The Social Cost of Carbon under Climate Volatility Risks

Xu Lin [1,2] Sweder van Wijnbergen [1,2,3]

[1] University of Amsterdam

[2] Tinbergen Institute

[3] CEPR

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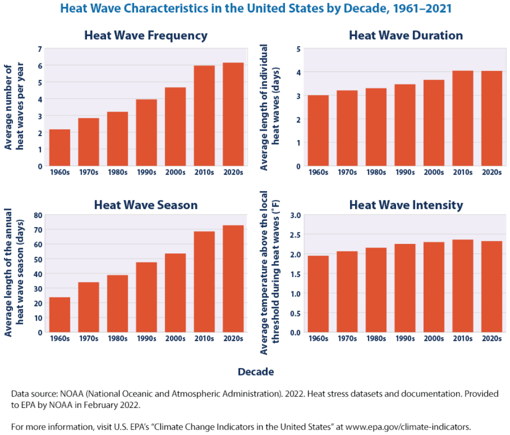
Motivation

- Extreme weather events will become more frequent and more intense (i.e. **more volatile**) with human-induced climate change (The National Climate Assessment (2018), IPCC (2021))
- But the timing and size of rising frequency and/or intensity is uncertain.
- Such uncertainty about climate volatility has not been studied by climate economists **(climate volatility risk)**



Climate Volatility and Climate Volatility Risk

Climate volatility

- Uncertainty about climate damage
  - The arrival of heatwaves is stochastic.
  - The damage from heatwave is a random variable.

Climate volatility risk

- Uncertainty about climate volatility itself (higher-order uncertainty)
  - How much more frequent will heatwaves be by the end of this century? (Uncertainty about how the frequency changes over time)
  - Will the distribution of damage size from an individual heatwave change by 2050? (Uncertainty about how the distribution shifts over time)

In this paper

Goal: The impact of climate volatility risk on the Social Cost of Carbon (SCC)

- SCC: a monetary metric for the damage caused by an additional ton of carbon emission
- A guideline for climate policy in regulatory impact assessments (Greenstone et al. 2013, Watkiss and Hope 2011)
- Determined by climate-economic integrated assessment models (IAMs)

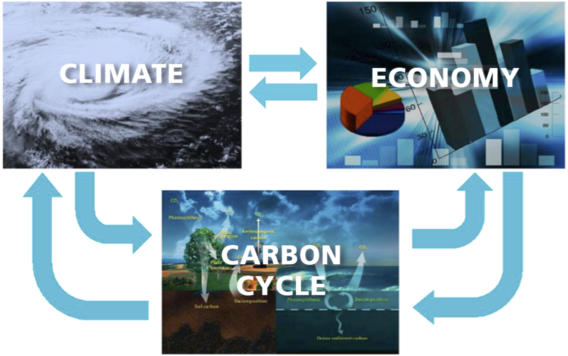


Figure: The interdependence of a climate-economic IAM (Krusell and Hassler (2013))

Model: Stochastic dynamic climate-economic IAM

(Extension to S-DICE (Cai and Lontzek (2019)); with richer risk structure of the climate volatility)

- Calculate SCC using ideas from consumption CAPM
- Two policy scenarios: Business As Usual (BAU), Optimal Abatement (OA)

Main results:

- Climate volatility risk substantially increases the SCC (as important as the climate volatility itself).
- Two types of volatility risk (frequency vs. size): Given the same expected climate damage, more severe disasters (size) leads to higher SCC than more frequent disasters.
- SCC is larger in the OA scenarios than the BAU scenarios (all else being equal).

Stochastic IAM: Climate Model

Mechanism: Carbon emission → Mean global surface temperature → More climate-related disasters

Emissions: two alternative specifications

- Exogenous: baseline scenario from Nordhaus (2017)
- Endogenous: proportional to aggregate output
- Here: focus on the **exogenous** setup
  - Analytical results
  - Endogenizing emissions does not qualitatively change the results

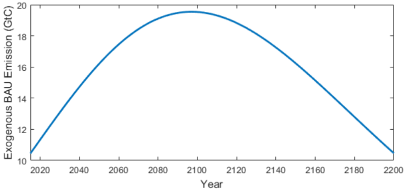


Figure: Exogenous carbon emissions (GtC) in the business-as-usual scenario

Stochastic IAM: Climate Model

Temperature increases linearly in actual emissions

$$dT_t = \overbrace{\chi}^{\text{Sensitivity}} \underbrace{(1-u_t)E_t}_{\text{Actual Emission}} dt, \quad \text{where } u_t \in [0,1] \text{ is the abatement control rate}$$

