The Rising Cost of Climate Change: Evidence from the Bond Market

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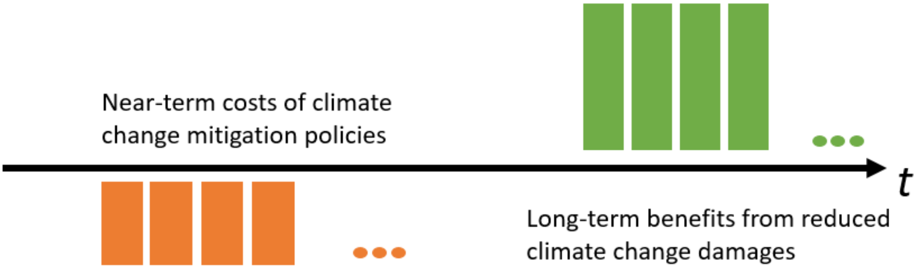
Intertemporal cost-benefit analysis of climate change

- Carbon emissions accumulate and cause severe climate damage: hotter temp.; more severe floods, storms, fires, droughts; sea level rise; ...
- Compare near-term costs of climate change mitigation to present value of reduced future damages:



Assessing climate policy requires social discount rates (SDRs)

- *Level* of SDR is crucial for evaluating long-lasting climate damages:
  - Present value of \$1 billion of damages in 100 years equals
    - \$138 million with 2% discount rate
    - \$607 million with $^1/_2$% discount rate.
- *Term structure* of SDRs is needed for different horizons:
  - SDRs should match horizons at which various costs and benefits are realized.
- Vast literature on social discounting and climate change.
  - Reviews by Arrow et al. (1996, 2014), Gollier (2013), Gollier and Hammitt (2014)
- Still, much disagreement remains about the SDRs appropriate for assessing climate policy and measuring the social cost of carbon.

Two approaches to social discounting

Prescriptive approach: What SDR is fair or morally acceptable?

- Based on social welfare theory, Ramsey rule, and normative judgments
- Example: Stern Review (2007) used a normative SDR $\approx$ 1.4%

Descriptive approach: What are observed real returns in financial markets?

- Nordhaus (2007): "look carefully [...] at the *real* real interest rate"
- Nordhaus (2013): "philosophical reflections are largely irrelvant"
- Financial market valuations embed preferences about intertemporal trade-offs.
- Example: Nordhaus (2013, etc.) generally uses a real return of 4%.

Descriptive SDRs tend to be significantly *higher* than prescriptive SDRs.

- 2 percentage points higher in survey of experts (Drupp et al., 2018).

Our macro/finance descriptive approach to SDRs

1. We show that conceptually the equilibrium or steady-state real interest rate, r_t^*, anchors the term structure of discount rates—an SDR level factor.
2. We incorporate r_t^* into an empirical time series model for risk-free SDRs
   - We estimate that r_t^* falls 1 to 2 p.p. in recent decades—consistent with macro-finance literature: Laubach and Williams (2016), Christensen and Rudebusch (2019), Bauer and Rudebusch (2020), and others.
3. We show that the lower r_t^* implies lower SDRs at all maturities.
   - We infer unobserved long-run SDRs from models of historical risk-free rates.
4. With lower SDRs, we estimate the social cost of carbon at least doubles.
   - Therefore, reduction in r_t^* has profound implications for climate economics, and our new descriptive SDRs align with previous low normative SDRs.

Large related literature on discounting climate change

- "Econometric expected net present value" of Freeman and Groom (2016):
  - Estimate stochastic process generating future interest rates from historical data.
  - Under assumption of risk-neutrality (i.e., the expectations hypothesis) long-term SDRs equal average expected future short-term SDRs.
- However, previous estimates of SDRs assumed a constant long-run mean r^*
  - Newell and Pizer (2003), Groom et al. (2007), Gollier et al. (2008), Hepburn et al. (2009), Freeman et al. (2015), Newell, Pizer, Prest (2020), and others.
- Our key contribution is a macro-fiance perspective that allows for a long-run trend or shifting endpoint in real interest rates—time variation in r_t^*—instead of imposing mean reversion to a fixed long-run mean.

We focus on risk-free SDRs

- We estimate term structures of *risk-free* discount rates from observed Treasury yields using time-series econometric models.
- *Risk-free* SDRs are appropriate for assessing:
  - Certain future payoffs
  - Uncertain but riskless payoffs — no systematic risk/correlation with marginal utility (wealth, growth)
  - Certainty-equivalent payoffs — expected payoffs that have been adjusted to account for risk characteristics (finance term: "risk-neutral" expectations)
- Important benchmark in social discounting
  - Risk-free SDRs required as first step for calculation of risk-adjusted SDRs

Asset pricing and risk adjustment in social discounting

If risk characteristics are important determinants of appropriate discount rates, why not adjust SDRs based on *risk* profile of climate mitigation projects?

