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Optimal climate policy under tipping risk and temporal risk aversion

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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.

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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 , β a discount factor derived from
 116 pure time preference and ϵ 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

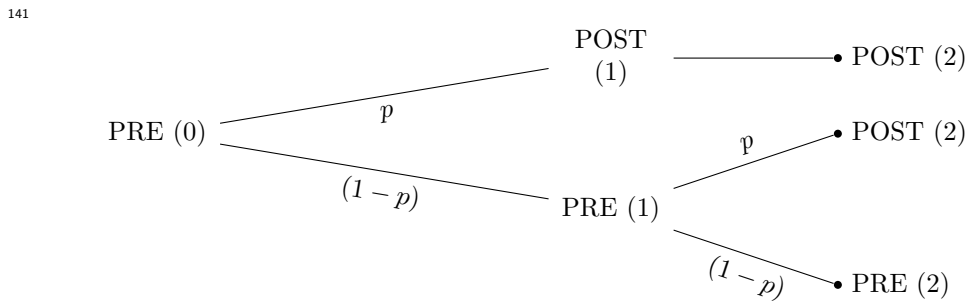
125 Firstly, we present our modelling approach (section 2): a dynamic stochastic
 126 climate-economy integrated model with a stylized tipping risk, in which we
 127 compare two alternative social welfare functions. Then, we discuss analytically
 128 how temporal risk aversion affects optimal policy 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 avoidance² [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.

²If 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 δ , 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 Λ_t of Y_t), and investment: $C_t = Y_t(1 - \Lambda_t - s_t)$. The mitigation cost Λ_t
192 depends on the abatement rate μ_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 σ_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 ψ 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 **Tiping 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 Ω 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 threshold³ 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

³The 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 η
 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 Γ 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 dominance⁴ [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

⁴A 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 ϵ . 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 preferences⁵, 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

⁵Risk-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 ϵ . We can therefore simply vary ϵ within a reasonable value range and
337 make comparisons between the two social choice criteria under risk for different
338 values of ϵ .

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 μ_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 μ_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 μ_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 β . Varying μ_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 ϕ 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 preferences⁶ and

⁶They 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 ϵ . 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 ϵ is counter-balanced
 408 by its negative impact on V^{eff} as V^{eff} is decreasing in ϵ . 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 ϵ 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 adjust⁷ 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].

⁷Taken 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 ϵ 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 ϵ . But the larger ϵ 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 ϕ , i.e., the strength of temporal risk aversion ϵ . 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 ρ is 1.5% [39]. The marginal utility parameter η 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 paths⁸. Thus, we can make compar-

⁸On the contrary, this is not the case for all values of ϵ under multiplicative preferences that

495 isons between the two social choice criteria under risk for different values of ϵ .
 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 ρ and relative risk aversion χ of EZW preferences on the other
 508 hand can thus be formulated in this precise case: $\epsilon = -(1 - \beta)(1 - \chi)$ with χ the
 509 coefficient of relative risk aversion with respect to atemporal wealth gambles,
 510 and β the discount rate. Following the IAM literature calibration for χ [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 ϵ so
 that additive and multiplicative preferences yield the same discount rate and are comparable.
 The calibration of ϵ 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 β 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 ϵ
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 ϵ 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

