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.

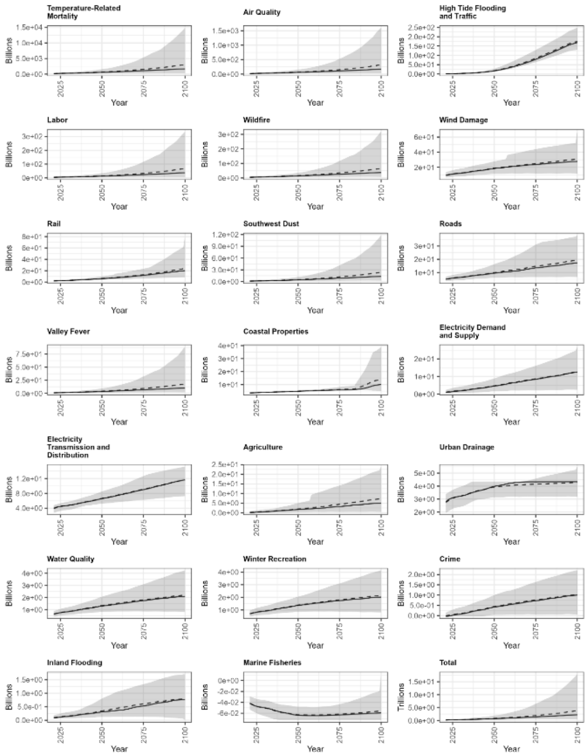
L469 - perfect foresight over what time frame?

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