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Methodology Matters:

A Careful Meta-analysis of Climate Damages

Malmsten Workshop in Sustainability Economics
Environmental Economics Group, University of Gothenburg
Sustainability Economimcs Group, ETH Zurich

Disclaimer: The views expressed in this paper are those of the author(s) and do not necessarily represent those of the NYU or any other institutions.

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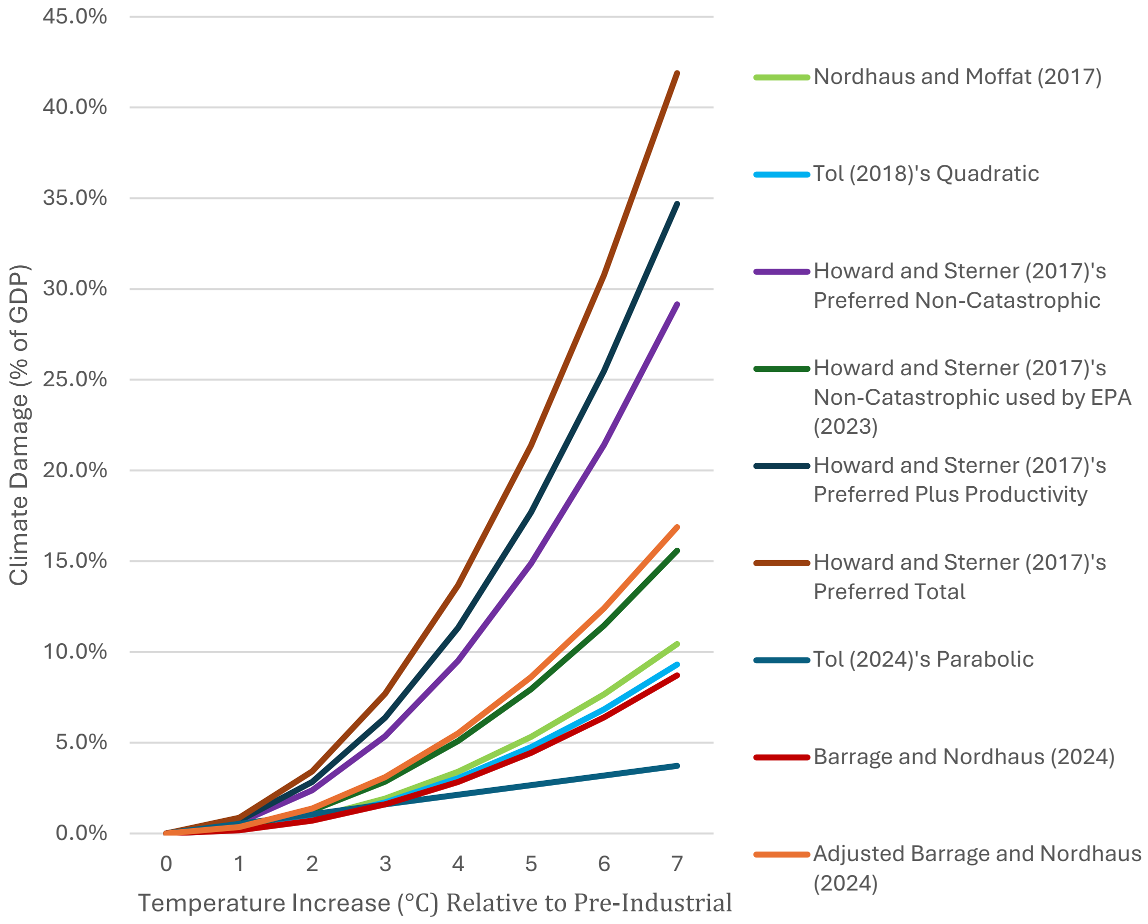
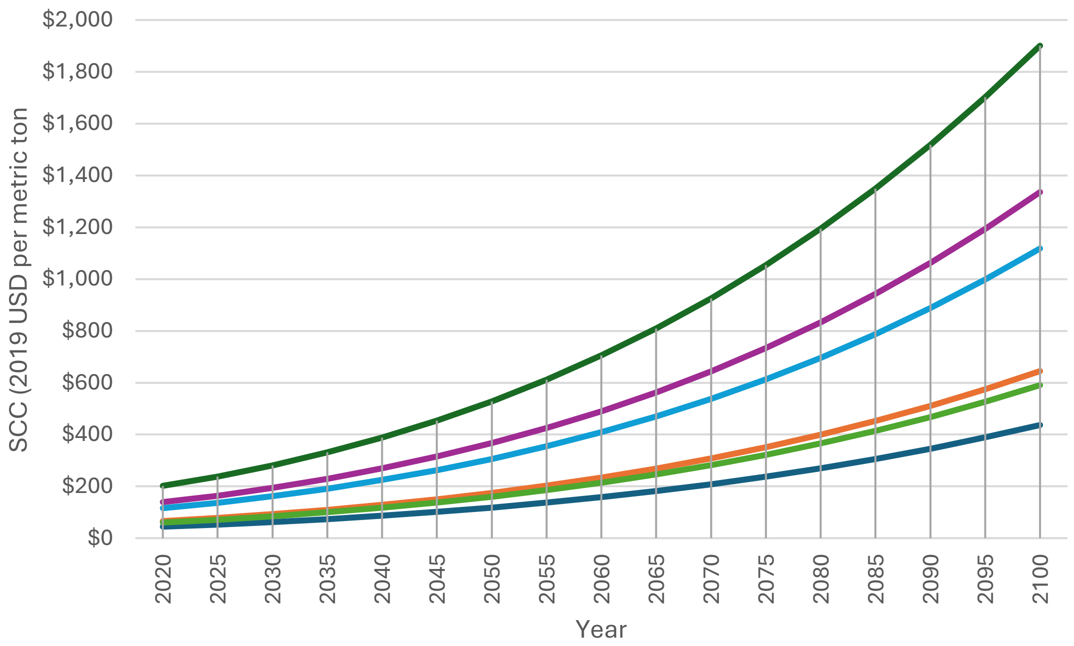
Introduction: Motivation

- Nordhaus (2019) highlights wide range of potential damages
  - ❑ Nordhaus and Moffat (2017) Vs. Howard and Sterner (2017)
  - ❑ Both estimated using meta-regression
  - ❑ EPA (2023)’s SC-GHGs uses HS
- Recent updates by Tol (2024) and Barrage and Nordhaus (2024)
  - ❑ Disparities remain
- Meta-analysis is considered the objective and scientifically rigorous way to combine estimates
  - ❑ Why are disparities arising?
- Goals
  - ❑ Update upper end of this range
  - ❑ Understand differences
  - ❑ Address inconsistencies

