



**HAL**  
open science

# Optimal climate policy under tipping risk and temporal risk aversion

Romain Fillon, Céline Guivarch, Nicolas Taconet

► **To cite this version:**

Romain Fillon, Céline Guivarch, Nicolas Taconet. Optimal climate policy under tipping risk and temporal risk aversion. *Journal of Environmental Economics and Management*, 2023, 121, pp.102850. 10.1016/j.jeem.2023.102850 . hal-04250702

**HAL Id: hal-04250702**

**<https://hal.science/hal-04250702>**

Submitted on 19 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - ShareAlike 4.0 International License

# Optimal climate policy under tipping risk and temporal risk aversion

Romain Fillon<sup>1a,b</sup>, Céline Guivarch<sup>b</sup>, Nicolas Taconet<sup>b,c,d</sup>

<sup>a</sup> *Université Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, F-91120, Palaiseau, France*

<sup>b</sup> *CIREN, AgroParisTech, CIRAD, CNRS, EHESS, Ecole des Ponts ParisTech, Univ Paris-Saclay, UMR 8568. CIREN, 94736 Nogent-sur-Marne, France*

<sup>c</sup> *Potsdam Institute for Climate Impact research - Member of the Leibniz Association, Potsdam, Germany*

<sup>d</sup> *Technical University Berlin, Germany*

---

## Abstract

We investigate the implications of absolute risk aversion with respect to intertemporal utility, i.e. *temporal* risk aversion, in the presence of a stylized climate tipping risk affecting productivity irreversibly. Optimal climate policy is more stringent under temporal risk aversion, in order to reduce all present and future probabilities of crossing the tipping point and avoid a situation where all generations are badly off. Temporal risk aversion implies a 30% increase in the social cost of carbon (SCC) under our benchmark calibration and for a 10% irreversible increase in the level of economic damage from climate change. The optimal SCC under temporal risk aversion increases sharply with the level of damage brought by a potential tipping point.

**Keywords** : stochastic climate-economy modelling, risk-sensitive recursive preferences, environmental policy, risk aversion. **JEL classification** : D61, D63, D71, D81, Q54, Q58.

---

<sup>1</sup>Corresponding author: rfillon@protonmail.com

## 1. Introduction

When it comes to decision-making, risk is all around. But the concept is equivocal. First, it can refer to a univariate risk bearing on a single prospect. The seminal work from Pratt [42] and Arrow [6] introduced this risk into the analysis of decision-making through univariate measures of absolute and relative risk aversion within expected utility theory. A substantial body of literature has developed to generalise these measures of risk aversion to multivariate risks [31]. A risk-averse portfolio manager does not sum the risk of each asset, but considers the aggregate risk bearing on the portfolio. Indeed, a positive correlation between these asset risks increases the aggregate risk. In intertemporal settings, the absolute risk aversion with respect to aggregate intertemporal risk is called the *temporal risk aversion* [14]. The standard discounted expected utility model assumes temporal risk-neutrality [2]. This assumption has large implications as it implies that the decision-maker has no preference on the correlation between individual risks. Introducing absolute risk aversion with respect to intertemporal utility, i.e. temporal risk aversion, on the other hand, allows to consider risk bearing on aggregate intertemporal utility. It can explain agent's intertemporal decisions [11, 15]. It is also of interest from a normative point of view, to define optimal policies in risky social situations that involve several successive generations whose welfare is correlated.

A prominent example of intertemporal social risk management is climate policy-making. A major concern of climate policy-making is the possibility of non-linearities such as tipping points in the climate system. Once some thresholds for greenhouse gas concentrations in the atmosphere are exceeded, the state of the climate system could be radically and irreversibly altered. Tipping elements with significant economic implications have been identified, including the slowdown of the Atlantic Meridional Overturning Circulation, the West Antarc-

28 tic ice sheet disintegration, the Amazon rainforest dieback, or the Greenland ice  
29 sheet disintegration [5]. In the states of the world where the tipping point oc-  
30 curs, the welfare of all subsequent generations is affected by this qualitative  
31 regime change. Consequently, considering absolute risk aversion with respect  
32 to intertemporal utility becomes imperative due to the substantial impact on  
33 intertemporal welfare.

34 Temporal risk aversion can be interpreted as positive intertemporal correla-  
35 tion aversion [44], as positive intertemporal correlation implies a larger aggregate  
36 risk over intertemporal utility. A temporally risk-averse social planner prefers  
37 the welfare of different generations to be negatively or not correlated rather  
38 than positively correlated, in order to lower the risk on the aggregate outcome.  
39 In other words, the temporally risk averse social planner would be ready to give  
40 up some social welfare to prevent a situation where the tipping point is crossed  
41 and all subsequent generations are badly off. Thus, this social diversification  
42 strategy is appealing from a normative point of view when facing irreversible  
43 catastrophic tipping risks. Also, from a positive point of view, empirical elic-  
44 itations of individual preferences suggest that individual agents might exhibit  
45 positive correlation aversion [24, 3, 27, 45, 34].

46  
47 In this article, we investigate how temporal risk aversion may affect optimal  
48 climate policy. We analyze both analytically and numerically why, how and by  
49 how much two social planners, i.e. a temporally risk-neutral and a temporally  
50 risk-averse planner, differ in their optimal policy under risk. We focus on a  
51 specific type of risk: a climate tipping risk. We use a dynamic stochastic climate-  
52 economy model [28, 48] and extend it to an alternative social welfare function  
53 which allows the analysis of temporal risk aversion: the risk-sensitive preferences  
54 axiomatized in Hansen and Sargent [29]. By comparing optimal climate policies

55 under risk-sensitive preferences with those under the standard additive form  
56 of expected discounted utility, which assumes temporal risk-neutrality, we shed  
57 light on the implications of temporal risk aversion for policy design.

58 We find that, in the presence of a tipping risk, climate policy is more strin-  
59 gent under risk-sensitive preferences. The social planner under risk-sensitive  
60 preferences is willing to sacrifice more today to reduce all present and future  
61 probabilities of crossing the tipping point to avoid a situation of low overall  
62 intertemporal utility level. The difference in optimal climate policy between the  
63 two planners increases more than proportionally to the increase in the possible  
64 shock or in the temporal risk aversion. Under our benchmark calibration, a  
65 change from additive to risk-sensitive preferences implies a 30% increase in the  
66 social cost of carbon (SCC) for a 10% irreversible increase in the damage fac-  
67 tor. Switching from additive to risk-sensitive preferences under a 10% possible  
68 shock is equivalent to a 5 percentage points increase in the shock if we keep  
69 additive preferences. The difference between the two social choice criteria in-  
70 creases steeply with risk. Furthermore, other things being equal, a 50% decrease  
71 in pure time preference (from 1.5% to 1% yearly) is needed to obtain the same  
72 optimal policy under additive preferences as under risk-sensitive preferences for  
73 a 10% tipping risk and under our benchmark calibration. Thus, a change in the  
74 structure of the social welfare function can be directly compared to a change in  
75 the value of some parameters that have been highly debated. Finally, we use  
76 an analytical decomposition of our optimal policy program to derive the key  
77 channels through which a tipping risk affects optimal policy under both social  
78 welfare functions.

79  
80 Our work contributes to the literature aiming to enhance the integration of  
81 different types of risk, particularly the risk of climate tipping points [36, 52,

19], into stochastic integrated assessment models (IAM). The first integrated  
climate-economy models were deterministic, e.g. Nordhaus [40]. These mod-  
els did not allow for a proper consideration of risk and uncertainty in planner’s  
decisions, even when Monte Carlo analyses were conducted [21]. In parallel, con-  
tributions to modeling endogenous catastrophic environmental risk were mostly  
stylized [20, 50, 14]. In particular, these models are based on the assumption  
that welfare after the catastrophic event is exogenous and independent of the  
planner’s actions. Tipping points are less extreme than catastrophes after which  
production and consumption would be exogenous and independent of the plan-  
ner’s decisions. Indeed, these are ecological regime shifts with large economic  
consequences rather than complete economic or institutional collapses. These  
events are also different from reversible extreme events that occur as one-off  
catastrophes along a smoothly evolving climate regime with fluctuations, tra-  
ditionally modelled with Poisson and Wiener processes in the macroeconomics  
literature on disasters, e.g. in Bretschger and Vinogradova [17]. Departing from  
the assumption of a geometric Brownian motion with rare and reversible catas-  
trophic events, we study irreversible regime changes. This modelling approach  
has counterparts in the real business cycles literature studying markov switching  
rational expectations models with Bayesian learning, e.g. in Bullard and Singh  
[18].

Our contribution confronts the standard discounted expected utility model  
with an alternative criterion: a risk-sensitive criterion stemming from social choice  
theory and axiomatized in Bommier et al. [13]. Exploration of alternative social  
choice criteria under endogenous climate change was undertaken to introduce  
relative risk aversion under Epstein-Zin-Weil preferences [8, 51], a robust control  
penalty [46] and ambiguity aversion under isoelastic preferences in a setting with  
uncertainty [37]. In comparison with EZW preferences, risk-sensitive preferences

109 are the only recursive preferences axiomatized by Kreps and Porteus [33] that  
 110 admit a separation of risk and intertemporal attitudes, while being monotone  
 111 [13]. This desirable normative property ensures that a more risk-averse planner  
 112 consistently prioritizes risk reduction. Those preferences can be defined through  
 113 the following recursion [29, 13]:

$$114 \quad V_t = \begin{cases} (1 - \beta) u_t + \beta \mathbb{E}[V_{t+1}] & \text{if } \epsilon = 0 \\ u_t - \frac{\beta}{\epsilon} \ln[\mathbb{E}(\exp[-\epsilon V_{t+1}])] & \text{if } \epsilon \neq 0 \end{cases} \quad (1)$$

115 with  $u_t$  the instantaneous utility at time  $t$ ,  $\beta$  a discount factor derived from  
 116 pure time preference and  $\epsilon$  the temporal risk aversion. We hereafter use the  
 117 denomination of risk-sensitive preferences only for those stationary preferences  
 118 for which the social planner is at least as risk averse ( $\epsilon > 0$ ) as a standard  
 119 planner with additive preferences. Cases where the social planner is temporally  
 120 risk-seeking ( $\epsilon < 0$ ) are not discussed because of potential nonconvexity issues  
 121 [15]. A temporally risk-seeking planner would choose a max-max strategy and  
 122 positive correlation between the social gambles. If  $\epsilon = 0$ , then the social planner  
 123 is temporally risk-neutral, which comes down to the additive form.

124

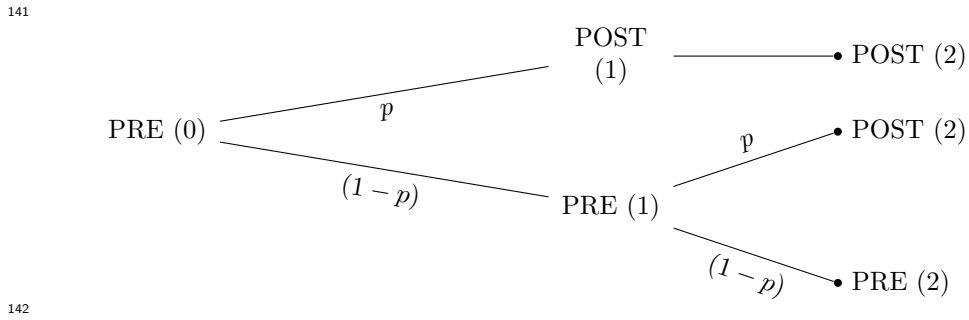
125 Firstly, we present our modelling approach (section 2): a dynamic stochastic  
 126 climate-economy integrated model with a stylized tipping risk, in which we  
 127 compare two alternative social welfare functions. Then, we discuss analytically  
 128 how temporal risk aversion affects optimal policy under a tipping risk (section 3).  
 129 Finally, we quantify numerically the differences between the two social welfare  
 130 functions under a tipping risk (section 4).

## 131 **2. A dynamic climate-economy stochastic model**

### 132 *2.1. A simple illustration*

133 Firstly, we illustrate the significance of temporal risk aversion in the analysis  
 134 of climate tipping risks using a simplified scenario. Consider three consecutive

135 time periods, representing distinct generations. Two climate regimes exist: pre-  
 136 tipping (PRE) and post-tipping (POST), each associated with different levels  
 137 of economic damage. Each generation  $t$  can either be in a high (PRE) or a low  
 138 (POST) welfare regime, described by the variable  $u_i^t$ ,  $i \in (pre, post)$ ,  $t \in 1, 2$ .  
 139 We assume that instantaneous welfare function in each potential situation is the  
 140 same for both generations, i.e.  $u_i^1 = u_i^2$ .