Climate disasters: a compound Poisson process causing economic losses

- Climate volatility measured by
  - Frequency: arrival rate $\lambda_{2,t}$ which increases in T_t
  - Size (disaster intensity): random variable J_2
- Climate volatility risk: stochastic shock to the climate volatility
  - One-off, irreversible, positive Poisson shocks
  - Two types of shocks: on the frequency or (the distribution of) the disaster size

Stochastic IAM: stochastic pure exchange economy

- Endowment Y_t

$$dY_t = \underbrace{\mu Y_t dt}_{\text{econ. growth}} + \underbrace{\sigma Y_t dZ_t}_{\text{econ. volatility}} - \underbrace{J_1 Y_{t-} dN_{1,t}}_{\text{econ. disasters}} - \underbrace{J_2 Y_{t-} dN_{2,t}}_{\text{climate disasters}}$$

  - Disasters follows Poisson processes (Barro-type rare disasters as in Barro (2009), Barro (2009))

	Arrival rate	Size
Economic disasters N_1	λ_1	J_1
Climate disasters N_2	$\lambda_{2,t}$	J_2

- Endowment Y_t = Consumption C_t+ Abatement A_t
  - Abatement cost A_t increases in the emission control rate u_t

Preferences

- Representative agents with Duffie-Epstein preferences (Duffie and Epstein (1992))
- In the Optimal Abatement scenario, agents choose emission control rate u_t to maximize the welfare:

$$V_0 = \max_{u_t} \mathbb{E}_0 \int_0^{\infty} f(C_t, V_t) dt$$

where the utility flow $f(C, V) = \frac{\beta}{1-\frac{1}{\epsilon}} \frac{C^{1-\frac{1}{\epsilon}} - [(1-\gamma)V]^{\frac{1}{\zeta}}}{[(1-\gamma)V]^{\frac{1}{\zeta}-1}}$ with

  - risk aversion γ
  - elasticity of intertemporal substitution (EIS) $\epsilon \neq 1$
  - $\zeta = \frac{1-\gamma}{1-\frac{1}{\epsilon}}$
  - time discount rate β

- In the BAU scenario, set $u_t = 0$

Social Cost of Carbon (SCC)

- SCC: The marginal damage of carbon emissions (scaled by marginal utility of consumption)

$$SCC_0 = -\chi \frac{\partial V_0 / \partial T_0}{f_C(C_0, V_0)}$$

- An explicit expression to identify the impact of climate volatility risk on the SCC

$$SCC_0 \approx \int_0^\infty \underbrace{\left(\int_0^t \chi \frac{\partial \lambda_{2,s}}{\partial T_0} \frac{1}{\alpha_{2,s} + 1 - \gamma} ds \right) \mathbb{E}_0 C_t}_{\text{Certainty Equivalent (CE) of damage from marginal emission}} \cdot \underbrace{\exp\left(- \int_0^t r_s^{(CDR)} ds \right)}_{\text{Stochastic Discount Factor (SDF)}} dt$$

where $r^{(CDR)}$ is the growth-adjusted consumption discount rate.

SCC at $t = 0$

$$SCC_0 \approx \int_0^\infty CE_t \cdot SDF_t dt$$

The impact of climate volatility risk

- on **Certainty Equivalent (CE)** : positive (Disasters are getting worse in the future.)
- on **Stochastic Discount Factor (SDF)**: unclear ex ante
  - SDF is negatively correlated with the growth-adjusted consumption discount rate $r^{(CDR)}$

$$r_t^{(CDR)} \approx \underbrace{r_t^f}_{Risk\ free\ rate} + \underbrace{r_{p,t}}_{Risk\ premium}$$

  - Numerically solve each term

Numerical Solutions

- Calibration:
  - Endowment: $\mu = 3\%$ (growth), $\sigma = 2.5\%$ (volatility), $\lambda_1 = 3.5\%$ (arrival rate of economic disasters), $\alpha_1 = 6.5$ ($\rightarrow$ mean economic disaster size $\mathbb{E}J_1 = 13.3\%$)
  - Preference: $\epsilon = 1.5, \gamma = 4.3, \beta = 0.026$
  - Climate disaster: $\bar{\lambda}^{(L)} = 6\%$, $\alpha_{2,t=0} = 6.5$ ($\rightarrow$ mean climate disaster size $\mathbb{E}J_2 = 1.5\%$)
  - Abatement costs: $A_t = 0.0741 e^{-0.019t} u_t^{2.8}$ (Nordhaus-type abatement cost function)
  - Temperature: $\chi = 1.8^\circ C/TtC$ (transient climate response to cumulative emissions)
- Climate Volatility Risk: Calibration is difficult for lack of time series data and volatility models $\Longrightarrow$ Therefore we experiment with
  - different sizes of Poisson shocks on either the disaster frequency or the (average) disaster size (e.g. $\times 2$, $\times 4$)
  - different arrival rate of such Poisson shocks to volatility

