Background Note on Damages

March 12, 2023

Advice on Background Notes for DICE-2023: These background notes are for informational purposes for modelers. They are not intended for publication and are not publication quality. Some of the details are sketched and not derived in detail in this document. They may be cited with the warning, "Background notes are for informational purposes and are not published."

SUMMARY

This note describes the calibration of the damage function for DICE-2023. The DICE-2023 damage function is constructed from three elements:

1. An updated literature-synthesis estimate of global aggregate warming impacts, suggesting a loss of 1.62% GDP-equivalent impact at 3°C warming over pre-industrial temperatures.
2. An adjustment for tipping points based on estimates from Dietz et al. (2021), adding +1% output loss due to 3°C warming.
3. A judgmental adjustment for further omitted impacts and uncertainty of +0.5% loss at 3°C warming.

Item #1 updates the synthesis of literature damage estimates from Nordhaus and Moffat (2017). The remainder of this note describes this update.

I. Adjustments to Nordhaus and Moffat (2017) Data

We use the review of global aggregate climate change impact estimates from Nordhaus and Moffatt (2017, "NM") as a starting point. They estimate a base damage function utilizing 38 impact estimates from 25 studies (see Table 1). NM's preferred specification is a weighted quantile regression with weights based on considerations such as study recency and quality. We first make three adjustments to NM's original data:

- We reduce the weight given to Cline's (1992) damage estimate for 10°C warming from 0.1 in NM to 0.0. This change is motivated by the speculative nature of the 10°C estimate especially relative to growing literature and understanding of impacts for lower levels of warming.
- We reduce the weight given to Dellink (2012) from 1.0 to 0.25 to reflect the fact that our updated review includes a newer version of the ENV-Linkages model in Dellink et al. (2019).

- We correct the temperature level corresponding to the Bosello et al. (2012) estimate from a pre-industrial to a 1920-40 temperature baseline to align with the other estimates (from 1.92°C to 1.52°C).

II. New Estimates added to Nordhaus and Moffat (2017) Data

We next update the NM data by adding estimates of global aggregate climate change impacts that have been published since the NM review. Piontek et al. (2021) presents a review of competing methodologies and recent studies quantifying aggregate impacts of climate change. We utilize their review as a basis for this update. This approach was chosen because Piontek et al. (2021) exhibits good coverage and alignment with a similar recent review by the IPCC.[1] We note that the inclusion criteria for new estimates in our analysis are thus not formally the same as for the original NM review.

We specifically consider the studies listed in Piontek et al.'s (2021) Supplementary Materials Table (Section 3). Among these, we focus our attention on new bottom-up and top-down aggregate damage assessments. That is, we exclude studies which use prior impact estimates to propose new damage functions but do not themselves produce new climate change impact estimates. We further restrict our attention to studies that are published and provide estimates of aggregate climate change impacts at the global level. We also exclude one study for which we were unable to replicate temperature projections and received no reply to an inquiry with the corresponding author. These restrictions leave us with 11 new studies from which we extract 18 new estimates as shown in Table 1 below.

We note as well that these estimates differ from those in Howard and Sterner (2017, 2022) used as our alternative damage estimates. Our reservations on the estimates in the 2017 study are that it did not weight studies and additionally it included studies that, in our view, were not empirically based. The new study has not published when the current estimates were prepared, and we will review those when completed.

[1] The IPCC's 6th Assessment Report presents a synthesis of "Global aggregate economic impact estimates by global warming level" in Figure Cross-Working Group Box ECONOMIC.1 (O'Neill et al., 2022). Our updated damage function includes all studies listed in this Figure except for two review-based estimates (Tol 2018 and Howard and Sterner 2017, where the latter is still considered in our analysis in the "alt. damages" scenario) and two studies that are arguably not independent from other prior literature that is included in the damage function (specifically Burke et al. (2018) which builds on Burke et al. (2015) and Rose et al. (2017) which builds on DICE, PAGE, and FUND).