- Asset pricing can disentangle time discounting and risk discounting. The latter depends on the climate beta.
- *Climate beta*: correlation of future damages from GHG emissions with future marginal utility. Payoffs with positive (negative) climate beta should be discounted at higher (lower) rate.
- Risk characteristics for climate change mitigation projects are largely unknown.
- Estimates of the climate beta range from unity (Dietz, Gollier, Kessler, 2017) to negative (Giglio et al. , 2018; Daniel, Litterman, Wagner, 2019)

Which empirical market-based rate of return to use?

- We use real (inflation-adjusted) government bond yields to estimate risk-free SDRs, "evidence from the bond market."
  - Risk-free SDRs are crucial benchmark for social discounting.
  - Available bond maturities rarely extend past 30 years, but for climate change analysis we need much longer maturities. $\Rightarrow$ Derive long-maturity SDRs from econometric interest rate models fit to Treasury yield data.
- Why not use economy-wide return on capital instead of Treasury yields?
  - Conceptually, return on capital is appropriate SDR only for projects with risk characteristics like those of the aggregate productive capital stock
  - Empirically, return on capital is difficult to measure and uncertain
  - Growing wedge between return on capital and risk-free rates—risk premia, market power, asymmetric information, measurement problems

The r_t^* anchor for the term structure of SDRs

Define r_t^* as the equilibrium/long-run level of real short rate, r_t:

$$r_t^* = \lim_{h\to\infty} E_t r_{t+h}.$$

r_t^* determines the level of the term structure of real discount rates:

$$y_t^{(n)} = \frac{1}{n}\sum_{j=0}^{n-1} E_t r_{t+j} + z_t^{(n)} = r_t^* + \frac{1}{n}\sum_{j=0}^{n-1} E_t \tilde{r}_{t+j} + z_t^{(n)},$$

where $\tilde{r}_t = r_t - r_t^*$ is cyclical component of the short rate and $z_t^{(n)}$ is a negative convexity term that reflects uncertainty.

Key results:

- Short-run SDRs are affected by current rates.
- Long-run SDRs are lowered by convexity (Weitzman effect).
- *All* SDRs move one-for-one with r_t^*.

Range of estimated decline in r_t^* from the literature

Table 1: Estimates of r_t^*; Decadal averages and changes

Source of estimate	1990s	2010s	Change
Del Negro et al. (2017)	2.3	1.1	-1.2
Johannsen and Mertens (2016)	1.4	0.7	-0.7
Laubach and Williams (2016)	2.8	0.3	-2.5
Kiley (2015)	1.6	0.7	-0.9
Christensen and Rudebusch (2019)	2.1	0.6	-1.5
UC model, 1y rate	1.6	0.7	-0.9
Mean	2.0	0.7	-1.3

(Christensen-Rudebusch estimate, based on TIPS yields, starts in 1998)

▸ Figure with r* estimates ▸ Updated Christensen-Rudebusch estimate

Reasons for secular decline in equilibrium real interest rate

A variety of economic forces have increased global savings, reduced desired investment, and pushed down the equilibrium real interest rate, including:

- Demographic change and aging populations
  - Fraction of working-age population and life expectancy linked to trend in real interest rate, Carvalho et al. (2016) and Lunsford and West (2019)
- Slower productivity growth
- Global savings glut—strong precautionary saving flows from emerging market economies (Bernanke, 2005)
- Secular stagnation (Summers, 2014)
- Fall in price of capital goods

We estimate a UC model that allows for shifts in r_t^*

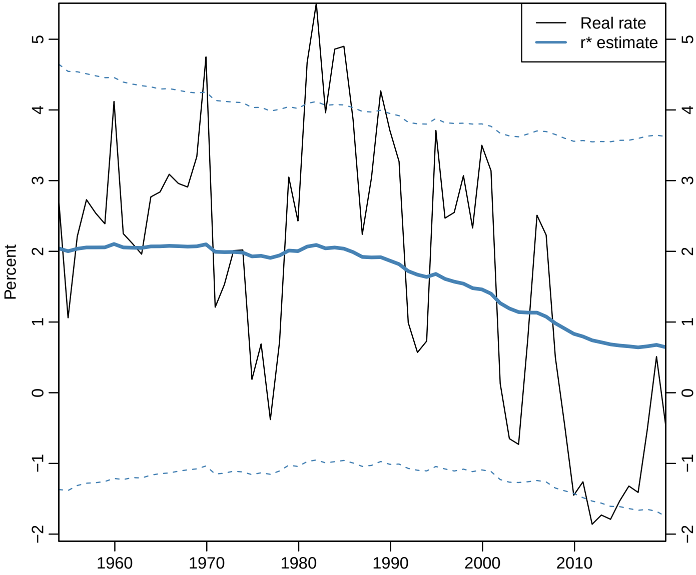
Unobserved-components (UC) model:

