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Advancing the estimation of future climate impacts within the United States

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Abstract.

Evidence of the physical and economic impacts of climate change is a critical input to policy development and decision making. The potential magnitude of climate change damages, where, when, and to whom those damages may occur across the country, the types of impacts that will be most damaging, and the ability of adaptation to reduce potential risks are all important and interconnected. This study utilizes the reduced-complexity model, Framework for Evaluating Damages and Impacts (FrEDI), to rapidly assess economic and physical impacts of climate change in the contiguous United States (U.S.). Results from FrEDI show that net national damages increase overtime, with mean climate-driven damages estimated to reach $2.9 trillion USD (95% CI: $510 billion to $12 trillion) annually by 2090. Climate-driven damages are largest for the health category, with the majority of damages in this category from the valuation estimates of premature mortality attributable to climate-driven changes in extreme temperature and air quality (O_3 and $PM_{2.5}$). Results from FrEDI also show that climate-driven damages vary by geographical region, with the Southeast experiencing the largest annual damages per capita (mean: $9,300 per person annually, 95% CI: $1,800-$37,000 per person annually), whereas the smallest damages per capita are expected in the Southwest region (mean: $6,300 per person annually, 95% CI: $840-$27,000 per person annually). Climate change impacts may also broaden existing societal inequalities, with Black or African Americans disproportionately affected by additional premature mortality from changes in air quality. This work significantly advances our understanding of the impacts from climate change to the U.S., in what U.S. regions impacts are happening, what sectors are being impacted, and which population groups being impacted the most.

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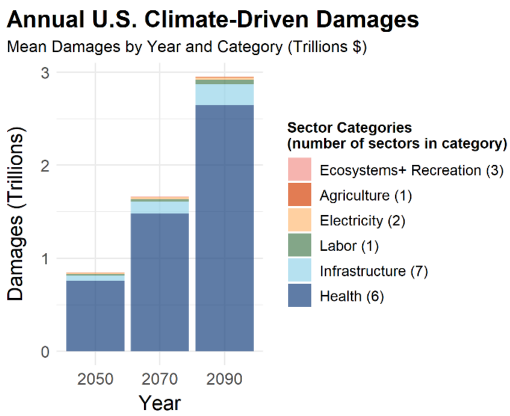

Graphical abstract figure.

1 Introduction

Evidence of the physical and economic impacts of climate change is a critical input to policy development and decision making. The potential magnitude of climate change damages, where, when, and to whom those damages may occur across the United States (U.S.), the types of impacts that will be most damaging, and the ability of adaptation to reduce potential risks are all important and interconnected (Martinich et al., 2018). Information about potential damages in different U.S. sectors and regions can help federal decision makers identify significant climate risks as an initial step toward prioritizing and managing such risks, especially through mitigation and adaptation actions (GAO, 2017). Results of recent multi-sector impact analyses show complex patterns of projected changes across the country, with damages in some sectors (for example, labor, extreme temperature mortality and coastal property) estimated to range in the hundreds of billions of U.S. dollars annually by the end of the century (Martinich and Crimmins, 2019; Hsiang et al., 2017).

Climate economics research has continued to develop and improve damage functions that represent impacts in broader economic frameworks, leveraging considerable advancements in the science and economics of estimating future climate change impacts (NAS, 2017). Advances in our understanding of the historical relationships between climatic variables and the economy have also enabled the development of methods to assess the economic effects from climate change within the U.S. under different scenarios (GAO 2017; Field et al., 2014). For example, the Climate Change Impacts and Risk Analysis (CIRA) project 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 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), energy (Rode et al., 2021), and labor (Burke et al., 2015).

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These studies typically use the large-scale global scenarios (e.g., the Representative Concentration Pathways (RCPs)) and are not run under different future trajectories. Temperature binning provides an alternative framework for analysing sector-specific impacts by degree of warming, which complements traditional scenario-based approaches. This framing can improve communication of results, comparability between models and studies, and flexibility for new scenario analysis (Sarofim et al., 2021). The recently developed Framework for Evaluating Damages and Impacts (FrEDI) (EPA, 2021b) utilizes this temperature binning approach to rapidly assess economic and physical impacts of climate change to the United States. FrEDI incorporates advances in peer-reviewed economic damage functions to develop relationships between mean surface temperature change and impacts across 20 sectors over the 21st century, providing an efficient and transparent damage estimation approach that operates independently of Integrated Assessment Models (IAMs). FrEDI has the flexibility to use any custom warming scenario derived from a climate model (e.g., the Finite Amplitude Impulse Response model (FaIR)) and couple it with any accompanying socioeconomic projections (e.g., gross domestic product (GDP) and population). Due to this level of detail and flexibility, FrEDI provides a useful framework to explore a variety of future baseline trajectories, emission reduction policies and, thereby, can complement the types of analyses and outputs provided by existing integrated assessment models (IAMs).

In this study, we utilize paired probabilistic emissions and socioeconomic projections and a reduced-complexity climate model to provide inputs for FrEDI to quantify both the physical and economic impacts of projected climate change across the contiguous United States (CONUS). These impacts incorporate a broad range of sectoral detail as well as spatial detail across seven U.S. regions. Our methodology extends out to the year 2300 to assess the net present damage in the U.S. resulting from an additional ton of CO_2 emissions. Summing net present damages across all sectors and regions provides a traceable estimate of the physical and economic damages from a marginal change in greenhouse gas emissions.

2 Methods

This study consists of three components, each representing recent scientific advances in their respective fields (Figure 1). Probabilistic projections of global greenhouse gas emissions (Figure 1, Input 1) are used as inputs into a simple climate model to derive trajectories of changes in global mean surface temperature (Figure 1, Output 1). These temperature trajectories are then passed to FrEDI (Figure 1, Input 2) alongside probabilistic projections of U.S. Population and GDP (Figure 1, Input 1) to model climate damages across 20 sectors, seven U.S. regions, multiple adaptation scenarios, and the option to explore impacts to socially vulnerable populations (Figure 1, Output 2). A unique feature of the probabilistic emissions and socioeconomic projections, and the reduced complexity climate model, is the rich range of uncertainty and uncertain parameters underlying them. In this study, we use 10,000 randomly sampled scenarios of global greenhouse gas emissions, U.S. population, and U.S. GDP from the Resources for the Future – Socioeconomic Projections (RFF-SPs) (Rennert et al., 2021) (Section 2.1).

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Probabilistic emission trajectories of CO_2, CH_4 and N_2O are used as inputs to the Finite Amplitude Impulse Response (FaIR) model, a simple emissions-based climate model (v1.6.2) calibrated based on historical data and IPCC AR6 assessed climate variables (Smith et al., 2018), to calculate the change in global mean surface temperature (relative to 1850-1900 average). The resulting 10,000 global mean surface temperature projections (along with corresponding population and GDP projections from the RFF-SPs) are then passed to FrEDI (v3.0) to calculate the physical and economic climate damages to the U.S. We describe each process in more detail below.

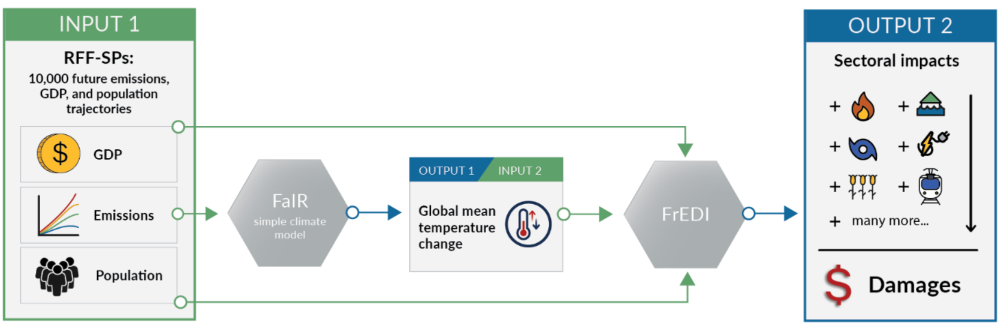

Figure 1: Flow diagram of the inputs and outputs needed to evaluate the economic damages within the U.S. Emission trajectories are passed as inputs into FaIR to calculate global mean surface temperature. Global mean surface temperature, population, and GDP are then passed as inputs to FrEDI to calculate sectoral climate impacts to the U.S. Not shown is the estimation of global mean sea level rise; these values are calculated within FrEDI using a semi-empirical approach from existing literature (Kopp et al., 2016) to calculate the impacts to the subset of FrEDI sectors that are impacted by sea level rise (i.e., high tide flooding and traffic, and coastal properties) (EPA, 2021b).

2.1 Emissions and Socioeconomics

Socioeconomic and emissions projections from 2020 to 2300 were recently developed under the Resources for the Future Social Cost of Carbon Initiative (Rennert et al., 2021). These include multi-century probabilistic projections of country-level population, GDP per capita, and global emissions of CO_2, CH_4 and N_2O. The projections represent a state-of-the-art set of probabilistic socioeconomic and emissions scenarios based on high-quality data, robust statistical techniques, and expert elicitation. In addition, these projections incorporate coupled uncertainty in the time-dependent relationship between GDP per capita and emissions, while also explicitly accounting for potential future climate policy and its contribution to the economy-emissions relationship (Rennert et al., 2021).

