

Draft Technical Documentation for the Framework for Evaluating Damages and Impacts (FrEDI)

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FRONT MATTER

Acknowledgements

This Technical Documentation was developed by the U.S. Environmental Protection Agency's (EPA) Office of Atmospheric Protection. As described herein, components of the Framework for Evaluating Damages and Impacts (FrEDI) are derived from sectoral impact modeling studies produced by many external academic experts, consultants, and Federal agencies, including but not limited to the Department of Energy (DOE) and the National Ocean and Atmospheric Administration (NOAA). Support for the Technical Documentation and FrEDI code development was provided by Industrial Economics, Inc. EPA gratefully acknowledges these contributions. EPA also gratefully acknowledges the following peer reviewers for their constructive comments and suggestions on the 2021 Technical Documentation.

Preface

The FrEDI Technical Documentation was originally developed in 2021 to describe the underlying theory, design, structure, components, and capabilities of the FrEDI framework and associated open-source code, referred to as the FrEDI R package. This original documentation was subject to a [public review](#) comment period and an independent, external expert peer review, in a process independently coordinated by ICF International and documented at [EPA's Science Inventory](#). The objective of the reviews was to ensure that the information developed by EPA was technically supported, competently performed, properly documented, consistent with established quality criteria, and clearly communicated. Upon completion of both reviews, the initial version of this Technical Documentation was published on October 15, 2021. Appendix A provides more information about the 2021 peer review.

Since initial publication, additional impacts and functionalities have been added to the FrEDI framework. These include additional state-level impact calculations and two modules for extending the FrEDI framework: one module that extends FrEDI temporally to calculate impacts through the year 2300 and a second Social Vulnerability module that extends the dimensionality of FrEDI to provide a distributional analysis of climate change impacts to different populations within the U.S. through 2090. The FrEDI Technical Documentation has been updated accordingly. As described herein, all sectoral impact models underlying the framework have been previously peer reviewed and published in the research literature. This 2024 Draft Technical Documentation is currently undergoing an independent external peer review and a 30-day public comment period. All comments raised during the review period will be published in EPA's Science Inventory and will be considered and addressed in the final 2024 Technical Documentation.

Recommended Citation

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Data and Code Availability

R-code and input/output data for the FrEDI R package are publicly available at the following sites:

- <https://github.com/USEPA/FrEDI> - Main FrEDI R package repository
- https://github.com/USEPA/FrEDI_Data - FrEDI input data repository
- <https://usepa.github.io/FrEDI/> - FrEDI R package webpage

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EXECUTIVE SUMMARY

The Framework for Evaluating Damages and Impacts (FrEDI) is a peer-reviewed, open-source, reduced complexity model that draws on peer-reviewed information to rapidly project the annual impacts of climate change within the United States, through the 21st century, under any custom temperature trajectory. This framework draws on over 30 existing peer-reviewed studies and climate change impact models, including from the U.S. Environmental Protection Agency's (EPA's) [Climate Change Impacts and Risk Analysis \(CIRA\)](#) project, to estimate the relationship between future degrees of warming and associated physical and economic impacts. When supplied with a user-defined temperature trajectory, the FrEDI R code then applies these temperature-impact relationships to rapidly project annual climate change impacts and damages across over 20 impact sectors, geographic regions, and populations through the end of the 21st century. This type of detailed information helps EPA to better understand and communicate the potential impacts and risks from future climate change in the United States, as well as the potential benefits of greenhouse gas mitigation and adaptation. This version of the Technical Documentation also introduces state-level climate impact projections, which furthers EPA's ability to communicate impacts in ways that resonate with a variety of potential audiences. Lastly, FrEDI is also designed as a flexible tool that can be updated to incorporate additional impact categories as relevant studies are published in the peer-reviewed literature. This ensures that FrEDI continues to reflect the latest available scientific information on climate change impacts to the United States.

FrEDI is intended to support analyses coordinated by EPA, however, the framework and its underlying damage functions may be of use to others working in the field. Example applications could include but are not limited to assessments of the distribution of climate change impacts across the United States, impacts of specific greenhouse gas (GHG) emission policies, net present damages per ton of GHG emissions, adaptation impacts, and uncertainties in projected damages from specific impact sectors, among others. The information provided in this Technical Documentation and its Appendices is intended to provide detailed information about the underlying theory, design, structure, components, and capabilities of FrEDI, as well as examples of some of its intended uses and applications.

ONE | INTRODUCTION

The Framework for Evaluating Damages and Impacts (FrEDI) provides a method of estimating the annual physical and economic impacts of climate change within U.S. borders, through the end of the century. This method relies on relationships between future levels of temperature change (or sea level rise) and associated impacts in the contiguous United States (CONUS). These relationships are derived from detailed peer-reviewed models and data from multiple studies on the effects of climate change to specific sectoral impact categories. Resulting ‘impact-by-degree’ damage functions can then be applied to custom scenarios to efficiently project impacts and damages under any custom temperature or emissions pathway. This Technical Documentation outlines the underlying theory, design, structure, components, and capabilities of FrEDI, which is implemented through the application of open-source code, referred to as the FrEDI R package¹, and provides examples of some of the intended applications and uses of annual impact data produced by FrEDI.

1.1 Background Information

The main objective of the framework, implemented through the associated FrEDI R package, is to provide projections of annual physical and economic impacts of climate change in the U.S. through the 21st century under any custom temperature scenario, for a broad range of economically important impact category sectors (e.g., impacts across human health, infrastructure, labor, electricity, agriculture, and ecosystems and recreation).

To enable future impact calculations, FrEDI synthesizes information from over 30 peer-reviewed climate impact studies into a common analytical ‘damage function’ framework. Many of the sectoral damage functions developed for FrEDI were produced using a “temperature binning” method (Sarofim et al., 2021) to relate the effects of warming in the CONUS to monetized damages for each degree of temperature change (EPA, 2017a; Hsiang et al., 2017; Martinich and Crimmins, 2019; Neumann et al., 2020). FrEDI, however, is not limited to studies that use this approach, and has the capacity to incorporate any damage function that relates temperature (either global or national) or global sea level rise to various impacts of climate change. The flexibility of the framework fills an important gap in assessing U.S. climate change impacts by enabling data from a broad range of studies to be incorporated into a common framework as new information becomes available.

FrEDI was originally developed to assess the impacts from climate change on nine sectors² within the U.S. (Sarofim et al., 2021), derived from the second modeling phase of the U.S. EPA’s Climate change Impacts

¹ R is an open-source software available for free download at r-project.org. The FrEDI R package is available for download at <https://github.com/USEPA/FrEDI>.

² The nine sectors in (Sarofim et al., 2021) are Labor, Roads, Extreme Temperature Mortality (Mills et al., 2014), Electricity Demand and Supply, Rail, Coastal Properties, Electricity Transmission and Distribution, Southwest Dust, and Winter Recreation.

and Risk Analysis (CIRA) project³ and its associated technical report (Environmental Protection Agency (EPA), 2021a). In 2021, FrEDI was updated to incorporate data from additional sectoral impact studies completed after the 2017 CIRA report, as well as peer-reviewed studies from other research groups (see Appendix B more information on the included sectoral impact studies). The Technical Documentation describing the 2021 version of the FrEDI R package was subject to an external peer-review and public review comment period. The 2021 documentation described the core functionality of FrEDI including the ability to estimate annual damages across multiple sectors at a subnational level for a defined temperature (or sea level rise) trajectory, drawing on underlying impact-by-degree damage functions. The current version of FrEDI (v4.0) includes these same functionalities, with the addition of more detailed spatial impacts information, additional sectoral impact studies, and additional modules that extend FrEDI's capabilities to assess impacts past 2090 and the differential impacts to various populations across the CONUS. Building on the 2021 Technical Documentation, these additional capabilities are described in detail in this 2024 Documentation.

1.2 Example Applications

The EPA developed this framework and the associated FrEDI R package to provide a quantitative storyline of how the physical and economic impacts of future climate change will impact the U.S., including how these impacts are projected to be experienced differently over time and across regions, sectoral impact categories, and populations. The added benefit of FrEDI's damage function approach is that FrEDI can support the rapid, detailed, and customizable analysis of climate change impacts under any warming or socioeconomic scenario.

Applications of FrEDI are intended to support analysis coordinated by EPA; however, the framework and its underlying damage functions may be of use to others working in the field. For example, FrEDI has been used in a variety of contexts including regulatory impact analyses for recent EPA rulemakings and several national climate impact reports (see the [FrEDI publications page](#) for an up-to-date list of applications).

Applications of FrEDI and its impact data include, but are not limited to:

- **Distributional U.S. climate change impact assessments.** FrEDI output provides quantitative information on the relative and absolute impacts of future climate change to the U.S. under various temperature scenarios, including the distribution of how impacts will be experienced across different regions or states, sectoral impact categories, and populations. Examples are provided in Chapter 3. The computational speed and flexibility of the FrEDI R package also allows users to rapidly assess a large number of future scenarios, as a way to examine various aspects of uncertainty in projected climate change impacts.

³ EPA's CIRA project seeks to quantify and monetize the impacts of climate change across sectors of the U.S., including how risks can be reduced through greenhouse gas mitigation and adaptation actions. CIRA is an ongoing project led by EPA, but with contributions from a large number of sectoral impact modeling teams. More information about the CIRA project, including links to reports and publications, can be found at: www.epa.gov/cira.

- **GHG emission policy impact analysis.** FrEDI can be used in combination with climate emulators, that relate emissions to temperature change, to assess how the magnitude and distribution of future monetized and physical climate-related impacts may change as a result of specific greenhouse gas (GHG) emission policies (U.S. or global). Scenario-specific assessments may be of interest to audiences outside the modeling community, including decisionmakers, planners, and the public. An example analysis of the climate-related impacts associated with an example GHG emissions mitigation scenario is discussed in Chapter 3.
- **Net present damage per ton of GHG emissions.** When run with the relevant temperature projections, the annual stream of monetized damages from FrEDI can be summed and discounted across the time series to assess the climate-related damages to the U.S. per metric ton of GHG emissions change. This information can supplement and complement more aggregate global economic impact estimates derived from integrated assessment models, such as the Social Cost of Greenhouse Gases.
- **Assessment of adaptation impacts.** Several impact categories within FrEDI include options for multiple damage functions that represent different adaptation strategies. These are discussed in Chapter 2. Comparing FrEDI output for different adaptation assumptions can provide information on the sensitivity of future physical and economic damages to different adaptation strategies and assumptions.
- **Assessment of uncertainty in projected damages from specific impact sectors.** For some impacts, FrEDI includes damage functions derived from multiple studies of the same impact category. Comparing results across damage functions from different studies can inform structural uncertainty assessments. Similarly, FrEDI includes damage functions for several impact categories that represent various moments in the estimate distribution, which can also be used to assess modeling uncertainty.
- **Input to other economic impact tools, such as economic macro-models.** FrEDI estimates the direct economic impacts of a wide range of climate and socioeconomic scenarios. The breadth of sectoral scope and capability to provide relevant physical damage metrics (e.g., lost labor hours) also make FrEDI results relevant as input to broader economic macro-models. Such use cases can generate measures of indirect, economy-wide impacts, as well as other metrics of interest, such as GDP impacts, which are not part of FrEDI's core scope. Currently, the outputs of FrEDI require some post-processing and customization for this type of application, for example, to disaggregate direct economic impacts into categories such as capital costs, annual operating and maintenance costs, welfare impacts, and sectoral revenue impacts.

Lastly, while FrEDI provides the most detailed information to date on projected impacts of climate change within U.S. borders, it does not provide a comprehensive accounting of all the ways in which climate

change is expected to impact U.S. residents and their interests, such as through additional impact categories or to assets outside of the CONUS (see Section 2.8 for a discussion of FrEDI Limitations). Therefore, users should carefully interpret FrEDI results with this caveat in mind. Chapter 2 includes a more detailed discussion of framework considerations and limitations with Chapter 3 presents two example applications.

1.3 Comparison of FrEDI to Other Climate Impact Approaches

In contrast to FrEDI, the modeling of climate change impacts has historically typically started with running a set of emissions or concentration scenarios (Hayhoe et al., 2017; Intergovernmental Panel on Climate Change (IPCC), 2014; IPCC, 2020; Meinshausen et al., 2011; Riahi et al., 2017; Taylor et al., 2012) through complex earth system models, followed by using the temperature and precipitation outputs of those climate models as inputs to sector-specific impacts models. Scenario-based analysis has been the “gold-standard” approach to projecting future climate impacts for several decades and has successfully served as the backbone of international and federal climate assessments and special reports (e.g., IPCC, 2018; USGCRP, 2018), modeling intercomparison efforts (e.g., Eyring et al., 2016; Knutti and Sedláček, 2013; Warszawski et al., 2014), and individual modeling studies. The Representative Concentration Pathways (RCP) (Moss et al., 2010) and the Shared Socioeconomic Pathways (SSP) (Riahi et al., 2017) are two commonly used products that provide projections over the 21st century of possible future climates ranging from low to high greenhouse gas concentrations and radiative forcing, allowing for economic modeling to proceed concurrently with, rather than sequential to, physical scientific modeling (van Vuuren et al., 2014). However, there are some important limitations and challenges to relying primarily on the traditional scenario-based approach for driving climate impacts analysis. One difficulty is that it is challenging to develop a comprehensive set of scenarios that explore all potential futures. In addition, different research groups and individual assessments choose to focus on different scenarios, which make it difficult to compare results from across different studies or those that focus on different impact sectors. Therefore, the ‘impacts-by-degree’ temperature framework employed within FrEDI and used by other studies and assessments (e.g., Sarofim, et al., 2021, Schleussner et al., 2016) allows for characterizing changes that track with temperature, rather than complex scenarios, which allows for more direct comparability across sectoral impacts and provides a more intuitive result for non-technical audiences, while still allowing for the rapid assessment of any custom temperature trajectory.

