Advancing the estimation of future climate impacts within the United States

Response to Reviewers

Reviewer #1

The manuscript describes a framework for evaluating long-term damages from climate change to a large number of different specific U.S. economic sectors. The damage functions have generally been previously published and have been extended to 2300 (from an original 21st century time horizon for most of them). The common FaIR climate model is used to simulate and take into account uncertainty in global climate, specifically temperature change, which is used as input to the various damage functions. Probabilistic projections for socioeconomic conditions (e.g., GDP, population change) from a recent study are used, and combined with different emissions scenarios. The work decomposes climate-driven damages by geographic region within the U.S. and by different vulnerable populations.

The manuscript is well-written and well-organized. As near as I can tell from the methodological descriptions of FrEDI provided in the manuscript, the conclusions and results follow nicely from the experiments that are conducted. However, my comments below revolve mostly around the theme of a need for further details about the structural assumptions baked into the damage function underlying FrEDI. You understandably defer a great deal to other recently published works that are the primary sources for these parameterizations, and I understand that this is not a model description paper. However, this makes it a bit more difficult for the reader to understand the context for the results presented, particularly for interpreting sector-specific damages. Most of these and my other comments I anticipate can be cleared up through adding some modeling details and/or caveats. Thus I recommend for minor revisions.

We thank Reviewer #1 for their comments, particularly related to our discussion regarding the treatment of adaptation and differential impacts in FrEDI. These have helped us improve the quality of our methods and discussion of results. We have addressed each comment in detail below in italics.

General comments:

L65-67 - Perhaps any of these FAIR warming scenarios *can* be paired with any socioeconomic projection, but *should* they? There are some SSP-RCP combinations (e.g.) that modelers use but shouldn't. For example, see O'Neill et al 2020, https://doi.org/10.1038/s41558-020-00952-0, particularly their Figure 2. I can imagine that your probabilistic framework may account for this in some way, but I'd be interested to know more about how you ensuring that unlikely/implausible combinations of scenarios aren't unduly biasing results?

Thank you for the comment. Both reviewers had similar comments with how the current text is written with respect to how we pair RFF-SPs scenarios with FaIR. We will update the text with a more complete description. Here is a description of the process conducted that will be included in the manuscript: Uncertainty from climate is treated independently from uncertainty in the emissions and socioeconomics. Within this study we are passing projected emissions of CO_2, N_2O, and CH_4 from the RFF-SPs to the FaIR model to calculate a temperature trajectory from each emission pathway. The FaIR model developers have provided 2,237 sets of climate parameters, calibrated to the IPPC AR6. In this work, we use the

Monte Carlo simulation capabilities of MimiGIVE.jl (https://github.com/rffscghg/MimiGIVE.jl) to randomly sample the RFF-SPs and FaIR parameter sets to generate 10,000 global temperature trajectories. The resulting temperature trajectory associated with each of the RFF emissions pathways are then paired with the corresponding RFF socioeconomic (U.S. GDP and population) trajectories, which are then passed into FrEDI to calculate the physical and economic impacts from each RFF-SP scenario.

L74, 159 - What assumptions about coastal adaptation (and other forms of adaptation/mitigation, and development) are baked into FrEDI? Can you comment on how realistic these are on such long time scales?

FrEDI maintains adaptation assumptions from the underlying studies that form the basis of FrEDI's temperature-driven sectoral damage functions. For most of these studies, because the implicit or explicit impact response function is calibrated to historical or current data, this means that historically practiced adaptation or hazard avoidance actions are "baked in" – but enhanced adaptation action, or new (currently unknown) technologies are not considered. The exceptions include coastal property and select other infrastructure sectors, where the underlying studies consider specific adaptation actions. These have been incorporated into FrEDI. For example, for the coastal flooding sector, FrEDI's default adaptation assumption is a Reactive Adaptation scenario, as defined in Neumann et al. (2021), and includes the costs (and reflects the hazard reduction benefits) of elevation of properties, where and when the benefits exceed the costs of this measure and expanded beach nourishment at locations where it is currently practiced. No other measures are included. There is an option in FrEDI, however, for the user to select either a No Adaptation scenario for this sector, which excludes the option to elevate properties as well as measures that might hold back floodwaters, or a Proactive Adaptation scenario, where adaptation measures include elevation, beach nourishment, and armoring (either with bulkheads in protected areas or more expensive seawalls in areas exposed to higher open ocean wave action). It is difficult to comment on the realism of future action. There is some discussion in both Neumann et al. (2021) and Lorie et al. (2020), both of which make the point that even under current coastal hazards, cost-effective adaptation measures have not been adopted, probably because they involve short term capital investment in order to yield future, uncertain benefits. This is one reason why Proactive adaptation is not the default scenario in FrEDI. In Table A3, we present the climate-driven damages under different adaptation assumptions, where available, to explore the sensitivity to adaptation and highlight this capability within FrEDI.