2.2. The Climate Model

The Finite Amplitude Impulse Response model (FaIRv1.6.2)[1] calculates atmospheric concentrations of greenhouse gases, radiative forcing, and global mean surface temperature from greenhouse gases, aerosols, and other gases

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[1] https://github.com/OMS-NetZero/FAIR

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(Smith et al., 2018). Version 1.6.2 was calibrated to and extensively used within the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (Forster, P. et al., 2021). We accessed a random sample of 10,000 trajectories from the RFF-SP emission scenarios (consisting of CO_2, CH_4, and N_2O) paired with a random sample from the calibrated set of uncertain parameters contained in FaIR.[2] The other gases and aerosols (e.g., HFCs, BC, OC, etc.) not included in the RFF-SP projections were set to the associated emissions in the SSP2-4.5 (Meinshausen et al., 2020) scenario, for which most closely match the median RFF-SP emission trajectories. From the 10,000 model simulations, the average change in global mean surface temperature relative to 1986-2005 (FrEDI baseline) is 1.9°C (95% confidence interval: 0.8°C to 3.5°C) by 2100 and increases to 3.1°C (95% CI: -0.2°C to 7.8°C) by 2300 (Figure A1).

2.3 Damages from Climate Change to the U.S.

The Framework for Evaluating Damages and Impacts (FrEDI) is a reduced complexity model that assesses and quantifies future impacts to the U.S. from a changing climate. As described in detail in the Technical Documentation (EPA, 2021b), FrEDI uses a temperature binning approach and data from previously published climate impact studies (Sarofim et al., 2021) to develop relationships between climate-driven changes in CONUS temperature or global mean sea level rise and the resulting physical and economic damages across 20 sectors (Table A1) in seven U.S. regions. FrEDI also provides insight into differences in impacts under various adaptation scenarios and contains a module that can be used to quantify impacts to socially vulnerable populations. The underlying studies in FrEDI consist of bottom-up detailed sectoral analyses from the CIRA project (EPA, 2017a) and other studies including those from the Climate Impact Lab (e.g., Hsiang et al., 2017) and the American Thoracic Society (e.g., Cromar et al., 2022). FrEDI was designed to fill the current need of monetizing a broad range of climate-driven impacts in the U.S. across various emission/socioeconomic trajectories while doing so in a significantly shorter computational timeframe (e.g., seconds) relative to existing impact models. To achieve this objective, the detailed spatial resolution of the underlying studies is reduced within FrEDI for ease, flexibility, and speed.

FrEDI currently consists of 20 sectors for which damages are modelled as functions of a climate driver (CONUS temperature or sea-level rise), regional GDP, and regional population. The population projections from the RFF-SPs are spatially aggregated total U.S. population. For the analysis, we disaggregate national values to populations for each of the seven FrEDI regions based on the percentage of regional to total U.S. population in the years 2010-2090 using projected regional populations derived from ICLUS (EPA, 2017b). The proportions for each region are held constant after 2090. Figure A1 shows the mean and 95th confidence intervals for U.S. population and time-

[2] FaIR developers provide 2,237 calibrated parameter sets from the full 1-million-member ensemble. 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. See Rennert et al. (2022) for more detail on the RFF-SPs and FaIR parameter sets. Each of the 10,000 RFF-SPs are assumed equally likely.

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averaged U.S. GDP per capita growth rates are 390 million (95% CI: 260-520 million) and 1.5% (95% CI: -0.4% to 4.0%), respectively in 2100.[3] By 2300, the average of all 10,000 trajectories for U.S. population and time-averaged U.S. GDP per capita growth rates are 370 million (95% CI: 43 million to 1.3 billion) and 0.9% (95%CI: -0.2% to 3.4%), respectively. The trends shown in Figure A1 reflect the aggregate of the 10,000 individual RFF-SP trajectories (each of which has a different, equally likely growth path).

For sectoral impacts driven by temperature change, damages in FrEDI are calculated as functions of CONUS degrees of warming over time, relative to a 1986-2005 average temperature baseline. In this analysis, CONUS mean temperature change is estimated for each FaIR-derived temperature projection (calculated from each RFF-SP emissions scenario), as CONUS temperature (°C) =1.42 × Global Temperature (°C) (EPA, 2021b). This relationship between CONUS and global temperatures is relatively stable across GCMs and over time, allowing the use of these available datapoints to develop a generalized relationship between global and CONUS temperature anomalies. For sectoral impacts driven by sea level rise (i.e., coastal properties and high tide flooding and traffic), global mean sea level is calculated within FrEDI from global mean surface temperature using a semi-empirical method that estimates global sea level change based on a statistical synthesis of a global database of regional sea-level reconstructions from Kopp et al. (2016). In FrEDI, for a given year, sea level-driven damages are calculated by interpolating between modelled damages at different sea level heights at that same point in time; this enables FrEDI to account for interactions between adaptation costs, increased coastal property values, and sea level rise over time (EPA, 2021b).

FrEDI was initially built to project damages through 2090 for temperature scenarios with a maximum value of 10°C of warming. For this work, we extend FrEDI through the year 2300 by linearly extrapolating the temperature-binned damage functions for each sector to account for the full range of the RFF-SPs temperature scenarios (some of which see degrees of warming above 10°C). See Section A1 for more information on the sector-specific changes implemented in this model extension.

2.4 Estimating Net Present Value of Future Damages per ton of GHG Emissions

Future monetary impacts are generally discounted relative to present value. Circular A-4 (White House, 2003) recommends a constant value of 3% for the “social rate of time preference”, which is considered to be the appropriate discount rate to use for impacts on private consumption (which would include most environmental and health impacts). The discount rate of 3% was calibrated to the real rate of return for 10-year Treasury notes from 1973 through 2003. However, OMB Circular A-4 also noted that for intergenerational impacts (a category in which climate change clearly falls), discount rates lower than 3% might be appropriate. Moreover, recent real rates

[3] All dollar values in this paper are presented in 2020 U.S. dollars. Any necessary transformations in the inputs (e.g., RFF-SPs are in 2011$ and FrEDI takes 2015$) are performed using the U.S. Bureau of Economic Analysis national data on annual implicit price deflators for U.S. GDP, the top row of BEA Table 1.1.9.

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of return for Treasury notes have been lower than 3%, adding support for use of a discount rate smaller than 3% (CEA, 2017). A number of economists, as well as the National Academies of Sciences (NAS, 2017) have alternatively suggested the use of Ramsey discounting (Eq. 2, ρ is the rate of pure time preference, g is a time-varying measure of per capita consumption or income, and η is the elasticity of the marginal value of consumption with changes in g_t) as an appropriate approach to discounting long-term problems such as climate change. The effect of Ramsey discounting is to value damages more highly in futures with less economic growth – e.g., future societies that have fewer resources available for adaptation, and vice versa. A recent study from Rennert et al. (2022) used a Ramsey approach calibrated to a near-term target discount rate of 2%, with ρ = 0.2% and η = 1.24.[4]

As described previously, FrEDI was extended in this work to project climate damages out to 2300 to quantify the net present damages in the U.S. resulting from an additional tonne of CO_2 emissions. For this analysis, FrEDI is run through to 2300 under two cases, a baseline and a perturbed case, where 1 GtC pulse of CO_2 is added in the year 2020. The emissions are identical between the cases for all other years. The marginal damages are calculated as the difference between the baseline and perturbed cases summed across all sectors and all regions for each year. Lastly, these marginal damages are discounted to the year of emissions and then aggregated across the timeseries into a single net present damage estimate. The results are normalized by the pulse size and gas chemistry (C to CO_2) and reported in 2020 U.S. dollars.

The net present value (NPV) for a constant discount rate is calculated such that

$$NPV\big(D(t)\big) = \sum_{t=2020}^{t=2300} \frac{D(t)}{(1+r)^t} \qquad (1)$$

The net present value for a Ramsey discounting approach is calculated using a time-varying and state-specific discount rate which is a function of per capita economic growth (gt):

$$r_t = \rho + \eta * g_t \qquad (2)$$

and where this time varying rate is then used in the net present value calculation such that

$$NPV\big(D(t), g(t)\big) = \sum_{t=2020}^{t=2300} \frac{D(t)}{\prod_{x=2020}^{x=t}(1+r_x)^x}$$

g_t has also been adjusted to reflect climate damages, such that in any given time period it is the per capita consumption as calculated by taking the exogenous RFF-SP GDP, subtracting the damages output by FrEDI, dividing by total population, and recovering the GDP per capita growth rate net of climate damages. Because most of the sectoral damages are proportional to GDP per capita (given that the default elasticity of VSL to GDP per capita is 1,

[4] For Ramsey discounting calibrated to near-term target discount rates of 1.5%, 2.5%, or 3%, ρ = 0.01%, 0.5%, and 0.8% and η = 1.02, 1.42, and 1.57 respectively.