Similar to FrEDI, work by researchers affiliated with the Climate Impact Lab (CIL)⁴ is also focused on estimating economic impacts of climate change for the U.S. using a damage function approach (e.g., Houser et al., 2015; Hsiang et al., 2017). As with some of FrEDI’s damage functions, the CIL’s sectoral analyses generally rely on interpretation of historical data to identify and develop damage function relationships between climate metrics or events and the economic impacts that result, which are then used to project

⁴ The Climate Impact Lab is collaboration of more than 25 climate scientists, economists, computational experts, researchers, and students from a number of research institutions. The Lab works to build a body of research quantifying the impacts of climate change, sector-by-sector, and community-by-community around the world. More information about the Lab’s research and publications can be found at: <https://impactlab.org/>

economic impacts for future climate and event forecasts. Multiple sectoral impacts from the CIL's work are currently included in FrEDI (i.e., Temperature-Related Mortality, Agriculture, and Crime). However, FrEDI's flexibility also allows the framework to accommodate different types of study methodologies, thereby enabling comparisons of structural uncertainties across different impact models of the same sector.

Many studies beyond the CIL have also simulated the impacts of climate change on various socio-economic outcomes within the U.S. However, many of these studies use distinct climate or socio-economic scenarios that are incompatible with each other, or report outcomes in units that require further processing to be comparable across sectors. In addition, many of the underlying impact models often require specialized, sector-specific knowledge to run or, in some cases, may require substantial computational resources, making them inaccessible for a typical user. FrEDI is intended to bridge this gap by processing different methods and studies for use in a common framework so that users can explore impacts across multiple sectors in a standardized way, while also being able to explore the effects of temperature, socioeconomic, and adaptation scenarios of interest.

Lastly, another class of economic impact estimation tools are integrated assessment models (IAMs), designed for damage estimation (e.g., PAGE, RICE and DICE, FUND, IMAGE). These IAMs contain relationships between temperature and damages, with a range of geographic and sectoral resolutions, and temporal scopes (typically beyond 2100). Nordhaus and Moffat (2017) and Diaz and Moore (2017) recently assessed the damage function representation in these models in the context of the broader literature. Some IAMs are used to identify an economically optimal GHG mitigation pathway which balances marginal costs of GHG abatement with marginal costs of GHG damage. To do so, marginal abatement cost functions (and GHG offset pools and their costs) are needed, and a means for translating GHG emissions into temperature pathways. These damage estimation IAMs are generally global in scope, although some estimate impacts at regional scales. FrEDI, by contrast, does not address emission abatement costs, focusing only on damage estimation, and, in this application, only for the U.S. region. Therefore, FrEDI provides an efficient and transparent damage estimation approach that operates independently of IAMs and adds the flexibility to use other means of determining temperature trajectories. By also relying on a relatively rich, recent, and peer-reviewed set of economic damage functions, FrEDI can help in responding to relevant policy questions by estimating the effects of an incremental policy to reduce GHGs, and thereby complement the types of analysis and outputs provided by IAMs.

TWO | THE FRAMEWORK

This Chapter describes the underlying theory, design, structure, components, and capabilities of FrEDI, including how this framework is implemented as the FrEDI R package. Sub-sections in this Chapter include: an overview of the FrEDI methodology (Section 2.1), a description of FrEDI's current impact category sectors (hereafter called 'sectors'), geographic scope, and sector variants (Section 2.2), an overview of the pre-processing steps used to incorporate peer-reviewed climate model and impact information into FrEDI's 'impacts-by-degree' analytical framework (Section 2.3), a description of the FrEDI R package runtime processes (Section 2.4), additional FrEDI modules and capabilities (Section 2.5), an overview of the approach used to incorporate new sectors and studies into FrEDI (Section 2.6), uncertainties within FrEDI (Section 2.7), and key limitations of this framework (Section 2.8).

2.1 Overview

FrEDI is a reduced complexity model that uses an 'impacts-by-degree'⁵ damage function approach to rapidly relate changes in future temperature or sea level rise (SLR) to future climate change impacts to the U.S. at annual timesteps across the 21st century (2010-2090).⁶ FrEDI also simultaneously accounts for projected changes in socioeconomic conditions (e.g., U.S. population and Gross Domestic Product or GDP) through the incorporation of additional year-specific scalars. These scalars allow for annual temperature- and SLR-driven impacts to be adjusted to account for socioeconomic changes over time, such as increasing population or wage rate.

As described in Section 2.2, FrEDI currently projects annual climate-related impacts in over 20 impact category sectors and in seven regions of the CONUS. Impacts from several sectors are also projected at the state level⁷. Sector-specific variants that are derived from the underlying impact studies are also built into FrEDI to allow for the additional assessment of various sector-specific adaptation options and differences across different impact types, as described further in Section 2.2.

As described in Section 2.3, peer-reviewed climate impact information is incorporated into FrEDI by first breaking down the study data into various elements of an impact function. These include 1) temperature-driven components, i.e., the simplest form of the damage function that defines the relationship between impacts and temperature, and 2) time-dependent components, i.e., direct and indirect links to population, GDP, and demographic composition. The components are then used in the pre-processing stage to develop

⁵ The term 'impacts by degree' should be interpreted to include 'impacts by sea level rise increment' for the select sectors where impacts are driven by sea level rise (i.e., Coastal Property and Transportation Impacts from High Tide Flooding).

⁶ FrEDI's primary estimator calculates impacts through 2090. The package contains a module to project results through 2300, as described in Section 2.5.

⁷ As of 2/23/24, 12 sectoral impact categories are estimated in FrEDI at the state level. Using the same methodologies employed in this set, the remaining sectoral impacts will be converted to state level upon final publication of this 2024 Technical Documentation.

by-degree damage functions and year-specific socioeconomic scalars that are incorporated into configuration data for use by the FrEDI R package during runtime.

When the FrEDI R package is run, FrEDI combines these two components (i.e., temperature or SLR-driven impact functions and time-dependent impact scalars) with input annual temperature and socioeconomic (i.e., population and GDP) trajectories to calculate the physical and economic impacts of climate change each year across different U.S. geographic regions and sectoral impact categories. Users can provide custom trajectories of temperature change and socioeconomic conditions or may choose to run FrEDI with its default⁸ temperature, population, and GDP trajectories. Section 2.4 provides additional methodological details underpinning these runtime processes.

A summary of the FrEDI methodological framework is shown in **Figure 1**.

FIGURE 1. FREDI FRAMEWORK SUMMARY

Pre-Processing	Sectoral Impact Model Data Pre-Processing	Data from underlying impact sector models are processed to produce impacts functions for use in FrEDI. This process is completed once per sector and pre-loaded into the FrEDI R package for use in analyses. The specific processing steps depend on the input data but may involve aggregating to regions or states, removing baseline impacts, pulling out year-specific adjustment factors, and binning impacts by degree. (See Section 2.3 and Appendix B).
FrEDI Runtime Processes (Implemented in FrEDI R Package)	Climate Input Processing	FrEDI converts global temperature trajectory provided as input into CONUS temperature trajectory and global SLR height trajectory to match the indices used in the damage by degree damage functions (See Section 2.4 and Appendix C).
	Impact Evaluation	FrEDI uses processed climate inputs to look up impacts by degree in the processed impact damage functions and adjusts for timing and socioeconomic scenarios using the time-series of scalars and socioeconomic multipliers (See Section 2.3).
Post-Processing	Post-Processing Analyses	Results from FrEDI can be used to analyze expected impacts of a defined emissions pathway, calculate benefits of emission reduction against a reference scenario, or used as inputs for economy-wide models, among other uses (See Chapter 3 for example applications).

Summary of the FrEDI framework, including pre-processing sectoral data, impact calculations, and post-processing and analysis. References in each component identify the relevant sections in this report for more information.

Section 2.5 continues on to describes additional user-defined runtime options that are not core to FrEDI’s default capabilities but can be selected to 1) extend FrEDI damage functions to higher temperatures to enable projections of climate change impacts through the year 2300 or 2) run FrEDI’s ‘Social Vulnerability’ module, which uses information from EPA’s Climate Change and Social Vulnerability Report (Environmental Protection Agency (EPA), 2021b) to additionally project impacts of climate change in six sectors across different population groups of concern within the United States.

⁸ See Section 2.4 for more information about default trajectories employed in FrEDI

Section 2.6 follows by providing additional details on the general process for continued incorporation of additional sectoral information into the FrEDI R package. This framework allows for the flexibility and ease of being able to incorporate additional information as new scientific information becomes available, which provides FrEDI with the unique capability to synthesize the latest scientific impact information from a broad range of bottom-up sectoral studies.

Lastly, Sections 2.7 and 2.8 provide additional discussion of key uncertainties and limitations.

2.2 Current Sectoral Impacts

This section describes the impact coverage (i.e., sectoral, adaptation scenario, and geographic coverage) included in FrEDI. Because of FrEDI's flexible framework, coverage across these dimensions will continue to be expanded as new impact studies are identified and incorporated.

Sectoral Impact Categories

FrEDI currently includes 25 sectoral impacts, many with multiple adaptation scenarios and sub-impact types, as shown in **Table 1**. This list will continue to evolve as new sector studies are published and processed for use in FrEDI (see Section 2.6 for a description of this approach). When run, FrEDI outputs an array of physical and economic impacts for each sector, region (or state), and year that are associated with the input temperature and socioeconomic trajectories. These results are also disaggregated into impacts for each impact type or adaptation (or other variant) option. See Appendix B for more details on the sectors currently processed for FrEDI, including full citations for the underlying studies. EPA will update relevant components of this Technical Documentation as additional sectoral studies and impacts are added to the FrEDI R package.

TABLE 1. SUMMARY OF IMPACT CATEGORY SECTORS IN FREDI

Gray shaded rows are alternate estimates for a particular sector and are not included as default in FrEDI. More details on the underlying studies can be found in Appendix B.

Aggregate Category: Impact Category Sector (study reference) ^a		Impact Types ^b	Adaptation or Variant Scenarios ^{c,d}	Spatial Scale of Underlying Data ^e	Spatial Level in FrEDI ^f
HEALTH					
Climate-Driven Changes in Air Quality (Fann et al., 2021)		<ul style="list-style-type: none"> Ozone Mortality Particulate Matter (PM) 2.5 Mortality 	<ul style="list-style-type: none"> 2011 Air Pollutant Emissions Level 2040 Air Pollutant Emissions Level 	State	State
Temperature Mortality	Extreme Temperature (Mills et al., 2015)	<ul style="list-style-type: none"> Heat-related mortality (VSL) Cold-related mortality (VSL) 	<ul style="list-style-type: none"> No Additional Adaptation Adaptation, using the bounding assumption that all cities exhibit an extreme heat response function consistent with the historical response of the city of Dallas 	City (sample of 50 major cities)	Region

Aggregate Category: Impact Category Sector (study reference) ^a		Impact Types ^b	Adaptation or Variant Scenarios ^{c,d}	Spatial Scale of Underlying Data ^e	Spatial Level in FrEDI ^f
	CIL Temperature- Related Mortality^g (Hsiang et al., 2017 citing Barreca et al., 2016; Deschênes and Greenstone, 2011)	<ul style="list-style-type: none"> Net heat- and cold-related mortality (VSL) 	<ul style="list-style-type: none"> No Additional Adaptation Median No Additional Adaptation Low (5th percentile) No Additional Adaptation High (95th percentile) 	State	Region
	ATS Temperature- Related Mortality^g (Cromar et al., 2022)	<ul style="list-style-type: none"> Net heat- and cold-related mortality (VSL) 	<ul style="list-style-type: none"> No Additional Adaptation Mean No Additional Adaptation Low (approximate 5th percentile) No Additional Adaptation High (approximate 95th percentile) 	County	State
Southwest Dust (Achakulwisut et al. 2019)		<ul style="list-style-type: none"> All Mortality All Respiratory Morbidity All Cardiovascular Morbidity Asthma ER Acute Myocardial Infarction Morbidity 	<ul style="list-style-type: none"> No Additional Adaptation 	Southwest Region	Region
Valley Fever (Gorris et al., 2021)		<ul style="list-style-type: none"> Morbidity - Hospitalization Costs Morbidity – Lost Productivity Mortality 	<ul style="list-style-type: none"> No Additional Adaptation 	State	Region
Wildfires (Neumann et al., 2021a)		<ul style="list-style-type: none"> Morbidity from air quality (hospitalization costs and lost productivity) Mortality from air quality Response Costs 	<ul style="list-style-type: none"> No Additional Adaptation 	County	State
CIL Crime^g (Hsiang et al., 2017) citing (Heaton P., 2010; Jacob et al., 2007; Ranson, 2014)		<ul style="list-style-type: none"> Violent crime value Property crime value 	<ul style="list-style-type: none"> No Additional Adaptation 	State	Region
Vibriosis (Sheahan et al., 2022)		<ul style="list-style-type: none"> Morbidity - Hospitalization Costs Morbidity – Lost Productivity Mortality 	<ul style="list-style-type: none"> No Additional Adaptation 	County	Region
Suicide (Belova et al., 2022)		<ul style="list-style-type: none"> Mortality from suicide 	<ul style="list-style-type: none"> No Additional Adaptation 	County	State
INFRASTRUCTURE					
Coastal Properties (SLR) (Neumann et al., 2021b) & (Lorie et al., 2020)		<ul style="list-style-type: none"> Costs related to armoring, elevation, nourishment, and abandonment (including storm surge impacts) 	<ul style="list-style-type: none"> No Additional Adaptation Reactive Adaptation Proactive Adaptation 	County	Region
Transportation Impacts from High Tide Flooding (SLR) (Fant et al., 2021)		<ul style="list-style-type: none"> Traffic delays, road elevation costs 	<ul style="list-style-type: none"> No Additional Adaptation Reasonably Anticipated Adaptation Direct Adaptation 	County	State
Hurricane Wind Damage^g (Dinan, 2017) with Congressional Budget Office (CBO) (2016) & Marsooli et al. (2019)		<ul style="list-style-type: none"> Property damage 	<ul style="list-style-type: none"> No Additional Adaptation beyond currently implemented wind risk mitigation at property level 	County	State

