, scientifically relevant uncertainties that decision makers need to account for in their assessment of climate change. We can think of uncertainty about the way the world economy is modelled, uncertainty about the way the various stocks of carbon in the oceans and in the atmosphere and their effect on global mean temperature are modelled, uncertainty about the damaging effect of global warming on aggregate production, consumption, and global welfare, and uncertainty about the relevant discount rate or willingness to sacrifice consumption today for the benefit of future generations. For illustrative purpose, we have used max-min and min-regret criteria to illustrate how uncertainties about damages and economic growth interact and conclude that prudent policy makers still prefer to price carbon ambitiously rather than do no climate policy at all. This kind of analysis is informative but only a first step. Further effort is needed to make policy truly robust to known unknowns using a modular approach (NAS, 2017) and inform updating of policy as unknown unknowns become known.

Scientific uncertainties are often cited in defence of not pricing carbon, giving politicians the subterfuge to avoid painful restructuring carbon-based industries and benefitting current generations by avoiding the economic burden of climate regulation. Our results, however, discredit this wait-and-see approach. We have not set out to disprove or prove either the climate deniers' or scientific view, but have used modern decision theory to show that agnostics should strive to decarbonise the economy rapidly as the consequences of erring on the "wrong" side are too grave. The agnostic policymaker's response to climate deniers is thus strikingly simply: price carbon!

References

Arrow, K. and L. Hurwicz (1977). An optimality criterion for decision-making under ignorance, in *Studies in Resource Allocation; Processes*, Cambridge University Press, Cambridge, U.K.

Barrage, L. (2016). Be careful what you calibrate for: social discounting in general equilibrium, mimeo., Brown University.

Belfiori, E. (2017). Carbon pricing, carbon sequestration, and social discounting, *European Economic Review*, 96, 1-17.

Below, D. von (2012). Optimal carbon taxes with social and private discounting, mimeo., Oxcarre, University of Oxford.

Berger, L. and M. Marinacci (2017). Model uncertainty in climate change economics, mimeo., IGIER, Bocconi University, Milan.

Bijgaart, I.M. van den, R. Gerlagh and M. Liski (2016). A simple rule for the social cost of carbon, *Journal of Environmental Economics and Management*, 77, 75-94.

Brock, W.A. and L. Hansen (2017). Wrestling with uncertainty in climate economic models, mimeo.

Dietz, S. and N. Stern (2015). Endogenous growth, convexity of damages and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal* 125, 583, 574-620.

Doran, P. T. and M. K. Zimmerman (2009). Examining the scientific consensus on climate change. *Eos, Transactions American Geophysical Union* 90, 3, 22-23.

Gilboa, I. and D. Schmeidler (1989). Maxmin expected utility with non-unique prior, *Journal of Mathematical Economics* 18, 141-153.

Golosov, M., J. Hassler and P. Krusell and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium, *Econometrica*, 82, 1, 48-88.

Heal, G. and A. Millner (2014). Uncertainty and decision in climate change economics, *Review of Environmental Policy*, 8, 1, 120-137.

Klibanoff, P., Marinacci, M. and S. Mukerji (2005). A smooth model of decision making under ambiguity. *Econometrica* 73, 6, 1849-1892.

Millner, A., Dietz, S. and G. Heal (2013). Scientific ambiguity and climate policy, *Environmental and Resource Economics* 55, 1, 21-46.

NAS, National Academies of Sciences, Engineering, and Medicine (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, The National Academies Press, Washington, DC. doi: 10.17226/24651.

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists* 1, 273-312.

Pascal, B. (1670). *Pensées* (Translated by W.F. Trotter), London, Dent, 1910).

Pindyck, R.S. (2017). The use and misuse of models for climate policy, *Review of Environmental Economics and Policy*, 11, 1, 100-114.

Ploeg, F. van der (2014). Abrupt positive feedback and the social cost of carbon, *European Economic Review*, 67, 28-41.

Rezai, A. and F. van der Ploeg (2016). Intergenerational inequality aversion, growth, and the role of damages: Occam's rule for the global carbon tax, *Journal of the Association of Environmental and Resource Economists*, 3, 2, 493-522.

Rezai, A. and F. van der Ploeg (2017a). Climate model uncertainty and the social cost of carbon: A modular approach, *mimeo*.

Rezai, A. and F. van der Ploeg (2017b). Climate policy under climate-model uncertainty: max-min and min-max regret, *Energy Economics*, forthcoming.

Savage, L.J. (1951). The theory of statistical decision, *Journal of the American Statistical Association*, 46, 55-67.

Savage, L.J. (1954). *Foundations of Statistics*, New York, John Wiley.

Schmitt, A. (2014). Optimal carbon and income taxation, *mimeo*, Ifo Institut, Munich.