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all sectors with a mortality endpoint also qualify), in extreme cases where damages become a substantial percentage of GDP a correction can be made to account for this relationship (Nordhaus, 2017) . For this analysis, we use the equation

$$D\big(t, g(t)\big) = \frac{D_0(t)}{1 + {D_0(t)}/{GDP_0(t)}}$$

Where $GDP_0(t)$ is the exogenous RFF-SP GDP, and $D_0(t)$ is the initial total damages output by FrEDI.

3 Results and Discussion

3.1 Annual U.S. Climate-Driven Damages by the End of 21st Century

FrEDI was developed to quantify the physical and economic damages in the U.S. from climate change over the 21st century. Figure shows the net annual mean economic climate-driven damages across 20 sectors in the U.S. in the years 2050, 2070, and 2090, as calculated from the 10,000 baseline RFF-SP scenarios (i.e., emission, population, and GDP trajectories). This analysis used the default adaptation assumptions of ‘reactive’ ‘reasonably anticipated adaptation’ or ‘no additional adaptation’ for each sector and groups resulting mean damages from each of 20 FrEDI sectors into six topical categories. Section A3 in the Appendix describes the impacts of modeling different adaptation options in more detail. FrEDI does consider both the positive and negative effects of climate change across sectors, however, the negative effects of climate change outweigh the positive for all sectors at the national scale. Total annual damages throughout this analysis are shown in 2020 U.S. dollars. Figure 2 shows that net national damages increase overtime, with mean climate-driven damages estimated to reach $2.9 trillion USD (95% CI: $510 billion to $12 trillion) annually by 2090. Table 1 provides the 2090 annual mean damages and 95% confidence interval (CI) for each aggregate category. The individual sectors that contribute to each category are listed in Table A2.

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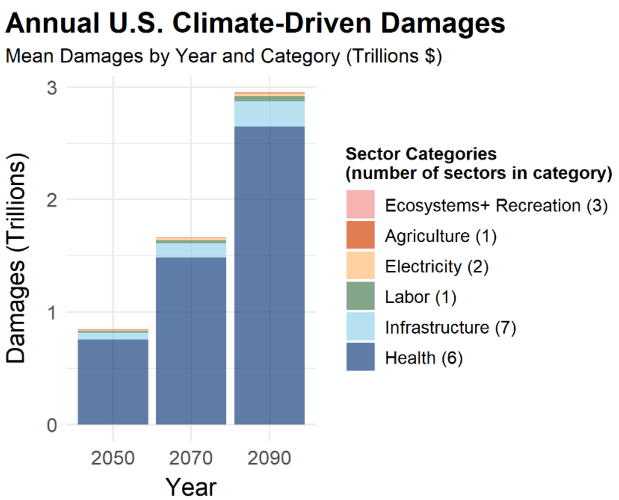

Figure 2: Annual mean U.S. climate-driven damages in 2050, 2070, and 2090. Damages are average values in billions of dollar (2020 USD) calculated from the 10,000 RFF-SPs. Sectors are grouped into six categories for visual purposes. The number of sectors included in each category is given in parenthesis in the legend. See Table A2 for the list of sectors in each cateogry

Table 1: The 95% confidence interval (CI) and mean annual U.S. climate-driven damages in 2090 for the six categories shown in Figure 2. All values are in 2020 USD. Totals may not sum due to rounding.

Category	Mean (billions)	95% CI (billions)
Health	$2,600	$350-$11,000
Infrastructure	$220	$140-$360
Labor	$51	$6.7-$220
Electricity	$22	$9.3-$35
Agriculture	$6.1	$0.42-$19
Ecosystems + Recreation	$4.0	$1.6 - $7.5
Total	$1,900	$510 – $12,000

Climate-driven damages as estimated by FrEDI are largest for the health category. The majority of damages in this category are from the valuation estimates of premature mortality attributable to climate-driven changes in extreme temperature and air quality (O_3 and $PM_{2.5}$), but also include monetized health damages attributable to valley fever, southwest dust, wildfire smoke exposure and suppression costs, and crime incidents. Another FrEDI category that includes the monetized value of directly estimated physical impacts (rather than a direct modelled relationship between temperature and monetized damages) is labor, which is the third largest category in 2090 and represents the damages resulting from lost hours of work when temperatures are too hot for workers to work outdoors or in unconditioned workplaces (e.g., warehouses). Table 2 provides the mean physical impacts from each of the sectors in the health and labor categories in 2090, along with the 95% CI. As shown in Table 2, climate-

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driven changes in extreme temperature have the largest impact on premature mortality, resulting in nearly 50,000 additional deaths (95% CI: 19,00-91,000 deaths) annually by 2090, followed by climate-driven changes in air quality (5,100 deaths; 95% CI: 2,100-10,000 deaths) and exposure to wildfire smoke (1,100 deaths; 95% CI: 460-1,700 deaths).

Table 2: The range of 2090 physical impact results across the 10,000 RFF-SP projections, including the 95% CI and mean. Totals may not add due to rounding.

Sector	Impact	95% CI	Mean
Extreme Temperature	Premature Mortality (deaths)	19,000 - 91,000	50,000
Air Quality		2,1 – 10,000	5,100
Wildfire		460 - 1,700	1,100
Southwest Dust		160 – 690	390
Valley Fever		130 - 480	300
Crime	Incidence (number of property and violent crimes)	-160 – 1,100	4,700
Labor	Work Hours lost (millions of hours)	170 – 830	430

To further illustrate the monetized contributions of each individual sector, Figure shows the range of 2090 annual climate-driven damages in each of the 20 sectors in FrEDI, across all 10,000 RFF-SP emission, GDP, and population scenarios, in decreasing order of sectoral mean damages. Figure 3 shows that national total damages in 2090 are primarily driven by the valuation of premature mortality attributable to climate-driven changes in extreme temperature (mean: $2.3 trillion per year; 95% CI: $0.31 – $9.9 trillion per year). The next four sectors with the largest monetary climate-driven damages include premature mortality attributable to changes in air quality (mean: $240 billion per year 95% CI: $32-$1000 billion per year), traffic delays associated with changes in high tide flooding (mean: $140 billion per year; 95% CI: $110-$200 billion per year), national labor hours lost (mean: $51 billion per year; 95% CI: $6.7-$220 billion per year), and health damages from wildfire smoke exposure and response costs from wildfire suppression (mean: $51 billion per year, 95% CI: $8.1-$220 billion per year). Climate-driven damages to coastal properties associated with change in tropical storm frequency and wind strength (mean: $29 billion per year; 95% CI: $12-$49 billion per year), damages attributable to changes in rail (mean: $19 billion per year; 95% CI: $7.7-$45 billion per year) and road systems (mean: $17 billion per year; 95% CI: $6.6-$35 billion per year), health damages from changes in southwestern dust exposure (mean: $18 billion per year ; 95% CI: $2.5-$77 billion per year), and the health burden of change in Valley fever incidence (mean: $14 billion per year; 95% CI: $2.0-$58 billion per year), round out the top 10 sectors with the largest annual damages in 2090. Figure A2 provides the mean and 95% confidence interval total damages for each sector over the entire 2020-2100

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timeseries. The large distribution of damages in each individual sector is driven by large range of RFF-SP emissions, population, and GDP projections and the dependence of the valuation approach for each sector on these parameters (as described in EPA, 2021b).

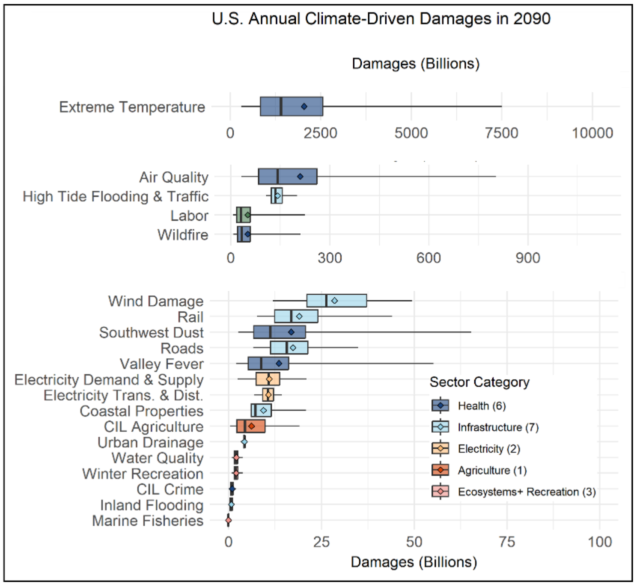

Figure 3: Annual U.S. damages in the year 2090 by sector, in order of decreasing mean damages, colored by six sector category groupings. Note the change in x-axis in each panel. Box and whiskers show the 2.5th, 25th, 50th, 75th, and 97.5th percentiles, and mean damages (diamonds) across all 10,000 projections. Damages are in billions of 2020USD.