Aggregate Category: Impact Category Sector (study reference) ^a		Impact Types ^b	Adaptation or Variant Scenarios ^{c,d}	Spatial Scale of Underlying Data ^e	Spatial Level in FrEDI ^f
Inland Flooding (Wobus et al., 2021, 2019)		<ul style="list-style-type: none"> Property damage 	<ul style="list-style-type: none"> No Additional Adaptation beyond currently implemented flood protection measures at property and collective level 	Census Block Group	Region
Rail (Neumann et al., 2021b) citing (Chinowsky et al., 2019)		<ul style="list-style-type: none"> Repair (including equipment and labor) and delay costs 	<ul style="list-style-type: none"> No Additional Adaptation Reactive Adaptation Proactive Adaptation 	Half-degree grid	State
Roads	All Roads (Neumann et al., 2021b) citing (Neumann et al., 2015)	<ul style="list-style-type: none"> Road repair, user cost (vehicle damage), and delay costs 	<ul style="list-style-type: none"> No Additional Adaptation Reactive Adaptation Proactive Adaptation 	Quarter degree grid	Region
	Asphalt Road Maintenance^g (Underwood et al., 2017)	<ul style="list-style-type: none"> Asphalt road surface repairs, temperature stress only 	<ul style="list-style-type: none"> No Additional Adaptation 	Weather Station	State
Urban Drainage (Price et al., 2016)		<ul style="list-style-type: none"> Upgrading urban stormwater infrastructure 	<ul style="list-style-type: none"> Proactive Adaptation 	City (100 cities in 34 states)	State
ELECTRICITY					
Electricity Demand and Supply (McFarland et al., 2015)		<ul style="list-style-type: none"> Power sector costs 	<ul style="list-style-type: none"> No Additional Adaptation 	State	State
Electricity Transmission and Distribution Infrastructure (Fant et al., 2020)		<ul style="list-style-type: none"> Repair or replacement of transmission and distribution lines, poles/towers, and transformers 	<ul style="list-style-type: none"> No Additional Adaptation Reactive Adaptation Proactive Adaptation 	County	State
ECOSYSTEMS & RECREATION					
Water Quality (Fant et al., 2017) with (Boehlert et al., 2015; Yen et al., 2016)		<ul style="list-style-type: none"> Lost recreational value 	<ul style="list-style-type: none"> No Additional Adaptation 	HUC-8	Region
Winter Recreation (Wobus et al., 2017)		<ul style="list-style-type: none"> Lost snowmobiling revenues Lost alpine skiing revenues Lost cross country skiing revenues 	<ul style="list-style-type: none"> No Additional Adaptation (defined by snowmaking for alpine skiing) 	State	Region
Marine Fisheries (Moore et al., 2021) & (Morley et al., 2018)		<ul style="list-style-type: none"> Lost value of marine fisheries landings 	<ul style="list-style-type: none"> No Additional Adaptation 	State	Region
LABOR					
Labor (Neidell et al., 2021)		<ul style="list-style-type: none"> Lost Wages 	<ul style="list-style-type: none"> No Additional Adaptation 	County	State
AGRICULTURE					
CIL Agriculture^g (Hsiang et al., 2017) citing Hsiang et al. (2013); McGrath and Lobell (2013); Schlenker and Roberts (2009)		<ul style="list-style-type: none"> Lost wheat production value Lost maize production value Lost soybeans production value Lost cotton production value 	<ul style="list-style-type: none"> With CO2 fertilization Without CO2 fertilization 	State	Region

Aggregate Category: Impact Category Sector (study reference) ^a	Impact Types ^b	Adaptation or Variant Scenarios ^{c,d}	Spatial Scale of Underlying Data ^e	Spatial Level in FrEDI ^f
<p>Notes:</p> <ul style="list-style-type: none"> a. References for the underlying studies are listed in the first column, the aggregate categories correspond to those in figures presented in Chapter 3. In cases where the framework includes multiple sectoral models (i.e., roads and temperature-related mortality), the shaded study rows are not considered the default FrEDI sectors and are excluded from summaries in the default settings to avoid double counting of impacts. b. Impact types refer to the sub-impacts processed for the framework and available as outputs in the framework. c. Available adaptation or other variant options available for each sector are listed in the third column (the bold variant is the default reported in FrEDI outputs). d. The two emissions levels in the underlying Air Quality study are not strictly adaptation scenarios, however they are entered into the framework using the same structure. Emissions scenarios for PM_{2.5} and ozone precursor pollutants are independent of GHG mitigation and temperature trajectory scenarios, although it is true that GHG mitigation would likely lead to changes in co-emitted PM_{2.5} and ozone precursors. CIL Agriculture also has two variants represented in the Adaptation/Variants column. e. The fourth column indicates whether impacts for that sector are currently calculated within FrEDI at the state or region level. f. As of 2/23/24, 12 sectoral impact categories are estimated in FrEDI at the state level. Using the same methodologies employed in this set, the remaining sectoral impacts will be converted to state level upon final publication of the 2024 Technical Documentation. g. Non-CIRA study. Non-CIRA studies are from the peer-reviewed literature and are processed the same way as CIRA-studies; however, they may not follow the same consistent framework assumptions as the CIRA-studies (GCM ensemble modeled, population assumptions, etc.). 				

Most of the sectors currently processed for FrEDI are temperature driven. Temperature-driven impacts within FrEDI use impact-by-degree damage functions and are indexed to projected U.S. temperatures. Note, however, that the relationship between climate and impacts in the underlying models often includes other factors in addition to temperature, such as precipitation. Other sectors in FrEDI Table 1 are driven by sea level rise (SLR). Impacts in these sectors are indexed to centimeters of projected global mean sea level rise (GMSL).

To account for potential overlap in impacts between sectors (e.g., All Roads and Asphalt Road Maintenance, or multiple studies of temperature-related mortality), select studies are identified in FrEDI’s output array as the priority measure (or default) for each sector (non-default sectors studies are shaded gray in Table 1). Similarly, for impacts with multiple variants or adaptation options, one variant is identified as the default to be included in any aggregated outputs of FrEDI (default variants are bold in Table 1). Note that there is still a small possibility of double-counting sectors with similar impact mechanisms. For example, three of the sectoral analyses listed in Table 1 (Air Quality, Wildfires, and Southwest Dust) estimate the health impact of exposure to fine particulate matter (PM_{2.5}). Each of these studies uses epidemiological functions which depend on a baseline PM_{2.5} estimate, presenting the possibility of inconsistency and/or double counting. Inconsistencies are avoided by using the same PM_{2.5} baseline data across all three studies. The non-linear nature of the epidemiological function, however, could imply some double-counting of benefits, but any issue with double-counting should be small as the relevant concentration-response function is nearly linear at PM_{2.5} concentrations typically encountered in the U.S. Additional details on the geographic scope and description of variants and adaptation options are described below.

Adaptation Options/Variants

The framework accounts for adaptation by reflecting treatment of adaptation in the underlying sectoral studies, grouped by an adaptation nomenclature adopted in the 4th national Climate Assessment (NCA) (reactive and proactive adaptation responses – see Lempert et al. (2018) for example). The third column in

Table 1 identifies the available adaptation scenarios for each sector currently in the framework. The available adaptation options fall in three categories, one reflecting current adaptation actions and two reflecting the impact of additional actions and investments in response to emerging climate hazards:

- **No additional adaptation.** The no additional adaptation scenario represents a “business as usual” scenario, but incorporates adaptive measures and strategies reflected in historical actions to respond to climate hazards. For econometrically based sectors (e.g., Labor), adaptation is included to the extent that adaptation is currently occurring. For infrastructure sectors (i.e., Rail, Roads, Electricity Transmission and Distribution Infrastructure, Coastal Properties, and Transportation Impacts from High Tide Flooding), a no additional adaptation approach to infrastructure management does not incorporate climate change risks into the maintenance and repair decision-making process beyond baseline expectations and practice.
- **Adaptation.** The adaptation scenario explicitly accounts for some climate change-induced behavioral change in response to changing climate. Currently, 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 Transportation Impacts from High Tide Flooding 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).

The adaptation options in FrEDI are based on scenarios and information included in the underlying sector impact studies. An absence of adaptation variants for certain sectors means that the underlying literature does not separately identify impact estimates that vary by projected adaptation effort, although in most cases some default specification of adaptation to climate hazards is included in the underlying study. To the extent that new and emerging literature addresses the dimension of multiple levels of human and natural system acclimation to future climate, as well as adaptation effort and investment uncertainty, future additions to FrEDI can reflect this additional information.

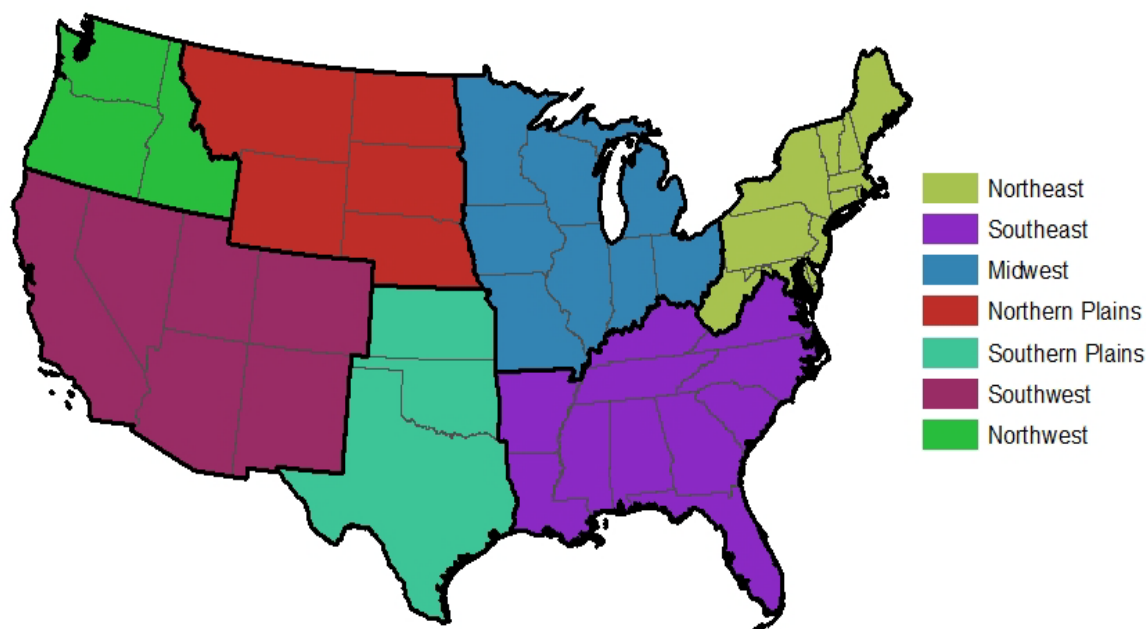
The general adaptation scenarios considered in the framework will not capture the complex issues that drive adaptation decision-making at regional and local scales. As such, the adaptation scenarios and estimates should not be construed as recommending any specific policy or adaptive action.

Also note that in some cases, the “Variant” scenario field in the FrEDI output array is used to describe a sector variant rather than a true adaptation scenario. For example, the CIL Agriculture sector includes results with and without a CO₂ fertilization treatment, which is not an adaptation scenario. In another example, the ATS Temperature-Related Mortality sector includes results from the mean, high and low confidence intervals, which are also not adaptation scenarios, but reflect uncertainty in the underlying study data. The same field is used for both adaptation scenarios and other types of variants to streamline the coding of the FrEDI R package.

Geographic Scope

While this document refers to “U.S.” climate-related impacts, FrEDI results currently include the 48 contiguous states (CONUS).⁹ FrEDI results are currently processed and presented at the regional levels used in the 4th and 5th National Climate Assessment (NCA) of the U.S. Global Change Research Program (see **Figure 2**). Impacts for several impact categories are calculated at the state level.^{10,11} State-level impact calculations enhance FrEDI’s ability to communicate the risks of climate change to the American public and can be summed to the NCA region and national levels for direct comparisons with other regional estimates. FrEDI uses NCA regions and states for consistency, however there is no methodological reason another spatial scale could not be used (e.g., counties). The pre-processing and runtime procedures described in Sections 2.3 and 2.4 are applied in the same manner regardless of the spatial scale of the estimates.