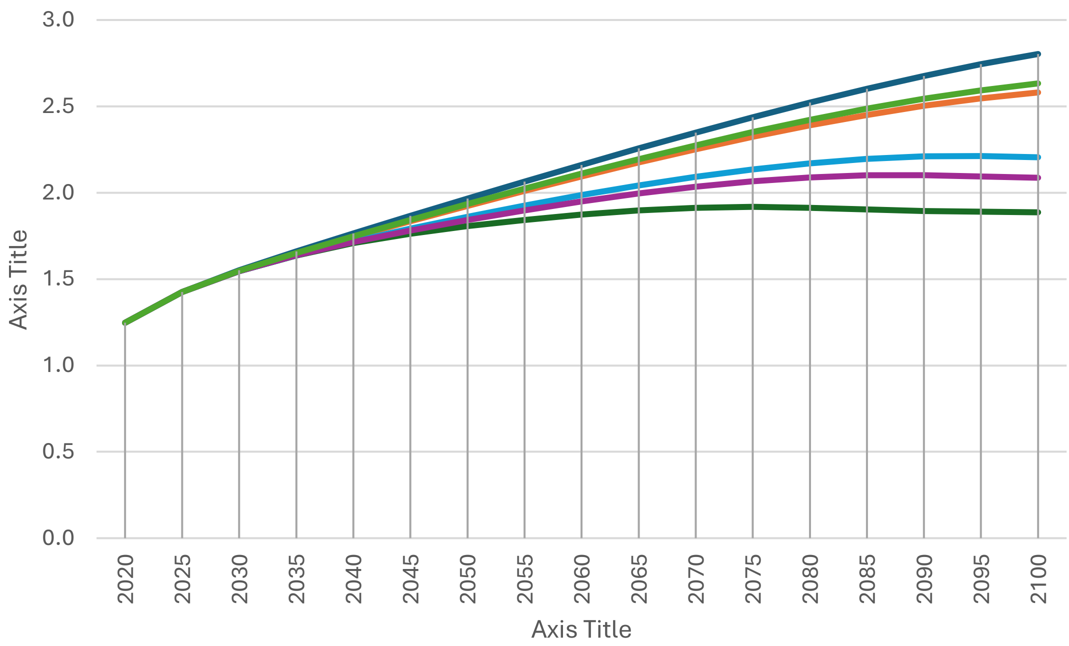


Introduction: Different Policy Recommendations (4.3% SDR in 2030)

Social Cost of Carbon



Optimal Temperature



Introduction: Meta-Regression Is a Study of Studies

What is meta-regression?

- Meta-analysis: “A method for the systematic quantitative summary of evidence across empirical studies” (Nelson and Kennedy, 2009)
- Meta-regression: Controlling for factual, methodological, and population differences between studies using regression analysis due to the non-random nature of the underlying data and studies

What are the steps?

Data

- Search
- Selection
- Entry (including variable definitions)

Estimation

- Estimator
- Define weights
- Run model and sensitivity analysis

Data: Search, Selection, and Entry

Reconduct search from HS to be consistent & up-to-date

- Search: Identified 55 new studies
  - ❑ Systematic review synthesis (SRS) ideally by a professional data scientist
  - ❑ As not possible, combine formal and informal search with documentation
  - ❑ Include grey literature
- Selection: 105 estimates from 38 studies (up from 26 estimates from 20 studies)
  - ❑ Develop selection criteria *a priori* and document

"Global willingness to pay to avoid climate change measured as a percent of global GDP"

  - ❑ Implement rigorously and transparently
  - ❑ Drop duplicate estimates
  - ❑ Drop low quality studies (new criteria)
- Data entry
  - ❑ Define variables transparently and *a priori*
  - ❑ Two reviewers input data separately

Data: Global Climate Damage Estimates

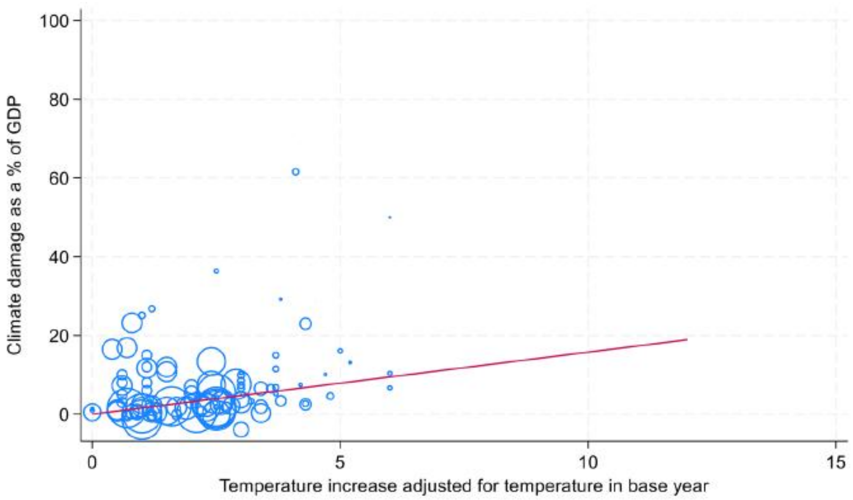
Estimation Methodologies

- Enumerative
  - ❑ Bottom-up IAMs
  - ❑ Meta-analytic IAMs (new)
- Expert elicitation
- CGE
  - ❑ CGE-IAMs
  - ❑ Agent-based IAMs (new)
  - ❑ Spatial IAMs (new)
- Statistical
  - ❑ Cross-section
  - ❑ Panel
  - ❑ Time-series (available after cutoff)
- Science-based
  - ❑ Limits of human respiratory system
  - ❑ Scientific consensus on 2°C limit

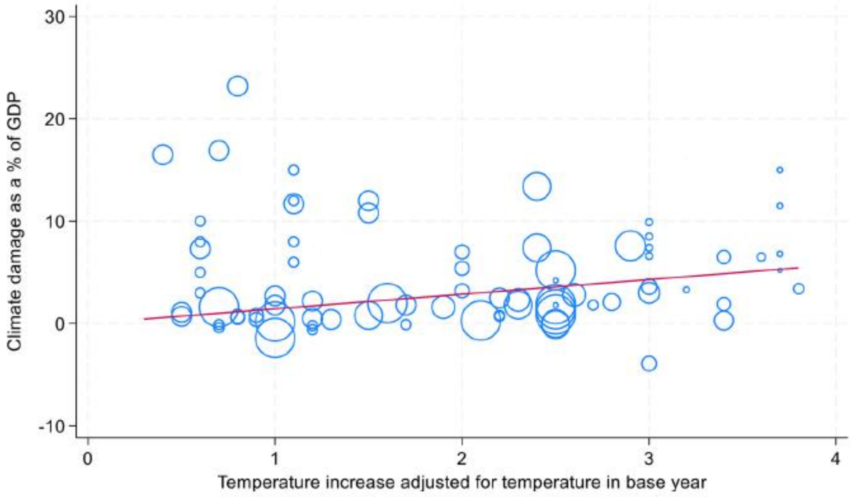
How Do Estimates Differ?

- Factual / Population
  - ❑ Temperature
  - ❑ Socio-economic and emission scenarios
  - ❑ Base period and temperature
- Damage types / Structural assumptions
  - ❑ Market only
  - ❑ Catastrophic / Tipping points
  - ❑ Productivity: Growth and Indirect
  - ❑ Growth: Level and Change
- Study
  - ❑ Author, method, and model
  - ❑ New, update, or cite other study
  - ❑ Age of study (time)
  - ❑ Design of study / quality