Climate change also may broaden existing societal inequalities (EPA, 2021a). Both the effects of climate change and the distribution of populations within the U.S. vary geographically and therefore it is also possible to project how climate changes may impact overburdened and underserved populations. In addition to estimating national and regional sectoral impacts, FrEDI also contains a module to generate, and report results of disproportionate exposure and distributional physical effects across four categories of potentially socially vulnerable populations for a subset of six sectors with larger economic damages. For example, results from this module suggest Black or African Americans are disproportionately affected by additional premature mortality from changes in air quality, while Hispanic or Latino Americans are more affected by lost labor hours (Figure A3) under a changing climate.

Lastly, results from FrEDI also show that climate-driven damages across the national population vary by geographical region. Figure 4 shows a map of the damages per capita in each CONUS region in the year 2090, with pie charts showing the per capita damages in each region and the share of the four sectors with the largest damages (same figure for absolute regional damages in Figure A4). Figure 4 shows that the Southeast will

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experience the largest annual damages per capita (mean: $9,300 per person annually, 95% CI: $1,800-$37,000 per person annually), whereas the smallest damages per capita are expected in the Southwest region (mean: $6,300 per person annually, 95% CI: $840-$27,000 per person annually). In each region, the largest monetary damages in 2090 are expected from premature mortality associated with changes in extreme temperature, ranging from $4,500 per person in the Southwest to $6,500 per person in the Southeast. Damages from traffic delays due to high tide flooding and premature mortality attributable to climate-driven change in air quality are the second and third largest in the coastal Southeast and Northeast regions. In the Northwest and Southwest, the sectors with the second and third largest climate-driven monetized damages are air quality and wildfires. In the Southern Plains, high tide flooding traffic delays and labor hours lost are the second and third largest sectors, while rail and wildfires are the second and third largest in the Northern Plains, and labor and rail are the second and third largest in the Midwest. There are some regions and sectors projected to benefit from warming temperatures, including an expected reduction in air pollution attributable mortality in the Midwest under warmer conditions. Overall, however, the negative impacts of climate change outweigh the positives such that net losses are projected in each region.

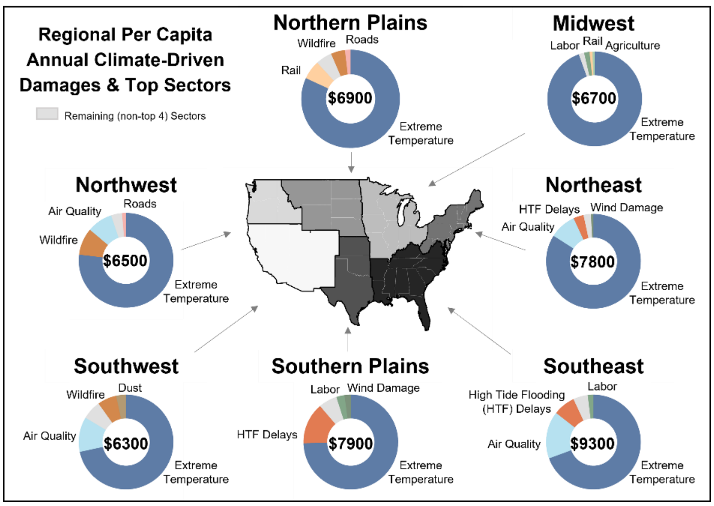

Figure 4: Mean per capita annual climate-driven damages across the seven regions in 2090. Donut charts show the annual per capita damages (2020$ per person annually) and the top four sectors with the largest damages in each region. All damages from remaining (non-top four) sectors are shown by the light gray wedges.

Figure 5 shows annual total national damages as a percentage of GDP out to 2100. The mean total damage share in 2100 is 3.4% and a maximum up to 13.0%. Given that the drop in GDP in 2009 during the Great Recession was

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2.2%[5], an annual decrease in GDP of over 3.0% per year reflects substantial damage to the national economy (though it is relevant to recognize that much of the damages estimated in FrEDI are a result of mortality, which is not directly reflected in historical GDP estimates).

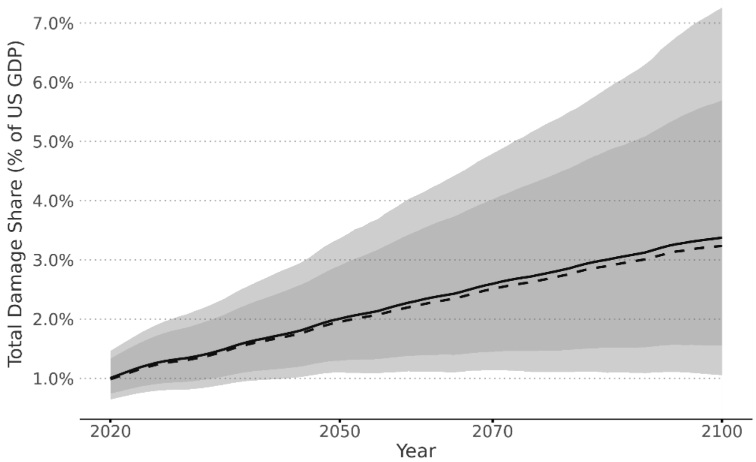

Figure 5: Share of U.S. GDP of climate-driven damages over time. Mean (solid) and median (dashed) lines along with 5th-95th (dark shaded) and 1st-99th (light shaded) percentile bounds.

3.2 Comparison with SSPs

To place mean damages in context of alternative future storylines, Table 3 shows a comparison of annual national climate-driven damages in the U.S. in the year 2090 from a subset of four Shared Socioeconomic Pathways (SSPs), which represent projected socioeconomic global changes up to 2100 (O'Neill et al., 2017). Annual damages in Table 3 are calculated following the same approach as outlined in Figure 1, but using SSP trajectories of emissions, U.S. GDP, and U.S. population from the SSP Public Database (v2.0)[6]. These trajectories do not include uncertainty related to climate and so we present only one value for each trajectory. Table 3 shows that annual U.S. climate-driven damages in 2090 from all but the SSP5-8.5 scenario fall below mean U.S. annual damages as predicted by the RFF-SP scenarios ($3.1 trillion). However, annual damages from all SSP scenarios fall within the 95% confidence interval (0.5-12.3 trillion $).

Table 3: Comparison of FrEDI damages from SSP and RFF socioeconomic input scenarios in 2090 (billions $2020 USD)

[5] Data from https://fred.stlouisfed.org/series/FYGDP, percentage decline in annual GDP from 2008 to 2009.
[6] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=80)

Scenario	Annual U.S. Damages (billion $2020USD)	Temperature Change in 2090 relative to FrEDI baseline (1986-2005 average)
SSP1-1.9	700	0.64
SSP2-4.5	1700	1.8
SSP3-7.0	1600	2.7
SSP5-8.5	7000	3.4
This study mean (95% CI)	2900 (510-12,000)	1.8 (0.80-3.2)

3.3 Net Present Damages per ton of GHG emissions

We extend FrEDI to project climate damages through to 2300 (Section A1 and Figure A5) to quantify the net present damages within the CONUS resulting from an additional tonne of CO_2 emissions. As described in Section 2.4, the net present value is the discounted sum of a stream of future damages produced by an emissions pulse in 2020 over the entire 2020-2300 time period. We explore the sensitivity of the remaining estimates to discounting assumptions by using Ramsey discounting calibrated to near-term target rates of 1.5%, 2.0%, 2.5%. Figure 6 shows the average, median, and range of estimated values for each discounting approach.[7]

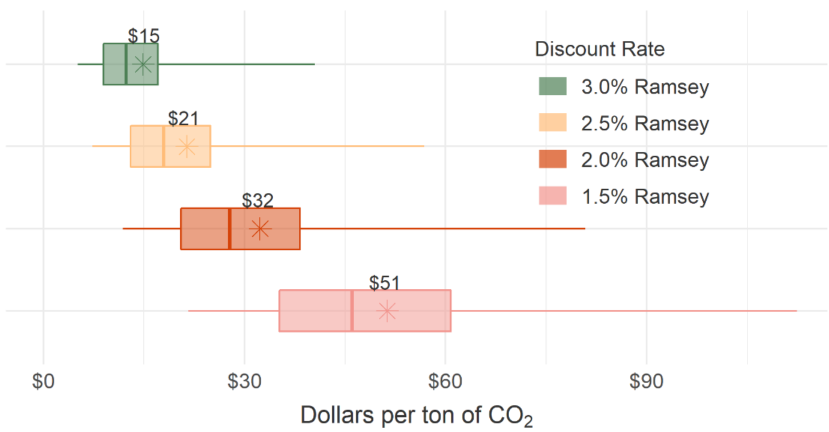

Figure 6. Net present value of future damages from one tonne of CO_2 for damages occuring only within the CONUS. Units are in dollars (2020 USD) per ton of CO_2 emitted. Whiskers represent the 2.5th and 97.5th percentiles, while boxes span the 25th to 75th. Mean values (stars and text) along with median values (vertical lines) are also shown.

