Advancing the estimation of future climate impacts within the United States

Response to Reviewers

Reviewer #2

“Advancing the estimation of future climate impacts within the United States.” EGUSphere, Manuscript #2023-114

General comments This paper presents new estimates of the impacts of climate change on the economy and society of the United States. The authors assess both marginal and non-marginal changes in the climate, and present results that include a comprehensive list of sectors, ranging from human health to infrastructure and labor supply. Climate change impacts are disaggregated into seven regions across the country, with an additional analysis assessing the racial breakdown of total impacts. The framework they utilize – FrEDI – is built to adapt to an evolving scientific literature, such that damage functions can be updated or additional sectors added, as the evidence base improves.

This is an important line of inquiry, both for informing climate change mitigation and adaptation policy and for pushing climate economic research forward. While many climate impacts analyses exist, especially in the US, this appears to be the most comprehensive set of estimates that cover many sectors and are presented in a framework that allows for the calculation of total projected damages and marginal damages (i.e., a domestic social cost of carbon).

Unfortunately, the inputs to the FrEDI model, and some of its key features, are well behind best available science, making the findings difficult to trust. For example, adaptation to future climate change is largely assumed away (at least for all empirically derived damages), spatial resolution is exceptionally limited relative to other work, and key dimensions of uncertainty are ignored. While I think the fundamental goals and structure of FrEDI are valuable for research and policy, I do not think the results represent best available evidence on the question at hand.

I detail my specific comments below and provide some technical corrections and smaller questions at the end of my review.

We thank Reviewer #2 for providing constructive comments and positive feedback that the fundamental goals and structure of FrEDI are valuable for research and policy. These have greatly helped us to refine and improve the clarity of our key points and methods, as well as improve our discussion and analysis related to the treatment of adaptation options and uncertainty characterization within FrEDI . We will walk through our responses to the major concerns below and include additional figures within the comments.

1. “well behind best available science” *Many of the underlying studies used to develop damage functions for FrEDI have been published since 2017. The most recent study to be incorporated into FrEDI is Cromar et al., 2022, which calculates temperature-related mortality and is also used within the GIVE model (Rennert et al. 2022). We strive to bring in and update FrEDI with the latest and best available science that currently exists and can be adapted to FrEDI temperature (and sea level rise) binning approach.*

2. "adaptation to future climate change is largely assumed away" *There are three categories of adaption options for select sectors within FrEDI, which are based on the available information in the underlying impact studies. First, there are five sectors (i.e., coastal property, roads, etc.) that explicitly explore alternative adaptation options (i.e., proactive and reactive). These options are available within FrEDI and are explored in more depth in section A4. Secondly, there are studies that do not explicitly include different adaptation scenarios but do include adaptation measures within the sectoral model. For example, in the electricity supply and demand sectoral analysis from McFarland et al., 2015 has air conditioner penetration within the sectoral models. Lastly, there are some sectors (i.e., marine fisheries) that do not explore additional adaptation options. Damages in this last category largely reflect the mitigation levels present during the time period of the analysis.*

3. "spatial resolution is exceptionally limited" *The spatial resolution for FrEDI v3.0 contains 7 regions within the CONUS. Each sector's damage functions are aggregated from highly spatially resolved sectoral modeling. Many of the sectors use the LOCA downscaling dataset for the climate model data (1/16th degree resolution), and then the impact models are run at county, census block, or other resolution. For example, the Neumann et al.,2021 study explores roads, rail, and coastal property at the county resolution, while the Fann et al., 2021 study explores air quality damages at 36km resolution. In order to maintain a flexible, modular, and computationally efficient model, FrEDI uses a relationship between temperature and damages at the NCA region level rather than the native resolution of the underlying impact model, allowing us to be able to conduct studies such as this one where uncertainties across tens of thousands of scenarios can be explored. Similar models in this space, like DSCIM and GIVE also trade spatial resolution for computational efficiency.*

