Online Appendix.

Projections and uncertainties about climate change in an era of minimal climate policies*

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A. Response Surface Method to Calculate Distributions

The study uses an approach with exact discretized distributions of the five uncertain variables. Using Monte Carlo methods proved unsuccessful because they was unable to produce a sufficiently large sample to provide reliable results.

Instead, the accuracy of the approach was tested using a response surface method. This approach is used extensively for the analysis of complex engineering and biochemical problems (for example, the strength of Roman cement) and was developed for this purpose in Gillingham et al. (2015). The basic idea is to fit a high-order polynomial function of the uncertain variables to the 3125 grid points using a response surface function (RSF), and then estimate the distribution of the output variables using a Monte Carlo with a large number of draws (N = 1,000,000).

Table A-1 compares the results of the two approaches. The first four columns show estimated means and standard deviations for major variables with the discretized version used in the text ("Discretized") and in the RSF approach ("RSF"). The fifth and sixth columns show the ratios of the means and standard deviations for the two approaches. All means using the discretized distributions are seen to be highly reliable compared to the SRF estimates. The standard deviations have a divergence differs by at most 7%. The major divergence for the standard deviation is for output and emissions, where the discrete underestimates because of the heavy-tailed nature of the lognormal distribution of output.

Outcome variable	Discretized Mean	Discretized St dev	RSF Mean	RSF St dev	Ratio (RSF/D) Mean	Ratio (RSF/D) St dev	R2bar	Standard error regr.
SCC,2015	33.62	30.63	33.58	29.96	1.00	0.98	0.983	4.05
Temp, 2100	4.17	0.99	4.17	0.97	1.00	0.98	0.999	0.02
CO2 conc, 2100 (ppm)	927	307	926	319	1.00	1.04	0.997	17
Output, 2100	1,140	1,009	1,140	1,082	1.00	1.07	0.991	94
CO2 emissions, 2100	102.4	86.2	102.4	90.8	1.00	1.05	0.996	5.2
Damage fraction, 2100	4.1%	3.3%	4.1%	3.3%	1.00	0.99	0.992	0.3%
Interest rate, 2100	3.6%	1.3%	3.6%	1.3%	1.00	1.00	0.998	0.1%
Objective function	4,028.7	2,493.4	4,028.8	2,534.9	1.00	1.02	1.000	50.1

Table A-1. Comparison of statistics with discretized quintile distribution and response surface method[i]

B. Supplementary Tables

Uncertain parameter	Average	Standard deviation	Q1	Q2	Q3	Q4	Q5
Damage coefficient (Y/(°C)2	0.0023	0.0014	0.0006	0.0014	0.0023	0.0024	0.0046
Productivity growth (%/year)	1.52%	0.93%	0.15%	1.00%	1.52%	2.04%	2.89%
Equilibrium temperature sensitivity (°C/2xCO2)	3.10	0.84	2.01	2.52	3.10	3.39	4.49
Rate of decarbonization (% per year)	-1.52%	0.32%	-2.00%	-1.69%	-1.52%	-1.33%	-1.06%
Carbon in intermediate reservoir (GtC)	360.0	97.0	233.6	293.0	360.0	394.4	519.3

Table A-2. Means, standard deviations, and quintile values of uncertain variables[ii]

Variable	Mean, grid	Median, grid	Best guess	Error of best guess
Damage parameter	0.0023	0.0023	0.0023	-2%
ETS	3.10	3.10	3.10	0%
Productiivity parameter	7.6%	7.6%	7.6%	0%
Carbon cycle parameter	360	360	360	0%
Decarbonization rate (% per year)	-1.52%	-1.52%	-1.52%	0%
SCC,2015	33.62	24.47	29.97	11%
Temperature, 2050	2.11	2.12	2.13	-1%
Temperature, 2100	4.17	4.08	4.10	2%
CO2, 2050 (ppm)	563.3	561.8	552.4	2%
CO2, 2100 (ppm)	926.8	839.9	826.6	11%
Output, 2050	319.3	293.6	292.7	8%
Output, 2100	1,140.3	766.3	758.8	33%
Emissions, 2050	63.9	58.3	58.2	9%
Emissions, 2100	102.4	71.2	70.9	31%
Damage fraction, 2050	1.03%	0.88%	1.03%	0%
Damage fraction, 2100	4.15%	3.25%	3.82%	8%
Interest rate, 2100	3.57%	3.61%	3.59%	-1%
Objective function	4,028.7	4,513.3	4,491.0	-11%

Table A-3. Error of best guess approach to DICE model

The last column shows the error from using a best guess rather than the uncertain version of the DICE-2016R model. The error is small where the distribution of the variable is close to symmetrical, but errors arise from skewed distributions. [iii]