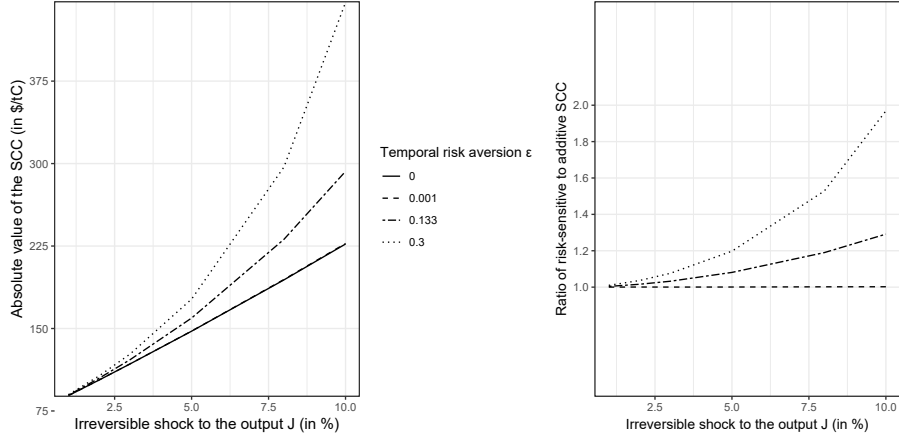


Figure 1: Absolute values of the additive and risk-sensitive SCC (in \$ per tC) at initial time (left) and ratio of the risk-sensitive SCC to the additive SCC (right) for various J and ϵ under our benchmark calibration ($\eta = 1.5$, $\rho = 1.5\%$). The curves overlap for the two smallest values of ϵ 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 ϵ . 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 η . The
560 ratio of the risk-sensitive to the additive SCC is increasing in the value of the

561 inequality aversion η . The SCC under risk-sensitive preferences is larger than
562 under additive preferences for any value of η 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 ρ [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 ρ 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 ρ 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

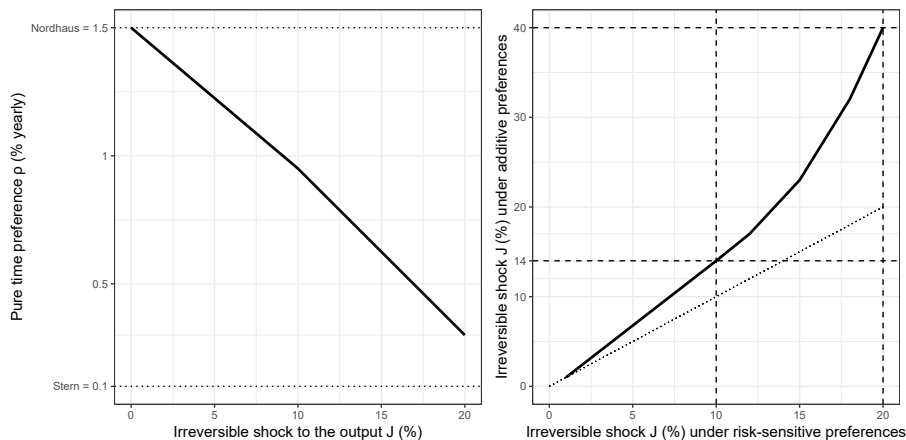


Figure 2: Equivalence in ρ (left) and J (right) needed to obtain the same SCC at initial time under additive and risk-sensitive preferences under our benchmark calibration. On the left, we represent the pure time preference (ρ) that is needed under additive preference (all else being equal) to match 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)

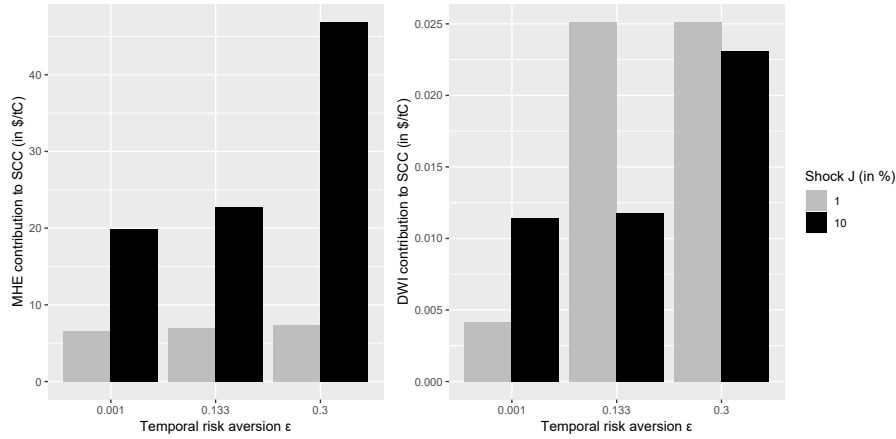


Figure 3: The graphs give the marginal contributions to the SCC at initial time (in \$) of the complete *MHE* (left) and the complete *DWI* (right) under risk-sensitive preferences for various J and ϵ . The scales for the two graphs are different because the two channels are several orders of magnitude 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 ϵ . 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, β the discount rate, δ the time
749 step, η the marginal utility parameter, α 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 ϵ 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 ϵ , 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 ϵ in \mathbb{R}^+ under risk-sensitive preferences, unlike for EZW prefer-
758 ences. As some pure risk is already priced under additive preferences with η ,
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 ϵ 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