143 We assume away time discounting and assume that the social planner has no  
 144 preference on the order of the attributes and no preference for early resolution of  
 145 uncertainty. Under the conditions listed above, a temporally risk-neutral social  
 146 planner would be indifferent between the two following lotteries [10]:

147

$$\left\{ \begin{array}{l} (u_1^{post}, u_2^{post}) \text{ with probability } 1/3 \\ (u_1^{pre}, u_2^{post}) \text{ with probability } 1/3 \\ (u_1^{pre}, u_2^{pre}) \text{ with probability } 1/3 \end{array} \right. \sim \left\{ \begin{array}{l} (u_1^{post}, u_2^{post}) \text{ with probability } 1/2 \\ (u_1^{pre}, u_2^{pre}) \text{ with probability } 1/2 \end{array} \right. \quad (2)$$

148 A social planner under additive preferences would be indifferent between  
 149 the two social lotteries A and B as the additive form assumes temporal risk-  
 150 neutrality, while a temporally risk-averse social planner has a preference for  
 151 lottery A. In other words, a temporally risk-averse social planner is willing to  
 152 pay a temporal risk premium to hedge risks across generations and reduce the  
 153 probability of complete failure across all generations.

154 In addition to positive intertemporal correlation aversion, temporal risk aver-



155 sion bears preference for catastrophe avoidance<sup>2</sup> [14], i.e. preference for a mean-  
156 preserving contraction in the distribution of catastrophic risks. The preference  
157 for catastrophe avoidance is highly debated in the literature for two main rea-  
158 sons. First, it is not clear that individual agents are catastrophe-averse [43].  
159 Furthermore, preference for catastrophe avoidance may be seen as unethical as  
160 a catastrophe-averse planner prefers to concentrate risk on a single generation  
161 rather than spreading it evenly [25]. Consequently, Fleurbaey [26] highlights  
162 that catastrophe aversion might be appealing only if the catastrophe has a mul-  
163 tiplier effect through externalities in society. The possible nonconvexities in  
164 the human-environment system, enhanced by ecological thresholds like climate  
165 tipping points, do have this multiplier property. Indeed, in the states of the  
166 world where the tipping point occurs, the regime change is *irreversible* and has  
167 an impact on all future generations.

168

169 We have described in a simple illustration the importance of temporal risk  
170 aversion in risky intertemporal settings. We now present a full-fledged stochastic  
171 climate-economy model to analyse and quantify the importance of temporal risk  
172 aversion for the definition of optimal climate policy under a tipping risk.

## 173 2.2. The model

174 A climate-economy integrated assessment model aims to study the inter-  
175 actions between the economy and the climate system. We introduce a simple  
176 growth model *à la Ramsey*, add a stylized representation of the climate dynam-  
177 ics and an endogenous stochastic tipping point in the climate system. We build  
178 on Guivarch and Pottier [28] and Taconet et al. [48], update the economic dy-  
179 namics to match DICE-2016 [39] and use an alternative social welfare function.

---

<sup>2</sup>If the social planner is temporally risk-seeking ( $\epsilon < 0$ ), she favors risk equity, i.e. equalizing and spreading the risk among generations.

180

181 **Economy** In our global model, a single good is produced at each period  
182  $t$  using two production factors, endogenous capital  $K_t$  and exogenous labour  
183  $L_t$ , through a Cobb-Douglas production function  $F(K_t, L_t) = A_t K_t^\alpha L_t^{1-\alpha}$  with  
184 exogenous Hicks-neutral technological change. The gross output  $F(K_t, L_t)$  is  
185 affected by a damage factor  $\Omega_t(T_t)$  that increases with global average tem-  
186 perature  $T_t$ . Net output  $Y_t$  is derived from the gross output net of damage:  
187  $Y_t = \Omega_t(T_t)F(K_t, L_t)$ . Capital dynamics is determined by  $\delta$ , the per-period cap-  
188 ital depreciation, and  $s_t$ , the savings rate. It writes:  $K_{t+1} - K_t = -\delta K_t + s_t Y_t$ .  
189 Gross output induces emissions, which can be mitigated at a certain cost. The  
190 social planner trades off consumption  $C_t$ , mitigation costs (which represent a  
191 share  $\Lambda_t$  of  $Y_t$ ), and investment:  $C_t = Y_t(1 - \Lambda_t - s_t)$ . The mitigation cost  $\Lambda_t$   
192 depends on the abatement rate  $\mu_t$  and on the cost of the abatement technology  
193 that decreases due to exogenous technical progress. The cost of the abatement  
194 technology is calibrated on Nordhaus [39] as other parameters of the economic  
195 module.

196

197 **Climate** We use a simple representation for the climate system with a lin-  
198 ear formula linking temperature change to the stock of carbon emissions [23].  
199 This approach avoids overestimating the delay between emissions and temper-  
200 ature rise. Indeed, the link between cumulative emissions and temperature has  
201 been shown to be almost independent of time and emissions pathways except  
202 for very high emission pathways [35] such as the RCP 8.5: it should thus hold  
203 for any reasonable optimal policy scenario. Emissions are derived from out-  
204 put:  $E_t = \sigma_t Y_t(1 - \mu_t)$ , where  $\sigma_t$  is the carbon content of production that  
205 decreases exogenously over time. Emissions increase carbon concentration in  
206 the atmosphere and there is no decay. Equation for temperature change is:

207  $T_t = \psi \left( CE_0 + \sum_{s=0}^t E_s \right) = \psi S_t$  where  $T_t$  is the global temperature increase  
 208 (in comparison with the pre-industrial era) at time  $t$ ,  $CE_0$  is cumulated emis-  
 209 sions up to the first period of the model,  $E_s$  the emissions at time  $s$ ,  $S_t$  the  
 210 carbon stock in the atmosphere at time  $t$  and  $\psi$  the transient climate response  
 211 to cumulative carbon emissions (TCRE,  $\psi = 1.65^\circ\text{C}$  per TtC, according to  
 212 Masson-Delmotte et al. [38]).

213

214 **Tippling risk** We model one stylized endogenous tipping point that may de-  
 215 crease the output via an increase in the damage factor affecting the productivity.  
 216 The tipping point is endogenous as its probability of occurrence is a function of  
 217 global average surface temperature. If the tipping point is crossed, the damage  
 218 factor  $\Omega$  faces an irreversible  $J\%$  increase. The pre-tipping damage function  
 219 writes:  $\Omega_1(T) = 1 - \pi T^2$ . Once the tipping point is crossed, the damage in-  
 220 crease by  $J\%$  and the new damage function writes:  $\Omega_2(T) = (1 - J)(1 - \pi T^2)$ .  
 221 The damage occurs with no delay. The probability of tipping is modeled with a  
 222 uniform distribution between initial temperature increase with respect to pre-  
 223 industrial era and an upper temperature threshold<sup>3</sup> to make as few assumptions  
 224 as possible about the precise temperature at which a tipping event may occur.  
 225 Along the path, this specification allows learnings from the bayesian policy-  
 226 maker as she updates her beliefs on the location of the threshold in the state  
 227 space and on the probability of tipping at each period. The key assumption  
 228 from this specification of the potential tipping event is that there is no tipping  
 229 risk if the temperature is stabilized [36]. At each period  $t$ , the tipping point is

---

<sup>3</sup>The lower bound is the 2015 current excess temperature in comparison with the preindustrial era (0.87°C in 2015). The upper bound is set to 5.7°C according to the upper bound of the temperature increase reached in 2100 in RCP 8.5 [5]. See Appendix E.1 for a sensitivity analysis.

230 crossed with probability  $h_t$ :

$$231 \quad h_t(T_t, T_{t-1}) = \begin{cases} \frac{T_t - T_{t-1}}{T_{max} - T_{t-1}} & \text{if } T_t < T_{max} \\ 1 & \text{if } T_t \geq T_{max} \end{cases} \quad (3)$$

232 We have presented above a stochastic model with a stylized tipping point. A  
 233 second step is to use a social welfare function that allows the study of temporal  
 234 risk aversion. We present this function in more depth below. To allow compar-  
 235 ison with previous literature, we compare how two forms of social preferences  
 236 behave in a risky intertemporal social setting. The first form is the additive one.  
 237 The second form is the one of risk-sensitive preferences with positive temporal  
 238 risk aversion.

### 239 *2.3. Social preferences*

240 In our model, we write two Bellman equations for the two possible situations,  
 241 pre- and post-tipping, under the additive and the risk-sensitive social welfare  
 242 functions, as welfare is affected by a J% increase in the damage factor once the  
 243 tipping point is crossed. If the tipping point is crossed, the Bellman equation  
 244 writes the same way for the two programs. The two social welfare functions yield  
 245 the same policy in the risk-free post-tipping situation: temporal risk aversion  
 246 plays no role in these risk-free situations, whatever its level. Once the tipping  
 247 is crossed, all risk is solved: the tipping risk is the sole risk we study here. The  
 248 state variables of our optimization program are  $x_t = (S_t, K_t)$  respectively the  
 249 cumulative emissions stock and the capital stock at time t. The control variables  
 250 are  $y_t = (\mu_t, s_t)$ , respectively the abatement rate and the savings rate at time  
 251 t. The instantaneous utility function writes:  $u_t(x_t, y_t) = C_t^{1-\eta}/(1-\eta)$  with  $\eta$   
 252 the elasticity of marginal utility.

253

254 **Additive preferences** Under additive preferences, once the tipping point  
 255 is crossed, we have:  $U_t^{post}(x_t, y_t) = \max_{y_t} [u_t(x_t, y_t) + \beta U_{t+1}^{post}(x_{t+1})]$  under the

256 constraints:  $x_{t+1} = G(x_t, y_{t+1})$  and  $y_t \in \Gamma(x_t)$ , with  $\Gamma$  the space of possible  
 257 (positive) values for the control variables and  $G$  a transfer function. If the  
 258 tipping point has not been crossed yet at time  $t$ , then it may be crossed at  
 259 time  $t+1$  with probability  $h_{t+1}$  or the world can stay in a pre-tipping situation  
 260 with a probability  $(1 - h_{t+1})$ . The pre-tipping Bellman equation under additive  
 261 preferences and under the same constraints as above writes:

$$262 \quad U_t^{pre}(x_t, y_t) = \max_{y_t} [u_t(x_t, y_t) + \beta[(1 - h_{t+1})U_{t+1}^{pre}(x_{t+1}) + h_{t+1}U_{t+1}^{post}(x_{t+1})]] \quad (4)$$

263 **Risk-sensitive preferences** Once the tipping point is crossed, the pro-  
 264 gram under risk-sensitive preferences reduces to the additive one. If  $\epsilon = 0$ , the  
 265 program under risk-sensitive preferences reduces to the additive one. Finally,  
 266 it should be noted that  $V^{post} = U^{post}$ . The Bellman equation under the same  
 267 constraints in the pre-tipping situation writes:

$$268 \quad V_t^{pre}(x_t, y_t) = \max_{y_t} \left( u_t(x_t, y_t) - \frac{\beta}{\epsilon} \ln [(1 - h_{t+1}) \exp(-\epsilon[V_{t+1}^{pre}(x_{t+1})]) + h_{t+1} \exp(-\epsilon[V_{t+1}^{post}(x_{t+1})])] \right) \quad (5)$$

#### 269 2.4. Comparison with alternative social preferences

270 We compare the additive expected utility model to risk-sensitive preferences  
 271 in order to study temporal risk aversion. Two main other frameworks have  
 272 been used to study risk aversion under endogenous catastrophic climate change:  
 273 the Epstein-Zin-Weil framework (hereafter, EZW) and the multiplicative pref-  
 274 erences.

##### 275 2.4.1. Epstein-Zin-Weil preferences

276 EZW preferences have been widely used in risky intertemporal settings to  
 277 discuss optimal policy, e.g. in Cai and Lontzek [19], because of their flexibility,  
 278 which allows to disentangle preference over time and preference over states of  
 279 the world. We depart from it for two main reasons.