L186 - Related to above, looking specifically at marginal damages means that the assumed adaptation strategies could be masking the real magnitude of these climate risks. For example, if it is assumed that you make least-cost decisions, then these marginal damages will be more of a lower bound. While the adaptation assumptions are provided in an appendix, it may be worth discussing these in main text more, because (my impression is that) the results rely a great deal on these assumptions.

In this analysis, we estimate the marginal damages by holding the adaptation scenario (that is, No Adaptation, Reactive, or Proactive) constant overtime, for those sectors where an option is provided. For other sectors, historically practiced adaptation or hazard avoidance actions are "baked-in" as described above. Therefore, while it is certainly true that marginal damages are higher under 'No Adaptation' versus 'Reactive' or 'Proactive' Adaptation scenarios, climate-driven damages under FrEDI's default adaptation assumptions are likely not masking the magnitude of climate risks, given the assumption that current mitigation levels will be held constant in the future. However, the user has a choice to explore *different adaptation options in select sectors. We will update the main and supplemental text to clarify the default adaptation assumptions included in this analysis.*

Note also that the sea level rise module uses financial smoothing so that costs are spread out over time to avoid discontinuities that could lead to odd effects with marginal damage calculations.

Related to the comment on coastal adaptation, the authors have separately done research investigating how to implement sub-optimal adaptation choices that might better represent real world behavior (see Lorie et al, 2020, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7433032/). FrEDI's capability to analyze three different assumptions about adaptation for many sectors allows exploration of more and less optimistic assumptions. It is difficult to determine if overall, the default FrEDI assumptions are too optimistic about rational adaptation, or include insufficient adaptation possibilities.

L210-212 - It isn't totally clear here what the default adaptation assumptions are for each sector (maybe cite Table A2 here?), or what each of these adaptation assumptions represents with respect to the individual sectors. For example, what does "reasonably anticipated adaptation" mean for coastal properties? And how reasonable are these assumptions on such long time scales, for each sector?

Thank you for the comment. We added a reference to Neuman et al., 2021 in table A2 and expanded on the meaning of these adaptation options within the text. Reasonably Anticipated Adaptation is an option for the High-Tide Flooding/Coastal Roads sector, but not for coastal properties. This adaptation scenario models reduced road delays associated with drivers seeking alternative, non-flooded routes (which still results in delays compared with conditions where flooding is not present, but delays of a much lower magnitude than under No Adaptation); it also includes the benefits of ancillary protection when/if nearby seaward properties would be likely to implement protective measures to hold back flooding (because benefits of armoring measures exceed costs at those properties). Reasonably Anticipated Adaptation is an "intermediate" adaptation assumption – it yields much lower costs than the No Adaptation option and higher costs than the Proactive Adaptation option.

Specific comments:

L23-27 - Is this by the year 2090? Or when?

Yes, the annual climate driven damages are for 2090. The text will be updated to reflect this.

L50 and 52 - "Climate Change Impacts and Risk Analysis (CIRA) project" and "Climate Impact Lab" - I'm aware of these projects/groups, but I'm not sure readers in general will know the context for these. Could be worth specifying where they're housed.