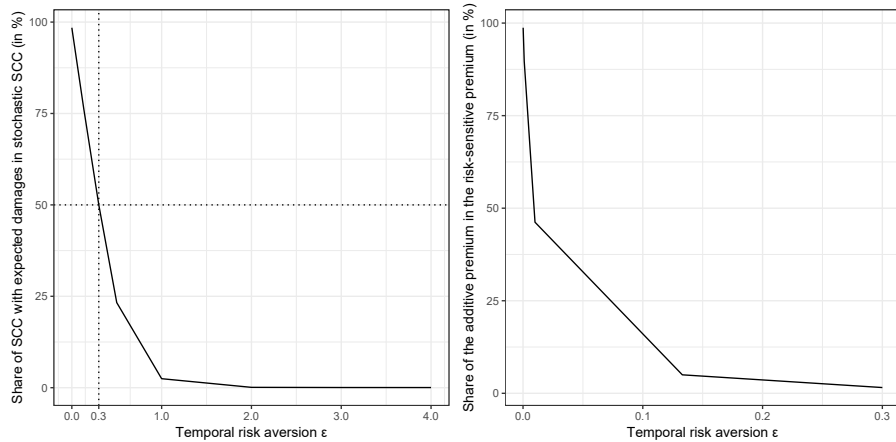


Figure C.4: The graph on the left gives the share of the stochastic SCC that is explained by expected damages (in %). The lowest value explored for ϵ is 0.0001 and the share would converge to 100 for $\epsilon \rightarrow 0$. The graph on the right gives the share of the risk-sensitive risk premium that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

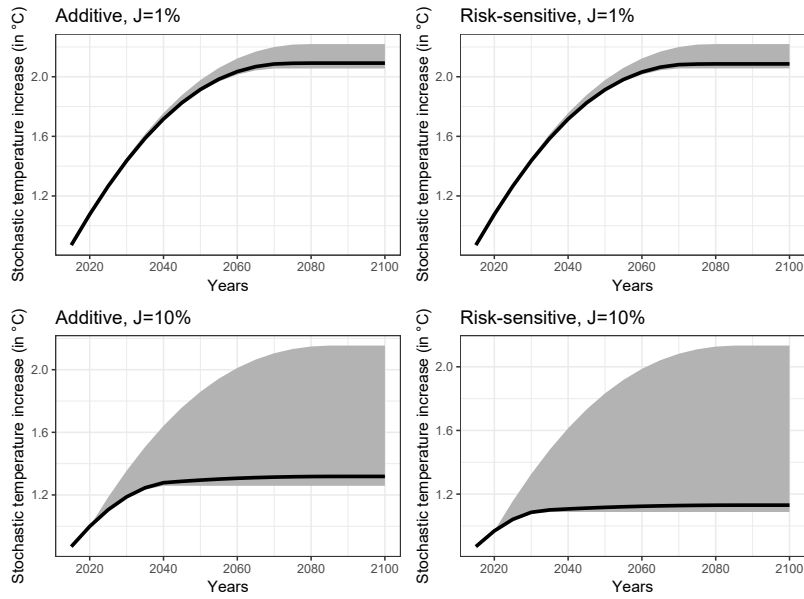


Figure D.5: The graphs give the time paths of the mean temperature increase until 2100 under additive (left) and risk-sensitive (right) preferences, for $J=1\%$ (up) and a $J=10\%$ (down), for $\epsilon = 0.133$. We give the mean (solid line) and [5% : 95%] confidence interval (shaded area) over 1.000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