Data: Summarized at Estimate Level

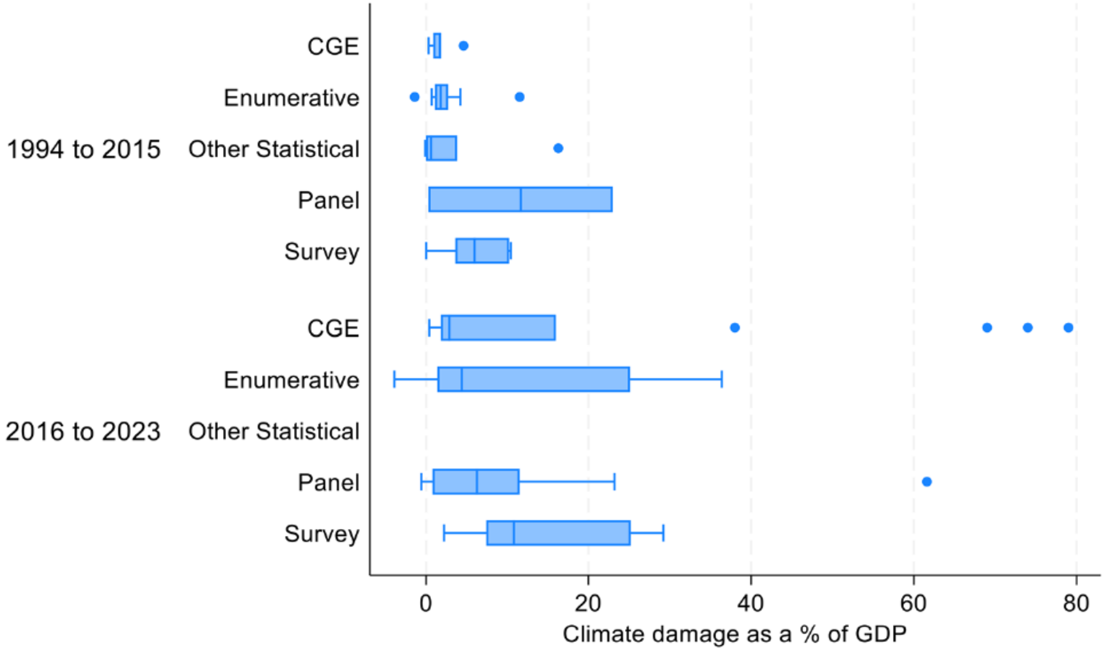


b. Total Damage Estimates Corresponding to Temperature Increases Less Than or Equal to 4°C



Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
Summary at Estimate Level						
D_new	Climate damage as a % of GDP	105	8.07	13.41	−3.9	99
damage	D_new without catastrophic impacts	93	5.96	8.22	−3.9	61.6
T_new	Temperature increase relative to base year	105	2.52	1.75	0.4	12
t	Temperature increase adjusted for temperature in base year (equal to 0 if catastrophic only impacts)	105	2.44	1.77	0	12
delta_t	Average annual rate of temperature change (°C/year)	101	0.02	0.01	0.01	0.06
T_Base	Temperature increase (°C) in base year	105	0.64	0.40	0	1.2
Base_Year	Year when base temperature increase occurs	105	1972	63	1850	2020
Impact_Year	Year when final temperature increase occurs	105	2103	54	1990	2300
Market	Indicator variable equal to 1 if includes only market (non-catastrophic) damages.	105	0.47	0.50	0	1
cat	Indicator variable equal to 1 if study includes catastrophic damages	105	0.13	0.34	0	1
prod	Indicator variable equal to 1 if productivity is affected by climate change	105	0.54	0.50	0	1
cross	Indicator variable equal to 1 if study uses cross-sectional data without country fixed effects	105	0.01	0.10	0	1
indirect	Indicator variable equal to 1 if study captures indirect market impacts	105	0.10	0.29	0	1
Growth	Indicator variable equal to 1 if the estimate captures growth	105	0.40	0.49	0	1
Level	Indicator variable equal to 1 if estimates growth effect using temperature level variable(s)	105	0.16	0.37	0	1
Change	Indicator variable equal to 1 if estimates growth effect using temperature change variable(s)	105	0.14	0.35	0	1
Time	Year published minus 1994	105	23.58	7.18	0	30

Data: Summarized at Method Level



Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
m_IAM	Indicator variable equal to 1 if study uses IAM (enumerative or CGE) to derive damages	*38*	*0.45*	*0.50*	*0*	*1*
m_science	Indicator variable equal to 1 if study uses the science-based method to derive damages	*38*	*0.05*	*0.23*	*0*	*1*
m_stat	Indicator variable equal to 1 if study uses the statistical method to derive damages	*38*	*0.39*	*0.50*	*0*	*1*
m_Survey	Indicator variable equal to 1 if study uses the survey-based method to derive damages	*38*	*0.11*	*0.31*	*0*	*1*
m2_cge	Indicator variable equal to 1 if study uses a CGE-IAM to derive damages	38	0.16	0.37	0	1
m2_cross	Indicator variable equal to 1 if study uses the cross-sectional statistical method to derive damages	38	0.03	0.16	0	1
m2_enum	Indicator variable equal to 1 if study uses the enumerative method to derive damages	38	0.29	0.46	0	1
m2_panel	Indicator variable equal to 1 if study uses panel-based statistical method to derive damages	38	0.37	0.49	0	1
m2_science	Indicator variable equal to 1 if study uses the science-based method to derive damages	38	0.05	0.23	0	1
m2_survey	Indicator variable equal to 1 if study uses the survey-based method to derive damages	38	0.11	0.31	0	1
Grey	Indicator variable equal to 1 if grey literature	38	0.16	0.37	0	1
Growth	Indicator variable equal to 1 if the study captures growth effect	38	0.28	0.45	0	1

Data: Standard Deviation Estimates

- Observed SE (preferred)
  - ❑ Directly observe
  - ❑ Observe confidence interval
- Calculated SE
  - ❑ Observe min and max
  - ❑ Calculate assuming 99.9% confidence interval

Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
Observed Standard Errors (at Estimate Level)						
SE	Standard error of climate damage estimate	35	10.10	9.55	0.04	39
T_new	Temperature increase relative to base year	35	2.52	1.55	0.3	7
cat	Indicator variable equal to 1 if study includes catastrophic damages	35	0.14	0.36	0	1
Observed and Calculated Standard Errors (at Estimate Level)						
SE	Standard error of climate damage estimate	59	6.59	8.54	0.02	39
T_new	Temperature increase relative to base year	59	2.66	1.63	0.3	7
cat	Indicator variable equal to 1 if study includes catastrophic damages	59	0.08	0.28	0	1

Econometric Model: Extend HS (2017)

- Hierarchical model
  - ❑ Data are estimates
  - ❑ Estimates' standard deviations are NOT always observed
- Random effects model
  - ❑ Weighted-least squares
  - ❑ Precision-based weights

$$w_i = \frac{1}{\sigma_{e,i}^2+\tau^2} \text{ for estimate } i$$

  - ❑ Estimate-specific weighs: $\sum_{i\in s} \omega_i = 1$
  - ❑ Knapp–Hartung variance estimator
- Three challenges
  - ❑ Varying baseline temperatures

$$t_{i,s,m.n} = g_n\left(T\_new_{i,s,m} + \theta_{i,s,m}\right) - g_n\left(\theta_{i,s,m}\right)$$

  - ❑ Only partially observe standard errors
  - ❑ Unknown functional forms:

AICc and BIC

- General model

$$\widehat{D} = g(T)\alpha + Rh(T)\beta + W\delta + \mu + e$$

$\mu \sim N(0,\tau^2)$ [unobserved methodological & factual differences]

$e \sim N(0,\sigma_e^2)$ [measurement error]

- Econometric model

$$\hat{\sigma}_{e,j,s,m} = \alpha_\sigma t_{j,s,m.n} + \beta_\sigma t_{j,s,m,cat} R_{j,s,m,cat} + \varepsilon_{j,s,m} \text{ where } \varepsilon_{j,s,m} \sim N(0,\sigma^2).$$

$$\widehat{D}_{i,s,m} = \alpha t_{i,s,m.n} + \sum_k \beta_k t_{i,s,m.k} R_{i,s,m,k} + \delta cross_{i,s,m} + \varepsilon_{i,s,m}$$

where $\varepsilon_{i,s,m} = \mu_i + e_{i,s,m}$

$$w_i = \frac{\omega_i}{\sigma_{e,i}^2+\tau^2} \text{ where } \sum_{i\in s} \omega_i = 1$$