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  - different arrival rate of such Poisson shocks to volatility

How climate volatility risk affects SCC

- $SCC_0 \approx \int_0^\infty CE_t \cdot SDF_t dt$
- where SDF_t is negatively correlated with growth-adjusted consumption discount rate

$$r_t^{(CDR)} \approx \underbrace{r_t^f}_{Risk\ free\ rate} + \underbrace{r_{p,t}}_{Risk\ premium}$$

We find numerically that under climate volatility risk

- Risk-free rate ↓, risk premium ↑ ▸ Analytical decomposition of r^f and r_p
- CE ↑, discount rate $r^{(CDR)}$ ↓ (i.e. SDF ↑) $\Longrightarrow$ Larger SCC
- Given the same expected climate damage, a positive shock on the size of a single disaster leads to larger CE (and thus larger SCC) than a shock on the disaster frequency.
  Intuitively, under risk aversion, utility is concave. Therefore an increase in disaster size leads to larger loss of marginal utility than an increase in disaster frequency.

BAU: Shock to Frequency vs. Size

Table: SCC ($/tC) in 2025, 2050 and 2100 in the BAU scenario. Disaster frequency/size is doubled (Multiplier=2) or quadrupled (Multiplier=4) after the shock arriving at rate 0.01.

Multiplier	Year	(a) Frequency	(b) Size
2	2025	505	522
	2050	955	998
	2100	2911	3044
4	2025	771	902
	2050	1476	1707
	2100	3976	4543

Given the same expected climate damage ("Multiplier"), a positive shock to the size of climate disasters leads to a higher SCC

BAU: How much climate volatility risk affects the SCC

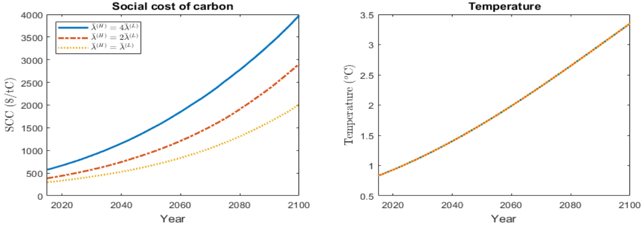
Table: SCC ($/tC) under BAU in Year 2025. The disaster *frequency* is doubled after the shock with arrival rate 0.01.

Risk aversion γ	EIS ϵ	(a) **Stochastic** shock	(b) **Deterministic** shock
4.3	**1.5**	**505**	**377**
6	1.5	359	268
4.3	0.75	243	173
6	0.75	360	242

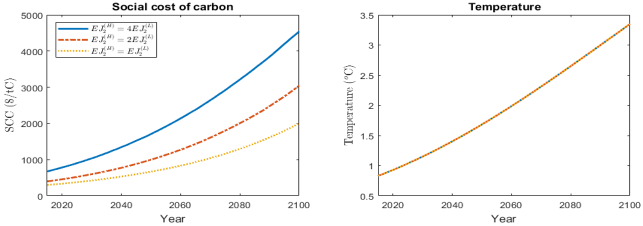
Column (a): shock is stochastic (with climate volatility risk);(b) shock is deterministic (without climate volatility)

- Under the same shock size, SCC is substantially larger if the shock arrives stochastically.
- **The stochasticity** of climate volatility substantially increases SCC
- Qualitative implications robust under different preference parameters (γ and ϵ)

BAU: Time paths of SCC



(A) Higher frequency



(B) Higher intensity

- SCC: increases in post-shock disaster frequency and size

Legends in (A)	Legends in (B)
— $\bar\lambda^{(H)} = 4\bar\lambda^{(L)}$	— $EJ_2^{(H)} = 4EJ_2^{(L)}$
---- $\bar\lambda^{(H)} = 2\bar\lambda^{(L)}$	---- $EJ_2^{(H)} = 2EJ_2^{(L)}$
····· $\bar\lambda^{(H)} = \bar\lambda^{(L)}$	····· $EJ_2^{(H)} = EJ_2^{(L)}$