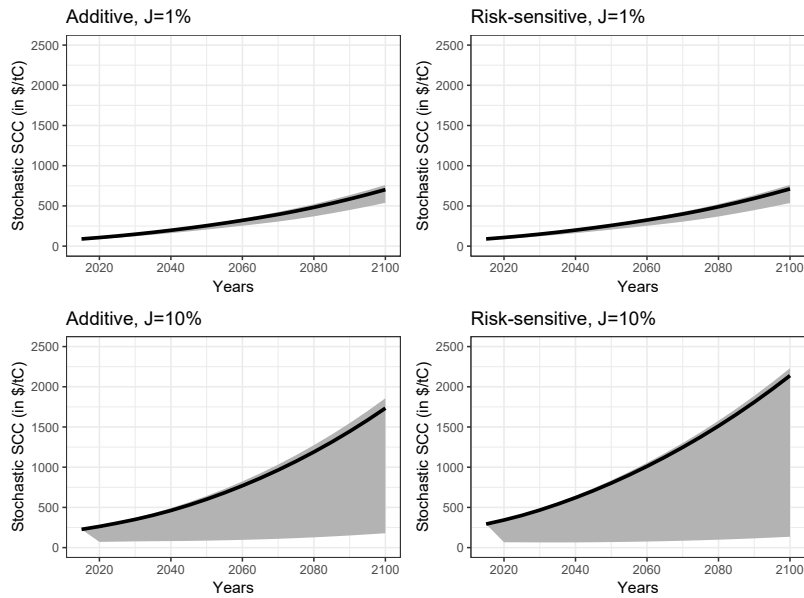


Figure D.6: Same graph as above but with the social cost of carbon.

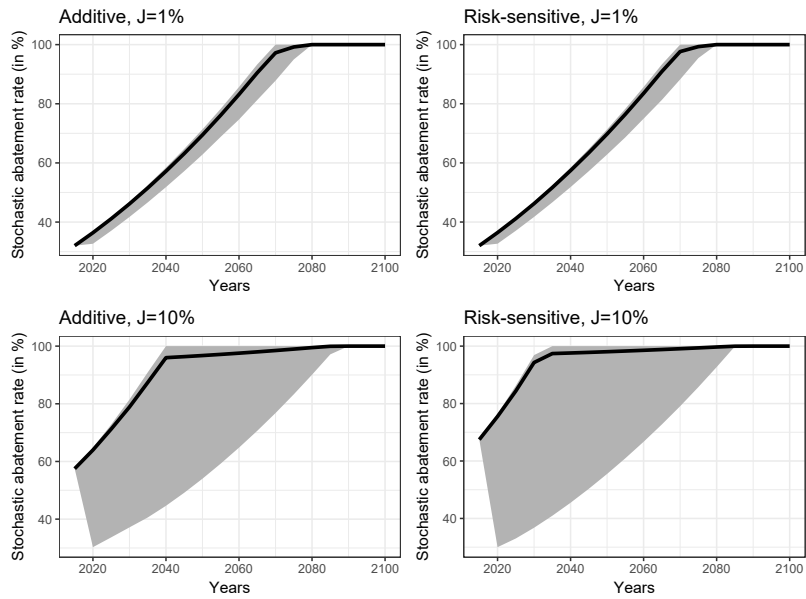


Figure D.7: Same graph as above but with the abatement rate.

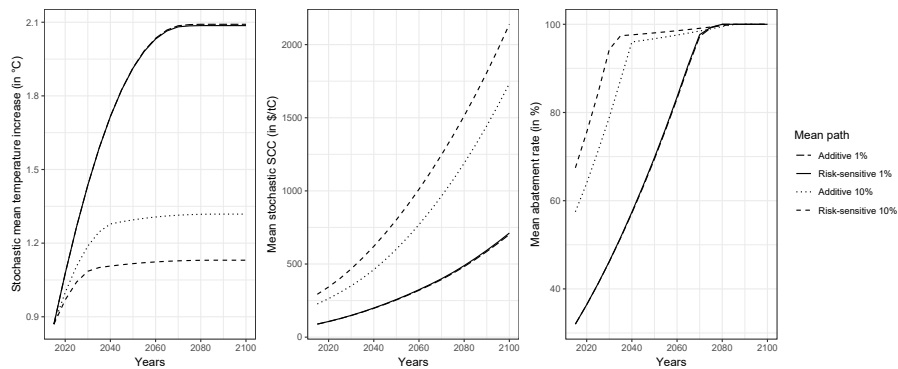


Figure D.8: The graphs give the mean time paths of the temperature increase in °C with respect to preindustrial era (left), the SCC (middle) and the abatement rate (in %) until 2100. In the risk-sensitive case and for $J=10\%$ ($J=1\%$), the tipping point is crossed 4.4% (22.8%) of the 1000 runs over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