FIGURE 2. NATIONAL CLIMATE ASSESSMENT (NCA) REGIONS



Map of seven NCA regions of the U.S. Global Change Research Program.

⁹ Efforts are underway to assess the availability of data needed to expand the geographic scope of FrEDI to include Alaska, Hawai’i, and Puerto Rico.

¹⁰ See **Table 1** for an identification of the sectors calculated by state.

¹¹ CONUS state level results include 48 states and the District of Columbia.

Table 1 presents the spatial scale of the underlying data pre-processed for use in FrEDI. Currently, all sectors within FrEDI have underlying data at the subnational level, with most sectoral studies reporting estimates by administrative boundaries (e.g., county, state, zip code) that sum cleanly to states and regions and do not require any weighting. Physical boundaries, such as Hydrological Unit Codes (HUCs)—common in water resource models or grid-based results, can also be attributed to regions or states using spatial weighting to account for areas that span regions or states. For example, the underlying data from the Roads sector is at a quarter degree grid scale. Grid-level results are allocated to regions or states via spatial weighting. It is not necessary for a sector study to include all states or regions to work in FrEDI. Southwest Dust and Winter Recreation, for example, are two studies that are limited to specific regions of the U.S., as are the SLR-driven sectors. Similarly, sectoral impact studies that only produce national estimates can also be used in the framework, either to produce national results or with impacts allocated across regions and states using a proxy scalar such as population. Aggregate national impacts are calculated by summing over the seven regions or 48 states.

2.3. Underlying Data Configuration & Pre-processing

Developing FrEDI Damage Functions

FrEDI evaluates climate impacts for the U.S. at annual timesteps across the 21st century by using information from pre-processed ‘impact-by-degree’ damage functions. Damage functions are sector-specific functions that define the estimated climate-related physical or economic impacts to that sector by each degree of future warming, which can then be applied to any user-input temperature and socioeconomic trajectories when the FrEDI R package is run. The temperature and SLR damage functions in FrEDI are not specifically designed for estimating effects of cooling, or negative changes in temperature, relative to the baseline period, however, impacts are also not required to increase with temperature or sea level rise. Thus, FrEDI has the capability to assess both positive and negative effects of climate change in each sector and region or state in each year.

To speed up runtime processes, a series of pre-processing steps (described in the Section) are used to develop these regional or state, sector-specific damage functions from peer-reviewed impact studies and models. These damage functions are stored in FrEDI configuration data that are then called during runtime and used to relate the level of warming (or cm of sea level rise)¹² in each year of the input trajectory to the resulting projected impacts. These initial impacts (e.g., impacts per capita, impacts per road mile) are then scaled or adjusted for additional time-dependent aspects of the impact function (e.g., demographic shifts and energy demand shifts) based on input socioeconomic trajectories. To incorporate impact studies into FrEDI in this way, underlying study data must be 1) available by degree of warming or centimeters of sea level rise, 2) attributable to sub-national regions (NCA region) or states, and 3) account for sector-specific, tailored socioeconomic scalars (to allow for custom scenario inputs, where possible) or other time-dependent factors, where applicable. These details are discussed below.

¹² While FrEDI currently only includes temperature- and SLR-driven damages, the framework could easily be extended to other stressors such as ocean acidification and methane emissions or concentrations.

Temperature-Driven Damages

Damage functions for FrEDI's temperature-driven sectors are developed by conducting a temperature binning analysis of existing peer-reviewed climate impact studies. As described more fully in Sarofim et al., (2021), the basic concept of temperature binning is to identify the arrival year of a given amount of CONUS warming (e.g., 1°, 2°, 3°C, etc.) for the specific general circulation model(s) (GCM) used in each underlying sectoral impact study, relative to a common baseline period (e.g., 1986-2005). Temperatures used in FrEDI are therefore temperature anomalies from the baseline era, referred to in this Documentation as temperature change (ΔT) or degrees of warming. While any method of developing impact-by-degree functions is suitable for FrEDI, indexing impacts to CONUS degrees of warming through temperature binning for each underlying GCM helps to streamline the required climate data to run FrEDI compared to alternative, more detailed impact models that might require more spatially or temporally refined climate inputs. In doing so, however, representation of spatial or temporal variation of climate variables in FrEDI is fixed and limited to the variation in the underlying climate scenarios used to produce the binned results. Wherever possible, FrEDI makes use of multiple GCM results to capture this variation. Further discussion on this limitation can be found in Section 2.8.

The resulting 'binned' physical or economic impacts centered around the arrival year of each degree of warming in each GCM are then used to develop the GCM- and sector-specific impacts-by-degree damage functions. These are saved as FrEDI configuration data. As each GCM has distinct warming arrival times due to inherent differences in their parameterizations of earth system processes, there is variation in the level of warming covered in each damage function. For example, some GCMs may only provide damages up to three degrees of warming while others reach six degrees or higher by the end of the century. Complete damage functions are constructed across the full temperature range for each sector and GCM by linearly extending each damage function based on the slope between the impacts associated with the highest two degrees of warming for each GCM.¹³ See Appendix B (Section B.1) for a report of arrival years by GCM used to define FrEDI sectoral impact functions. These extended damage functions are then called and used within the FrEDI R package at runtime. Developing damage functions in this way allows resulting impacts within FrEDI to be compared across different climate models, climate scenarios, and studies. Appendix B provides the development details for each sectoral impact damage function used within FrEDI.

The specific peer-reviewed impact studies and data that are chosen to develop FrEDI damage functions are typically sourced from sectoral studies that assess the impacts influenced by temperature and precipitation stressors for the years 2006 to 2100 across multiple GCMs. Studies, however, are not limited to a 2100 endpoint and studies extending further into the future would provide a significant contribution to FrEDI

¹³ While the FrEDI R package does not limit temperature inputs to a maximum degree of warming, users should consider the increasing uncertainty at higher degrees of extrapolation above six degrees. The assumption of a linear relationship between temperature and damages at high temperatures is likely to be conservative. For example, Hsiang et al. (2017) found that combined damages in the United States increased quadratically with temperature. In addition, Weitzman (2012) suggested that while a quadratic damage form might be reasonable for temperature changes up to 2.5C° globally, damages might also increase more quickly at higher temperatures, 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 substantially higher temperature changes.

2300 Extension module (see Section 2.5). Other considerations for developing temperature-driven damage functions include the fact that not all sectoral impact studies produce a complete timeseries of annual results to construct the by-degree damage functions from, either due to computational constraints or the structure of the underlying sectoral model. For example, Urban Drainage and Water Quality produce results only at a set number of eras. Similarly, asphalt roads also provide era-level results. The framework is flexible to these inputs provided that the underlying climate projections are well-documented and available. For these sectors, bins are defined by first constructing a time series of impacts using the era-impact pairings, with an added pair for zero damages for the baseline period (1986-2005). Years within known pairings are linearly interpolated and end of century results are extrapolated linearly based on the latest two available pairings. Binning windows are defined for the synthetic time series of impacts using the underlying climate data. This process adds uncertainty through imposing linear interpolations between known points, and the level of uncertainty is higher when fewer eras of results are available (for example, Water Quality impacts rely on 2050 and 2090-era results only, while projections for Urban Drainage impacts are available for 2030, 2050, 2070, and 2090 eras). Building a synthetic time series potentially overstates confidence in the shape of the time series, but it allows for the inclusion of a wider set of potential impact studies.

A final consideration in defining impacts-by-degree functions from the underlying studies is the assignment of baseline periods. By accounting for relevant impacts in the baseline period, the damage functions developed for FrEDI have isolated the impacts from climate change that have occurred since the FrEDI baseline period (1986-2005 average). While many sector studies used within FrEDI use an average 1986-2005 climate baseline, many studies also define future climate change against different baseline periods. Where possible (i.e., where consistent baseline data is available), the baseline is shifted to match the framework default (1986-2005). This is not possible in all cases, and in those instances, temperature binning windows are developed based on the available baseline. Therefore, a requirement for a study to be included in FrEDI is, at minimum, a clearly defined and transparent baseline scenario.

Sea-Level Driven Damages

For sectors where impacts are primarily driven by changes in sea level, developing by-degree damage functions presents challenges for precisely capturing the links between climate stressors and economic impacts. Degrees of warming are correlated with sea level rise but non-linearities and time dependencies in the relationship make tying sea level rise driven impacts to temperatures a suboptimal option. Therefore, the relevant sector studies currently included within FrEDI are from the CIRA project, where economic impacts were estimated for six probabilistic GMSL projections first established by Kopp et al. (2014) and more recent localized scenarios developed by Sweet et al. (2017), ranging from 30cm (about 1 ft) to 250cm (about 8 ft) of GMSL rise by the end of the century.¹⁴

¹⁴ Though the current set of SLR-driven sectors in FrEDI utilize the same set of GMSL projections, the framework could accept damage functions based on any SLR scenarios as long as the impact study included at least two different scenarios to allow for interpolation during runtime.

This method makes use of these results in a two-step process that includes 1) a reduced complexity model of the relationship between temperature and GMSL (Appendix C), and 2) a mapping of results using time-specific damage trajectories established by the underlying studies. These time-specific trajectories are derived from the six data points per year from each of the six SLR scenarios, which relate centimeters of SLR to damages in each specified year. To include GMSL heights that exceed the (Sweet et al., 2017) maximum scenario (250 cm by 2100) in any given year, the damage functions for FrEDI are extrapolated per centimeter between the two highest scenarios. Impact data are sourced from impact studies that assess the vulnerability to sea level rise for the years 2000 to 2100, as the SLR sector models run from the base year 2000. Therefore, like temperature, SLR values in this report are sea level anomalies from the baseline era, referred to as SLR or Δ SLR.

Regional and local sea levels are also mapped to GMSL based on the localized sea level rise projections from Sweet et al. (2017), which include effects such as land uplift or subsidence, oceanographic effects, and responses of the geoid and the lithosphere to shrinking land ice. When custom sea level rise scenarios are used in FrEDI, the relationship between the input GMSL and local sea levels, and ultimately local impacts, are mapped implicitly based on the underlying Sweet et al. (2017) models.¹⁵

Developing Scalars to Account for Socioeconomic Conditions

Total impacts within a sector for a given period are a function of both climate and socioeconomic drivers. One of the key characteristics of FrEDI is the ability to analyze changes in temperature at different points throughout the century, while also accounting for socioeconomic trends.¹⁶ Previous methods have allowed for scaling climate change damages by presenting impacts as proportional to GDP (see Hsiang et al. (2017) for example). This method, however, does not account for non-linearities in the relationship between GDP, population, and impacts (e.g., the value of a statistical life, which is valued using an elasticity of GDP per capita¹⁷) and it does not capture how variations in population demographics (particularly geographic distribution and age) affect impact estimates.

The FrEDI framework improves on this traditional scalar approach by explicitly accounting for two components of time dependencies that can broadly be thought of in terms of 1) quantity and 2) composition. Quantity is the traditional scalar (e.g., damages per capita or as a percent of GDP) and composition refers to the changes in vulnerability or exposure within a given population. For example, at a given degree of temperature change, health and recreation impacts in 2010 will differ from those in the year 2090, due to changes in both the total population and the demographic composition of the population

¹⁵ Analyses conducted to support Neumann et al. (2020), Yohe et al. (2020), and Lorie et al. (2020) showed that economic impact results for the Coastal Property sector were consistent for like increments of SLR across SLR trajectories within about 10 percent tolerance, if socioeconomic trends are controlled (socioeconomics drives a function for real property value appreciation in the National Coastal Property Model).

¹⁶ FrEDI does not model feedbacks between climate and socioeconomic scenarios. It also does not account for the relationship between socioeconomics and adaptation capacity. See Sections 2.6 and 2.7 for more details.

¹⁷ The FrEDI v4.0 allows the user to choose a custom income elasticity, with a default value of 1.0, such that estimates VSL is proportional to income.

in each year. Year-specific adjustment factors are developed during the data pre-processing stage to account for these changes, as described in the next section.

Year-Specific Adjustment Factors

A subset of sectors included within FrEDI (**Table 2**) are process-based sectors. For these sectors, the damage functions are sensitive to population and GDP per capita in complex ways. Therefore, scaling the per capita impacts using input socioeconomic scenarios during runtime is not currently possible. For example, in the Coastal Property sector, property values are projected to change over time, and therefore an efficient adaptation option late in the century may not be efficient early in the century when property values are different. At the same time, threats early in the century trigger adaptation actions, and therefore the property is no longer vulnerable later in the century, which could cause damages to decrease over time. The Roads sector provides another example. Under no additional adaptation, increases in population lead to increased road traffic which, in combination with freeze/thaw patterns, lead to road surface degradation. In other cases, there are sectors where the underlying studies calculate impacts at a finer resolution than FrEDI accepts, such as age-stratified impact functions (e.g., for Southwest Dust and Extreme Temperature (Mills et al., 2015)). While impacts primarily scale linearly with the total population exposed, the vulnerability of that population changes over time. These types of dynamic decision-making, feedback loops, and demographic distributions cannot be calculated during runtime for custom GDP and population scenarios.