280 The first reason is that these preferences are monotone with respect to first-

281 order stochastic dominance<sup>4</sup> [13] only in the limit cases where relative risk aver-  
 282 sion equals the inverse of the elasticity of intertemporal substitution (they re-  
 283 duce to the standard additive model) or when the elasticity of intertemporal  
 284 substitution equals one (EZW preferences are then risk-sensitive). If EZW pref-  
 285 erences are well ordered in terms of risk aversion ‘in the large’ (willingness to  
 286 pay to eliminate all risks), those preferences are not well ordered in terms of risk  
 287 aversion ‘in the small’ (willingness to pay for marginal risk reductions). Thus,  
 288 a social planner under EZW preferences might choose dominated strategies in  
 289 social settings where it is not possible or optimal to eliminate all risk which  
 290 may precisely be the case with climate change. In particular, it has been shown  
 291 in the theoretical and applied literature that this non-monotonicity can lead to  
 292 two types of counter-intuitive behaviours. On the one hand, the EZW agent  
 293 can make more precautionary choices than necessary, choosing to build up more  
 294 precautionary savings in a risky situation than the savings chosen in the worst  
 295 state of the world that could occur under this risk if it happened determinis-  
 296 tically [13]. This leads to a more extreme behavior than a max-min approach.  
 297 On the other hand, the role of risk aversion could be non-monotone, meaning  
 298 that for a higher relative risk aversion and the same risk, the planner can be  
 299 less precautionous [32, 15]. The fact that such dominated strategies can be cho-  
 300 sen, even if not always, makes this criterion less appealing for the definition of  
 301 the optimal policy. Unlike the EZW framework, risk-sensitive preferences are  
 302 monotone with respect to first-order stochastic dominance, which means that  
 303 dominated strategies are never chosen. In particular, in our setting, we show  
 304 in annex Appendix C that the risk premium is always positive and increasing

---

<sup>4</sup>A social planner has preferences that respect first-order dominance if, for two lotteries A and B with A dominating B, she prefers A to B regardless of her utility function, as long as it is weakly increasing. The lottery A dominates B if it gives more wealth than B realization by realization.

305 in the temporal risk aversion  $\epsilon$ . When relative risk aversion is lower than the  
306 inverse of the elasticity of intertemporal substitution, EZW preferences show  
307 preference for late resolution of uncertainty and a negative risk premium, while  
308 risk-sensitive preferences exhibit preference for early resolution of uncertainty  
309 whenever  $\epsilon > 0$ . Risk-sensitive preferences thus allow a more rational social  
310 choice while preserving the flexibility and recursivity properties of the Kreps  
311 and Porteus [33] framework.

312

313 The second reason why we use risk-sensitive preferences rather than EZW  
314 preferences is that the coefficient of relative risk aversion studied in EZW pref-  
315 erences does not directly compare with the absolute risk aversion with respect  
316 to intertemporal utility studied under risk-sensitive preferences<sup>5</sup>, as a reduction  
317 in relative risk does not always come with a reduction in aggregate risk [12].  
318 A relative risk averse agent prefers to have non-extreme payoffs across states  
319 of the world within periods, while a temporally risk-averse planner prefers to  
320 have non-extreme payoffs across states of the world over the whole time horizon  
321 considered.

#### 322 2.4.2. *Multiplicative preferences*

323 The second form are the multiplicative preferences [14] that rule out pure  
324 time preference so that different generations are not given different utility weights  
325 because they were born at different dates. Instead, we use an intermediate form

---

<sup>5</sup>Risk-sensitive preferences use a constant *absolute* risk aversion certainty equivalent, whereas EZW preferences use a constant *relative* risk aversion certainty equivalent [14]. When comparing temporal lotteries of consumption, constant absolute risk aversion has been seen as unrealistic because risk aversion is the same for all levels of wealth under this assumption. Here, the constant absolute risk aversion certainty equivalent is applied to distributions of utility levels rather than consumption levels. This assumption is made under risk-sensitive preferences as monotonicity implies that risk aversion is considered with respect to aggregate utility. Thus, in order to preserve history independence, constant absolute risk aversion with respect to aggregate intertemporal risk ensures that the utility of the first periods does not impact social choice afterwards [13].

326 of risk-sensitive preferences that does not assume away time discounting for  
327 three reasons. Firstly, we do not include an extinction risk, so that without  
328 pure time preference, our undiscounted dynamic program would be too sensi-  
329 tive to the arbitrary terminal value and limit the comparability between the two  
330 programs. The second reason is that we want to analyze the sole role of tempo-  
331 ral risk aversion on social choice rather than intertwining this questioning with  
332 the debate between discounted and undiscounted utilitarianism [47, 40]. The  
333 third reason is the comparability between additive and risk-sensitive preferences.  
334 Indeed, additive and risk-sensitive social planners have the same rankings over  
335 deterministic consumption paths regardless of the value of the temporal risk  
336 aversion  $\epsilon$ . We can therefore simply vary  $\epsilon$  within a reasonable value range and  
337 make comparisons between the two social choice criteria under risk for different  
338 values of  $\epsilon$ .

339 We have characterized the additive and the risk-sensitive social welfare func-  
340 tions and explained how temporal risk aversion can be an important determi-  
341 nant of climate policy. We now assess analytically the impact of temporal risk  
342 aversion on optimal climate policy under a tipping risk.

### 343 **3. How does temporal risk aversion affect optimal policy under a** 344 **tipping risk?**

345 Firstly, we derive analytically the impact of temporal risk aversion on the  
346 optimal policy under a tipping risk. We decompose the pre-tipping value func-  
347 tions (4) and (5) which incorporate the risk of tipping and analyze the case  
348 where a single state variable determines the chance of crossing the threshold.  
349 We focus solely on  $S_t$ , the cumulated stock of emissions at time  $t$ . As we are  
350 considering optimal climate policy, we focus on the abatement rate  $\mu_t$  and derive  
351 the first-order condition of our policy programs. Our analytical decomposition  
352 is a two-step procedure. First, we decompose the immediate short-term effect



353 on next-period welfare of a marginal variation in abatement rate departing from  
 354 the optimum, following Lemoine and Traeger [36]. Then, we derive the complete  
 355 long-term effect of a marginal variation in the cumulative emissions stock on all  
 356 future probabilities of tipping. The decomposition is done for the additive and  
 357 risk-sensitive preferences: thus, we can derive how the channels through which a  
 358 tipping risk affects optimal policy under additive preferences adjust to temporal  
 359 risk aversion, in both the short and long term.

360

361 From the first-order condition of our policy programs, we show that the tip-  
 362 ping risk affects optimal policy through three short-term channels. The first  
 363 channel, the marginal hazard effect *mhe*, measures the impact of the control  
 364 variable on the immediate probability of tipping. The second channel, the dif-  
 365 ferential welfare impact *dwi*, measures the differential impact of the control  
 366 variable on welfare depending on the situation, i.e. pre- or post-tipping, and if  
 367 the tipping point is crossed. The last channel, the marginal impact pre-tipping  
 368 *mpre*, defines the decrease in next-period's welfare resulting from an increase  
 369 in the abatement policy if the tipping point has not been crossed yet: possible  
 370 future tipping points are included in this last channel. Removing all arguments  
 371 that are independent of  $\mu_t$  in equation (3), the value of the optimal policy  
 372 program in the pre-tipping situation under additive preferences writes:

$$373 \quad u_t[\mu_t^*] + \beta \underbrace{[h_{t+1}(\mu_t^*)U_{t+1}^{post}(\mu_t^*) + (1 - h_{t+1}(\mu_t^*))U_{t+1}^{pre}(\mu_t^*)]}_{U_{t+1}^{eff}} \quad (6)$$

374 The first term of equation (8) corresponds to the level of instantaneous utility  
 375 at time t for an optimal choice of the control variable  $\mu_t^*$ . The second term  
 376 gives the expected welfare at time t+1 when there is a probability of tipping  
 377 point under temporal risk neutrality and for an optimal choice of the control  
 378 variable, scaled by the discount factor  $\beta$ . Varying  $\mu_t$  gives us the immediate

379 decomposition under additive preferences characterizing optimal policy:  $u'_t =$   
 380  $\beta(dw_{t+1}^{add} + mhe_{t+1}^{add} + mpre_{t+1}^{add})$ , with the following channels:

$$381 \quad \left\{ \begin{array}{l} mhe_{t+1}^{add} = \frac{\partial h_{t+1}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial \mu_t} (U_{t+1}^{pre} - U_{t+1}^{post}) \\ dw_{t+1}^{add} = h_{t+1} \frac{\partial S_{t+1}}{\partial \mu_t} \left( \frac{\partial U_{t+1}^{pre}}{\partial S_{t+1}} - \frac{\partial U_{t+1}^{post}}{\partial S_{t+1}} \right) \\ mpre_{t+1}^{add} = -\frac{\partial U_{t+1}^{pre}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial \mu_t} \end{array} \right. \quad (7)$$

382 The risk-sensitive social planner maximizes at time  $t$  a utility function  $V_t$   
 383 which is linked to the random continuation utility  $V_{t+1}$  through the following  
 384 recursion:  $V_t = u_t + \beta\phi^{-1}(\mathbb{E}[\phi(V_{t+1})])$ . The function  $\phi$  writes  $\phi(V) = (1 -$   
 385  $\exp(-\epsilon V))/\epsilon$ . It is increasing and strictly concave for any  $\epsilon > 0$ . The value  
 386 of the optimal policy program in the pre-tipping situation under risk-sensitive  
 387 preferences is:

$$388 \quad u_t[\mu_t^*] + \beta \underbrace{\phi^{-1} [h_{t+1}(\mu_t^*)\phi(V_{t+1}^{post}(\mu_t^*)) + (1 - h_{t+1}(\mu_t^*))\phi(V_{t+1}^{pre}(\mu_t^*))]}_{V_{t+1}^{eff}} \quad (8)$$

389 The immediate decomposition under risk-sensitive preferences writes:  $u'_t =$   
 390  $\beta(dw_{t+1}^{rs} + mhe_{t+1}^{rs} + mpre_{t+1}^{rs})$ , with the following channels:

$$391 \quad \left\{ \begin{array}{l} mhe_{t+1}^{rs} = \frac{B_{t+1}}{\epsilon} \left( \frac{\partial h_{t+1}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial \mu_t} [exp(-\epsilon V_{t+1}^{post}) - exp(-\epsilon V_{t+1}^{pre})] \right) \\ dw_{t+1}^{rs} = B_{t+1} \left( h_{t+1} \frac{\partial S_{t+1}}{\partial \mu_t} \left[ \frac{\partial V_{t+1}^{pre}}{\partial S_{t+1}} exp(-\epsilon V_{t+1}^{pre}) - \frac{\partial V_{t+1}^{post}}{\partial S_{t+1}} exp(-\epsilon V_{t+1}^{post}) \right] \right) \\ mpre_{t+1}^{rs} = -B_{t+1} \left( \frac{\partial V_{t+1}^{pre}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial \mu_t} exp(-\epsilon V_{t+1}^{pre}) \right) \\ \text{with } B_{t+1} = ((1 - h_{t+1})exp(-\epsilon V_{t+1}^{pre}) + h_{t+1}exp(-\epsilon V_{t+1}^{post}))^{-1} \end{array} \right. \quad (9)$$

392 We highlight how temporal risk aversion implies an adjustment on these  
 393 channels in comparison with additive temporally risk-neutral preferences. We  
 394 extend the reasoning of Lemoine and Traeger [37] under uncertainty and ambi-  
 395 guity aversion to a related setting with risk and risk-sensitive preferences<sup>6</sup> and

<sup>6</sup>They use an isoelastic function for the transformation with uncertainty aversion in a setting with an ambiguous tipping point. The equivalent of risk-sensitive preferences in an

396 use their general approximations for the adjustments on the channels implied  
397 by a concave transformation of the additive social welfare function under a tip-  
398 ping risk. The complete procedure is depicted in Appendix A. The measure of  
399 absolute temporal risk aversion  $\left. \frac{-\phi''}{\phi'} \right|_{V^{eff}}$  is equal to  $\epsilon$ . We adjust the tempo-  
400 rarily risk-neutral marginal hazard effect channel  $mhe^{add}$  obtained from additive  
401 preferences to find the risk-sensitive marginal hazard effect  $mhe^{rs}$ :

$$402 \quad mhe^{rs} \approx mhe^{add} \left[ 1 + \epsilon \left( V^{eff} - \frac{V^{pre} + V^{post}}{2} \right) \right] \quad (10a)$$

403 where  $V^{post}$  is the continuation value if the tipping point has already been  
404 crossed,  $V^{pre}$  the continuation value if the tipping point has not been crossed  
405 yet and  $V^{eff}$  the random continuation value for an optimal choice of the policy  
406 variable. The amplitude and the sign of the adjustment can not be derived  
407 analytically. Indeed, an increase in temporal risk aversion  $\epsilon$  is counter-balanced  
408 by its negative impact on  $V^{eff}$  as  $V^{eff}$  is decreasing in  $\epsilon$ . In comparison with  
409 the arithmetic mean  $(V^{pre} + V^{post})/2$ , the two possible regimes in  $V^{eff}$  are  
410 weighted by the probability of (not) tipping, lower (higher) than one half in  
411 any optimal policy paths considered here. We thus expect the marginal hazard  
412 effect to be increasing with  $\epsilon$  in our setting. The marginal hazard effect, depict-  
413 ing the marginal impact of a marginal increase in abatement on the immediate  
414 probability of tipping, relates to the social value of catastrophic risk reduction  
415 [14] and the VSL-like parameter of Weitzman [53]. This channel is associated  
416 with self-protection in Lemoine and Traeger [36].