Thank you for the suggestion. The following text will be included in the manuscript: For example, the Climate Change Impacts and Risk Analysis (CIRA) project, coordinated by the USEPA involving researchers from government, academics and consultants, quantifies the physical effects and economic damages of climate change in the U.S., using detailed models of sectoral impacts (e.g., human health, infrastructure, and water resources) (EPA, 2017a). In addition, the Climate Impact Lab is a collaboration of more than 30 climate scientists, economists and researchers from across the U.S. and has focused its work on understanding the economic damages from climate change within the U.S. (Hsiang et al., 2017) and *across the globe, including impacts to human health (Carleton et al., 2022), agriculture (Rising and Devineni, 2020; Hultgren et al., 2022), coastal property (Depsky et al., 2022), and energy (Rode et al., 2021).*

L70 - In what way(s) is FrEDI distinguishable from a traditional IAM?

FrEDI is similar to traditional IAMs in that it tries to link society and the economy with climate change into one modeling framework. However traditional IAMs include economic processes as well as processes that produce greenhouse gases. Simple IAMs compare costs and benefits of avoiding levels of warming. Other, more complex IAMs, investigate processes that cause or prevent greenhouse gas emissions, such as, energy technologies, energy use choices, and land-use changes. These models will typically trade off to find optimal policies to reduce emissions. Within this analysis, emissions are an input to FaIR, which produces temperature change for an input to FrEDI.

L114-116 - Are there or should there be correlations and/or feedbacks represented between the RFF-SP emission scenarios and the FaIR scenarios?

Following up on the response in the first comment, no there are no correlations and/or feedbacks between the RFF-SPs and the FaIR uncertainty. There are two types of uncertainty explored here, the socioeconomic and emission uncertainty coming from the RFF-SPs and the physical climate parameter uncertainty coming from FaIR. These are treated independently from each other by using the Monte Carlo simulation capabilities of MimiGIVE.jl (https://github.com/rffscghg/MimiGIVE.jl) to randomly sample the RFF-SP emission and FaIR parameter sets. There is the possibility that high climate sensitivities could lead to implementation of climate policies (Webster et al. 2008), however, we do not include this in our analysis. The analysis presented within this paper is a common method for assessing future uncertainty and can be found throughout WG3 of the IPCC, within Rennert et al., 2022 using the RFF-SPs and the FaIR climate model, Yang et al., 2021 using GCAM and the climate model MAGICC to assess probability of staying below 2°C. We have clarified this in the main text.

Rennert et l., 2022, "Comprehensive evidence implies a higher social cost of CO_2". Nature.

Yang et al., 2021, "Can updated climate pledges limit warming well below 2°C?". Science.

L116-118 - How sensitive are the results to this moderate assumption? And no uncertainty sampled in these other gases/aerosols.

There has been some recent work to be able to infill scenarios with gases and aerosols by matching to the WG3 databases of 1000s of emission scenarios to CO_2, CH_4 and N_2O emissions (https://silicone.readthedocs.io/en/latest/#). We did not include this within our current analysis and is a potential source of uncertainty. We have a separate project working on using the Silicone model (Lamboll et al. 2020) to extrapolate to other gases and aerosols. The early indication of this work is that the effects are not large: generally, aerosols are projected to decrease across almost all scenarios, so there isn't much radiative forcing spread between the high and low aerosol scenarios (and the other GHGs are small contributors relative to big three).

L175 - should this be g_t?

Yes this was a typo and will be updated.

Table 2 - should “2,1” be “2,100” in the 95% CI column?

Yes this was a typo and will be updated.

L270-272 - I’m intrigued by this and would love to see more work on this prominently featured in contemporary research. But I’m also curious about how this modeling is done within FrEDI and what scale data is being used, and what assumptions there are when disaggregating damages for socially vulnerable populations.

Thank you for the comment. We will move much of the current social vulnerability analysis from the Supplement to a new section in the main text and provide more background and detail about this capability. We provide a general overview here.