Results – Standard Deviation

- Identify functional form: iterate over λ and ϑ by values of 0.1
  - Polynomial: $g(T) = \alpha_\sigma T^\lambda$
  - Linear spline: $g(T) = \alpha_{\sigma,1}T + 1[T > \lambda] \times \alpha_{\sigma,2}T$
  - Linear spline with intercept: $g(T) = \alpha_{\sigma,1} + 1[T > \lambda] \times \alpha_{\sigma,2}T$
  - Constant: $g(T) = \alpha_{\sigma,1}$
  - Catastrophic: $g(T) = \beta_\sigma cat \times T^\vartheta$
- Minimize AICc and BIC over multiple datasets (to address concerns of overfitting)
  - Catastrophic impacts included and excluded: *D_new* & *damage*
  - Estimates for t >4ºC included and excluded
  - "Observed SE" and "Observed and calculated SE"
- Preferred (robust and closer to equal weighting):

$$SD = 4.2 + 1[t > 2.6] \times 6.5 \times t + 19.0 \times \text{cat} \times \sqrt{t}$$

- Alternative (theoretically consistent, but overweighs $t < 1$):

$$SD = 1.4 \times t^{1.5} + 16.8 \times \text{cat} \times \sqrt{t}$$

Results – Damage Function

- Identify functional forms for each component: iterate over λ by values of 0.1
  - Polynomial: $g(T) = \alpha_\sigma T^\lambda$
  - Linear Spline: $g(T) = \alpha_{\sigma,1} T + 1[T > \lambda] \times \alpha_{\sigma,2} T \ (\lambda = 3.3)$
  - Quadratic: $g(T) = \alpha_1 T + \alpha_2 T^2$
  - Sextic: $g(T) = \alpha_1 T^2 + \alpha_2 T^6$
- Minimize AICc and BIC over multiple specifications and datasets (to address concerns of overfitting)
  - Sets of control variables
  - Datasets: Catastrophic impacts included and excluded; Estimates for t >4ºC included and excluded
  - Two standard error specifications: preferred and alternative
- Preferred model:

$$D = 0.622 \times T^{1.5} + 1.775 \times cat \times T^{1.5} + 1.997 \times Growth \times T$$

  - Non-catastrophic: 3.2% to 9.2% of GDP for a 3°C increase depending on growth included
  - Total: 12.5% to 18.5% of GDP for a 3°C increase depending on growth included

Results – Primary Results and Sensitivity Analyses

Table 3 Base Regressions: Random Effects Model, by Methodological Controls, SE Calculation Assumptions, and Other Model Specifications

Specification[A]	Random Effects Modeling Using All Data and Forecasted SE Using Linear Spline with Intercept, Varying by Methodological Controls					Random Effects Model Using Growth Specification, Varying SE Calculation, Data, or Method for Forecasting SE				
	Simple	Extended Simple	Growth	Extended Growth	Theoretically Consistent Model	Cluster Robust SE at Estimation Method	Double Bootstrap (2,000 Draws)	Non-catastrophe	T≤4°	Alternative SE
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VARIABLES[B]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	damage	D_new	D_new
$t^{1.5}$	0.839***	0.803**	0.622**	0.647**	0.806*	0.622***	0.652***	0.571	0.587**	0.578
	(0.226)	(0.339)	(0.265)	(0.259)	(0.423)	(0.165)	(0.131)	(0.348)	(0.254)	(0.368)
$cat*t^{1.5}$	1.765	1.775	1.775	1.743	1.629	1.775***	1.864***		2.507	1.633
	(1.858)	(1.862)	(1.858)	(1.863)	(1.882)	(0.468)	(0.556)		(2.987)	(1.681)
$prod*t^{1.5}$		0.103								
		(0.457)								
$Growth*t$			1.997*		1.898	1.997***	2.364***	1.956	0.721	3.838***
			(1.130)		(1.280)	(0.427)	(0.728)	(1.390)	(0.886)	(1.322)
$Level*t$				2.127						
				(1.944)						
$Change*t$				2.024						
				(1.386)						
Cross		-3.275	-2.559	-2.657	-2.689	-2.559***		-2.359	-2.422	-2.383
		(6.084)	(6.026)	(6.022)	(6.154)	(0.651)		(9.440)	(6.746)	(8.872)
$Market*t^{1.5}$					-0.151					
					(0.540)					
$indirect*t^{1.5}$					-0.296					
					(0.602)					
Observations	105	105	105	105	105	105	105	93	89	105
F-statistic	7.795	3.995	4.763	3.785	3.249	-	-	3.560	3.791	6.331
Prob>F	0.001	0.005	0.001	0.004	0.006	-	-	0.017	0.007	0.000
Tau2	0.000	0.000	0.000	0.000	0.000	-	-	0.000	0.000	18.280
AICc	767.528	770.718	760.942	763.621	764.009	756.574	-	639.981	600.281	794.581
Adjusted R2	-	-	-	-	-	0.352	-	-	-	-
Damages at 3°C										
Non-catastrophic/Level	4.4%	4.2%	3.2%	3.4%	4.2%	3.2%	3.4%	3.0%	3.1%	3.0%
Growth	-	4.5%	9.2%	9.6%	9.9%	9.2%	10.5%	8.8%	5.2%	14.5%
Catastrophic	9.2%	9.2%	9.2%	9.1%	8.5%	9.2%	9.7%	-	13.0%	8.5%

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Results – Hypothesis Tests

- Level and Change have the same impact
    - ❑ Not controlling for lags or persistence
- Adaptation
    - ❑ Scenario (preferred and BAU) does not impact results
    - ❑ Average annual rate of temperature change is statistically insignificant
- Grey literature has no significant impact
- Damage estimates increased by 0.1% annually (controlling for temperature and interactions)

Specification[A]	Random Effects Modeling Using All Data and Forecasted SE Using Linear Spline with Intercept, Varying by Methodological Controls						
	Preferred	Delta[B]	Primary Scenario[B]	BAU Scenario[B]	Time Linear	Grey	GDP Per Capita
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES[C]	D_new	D_new	D_new	D_new	D_new	D_new	D_new
$t^{1.5}$	0.622**	0.406	0.608**	0.695**	0.170	0.620**	0.429
	(0.265)	(0.430)	(0.250)	(0.279)	(0.370)	(0.267)	(0.281)
$cat*t^{1.5}$	1.775	2.199	1.236	1.050	1.817	1.780	2.024
	(1.858)	(2.042)	(1.780)	(2.553)	(1.858)	(1.860)	(1.862)
*Growth*t*	1.997*	2.005*	2.404**	1.776	1.774	1.959	0.990
	(1.130)	(1.133)	(1.110)	(1.177)	(1.138)	(1.266)	(1.232)
Cross	-2.559	-2.096	-2.504		-1.456	-2.550	-1.794
	(6.026)	(6.071)	(6.016)		(6.059)	(6.027)	(6.037)
delta_t		39.252					
		(60.272)					
Time					0.114*		
					(0.065)		
Grey* $t^{1.5}$						0.103	
						(1.540)	
GDPPC* $t^{1.5}$							1.147**
							(0.559)
Observations	105	101	79	45	105	105	105
F-statistic	4.763	3.932	5.575	5.989	4.422	3.811	4.652
Prob>F	0.001	0.003	0.001	0.002	0.001	0.003	0.001
Tau2	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AICc	760.942	732.741	588.41	338.57	750.209	760.927	745.8819

Results – Sensitivity Analysis

- Study selection criteria
  - ❑ Drop each study (Kotz et al. 2024; Dell et al. 2012; Kikstra et al. 2021)
  - ❑ Narrow to preferred, recent studies, and low temperature estimates
  - ❑ Include screened out studies
- Standard error assumptions in weights
  - ❑ Include calculated SE
  - ❑ Use alternative polynomial form
  - ❑ Replace only missing SE
- Barrage and Nordhaus (2024)
  - ❑ Quality weights
  - ❑ Outliers