417

418 We then adjust<sup>7</sup> the temporally risk-neutral differential welfare impact  $dwi^{add}$   
419 to obtain the risk-sensitive differential welfare impact  $dwi^{rs}$ . This channel is de-

---

uncertain setting would be the multiplier criterion [13].

<sup>7</sup>Taken from [37], the approximation holds for a low shock.

420 pictured as self-insurance in Lemoine and Traeger [36]. The adjustment writes:

421

$$422 \quad dwi^{rs} \approx dwi^{add} + \epsilon h \left[ (V^{eff} - V^{pre}) \left( \frac{\partial V^{pre}}{\partial \mu} \right) - (V^{eff} - V^{post}) \left( \frac{\partial V^{post}}{\partial \mu} \right) \right] \quad (10b)$$

423 Similarly, the sign of the adjustment of temporal risk aversion on the risk-  
 424 neutral DWI cannot be determined analytically. An increase in the temporal  
 425 risk aversion  $\epsilon$  decreases  $V^{eff}$  and both terms in the bracket, so that the overall  
 426 sign depends on the relative level of the marginal welfare impact of the change  
 427 in policy variable in the pre-threshold and the post-threshold worlds as in the  
 428 temporally risk-neutral case. The adjustment decreases with the probability of  
 429 tipping. We expect this channel and the adjustment to be negligible. Indeed,  
 430 they depend on the value and the trajectory of the tipping probability with  
 431 respect to  $\epsilon$ . But the larger  $\epsilon$  is, the lower the probability of tipping, because  
 432 optimal policy under large temporal risk aversion is expected to be stricter. In  
 433 our specification as in Lemoine and Traeger [36, 37], the  $dwi$  might be com-  
 434 pletely overwhelmed by the  $mhe$ .

435

436 One can finally adjust the last channel: the direct impact of the change in  
 437 policy variable on the welfare if one stays in a pre-tipping situation in the next  
 438 period:

$$439 \quad mpre^{rs} = mpre^{add} \frac{\phi'(V^{pre})}{\phi'(V^{eff})} \quad (10c)$$

440 The adjustment implied by temporal risk aversion is the relative slope of the  
 441 transformed continuation value if we stay in a pre-tipping situation on the slope  
 442 of the transformed random continuation value. The size of the adjustment de-  
 443 pends on the concavity of  $\phi$ , i.e., the strength of temporal risk aversion  $\epsilon$ . This  
 444 term is equal to one when there is no tipping risk, i.e. if the temperature is sta-  
 445 bilized, and goes to 0 if the probability of tipping  $h$  increases. The adjustment  
 446 implied by temporal risk aversion decreases  $mpre$  unambiguously as  $V_{pre} > V_{eff}$ .

447

448 We have focused on the immediate impact of a marginal variation of the  
 449 policy variable around the optimum and identified the channels through which  
 450 the tipping risk affect next-period welfare under additive and risk-sensitive pref-  
 451 erences. So far, we have only analyzed the immediate channels (*mhe* and *dwi*)  
 452 and left all future impacts of a marginal change in the policy variable in the  
 453 pre-tipping continuation value included in *mpre* as in Lemoine and Traeger [37].  
 454 Indeed, today's emissions also affect all future probabilities of triggering the  
 455 tipping point. In order to recover the full impact of temporal risk aversion on  
 456 the optimal policy under a tipping risk, we need to decompose further this *mpre*  
 457 channel. We do not focus on the marginal impact of an increase in a control vari-  
 458 able (i.e. the abatement rate), but on the marginal impact on the pre-tipping  
 459 value function of a marginal increase in a state variable (the concentration stock  
 460 *S*). As we assume that there is no decay, a marginal increase in the concentration  
 461 stock can be analyzed as a marginal increase in carbon emissions. As in Jensen  
 462 and Traeger [30], we assume that the dynamic system is well-defined so that the  
 463 shadow value of the carbon concentration increase  $\partial V^{pre} / \partial S$  grows sufficiently  
 464 slowly along the optimal path to make the limit approach zero over our large  
 465 time horizon. We can advance the derivative of our pre-tipping value function  
 466 with respect to emissions by one period and reinsert it in itself:

$$467 \quad \frac{\partial V_t^{pre}}{\partial S_t} = u'_t - \beta \left( mhe_{t+1}^{rs} + dwi_{t+1}^{rs} - B_{t+1} \exp(-\epsilon V_{t+1}^{pre}) \left[ u'_{t+1} - \beta (mhe_{t+2}^{rs} + dwi_{t+2}^{rs} - B_{t+2} \exp[-\epsilon V_{t+2}^{pre}] \frac{\partial V_{t+2}^{pre}}{\partial S_{t+2}}) \right] \right) \quad (11)$$

468 Iterating the procedure eventually yields a general expression of the marginal  
 469 impact of a marginal increase in carbon emissions on all present and future  
 470 periods. The complete decomposition under risk-sensitive preferences writes:

$$471 \quad \frac{\partial V_t^{pre}}{\partial S_t} = u'_t - \beta [mhe_{t+1}^{rs} + dwi_{t+1}^{rs}] + \sum_{i=t+1}^{\infty} \beta^{i-t} \left( \prod_{k=t+1}^i \underbrace{\frac{\phi'(V_k^{pre})}{\phi'(V_k^{eff})}}_{\text{adjustment}(mpre)} \right) (u'_i - \beta [mhe_{i+1}^{rs} + dwi_{i+1}^{rs}]) \quad (12)$$

472 The *mpre* channel of the immediate decomposition disappears. To differentiate  
473 them from the immediate decomposition terms, the full decomposition terms are  
474 in capital letters. The complete decomposition  $\partial V_t^{pre} / \partial S_t = U'_t - MHE_t^{rs} -$   
475  $DWI_t^{rs}$  now includes all present and future effects:

$$476 \quad \left\{ \begin{array}{l} U'_t = u'_t + \sum_{i=t+1}^{\infty} \beta^{i-t} \left( \prod_{k=t+1}^i \frac{\phi'(V_k^{pre})}{\phi'(V_k^{eff})} \right) u'_i \\ MHE_t^{rs} = \beta mhe_{t+1}^{rs} + \sum_{i=t+1}^{\infty} \beta^{i-t+1} \left( \prod_{k=t+1}^i \frac{\phi'(V_k^{pre})}{\phi'(V_k^{eff})} \right) mhe_{i+1}^{rs} \\ DWI_t^{rs} = \beta dwi_{t+1}^{rs} + \sum_{i=t+1}^{\infty} \beta^{i-t+1} \left( \prod_{k=t+1}^i \frac{\phi'(V_k^{pre})}{\phi'(V_k^{eff})} \right) dwi_{i+1}^{rs} \end{array} \right. \quad (13)$$

477 The complete  $MHE^{rs}$  and  $DWI^{rs}$  depend on the sign and amplitude of all  
478 the present and future immediate  $mhe^{rs}$  and  $dwi^{rs}$ , and all future effects are  
479 scaled by the discount factor and the positive adjustment implied by temporal  
480 risk aversion. We have described analytically how temporal risk aversion changes  
481 the various channels through which a tipping risk affects a decision-maker, both  
482 short and long term. We assess numerically the impact of temporal risk aver-  
483 sion in a dynamic climate-economy stochastic model under a tipping risk and  
484 quantify the different channels depicted.

## 485 4. A numerical investigation

### 486 4.1. Calibration

487 We use the same specifications for the macroeconomic model as Nordhaus  
488 [39]. We use typical ranges of possible values for the key parameters. The pure  
489 rate of time preference  $\rho$  is 1.5% [39]. The marginal utility parameter  $\eta$  is set  
490 to 1.5 with a sensitivity analysis from 0.5 to 2.5. We explore a large range for  
491 the shock  $J$ , ranging from 0 to 10% as explored in van der Ploeg and de Zeeuw  
492 [51], Cai and Lontzek [19] and van der Ploeg and de Zeeuw [52].

493 Social planners under additive and risk-sensitive preferences have the same  
494 ordering over deterministic consumption paths<sup>8</sup>. Thus, we can make compar-

---

<sup>8</sup>On the contrary, this is not the case for all values of  $\epsilon$  under multiplicative preferences that

495 isons between the two social choice criteria under risk for different values of  $\epsilon$ .  
 496 We look for a range of plausible values for this parameter and a benchmark value  
 497 within it to set a default value and perform a sensitivity analysis. The range of  
 498 values used in the literature is large. Anderson [4] uses 0.1, 1 and 2 to study the  
 499 dynamics of optimal Pareto allocations of risk-sensitive agents. When studying  
 500 precautionary savings, Bommier et al. [13] explore large values ranging from 0  
 501 to 4, and Bommier and Le Grand [15] explore very large values, up to 100. In  
 502 order to reduce the plausible range, we use the fact that, when the elasticity of  
 503 intertemporal substitution is set to one, the EZW preferences are risk-sensitive  
 504 preferences [49]. Indeed, risk-sensitive and EZW preferences are special cases  
 505 of the more general family of recursive Kreps and Porteus [33] preferences. An  
 506 analytical relation between the temporal risk aversion on the one hand and pure  
 507 time preference  $\rho$  and relative risk aversion  $\chi$  of EZW preferences on the other  
 508 hand can thus be formulated in this precise case:  $\epsilon = -(1 - \beta)(1 - \chi)$  with  $\chi$  the  
 509 coefficient of relative risk aversion with respect to atemporal wealth gambles,  
 510 and  $\beta$  the discount rate. Following the IAM literature calibration for  $\chi$  [1, 19],  
 511 we use  $\chi = 10$  as a benchmark and run a sensitivity analysis around this value.  
 512 In our benchmark case, with  $\chi = 10$  and  $\rho = 1.5\%$  yearly, we have  $\epsilon = 0.133$ .  
 513 A low  $\chi = 1.1$  would yield  $\epsilon = 0.0015$  while a large  $\chi = 20$  would yield  $\epsilon = 0.3$ .  
 514 The lower the pure time preference, the lower the difference between additive  
 515 and risk-sensitive preferences [14]. Our benchmark measure may not be adapted  
 516 to social settings : a welfare-maximizing social planner might be more tempo-  
 517 rally risk averse than individuals when a catastrophic and irreversible risk bears  
 518 on all future generations. In an empirical elicitation of the aversion towards

---

are undiscounted ( $\rho = 0$ ). Thus, Bommier et al. [14] have to rely on a specific calibration of  $\epsilon$  so  
 that additive and multiplicative preferences yield the same discount rate and are comparable.  
 The calibration of  $\epsilon$  under multiplicative preferences depends on the form of the instantaneous  
 utility, the level of pure time preference and the post-tipping exogenous consumption.

519 correlated risks in the context of donations to risky aid projects, Gangadharan  
520 et al. [27] find that individuals are more averse to correlated risks when they  
521 donate other people’s money. This is an interesting line of thought for climate  
522 change, where the contemporary social planner has to choose an appropriate  
523 level of temporal risk aversion for other generations than the one he belongs to.  
524 Thus, our benchmark value for the temporal risk aversion is conservative and  
525 in the lower bound of those estimates.