A. Temperature Baseline Harmonization Notes

The following are general procedures for our estimates:

We harmonize all impact estimates' corresponding temperatures to a 1920-40 baseline so as to align with the original NM data.

We generally use warming estimates from within papers when available, including for adjustments to alternate baselines. Otherwise, we assume 0.4 °C warming between 1920-40 and pre-industrial, and use an average of GISS, Hadley, and NCDC temperature anomaly series to infer warming between additional periods as needed (0.5 °C warming between 1980-2004 and 1920-40, 0.55 °C warming between 1985-2005 and 1920-40, 0.56 °C warming between 1980-2010 and 1920-40, and 1.05 °C warming from 1920-40 and 2015-19).

We note that the data sources used for temperature adjustments matter: RCP 8.5 warming in 2100 may be considered as 3.91 °C or 4.25 °Cover 1920-40 levels depending on whether one uses IPCC or the three-averaged data series, for example. These differences will affect the estimated damage function as well.

B. Weights

In line with the NM approach, we also consider weights for each of the new estimates based on our evaluation of each estimate's quality, novelty, and independence (see study notes below). We note that there is not one unique way to construct such weights and that one could create reasonable alternative weighting schemes (including more formal adjustments for considerations such as sectoral coverage of each underlying study). While we prefer the weighted regressions, we also show results for unweighted regressions (Table 2). Both weighted and unweighted regressions yield results of the same order of magnitude but estimates for weighted impacts are generally larger.

C. Updated Data

Study	Year	Temp (°C)	Impact (%)	New	Weight
Cline	1992	2.5	-1.1	0	0.9
Cline	1992	10	-6	0	0
Nordhaus a	1994	3	-1.33	0	0
Nordhaus b	1994	3	-3.6	0	0.5
Nordhaus b	1994	6	-10.4	0	0.5
Frankhauser	1995	2.5	-1.4	0	1
Tol	1994	2.5	-1.9	0	0.1
Nordhaus and Yang	1996	2.5	-1.7	0	0.1
Mendelsohn et al.	2000	2.2	0.03	0	0.1
Mendelsohn et al.	2000	2.2	0.07	0	0.1
Mendelsohn et al.	2000	2	0.08	0	0.1
Mendelsohn et al.	2000	3.5	0.01	0	0.1
Nordhaus and Boyer	2000	2.5	-1.5	0	1
Tol	2002	1	2.3	0	0.1
Maddison	2003	3.1	-2.2	0	0.1
Rehdanz and Maddison	2005	1.24	-0.32	0	0.1
Rehdanz and Maddison	2005	0.84	-0.32	0	0.1
Hope	2006	4.085	-3.04	0	0.25
Nordhaus	2006	3	-1.05	0	1
Nordhaus	2008	3	-2.49	0	0.25
Nordhaus	2010	3.4	-2.8	0	0.25
Maddison and Rehdanz	2011	4	-17.8	0	0.1
Bosello et al.	2012	1.52	0.5	0	1
Ronson and Mensbrugghe	2012	3.1	-2.14	0	0.1
Ronson and Mensbrugghe	2012	5.5	-6.05	0	0.1
Dellink	2012	2.5	-1.1	0	0.25
Kemfert	2012	0.25	-0.17	0	0.1
Hambel	2012	1	-0.3	0	0.1
Nordhaus	2013	3	-2.25	0	0
FUND	2015	2	0.2	0	0.3
FUND	2015	3	-0.17	0	0.4
FUND	2015	4	-0.85	0	0.3
WITCH	2015	2	-1.84	0	0.3
WITCH	2015	3	-3.72	0	0.4
WITCH	2015	4	-6.25	0	0.3
PAGE09	2017	2	-0.72	0	0.3
PAGE09	2017	4	-2.9	0	0.4
PAGE09	2017	6	-6.51	0	0.3
Dellink et al.	2019	2.1	-2	1	0.75
Dellink et al.	2019	3.6	-6	1	0.25
Roson and Sartori	2016	3.55	-1.72	1	0.1
Takakura et al.	2019	2.6	-2.24	1	0.33