[7] Figure A6 additionally compares these results to those using a constant discount rate of 3%, for a comparison with the historical approach in Circular A-4 (White House, 2003).

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This methodology can also be extended to explore the net present value of future damages resulting from an additional tonne of CH_4, N_2O, or other greenhouse gas emissions. These results show that even considering only the direct CONUS impacts as estimated by FrEDI, damages per tonne of CO_2 are almost 20% of a recently estimated global value ($185 per tonne of CO_2 under a 2% Ramsey discounting, (Rennert et al. 2022)). While the damages estimated within FrEDI are constrained to the 48 contiguous United States that are included within the model, it is important to note that the appropriate climate damages to consider when evaluating policy-induced changes in a global pollutant such as greenhouse gases would be damages that account for impacts around the globe. For example, The National Academies of Sciences advised that "[i]t is important to consider what constitutes a domestic impact in the case of a global pollutant that could have international implications that affect the United States" (NAS, 2017). Impacts that occur outside of U.S. borders (and outside of FrEDI) will impact the welfare of U.S. residents and firms because of the interconnectedness of the global economy, international markets, trade, tourism, national security, political destabilization, additional spillover effects, and many other activities not yet captured in the model. Moreover, the act of international reciprocity has been highlighted as motivation for including damages occurring outside of U.S. borders in a social cost estimate of global pollutants (Carleton and Greenstone, 2022; Revesz et al., 2017; and references within). It has also been shown that accounting for global damages in domestic policymaking can be individually rational (Kotchen, 2018). Therefore, we emphasize the contribution of the damages estimated within FrEDI as providing a useful understanding of the channels through which climate change can affect U.S. citizens and residents and their relative magnitudes beyond what is currently possible in many global models yet remain a partial estimate of the total damages from greenhouse gas emissions.

4 Conclusions

This study presents an evolving framework to quantify the damages of climate change to the U.S. economy, relying on more than a decade of research exploring individual sectoral impacts within the contiguous U.S. (EPA, 2021b). Impacts are dependent upon a change in global mean surface temperature, U.S. GDP and U.S. population, and assumptions about adaptation. Adaptation is relevant in many sectors when quantifying benefits (Section A3), however, there are some sectors within FrEDI that do not have explicit options to model adaptation. For example, the largest sector, premature mortality from extreme temperature, dominates the monetized damages across all regions. The mortality approach used in this paper is based on a well-regarded systematic review and meta-analysis of temperature-related mortality studies (Cromar et al., 2022). However, there is substantial uncertainty based both on difficulty of relating historical mortality to extreme temperatures, but also the potential for future adaptive responses to reduce vulnerability to extreme temperatures (Carleton et al., 2022; Lay et al., 2021).

While this work advances our understanding of climate-related impacts to the U.S., it is far from a comprehensive accounting of sectoral damages within the U.S. The FrEDI framework is dynamic, with new sectors being added to the framework on a continuous basis (including in the near term several types of health impacts including mental

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health, vibriosis, and health impacts of extreme storms), as well as broader coverage of direct and indirect impacts of inland flooding, but reflecting the overall status of underlying literature, the framework still omits coverage of many nonmarket sectors such as biodiversity, ocean acidification, many other ecosystem service losses, climate-forced migration, conflict, etc. We anticipate that the inclusion of more sectors will increase the estimates of net present damages due to GHG emissions. This work also omits the impacts of tipping elements due to climate change, which may lead to abrupt and irreversible impacts (Armstrong McKay et al., 2022). This study does not explore tipping elements like permafrost thaw or Antarctic ice sheet instability. Future work may entail coupling BRICK to the framework to better explore the uncertainty within sea level rise (Wong et al., 2022, 2017). While CO_2 fertilization effects are included in the damage estimates for the agriculture sector, the work does not account for any other direct effects of GHGs, such as the health, agriculture, or ecosystem damages resulting from ozone produced by methane's reaction in the atmosphere. Lastly, this work does not account for interactions among sectors, interactions between non-U.S. and U.S. damages through global markets, and their feedback on the U.S. economy. While we focus on U.S. damages, we acknowledge that impacts resulting from GHG emissions, regardless of where they originate, are global in nature. The bulk of the economic damages from climate change will be outside of the U.S. and the U.S. may also experience indirect effects through trade, business, migration, etc. (NAS, 2017; Hsiang et al., 2017).

This work significantly advances our understanding of the impacts from climate change to the U.S., in what U.S. regions impacts are happening, what sectors are being impacted, and which population groups being impacted the most. These results imply that there can be significant benefits to the U.S. from greenhouse gas mitigation, and significant benefits to the people of the U.S. Due to FrEDI's flexible framework, it allows for the model to be continually updated as studies of impacts to new sectors, or updates to outdated sectoral studies become available. Since this work incorporates multiple disciplines, emission projections, climate modeling, impact modeling, and economic communities, it has the potential to be a useful tool in bridging the research gap between these communities and helping to address some of the omitted climate change risks currently within this field (Rising et al., 2022).

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Appendix

Section A1: Extrapolation method(s) past 2090

FrEDI was calibrated to estimate impacts for detailed 21st century scenarios and trajectories, as described in Sarofim et al. (2021). Extending the FrEDI approach to 2300 requires two adjustments to adapt the sensitivity of the model to climate drivers and to socioeconomic conditions beyond the 21st century. First, we consider how the sensitivity to climate drivers (temperatures and SLR inputs) might differ from 21st century conditions. FrEDI damages were originally calibrated for temperatures from 0 to 6-degrees, relative to the 1986 to 2005 era, and SLR for 21st century trajectories that result in 30 to 250 cm GMSL outcomes by 2100. The original framework only returns physical and economic damage estimates within those bounds. In the modified FrEDI framework used within this study, damage estimates for temperature or SLR below those bounds are set to zero, because FrEDI does not consider benefits from reductions in temperatures or sea level relative to the calibration baseline (although FrEDI does consider benefits of warming – for example in the current demonstration of the framework both the Air Quality and Marine Fisheries sectors return benefits of climate change at regional scales across the temperature trajectory examined). Damage estimates for temperature inputs above these bounds are calculated by extrapolating damages per degree using the change in damages between 5 and 6 degrees. SLR inputs above the bounds are extrapolated based on the damages per centimeter of SLR modelled by the two highest sea level scenarios in 2090.

Second, we consider how the sensitivity to socioeconomic drivers continues beyond 2090 through 2300 on a sector-specific basis (the supplement provides a full tabular summary of socioeconomic extensions for all FrEDI sectors). In general, health-based sectors (e.g., extreme temperature mortality) are driven by population which enters linearly; infrastructure sectors (e.g., rail) are driven by population for passenger use and GDP for freight use; and coastal infrastructure is adjusted by expected real property price appreciation, using GDP per capita and income elasticity of 0.45, consistent with the underlying Neumann et al., (2021). For many sectors, economic valuation is a separable process from the overall damage calculation in FrEDI – for example willingness to pay to reduce fatality risk (referred to as the value of statistical life or VSL) is adjusted based on the projection of GDP per capita and a default income elasticity of 1.0. Some sectors – which, in general, make up a small portion of overall damages– are not adjusted for socioeconomic projections but vary based only on sensitivity to projected temperature or sea level.

An additional consideration is FrEDI's application of custom scalars to account for sector-specific physical impact adjustments not directly tied to GDP or population, but that vary through the 21st century and/or over space. For example, some morbidity outcomes are based on baseline incidence rates, while winter recreation activities depend on activity-demand projections. For these scalars, we adopt region-specific 2090 values, which we consistently apply throughout the post-2090 period. This approach--i.e., using the 2090 conditions throughout the

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post-2090 simulation--is also applied for sectors for which FrEDI is calibrated based solely on 2010 and 2090 socioeconomic boundary conditions (rather than as a direct function of varying GDP and population inputs).

The assumption that damages outside of the calibration regime increase linearly at the rate of the increase over the change from 5 degrees to 6 degrees is likely to be a conservative one. Hsiang et al. (2017) found that combined damages in the United States increased quadratically with temperature, and Weitzman (Weitzman, 2012) suggested that while a quadratic damage form might be reasonable for temperature changes up to 2.5 degrees C globally, for higher temperatures it would make sense for damages to increase more quickly, as standard damage functions are unlikely to capture the sheer magnitude of impacts resulting from the kind of dramatic changes the planet would undergo at temperature changes substantially higher than that.

Table A1. Summary of Strategy for Extending FrEDI Sectoral Results from 2090 to 2300 Modeling Horizon. Impact column provides detail for subcategories of impacts estimated within the Framework. Wildfire sector subcategories include morbidity and mortality associated with air quality impacts and fire suppression response costs – these two classes of subcategories are listed separately because they emloy different extension strategies.