526 *4.2. A comparison of the two social welfare functions under risk*

527 We derive the optimal climate policy under the two social welfare functions  
528 in a risky intertemporal social setting using dynamic programming. Details of  
529 the resolution are in Appendix B. A key instrument to compare optimal policy  
530 along the trajectory is the social cost of carbon (SCC) at initial time. For both  
531 specifications, it writes:  $-\beta(\partial_S \mathbb{E}[W_1]|_{y_1} / \partial_C W_0|_{x_0, y_0^*})$  with  $y_0^*$  the optimal  
532 abatement and investment of the program at initial time given  $x_0$  and  $\beta$  the  
533 discount rate derived from pure time preference.  $W$ , the value function, can be  
534  $U$  (additive) or  $V$  (risk-sensitive). Figure 1 gives the absolute value of the SCC  
535 ( $\$/tC$ ) under additive and risk-sensitive preferences at initial time for a range  
536 of irreversible increase in the damage factor  $J$  and the ratio of the SCC under  
537 risk-sensitive preferences to the SCC under additive preferences for various  $\epsilon$   
538 and  $J$ .

539 We can draw three conclusions from the graphs above. First, optimal cli-  
540 mate policy under risk-sensitive preferences is more stringent for any value of  
541  $\epsilon$  and  $J$  than under additive preferences. An increase in temporal risk aversion  
542 unambiguously leads to an increase in the social cost of carbon due to the mono-  
543 tonicity of risk-sensitive preferences. The second conclusion is that switching  
544 from additive to risk-sensitive preferences under a tipping risk induces a large  
545 change in optimal policy: the form of the social welfare function matters, as



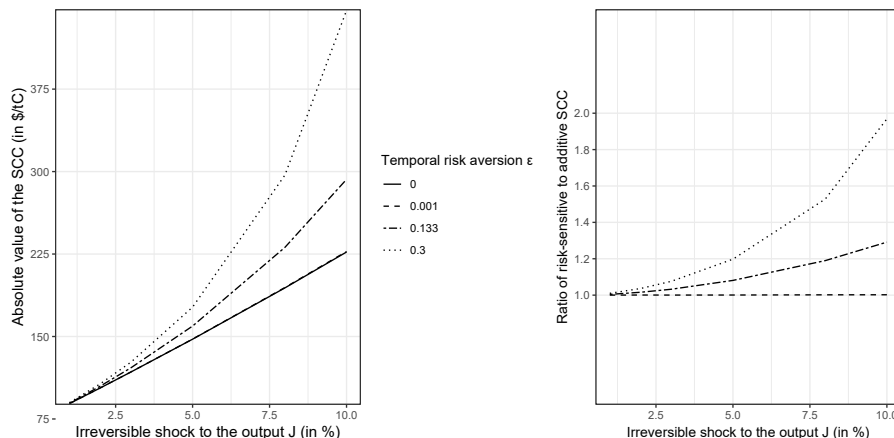


Figure 1: Absolute values of the additive and risk-sensitive SCC (in \$ per tC) at initial time (left) and ratio of the risk-sensitive SCC to the additive SCC (right) for various J and  $\epsilon$  under our benchmark calibration ( $\eta = 1.5$ ,  $\rho = 1.5\%$ ). The curves overlap for the two smallest values of  $\epsilon$  in the left-hand graph. Same graphs with a wider range for J are given in Appendix E.1.

546 already highlighted in Bommier et al. [14] for more catastrophic collapses. For  
 547 a tipping point inducing a 10% irreversible increase in the damage factor, the  
 548 SCC under risk-sensitive preferences is 30% higher than under additive prefer-  
 549 ences under our benchmark  $\epsilon = 0.133$ : it goes from 227\$ per tC to 293\$ per  
 550 tC. This difference is increasing with the size of the possible shock J: the larger  
 551 the tipping risk, the larger the difference between the optimal policies. Finally,  
 552 temporal risk aversion plays a key role: under risk-sensitive preferences, for the  
 553 largest  $\epsilon = 0.3$ , the SCC at initial time is 2-times higher than under additive  
 554 preferences for a 10% shock. The slope of the ratio of the risk-sensitive SCC  
 555 to the additive SCC is also increasing with  $\epsilon$ . Increasing temporal risk aversion  
 556 increases unambiguously the weights attributed to the catastrophic states of  
 557 the world where numerous generations are badly off with a low intertemporal  
 558 utility level. We run a sensitivity analysis in Appendix E.3 to check if our result  
 559 is not affected by the calibration of the inequality aversion parameter  $\eta$ . The  
 560 ratio of the risk-sensitive to the additive SCC is increasing in the value of the

561 inequality aversion  $\eta$ . The SCC under risk-sensitive preferences is larger than  
562 under additive preferences for any value of  $\eta$  explored here.

563

564 To illustrate the magnitude of the change in optimal climate policy arising  
565 from temporal risk aversion, we show how switching from additive to risk-  
566 sensitive preferences compares with changes in the value of some parameters  
567 under additive preferences. We focus on two parameters that have been subject  
568 to debates in the literature. On the one hand, we consider the rate of pure  
569 time preference  $\rho$  [47, 40]. On the other hand, we focus on the value of the  
570 economic damage generated by climate change [41], and more specifically by a  
571 climate tipping point. First, Figure 2 (left) shows how a change from additive to  
572 risk-sensitive preferences compares to a change in  $\rho$  under additive preferences.  
573 Switching from additive to risk-sensitive preferences under a 10% tipping risk  
574 and for our benchmark calibration of the temporal risk aversion ( $\epsilon = 0.133$ )  
575 is equivalent to a 50% decrease in the value of  $\rho$  under additive preferences.  
576 In other words, the optimal policy derived from risk-sensitive preferences for  
577 our benchmark calibration ( $\epsilon = 0.133$ ,  $\eta = 1.5$ ,  $\rho = 1.5\%$ ) and under a 10%  
578 tipping risk is obtained under additive preferences when  $\rho = 1\%$  other things  
579 being equal. Figure 2 (right) shows that it takes a 14% shock for the addi-  
580 tive preferences to give the same SCC as for a 10% irreversible increase in the  
581 damage factor under risk-sensitive preferences. The difference between the two  
582 approaches becomes more pronounced as the level of risk intensifies.

583 The numerical estimation of the channels analytically depicted in section (3)  
584 provides an understanding of the channels through which a tipping risk affects  
585 a temporally risk-averse planner. In our analytical decomposition, we firstly  
586 derived the channels through which a marginal increase in the policy variable  
587 departing from the optimum affects welfare in the next period under a tipping

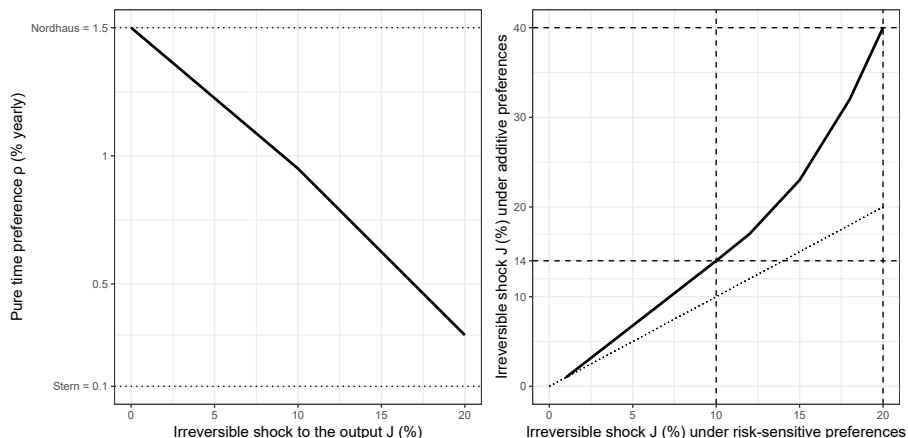


Figure 2: Equivalence in  $\rho$  (left) and  $J$  (right) needed to obtain the same SCC at initial time under additive and risk-sensitive preferences under our benchmark calibration. On the left, we represent the pure time preference ( $\rho$ ) that is needed under additive preference (all else being equal) to match the risk-sensitive SCC for various  $J$ . On the right, we represent the irreversible shock  $J$  that is needed under additive preference (all else being equal) to match the risk-sensitive SCC for various  $J$ . The dotted line from the right-hand graph is the identity function.

588 risk and for a risk-sensitive planner. Thus, we have left aside all the future  
 589 impacts on subsequent periods in this immediate decomposition, in particular  
 590 the impact of the change in the policy variable on all future probabilities of  
 591 crossing the threshold. Then, we have performed a full decomposition to take  
 592 into account the impact of this change in policy on welfare in all future periods:  
 593 this is the complete decomposition. We have shown that there are two channels  
 594 through which tipping risk can influence optimal policy: the marginal hazard  
 595 effect (immediate and complete) and the differential welfare impact (immediate  
 596 and complete). We now run a numerical estimation of these channels to un-  
 597 derstand how temporal risk aversion may affect the channels through which the  
 598 tipping risk affects the planner.

599 We can draw two conclusions from Figure 3. First, we see from our numerical  
 600 estimation that the main channel is the marginal hazard effect. Indeed, the  
 601 planner is ready to give up welfare in order to reduce all present (immediate)

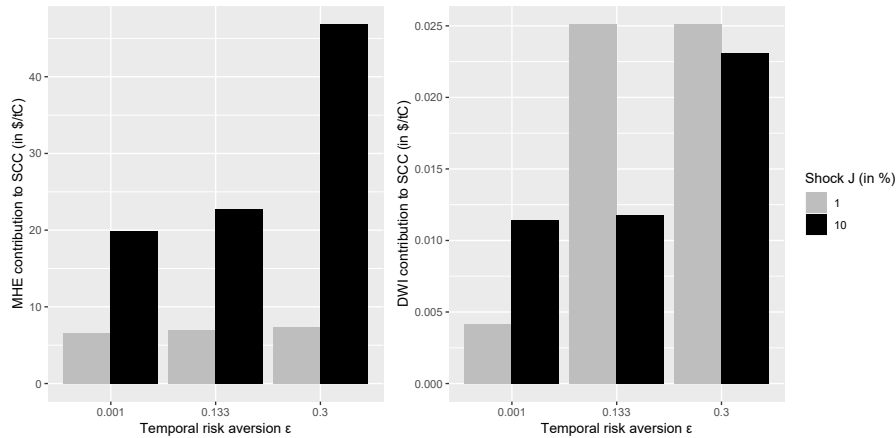


Figure 3: The graphs give the marginal contributions to the SCC at initial time (in \$) of the complete *MHE* (left) and the complete *DWI* (right) under risk-sensitive preferences for various  $J$  and  $\epsilon$ . The scales for the two graphs are different because the two channels are several orders of magnitude apart. We give the same graphs for the immediate decomposition in Appendix E.4.

602 and future (complete) probabilities of crossing the threshold. This is partly due  
 603 to the setting generally chosen in the literature to represent tipping points, as  
 604 we do not model adaptation as an endogenous choice, which could for example  
 605 decrease the level of damage  $J$ . Whether some form of adaptation can decrease  
 606 the damage of such regime shifts remains uncertain, thus justifying its exclusion  
 607 from our framework. The second conclusion from the numerical estimation  
 608 is that the marginal hazard effect channel is increasing in the possible shock  
 609 and in temporal risk aversion. A higher temporal risk aversion increases the  
 610 stringency of the optimal policy, as highlighted above, and decreases even further  
 611 the relative weight of the differential welfare impact in comparison with the  
 612 marginal hazard effect.

## 613 5. Discussion

614 We study analytically and numerically in an integrated model with a stochas-  
 615 tic tipping risk the role of absolute risk aversion with respect to intertemporal

616 utility, i.e. temporal risk aversion. We compare the optimal climate policy  
617 arising from the expected discounted utility model to a risk-sensitive social wel-  
618 fare function exhibiting temporal risk aversion. A temporally risk-averse social  
619 planner maximising the welfare of successive generations prefers to lower the  
620 possibility of an irreversible damage bearing on all subsequent generations. In  
621 this sense, she adopts a social risk diversification strategy to hedge against po-  
622 tential environmental regime shifts.