Takakura et al.	2019	3.6	-4.69	1	0.33
Takakura et al.	2019	1.6	-1.02	1	0.33
Kompas et al.	2018	3.55	-3	1	0.2
Kompas et al.	2018	4.55	-7.24	1	0.2
Kompas et al.	2018	2.55	-1.77	1	0.2
Zhao et al.	2019	3.1	-2.42	1	0
Letta and Tol	2018	4.412	-1.88	1	0.5
Burke et al.	2015	4.86	-23	1	0.5
Newell et al.	2021	3.91	-2.53	1	1
Pretis et al.	2018	1.6	-13	1	0.35
Pretis et al.	2018	1.1	-8	1	0.15
Kahn et al.	2021	3.91	-7.64	1	1
Kalkuhl and Wenz	2020	4.25	-7.4	1	0.05
Kalkuhl and Wenz	2020	4.25	-13.4	1	0.05

Color Key:	
	Adjusted NM data point
	New bottom-up studies
	New top-down studies

Table 1: Updated data of global climate change impact estimates. "Temp" refers to °C warming over 1920-40 levels. "Impact" refers to estimated global GDP impact in percent. "New" is an indicator equal to 0 for studies already featured in NM and equal to 1 for new studies.

D. Estimation Results

Table 1 summarizes predicted impacts at 3°C and 6°C warming over 1920-40 levels for different data samples and regression specifications (OLS or median, denoted "Qtile"). All estimates are based on a simple quadratic function in temperature (without a constant). We present results for different data samples that exclude damage estimates above certain temperature levels (e.g., "T limit T<10°C" implies that only estimates for less than 10 °C warming are included). The updated preferred estimate – using weighted quantile regression - is highlighted in bold. It suggests around 30% larger impacts (-2.16%) than the corresponding estimate in NM (-1.63%).

			Predicted Impacts at:	
Method	Weights?	T limit	3°C over 1920-40	6°C over 1920-40
OLS	-	-	-1.71%	-6.84%
OLS	-	T<10°C	-2.94%	-11.74%
OLS	-	T<5°C	-3.46%	-13.84%
OLS	Yes	-	-2.94%	-11.74%
OLS	Yes	T<5°C	-3.35%	-13.38%
Qtile	-	-	-1.80%	-7.20%
Qtile	**Yes**	**-**	**-2.16%**	**-8.63%**

Table 2: Predicted impacts based on updated regression results.

E. Detailed Study Notes

This section describes how impact estimates were extracted from each of the studies added to the NM data, as well as brief notes on weights.

<u>Dellink et al. (2019)</u>

- Climate impact projections:
    - Headline: 2.5 °C warming by 2060 induces average global GDP loss of 2% (by 2060). We infer that the temperature baseline must be preindustrial based on the paper's use of the MAGICC Model and the fact that, in Figure 3, warming levels appear to be 1 °C at 2015.
    - The paper also makes a damage prediction post 2060. We infer a 6% loss at 4 °C based on the "central projection - full damages" line in Figure 12.

  ⇨ Global GDP losses of 2% for 2.1 °C and 6% for 3.6 °C increases over 1920-40 temperature levels.
- Weights: 1 total (0.75 on 2.1 °C estimate and 0.25 on 3.6 °C estimate)
    - Notes: Solid methodology. Put higher weight on the 2.1 °C estimate since the ENV-Linkages model is more detailed and there is more uncertainty about the extrapolation to the AD-DICE model used for the 3.6 °C projection.

<u>Takakura et al. (2019)</u>

- Climate impact projections:
    - Study considers impacts across 4 RCP scenarios x 5 climate models x 5 SSP scenarios.