4. "key dimensions of uncertainty are ignored" *Thank you for bringing up uncertainty. We will expand our text to include a more thorough analysis of the uncertainty characterization that we can explore within FrEDI. In addition to climate parameter, emission, and economic uncertainties already explored in the analysis, FrEDI also includes the structural uncertainty in damage functions within and across the three temperature-related mortality studies included in FrEDI. This sector is the largest single impact category in our analysis. FrEDI already includes three distinct damage function estimates from three distinct studies and includes high and low confidence intervals for two of these (based on the information in each underlying study). The physical impacts from these three estimates in 2090 can differ by over a factor of 10 and can be sensitive to available adaptation assumption. We chose to use the Cromar et al., damage function as our default temperature-related mortality function in order to align with the GIVE model. While this function yields significantly larger results than the other two functions, the resulting damages in 2090 are not inconsistent with similar previous published studies (see below response). Within the FrEDI framework, we are continually working towards including more sectoral studies from different authors to be able to further characterize these types of uncertainties. We have added additional discussion to the main text and supplement presenting these results to help to better characterize this additional aspect of uncertainty.*

Specific comments

1. Damage functions do not represent best available science

   The damage functions that form the building block of FrEDI are outdated and, critically, fail to incorporate empirically-based estimates of adaptation. It is increasingly clear in a growing climate econometrics literature that populations adapt to a gradually changing climate (e.g., Auffhammer, 2018); generating projections that assume people will act in 2090 as if climate change hit them unexpectedly and without warning is unrealistic. This is particularly problematic in this study with respect to health, which completely dominates all projected damages. There is clear evidence that people adapt to temperature-driven mortality (Barreca et al., 2016; Heutel et al., 2021; Carleton et al., 2022), and yet this large literature is ignored and a damage function is used that assumes no adaptation (from Cromar et al., 2022). Based on prior work, damages via temperature-induced mortality are likely far too large in this manuscript due to this implausible assumption.

   See responses above re 'the best available science' and adaptation options.

   We agree with the reviewer that the lack of additional adaptation within the Cromar et al., 2022 is not ideal. However, when exploring the physical impacts from multiple temperature-related mortality studies we find that by the end of the century, the estimates from FrEDI for premature mortality are in line with several other studies. For example, FrEDI calculates 19,000 to 91,000 premature deaths with a mean of 50,000 in 2090 from the Cromar et al., 2021 study. Shindell et al., 2020 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7125937/) finds 100,000 deaths in 2100, even after including adaptation options. The Lancet Health Explorer calculates 84,000 deaths in 2100 from SSP3-7.0, which builds upon the 2022 report (Romanello et al., 2022). (https://climatevulnerabilitymonitor.org/health/usa/heat-related-impacts/heat-related-mortality/).We are, however, communicating with the authors of Carleton et al. to investigate whether the underlying data in their analysis is compatible with the FrEDI damage function approach, and given that the temperature-related mortality sector is so important, are continuing to pursue additional options. I don't know that either is the gold standard of studies, but they show that Cromar et al. is not alone at that high end, and they are all reputable research groups.

   Other inadequacies with damage functions include:
   • Damages are assumed to be proportional to income (as far as I can tell), which fails to account for the fact that future incomes are likely to dramatically lower sensitivity to climate extremes (e.g., Rode et al., 2021)

   While the health sectors that use a value of statistical life are based on GDP (i.e., air quality, temperature related mortality, wildfire, valley fever, southwest dust), not all sections within FrEDI are a function of GDP. We will clarify in the text which sectors are proportional to GDP (Table A1). While there may be evidence that wealthier societies may be less sensitive to climate extreme, we also note evidence that the number of billion-dollar disasters from NOAA are *trending upward even though the US is getting wealthier. https://www.ncei.noaa.gov/access/billions/time-series*

We can also note that there is some evidence that historical trends in some kinds of infrastructure-based damages appear to increase roughly proportionally to GDP – see, e.g., research on normalizing hurricane damage by GDP (Grinsted et al., 2019, https://www.pnas.org/doi/10.1073/pnas.1912277116). While in theory improvements in technology, building codes, weather forecasting, and other aspects of societal advancements would be expected to reduce damages relative to GDP, there appear to be other factors involved that seem to counteract such benefits.