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Industrial Emissions GTCO2 per year	35.7	39.4	42.9	46.4	49.6	52.7	55.6	58.2	60.6	62.7	64.6	66.3	67.7	68.8	69.7	70.4	70.8	70.9
Atmospheric concentration C (ppm)	399.5	418.5	438.3	459.2	481.0	503.9	527.7	552.4	577.9	604.1	630.9	658.2	685.8	713.8	742.0	770.2	798.5	826.6
Atmospheric Temperature	0.85	1.02	1.19	1.37	1.55	1.74	1.93	2.13	2.32	2.52	2.72	2.93	3.13	3.33	3.52	3.72	3.91	4.10
Output Net Net)	105	125	147	172	199	228	259	293	329	367	408	451	497	544	595	647	702	759
Climate Damages fraction output	0.0016	0.0023	0.0032	0.0042	0.0055	0.0069	0.0085	0.0103	0.0123	0.0145	0.0168	0.0194	0.0222	0.0251	0.0282	0.0314	0.0348	0.0382
Consumption Per Capita	10.50	11.84	13.31	14.89	16.61	18.47	20.46	22.59	24.87	27.30	29.87	32.60	35.48	38.51	41.69	45.03	48.52	52.16
Carbon Price (per t CO2)	2.00	2.21	2.44	2.69	2.97	3.28	3.62	4.00	4.42	4.88	5.38	5.94	6.56	7.25	8.00	8.83	9.75	10.77
Emissions Control Rate	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.08	0.08	0.09	0.10	0.10	0.11
Social cost of carbon	29.97	35.75	42.26	49.53	57.60	66.48	76.21	86.81	98.31	110.71	124.05	138.33	153.57	169.77	186.94	205.09	224.23	244.37
Interest Rate	0.051	0.050	0.049	0.048	0.047	0.046	0.045	0.044	0.043	0.042	0.041	0.040	0.039	0.039	0.038	0.037	0.037	0.036
Population	7,403	7,853	8,265	8,639	8,977	9,280	9,550	9,791	10,004	10,193	10,359	10,505	10,633	10,745	10,844	10,929	11,004	11,069
TFP	5.12	5.54	5.98	6.44	6.93	7.45	7.98	8.54	9.12	9.73	10.36	11.01	11.68	12.38	13.10	13.84	14.60	15.38
Output gross,gross	105	125	148	173	200	229	261	296	333	373	415	460	508	558	612	668	727	789
Change tfp	0.076	0.074	0.072	0.071	0.069	0.067	0.065	0.064	0.062	0.061	0.059	0.058	0.056	0.055	0.054	0.052	0.051	0.050
Capital	223	268	319	375	437	505	580	660	747	841	941	1,049	1,162	1,283	1,411	1,545	1,687	1,835
s	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
I	27.27	32.07	37.35	43.14	49.44	56.26	63.61	71.51	79.95	88.96	98.52	108.65	119.35	130.62	142.46	154.87	167.86	181.40
Y gross net	105	125	147	172	199	228	259	293	329	367	408	451	497	544	595	647	702	759
damages	0.17	0.29	0.47	0.73	1.09	1.58	2.21	3.04	4.08	5.39	6.99	8.94	11.26	14.02	17.24	20.98	25.28	30.18
damfrac	0.0016	0.0023	0.0032	0.0042	0.0055	0.0069	0.0085	0.0103	0.0123	0.0145	0.0168	0.0194	0.0222	0.0251	0.0282	0.0314	0.0348	0.0382
abatement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04
sigma	0.35	0.32	0.30	0.28	0.26	0.24	0.22	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.13	0.12	0.11	0.10
Forcings	2.46	2.74	3.01	3.29	3.57	3.84	4.12	4.39	4.66	4.92	5.18	5.44	5.69	5.93	6.16	6.39	6.61	6.82
Other Forcings	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.71	0.74	0.76	0.79	0.82	0.85	0.88	0.91	0.94	0.97	1.00
Period utilty	0.45	0.49	0.53	0.56	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.79	0.81	0.82	0.83	0.85
Consumption	77.73	93.00	109.97	128.67	149.14	171.37	195.39	221.21	248.83	278.24	309.46	342.46	377.24	413.80	452.11	492.16	533.93	577.40
Objective	4,491.07																	
Land emissions	2.60	2.30	2.04	1.80	1.59	1.41	1.25	1.11	0.98	0.87	0.77	0.68	0.60	0.53	0.47	0.42	0.37	0.33
Cumulative ind emissions	400	449	502	561	624	692	764	840	919	1,002	1,087	1,175	1,266	1,358	1,452	1,547	1,643	1,739
Cumulative total emissions	500	552	609	670	736	806	880	957	1,038	1,122	1,209	1,298	1,389	1,483	1,577	1,673	1,769	1,866
Atmospheric concentrations Gt	851	891	934	978	1,025	1,073	1,124	1,177	1,231	1,287	1,344	1,402	1,461	1,520	1,580	1,641	1,701	1,761
Atmospheric concentrations ppm	400	418	438	459	481	504	528	552	578	604	631	658	686	714	742	770	798	827
Total Emissions GTCO2 per year	38	42	45	48	51	54	57	59	62	64	65	67	68	69	70	71	71	71
Atmospheric concentrations upper	460	471	485	501	519	539	561	585	610	636	664	693	723	754	786	819	852	886
Atmospheric concentrations lower	1,740	1,741	1,741	1,742	1,743	1,744	1,746	1,747	1,748	1,750	1,752	1,754	1,756	1,759	1,762	1,765	1,768	1,771
Atmospheric fraction since 1850	0.53	0.55	0.57	0.58	0.59	0.60	0.61	0.61	0.62	0.62	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Atmospheric fraction since 2010	-	0.77	0.76	0.74	0.73	0.73	0.72	0.71	0.71	0.70	0.70	0.69	0.69	0.68	0.68	0.67	0.67	0.67