623 First, while the two social welfare functions yield the same optimal climate  
624 policy in a risk-free setting, they differ once a tipping risk is introduced. As-  
625 sumptions regarding the structure of the social welfare function appear as least  
626 as important as the debated value of some parameters in the expected utility  
627 model, such as the damage from a tipping point or the value of pure time pref-  
628 erence. It should be emphasized that the assumption of temporal risk neutrality  
629 embedded in expected utility, while justifiable in risk-free models with smooth  
630 climate change, may not adequately capture possible non-linearities and abrupt  
631 regime changes in the climate system, which have been extensively documented  
632 in climate science [5]. Ignoring temporal risk aversion may lead to underesti-  
633 mating the severity of climate risks and result in more lenient climate policies.  
634 Therefore, considering temporal risk aversion becomes crucial when studying  
635 correlated intertemporal social risks.

636 Second, optimal policy under temporal risk aversion is more stringent than  
637 under temporal risk neutrality. The difference between the two social welfare  
638 functions increases more than proportionally to the increase in the shock  $J$  or  
639 the temporal risk aversion  $\epsilon$ . For a 10% irreversible increase in the damage  
640 factor, the SCC under temporal risk aversion is 30% higher than the SCC under  
641 risk neutrality under our benchmark calibration. Our key take-away is that  
642 if one believes that major catastrophes bearing large multiplier effects such

643 as irreversible regime shifts are possible, the social planner's aversion towards  
644 those risks bearing on intertemporal utility should be accounted for. On the  
645 other hand, if there is no such risk or if the possible damage is low, then we  
646 should stick to the additive model as it does not come with the ethical drawbacks  
647 catastrophe aversion bears.

648 The last conclusion is that optimal climate policy in our setting is mainly  
649 driven by the marginal hazard effect. The tipping risk affects optimal policy as  
650 the social planner wants to reduce all present and future probabilities of cross-  
651 ing the tipping point. This channel is increasing in the possible shock  $J$  and  
652 increasing in the temporal risk aversion. The risk-sensitive planner is willing to  
653 give up more wealth to avoid the catastrophic event.

654

655 Our analysis suffers three main limitations. Firstly, our model, although  
656 including a stochastic risk, suffers from the limitations often pointed out in in-  
657 tegrated climate-economy models: the specification of the damage function, the  
658 exogenous technological change dynamics and the assumptions regarding future  
659 growth are for example uncertain. Secondly, our representation of tipping points  
660 is limited, as we focus on a single tipping point and do not consider various char-  
661 acteristics, such as their probability of occurrence, reversibility, abruptness, and  
662 time horizons. Additionally, our tipping probability is solely a function of global  
663 temperature, while other drivers, such as deforestation, can also contribute to  
664 tipping points. These limitations leave room for further research to provide a  
665 more comprehensive and precise representation of climate tipping points and  
666 damages. Lastly, our model assumes known probabilities for the tipping risk.  
667 Under ambiguity about the tipping points, a temporally risk averse planner  
668 might not prefer higher diversification [9].

669 Finally, we do not take any stance on what the *right* social welfare function

670 is. This question remains open to scientific and public debates. In particular,  
671 the risk-sensitive social planner is not an expected utility maximizer. This may  
672 be defensible as one may ‘accept the sure-thing principle for individual choice  
673 but not for social choice, since it seems reasonable for the individual to be  
674 concerned solely with final states while society is also interested in the process  
675 of choice’ [22]. Temporal risk aversion helps us understand the specificity of the  
676 social choice issue climate change raises when it is considered not as a linear and  
677 smooth phenomenon, but as a phenomenon that can give rise to non-linearities  
678 and abrupt regime changes. A future research avenue could be to elicit the  
679 value that individuals would give to this parameter in the context of normative  
680 intergenerational social choice.

681 If our analysis is applied to a stylized climatic tipping risk, we believe that  
682 risk-sensitive preferences and temporal risk aversion might be used for the study  
683 of more standard smooth risks, as long as they are endogenous and correlated.  
684 Indeed, as risk-sensitive preferences exhibit preference for catastrophe avoid-  
685 ance when the social planner has temporal risk aversion, they comply with a  
686 weaker pareto axiom in comparison with additive preferences [16]: this axiom  
687 states that there is no difference between the social planner’s and the individ-  
688 uals’ preferences as long as uncorrelated risks are considered, but that some  
689 divergence may occur when correlated risks are at play. This intertemporal so-  
690 cial choice criterion might thus bear critical implications for the management  
691 of correlated risks, for instance the large aggregate social risks due to potential  
692 ecological thresholds (e.g. biodiversity collapse).

693 **Appendix A. Analytic decomposition details**

694 We follow Lemoine and Traeger [37] to find an analytic approximation of  
 695 how the risk-neutral channels adjust under temporal risk aversion. In addition,  
 696 we disentangle  $mpre$  from  $dwi$ . Starting from expression of  $mhe^{add}$  and  $mhe^{rs}$   
 697 in equation (7) and (9), we write:

$$698 \quad mhe_{t+1}^{rs} = \frac{\partial h_{t+1}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial \mu_t} \left( \frac{\phi(V_{t+1}^{pre}) - \phi(V_{t+1}^{post})}{\phi'(V_{t+1}^{eff})} \right) \quad (A.1)$$

699 Thus:

$$700 \quad mhe_{rs} = mhe_{add} \underbrace{\frac{\phi(V^{pre}) - \phi(V^{post})}{\phi'(V^{eff})(V^{pre} - V^{post})}}_{adj_{mhe}} \quad (A.2)$$

701 and recall that  $\phi(V) = (1 - \exp(-\epsilon V))/\epsilon$ . A second order Taylor expansion  
 702 for  $\phi(V^i)$  around  $\phi(V^{eff})$  gives:  $\phi(V^i) \approx \phi(V^{eff}) + \phi'(V^{eff})[V^i - V^{eff}] +$   
 703  $\frac{1}{2}\phi''(V^{eff})[V^i - V^{eff}]^2 + O([V^i - V^{eff}]^3)$ . We have:

$$704 \quad \phi(V^{pre}) - \phi(V^{post}) \approx \phi'(V^{eff})[\phi(V^{pre}) - \phi(V^{post})] + \frac{1}{2}\phi''(V^{eff})[(V^{pre})^2 - (V^{post})^2 + 2V^{eff}(V^{post} - V^{pre})] \quad (A.3)$$

705 And :

$$706 \quad adj_{mhe} \approx 1 + \frac{-\phi''}{\phi'} \Big|_{V^{eff}} \left[ V^{eff} - \frac{V^{pre} + V^{post}}{2} \right] \quad (A.4)$$

707 This yields our final expression for the adjustment implied by temporal risk  
 708 aversion on  $mhe^{rs}$ . Expression for  $dwi^{add}$  is in equation (7). For  $dwi^{rs}$  in  
 709 equation (9), we use a more restricted expression than Lemoine and Traeger [37].  
 710 Indeed, we exclude  $mpre$  from  $dwi$  and consider only the differential impact of  
 711 a marginal increase in the pre and post tipping if the tipping point is actually  
 712 crossed (with probability  $h$ ). The expression writes:

$$713 \quad dwi_{t+1}^{rs} = h_{t+1} \frac{\partial S_{t+1}}{\partial \mu_t} \left( \frac{\phi'(V^{pre})}{\phi'(V^{eff})} \frac{\partial V_{t+1}^{pre}}{\partial S_{t+1}} - \frac{\phi'(V^{post})}{\phi'(V^{eff})} \frac{\partial V_{t+1}^{post}}{\partial S_{t+1}} \right) \quad (A.5)$$



714 Then, we can write:

$$715 \quad dwi_{t+1}^{rs} = dwi_{t+1}^{add} + h_{t+1} \frac{\partial S_{t+1}}{\partial \mu_t} \left( \left[ \frac{\phi'(V^{pre})}{\phi'(V^{eff})} - 1 \right] \frac{\partial V_{t+1}^{pre}}{\partial S_{t+1}} - \left[ \frac{\phi'(V^{post})}{\phi'(V^{eff})} - 1 \right] \frac{\partial V_{t+1}^{post}}{\partial S_{t+1}} \right) \quad (\text{A.6})$$

716 We do a first-order approximation of  $\phi'(V^i)$  for  $i \in \{pre, post\}$  as Lemoine  
 717 and Traeger [37], assuming that the tipping point does not cause too large a  
 718 welfare loss, to obtain  $\frac{\phi'(V^i)}{\phi'(V^{eff})} - 1 \approx \frac{\phi'(V^{eff}) + \phi''(V^{eff})[V^i - V^{eff}]}{\phi'(V^{eff})} - 1 \approx -\epsilon(V^i -$   
 719  $V^{eff})$ . This approximation, together with equation (A.6), yields equation (10b).  
 720 Finally, equation (10c) is derived from equations (7) and (9).

## 721 Appendix B. Resolution

722 We solve our recursive programs using dynamic programming. For each so-  
 723 cial welfare function, we approximate the value function in the post-tipping  
 724 world and then in the pre-tipping world using the solution from the post-  
 725 threshold problem. We interpolate recursively starting from the last period  
 726 and approximate the unknown value functions with Chebyshev polynomials.  
 727 We choose a  $10^{-3}$  tolerance for the solver: our result is not affected by stricter  
 728 tolerance. In each regime (pre- and post-tipping), the value functions are ex-  
 729 pected to be smooth as the tipping risk is the only risk we consider. We use  
 730 a four degree complete Chebyshev approximation in the two-dimensional state  
 731 space. Additional degrees do not affect the results. The state variables are the  
 732 carbon stock in the atmosphere  $S_t$  and the stock of capital  $K_t$  at time  $t$ . The  
 733 time-dependent approximation space is defined around a deterministic growth  
 734 path derived from Ramsey formula. Once we have interpolated recursively at  
 735 each time step, we simulate the optimal path for each control and state vari-  
 736 ables starting from the first period. In the stochastic case with a tipping point,  
 737 we run 1.000 simulations. An increase in the number of simulations does not  
 738 affect significantly the median path. A key element is the definition of a ter-  
 739 minal value in the program. The calculation is done on a finite horizon ( $T =$

740 600 years) as an approximation of the infinite program. The terminal value  
741 is defined as the sum of all the period utilities from time T to infinity. The  
742 assumption made is that the consumption will grow for a constant capital per  
743 efficient capita and total abatement, with a deterministic path for the capital  
744 derived from Ramsey. The terminal constraint uses a modified discount factor  
745 [7]. The choice of the terminal value does not affect the program : a 10% in-  
746 crease in the terminal value does not significantly affect the optimal path. It  
747 writes:  $TVF = u(\bar{c}) / (1 - \beta(1 + GA))^{\delta(\frac{1-\eta}{1-\alpha})}$  with  $\bar{c}$  the consumption for constant  
748 capital per efficient capita and total abatement,  $\beta$  the discount rate,  $\delta$  the time  
749 step,  $\eta$  the marginal utility parameter,  $\alpha$  the capital elasticity in the production  
750 function, and GA the annual growth rate of productivity from the last period.

### 751 **Appendix C. Risk-sensitive preferences and the risk premium**

752 We show that the risk premium is positive for all  $\epsilon$  under risk-sensitive  
753 preferences. We give the share of the risk-sensitive SCC under expected dam-  
754 ages in the risk-sensitive stochastic SCC for various values of  $\epsilon$ , J and for our  
755 benchmark  $\eta = 1.5$ , following Taconet et al. [48]. In particular, we show nu-  
756 merically on the graph on the left below that the risk premium is positive for  
757 all values of  $\epsilon$  in  $\mathbb{R}^+$  under risk-sensitive preferences, unlike for EZW prefer-  
758 ences. As some pure risk is already priced under additive preferences with  $\eta$ ,  
759 we also want to highlight how much the risk premium is increased by tem-  
760 poral risk aversion under our benchmark calibration: we plot on the graph  
761 on the right, for different values of  $\epsilon$  and under a benchmark  $J = 10\%$  and  
762  $\eta = 1.5$ , the share of the additive risk premium in the risk-sensitive risk-  
763 premium:  $100 * (SCC_{stoch}^{add} - SCC_{ed}^{add}) / (SCC_{stoch}^{rs} - SCC_{ed}^{rs})$ . The additive risk  
764 premium is always lower than the risk-sensitive risk premium for all  $\epsilon \in \mathbb{R}^+$ , i.e.  
765 when the social planner has temporal risk aversion.