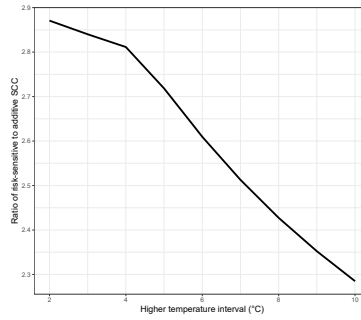


Figure E.9: Ratio of risk-sensitive to additive SCC for a benchmark $\epsilon = 0.133$, $J = 20\%$ and various upper temperature threshold.

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.

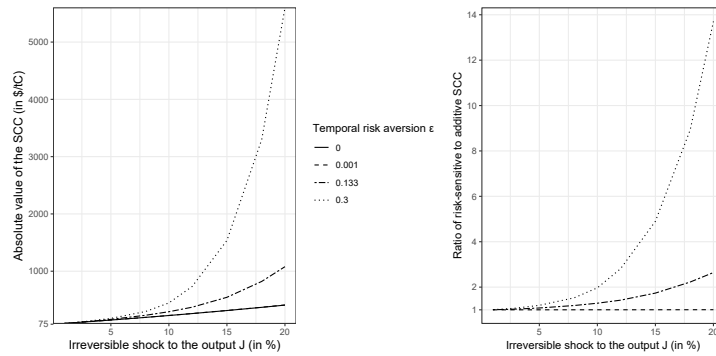


Figure E.10: Ratio of risk-sensitive to additive SCC at initial time for a benchmark $\epsilon = 0.133$ and various J.

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 η , with $\epsilon = 0.133$. The ratio
 increases with the elasticity of marginal utility.

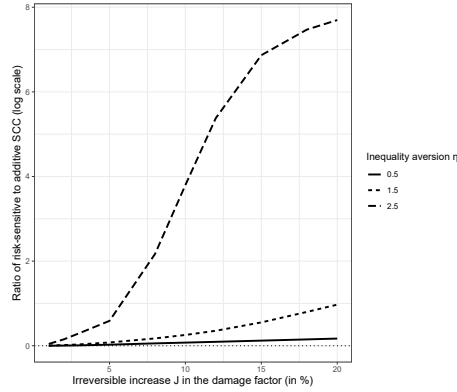


Figure E.11: Ratio of the SCC at initial time under risk-sensitive preferences on the SCC under additive preferences (benchmark calibration) for different J and η .

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 ϵ .

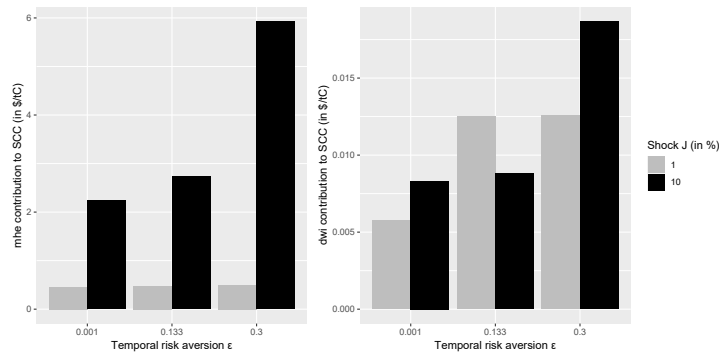


Figure E.12: Marginal contribution to the SCC at initial time (in \$) of the immediate *mhe* (left) and the immediate *dwi* (right) under risk-sensitive preferences for various J and ϵ . Results based on 1000 stochastic runs.

788 **Disclosure statement**

789 No competing interest to declare.

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