For these process-based sectors, FrEDI adjusts for the modeled differences in the binned relationship between temperature and impacts over time by using a series of year-specific adjustment factors for each region or state, defined empirically from the underlying studies, as shown in **Table 2**. Because the year-specific adjustment factors are not linked to FrEDI's population and GDP inputs during runtime, it is possible that results for these sectors become out of sync with the custom inputs. This is a limitation of the method. However, the adjustment factors are designed to approximate changes in the relationship between temperature and impacts for the most commonly evaluated and direct effects of population and GDP scenarios. They also minimize the required spatial resolution of custom inputs by working off regional or state-level population and GDP inputs to estimate more detailed changes over time.

TABLE 2. SECTORAL IMPACTS AND YEAR-SPECIFIC ADJUSTMENT FACTORS

Year-specific adjustment factors are used to transform general estimates of impacts by degree to estimates tied to a particular year based on socioeconomic trends that are too complex to model in FrEDI during runtime but are observed in the underlying sector models.

Sector	Adjustment Factor	Adjustment Factor Construction
Electricity Demand and Supply	Electricity demand and supply growth factor	Adjustment A: Ratio of impacts with conditions held constant at 2010 levels and impacts with dynamic conditions ^a
Electricity Transmission and Distribution Infrastructure	Electricity demand growth factor	
Suicide	Demographic composition factor	
Rail	Rail traffic growth factor	
Roads	Road traffic growth factor	

Sector	Adjustment Factor	Adjustment Factor Construction
Extreme Temperature (<i>Mills et al., 2015</i>)	Demographic composition factor	Adjustment B: Interpolation between impacts with conditions held constant at 2010 levels and impacts with conditions held constant at 2090 ^b
Southwest Dust	Demographic composition factor	
Winter Recreation	Demographic composition factor	
Coastal Properties	Property values and adaptation decision making	Adjustment C: No adjustment factor needed because SLR damage functions are year-specific
Transportation Impacts from High Tide Flooding	Road traffic and adaptation decision making	
Notes:		
a. These factors are calculated by comparing an annual series of impacts with socioeconomic change to a constant 2010 socioeconomic scenario run. Due to the combination of available runs, for Electricity Demand and Supply, 'the adjustment factors' are entered as damages with socioeconomic growth and no climate change in each year. The damage function for this impact represents multipliers on no climate damages by degree. See Appendix B for details.		
b. Impacts are estimated using constant 2010 socioeconomic conditions and 2090 socioeconomic conditions, then a ratio is taken between the two and interpolated for the intervening years.		

There are multiple methods for constructing year-specific adjustment factors from the underlying sectoral study results. For the first four sectors listed in **Table 2** (Adjustment A), adjustment factors are calculated as the ratio of future annual impact projections (i.e., changing climate and changing socioeconomics) versus impacts with a constant 2010 socioeconomic scenario (i.e., changing climate and constant socioeconomics). Comparing the two runs yields an adjustment factor for each year that represents the difference in the relationship between temperature and impacts relative to 2010 socioeconomic conditions.^{18,19} This type of information is most often provided for processed-based sectoral modeling, where socioeconomic growth can be switched on and off. The next three sectors in **Table 2** (Adjustment B) use year-specific adjustment factors based on two runs with constant socioeconomic conditions, defined by 2010 and 2090. The 2090 scalar is calculated as the ratio of estimated impacts using 2090 population versus 2010 population. Scalars for years between 2010 and 2090 are interpolated between the two end points. This option is less data intensive but does not provide the same level of detail as the scalars developed under Adjustment A.²⁰ The final two sectors in the table are SLR-driven sectors which do not require any additional year-specific scaling because the damage functions for SLR-driven sectors are already defined specifically for each year, accounting for socioeconomic conditions. These scalars are saved in the FrEDI configuration data and are used at runtime to scale calculated annual impacts for these sectors.

¹⁸ Note that the FrEDI framework calculates trajectory-based scalars for every five years (not annually), but the method and framework would support annual scalars as well.

¹⁹ Specific descriptions of the runs used to calculate these factors for each sector are provided in Appendix B.

²⁰ A possible extension could be to add more intermediate runs, such as 2050 scenario run to add detail to the interpolated scalars. Linear interpolation between the two time periods does not perfectly capture non-linear trends in the year-specific factors, however this is likely to be a small uncertainty relative to the scaling for population and GDP, which does capture non-linear trends.

Economic Valuation Measures

The monetization of climate change impacts in the underlying sectoral studies is also conducted using a variety of valuation measures that are best suited to each sector and its methods. For some sectors and sub-impacts, valuation represents direct costs, e.g., the medical cost to treat an illness, or the expense to repair a road or other physical structure damaged by a climatic hazard. In other cases where no market transactions take place, such as when an individual dies prematurely from a climatic hazard or when water quality is impaired, the economic valuation involves the use of welfare economic techniques. These methodologies are often used to estimate what individuals would be willing to pay to avoid the risk of an undesirable outcome. The Value of a Statistical Life (VSL) is one such measure used to value mortality outcomes in many of the health sectors.

For some sectors, the pre-processed damage functions from the underlying studies provide estimates of physical impacts (e.g., number of crimes or pre-mature mortality counts), which are then monetized when FrEDI is run, based on a multiplier on that physical impact (e.g., the VSL used to monetize premature mortality during runtime). In many of the processed-based sectors (e.g., Roads, Rail, and Coastal Property), the underlying studies directly provide economic impacts and therefore the economic measures are directly built-in to the pre-processed damage functions that are stored and then used within FrEDI during runtime.

Table 3 presents the valuation measures used for each of the sectors and impacts within FrEDI. Sectoral models that provide both physical and economic impacts are preferred, where possible, as they provide an alternative method for communicating climate impacts and comparing the effectiveness of adaptation options (e.g., using number of deaths avoided).

TABLE 3. ECONOMIC VALUATION MEASURES BY SECTORAL IMPACT

For each sector and impact, this table provides the valuation measure and a short description of how the valuation is calculated, either directly from the underlying model (as is more common in process-based models) or as a multiplier on a physical impact measurement (as is more common in econometric models).

Impact Category		Impact Type	Valuation Measure	Valuation Application
Climate-Driven Changes in Air Quality		Ozone mortality	VSL	Multiplier on premature mortality
		PM2.5 mortality	VSL	
Temp. Mortality	Extreme Temperature	Extreme cold mortality	VSL	Multiplier on premature mortality
		Extreme heat mortality	VSL	
	CIL Temperature-Related Mortality	Extreme heat mortality	VSL	Multiplier on premature mortality
	ATS Temperature-Related Mortality	Extreme cold mortality	VSL	Multiplier on premature mortality
Extreme heat mortality		VSL		
Southwest Dust		Hospitalization (acute myocardial infarction)	Hospitalization costs: cardiovascular	Multiplier on incidences
		Hospitalization (cardiovascular)	Hospitalization costs: cardiovascular	

Impact Category		Impact Type	Valuation Measure	Valuation Application
		All mortality	VSL	
		Hospitalization (respiratory)	Hospitalization costs: respiratory	
		Asthma ED visits	Hospitalization Costs: Asthma	
Valley Fever		Mortality	VSL	Multiplier on incidences
		Morbidity	Cost of illness: Valley Fever	
		Lost wages	Wages: daily, all workers	
Wildfire		Morbidity	Hospitalization costs	Direct cost, as output from underlying model
		Mortality	VSL	Multiplier on premature mortality
		Response or suppression costs	Wildfire response costs	Multiplier on acres burned
CIL Crime		Violent crime	Injury/loss of life, enforcement, and other indirect costs	Multiplier on incidences
		Property crime	Property damage, enforcement costs, and other indirect costs	
Vibriosis		Direct medical costs	Medical cost of illness for doctor visit or hospitalization	Direct cost, as output from underlying model
		Lost wages	Wages: daily, all workers	Multiplier on lost days of work
		Mortality	VSL	Multiplier on premature mortality
Suicide		Mortality	VSL	Multiplier on premature mortality
Coastal Properties		Coastal property damage	Property damage/adaptation costs	Direct cost, as output from underlying model
Transportation Impacts from High Tide Flooding		Traffic delays and adaptation costs due to high tide flooding	Delay costs	Direct cost, as output from underlying model
Hurricane Wind Damage		Property damage from hurricane winds	Lost property value	Direct cost, as output from underlying model
Inland Flooding		Inland property damage	Property damage	Direct cost, as output from underlying model
Rail		Rail impacts, risk of track buckling	Repair and delay costs	Direct cost, as output from underlying model
Roads	All Roads	Damage to paved and unpaved road surfaces	Repair and delay cost	Direct cost, as output from underlying model
	Asphalt Roads Maintenance	Road impacts	Repair costs	Direct cost, as output from underlying model

Impact Category	Impact Type	Valuation Measure	Valuation Application
Urban Drainage	Proactive costs of improving urban drainage infrastructure	Repair costs	Direct cost, as output from underlying model
Electricity Demand and Supply	Change in power sector costs from reference scenario	Capital, operations/maintenance, and fuel costs	Direct cost, as output from underlying model
Electricity Transmission and Distribution Infrastructure	Stress to transmission and distribution infrastructure	Repair and replacement costs	Direct cost, as output from underlying model
Water Quality	Water quality impacts	Lost welfare	Willingness to pay for improvements in water quality, direct from underlying model
Winter Recreation	Lost ticket sales from alpine skiing	Lost ticket revenues	Direct cost, as output from underlying model
	Lost ticket sales from cross-country skiing	Lost ticket revenues	
	Lost ticket sales from snowmobiling	Lost ticket revenues	
Marine Fisheries	Change in weight of marine fisheries landings	Lost or increased <i>ex vessel</i> revenue	Direct cost, as output from underlying model
Labor	Lost wages for high-risk occupations	Wages: annual, high-risk workers	Multiplier on hours lost
CIL Agriculture	Lost maize production value	Production values: maize	Direct cost, as output from underlying model
	Lost wheat production value	Production values: wheat	
	Lost soybean production value	Production values: soybean	
	Lost cotton production value	Production values: cotton	

2.4 FrEDI Runtime Processes

FrEDI R Package Overview

FrEDI is implemented through the use of a model developed in R, a popular free software environment for statistical computing and graphics. The model code consists of an R Package available for download and installation at <https://github.com/USEPA/FrEDI>. The R Package allows users to import custom temperature, sea level rise, national GDP, and regional population scenarios into R from Excel or CSV files, and to use these scenarios to project annual average impacts through the 21st century due to climate change.²¹ The pre-processing described in Section 2.3 is used to develop a database of model, region, and sector-specific damage functions that can be called when the FrEDI R package is run, so that annual impacts of climate change across FrEDI's multiple sectors and variants can be computed in a quick process (~seconds). When FrEDI is then run the code first transforms the input temperature and socioeconomic data into the

²¹ The R code, by default, calculates projected damages for all sectors, impact types, and adaptation and variant options. Alternatively, users have the option to select a specific set of sectors for which to calculate damages.

necessary units (i.e., CONUS degrees of warming and GMSL rise, see Appendix C) and then combines these with the pre-processed impact-by-degree damage functions and any relevant socioeconomic or year-specific adjustment factors to calculate the annual impacts associated with the specific level of warming and socioeconomic conditions in each year of the input scenario.

The resulting default output from FrEDI is a table array of average annual physical (where available) and economic damage estimates at single year intervals from 2010 through 2100 for each sector, variant (or adaptation), impact type, model (GCM or SLR scenario), region, and state.²² The code also includes user-input options for aggregating outputs (i.e., summing all impact types for each sector or all regions to the national total), extending results past 2100 (see Section 2.5), limiting the calculations to specific sectors, and formatting outputs. FrEDI and its results can be therefore used to estimate climate impacts in several ways, including impacts for a specified scenario, or the change in impacts between two custom scenarios, as demonstrated in Chapter 3. Further details about the FrEDI R package inputs, runtime processes, and outputs are provided in the sections below.

FrEDI R Package Inputs

Climate & Socioeconomic Inputs

To support rapid, flexible, and customizable assessments, FrEDI aims to provide reliable climate-related impact projections with minimal, but flexible input requirements. FrEDI can be run with default²³ temperature and GMSL rise, population, and/or GDP projections, or with the following custom inputs:

- Temperature Inputs: CONUS or Global temperature change, relative to a 1986-2005 baseline.**²⁴ A timeseries of annual CONUS temperature change relative to the FrEDI baseline is preferred, although interpolation (and extrapolation) can be used to fill in a timeseries from a minimum of two points. CONUS degrees of warming are used in FrEDI because, relative to global temperatures, they provide a closer link to the local U.S.-specific climate stressors influencing the underlying models (Sarofim et al., 2021). For some climate models and other sources of temperature trajectories, CONUS degrees of warming might not be readily available, and instead the climate scenarios are defined by global temperature change. FrEDI includes a translation function to convert global

²² The main output also includes information about the underlying input scenario (e.g., temperature change, population, and GDP), for user reference. State is “N/A” for impacts currently processed at the region level.