766 On the graph on the left, we see that the share of expected damages in the

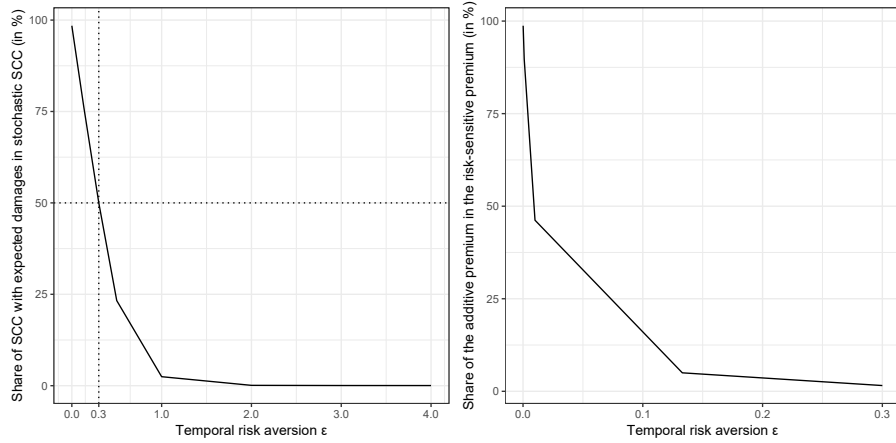


Figure C.4: The graph on the left gives the share of the stochastic SCC that is explained by expected damages (in %). The lowest value explored for  $\epsilon$  is 0.0001 and the share would converge to 100 for  $\epsilon \rightarrow 0$ . The graph on the right gives the share of the risk-sensitive risk premium that is already priced under additive preferences. The lowest value explored for  $\epsilon$  is 0.0001 and the share would converge to 100 for  $\epsilon \rightarrow 0$ . Both graphs are given for various  $\epsilon$  and a benchmark  $J=10\%$  and  $\eta = 1.5$ . The two graphs do not have the same scale for  $\epsilon$  as the share goes quickly to 0 for values above  $\epsilon > 0.3$  for the graph on the right

767 stochastic SCC is 50% for  $\epsilon = 0.3$ . In the remaining 50% of the stochastic SCC  
 768 that are due to pure risk for  $\epsilon = 0.3$ , we see on the graph on the right that  
 769 the pure risk already priced under additive preferences represents around 2% of  
 770 the risk-sensitive risk premium. Most of the risk premium under risk-sensitive  
 771 preferences stems from temporal risk aversion.

## 772 Appendix D. Time paths

773 We provide some time paths for our key variables.

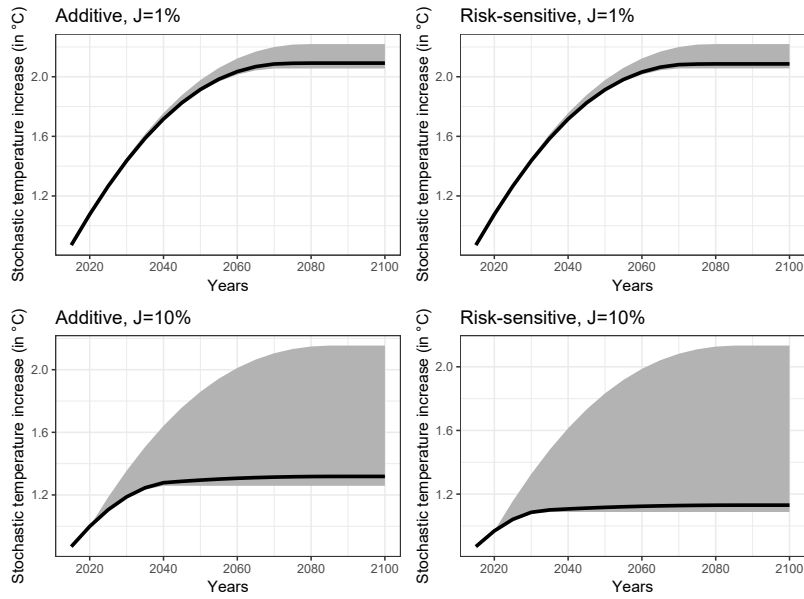


Figure D.5: The graphs give the time paths of the mean temperature increase until 2100 under additive (left) and risk-sensitive (right) preferences, for  $J=1\%$  (up) and a  $J=10\%$  (down), for  $\epsilon = 0.133$ . We give the mean (solid line) and [5% : 95%] confidence interval (shaded area) over 1.000 stochastic runs.

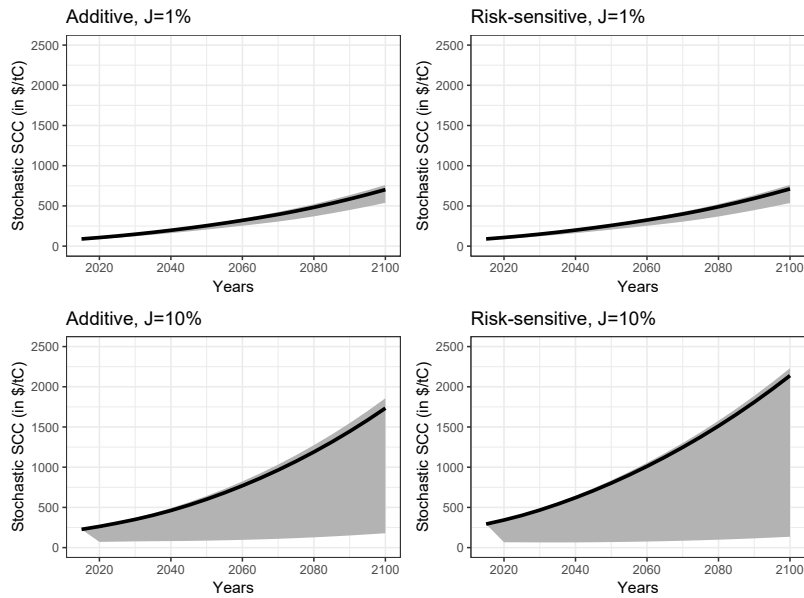


Figure D.6: Same graph as above but with the social cost of carbon.

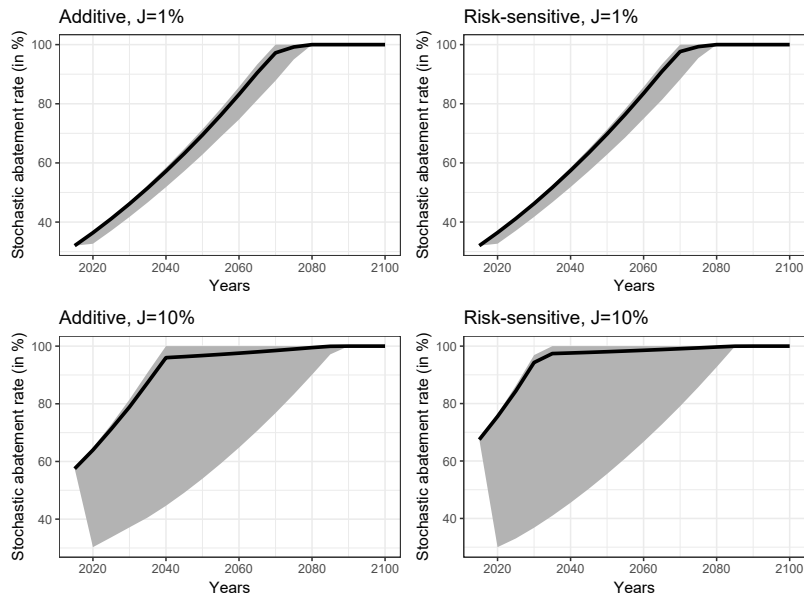


Figure D.7: Same graph as above but with the abatement rate.

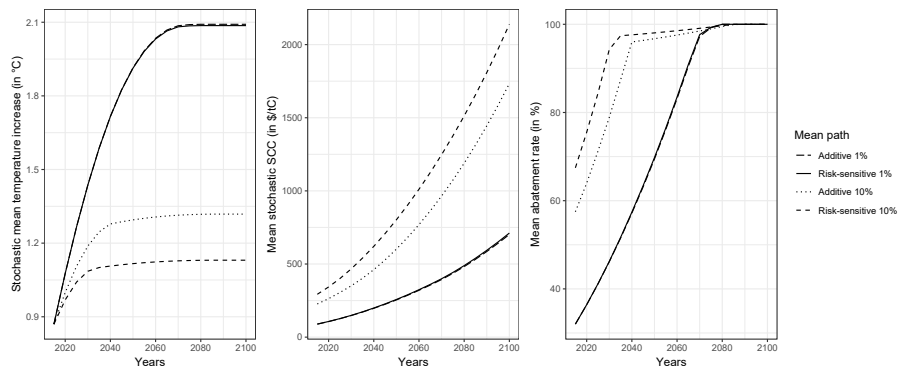


Figure D.8: The graphs give the mean time paths of the temperature increase in °C with respect to preindustrial era (left), the SCC (middle) and the abatement rate (in %) until 2100. In the risk-sensitive case and for  $J=10\%$  ( $J=1\%$ ), the tipping point is crossed 4.4% (22.8%) of the 1000 runs over the whole time horizon considered. In the additive case and for  $J=10\%$  ( $J=1\%$ ), it is 7.4% (26.9%).

774 **Appendix E. Sensitivities**

775 *Appendix E.1. Upper temperature threshold*

776 The ratio of the SCC under risk-sensitive preferences to the SCC under  
 777 additive preferences decreases with the upper threshold, i.e. a lower probability  
 of tipping decreases the difference between the two criteria.

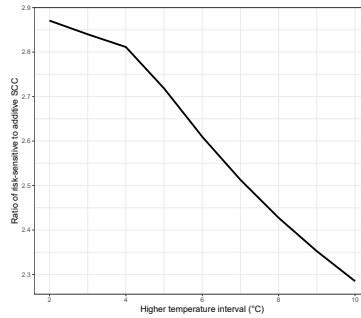


Figure E.9: Ratio of risk-sensitive to additive SCC for a benchmark  $\epsilon = 0.133$ ,  $J = 20\%$  and various upper temperature threshold.

778

779 *Appendix E.2. Higher tipping damage J*

We give the same graph as in the main text but for a larger range of J.

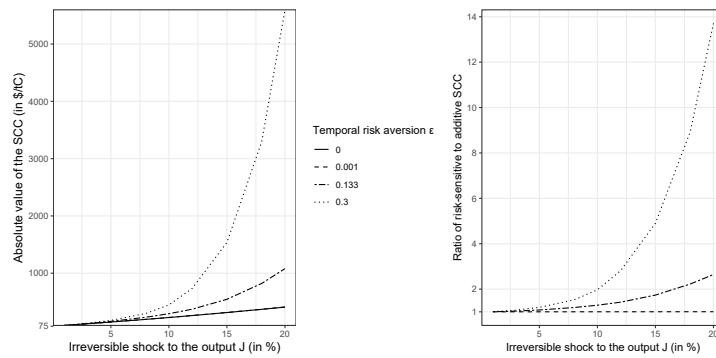


Figure E.10: Ratio of risk-sensitive to additive SCC at initial time for a benchmark  $\epsilon = 0.133$  and various J.

780

781 *Appendix E.3. Inequality aversion*

782 We plot the log ratio of the SCC under risk-sensitive preferences to the SCC  
 783 under additive preferences for different  $J$  and  $\eta$ , with  $\epsilon = 0.133$ . The ratio  
 increases with the elasticity of marginal utility.

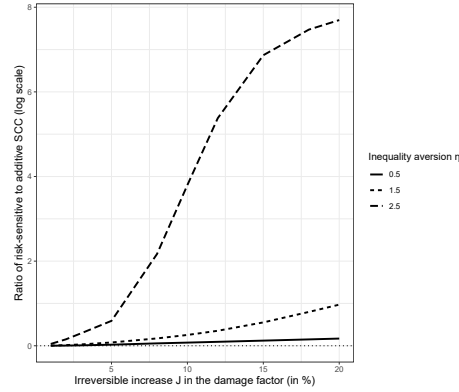


Figure E.11: Ratio of the SCC at initial time under risk-sensitive preferences on the SCC under additive preferences (benchmark calibration) for different  $J$  and  $\eta$ .

784

785 *Appendix E.4. Sensitivity - immediate decomposition*

786 We give the numerical decomposition for the immediate channels under risk-  
 787 sensitive preferences for various  $J$  and  $\epsilon$ .