• Electricity demand is included but consumption of other energy sources, such as natural gas, are excluded. This, by construction, leads to an inflated projection of damages, as electricity is largely used for cooling while other energy sources are used for heating, demand for which will fall under a warming climate (Deschenes and Greenstone, 2011; Wenz et al., 2017; Rode et al., 2021)

The damage function for electricity demand and supply in FrEDI v3.0 is developed from McFarland et al., 2015 (Climatic Change). The study accounted for changes in both heating and cooling degree days, accounting for different fuel sources. One of the models used in McFarland et al., 2015 is the GCAM model modeling four types of fuels including electricity, natural gas, fuel oil and biomass.

• Uncertainty in damage functions appears to be ignored (e.g., see line 260), although it has been shown to play a critical role in overall uncertainty in prior work (Hsiang et al., 2017; Carleton et al., 2022)

Uncertainty in damage functions is typically not well represented in of the underlying sectoral modeling studies used to develop FrEDI damage functions. However, FrEDI has included confidence interval ranges for temperature-related mortality that were available from the from Cromar et al., and Hsaing et al., studies. The confidence intervals between these studies overlap, but estimate different extremes. For instance, the Cromar-derived damage function estimates net damages from temperature-related mortality, while the low confidence range for the Hsiang-derived damage function has a small potential for net benefits in this sector in 2090.

In addition to uncertainties within each damage function, FrEDI also has the capability to explore some structural uncertainty by providing incorporating multiple studies for the same sector (i.e., temperature-related mortality). We will include a section in the Appendix that evaluates total mean climate damages in 2090 under the three temperature-related mortality estimates, as well as show the confidence intervals for the 2 studies in 2090.

2090 Premature mortality – Billions USD			
Model	5th	95th	Mean
Cromar et al.,	300	3,900	2,100
Hsiang et al.,	-280	1,800	740

Mills et al., (w/ adaptation)	-	-	31.0
Mills et al., (w/o adaptation)	-	-	110

2. Other features of FrEDI that fail to integrate best available science There are two other features of FrEDI that fail to meet current literature standards.

   • As far as I can tell, uncertainty in climate conditional on emissions is ignored (if this is not the case, it should be made much clearer how this is being handled). This uncertainty is large but also easily quantifiable using FaIR.

   We will update the text to provide more detail on how the analysis was conducted. Please see our response to a similar question raised by Reviewer #1.

   • Spatial heterogeneity in warming rates across the United States, as well as uncertainty in this spatial heterogeneity, are also ignored. This is unrealistic and easily remediable using available climate models.

   FrEDI embodies spatial heterogeneity within the underlying damage functions. Uncertainty in these spatial patterns is partially captured by the different GCMs from the underlying studies. In this analysis, we use the average of the temperature/damage relationship derived from running the output of the different GCMs through the various impact models. Sarofim et al., 2021 finds that for the sectors that contain estimates for multiple GCMs (e.g., labor, electricity demand and supply, southwest dust), the damage functions are similar across GCMs for each degree of warming. Therefore, we use the average of the impact models within this analysis.

   • The spatial resolution of FrEDI, at just 7 regions across the U.S., fails to generate insights that can be used by local adaptation planners or policymakers, and fails to capture important local heterogeneities in exposure and vulnerability (which are particularly important in key sectors like health where damage functions are highly nonlinear in temperature).

   FrEDI was not designed with local adaptation planners in mind, and instead developed to rapidly produced national and regional scale estimates under different temperature pathways. We appreciate the comment that as FrEDI is now with only 7 regions it may not be applicable to local adaptation planners or policymakers. We will keep this in mind as we develop FrEDI in the future.

   The spatial resolution for FrEDI v3.0 contains 7 regions within the CONUS. Each sector's damage functions are developed from highly spatially resolved sectoral modeling (see above response referencing LOCA). For example, the Neumann et al.,2021 study explores roads, rail, and coastal *property at the county resolution. In order to maintain a flexible, modular, and computationally efficient model, we have aggregated the detailed spatial variability data in the underlying studies in order to build a flexible and computationally inexpensive framework. This allows us to be able to conduct studies such as this one where 1000s of scenarios can be simulated. Similar models in this space, like DSCIM and GIVE also trade in spatial resolution for computational efficiency.*

3. Motivation is unclear

I am slightly confused by multiple claims made in the introduction regarding how this paper improves upon prior work. First, what exactly is meant by the "temperature binning approach" and why is it beneficial? If the authors intend to refer to the approach of reporting climate change impacts by warming levels (e.g., 2C by end of century), as opposed to reporting impacts by emission scenario (e.g., RCP4.5), this doesn't appear to be what is done throughout the paper. Moreover, such an approach doesn't "improve comparability between models" (line 59), it just hides this lack of comparability the background, as different scenarios and models will arrive at a given warming level under very different sets of assumptions.