- Temperature: same and deterministic

▸ Endogenous Emission under BAU ▸ RP and DR under BAU

Optimal Abatement: Time paths of SCC

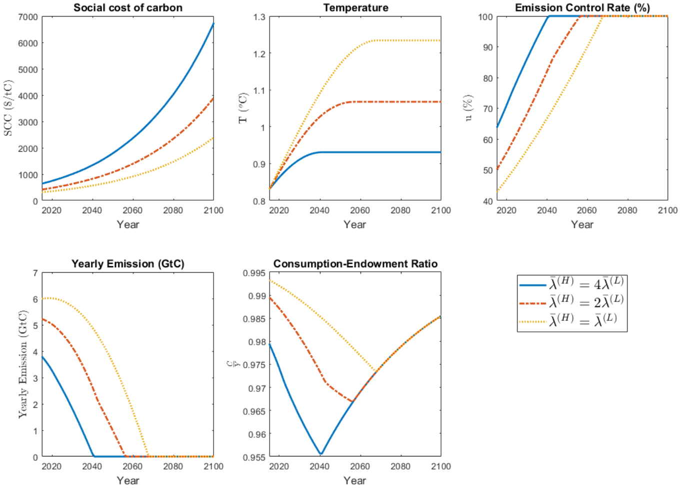


Figure: SCC under optimal abatement, exogenous E and positive Poisson shock on the **frequency**

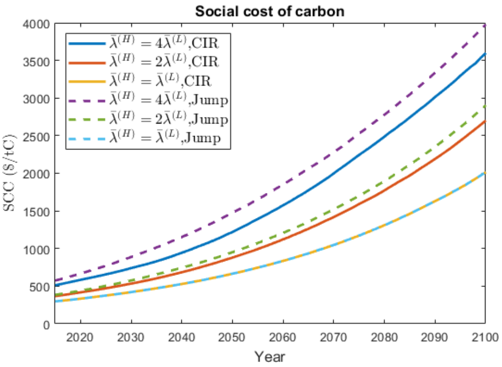
- SCC higher than BAU
  Under OA: Higher output, therefore larger marginal economic damage
- Emission control rate increases in disaster frequency: equate marginal damage with marginal abatement cost
- Same implications when shock on **disaster size**

▸ Shock on disaster size

▸ Endogenous Emission under Optimal Abatement ▸ RP and DR under Optimal Abatement

Alternative Volatility Risk Model

- What looks like an instantaneous jump on a geographical time scale unfolds more gradually on a regular timescale (Dietz et al. (2021))



- **Model**: Gradual unfold tipping on disaster frequency (CIR process), instead of a Poisson jump.
- **Figure**: SCC in the BAU scenario under different volatility models
  - Solid lines: gradual
  - Dashed lines: jump
- **Result**: A more gradual increase in volatility (*solid*) leads to a lower SCC than an abrupt increase (*dashed*)

Conclusion

- The stochasticity of climate volatility substantially increases the SCC (**as important as the climate volatility itself**)
- Given the same expected climate damage, an increase in the size of climate disasters leads to a higher SCC than an increase in the disaster frequency.
- All else being equal, the SCC is larger in the OA scenario than the BAU scenario.
- Smoothing the increase in climate volatility leads to lower SCCs.
- Endogenizing carbon emissions does not qualitatively change the results obtained under exogenous emissions.

Thank you!

Risk-Free Rate and Risk Premium

Both the risk-free rate and the risk premium are affected by climate volatility risk (directly and indirectly)

$$r_t^f = \underbrace{\beta + \frac{\mu_{C,t}}{\epsilon} - \frac{\gamma}{2}\left(1+\frac{1}{\epsilon}\right)\sigma^2}_{\textit{Standard}} + \underbrace{\lambda_1\left(\frac{\gamma - 1/\epsilon}{\alpha_1 + 1 - \gamma} - \frac{\gamma}{\alpha_1 - \gamma}\right)}_{\textit{Econ. disasters}(<0)} + \underbrace{\lambda_{2,t}\left(\frac{\gamma - 1/\epsilon}{\alpha_{2,t} + 1 - \gamma} - \frac{\gamma}{\alpha_{2,t} - \gamma}\right)}_{\textit{Clim. disasters}(<0)} + \underbrace{\lambda_{0,t}\mathcal{J}_{f,t}}_{\textit{Regime shift risk}(\leq 0)}$$

$$r_{p,t} = \underbrace{\gamma\sigma^2}_{\textit{Standard}} + \underbrace{\lambda_1\left[\frac{-1}{\alpha_1+1} + \frac{\gamma}{\alpha_1 - \gamma} + \frac{1-\gamma}{\alpha_1 + 1 - \gamma}\right]}_{\textit{Econ. disasters}(>0)} + \underbrace{\lambda_{2,t}\left[\frac{-1}{\alpha_{2,t}+1} + \frac{\gamma}{\alpha_{2,t} - \gamma} + \frac{1-\gamma}{\alpha_{2,t} + 1 - \gamma}\right]}_{\textit{Clim. disasters}(>0)} + \underbrace{\lambda_{0,t}\mathcal{J}_{rp,t}}_{\textit{Regime shift risk}(>0)}$$