Differential climate change risks are a function of exposure to where climate change impacts are projected to occur and vulnerability, in terms of an individual’s capacity to prepare for, cope with, and recover from climate change impacts (https://www.epa.gov/cira/social-vulnerability-report). The capability of exploring differential impacts to U.S. populations within FrEDI is based on data on the locations of where populations live as an indicator of exposure and for vulnerability, considers four categories for which there is evidence of differential vulnerability. Differential impacts in each group are calculated in FrEDI at the Census tract level as a function of current population demographic patterns (i.e., percent of each group living in each census tract), projections of CONUS population (from ILCUS, U.S. Environmental Protection Agency, 2017), and projections of where climate-driven impacts are projected to occur (i.e., using FrEDI temperature-impact relationships) at the Census tract level. We assess impacts in FrEDI across four different population categories: income, age, race and ethnicity, and education, and breaking the race and ethnicity category into BIPOC populations. Results show that the BIPOC group is more likely to be impacted by climate-driven changes to air quality attributable mortality as well as lost labor hours due to increasing temperatures. Breaking down the results further, Black or African Americans are more likely to experience additional pre-mature mortality from climate-driven changes in air quality, and Hispanic or Latino are more likely to experience additional lost labor hours.

L424-430 - You cite two studies that used a power law relationship, finding that it fit the temperature-damage relationship better than linear. Why choose to use linear instead in FrEDI?

Sarofim et al., 2021, showed that for most of the analyzed sectors, a linear fit best described the relationships between temperature and damages were linear. However, we are using a piecewise linear function for FrEDI, where a damage function is calculated within every temperature bin (1-2°, 2-3°, etc.), FrEDI can capture nonlinearities resulting from the underlying impact models up to the largest temperature changes assessed in the underlying studies. As described in the main text and Section A1, FrEDI’s damages functions are extended to warmer temperatures (i.e., later years), by linearly extrapolating each sectoral damage function.

Figure A2 - There is a lot to unpack here, including a few of what appear to be some tipping points or other kinds of jumps in some of these sectoral damages around 2060 or so. E.g., wind damage, agriculture, or the sudden jump in coastal property damages after about 2080 - how do you make sense of these results, in light of the adaptation assumptions embedded in FrEDI?

We provide Figure A2 as an illustration of the overall trends and relative magnitudes of damages projected to occur within each impact sector currently included in FrEDI. As described in the FrEDI technical documentation (https://www.epa.gov/cira/fredi), the damages in many of these sectors are a function of the climate driver (e.g., temperature or sea level change), as well as additional scaling factors, such as socioeconomics (e.g., damages resulting from mortality rely on the Value of a Statistical Life, which is proportional to per capita income). The temporal trends in Figure A2 reflect the combination of the projected changes in both the climate drivers and these scalars, the latter of which exhibit relatively smooth trends (Figure A1). In contrast, damages in other sectors are only a function of climate drivers (e.g., agriculture, wind damage, coastal properties) and therefore the trends in Figure A2 are more directly reflective of the underlying by-degree piece-wise linear temperature (or sea level rise) binned damage functions. The slight discontinuities pointed out in some of these sectors (e.g., agriculture) can occur either at the boundary between temperature bins (e.g., for agriculture and wind damage) or due to thresholds in the underlying studies. For example, the sharp increase in damages in the coastal property damage sector after 2080 are directly reflected in the underlying damage functions (See FrEDI Technical Documental Appendix B) and correspond to a sharp increase in damages that occur after sea levels breach 100 cm. These trends also reflect the default adaptation assumptions included in FrEDI. For example, the damage functions for the default reactive adaptation scenario for the coastal property sector include large increases in damages above 100 cm of sea level rise, whereas the proactive adaptation scenario, which includes collective action such as seawall construction, does not include the same rate of damage increase at 100cm of sea level rise. Details about the underlying studies and damage function development details for each sector are included in the FrEDI Technical Documentation.

We have added a brief explanation in the caption of Figure A2.

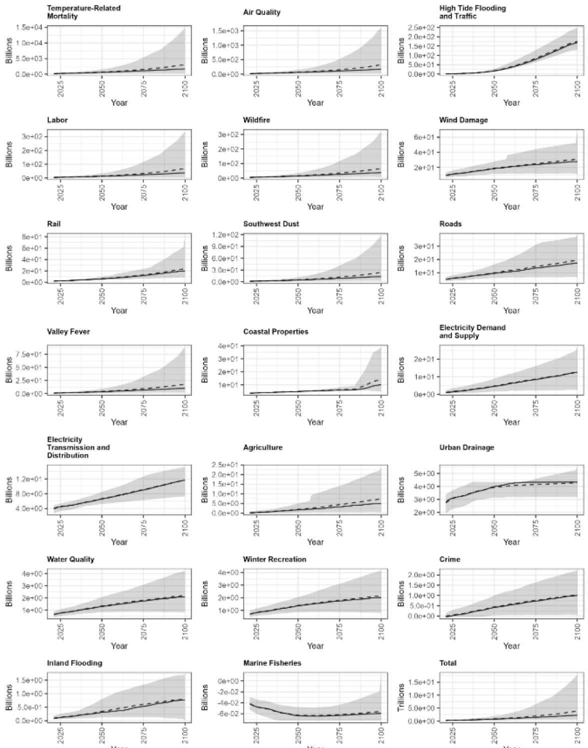
L469 - perfect foresight over what time frame?