Thank you bringing this to our attention. After re-reading the manuscript we have deleted the text about temperature binning. The temperature binning approached used within FrEDI is captured within Sarofim et al., 2021. Essentially, impacts are binned into degree integer bins. A damage function is calculated for each degree bin and then interpolated between bins. This methodology allows for more comparability between studies and not bounded by the particular scenario within the underlying study. We have also updated our text throughout the introduction and abstract to clarify and refine our key points and the novel aspects of this approach.

Second, the authors claim that studies relying on the RCPs and SSPs are not run under "different future trajectories" (line 57), but this is not true. Most of these studies report impacts across the full ensemble of feasible RCPxSSP combinations; these are not probabilistic runs, but they are also not singular scenarios.

The underlying studies used within FrEDI typically use two RCPs trajectories and a few climate models. For example, Neuman et al., 2021 uses RCP4.5 and RCP8.5 across 5 climate models to assess the climate effects on costal properties, roads, and rail. These studies can't be used to assess marginal changes, policy pathways, or scenarios such as the Nationally Determined Contributions. After reading through the introduction again, we decided that this information was not needed within the text and have deleted it. We thank the reviewer for bringing this to our attention.

4. FrEDI faces key challenges as a "dynamic" framework

The authors describe FrEDI as a dynamic framework that can be updated over time as science evolves. However, this bottom-up framework that adds independently constructed sectors cumulatively to build estimates of a total impact of climate change will increasingly face two key challenges, both of which are left unaddressed by the authors. First, as more sectors are added, "double counting" of sectoral impacts becomes an increasing concern. This is likely already a problem in the current manuscript – labor hours lost and temperature-induced mortality likely overlap; labor supply and recreation likely overlap; flooding related traffic delays and damages associated with rail and roads likely overlap; etc. The authors should present a plan for addressing this issue both within this paper and in future applications of FrEDI, once more sectors are added.

Thank you for the comment. We agree that double counting of impacts poses a real problem and are very aware of this problem as we add in additional sectors. For example, FrEDI contains 3 different temperature-related mortality studies, and only one is used to aggregate up to regional and national impacts. There are also 2 roads studies, one that includes different kinds of road material and the other one that only explores impacts to asphalt roads. We take care to not include both road estimates when we are aggregating up to regional or national totals and include data flags and documentation to help FrEDI users avoid double counting as well. While the examples provided above may have overlapping effects, the sectoral studies do not include these overlapping effects. As a dynamic framework we can refine existing damage functions and add new damage functions to reflect the latest available science. Within the section A.2 of the technical documentation, we lay out a table of how we incorporate new studies and sectors within FrEDI. www.epa.gov/cira/fredi

Similarly, impacts in these sectors link to one another, but such interlinkages are ignored. For example, changes in the labor market will likely lead to population reallocations that shift health risks through demographically differentiated migration. Many other examples of interlinkages exist, and the importance of such links will only grow as more sectors are added to FrEDI. As with double counting, I think this issue should be addressed in this paper.

We agree with the reviewer here that we are missing some potentially large interlinkages and interdependencies. The research community as a whole is pushing further into this space; however it still remains a challenge to model. As studies that explore these linkages become available, we will look for ways to add them to FrEDI. We will add in more language caveating this to the manuscript.