    - Temperature baseline is pre-industrial as per SI Figure 2.
    - We use the paper's Supplementary Information to calculate averages of global impact estimates across years and scenarios for three temperatures of interest: 2 °C warming over preindustrial (by averaging across years and scenarios with warming between 1.98 °C <T<2.02 °C), 3 °C warming over preindustrial (averaging across observations with 2.98 °C <T<3.02 °C), and 4 °C warming over preindustrial (averaging across observations 3.98 °C <T<4.02 °C). We note that we compute aggregate impacts by aggregating the sectoral impacts at the "World" level.

  ⇨ Global GDP losses of 1.02% for 1.6 °C , 2.24% for 2.6 °C , and 4.69% for 3.6 °C over 1920-40 levels.

- Weights: 1 total (0.33 on each temperature estimate)
    - Notes: Independent estimate.

Roson and Sartori (2016)

- Climate impact projections:
    - Paper presents country-level GDP impact estimates for a +3.0 °C increase in average temperature.
    - The temperature baseline is 1985-2005 for sea level rise, 1980-2004 for agriculture method 2, and not explicitly stated for some of the other impacts, although several infer warming damages relative to current average temperatures. We thus assume a 1985-2005 baseline overall.
    - No global impact estimate is provided. We constructed one using the country level GDP impact estimates for 3 °C warming presented in Appendix Table A1.1 using 2019 GDP weights (World Bank, PPP, constant 2017 dollars). Note: For countries with missing estimates, we adopt the relevant regional "Rest of Region" estimate (e.g., "Rest of Oceania" for Vanuatu, etc.)

  ⇨ Global GDP loss of 1.72% for 3.55 °C over 1920-40.

- Weight: 0.1
    - Notes: Questions over methodology especially in going from damage functions to GDP impacts.

Zhao et al. (2020)

- Climate impact projections:
    - Damages are reported as the percentage of cumulative discounted climate damages relative to cumulative discounted Gross World Product from 2011-2100. For their "Business as usual" scenario,

this percentage is 2.42%. We are inferring associated temperature increase based on Figure 5 as 3.5 °C .
    - The temperature baseline seems to be preindustrial based on the definition of T variable in equation (3).
  - ⇨ Global GDP loss of 2.42% for 3.1 °C warming over 1920-40.
- Weight: 0
    - Notes: Very close to FUND & methodological concerns such as over addition of earthquake and volcano damages in climate impacts.

<u>Kompas et al. (2018)</u>
- Climate impact projections:
    - Project global GDP losses of 3% for 3 °C warming (stated in text).
    - Temperature baseline is 1985-2005 (confirmed by author in correspondence).
    - Table A1 gives projected losses in dollars for 4 °C and 2 °C . We calculate the corresponding GDP percentages by backing out the assumed global GDP in 2100 (319.79 trillion). This yields predicted losses of 1.77% for 2 °C and 7.24% for 4 °C over the presumed 1985-2005 baseline.
  - ⇨ Global GDP loss of 1.77% for 2.55 °C , 3% for 3.55 °C , and 7.24% for 4.55 °C over 1920-40.
- Weight: 0.6 (divided evenly over each estimate)
    - Notes: Improved methods over but lack of independence from Roson and Sartori (2016).

<u>Kalkuhl and Wenz (2018)</u>
- Climate impact projections:
    - Focus on GRP-weighted aggregate results (Table 7).
    - Climate impacts are calculated relative to no additional warming beyond 2015-19 base period.
    - Assume RCP 8.5. The implied average temperature increase from 2015-2019 and 2095-99 is 3.2 °C (population-weighted).
      - Cross-sectional estimates imply 7.4% global GRP loss in 2099.
      - Panel estimates imply 13.4% global GRP loss in 2099.
  - ⇨ Global GDP losses of 7.4% or 13.4% from 3.2 °C +1.05 °C = 4.25 °C over 1920-40 levels.
- Weight: 0.1 (divided evenly over each estimate)
    - We were unable to replicate the data on real output using data for several countries. We are concerned about the study because the damage estimates appear to be based on nominal rather than real

output. They will include differences in price levels in the estimates, which is non-standard in damage estimates. This approach was confirmed with the authors.