Yes, thank you: different sectors have different time frames: e.g., the coastal property model does a 30 year look ahead for infrastructure spending decisions. We've edited the sentence to remove the phrase "perfect foresight".

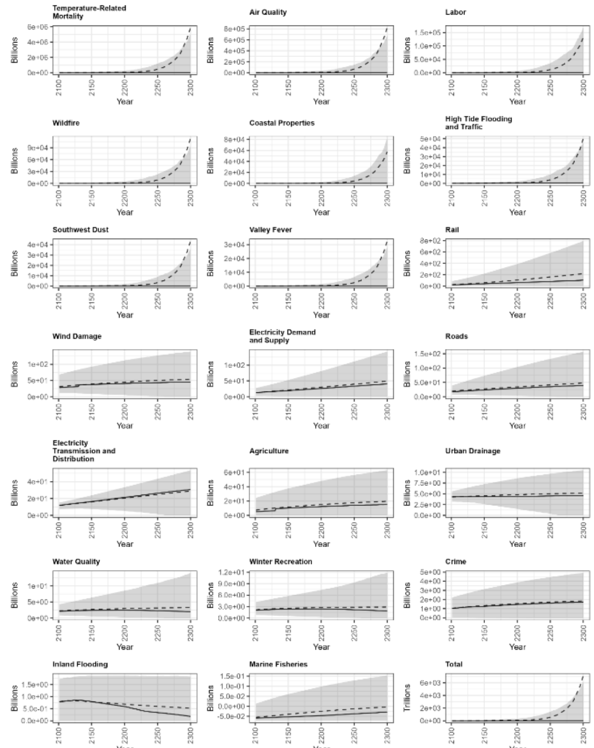
Figure A5 - Are some of these damage distributions in later years so heavily skewed that the means are outside of the 95% CI? It might be tidier to display the median, and perhaps more consistent with the use of percentiles for the 95% CI too.

We present two figures within the Appendix that have been updated with mean and median lines. Citing Webster et al., 2008, under a risk based framework, the most important causes for concern are not the median projections of future climate change, but the low-probability, high-consequence impacts. Therefore, we present the mean damages over the median, as well as the 95% confidence rank. We note that in figure A5, the mean is much larger than the median due to significant growth projected to occur in the socioeconomics (GDP/capita) between2100 and 2300. In these cases, a small number of high impact scenarios are resulting in the mean damages exceeding the 97.5th percentile. Below are the new versions of figures that will be included in the Appendix.

Annual Climate-Driven Impacts



Annual Climate-Driven Impacts



Relevant changes to the manuscript to address reviewer 1:

1. Updated the text to better reflect how the RFF-SPs and FaIR are paired within the Methods section.
2. Updated the text within Section 2.3 and Section A3 to better reflect the adaptation options and assumptions available within FrEDI.
3. Included new text that explores the social vulnerability aspect of this work within section 3.1
4. Included new figures within the appendix that are updated with both mean and median estimates.

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	5^{th}	95^{th}	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.

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Relevant changes to the manuscript to address reviewer 2:

5. Updated the text to better reflect how the RFF-SPs and FaIR are paired within the Methods section.
6. Updated the text within Section 2.3 and Section A3 to better reflect the adaptation options and assumptions available within FrEDI.
7. Updated the text to explain the key dimensions of uncertainty (structural and damage function uncertainty within the temperature-related mortality sector) explored within this work within Section A3.
8. Updated the introduction to better reflect our motivation of this work.