Table A-4. Detailed results for baseline run by time period[iv]

Note that this run is for the standard DICE-2016R2 model and differs slightly from the modified version used for the uncertainty runs.

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Industrial Emissions GTCO2 per year	35.7	33.3	35.3	37.0	38.3	39.2	39.7	39.7	39.2	38.3	36.8	35.0	32.6	29.8	26.6	22.9	18.8	14.3
Atmospheric concentration C (ppm)	399.5	418.5	434.4	450.8	467.6	484.6	501.6	518.4	534.8	550.7	565.7	579.8	592.7	604.3	614.3	622.7	629.2	633.7
Atmospheric Temperature	0.85	1.02	1.18	1.35	1.52	1.70	1.87	2.04	2.20	2.37	2.53	2.69	2.84	2.99	3.13	3.26	3.39	3.50
Output Net Net)	105	125	147	172	199	228	259	293	329	367	408	452	498	546	597	651	707	766
Climate Damages fraction output	0.0016	0.0023	0.0032	0.0042	0.0053	0.0065	0.0079	0.0094	0.0110	0.0127	0.0145	0.0164	0.0183	0.0203	0.0222	0.0241	0.0260	0.0279
Consumption Per Capita	10.49	11.83	13.28	14.87	16.58	18.43	20.41	22.54	24.81	27.23	29.81	32.53	35.42	38.46	41.67	45.05	48.59	52.31
Carbon Price (per t CO2)	2.01	35.30	41.85	49.20	57.40	66.49	76.52	87.54	99.58	112.70	126.94	142.33	158.93	176.76	195.86	216.27	238.02	261.15
Emissions Control Rate	0.03	0.18	0.21	0.23	0.26	0.29	0.32	0.35	0.39	0.43	0.47	0.51	0.56	0.60	0.65	0.71	0.76	0.82
Social cost of carbon	29.51	35.30	41.85	49.20	57.40	66.49	76.52	87.54	99.58	112.70	126.94	142.33	158.92	176.75	195.85	216.26	238.01	261.14
Interest Rate	0.051	0.050	0.049	0.048	0.047	0.046	0.045	0.044	0.043	0.042	0.041	0.040	0.040	0.039	0.038	0.038	0.037	0.036
Population	7,403	7,853	8,265	8,639	8,977	9,280	9,550	9,791	10,004	10,193	10,359	10,505	10,633	10,745	10,844	10,929	11,004	11,069
TFP	5.12	5.54	5.98	6.44	6.93	7.45	7.98	8.54	9.12	9.73	10.36	11.01	11.68	12.38	13.10	13.84	14.60	15.38
Output gross,gross	105	125	148	173	200	230	262	296	334	373	416	462	510	561	615	672	732	795
Change tfp	0.076	0.074	0.072	0.071	0.069	0.067	0.065	0.064	0.062	0.061	0.059	0.058	0.056	0.055	0.054	0.052	0.051	0.050
Capital	223	269	319	376	439	507	583	664	753	848	950	1,060	1,177	1,301	1,434	1,574	1,722	1,879
s	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
I	27.37	32.17	37.49	43.32	49.69	56.59	64.05	72.08	80.70	89.91	99.74	110.20	121.30	133.06	145.49	158.58	172.35	186.75
Y gross net	105	125	147	172	199	228	260	294	330	369	410	454	500	549	601	656	713	772
damages	0.17	0.29	0.47	0.72	1.05	1.50	2.07	2.79	3.68	4.76	6.05	7.57	9.34	11.37	13.66	16.22	19.05	22.13
damfrac	0.0016	0.0023	0.0032	0.0042	0.0053	0.0065	0.0079	0.0094	0.0110	0.0127	0.0145	0.0164	0.0183	0.0203	0.0222	0.0241	0.0260	0.0279
abatement	0.00	0.10	0.15	0.21	0.30	0.41	0.55	0.73	0.96	1.24	1.59	2.00	2.50	3.09	3.79	4.61	5.55	6.64
sigma	0.35	0.32	0.30	0.28	0.26	0.24	0.22	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.13	0.12	0.11	0.10
Forcings	2.46	2.74	2.97	3.19	3.42	3.64	3.85	4.05	4.25	4.43	4.60	4.76	4.91	5.04	5.16	5.26	5.35	5.41
Other Forcings	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.71	0.74	0.76	0.79	0.82	0.85	0.88	0.91	0.94	0.97	1.00
Period utilty	0.45	0.49	0.53	0.56	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.79	0.81	0.82	0.84	0.85
Consumption	77.63	92.87	109.80	128.45	148.85	171.01	194.95	220.69	248.23	277.58	308.75	341.76	376.60	413.30	451.87	492.33	534.71	579.06
Objective	4,520.56																	
Land emissions	2.60	2.30	2.04	1.80	1.59	1.41	1.25	1.11	0.98	0.87	0.77	0.68	0.60	0.53	0.47	0.42	0.37	0.33
Cumulative ind emissions	400	449	494	542	593	645	699	753	807	860	913	963	1,011	1,055	1,096	1,132	1,163	1,189
Cumulative total emissions	500	552	601	652	705	759	815	871	926	981	1,034	1,086	1,134	1,180	1,221	1,258	1,290	1,316
Atmospheric concentrations Gt	851	891	925	960	996	1,032	1,068	1,104	1,139	1,173	1,205	1,235	1,262	1,287	1,308	1,326	1,340	1,350
Atmospheric concentrations ppm	400	418	434	451	468	485	502	518	535	551	566	580	593	604	614	623	629	634
Total Emissions GTCO2 per year	38	36	37	39	40	41	41	41	40	39	38	36	33	30	27	23	19	15
Atmospheric concentrations upper	460	471	485	500	516	534	552	571	590	609	629	648	668	686	704	721	736	750
Atmospheric concentrations lower	1,740	1,741	1,741	1,742	1,743	1,744	1,745	1,747	1,748	1,750	1,751	1,753	1,755	1,757	1,760	1,762	1,764	1,767
Atmospheric fraction since 1850	0.53	0.55	0.56	0.57	0.58	0.59	0.59	0.59	0.60	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.58	0.58
Atmospheric fraction since 2010	-	0.77	0.74	0.72	0.71	0.70	0.69	0.68	0.68	0.67	0.66	0.66	0.65	0.64	0.63	0.63	0.62	0.61