$$
\begin{aligned}
r_t &= r_t^* + \tilde{r}_t \\
r_t^* &= r_{t-1}^* + u_t, \qquad u_t \sim N(0, \sigma_u^2) \\
\tilde{r}_t &= \phi \tilde{r}_{t-1} + v_t, \qquad u_t \sim N(0, \sigma_v^2)
\end{aligned}
$$

- Use annual data on r_t, difference between one-year Treasury yield and survey expectations (Livingston) of CPI inflation
- Bayesian estimation using MCMC sampler
- Tight prior on σ_u^2 to avoid overly volatile r_t^*. (Other priors uninformative.)

Model provides new estimates of r_t^* and of term structure of risk-free SDRs, based on time series of real interest rate

Our new estimate of r_t^* based on the UC model, 1y real rate



We consider a variety of additional models for robustness

- UC model for 10-year real Treasury yield
  - Real rate proxy: nominal yield minus FRB/US PTR
- State-space model with nominal yield and inflation
  - Two trends: π_t^* (PTR) and r_t^* (unobserved)
  - Data: 1y nom. yield, inflation (core PCE), PTR
- Alternative model without random walk: mean-shifting AR(1)

$$r_t = \phi r_{t-1} + \alpha + \beta D(t \geq \tau) + u_t$$

  - Estimate for 1y and 10y real rate r_t
  - Different mean (r_t^*) before and after $\tau = 1995$
  - Optimal choice of τ gives similar results

▸ Estimates 1y yield ▸ Estimates 10 yield

Estimates of r_t^* declined substantially for all of our models

Estimated equilibrium real interest rate r_t^* in 1990 and 2019
from all of our alternative models

Model	1990	2019	Change
UC model, 1y rate	1.8	0.6	-1.2
UC model, 10y rate	3.1	1.2	-1.9
State-space model, 1y rate	1.9	1.0	-1.0
Mean shift model, 1y rate	2.6	0.0	-2.6
Mean shift model, 10y rate	3.8	1.3	-2.4

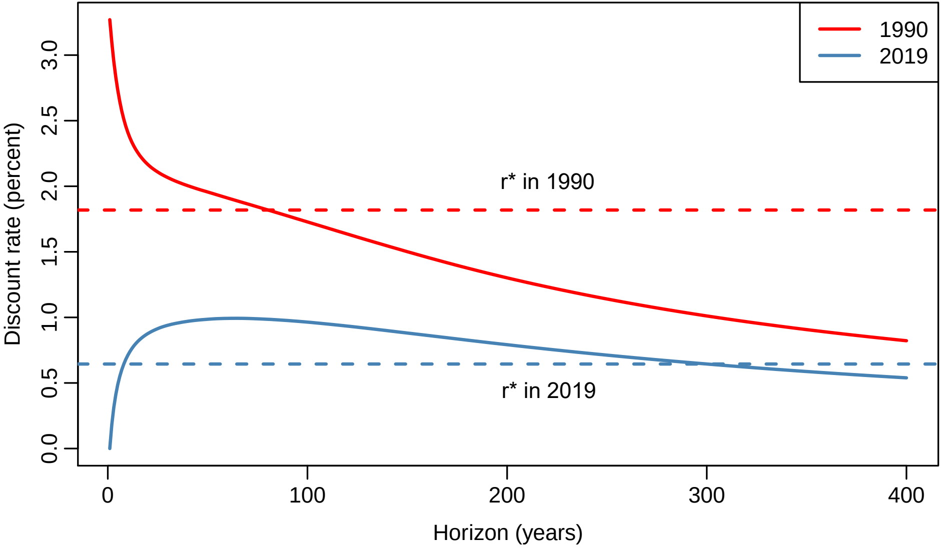
Calculating the implied term structure of SDRs

- Calculate model-implied term structure at $t = 1990$ and $t = 2019$ to quantify shift in SDRs due to lower r_t^*
- Assume risk-neutrality to obtain term structure from short rate
- Simulation approach to solve for bond prices/long rates:
  1. Use point estimates of parameters and time-t state variables
  2. Simulate 100,000 paths of state variables
  3. Calculate effective real short rate using *shadow rate* specification to rule out negative SDRs: $r_t = \max(0, r_t^* + \tilde{r}_t)$
  4. Calculate term structure of SDRs:

$$y_t^{(n)} = -\frac{1}{n} \log E_t \left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j} \right) \right]$$