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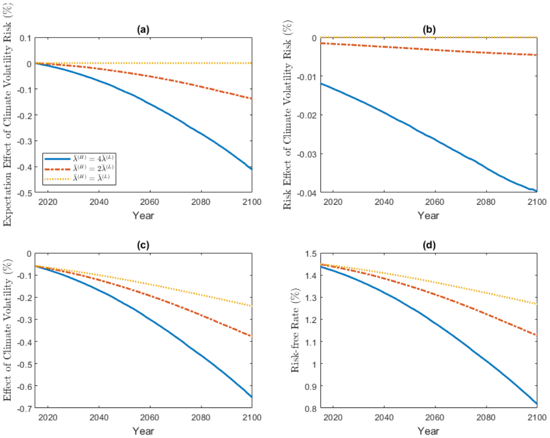
Risk-free Rates under BAU

Figure: **Risk-free rates** under BAU and exogenous emissions: (a) Expectation channel (b) Risk channel (c) 1st-order climate risk (d) Risk-free rate



Higher frequency $\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}, \bar{\lambda}^{(L)}$:

- All risks: negative
- Magnitude increases in $\bar{\lambda}^{(H)}$
- 1st-order risk $\sim$ Expectation channel $>$ Risk channel

—— $\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$

-·-· $\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$

······ $\bar{\lambda}^{(H)} = \bar{\lambda}^{(L)}$

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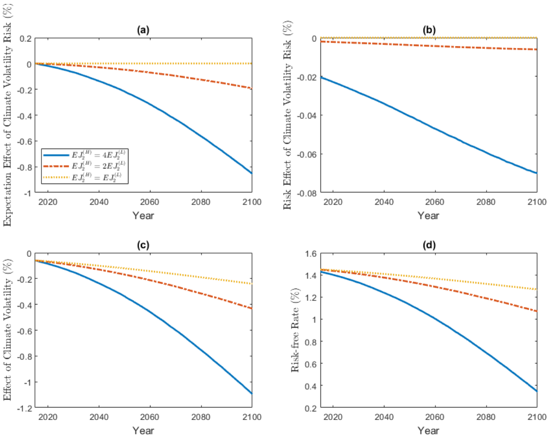


Higher intensity $\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}, \mathbb{E}J_2^{(L)}$:

- Magnitudes in (a), (b) and (c) slightly larger than switching to a regime with higher frequency
- Slightly lower risk-free rate

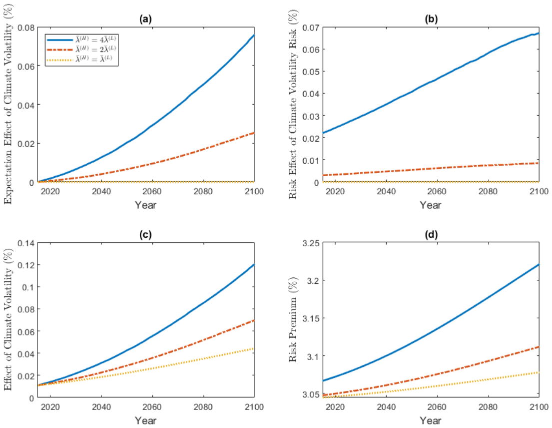
$EJ_2^{(H)} = 4EJ_2^{(L)}$

$EJ_2^{(H)} = 2EJ_2^{(L)}$

$EJ_2^{(H)} = EJ_2^{(L)}$

Exogenous Emission under BAU

FIGURE: **Risk premia** under BAU and exogenous emissions: (a) Expectation channel (b) Risk channel (c) 1st-order climate risk (d) Risk premia



Higher frequency in the new regime:

- Positive and increasing in $\bar{\lambda}^{(H)}$

- Climate volatility risk ((a)+(b)) as important as climate volatility itself (c)

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = \bar{\lambda}^{(L)}$

Exogenous Emission under BAU

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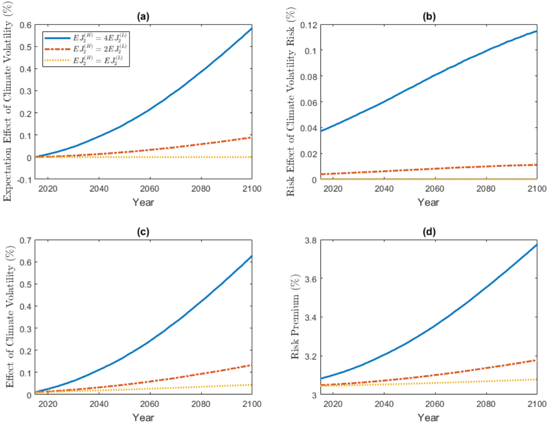