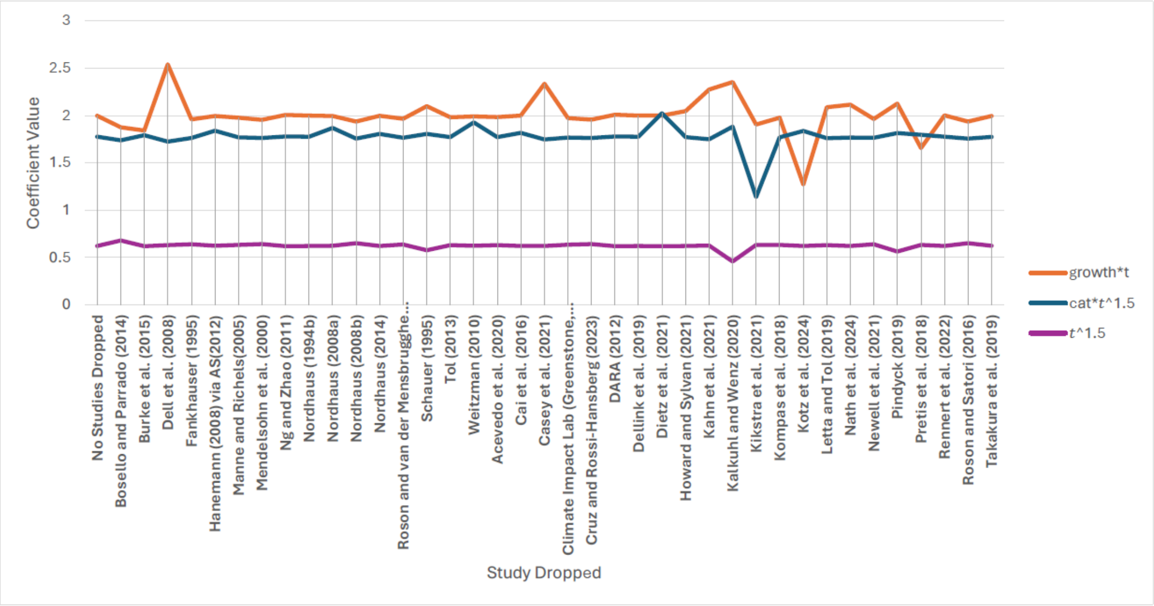


Fig SM.1 Impact of dropping each study on coefficient values of our preferred regression [regression 3 on Table 3], by study dropped and coefficient value. $t^{1.5}$ is temperature change adjusted for its baseline temperature to the 1.5 power, while $cat*t^{1.5}$ is temperature change adjusted for its baseline temperature to the 1.5 power interacted with an indicator variable for whether the estimate includes catastrophic impacts. The variable *growth*t* is an indicator variable for whether the estimate captures a growth effect interacted with temperature change adjusted for its baseline temperature.

Table 4 Replication of Barrage and Nordhaus' (2024) Weighted OLS and Median Regression Using Our Data, by Modified Assumptions

Specification[A]	Preferred Model (with Knapp–Hartung Variance Estimator)	Preferred Model (with Clustered Standard Errors at Estimation Method Level)	Drop Method - ological Controls	Change Exponent	Drop Base Temperature Adjustment	Drop Standard Errors Weights and Stop Clustering SE	Adopt BN's Alternative Damage and Temperature Data for Overlapping Estimates	Switch to BN's Set of Studies	Adopt BN's Quality Weights	Adopt Median Regression
	(0)		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES[B]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
$t^{1.5}$	0.622**	0.622***	0.861***							
	(0.265)	(0.165)	(0.222)							
$cat*t^{1.5}$	1.775	1.775***								
	(1.858)	(0.468)								
*growth*t*	1.997*	1.997***								
	(1.130)	(0.427)								
cross	-2.559	-2.559***								
	(6.026)	(0.651)								
t^2				0.448***						
				(0.099)						
T_new^2					0.501***	0.652***	0.647***	0.389***	0.350***	0.222***
					(0.125)	(0.033)	(0.032)	(0.063)	(0.057)	(0.059)
Observations	105	105	105	105	105	105	103	31	31	31
R2	-	0.377	0.291	0.297	0.217	0.791	0.802	0.563	0.56	
Adjusted R2	-	0.352	0.284	0.29	0.209	0.788	0.8	0.548	0.545	
Likelihood	-	-375.2	-382	-381.5	-387.2	-397.6	-387.6	-91.08	-93.72	
Non-catastrophic/Level damages for a 3°C										
Damages (% GDP)	3.2%		4.5%	4.0%	4.5%	5.9%	5.8%	3.5%	3.2%	2.0%
% Change From Previous Column	-		38%	-10%	12%	30%	-1%	-40%	-10%	-37%
Non-catastrophic/Level damages for a 6°C										
Damages (% GDP)	9.1%		12.7%	16.1%	18.0%	23.5%	23.3%	14.0%	12.6%	8.0%
% Change From Previous Column	-		38%	27%	12%	30%	-1%	-40%	-10%	-37%

*** p<0.01, ** p<0.05, * p<0.1

Replication of Barrage and Nordhaus (2024): Method-ological Controls Are Critical

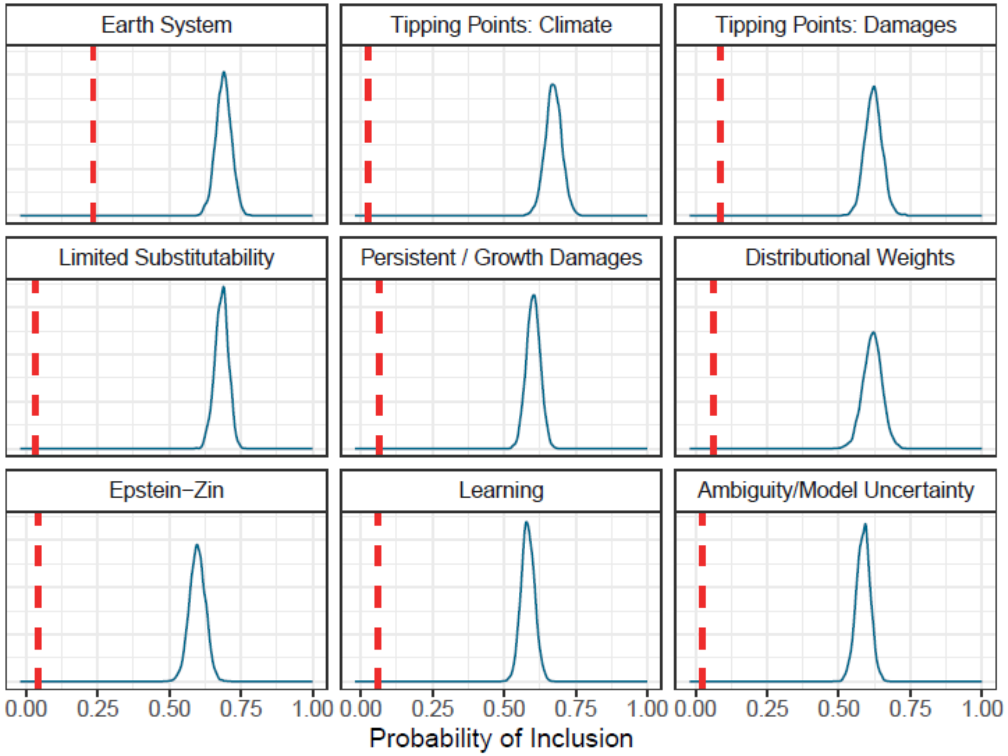
Results – Synthetic Damage Functions

- Structural assumptions differ between studies
  - Produces wide set of damage estimates
  - Whether to include structural assumptions, like growth, is unclear
  - Implicitly weights methodologies and structural assumptions
- Use inclusion probabilities as ex-post weights in preferred specification