Table A-5. Detailed results for optimal run by time period[v]
See note to Table A-4.

Variable	mean	stdev	10%ile	25%ile	50%ile	75%ile	90%ile
SCC, 2015	28.09	23.84	6.37	11.63	21.32	36.86	57.49
Temperature, 2050	1.63	0.27	1.25	1.42	1.63	1.83	2.00
Temperature, 2100	2.12	0.54	1.41	1.71	2.10	2.55	2.81
Temperature, 2200	2.36	0.72	1.46	1.82	2.36	2.89	3.27
CO2 concentrations, 2050	410	36	357	392	405	432	462
CO2 concentrations, 2100	406	39	346	388	401	431	462
CO2 concentrations, 2200	400	39	342	383	396	425	456
Damage as % of output, 2050	0.62%	0.44%	0.16%	0.28%	0.51%	0.82%	1.24%
Damage as % of output, 2100	1.08%	0.90%	0.25%	0.43%	0.81%	1.47%	2.22%

Table A-6. Detailed results for maximum abatement run[vi]

Learning structure	Optimal carbon prices							
	2015	2020	2025	2030	2035	2040	2045	2050
Learn then act	34.15	39.80	45.52	51.57	58.18	65.53	73.78	83.05
Act then learn	36.10	42.10	48.72	55.19	62.27	70.15	79.00	88.94

Note that Act then learn prices are not state contingent for 2015-2050.

Table A-7. Optimal carbon prices with and without learning[vii]

References for tables and figures:

[i] Results RSF 090217a u121517..xlsx; page new
[ii] quint-calib-121417.xlsx,solvernew
[iii] tables-unc-121517a.xlsx; errorbg
[iv] tables-unc-121517a.xlsx; r2base.
[v] tables-unc-121517a.xlsx; r2opt.
[vi] Maxabate-121817.xlsx; maxnew
[vii] LtA.xlsx; page LtA.