Higher intensity:

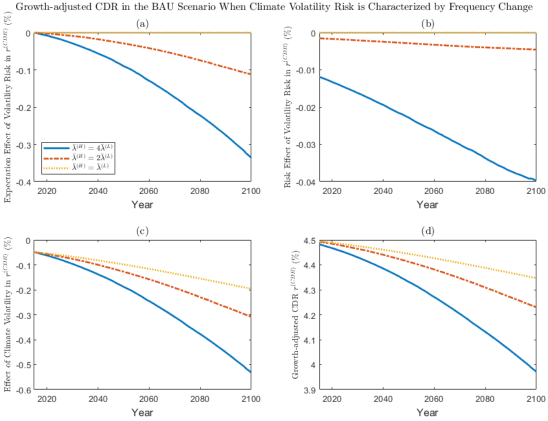
- Positive and increasing in $\mathbb{E}J_2^{(H)}$
- Climate volatility risk ((a)+(b)) as important as climate volatility itself (c)
- (a) and (c) substantially larger than switching to a high-frequency regime

$\Longrightarrow$ Higher risk premium

$EJ_2^{(H)} = 4EJ_2^{(L)}$
$EJ_2^{(H)} = 2EJ_2^{(L)}$
$EJ_2^{(H)} = EJ_2^{(L)}$

Exogenous Emission under BAU

FIGURE: Growth-adjusted consumption discount rate under BAU and exogenous emissions: (a) Expectation channel (b) Risk channel (c) 1st-order climate risk (d) Growth-adjusted consumption discount rate



Higher frequency $\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}, \bar{\lambda}^{(L)}$:

- All risks: negative
- Magnitude increases in $\bar{\lambda}^{(H)}$
- $r^{(CDR)}$ decreases in $\bar{\lambda}^{(H)}$

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$
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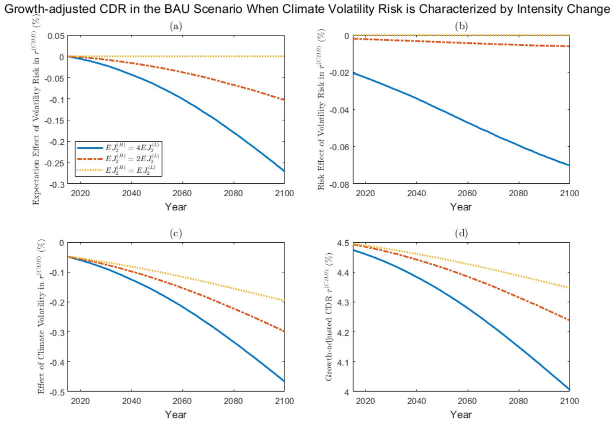

Higher intensity $\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}, \mathbb{E}J_2^{(L)}$:

- $r^{(CDR)}$ does not differ much from the case when the new regime has higher disaster frequency

$EJ_2^{(H)} = 4EJ_2^{(L)}$
$EJ_2^{(H)} = 2EJ_2^{(L)}$
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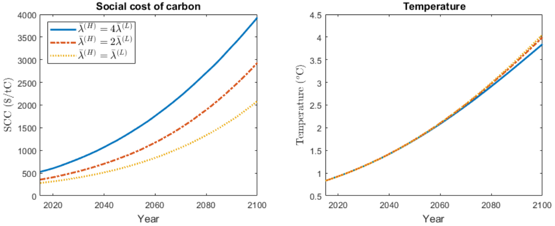
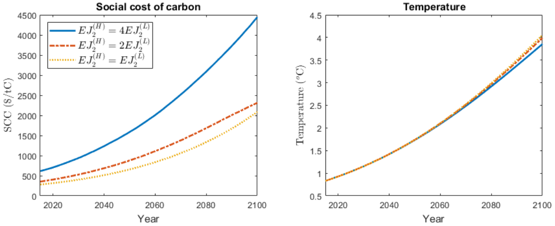
Exogenous Emission under BAU

Endogenous Emission and BAU



(A) Higher frequency ($\bar\lambda^{(H)} = 4\bar\lambda^{(L)}, 2\bar\lambda^{(L)}$ and $\bar\lambda^{(L)}$)



(B) Higher intensity ($\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}$ and $\mathbb{E}J_2^{(L)}$)