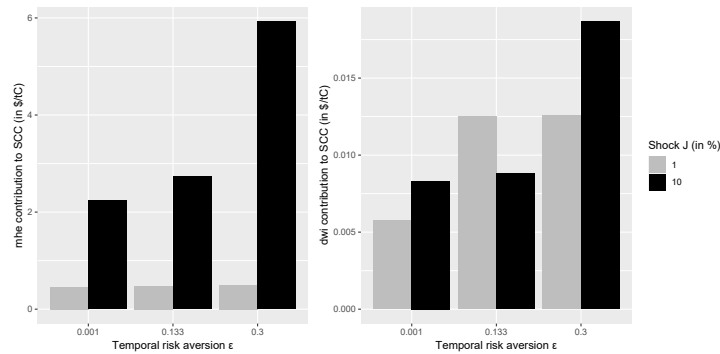


Figure E.12: Marginal contribution to the SCC at initial time (in \$) of the immediate *mhe* (left) and the immediate *dwi* (right) under risk-sensitive preferences for various  $J$  and  $\epsilon$ . Results based on 1000 stochastic runs.

788 **Disclosure statement**

789 No competing interest to declare.

790 **Acknowledgments**

791 We thank two anonymous referees for their invaluable help in improving  
792 the manuscript. We also thank Thomas Douenne, Johannes Emmerling, Si-  
793 mon Jean, Vincent Martinet, Aurelie Méjean, Eddy H.F. Tam and Stephane  
794 Zuber for comments on earlier versions of this work. Any remaining errors are  
795 ours. Céline Guivarch received funding from the European Union’s Horizon Eu-  
796 rope research and innovation programme under grant agreement No. 101081604  
797 (PRISMA).

798 **References**

- 799 [1] Ackerman, F., E. A. Stanton, and R. Bueno (2013). Epstein–zin utility  
800 in dice: Is risk aversion irrelevant to climate policy? *Environmental and*  
801 *Resource Economics* 56(1), 73–84.
- 802 [2] Ahn, C. M. (1989). The effect of temporal risk aversion on optimal consump-  
803 tion, the equity premium, and the equilibrium interest rate. *The Journal of*  
804 *Finance* 44(5), 1411–1420.
- 805 [3] Andersen, S., G. W. Harrison, M. I. Lau, and E. E. Rutström (2018). Mul-  
806 tiattribute utility theory, intertemporal utility, and correlation aversion. *In-*  
807 *ternational Economic Review* 59(2), 537–555.
- 808 [4] Anderson, E. W. (2005). The dynamics of risk-sensitive allocations. *Journal*  
809 *of Economic theory* 125(2), 93–150.
- 810 [5] Arias, P., N. Bellouin, E. Coppola, R. Jones, G. Krinner, J. Marotzke,  
811 V. Naik, M. Palmer, G.-K. Plattner, J. Rogelj, et al. (2021). Climate change



- 812 2021: The physical science basis. contribution of working group i to the sixth  
813 assessment report of the intergovernmental panel on climate change; technical  
814 summary.
- 815 [6] Arrow, K. J. (1971). The theory of risk aversion. chapter 3 in essays in the  
816 theory of risk bearing. *New York: American Elsevier*.
- 817 [7] Barr, J. L. and A. S. Manne (1967). Numerical experiments with a finite  
818 horizon planning model. *Indian Economic Review* 2(1), 1–31.
- 819 [8] Belaia, M., M. Funke, and N. Glanemann (2017). Global warming and a  
820 potential tipping point in the atlantic thermohaline circulation: the role of  
821 risk aversion. *Environmental and Resource Economics* 67(1), 93–125.
- 822 [9] Berger, L. and L. Eeckhoudt (2021). Risk, ambiguity, and the value of  
823 diversification. *Management Science* 67(3), 1639–1647.
- 824 [10] Bommier, A. (2007). Risk aversion, intertemporal elasticity of substitution  
825 and correlation aversion. *Economics Bulletin* 4(29), 1–8.
- 826 [11] Bommier, A. (2013). Life-cycle preferences revisited. *Journal of the Euro-*  
827 *pean Economic Association* 11(6), 1290–1319.
- 828 [12] Bommier, A., A. Chassagnon, and F. Le Grand (2012). Comparative risk  
829 aversion: A formal approach with applications to saving behavior. *Journal*  
830 *of Economic Theory* 147(4), 1614–1641.
- 831 [13] Bommier, A., A. Kochov, and F. Le Grand (2017). On monotone recursive  
832 preferences. *Econometrica* 85(5), 1433–1466.
- 833 [14] Bommier, A., B. Lanz, and S. Zuber (2015). Models-as-usual for unusual  
834 risks? on the value of catastrophic climate change. *Journal of Environmental*  
835 *Economics and Management* 74, 1–22.

- 836 [15] Bommier, A. and F. Le Grand (2019). Risk aversion and precautionary  
837 savings in dynamic settings. *Management Science* 65(3), 1386–1397.
- 838 [16] Bommier, A. and S. Zuber (2008). Can preferences for catastrophe avoid-  
839 ance reconcile social discounting with intergenerational equity? *Social Choice*  
840 *and Welfare* 31(3), 415–434.
- 841 [17] Bretschger, L. and A. Vinogradova (2019). Best policy response to environ-  
842 mental shocks: Applying a stochastic framework. *Journal of Environmental*  
843 *Economics and Management* 97, 23–41.
- 844 [18] Bullard, J. and A. Singh (2012). Learning and the great moderation. *In-*  
845 *ternational Economic Review* 53(2), 375–397.
- 846 [19] Cai, Y. and T. S. Lontzek (2019). The social cost of carbon with economic  
847 and climate risks. *Journal of Political Economy* 127(6), 2684–2734.
- 848 [20] Clarke, H. R. and W. J. Reed (1994). Consumption/pollution tradeoffs in  
849 an environment vulnerable to pollution-related catastrophic collapse. *Journal*  
850 *of Economic Dynamics and Control* 18(5), 991–1010.
- 851 [21] Crost, B. and C. P. Traeger (2013). Optimal climate policy: uncertainty  
852 versus monte carlo. *Economics Letters* 120(3), 552–558.
- 853 [22] Diamond, P. A. (1967). Cardinal welfare, individualistic ethics, and inter-  
854 personal comparison of utility: Comment. *Journal of political economy* 75(5),  
855 765–766.
- 856 [23] Dietz, S. and F. Venmans (2019). Cumulative carbon emissions and eco-  
857 nomic policy: in search of general principles. *Journal of Environmental Eco-*  
858 *nomics and Management* 96, 108–129.
- 859 [24] Ebert, S. and G. van de Kuilen (2015). Measuring multivariate risk pref-  
860 erences. *Available at SSRN 2637964*.

- 861 [25] Fleurbaey, M. (2010). Assessing risky social situations. *Journal of Political*  
862 *Economy* 118(4), 649–680.
- 863 [26] Fleurbaey, M. (2018). Welfare economics, risk and uncertainty. *Canadian*  
864 *Journal of Economics/Revue canadienne d'économique* 51(1), 5–40.
- 865 [27] Gangadharan, L., G. W. Harrison, and A. D. Leroux (2019). Are risks  
866 over multiple attributes traded off? a case study of aid. *Journal of Economic*  
867 *Behavior & Organization* 164, 166–198.
- 868 [28] Guivarch, C. and A. Pottier (2018). Climate damage on production or on  
869 growth: what impact on the social cost of carbon? *Environmental Modeling*  
870 *& Assessment* 23(2), 117–130.
- 871 [29] Hansen, L. P. and T. J. Sargent (1995). Discounted linear exponential  
872 quadratic gaussian control. *IEEE Transactions on Automatic control* 40(5),  
873 968–971.
- 874 [30] Jensen, S. and C. P. Traeger (2014). Optimal climate change mitigation  
875 under long-term growth uncertainty: Stochastic integrated assessment and  
876 analytic findings. *European Economic Review* 69, 104–125.
- 877 [31] Kihlstrom, R. E. and L. J. Mirman (1974). Risk aversion with many com-  
878 modities. *Journal of Economic Theory* 8(3), 361–388.
- 879 [32] Kimball, M. and P. Weil (2009). Precautionary saving and consumption  
880 smoothing across time and possibilities. *Journal of Money, Credit and Bank-*  
881 *ing* 41(2-3), 245–284.
- 882 [33] Kreps, D. M. and E. L. Porteus (1978). Temporal resolution of uncertainty  
883 and dynamic choice theory. *Econometrica*, 185–200.

- 884 [34] Lanier, J., B. Miao, J. K.-H. Quah, and S. Zhong (2022). Intertemporal  
885 consumption with risk: A revealed preference analysis. *Review of Economics*  
886 *and Statistics*.
- 887 [35] Leduc, M., H. D. Matthews, and R. de Elía (2015). Quantifying the limits  
888 of a linear temperature response to cumulative co2 emissions. *Journal of*  
889 *Climate* 28(24), 9955–9968.
- 890 [36] Lemoine, D. and C. Traeger (2014). Watch your step: optimal policy in a  
891 tipping climate. *American Economic Journal: Economic Policy* 6(1), 137–66.
- 892 [37] Lemoine, D. and C. P. Traeger (2016). Ambiguous tipping points. *Journal*  
893 *of Economic Behavior & Organization* 132, 5–18.
- 894 [38] Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger,  
895 N. Caud, Y. Chen, L. Goldfarb, M. Gomis, et al. (2021). Climate change  
896 2021: the physical science basis. *Contribution of working group I to the sixth*  
897 *assessment report of the intergovernmental panel on climate change 2*.
- 898 [39] Nordhaus, W. (2018). Evolution of modeling of the economics of global  
899 warming: changes in the dice model, 1992–2017. *Climatic change* 148(4),  
900 623–640.
- 901 [40] Nordhaus, W. D. (2008). *A question of balance*. Yale University Press.
- 902 [41] Piontek, F., L. Drouet, J. Emmerling, T. Kompas, A. Méjean, C. Otto,  
903 J. Rising, B. Soergel, N. Taconet, and M. Tavoni (2021). Integrated perspec-  
904 tive on translating biophysical to economic impacts of climate change. *Nature*  
905 *Climate Change*, 1–10.
- 906 [42] Pratt, J. W. (1964). Risk aversion in the large and in the small. *Econo-*  
907 *metrica* 32(1-2), 122–136.

- 908 [43] Rheinberger, C. M. and N. Treich (2017). Attitudes toward catastrophe.  
909 *Environmental and Resource Economics* 67(3), 609–636.
- 910 [44] Richard, S. F. (1975). Multivariate risk aversion, utility independence and  
911 separable utility functions. *Management Science* 22(1), 12–21.
- 912 [45] Rohde, K. I. and X. Yu (2022). Intertemporal correlation aversion—a model-  
913 free measurement. *Available at SSRN 4079812*.
- 914 [46] Rudik, I. (2020). Optimal climate policy when damages are unknown.  
915 *American Economic Journal: Economic Policy* 12(2), 340–73.
- 916 [47] Stern, N. (2006). Stern review: The economics of climate change.
- 917 [48] Taconet, N., C. Guivarch, and A. Pottier (2021). Social cost of carbon under  
918 stochastic tipping points. *Environmental and Resource Economics* 78(4),  
919 709–737.
- 920 [49] Tallarini Jr, T. D. (2000). Risk-sensitive real business cycles. *Journal of*  
921 *monetary Economics* 45(3), 507–532.
- 922 [50] Tsur, Y. and A. Zemel (1996). Accounting for global warming risks: Re-  
923 source management under event uncertainty. *Journal of Economic Dynamics*  
924 *and Control* 20(6-7), 1289–1305.
- 925 [51] van der Ploeg, F. and A. de Zeeuw (2018). Climate tipping and economic  
926 growth: precautionary capital and the price of carbon. *Journal of the Euro-*  
927 *pean Economic Association* 16(5), 1577–1617.
- 928 [52] van der Ploeg, F. and A. de Zeeuw (2019). Pricing carbon and adjusting  
929 capital to fend off climate catastrophes. *Environmental and Resource Eco-*  
930 *nomics* 72(1), 29–50.

931 [53] Weitzman, M. L. (2009). On modeling and interpreting the economics of  
932 catastrophic climate change. *The review of economics and statistics* 91(1),  
933 1–19.