Extension Strategy	Sector	Impact	Notes
Impacts scale by Input Population and/or GDP	Air Quality	Ozone	No change to method, continue to scale with input socioeconomic trajectories
		$PM_{2.5}$	
	Extreme Temperature Mortality (Cromar et al., 2022)	N/A	
	Labor	N/A	
	Valley Fever	Mortality	
		Morbidity	
		Lost Wages	
	Water Quality	N/A	
	Wildfire	Morbidity	
		Mortality	
	Winter Recreation	Alpine Skiing	Multiple Impact Years, use 2090 for all years past 2090
		Cross-Country Skiing	
		Snowmobiling	
	Southwest Dust	Acute Myocardial Infarction	
		All Cardiovascular	
		All Mortality	

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		All Respiratory	
		Asthma ER	
Develop New multipliers	Electricity Supply and Demand	N/A	Extend existing scalars linearly past 2090
	Electricity Transmission and Distribution	N/A	
	Roads	N/A	
	Coastal Properties	N/A	New multipliers scale results with GDP or GDP per capita
	High Tide Flooding and Traffic	N/A	
	Rail	N/A	
No Time Dependent Multipliers	Asphalt Roads	N/A	
	Inland Flooding	N/A	
	Urban Drainage	N/A	
	Wildfire	Response Costs	
	Wind Damage	N/A	
	Marine Fisheries	N/A	
	Agriculture	Cotton	
		Maize	
		Soybean	
		Wheat	
	Crime	Property	
		Violent	

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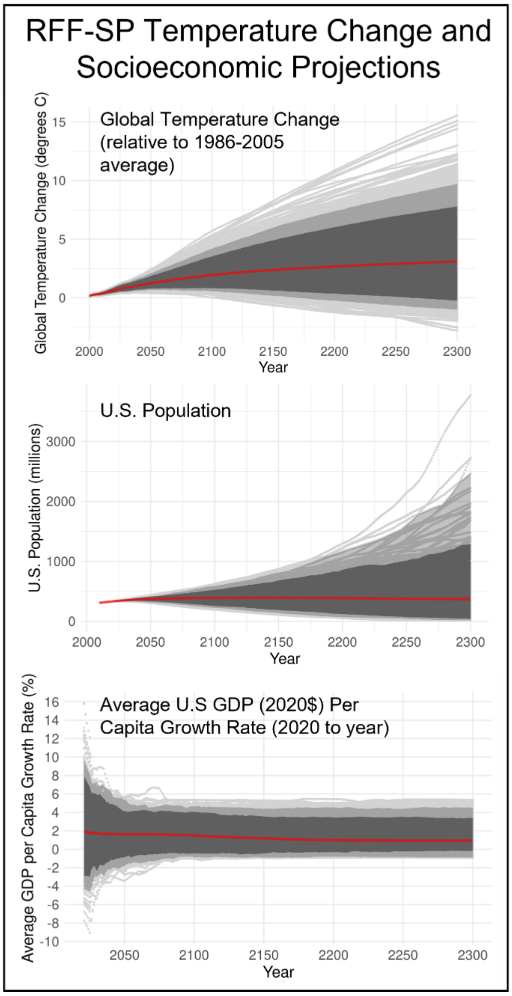

Figure A1. Timeseries of global mean temperature (°C) relative to 1986-2005 baseline, U.S. population (millions), and average U.S. GDP percapita growth rate (2020$) for the 10,000 RFF-SP scenarios from 2020-2300. Temperature trajectories are derived from FaIR model runs of the 10,000 RFF-SP emission scenarios. Individual scenarios are shown by light gray lines. Medium and dark gray shaded regions represent the 99th and 95th percent confidence intervals, respectively. The red line is the mean value overtime.

Section A2: Detailed results to 2090

Table A2. National Annual Damage Statistics (mean and 95% confidence interval) for the year 2090, in billions of 2020 USD, listed alphabetically by Sector

Sector	Category	Default Adaptation or Variant	Impact Type	95% CI ($billion/year)	Mean ($billion/year)
Agriculture	Agriculture	With CO_2 fertilization	Revenue lost from changes in wheat, cotton, soybean, and maize crop yields	$0.42-$19	$6.1

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Coastal Property	Infrastructure	Reactive Adaptation	Damage to coastal property value	$5.9-$21	$9.4
Electricity demand and supply	Electricity	No Adaptation	Increases in power sector costs (e.g., capital, fuel, variable operation and maintenance (O&M), and fixed O&M cost)	$2.4-$21	$11
Electricity transmission and distribution	Electricity	Reactive Adaptation	Damages to transmission & distribution infrastructure	$6.9-$14	$11
Extreme Temperature	Health	No Adaptation	Mortality from changes in hot and cold extreme temperatures	$310 -$9,900	$2300
Hightide Flooding and Traffic	Infrastructure	Reasonably Anticipated Adaptation	Costs of traffic delays from flooding and cost of related infrastructure improvements	$110 -$200	$141
Inland Flooding (residential)	Infrastructure	No Adaptation	Damages from riverine flooding	$0.1-$1.6	$0.74
Labor Allocation	Labor	No Adaptation	Damages from work hours lost	$6.7-$220	$51
Marine Fisheries	Ecosystems + Recreation	No Adaptation	Changes in thermally available habitat for commercial fish species	-$0.1-$0	-$0.06
Long-Term Air Quality Exposure	Health	2011 Precursor Emissions	Mortality from ozone and fine particulate matter exposure	$32 -$9,900	$230
Property and Violent Crime	Health	No Adaptation	Change in the number of Property and Violent crimes	$0.1-$2.0	$0.92
Rail Infrastructure	Infrastructure	Reactive Adaptation	Infrastructure costs associated with temperature-induced track buckling	$7.7-$45	$19
Road Infrastructure	Infrastructure	Reactive Adaptation	Cost of road repair, user costs (vehicle damage), and road delays due to changes in road surface quality	$6.6-$35	$17
Southwest Dust	Health	No Adaptation	Mortality from changes in fine and coarse dust particle exposure	$2.5-$77	$18
Tropical Storm Wind Damage	Infrastructure	No Adaptation	Cost of changes in hurricane wind damage to coastal properties	$12-$49	$28
Urban Drainage	Infrastructure	Proactive Adaptation	Costs of proactive urban drainage infrastructure adaptation	$3.2-$5.0	$4.2
Water Quality	Ecosystems + Recreation		Willingness to pay to avoid water quality changes	$0.83-$3.8	$2.0
Wildfire Air Quality Health Effects and Suppression Costs	Health	No Adaptation	Mortality from wildfire emission exposure and response cost for fire suppression	$8.1-$210	$51
Winter Recreation	Ecosystems + Recreation	Adaptation	Revenue lost from suppliers of alpine, cross-country skiing, and snowmobiling	$0.83-$3.7	$2.0
Valley Fever	Health	No Adaptation	Mortality, morbidity, and lost wages	$2.0-$58	$14

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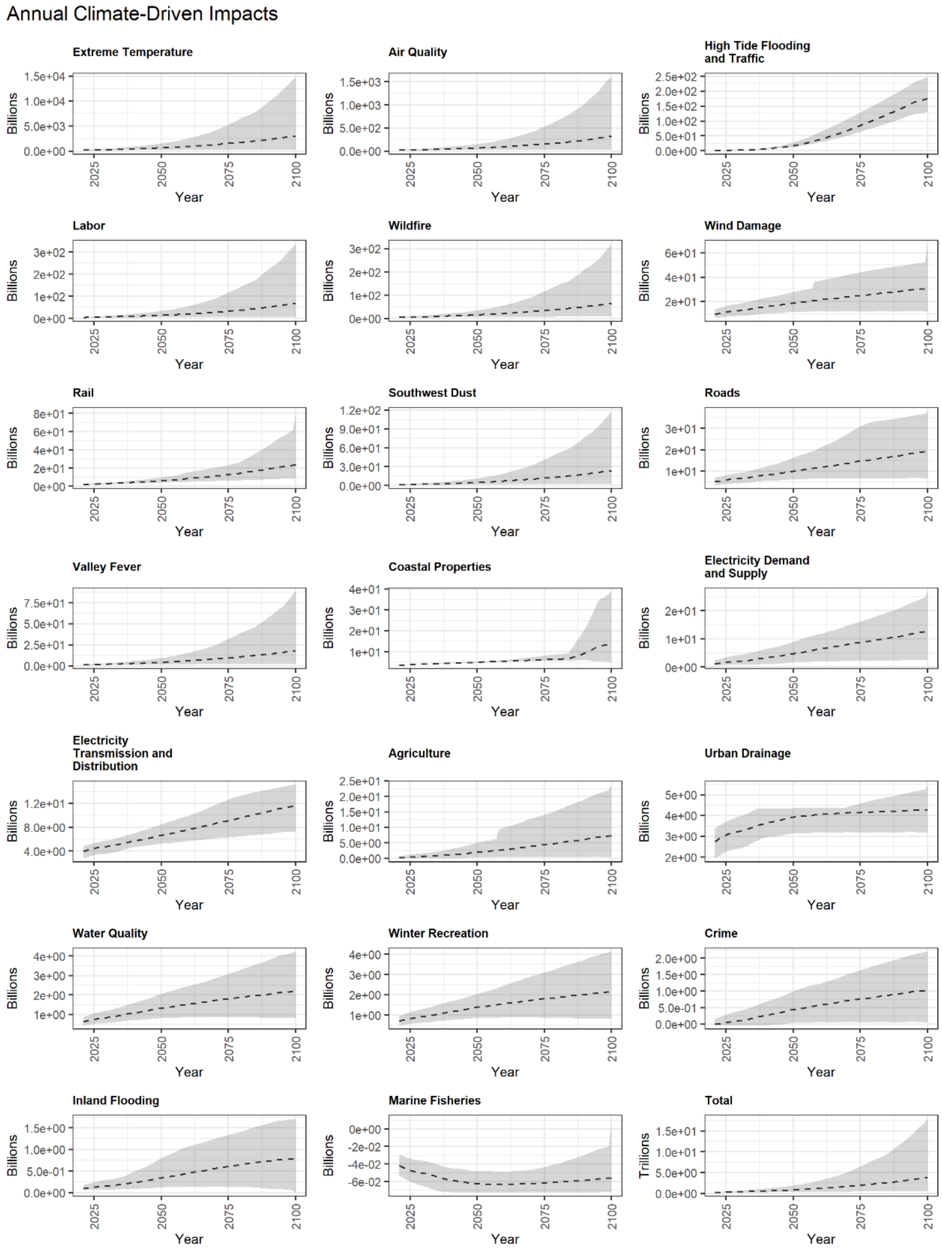