We disagree with specific double counting issues raised by the reviewer: labor hours lost is based solely on living individuals working fewer hours, and therefore should not have much overlap with temperature-induced mortality (in the unfortunate cases where outdoor laborers pass away, they would be replaced by new laborers who would have similar responses to elevated temperatures). Any connection between reduced labor hours and the various recreation sectors in FrEDI will be tenuous: perhaps laborers who reduce working hours due to high temperatures might want to avail themselves of outdoor recreation, but this would not be anticipated to have a substantial effect relative to the total impacts on recreation and labor by themselves, and if anything, would lead to increased damages due to more demand for the degraded recreational supply. Finally, the road infrastructure analysis only considered temperature and precipitation-

based impacts on roads, and so would be mostly orthogonal to the coastal sea level surge-based flooding traffic delay analysis. We agree that in the future, there will be more potential for double-counting, and will need to address those possibilities carefully.

Technical corrections/questions

- Why avoid social cost of carbon (SCC) language when computing the net present value of a marginal ton? The authors are computing what the literature calls a "domestic SCC" – why not use this term to ensure consistency and clarity?

We use the term net present damage to avoid any potential confusion with the governmental SC-GHG process, though "net present damages of an additional ton" is indeed a synonym with the term "domestic SCC". Because we think that the global SC-GHG is the appropriate value to be used for cost-benefit, we wanted to avoid any implication that the domestic net present damages shown here should be considered a potential substitute in that kind of analysis. We will add a footnote clarifying that these numbers are comparable.

- Line 87 suggests socioeconomic and emissions scenarios are randomly and independently sampled, but my understanding of the RFF scenarios was that there is a joint distribution and that draws should therefore be jointly sampled.

We will clarify the dependance between the socioeconomic and emissions pathways (they are coupled draws). "we first utilize 10,000 paired probabilistic emissions and socioeconomic projections and a reduced-complexity climate model to provide inputs for FrEDI to assess the annual physical and economic impacts of climate change projected to occur through the end of the 21st century within 20 sectors in the contiguous United States (CONUS)."

Only the climate uncertainty is independently sampled.

- Line 243 – what figure is being referred to?
We will update the text to reflect the correct figure.

- It is very unclear how the racial breakdown was done – are these populations modeled as differentially vulnerable to the same physical hazards? Or are the authors simply calculating how these populations are distributed across the 7 regions? More detail on what these estimates do and do not include is needed.
Both reviewers commented on needing more information on social vulnerability analysis. We will add a new section to the paper that lays out the details and presents the figure in the main text and not in the Appendix. Please see our response to a similar request from Reviewer #1.

- The Burke et al. (2015) citation on line 55 appears to be misplaced.
We deleted this reference.

- Is it a feature or a bug that FrEDI can combine any socioeconomics with any warming scenario? Should these things be linked so as to ensure feasibility/plausibility? Lines 65- 68)

Thank you for bringing this to our attention. We do intend for the GDP and population scenarios that are inputs to FrEDI to be consistent with the emission scenario that is used to create the temperature projections that are also inputs to FrEDI. In this study the projected temperatures resulting from running a given emission scenario through the FaIR model are matched with the GDP and population corresponding to that emission scenario (based on the RFF scenarios). We could include some text within FrEDI's technical documentation cautioning the user.

References

Auffhammer, Maximilian. "Quantifying economic damages from climate change." Journal of Economic Perspectives 32, no. 4 (2018): 33-52.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro. "Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century." Journal of Political Economy 124, no. 1 (2016): 105-159.

Carleton, Tamma, Amir Jina, Michael Delgado, Michael Greenstone, Trevor Houser, Solomon Hsiang, Andrew Hultgren et al. "Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits." The Quarterly Journal of Economics 137, no. 4 (2022): 2037-2105.

Deschênes, Olivier, and Michael Greenstone. "Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US." American Economic Journal: Applied Economics 3, no. 4 (2011): 152-185.

Heutel, Garth, Nolan H. Miller, and David Molitor. "Adaptation and the mortality effects of temperature across US climate regions." The review of economics and statistics 103, no. 4 (2021): 740-753.

Rode, Ashwin, Tamma Carleton, Michael Delgado, Michael Greenstone, Trevor Houser, Solomon Hsiang, Andrew Hultgren et al. "Estimating a social cost of carbon for global energy consumption." Nature 598, no. 7880 (2021): 308-314.

Wenz, Leonie, Anders Levermann, and Maximilian Auffhammer. "North–south polarization of European electricity consumption under future warming." Proceedings of the National Academy of Sciences 114, no. 38 (2017): E7910-E7918.