Legend in (A)

— $\bar\lambda^{(H)} = 4\bar\lambda^{(L)}$
- - $\bar\lambda^{(H)} = 2\bar\lambda^{(L)}$
··· $\bar\lambda^{(H)} = \bar\lambda^{(L)}$

Legend in (B)

— $EJ_2^{(H)} = 4EJ_2^{(L)}$
- - $EJ_2^{(H)} = 2EJ_2^{(L)}$
··· $EJ_2^{(H)} = EJ_2^{(L)}$

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Optimal Abatement: Time paths of SCC if shock on size

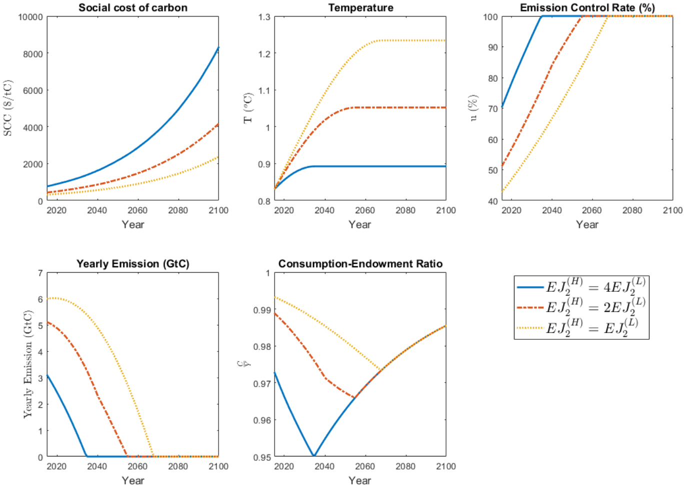

Figure: SCC under optimal abatement, exogenous E and increasing **intensity**

- SCC higher than BAU
- Emission control rate increases in disaster intensity

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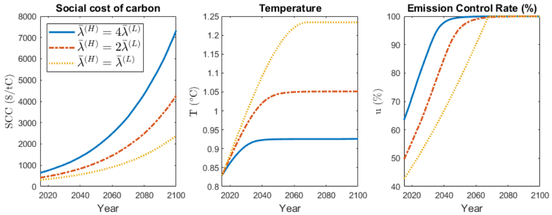
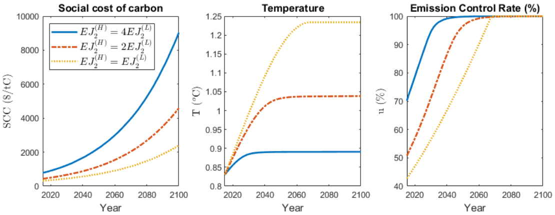
Endogenous Emission and Optimal Abatement



(A) Higher frequency ($\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}$ and $\bar{\lambda}^{(L)}$)



(B) Higher intensity ($\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}$ and $\mathbb{E}J_2^{(L)}$)

Legend in (A)

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = \bar{\lambda}^{(L)}$

Legend in (B)

$EJ_2^{(H)} = 4EJ_2^{(L)}$
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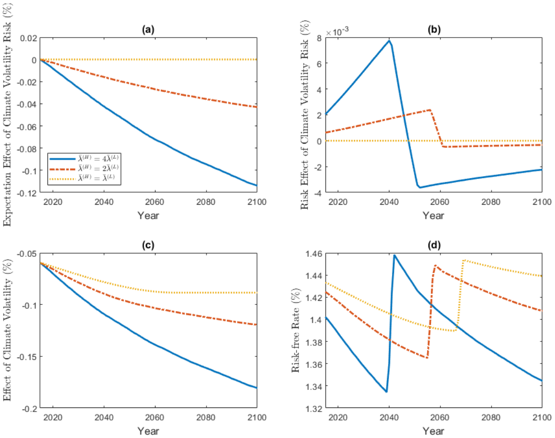
▸ Exogenous Emission under Optimal Abatement

Risk-free Rate under Optimal Abatement

Figure: Risk-free rates under optimal abatement and exogenous emissions: (a) Expectation channel (b) Risk channel (c) 1st-order climate risk (d) Risk-free rate



Higher frequency $\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}, \bar{\lambda}^{(L)}$:

- Magnitude increases in $\bar{\lambda}^{(H)}$ but much smaller than BAU
- Higher risk-free rate than BAU
- Jump in (b): stronger precautionary saving effect after emission control rate reaches 100%,
- Jump in (d): μ_C higher after emission control rate reaches 100%