Figure A2. Timeseries of sectoral damages across all 10,000 projections through 2100. Ordered by decreasing mean damages in the year 2090. The lower right panel shows total damages summed across all sectors. Dashed line shows the mean damages each year. Shaded areas show the 95% CI. Annual damages are in units of billions of 2020USD (trillions for total panel).

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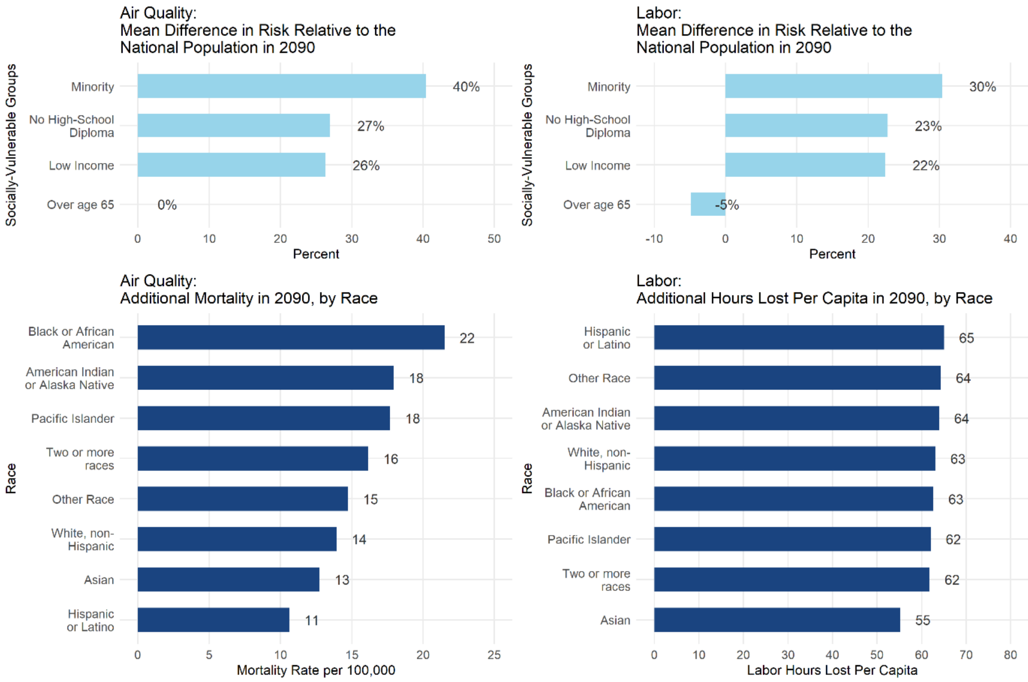

450 **Figure A3: Disproportionate vulnerability to climate-driven changes in air quality attributable mortality and labor hours lost, by race and vulnerable groups in 2090. Top panels) Difference in risk in 2090 for four vulnerable populations. Bottom panels) Additional rates of impacts in 2090, by race.**

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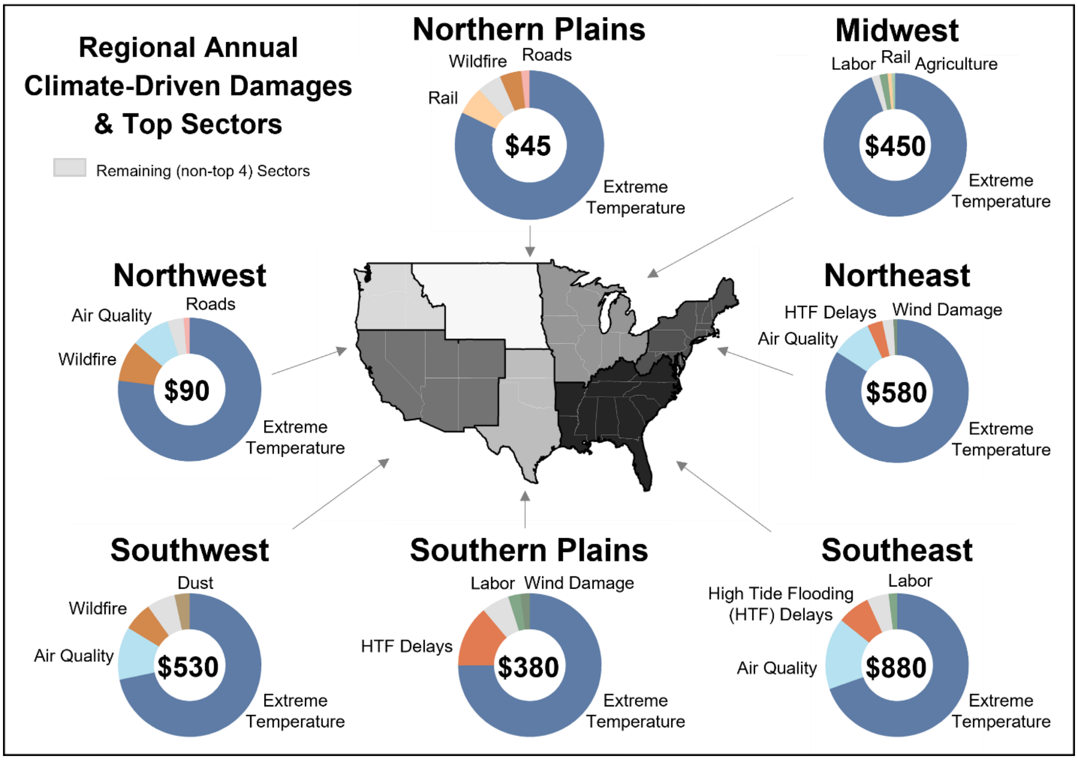

460 **Figure A4. Map of mean total annual climate-driven damages across 10,000 projections in each of the seven U.S. regions in the year 2090 (undiscounted). Damages are in billions of 2020USD. Donut charts show the absolute total damages in each region (in billions) and the top four sectors with the largest annual climate-driven damages. The share of damages from all remaining sectors are shown by the light gray wedge.**

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Section A3: Adaptation Results

FrEDI also has the additional capability to investigate some of these adaptation options in select sectors by reflecting the treatment in the underlying sector studies. Table A3 lists the FrEDI sectors that currently include adaptation options and the climate-driven damages for each in the year 2090. The no adaptation scenario represents a "business as usual" scenario, while 'reactive' or 'reasonably anticipated' adaptation options reflect options taken without advanced warning or foresight, and 'proactive' or 'direct' adaptation reflects damages where cost-effective adaptations are implemented with perfect foresight.

For econometrically based sectors (e.g., Labor), adaptation is included to the extent that adaptation is currently occurring (e.g., work-place safety procedures currently being utilized to protect against extreme temperatures; individual risk/damage avoidance behavior reflected in current practice). For infrastructure sectors (i.e., Rail, Roads, Electricity Transmission and Distribution Infrastructure, Coastal Properties, and High Tide Flooding), a no adaptation approach to infrastructure management does not incorporate climate change risks into the maintenance and repair decision-making process beyond baseline expectations and practice. The infrastructure sectors include two adaptation scenarios, following Melvin et al. (2017): Reactive adaptation, where decision makers respond to climate change impacts by repairing damaged infrastructure, but do not take actions to prevent or mitigate future climate change impacts (a variant on this scenario is the "Reasonably anticipated adaptation" option for the High-Tide Flooding and Traffic sector, which is defined similarly to the Reactive scenario); and Proactive adaptation, where decision makers take adaptive action with the goal of preventing infrastructure repair costs associated with future climate change impacts. This Proactive Adaptation scenario assumes well-timed infrastructure investments, which may be overly optimistic given that such investments have oftentimes been delayed and underfunded in the past, and because decisionmakers and the public are typically not fully aware of potential climate risks (these barriers to realizing full deployment of cost-effective adaptation are described in Chambwera et al., 2014).