Term structure of SDRs has shifted down

Discount rates, $y_t^{(n)}$, across maturities (from UC model for 1y rate)



The Social Cost of Carbon (SCC)

SCC is present value of future damages, MD_{t+n}, from one additional ton of CO_2:

$$SCC_t = \sum_{n=0}^{\infty} \exp\left(-y_t^{(n)}\right) E_t(MD_{t+n})$$

Two ingredients required to calculate SCC:

1. **Term structure of discount rates** $y_t^{(n)}$
   - Use model-based term structures from 1990 and 2019 to assess how lower r_t^* affects SCC

2. **Future marginal damages** MD_{t+n}
   - Take as given: use estimates from Integrated Assessment Models (IAMs)

DICE model provides estimates of future marginal damages

- DICE model, developed by Bill Nordhaus, is (most?) prominent IAM and widely used for policy analysis
- Our baseline: take same marginal damages as Newell and Pizer (2003) and others (DICE-94)
- Marginal damages over the next 400 years
- Robustness checks:
  - Current vintage of DICE model (DICE-2016)
  - Improved version by Dietz et al. (2020)
- DICE model is deterministic
  - In principle, risk-free real interest rates thus appropriate for discounting

Our lower empirical SDRs boost social cost of carbon

Table 2: Our Estimates of SCC using DICE-94 damages
(constant $ per metric ton of CO_2)

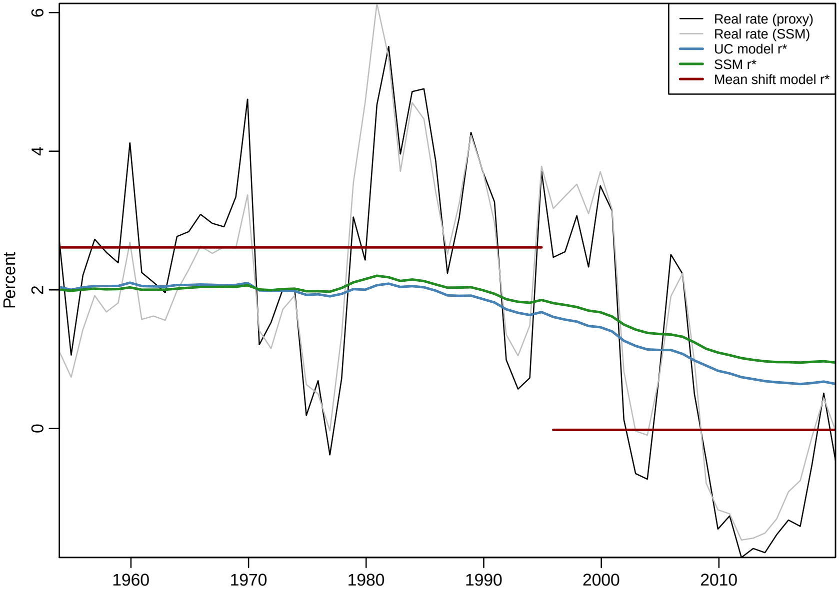
Model	Δr_t^*	1990	2019	Change
UC model, 1y rate	-1.2	31.8	68.7	116%
UC model, 10y rate	-1.9	14.3	58.9	313%
State-space model, 1y rate	-1.0	29.8	58.5	96%
Mean shift model, 1y rate	-2.6	13.3	95.3	618%
Mean shift model, 10y rate	-2.4	6.3	37.9	503%

(Estimated mean Δr_t^* from 1990 to 2019 is shown in percentage points.)