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$
$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$
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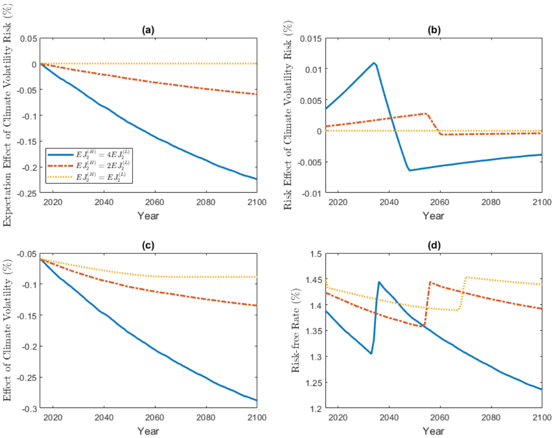
Figure: Risk-free rates under optimal abatement and exogenous emissions: (a) Expectation channel (b) Risk channel (c) 1st-order climate risk (d) Risk-free rate



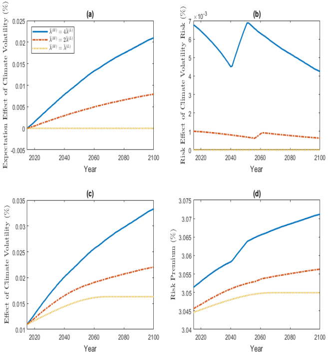
Higher intensity $\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}, \mathbb{E}J_2^{(L)}$:

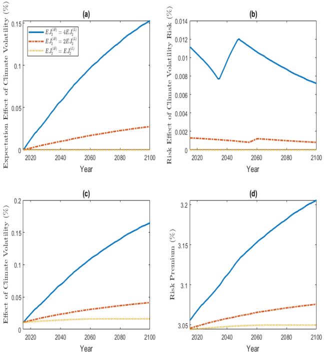
- Larger risk effects than the high-frequency case but still small relative to BAU
- Jump in (b): precautionary saving effect stronger when emission control rate reaches 100%,
- Jump in (d): μ_C higher after emission control rate reaches 100%

$EJ_2^{(H)} = 4EJ_2^{(L)}$
$EJ_2^{(H)} = 2EJ_2^{(L)}$
$EJ_2^{(H)} = EJ_2^{(L)}$

Exogenous Emission under Optimal Abatement

Figure: Risk premia under optimal abatement and exogenous emissions





Legend in (A)

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$

$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$

$\bar{\lambda}^{(H)} = \bar{\lambda}^{(L)}$

Legend in (B)

$EJ_2^{(H)} = 4EJ_2^{(L)}$

$EJ_2^{(H)} = 2EJ_2^{(L)}$

$EJ_2^{(H)} = EJ_2^{(L)}$

(A) Higher frequency ($\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}$ and $\bar{\lambda}^{(L)}$)

(B) Higher intensity ($\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}$ and $\mathbb{E}J_2^{(L)}$)

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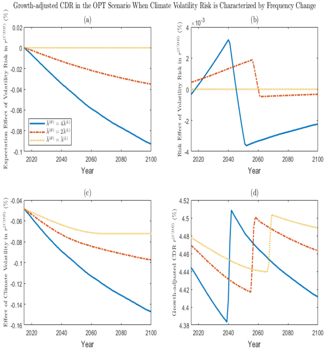
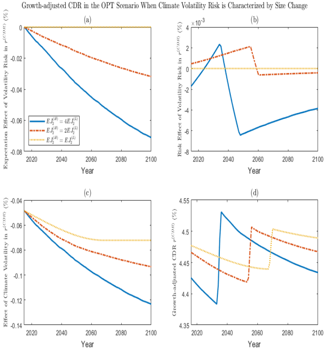
FIGURE: Growth-adjusted consumption discount rate under OPT and exogenous carbon emissions



(A) Higher frequency
($\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}, 2\bar{\lambda}^{(L)}$ and $\bar{\lambda}^{(L)}$)



(B) Higher intensity
($\mathbb{E}J_2^{(H)} = 4\mathbb{E}J_2^{(L)}, 2\mathbb{E}J_2^{(L)}$ and $\mathbb{E}J_2^{(L)}$)

Legend in (A)

$\bar{\lambda}^{(H)} = 4\bar{\lambda}^{(L)}$

$\bar{\lambda}^{(H)} = 2\bar{\lambda}^{(L)}$

$\bar{\lambda}^{(H)} = \bar{\lambda}^{(L)}$

Legend in (B)

$EJ_2^{(H)} = 4EJ_2^{(L)}$

$EJ_2^{(H)} = 2EJ_2^{(L)}$

$EJ_2^{(H)} = EJ_2^{(L)}$

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