Table A3 shows that climate damages are sensitive to assumptions in the adaptation scenarios with mean 2090 annual damages of up to 2 to nearly 500 times larger in proactive or direct adaptation scenarios relative to damages when considering no adaptation. This illustrates adaptation has the capacity to both exacerbate and ameliorate future climate-driven damages.

Table A3: Annual mean (and 95% confidence interval) climate-driven damages in 2090 for sectors that include different adapation options. Damages are in billions of dollars (2020 USD).

Sector	Adaptation Option [A]	Mean ($billions/year)	95% CI ($billions/year)
Electricity Transmission and Distribution	No Adaptation	$12	$7.3-$18
	Reactive Adaptation	$11	$7.0-$14
	Proactive Adaptation	$6.3	$5.0-$8.3
Rail	No Adaptation	$21	$7.2-$55
	Reactive Adaptation	$19	$7.7-$45

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	Proactive Adaptation	\$1.5	\$0.28-\$3.9
Roads	No Adaptation	\$135	\$25-\$330
	Reactive Adaptation	\$17	\$6.6-\$35
	Proactive Adaptation	\$7.3	\$5.8-\$8.4
Coastal Properties	No Adaptation	\$17	\$10.1-\$39
	Reactive Adaptation	\$9.4	\$6.0-\$21
	Proactive Adaptation	\$7.5	\$7.0-\$8.3
High Tide Flooding and Traffic	No Adaptation	\$890	\$680-\$1,200
	Reasonably Anticipated Adaptation	\$140	\$110-\$200
	Direct Adaptation	\$2.0	\$1.3-\$3.4
[A]Default adaptation assumption in FrEDI is the Reactive or Reasonably Anticipated Adaptation variant			

In addition to adaptation scenarios, FrEDI also has the capability to explore the sensitivity of future climate damages to specific changes in additional sectors, including agricultural damages with and without CO_2 fertilization, a lower air quality precursor emissions scenario, and high and low confidence intervals associated with damages specially from extreme temperature mortality. These results are not discussed here, but further illustrate the breadth of information provided by FrEDI.

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Section A4: FrEDI through 2300

As described in the main text, FrEDI is run through 2300 (Figure A5) to calculate the net present damages associated with an additional pulse of 1 tonne of CO_2 in the year 2020. In addition to the Ramsey discounting approach presented in the main text, Figure A6 provides a comparison to the net present damages calculated using a constant discount rate of 3%, consistent with OMB Circular A-4 (White House, 2003).

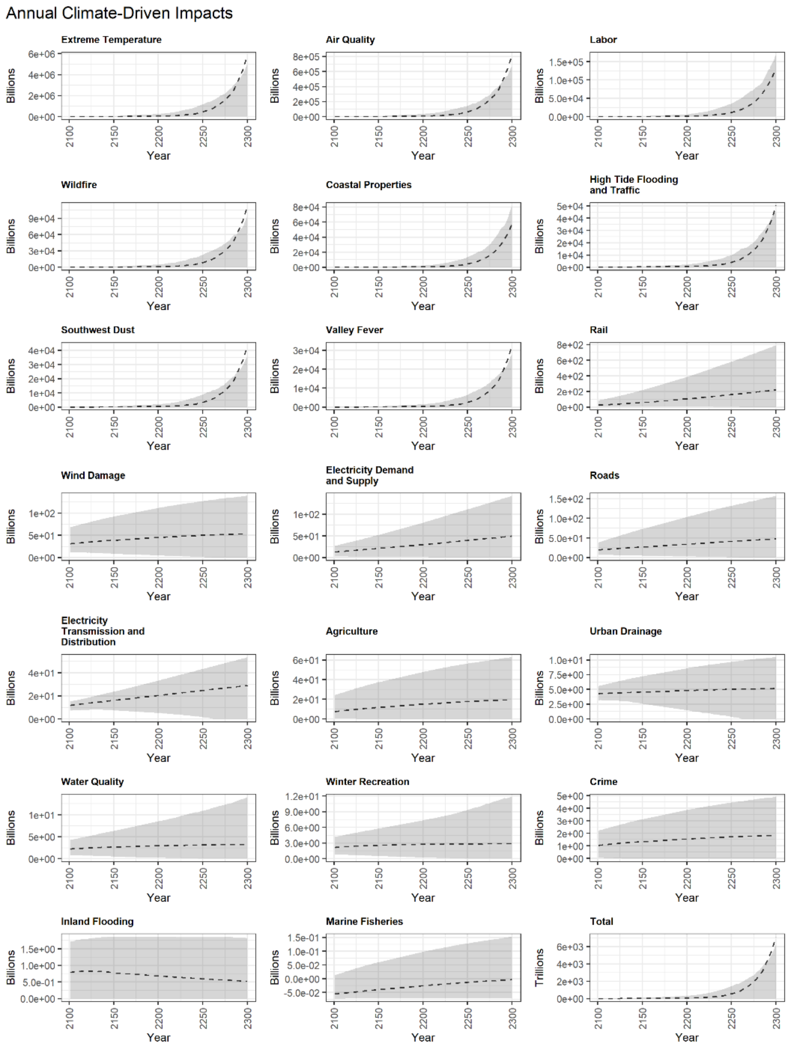

Figure A5. Timeseries of sectoral damages across all 10,000 projections from 2100-2300. Ordered by decreasing mean damages in the year 2300. The lower right panel shows total damages summed across all sectors. Dashed line shows the mean damages each year. Shaded areas show the 95% CI. Annual damages are in units of billions of 2020USD (trillions for total panel).

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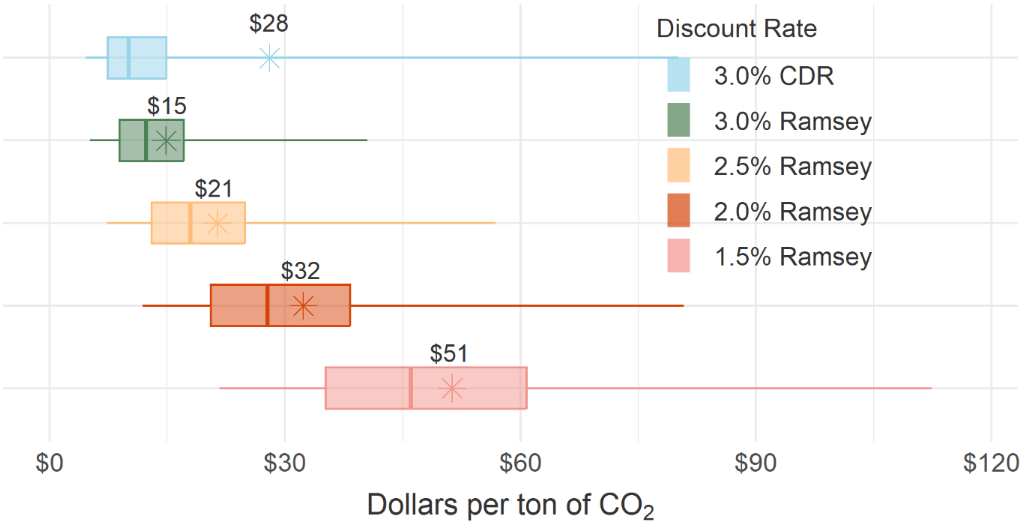

510 **Figure A6. Net present value of future damages from one tonne of CO_2 for damages occuring only within the CONUS. Units are in dollars (2020 USD) per ton of CO_2 emitted. 'CDR' refers to Constant Discount Rate. Whiskers represent the 2.5th and 97.5th percentiles, while boxes span the 25th to 75th. Mean values (stars and text) along with median values (vertical lines) are also shown.**

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Code Availability

The Framework for Evaluating Damages and Impacts (FrEDI) is available on the U.S. EPA Enterprise GitHub https://github.com/USEPA/FrEDI/releases/tag/FrEDI_2300. FaIR is available at https://github.com/OMS-NetZero/FAIR. The RFF SP projections are available at https://zenodo.org/record/6016583 and the SSP projections are available at https://tntcat.iiasa.ac.at/SspDb/.

Data Availability

All code and data associated with this study are available at www.github.com/USEPA/FrEDI_NPD.

Author Contributions

CH, EEM, MS drafted the manuscript text and figures with contributions from all co-authors. BP, EEM, KN, and CH conducted the computational analysis. KN and JW developed the FrEDI code. SB drafted and provided input on graphics and all authors contributed to the writing of this manuscript.

Competing Interests

The authors declare that they have no conflict of interest

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