²³ In the absence of custom scenarios, FrEDI applies default population and GDP projections that are consistent with the CIRA project’s scenarios (see EPA (2017) for more details), and therefore align with the scenarios used in many of the underlying sectoral impact studies. The default population scenario is based on the national-level UN Median Population projection (United Nations, Department of Economic and Social Affairs, Population Division, 2015), disaggregated to the county-level using EPA’s ICLUSv2 model (Bierwagen et al., 2010; EPA, 2017b) and reaggregated to NCA regions for this analysis. GDP projection is defined by the EPPA, version 6 model (Chen et al., 2015), using the aforementioned UN Median population projection for the U.S. (United Nations, Department of Economic and Social Affairs, Population Division, 2015) and the 2016 Annual Energy Outlook reference case (USEIA, 2016) for the U.S. through 2040. The extended FrEDI module through 2300 does not include default GDP or population projections from 2091 to 2300. The default inputs are zero.

²⁴ If analysts begin with an emissions scenario, rather than a global mean temperature trajectory, emissions trajectories can be converted to global mean temperatures using a reduced complexity climate model, as described in Chapter 3.

changes in temperature (from the 1986-2005 baseline) to CONUS changes in temperature, based on a statistical relationship derived from the LOCA dataset.^{25,26}

- **Sea Level Rise Inputs: Global mean sea level, relative to a 2000 baseline or no custom input (optional).** Sea level-driven damages are indexed to global mean sea levels, relative to a 2000 baseline. Although considered a separate input from the temperature pathway, the sea level rise inputs should be consistent with the temperature pathway to maintain consistency across all sectoral results. In some cases, the same models used to develop temperature trajectories might also produce sea level rise pathways. In other cases, sea level rise pathway could be developed in a separate model from the same emissions trajectory used to develop the temperature trajectory. If the input climate scenario does not include a defined sea level pathway, FrEDI includes a translation function, modeled after Kopp et al. (2014), so that FrEDI can estimate global mean sea level from global temperatures if a sea level pathway is not provided.²⁷
- **U.S. Population.** State-level U.S. population projection for 2010 through 2090.²⁸ The FrEDI R package will linearly interpolate between input values to create an annual population timeseries. The package requires values in 2010 and 2090 but can accept any frequency down to annual values (e.g., every five years).
- **U.S. Gross Domestic Product (GDP).** National U.S. GDP, in \$2015 dollars, for 2010 through 2090 (or 2300). As with the population input, FrEDI can accept any frequency of data and will create an annual time series from provided points as long as values are provided from 2010 and 2090.

²⁵ U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey, 2016: Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. Available online at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf. Data available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

²⁶ Global to CONUS mean temperature change estimated as $\text{CONUS Temp} = 1.42 * \text{Global Temp}$. See Appendix C for more information.

²⁷ Global mean sea level is calculated from global mean temperature using a semi-empirical method that estimates global sea level change based up a statistical synthesis of a global database of regional sea-level reconstructions from Kopp et al. (2014). The function used in the temperature input stage to translate global temperatures to CONUS temperatures is inverted to produce global temperature from CONUS inputs when necessary. See Appendix C for more information.

²⁸ FrEDI aggregates state level inputs to regions for sectors that are currently processed at the state level.

Defining Output Sets

FrEDI calculates impacts across multiple dimensions: year, region or state, sector, GCM,²⁹ impact type, and adaptation scenario or other variant options. Users can specify as an input to FrEDI, the extent to which output results should be aggregated across these dimensions to meet the needs of analysis³⁰, except for the adaptation and variant options, which represent different options for future societal responses to climate change and should not be summed. The results can feed into post-processing analyses, including comparisons across emission policies or climate sensitivities, or into economy-wide models, as described in Section 1.2.

Runtime Impact Calculations

Calculating Unadjusted Annual Impacts for Temperature-Driven Impact Categories

For temperature-driven sectors, unadjusted impacts are first calculated in FrEDI by combining the pre-processed impact-by-degree damage functions with annual warming levels in the user-defined temperature trajectory. In other words, each year in the damage projection is first assigned a temperature based on the user input trajectory and then that temperature is used to assign a damage based on a look up to the relevant GCM-, region-, sector-, or variant-specific by-degree damage function. The annual unadjusted impacts represented in this intermediate stage do not include any adjustments for changing socioeconomic conditions over time, and represent physical damages for sectors where economic valuation is applied in runtime.

Adjusting Annual Impacts

Next, intermediate annual damages are adjusted based on the year-specific adjustment factors described in **Table 2**. As described in Section 2.3, these adjustments typically apply to process-based sectors where population and GDP per capita impact the damage function in complex ways and adjusting impact results in FrEDI based on custom GDP and population scenarios is not currently possible.

Scaling for Population and GDP/Capita

In some sectors (see **Table 4**), the input GDP and population values are then used to scale the adjusted impact results to account for changes in socioeconomic conditions (in addition to the year adjustment factors presented in **Table 2**). The ability of FrEDI to include a linkage between input population and GDP and sectoral impacts is dependent on the modeling assumptions and data outputs of the underlying sector studies. Many of the underlying health impact studies generate mortality per capita estimates, which are scaled by population for total impacts in this step.

²⁹ Note that here GCM results represent variation in other factors indexed to temperature that impact damages in the underlying studies such as precipitation and spatial variation of temperatures across CONUS. The GCM results all reflect the same temperature trajectory defined for the run. FrEDI also outputs an 'average' result which is an average across results from all GCMs.

³⁰ Regional impacts are calculated as the sum of state impacts for sectors processed at the state level. See Section 2.7 for a discussion of the extent to which aggregated state-level impacts differ from impacts previously estimated at the regional level.

TABLE 4. SECTORAL IMPACTS LINKED TO CUSTOM SOCIOECONOMIC SCENARIOS

Identification of sectors for which impacts scale with population and GDP per capita inputs. Sectors that scale with population at aggregations other than the regional level are noted. These instances are driven by the populations studied in the underlying sectoral models.

Sector	Link with Population Input	Link with GDP per Capita Input
Air Quality	X	X
Extreme Temperature	X ^a	X
CIL Temperature-Related Mortality	X	X
ATS Temperature-Related Mortality	X	X
Southwest Dust	X ^b	X ^c
Valley Fever	X	X ^d
Wildfire ^e	X	X ^c
Vibriosis ^f		X
Suicide	X ^g	X
Water Quality	X	
Winter Recreation	X	
Labor ^h		X
Notes:		
a. Scaled to city populations to reflect the coverage of the underlying study. b. Scaled to Arizona, Colorado, New Mexico, and Utah populations to reflect the coverage of the underlying study. c. Mortality impacts scale with GDP per capita; morbidity impacts do not. d. Mortality impacts and lost productivity scale with GDP per capita; morbidity impacts do not. e. Wildfire mortality and morbidity impacts. Wildfire response costs do not scale with population or GDP per capita. f. The underlying vibriosis study does not tie impacts to population because cases are not tied to where people live and, given limits on shellfish harvesting, cases are unlikely to scale linearly with population. g. Scaled to population over 5 years of age to reflect the coverage of the underlying study. h. The underlying labor study finds that the number of high-risk workers is projected to remain constant in absolute terms throughout the century; therefore, labor impacts do not scale with population.		

Economic Valuation of Impacts

As described in Section 2.3. (**Table 3**), a variety of valuation measures are used for the sectors included within FrEDI. While a subset of underlying sectoral studies provide direct estimates of economic impacts built into these ‘by-degree’ damage functions, the economic valuation of physical sector impacts is conducted when FrEDI is run. This allows for the flexibility of allowing users to specify select monetization parameters, such as GDP per capita and the income elasticity used to calculate the value of statistical life (VSL) and allows FrEDI to report physical outcomes such as premature deaths or acres burned in wildfires separately from the economic impacts. In these cases, valuation of impacts can scale linearly (e.g., wage rates for Labor and Valley Fever sectors, where impacts are multiplied by the ratio of the future year GDP per capita to 2010 GDP per capita) or via non-linear elasticities³¹ (e.g., VSL for Air Quality, Extreme Temperature, Southwest Dust, Wildfire, and Valley Fever sectors).

Users should note that the underlying sector studies measure economic impacts through widely varying methods, including welfare economic measures, expenditure/direct cost measures, or a mix of these methods. Details are provided in Appendix B for each of the underlying sectoral studies. Therefore,

³¹ The default elasticity in FrEDI is linear (elasticity = 1), though users are able to assign any custom non-linear value.

summing across these measures may result in some confusion about what is represented by the total and is not strictly supported by economic theory. In applied economic analyses such as EPA Regulatory Impact Analyses, however, these sums are commonly encountered, and no specific advice is yet provided in EPA's Guidelines for Preparing Economic Analyses (2014).³² As a result, values are summed in this Documentation, but users are advised that the subsequent use of the sums include an appropriate caveat.

SLR-driven sectors

Because SLR-driven sectors are pre-processed as inputs for FrEDI at year-SLR combinations rather than by decoupled degree of warming and time-related socioeconomic drivers (as is the case in temperature-driven impact categories) the runtime processes for SLR-driven sectors differ from those described above. For SLR-driven sectors, FrEDI interpolates impacts between the six SLR scenarios used in the underlying studies based on the amount of GMSL rise at any given time point to estimate the damages in that given year. No additional valuation, adjustments, or scaling is required since the pre-processed damaged functions are already in economic terms and are specific to years, so they already incorporate time-dependent adjustments and socioeconomics.

2.5 Additional Modules & Features

The FrEDI R code currently includes two modules that extend FrEDI's capabilities to assess impacts past 2100 and to different population groups of concern, described below. These modules can be run within the FrEDI package when toggled-on within the code, so as to preserve efficiency during runs that do not make use of these capabilities. Additional extended functionality in the form of new modules may also be added to FrEDI in the future, based on the availability of relevant peer-reviewed information.

2300 Extension

Although the default FrEDI framework is designed to project damages through 2090, FrEDI also contains an extension module that projects impacts through 2300. Users have the option to turn on this functionality using an input parameter when calling the main FrEDI R function (*run_fredi()*). This extension linearly extrapolates temperature-binned damage functions above six degrees and extrapolates time-dependent trends from 2010-2090 out to 2300. Sea level rise-based damages are also extrapolated using the variation in sea level across scenarios in 2090, along with an adjusted for property values tied to GDP per capita.

FrEDI defines extensions of the socioeconomic condition adjustments through 2300 as follows:

1. **Impacts that scale with population and/or GDP per capita (Table 4):** Custom population and GDP trajectories continue to scale damage estimates through 2300.
2. **Year-specific Adjustment Factors (Table 2).**

³² See in particular Chapter 11 of (EPA, 2014), on Presentation of Analysis and Results, which implies an inclusive approach to estimates of total monetized benefits rather than a disaggregation by method by which they are monetized or special considerations in developing the sums (such as use of compensating variation equivalents for welfare estimates or use of a general equilibrium approach for aggregating expenditure/direct cost estimates). As recommended in the Guidelines, in this report we provide detailed information on how each of the monetized estimates were developed. In addition to the summary provided in Table 6, detailed information is provided in Appendix B for each of the underlying sector studies.

- a. For adjustment factors derived by comparing per capita damage rates from a constant population run to a run that incorporates population growth, the time series of adjustment factors is either linearly extrapolated through 2300 or held constant at 2090 levels based on the observed trends 2010 through 2090 and the interpretation of the factor.
 - b. For adjustment factors derived by comparing per capita damage rates for two constant population scenarios (i.e., 2010 and 2090) and interpolating for between years, per capita damage rate adjustments are held at 2090 levels through 2300. These adjustment factors tend to change only modestly over the 2010 to 2090 period and holding them constant at 2090 levels avoids extreme adjustments due to extrapolation.
3. **No time-dependent adjustments.** 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. No additional adjustment is necessary for these sectoral impacts through 2300.

Table 5 provides details on which strategy is used for each sectoral impact currently in the framework.

TABLE 5. SUMMARY OF STRATEGIES FOR EXTENDING SECTORAL RESULTS FROM A 2090 TO 2300 MODELING HORIZON

Sector	Impact ^a	Extension Strategy
Climate-Driven Changes in Air Quality	Ozone	Impacts continue to scale with population and/or GDP per capita (<i>Adjustment 1 in list above</i>)
	PM _{2.5}	
ATS Temperature-Related Mortality	N/A	
CIL Temperature-Related Mortality	N/A	
Valley Fever	Mortality	
	Morbidity	
	Lost Wages	
Wildfire ^b	Morbidity	
	Mortality	
Vibriosis	Mortality	
Water Quality	N/A	
Labor	N/A	
Extreme Temperature (Mills et al., 2014)	Heat-related mortality	Impacts continue to scale with population and/or GDP per capita (<i>Adjustment 1</i>) AND Year-specific adjustment factors developed from two constant population scenarios: per capita damages rates from 2090 applied 2090-2300 (<i>Adjustment 2b</i>)
	Cold-related mortality	
Southwest Dust	Acute Myocardial Infarction	
	All Cardiovascular	
	All Mortality	
	All Respiratory	
	Asthma ER	
Suicide	Mortality ^c	
Winter Recreation	Alpine Skiing	
	Cross-Country Skiing	

Sector	Impact ^a	Extension Strategy
	Snowmobiling	
Rail	N/A	Year-specific adjustment factors developed based on comparison of with and without population growth scenarios: extend existing scalars linearly past 2090 (<i>Adjustment 2a</i>)
Roads	N/A	
Electricity Supply and Demand	N/A	
Electricity Transmission and Distribution	N/A	
Coastal Properties	N/A	Sea level rise-based sectors: post-2100 impacts scale with population or GDP per capita
Transportation Impacts from High Tide Flooding	N/A	
Wildfire	Response Costs	No time dependent multipliers used to adjust temperature-driven impacts over time
Crime	Property	
	Violent	
Vibriosis	Morbidity, Hosp. costs	
	Morbidity, Lost Productivity	
Wind Damage	N/A	
Inland Flooding	N/A	
Asphalt Roads	N/A	
Urban Drainage	N/A	
Marine Fisheries	N/A	
Agriculture	Cotton	
	Maize	
	Soybean	
	Wheat	
Note: <ul style="list-style-type: none"> a. Impact column provides detail for subcategories of impacts estimated within the framework. b. 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 employ different extension strategies. c. Suicide mortality scalar through 2300 equal to 2091 value, the last year of available scalars for this impact. 		