Kahn et al. (2021)

- Climate impact projections:
    - Their benchmark estimates measure damages relative to a baseline scenario under which temperature in each country continues to increase according to its historical trend from 1960-2014. This is not ideal for our purposes.
    - For one scenario, the authors also estimate damages relative to a "no warming" beyond 2015 baseline. We use this figure as it is closest to what we want to measure.
    - The results suggest a global GDP-weighted average income loss of 7.64% in RCP 8.5 by 2100.
    - As a corresponding temperature increase, we utilize the mean global surface temperature change from RCP 8.5 across models as reported in IPCC (2014), which is 3.7 °C +0.61 °C = 4.31 °C over 1850-1900 levels.
  - ⇨ Global GDP losses of 7.64% from 4.31 °C -0.4 °C =3.91 °C over 1920-40.
- Weight: 1
    - Notes: This study has high weight because it uses a different methodology from most other top-down estimates.

Burke et al. (2015)

- Climate impact projections:
    - Headline result is 23% global output loss in 2100 in RCP 8.5 scenario resulting in (population-weighted) average global average temperature change in 2100 of 4.3 °C .
    - Base period is 1980-2010.
  - ⇨ Global GDP losses of 23% for 4.3 °C +0.56 °C = 4.86 °C warming over 1920-40 levels.
- Weight: 0.5
    - Notes: Partial superseded by Newell et al. (2021) and methodological similarities with other top-down estimates.

Pretis et al. (2018)

- Climate impact projections:
    - Compare, relative to a baseline of "no additional warming" over 2006-15 levels, 0.6 °C additional warming or 1.5 over

    - preindustrial, and 1.1 °C additional warming or 2 °C over preindustrial.
  - Headline numbers:
    - Median projected global GDP per capita is 8% lower in 2100 for 1.5 °C (imprecisely estimated).
    - Median projected global GDP per capita is 13% lower in 2100 for 2 °C .
  - ⇨ Global GDP loss of 8% for 1.5 °C -0.4 °C = 1.1 °C and 13% for 2 °C - 0.4C = 1.6 °C over 1920-40 levels.
- Weight: 0.5 (0.35 on 1.6 °C estimate and 0.15 on 1.1 °C estimate)
  - Notes: Methodological similarities to other top-down estimates. Higher weight on 1.6 °C estimate due to higher statistical precision.

Letta and Tol (2019)
- Climate impact projections:
  - Consider impacts for RCP 8.5 resulting in sample average warming of 3.912 °C over reference period of 1980-2004.
  - We infer aggregate impacts based on the regression results for the full sample (Table 2 Column 1) and calculate average cumulative impacts, which would suggest 1.88% lower TFP levels by 2095.
  - ⇨ Global GDP loss of 1.88% for 3.912 °C +0.5 °C = 4.412 °C over 1920-40.
- Weight: 0.5
  - Notes: Methodological similarities to other top-down estimates.

Newell et al. (2021)
- Climate impact projections:
  - We calculate the mean of the distribution of predicted climate impacts across the bootstrapped "levels effects" models in the MCSs (Figure 6 bottom panel). The authors kindly shared their data for us to be able to perform this calculation.
  - We focus on the "levels effects" since they are precisely estimated.
  - The results imply a GDP loss of 2.53% in RCP 8.5 year 2100, which they note to have an associated CMIP5 average warming level of 4.31 °C over pre-industrial.
  - ⇨ Global GDP loss of 2.53% from 4.31 °C -0.4C = 3.9 °C over 1920-40 levels.
- Weight: 1
  - Notes: Comprehensive analysis nesting hundreds of potential top-down specifications including those of other studies.