$$D = 1.202 \times T + 1.724 \times T^{1.5}$$

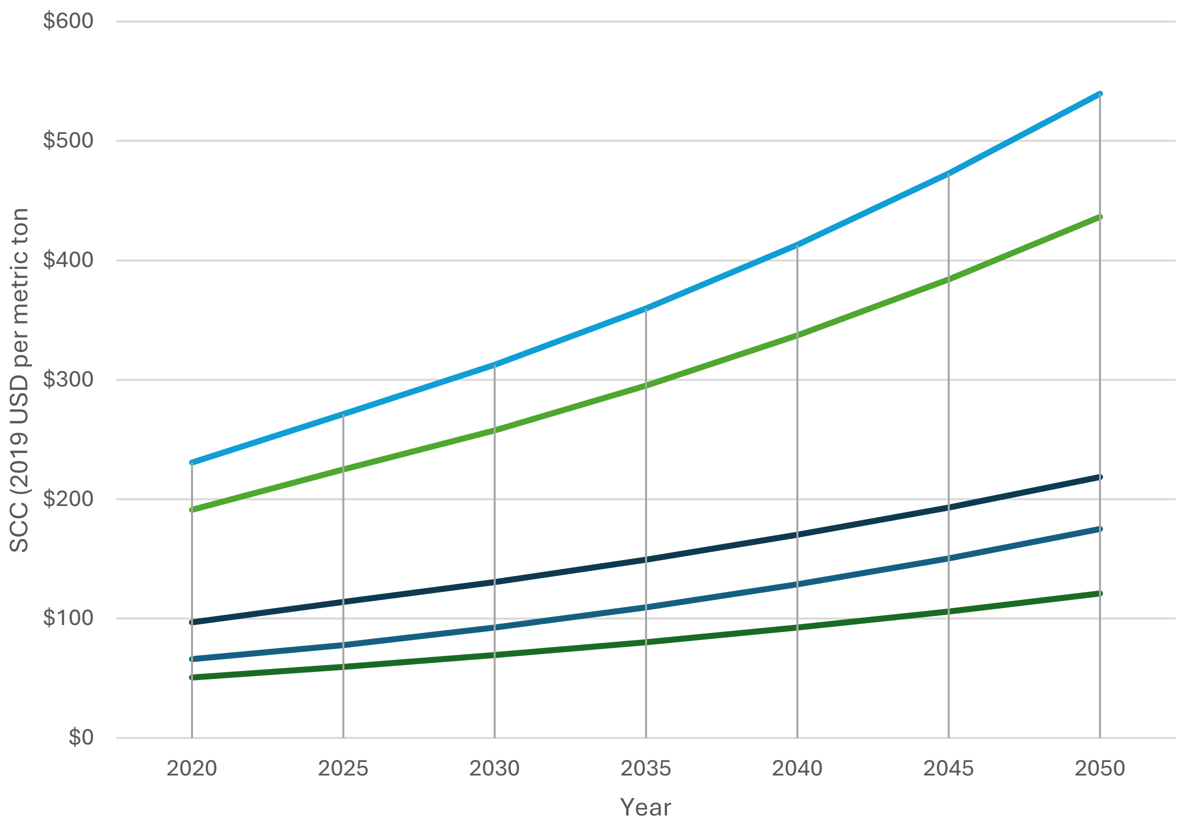
- Inclusion probability for tipping point damages NOT catastrophic impacts
  - Use Dietz et al. (2021)'s estimate of GDP loss from tipping points following BN

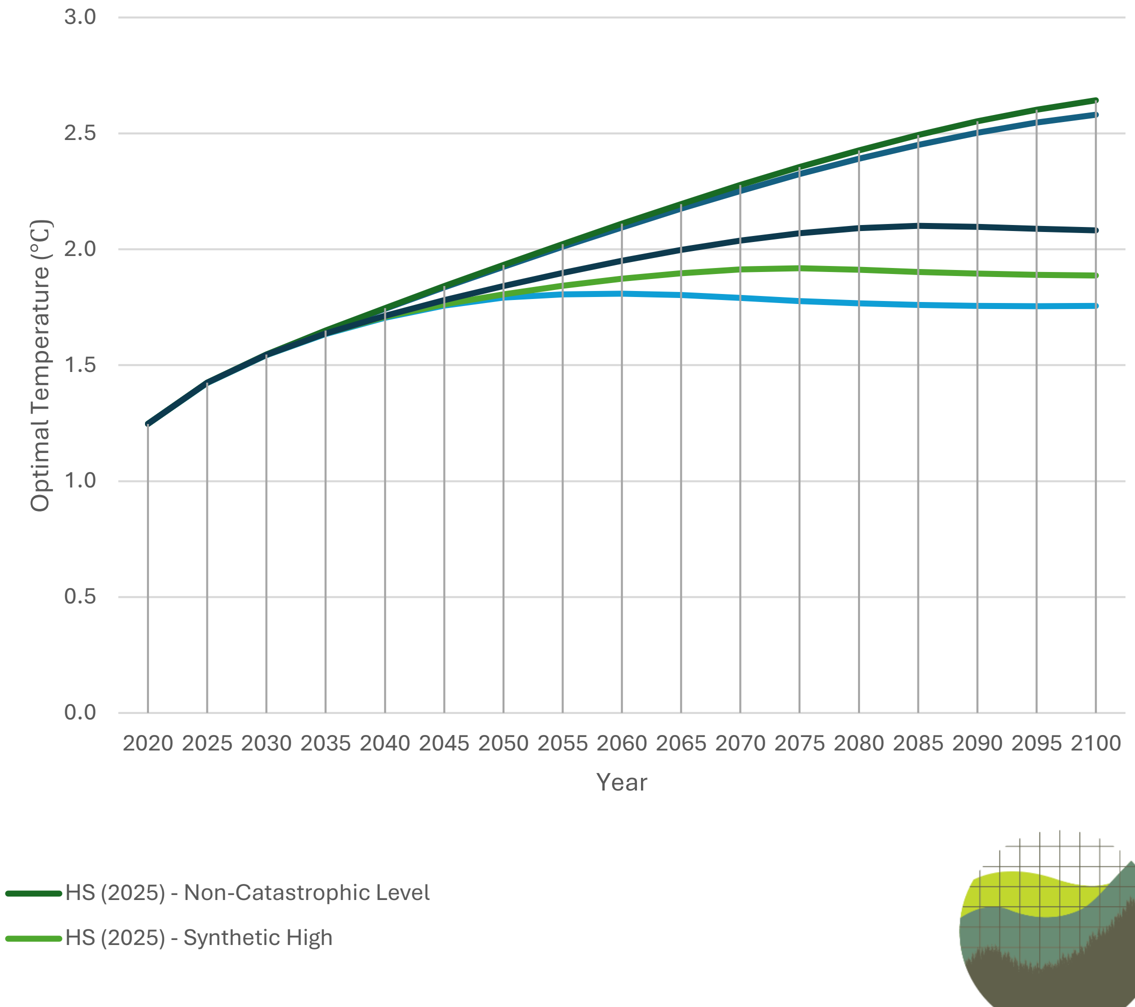
$$D = 1.178 \times T + 0.691 \times T^{1.5}.$$



Moore et al. (2024) calculates inclusion probabilities of tipping point damages (62.1%) and growth impacts (60.2%)

Results – Policy Recommendations (4.3% SDR in 2030)





Conclusion – Takeaways

- Barrage and Nordhaus (2024)'s level damages for 3ºC increase
  - ❑ Non-catastrophic: 1.6% to 2.1% (depending on adjustment)
  - ❑ Total: 3.1% to 9.0% (preferred versus alternative)
- Our damages for 3ºC increase
  - ❑ Non-catastrophic: 3.2% to 9.2% (level or growth)
  - ❑ Total: 12.5% to 18.5% (level or growth)
  - ❑ Synthetic: 7.1% to 12.6% (tipping point versus catastrophic)
- Going forward
  - ❑ Continue to expand data
  - ❑ Control for sectors or additional structural assumptions
  - ❑ Improve quality weights (including age of study) and estimators
  - ❑ Stay humble