Sea level rise-based damages in FrEDI are derived from damages in the underlying studies that are year and sea level rise specific through 2100. Damages in each year reflect real property prices and adaptation decisions made in previous periods. Damages post-2100 are based on sea level rise-based damages from 2100 adjusted for real property price appreciation using GDP per capita and income elasticity of 0.45, consistent with the underlying Neumann et al. (2021b). Damages associated with GMSL above 250 cm (the highest scenario in the underlying literature) are extrapolated based on the incremental damage per centimeter observed between the two highest GMSL scenarios in 2090.

Social Vulnerability Module

FrEDI also includes the capacity to assess the degree to which different populations are disproportionately exposed to the impacts from climate change in select impact categories. This capability is provided through a module within the FrEDI R package (`run_fredi_sv()`), hereafter called the ‘SV module’ or ‘FrEDI-SV’) that can be run separately from the main FrEDI application. The basic structure, specific methodology, and

underlying data supporting FrEDI-SV are derived from EPA’s independently peer-reviewed September 2021 report, *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts*.³³ This module is described in more detail in Appendix D and a demonstration is presented in Chapter 3. Appendix D also includes reports of several validation tests which demonstrate consistency between results from the FrEDI-SV module and those presented in EPA’s Climate Change and Social Vulnerability report.

The FrEDI SV module allows users to explore how the impacts of climate change will be distributed among four population groups of concern: (1) individuals with low income (individuals living in households with income at or below 200% of the poverty level), (2) those identifying as Black, Indigenous, or people of color (BIPOC)³⁴, (3) educational attainment (individuals ages 25 and older with less than a high school diploma or equivalent), and (4) those that are 65 years of age or older (**Table 6**). These categories are consistent with a subset of the population groups of concern highlighted in EPA’s Technical Guidance for Assessing Environmental Justice in Regulatory Analysis (EPA, 2016).³⁵

TABLE 6. FOUR POPULATION GROUPS OF CONCERN AND THEIR REFERENCE GROUPS, CONSIDERED IN THE FREDI SV MODULE

Categories	Group Name	Description	Reference Group
Income	Low income	Individuals living in households with income that is 200% of the poverty level or lower	Individuals living in households with income greater than 200% of the poverty level.
Age	65 and Older	Ages 65 and older	Under age 65
Race and ethnicity	BIPOC	Individuals identifying as one or more of the following: Black or African American, American Indian or Alaska Native, Asian, Native Hawaiian or Other Pacific Islander, and/or Hispanic or Latino	Individuals identifying as White and/or non-Hispanic
Education	No High School Diploma	Individuals aged 25 and older with less than a high school diploma or equivalent	Individuals aged 25 or older with educational attainment of a high school diploma (or equivalent) or higher.

³³ See EPA. 2021. Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. U.S. Environmental Protection Agency, EPA 430-R-21-003. www.epa.gov/cira/social-vulnerability-report

³⁴ Consistent with other EPA reports, FrEDI-SV uses the abbreviation “BIPOC” (for Black, Indigenous, and people of color) to refer to individuals identifying as Black or African American; American Indian or Alaska Native; Asian; Native Hawaiian or Other Pacific Islander; and/or Hispanic or Latino. It is acknowledged that there is no ‘one size fits all’ language when it comes to talking about race and ethnicity, and that no one term is going to be embraced by every member of a population or community. The use of BIPOC is intended to reinforce the fact that not all people of color have the same experience and cultural identity. This report therefore includes, where possible, results for individual racial and ethnic groups. Note the SV report reported results for this group as attributed to a “minority” category. The results are the same here but the category title has been updated.

³⁵ EPA’s 2016 Technical EJ Guidance additionally considers ‘populations that principally rely on subsistence consumption of self-caught fish and wildlife’, who were not explicitly included in the EPA SV Report analysis framework.

As described in more detail in EPA’s SV Report, the assessment of social vulnerability implications in FrEDI SV is based on the spatial intersection of where physical climate change are projected to occur and vulnerability, in terms of an individual’s capacity to prepare for, cope with, and recover from these impacts. This framework uses data on where populations live as an indicator of exposure to climate change impacts, and for vulnerability, considers the four categories in Table 6 for which there is evidence of differential vulnerability. Within the FrEDI-SV module, differential impacts in each group are calculated at the Census tract level as a function of current demographic patterns (e.g., percent of each group living in each Census tract as characterized by the 2014-2018 Census American Community Survey (ACS),³⁶ projections of U.S. population, and Census-tract estimates of where climate impacts are projected to occur. This requires the additional pre-processing of impact-by-degree damage functions at the Census-tract level. The module’s current scope includes a subset of FrEDI’s impact categories:³⁷

- Climate-driven change in air quality (mortality (ages 65+) and childhood asthma cases)
- Extreme Temperature (from Mills et al., (2015))
- Labor
- Roads
- Transportation Impacts from High Tide Flooding
- Coastal Properties

Results are calculated for individuals within four population groups of concern: Low Income; Black, Indigenous, and People of Color (BIPOC); No High School Diploma; and 65 and Older, with the additional option to assess multiple specific racial and ethnic subdivisions of the BIPOC category. The module aggregates and outputs results at the regio level, to be consistent with EPA’s SV Report.

Example analyses using these results is described in Chapter 3 and details about the module and its performance are in Appendix D.

2.6 Process for Incorporating New Studies

The FrEDI framework is a secondary data synthesis application that relies on existing primary climate change impacts research and is designed to accommodate a variety of impact estimates, including those run with unique climate trajectories, socioeconomic assumptions, and temporal scopes. EPA intends to carefully monitor the literature to identify appropriate sectoral studies for inclusion in the framework. To advance the utility of the framework, EPA encourages researchers and practitioners to develop additional sectoral impact studies that can be considered for use in FrEDI. Moving forward, EPA intends to prioritize

³⁶ Future impacts are assessed based on present data demographic patterns from the ACS dataset. The relative percent of each socially vulnerable group in each Census tract are from the 2014-2018 U.S. Census American Community Survey dataset (U.S. Census) and are held constant overtime because robust and long-term projections of local changes in demographics are not readily available.

³⁷ This module could be expanded using the same approach to incorporate additional impact categories. See Table D1 for further details on each sector

adding sectoral studies that fill gaps in the existing coverage and/or provide alternative estimates for the sectors with the largest impacts.

Many of the sectoral studies currently processed for this framework are part of the CIRA framework, and therefore rely on a consistent set of climate models and socioeconomic scenarios (see EPA, 2017a; Martinich and Crimmins, 2019; Neumann et al., 2021a; Sarofim et al., 2021 for more details on sector studies and the CIRA framework). However, other studies with different climate or socioeconomic projections can also be integrated into the framework if the necessary information is available. Necessary data and specifications include that the underlying study provides subnation impacts-by-degree of warming (or cm of SLR) that can be scaled for socioeconomic changes and adjusted for other time dependencies unique to the sectoral impact function. Although ideally the introduced sectors meet all these qualifications, there may be instances where methods are adapted to allow for the inclusion of certain studies and their results. For example, if a study only provides national estimates, impacts could be distributed to the regions based on population or another relevant proxy. In addition to CIRA framework studies, the FrEDI framework currently incorporates multiple sectoral results from the Climate Impact Laboratory (CIL), and single sectoral studies from several other researchers, including a panel organized through the American Thoracic Society (ATS).

A requirement for a study to be included in FrEDI is, at minimum, a clearly defined and transparent baseline scenario – including potentially important information beyond the climate baseline, such as any projection of baseline mortality rates, or assumptions about baseline infrastructure repair or replacement cycles, with information provided in the study that is sufficient to facilitate an adjustment if necessary. Overall, the approach, as demonstrated in this documentation, is well-suited to incorporate results from other studies. This is important as the current version of FrEDI only includes a subset of the potential impacts of climate change in the U.S. FrEDI’s flexibility to incorporate results from external studies drives a long-term objective to populate the framework with impact estimates and functions from the broader climate literature. This will ensure that FrEDI is informed by the best available data and methods, which can then be revisited and updated over time as scientific and economic capabilities continue to advance.

A series of quality control procedures are followed when a new sector is added to FrEDI. First, a test compares the new results to a benchmark run results based on default input parameters to ensure that the only change is the addition of the new sector (i.e., no existing sectors were inadvertently altered during the addition process). Next, results of FrEDI runs with input parameters designed to reflect the parameters of the underlying study to the extent possible are compared to reported results figures in the underlying study. FrEDI is not expected to perfectly replicate original sectoral modeling results but agreement within a reasonable margin across all available comparison points is expected.³⁸ In cases where the results do not align for reasons anticipated based on limited reported values in the underlying study (e.g., the underlying study only reports discounted results) or because of intended deviations from the underlying study during

³⁸ There is no absolute threshold margin of error accepted in this step. Each underlying study has unique factors and deviations from the FrEDI framework that might introduce more or less uncertainty or expected disagreement.

pre-processing (e.g., the underlying study used a different baseline), these deviations are documented and the differences in results are subject to additional reasonableness checks to confirm the difference in results matches expectations.³⁹

As information is added to the framework moving forward, the FrEDI R code (and associated GitHub documentation) and relevant sections in this Technical Documentation (including text, figures, and appendix) will be updated accordingly and documented in Appendix E.

2.7 Treatment of Uncertainty

FrEDI is fundamentally an analytical communications tool that synthesizes and standardizes a broad set of U.S. sectoral studies for use with common climate inputs and socioeconomic and impact valuation driver data to better understand how future climate change impacts will be experienced across the United States. With respect to uncertainty, the framework can be used to assess multiple sources of uncertainty, including to but not limited to:

- **Damage Function (or Structural) Uncertainty.** FrEDI currently includes two approaches for assessing structural uncertainty in the underlying impact-by-degree damage functions.

The first is by accounting for additional sectoral variants that either reflect the uncertainty in the central impact estimates or the sensitivity to additional factors in the underlying studies. For some sector models, a partial representation of these uncertainties can be characterized by statistical uncertainty around relevant parameter estimates. In these cases, high and low uncertainty bounds are included as additional variants within FrEDI. For example, the authors of the Climate Impact Lab (CIL) sector studies provided impact result distributions which could be used to derive two additional damage functions for the (CIL) Temperature-Related Mortality sector that reflect the 90% damage Confidence Interval. For other sector models that rely on simulation approaches (e.g., Transportation Impacts from High Tide Flooding, Coastal Properties, and Inland Flooding), uncertainties are not generally characterized by statistical methods. In these cases, the underlying estimates are either calibrated by or compared to current historical/baseline results during the pre-processing, which increases confidence in FrEDI's central damage function, but the impact of these uncertainties in the range of outcomes for these sectors remains mostly unknown. For other sectoral impacts that are sensitive to additional known factors, these are also represented as additional variants in FrEDI. For example, the extent to which climate change will impact air quality depends on the level of air pollutant precursor emissions and climate-driven impacts to agriculture depend on assumptions about the level of CO₂ fertilization. In these cases, both of these sensitivities were quantified by authors in the underlying sector studies and therefore have been

³⁹ Quality control documentation as described in this paragraph is an ongoing progress as new sectors are added to FrEDI. Full documentation of original FrEDI sectors will be available upon final publication of this Documentation.

included as impact variants within FrEDI to be able to assess the sensitivity of impact results to varying assumptions.

The second approach is to include multiple damage functions for the same impact sector, derived from multiple different peer-reviewed studies. For example, FrEDI currently includes three estimates of temperature-related mortality: CIL and ATS Temperature-Related Mortality, and Extreme Temperature from Mills et al. (2015). While comparisons across FrEDI informed by these studies (see Table A4 in Hartin et al. (2023)) can help assess certain aspects of structural damage function uncertainty, most sectors currently included within FrEDI only include a single study option due to the limited number of distinct national-level impact models that currently exist. As the underlying sectoral literature develops, it may also be possible to incorporate multiple sectoral model formulations within FrEDI (as is currently done for temperature-related mortality).

- **Uncertainty in Adaptation Assumptions.** Depending on the sector, FrEDI includes impact estimates that employ a variety of assumptions regarding adaptive responses to climate impacts. For some sectors, the framework includes estimates that incorporate adaptation, which reflect the current understanding of the effects of adaptation on climate risk mitigation. Much of the current literature reflects impact estimates developed for limited or no additional adaptation conditions. This is in part because the historical experience of climatic conditions, such as those expected to be experienced in the future is limited, so mechanisms of adaptation are poorly understood for some sectors. As a result, reliably quantified estimates of the effectiveness of adaptation are not currently available for all sectors addressed in this framework. In addition, in many sectors, adaptive action to date has been surprisingly slow, even where literature suggests that the economic benefits of taking action to mitigate climatic risks exceed the costs – for example, in response to coastal risks of accelerated storm surge and sea level rise (Lorie et al., 2020).