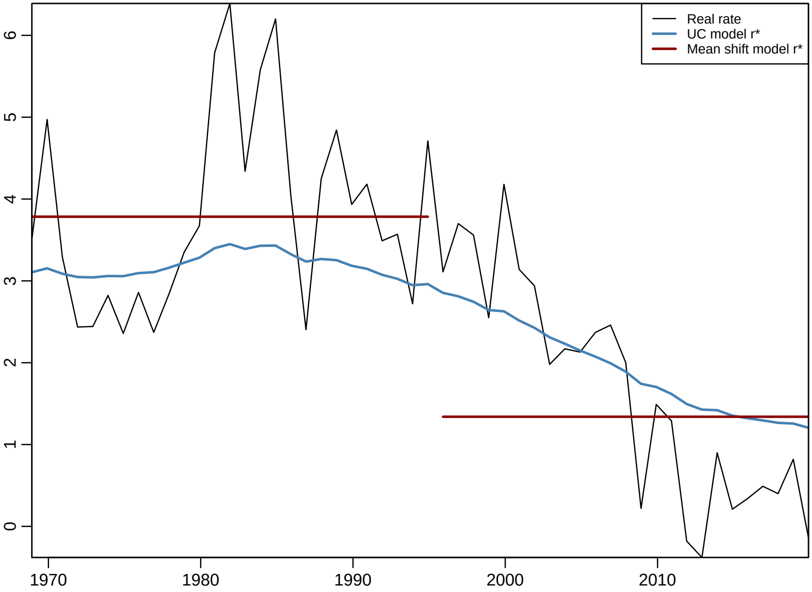
Conclusion and Outlook

- Macro-finance shifts are important for the economics of climate change.
- Secular decline in r_t^* lowers all discount rates and substantially boosts social cost of carbon.
- Previously, SDRs from descriptive approach (market rates) significantly higher than from prescriptive approach (normative judgement). Our results bring both approaches into close alignment.
- Future climate change may lower equilibrium interest rates further. Deeper understanding requires joint modeling of macro-finance trends, the economy and the climate system.

Alternative r_t^* estimates from one-year yield

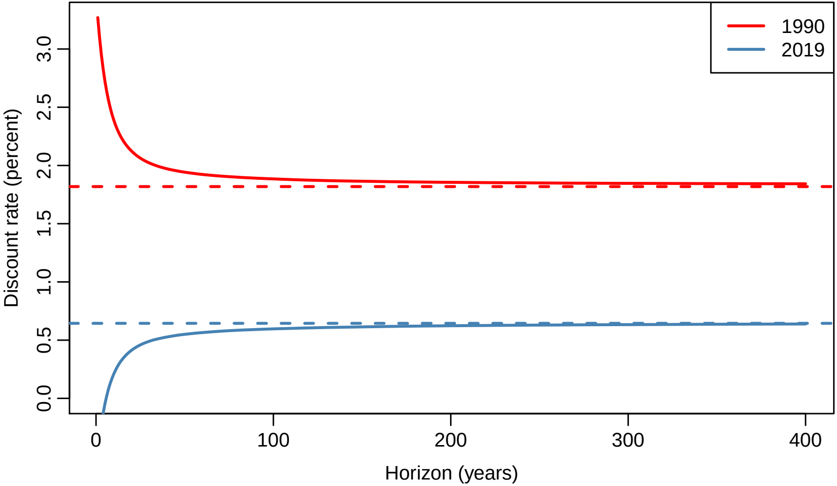


Alternative r_t^* estimates from ten-year yield

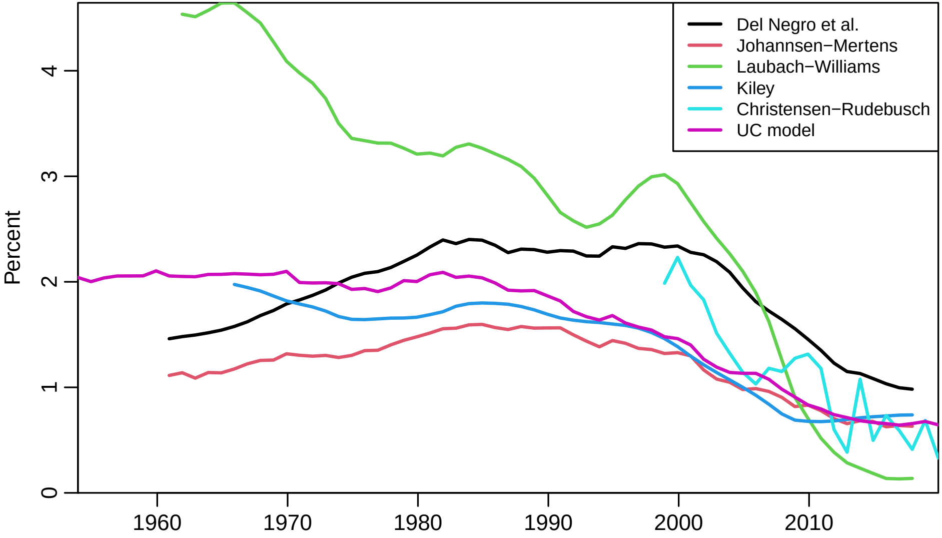


Term structure of SDRs without convexity

Long rates as averages of expected future short rates
(UC model for 1y real Treasury yield)



Macro-finance estimates show secular decline in r_t^*



Updated Christensen-Rudebusch estimate of r_t^*