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Results – Howard and Sterner (2017) Regression

Table 2 Howard and Sterner's (2017) weighted-least squares regression with cluster robust standard errors at the method level estimated with new data, by dataset[A]

Specification	Estimates from 2016 to 2023				Estimates from 1994 to 2023			
	Low Damages Estimates Only ($t \leq 4°C$)		All Damages Estimates		Low Damages Estimates Only ($t \leq 4°C$)		All Damages Estimates	
	Simple	Extended	Simple	Extended	Simple	Extended	Simple	Extended
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variables[B]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
t^2	0.804*	0.803*	0.720***	0.507*	0.624**	0.556**	0.440***	0.328***
	(0.337)	(0.395)	(0.174)	(0.230)	(0.197)	(0.244)	(0.036)	(0.067)
Market* t^2	−0.249	−0.250	−0.207	−0.213	−0.216	−0.336	0.025	−0.182
	(0.393)	(0.396)	(0.252)	(0.209)	(0.236)	(0.304)	(0.141)	(0.154)
cat* t^2	1.065*	1.064**	0.634	0.585	0.737**	0.701**	0.214***	0.312***
	(0.446)	(0.428)	(0.512)	(0.465)	(0.273)	(0.239)	(0.064)	(0.088)
prod* t^2		0.002		0.337		0.230		0.427*
		(0.328)		(0.300)		(0.362)		(0.232)
Cross		-		-		−1.472		−1.008
						(2.079)		(1.175)
Observations	68	68	79	79	88	88	105	105
Likelihood	−256.900	−256.900	−308.400	−307.400	−293.600	−293.200	−359.800	−356.700
F-statistic	27.130		39.080		43.960		155.400	
Prob>F	0.001		0.000		0.000		0.000	
R2	0.313	0.313	0.308	0.325	0.282	0.288	0.513	0.541
Adjusted R2	0.282	0.270	0.281	0.289	0.256	0.245	0.499	0.519

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

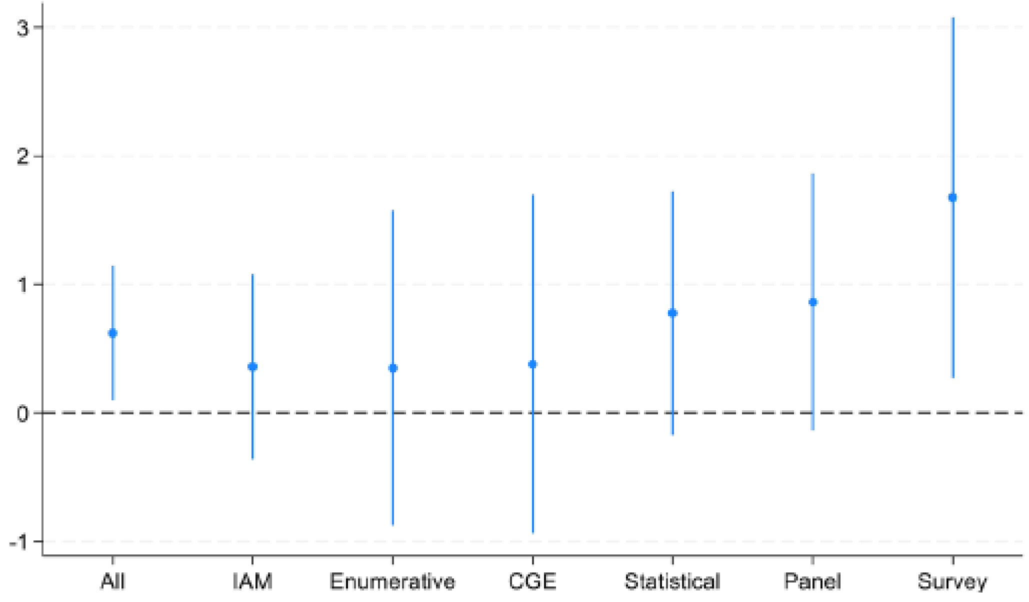
[A]Howard and Sterner's (Howard and Sterner 2017) preferred WLS regression using an inverse temperature weight assuming a quadratic damage function and the Simple and the Extended Specifications for methodological controls

[B]See variable definitions in Table 1A

Results – Method-Specific Regressions

- Methods-specific regressions
  - ❑ No methodological controls (*All* is weighted sum)
  - ❑ Relevant controls included
- Drop each estimation method from preferred regression
  - ❑ Robust due to controls
- Include method-temperature interactions in preferred regression
  - ❑ Survey and panel are statistically higher
  - ❑ Panel unexpectedly higher even when control for growth

Non-catastrophic, level effect



Alternative Selection Assumption

Specification	Preferred	Include Low Quality and Some Superseded Studies	Include Estimates Screened Out in Selection Process	Jointly Include Both Sets of Estimates Added in the Previous Two Columns	Focus Exclusively on Estimates Preferred by Authors	Focus Exclusively on Studies Published After 2015	Drop Dell et al. (2012); Kikstra et al. (2021); and Kotz et al. (2024)	Drop Only Kotz et al. (2024)	Replace Kotz et al. (2024) with Waidelich et al. (2024)	Replace Kotz et al. (2024) with Waidelich et al. (2024) Assuming the Latter Is a Growth Paper
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VARIABLES	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
t_5	0.622**	0.705***	0.647**	0.636**	0.583**	0.820**	0.637**	0.622**	0.647**	0.621**
	(0.265)	(0.250)	(0.260)	(0.244)	(0.243)	(0.370)	(0.265)	(0.265)	(0.263)	(0.265)
cross	-2.559	0.460	-2.657	-0.796	-		-2.619	-2.560	-2.659	-2.555
	(6.026)	(2.011)	(6.023)	(2.007)	-		(6.026)	(6.026)	(6.025)	(6.026)
growth_t	1.997*	1.909*	1.944*	2.053**	2.544**	1.979	1.605	1.270	1.216	1.379
	(1.130)	(1.032)	(1.125)	(1.006)	(1.153)	(1.360)	(1.224)	(1.147)	(1.145)	(1.123)
cat_t_5	1.775	2.162	1.759	2.202	1.743	2.383	1.133	1.837	1.821	1.829
	(1.858)	(1.636)	(1.858)	(1.635)	(1.837)	(3.104)	(2.070)	(1.858)	(1.858)	(1.858)
Observations	105	124	111	145	81	79	95	101	104	104
F-statistic	4.763	6.767	4.930	6.385	7.249	5.764	3.48	3.547	3.681	3.776
Prob>F	0.001	0.000	0.001	0.000	0.000	0.001	0.011	0.010	0.008	0.007
Tau2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

New Analysis: Address Kotz et al. (2024)

Specification	Preferred	Replace Kotz et al. (2024) with Bearpark et al. (2025)	Replace Kotz et al. (2024) & add Waidelich et al. (2024)	Replace Kotz et al. (2024) & add Waidelich et al. (2024) with Growth Assumption	Replace Kotz et al. (2024), add Waidelich et al. (2024), & drop Dell et al. (2012)
	(1)	(2)	(3)	(4)	(5)
VARIABLES	D_new	D_new	D_new	D_new	D_new
t_5	0.622**	0.614**	0.639**	0.612**	0.642**
	(0.265)	(0.265)	(0.263)	(0.265)	(0.263)
cat_t_5	1.775	1.864	1.848	1.856	1.813
	(1.858)	(1.858)	(1.858)	(1.858)	(1.858)
growth_t	1.997*	1.045	0.990	1.158	1.356
	(1.130)	(1.115)	(1.113)	(1.094)	(1.173)
cross	-2.559	-2.526	-2.625	-2.518	-2.639
	(6.026)	(6.026)	(6.024)	(6.026)	(6.024)
Observations	105	102	105	105	104
F-statistic	4.763	3.370	3.503	3.586	3.750
Prob>F	0.001	0.013	0.010	0.009	0.007
Tau2	0.000	0.000	0.000	0.000	0.000
I2	0.000	0.000	0.000	0.000	0.000
Q	31.480	16.170	16.780	16.450	15.790
Chi corrected	0.000	0.000	0.000	0.000	0.000