Wald, A. (1945). Statistical decision functions which minimize the maximum risk. *The Annals of Mathematics* 46, 2, 265-280.

Weitzman, M. (2010). What is the "damage function" for global warming- and what difference does it make?, *Climate Change Economics* 1, 57-69.

Appendix: Model details and computational implementation

In our simulations we use the DICE2013R integrated assessment model in its baseline calibration. The key ethical parameters in this model are the pure rate of time preference (1.5% per annum) and the IIA (1.45). Damages to economic production are based on previous studies by Nordhaus, capturing market and non-market impacts. The remainder of the economic parameters is calibrated to the global economy with exogenous growth trajectories for total factor productivity and population. A 3-box carbon model and 2-box temperature model describe the climate dynamics. DICE2013R is a Ramsey growth model where all decisions are taken to maximise the present discounted value of aggregate utility. A social planner (or a government in the decentralised equilibrium described below) chooses a tax on carbon which incentivises the emission of less carbon. A representative household makes the consumption/saving decision. A detailed description of the integrated assessment model DICE2013R is given in (*5*). Further details on the specification and calibration of the economy, especially damages, and the climate are given in the model's user manual under

http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_100413r1.pdf.

The 'science' model corresponds to the original version of the DICE2013 model. The 'denier' model amends the carbon emissions equation by setting industrial carbon emissions to zero, so that only exogenous non-industrial carbon emissions are entering the atmosphere. Hence, the climate dynamics becomes independent of the economy and the climate externality disappears. Climate change in the 'denier' model still exists with temperature peaking at 1.3°C due to committed warming, but it is unaffected by the anthropogenic emissions of the economy. These two models give us the baseline cases of the 'science' and 'denier' policy for Table 3.

The fundamental theorem of welfare economics that guarantees that the command optimum can be decentralised in a market economy does not necessarily hold under climate model uncertainty. We therefore need to augment the DICE2013R model by deriving and adding the decentralised equilibrium of the global economy as a constraint. The decentralised equilibrium contains the firms' static and the households' intertemporal decision problems. The optimal saving decision for the representative household has to satisfy the Euler equation

$$\frac{C_{t+1}/L_{t+1}}{C_t/L_t}=\left(\frac{1+r_{t+1}}{(1+\rho)^{\Delta t}}\right)^{1/IIA}, \quad r_{t+1}\equiv(1-\delta)^{\Delta t}-1+\Delta t\,\varsigma_{t+1}\left(1-\frac{(1-\mu_{t+1})\Lambda'[\mu_{t+1}]}{1-\Omega[T_{t+1}^{atm}]-\Lambda[\mu_t]}\right). \qquad \text{(A1)}$$

This expression corresponds to the Ramsey-Keynes rule of the standard Ramsey growth model, but has been augmented to match the specifics of DICE where only output net of damages and mitigation costs are available for consumption and investment purposes. Growth of consumption per capita, C_t/L_t, increases in the ratio of the rate of interest, r_t, and the pure rate of time preference, δ, and especially so if the *IIA* is small. The rate of interest is a convoluted expression to meet the different time-steps of the DICE model where annual flows are compounded to a semi-decadal time scale (Δt = 5 years). Here δ is the annual depreciation rate, $\varsigma_t=\partial Y_t/\partial K_t$ is the rental rate of capital with $Y_t=\left(1-\Omega[T_{t+1}^{atm}]-\Lambda[\mu_t]\right)F\left[K_t,L_t\right]$ usable output after mitigation cost, $\Lambda[\mu_t]$, and climate damage, $\Omega[T_{t+1}^{atm}]$. The global policy maker maximises welfare, $W=\sum_{t=0}^{T}(1+\rho)^{-\Delta t}L_t\left[\frac{(C_t/L_t)^{1-\eta}-1}{1-\eta}\right]$, given the decentralised equilibrium. To achieve this, we add equation (A.1) as a constraint to the maximisation problem of DICE2013R. Policy makers choose a sequence of carbon prices or taxes, $\{\tau_t\}_{t=0}^{T}$, to maximise welfare. Since DICE has a one-to-one relationship between the share of emissions mitigated, μ_t, and the imposed carbon price or tax, τ_t, one can treat μ_t as the instrument directly.

In scenarios where optimal policy of one model is implemented in the other, we fix $\{\tau_t\}_{t=0}^{T}$, which computationally leaves the initial level of consumption C_0 to maximise welfare. Its optimal value will satisfy the terminal condition that the shadow value of capital has to equal zero in the terminal period. With climate model uncertainty policy makers have to choose the same policy time path $\{\tau_t\}_{t=0}^{T}$ across models and we add this uniformity constraint as a constraint to the maximisation problem of DICE2013R.