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Dropping Each Estimation Method

Specification	Preferred	Dropped Estimation Method Using General Classification of Estimation Methodologies				Dropped Estimation Method Using Detailed Classification of Estimation Methodologies				
	All Methods	IAM	Science	Statistical	Survey	Enumerative	CGE	Science	Panel	Survey
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VARIABLES[A]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
$t^{1.5}$	0.622**	0.977**	0.624**	0.552*	0.505*	0.700**	0.765**	0.624**	0.528*	0.505*
	(0.265)	(0.404)	(0.265)	(0.321)	(0.282)	(0.298)	(0.331)	(0.265)	(0.314)	(0.282)
Cross	-2.559	-3.962	-2.566		-2.095	-2.867	-3.123	-2.566	-2.185	-2.095
	(6.026)	(6.145)	(6.026)		(6.038)	(6.050)	(6.077)	(6.026)	(6.062)	(6.038)
Growth*t	1.997*	1.154	1.988*	2.388	2.302*	1.756	1.689	1.988*	2.429	2.302*
	(1.130)	(1.315)	(1.133)	(2.968)	(1.202)	(1.174)	(1.209)	(1.133)	(2.966)	(1.202)
cat*$t^{1.5}$	1.775	1.229	2.011	1.800	1.847	1.506	1.682	2.011	1.817	1.847
	(1.858)	(2.520)	(2.769)	(1.878)	(1.859)	(2.505)	(1.863)	(2.769)	(1.878)	(1.859)
Observations	105	70	101	52	92	84	91	101	54	92
F-statistic	4.763	4.469	4.570	2.010	3.999	4.382	4.72	4.570	1.475	3.999
Prob>F	0.001	0.003	0.002	0.125	0.005	0.003	0.002	0.002	0.224	0.005
Tau2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Outlier Robust Estimator

Specification	Preferred	Consistent Data	Quality Weights		Outlier Robust[A]			
		For Overlapping Studies, Replace Our Damage & Temp. Data with Nordhaus' Damage & Temp. Data	Use Nordhaus' Quality Weights	Use Our Own Quality Weights	Median Regression	M-estimator (Huber 1973)	S-estimator (Salibian-Barrera and Yohai 2006)	MM-estimator (Yohai 1987)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES[B]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
$t^{1.5}$	0.622**	0.672**	0.289	0.544*	0.481***	0.497***	0.341***	0.410***
	(0.265)	(0.263)	(0.346)	(0.297)	(0.123)	(0.094)	(0.068)	(0.084)
Cross	-3.275	-2.756	0.434	-2.252	-2.000	-2.066***	-1.448***	-1.719***
	(6.084)	(6.025)	(5.866)	(6.049)	(0.000)	(0.370)	(0.268)	(0.330)
Growth*t	1.997*	2.001*	3.188*	2.337*	1.634	1.601***	1.751***	1.454***
	(1.130)	(1.118)	(1.848)	(1.300)	(2.604)	(0.588)	(0.274)	(0.323)
cat*$t^{1.5}$	1.775	1.733	0.166	1.560	5.212	0.328*	0.137***	0.187**
	(1.862)	(1.858)	(5.269)	(1.976)	(3.602)	(0.172)	(0.036)	(0.079)
Observations	105	103	31	105	102	105	105	105
F-statistic	7.795	5.275	1.498	3.543	-	0.153	0.0719	0.144
Prob>F	0.001	0.001	0.231	0.010	-	0	0	0
Tau2	0.000	0.000	0.000	0.000	-	-	-	-

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Sensitivity to SE Assumptions

Specification	All Damages Estimates				Damages Estimates Above 1ºC Temperature Change (t≥1ºC)				Double Bootstrap (2,000 Draws)
	Spline SE		Polynomial SE		Spline SE		Polynomial SE		Polynomial (Boxcox) SE[A]
	Non-catastrophic	Total	Non-catastrophic	Total	Non-catastrophic	Total	Non-catastrophic	Total	Total
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES[B]	damage	D_new	Damage	D_new	damage	D_new	damage	D_new	D_new
$t^{1.5}$	0.571	0.622**	0.576	0.578	0.580	0.627**	0.512*	0.497	0.674***
	(0.348)	(0.265)	(0.354)	(0.368)	(0.348)	(0.266)	(0.300)	(0.314)	(0.196)
cat*$t^{1.5}$		1.775		1.633		2.129		2.272	1.011**
		(1.858)		(1.681)		(2.033)		(1.900)	(0.834)
Growth*t	1.956	1.997*	3.748***	3.838***	1.646	1.456	2.201*	2.334*	5.599***
	(1.390)	(1.130)	(1.317)	(1.322)	(1.404)	(1.151)	(1.244)	(1.248)	(1.237)
Cross	-2.359	-2.559	-2.379	-2.383	-2.391	-2.578	-2.124	-2.066	
	(9.440)	(6.026)	(8.868)	(8.872)	(9.440)	(6.027)	-7.744	(7.736)	
Observations	93	105	93	105	76	85	76	85	85
F-statistic	3.56	4.763	7.511	6.331	3.09	3.918	3.972	3.678	-
Prob>F	0.017	0.001	0.000	0.000	0.032	0.006	0.011	0.008	-
Tau2	0	0	18.11	18.28	0	0	0	0	-
I2	0	0	0.229	0.148	0	0	0	0	-
Q	16.1	31.48	116.8	118.6	10.56	17.65	17.03	18.73	-
Chi corrected	0	0	40.74	41.09	0	0	0	0	-

Sensitivity to SE Assumptions

Specification[A]	Use Observed Data, Spline Function & Approx. All SE (Preferred)	Use Observed Data, Alternative SE Function (Polynomial) & Approx. All SE	Use Calculated Data, Spline Function & Approx. All SE	Use Calculated Data, Polynomial Function, & Approx. All SE	Use Observed Data, Spline Function & Keep Observed SE	Use Observed Data, Poly. Function & Keep Obs. SE	Use Calculated Data, Spline Function & Keep Obs. and Calc. SE	Use Calculated Data, Poly. Function & Keep Obs. and Calc. SE
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES[A]	D_new	D_new	D_new	D_new	D_new	D_new	D_new	D_new
$t^{1.5}$	0.622**	0.578	0.609***	0.575*	0.560***	0.551***	0.558***	0.551***
	(0.265)	(0.368)	(0.216)	(0.291)	(0.077)	(0.077)	(0.076)	(0.075)
Cross	-2.559	-2.383	-2.509	-2.374	-2.312	-2.276	-2.308	-2.277
	(6.026)	(8.872)	(5.111)	(7.192)	(6.020)	(7.696)	(5.137)	(5.383)
Growth*t	1.997*	3.838***	1.982**	3.294***	1.297	1.775*	1.245	1.818**
	(1.130)	(1.322)	(0.889)	(1.051)	(0.892)	(0.924)	(0.760)	(0.739)
cat*$t^{1.5}$	1.775	1.633	1.771	1.742	0.731	0.635	0.854	0.696
	(1.862)	(1.681)	(1.677)	(1.659)	(1.299)	(1.219)	(1.227)	(1.208)
Observations	105	105	105	105	105	105	105	105
F-statistic	7.795	6.331	7.421	8.382	15.60	15.84	16.77	16.31
Prob>F	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tau2	0.000	18.280	0.000	22.38	0.937	0.830	0.914	1.012