For sectors where this information is available in the underlying studies (Table 1), the framework provides the user an option to assess impacts under alternative human response scenarios, including no additional adaptation (limited to currently practiced and/or budgeted adaptation actions), reactive adaptation (to repair damage but without forward planning to avoid future damage), and proactive adaptation (including action and investment in risk mitigation based on some level of foresight of future conditions). For several sectors where the current scope of the framework does not provide options to assess the effects of alternative adaptation assumptions, such as Labor or Winter Recreation, adaptation is partially represented in the underlying data used to create FrEDI's damage functions. For example, the econometric methodology used in the Labor analysis would capture any extreme temperature adaptations employed in weather-exposed industries in the base period. Also, the Winter Recreation analysis included the use and potential expansion of artificial snow creation/blowing.

For the underlying sector studies that do account for adaptation, these analyses treat adaptation in unique ways, with some sectors directly modeling the implications of adaptation responses, and others implicitly incorporating well-established pathways for adapting to climate stress. For

example, ATS Temperature-related Mortality, Air Quality, Extreme Temperature Mortality (Mills et al., 2015), and Labor all incorporate empirical analyses of individual, community, and infrastructure adaptation in estimating a climate stressor-response function, and so they reflect historical responses to these stressors. As climate stress worsens and expands geographically, wider adoption of historical adaptation actions (e.g., wider adoption of air conditioning as a response to extreme heat) therefore is implicitly incorporated in the estimated response function, and by extension in the results from the framework. The Roads and Coastal Properties analyses employ a simulation modeling approach which allows for incorporation of baseline adaptation actions (e.g., in high tide flooding a set of “reasonably anticipated actions” such as traffic re-routing are incorporated in the baseline – and continuation and expansion of existing beach nourishment at locations where it is currently practiced is incorporated in the coastal flooding analysis). These simulation modeling approaches also facilitate future adoption of more complex and extensive adaptive actions, such as changing maintenance practices and extending seawall and beach nourishment protections, which constitute new adaptation responses that are known to be cost-effective but which in some current situations have not yet been widely adopted.

Adaptation actions that go beyond historically implemented practices, however, require planning, potentially complex financing, and evaluation of efficacy with consideration of the specific human and natural environment contexts. Adaptation plans therefore are typically developed and implemented at local scales. As such, the general adaptation scenarios considered in the underlying will not capture the complex issues that drive adaptation decision-making at regional and local scales. For example, the Coastal Properties sector study considers the cost effectiveness of adaptive responses to sea level rise inundation and storm surge damages by comparing the costs of protection to the value of those properties at risk. While many factors at the property, community, region, and national levels will determine adaptive responses to coastal risks, this sectoral analysis uses the simplistic cost/benefit metric to enable consistent comparisons for the entire coastline. However, the adaptation scenarios and estimates presented in all sections of this report should not be construed as recommending any specific policy or adaptive action.

Overall, the potential for adaptation in sectors where adaptation is not assessed likely leads to an overestimation of future climate-related impacts. Adaptation response can lead to orders of magnitude differences in impact estimation in some sectors (e.g., Transportation Impacts from High Tide Flooding, see Hartin et al. (2023)) and are therefore these sensitivities remain important to consider when assessing the risks of future climate change.

- **Climate Model (or GCM) Uncertainty.** Nearly all of the peer-reviewed studies underlying FrEDI examine climate-related impact outcomes across multiple climate model projections (combinations of CMIP5 GCMs and RCPs, although the method can also accommodate CMIP6 GCMs and SSPs if temperature arrival times can be mapped to the damage results). These data are used to develop multiple GCM-specific damage functions for each sectoral impact within FrEDI. When run, FrEDI

then outputs sector-specific impact results for each GCM, as well as an average across all available GCMs, thereby allowing direct assessment of impact variability across climate models for each sector. Variability across GCMs, particularly at the local scale, for both temperature and precipitation can be substantial (see related discussion of limitations in Section 2.8). For those sectors where there is little variation in impacts resulting from the different GCMs, such as Winter Recreation and Temperature-Related Mortality, there can be reasonable confidence in the resulting range of impact outcomes. For other sectors with more GCM-to-GCM variability, or those with fewer GCM results, such as for climate impacts on the Rail sector, confidence in the resulting range will be lower. However, even within the full suite of six CMIP5 GCMs that are used in many of FrEDI's underlying studies, these GCMs do not represent the full range of possible future temperature and precipitation outcomes, and therefore the derived impact-by-degree damage functions may be limited. More work understanding the causes of this variability, such as whether it is related to GCM-specific changes in precipitation or temperature changes in specific regions, could enable more sophisticated assessments. These sources of uncertainty likely have a minor impact on central estimates, but a potentially major impact on variability.

- **Sea-Level Rise Uncertainty.** For SLR-driven sectors, the current configuration of the framework relates temperature to SLR in a deterministic fashion, but other research has quantified broad uncertainty bands for both GMSL and specific locations where SLR could occur, as summarized in Kopp et al. (2014). The FrEDI framework could be run in batch mode with multiple custom trajectories of future SLR to assess this component of uncertainty.
- **Socioeconomic and GHG Emissions Uncertainty.** While the FrEDI R package cannot internally account for uncertainty in GHG emission projections associated with input temperatures or population and GDP trajectories, FrEDI can be run in batch mode as a way to assess uncertainties in these input parameters. For example, as described in Hartin et al. (2023) FrEDI was run in batch mode, in combination with a simple climate emulator, to project the impacts of climate change to the U.S. under 10,000 probabilistic trajectories of global GHG emissions, U.S. population, and U.S. GDP (Rennert et al., 2022). FrEDI impact results from the 10,000 individual runs provided valuable insight into the sensitivity of impacts to changes in input parameters and uncertainties associated with assumptions underlying the development of the probabilistic scenarios.

In addition to input uncertainty, there may also be uncertainties associated with socioeconomics in FrEDI's underlying sectoral studies, that are not currently captured in framework. The ability to fully evaluate uncertainty in impacts associated with socioeconomic inputs is limited in FrEDI for four reasons: 1) The underlying sector studies may incompletely incorporate the effect of changes in population, GDP, demographic distribution, or other socioeconomic factors on impact estimates; 2) The underlying studies model impacts as a non-linear and/or dynamic process such that custom population and GDP scenarios cannot be fully assessed in FrEDI and year-specific adjustment factors must be used instead; 3) The underlying studies generally do not assess how socioeconomic factors

affect adaptive capacity, which in turn can affect impact estimation; 4) Socioeconomic drivers may have important correlative dependency on climate scenarios, because of feedback of climate impacts and mitigation policy costs and incidence on population and economic output and its spatial distribution.

The following sources of uncertainty cannot be directly assessed in the current FrEDI framework but are qualitatively discussed here.

- **Warming Arrival Times:** As described in Section 2.3 of this technical documentation, FrEDI damage functions have typically been estimated using a single or limited number of emissions scenarios (e.g., RCP8.5), and a limited number of climate models. However, there may be differences in any temperature change scenario depending on how and when that level of warming is reached (Sarofim et al., 2021). Aspects of this question have been addressed by several researchers (Baker et al., 2018; Ruane et al., 2018; Tebaldi et al., 2021, 2020; Tebaldi and Knutti, 2018); generally, these studies find that the sensitivity of impacts for a given temperature level to the specific scenario is low compared to other sources of uncertainty or similar to range of impacts predicted across different GCMs, but that there are important sensitivities in the CO₂ concentration, aerosol concentration, and interannual variability across scenarios.⁴⁰ One physical difference that can arise when a temperature threshold is reached later in time is that the land-ocean differential would be expected to be smaller as a scenario approaches stabilization: this potential issue is partially addressed by using national rather than global temperatures for the binning.
- **Socioeconomic Scalar Inconsistencies.** There may be inconsistency between sector results with fully scalable and those with incompletely scalable socioeconomic inputs. Some sectors in the framework incorporate two types of socioeconomic input adjustments: direct impacts of population and GDP, and additional impacts associated with some sector and location specific adjustments such as age distribution of the subject population. The primary adjustments are “user-controlled”, and their influence can be readily observed, but the secondary adjustments are not transparent and, while they remove overall bias, could be inconsistently applied.
- **Uncertainty Aggregation or Propagation.** There are currently a limited set of other sectoral or aggregation studies that attempt to propagate uncertainty across the major steps in climate impact assessment. One notable effort to do so is Hsiang et al. (2017) which estimates the joint uncertainty in impact estimates across the dimensions of emissions uncertainties (characterized by three RCPs); climate projections (characterized by a wide range of individual GCM inputs); and statistical

⁴⁰ Additional sensitivity analyses of the impact of different numbers of year in the temperature bin indicate that the arrival year is not particularly sensitive to this factor. For example, the sensitivity of results to the use of RCP4.5 (rather than RCP8.5) to parameterize the framework for a key sector (Roads) is assessed. The Roads sector relies on both temperature and precipitation climate inputs, the combination of which could see large differences in patterns at various temporal and spatial scales. The analysis concludes that while there are important differences among specific GCMs, for the ensemble mean and overall range of results across GCMs there is a small effect on the economic impact results.

econometric estimation of impacts for six sectors (agriculture, extreme temperature mortality, electricity demand, labor, violent and property crime, and coastal properties). The FrEDI framework, however, is designed primarily to estimate the sensitivity of impact estimates to alternative individual choices for inputs, including varying adaptation responses, rather than propagating uncertainty across these dimensions. Attempting to propagate quantitative uncertainty estimates across analytic steps in the FrEDI framework, as currently configured, would involve mixing estimates of variability (e.g., across GCMs) with estimate of statistical uncertainty (e.g., for sector impacts that rely on statistically estimated exposure-response or stressor-response relationships, to the extent they are identified in the underlying literature), and could not be comprehensively applied across sectors. In addition, a joint estimate of uncertainty would necessarily ignore other sources of uncertainty that cannot be quantified (e.g., structural uncertainty associated with the choice of a single sector impacts model) and potential correlation in sources of uncertainty that may not be fully independent (e.g., many GCMs share a common structural foundation).

Limitations specific to the framework (such as geographic and sectoral scope) are described in the next Section. Limitations of individual sectoral analyses are summarized in Appendix B and detailed more fully in the peer-reviewed literature underlying the sectoral analyses.

2.8 Framework Limitations and Considerations

FrEDI provides a method of utilizing existing climate change sectoral impact studies to create estimates of the physical and economic impacts by degree of warming. EPA designed the framework to readily synthesize the results of a broad range of peer-reviewed climate change impacts projections, and to support analysis of other climate change and socioeconomic scenarios not directly assessed in the supporting literature. Projected physical and economic impacts from the framework are intended to provide insights about the potential magnitude and distribution of climate change impacts within U.S. borders. While FrEDI provides the most comprehensive and detailed estimates to date of future climate change impacts to the U.S., none of the estimates should be interpreted as definitive predictions of future impacts and damages. Instead, the intention is to produce estimates of future effects using a reliable and flexible method for generating rapid results, which can be revisited and updated over time as science and modeling capabilities continue to advance.

In addition to the uncertainties discussed in Section 2.7 above, the results provided by FrEDI should be used and interpreted with consideration of the following limitations, some of which may be addressed through future refinement of the framework, particularly continued addition of new sectoral studies:

- Coverage of Sectors and Impacts:** FrEDI incorporates a subset of all known climate change impacts, chosen based on current understanding, available data and methods, and demonstrated magnitudes of economic effect. EPA (2017a) further identifies additional sectors and impacts not addressed in the broader CIRA project, including cross-sectoral impacts, and incomplete coverage of effects within sectors – those are also omitted here. Examples of key missing sectors include the impacts of climate change on forestry, migration, broad-scale effects on ecosystem services and

species, and political instability. Sectors that have already been modeled and incorporated into the framework can be improved to capture more of the physical and/or economic effects, such as by expanding the population coverage and characterization of adaptation for temperature-related mortality. Using more than one sectoral model to estimate impacts for a given sector would also lead to increased understanding of the results (and increased confidence if the models agree). Further, the sectoral studies largely omit potentially important indirect effects (e.g., how does road and electricity distribution infrastructure failure affect health and welfare, particularly during extreme events), the potential for cascading failures, and the inability comprehensively to value all outcomes (e.g., the underestimation that results from using only cost to treat illness in some health sector studies, as opposed to the full willingness to pay to avoid sickness). As a result, the scope of estimates included in this framework very likely underestimates impacts that could be reasonably expected under future climate scenarios.

- **Interactive or Correlative Effects.** In general, the impact analyses were developed independently of one another, and, as a result, the estimated impacts may omit important interactive or correlative effects. Cross-sectoral impacts, particularly in infrastructure sectors, have been shown to amplify effects.⁴¹
- **Feedbacks:** The socioeconomic scenarios that drive the modeling analyses do not incorporate potential feedbacks from climate change impacts to the socioeconomic system (e.g., changes in albedo from land use change or increased GHG emissions resulting from vegetative changes) nor from sectoral damages to the economy (e.g., significant expenditures on protective adaptation measures, such as seawalls, would likely reduce available financial capital to the economy for other productive uses). Feedback effects of GHG mitigation policy on infrastructure, such as energy demand reduction, decarbonization policies, or the potential decentralization of the grid, are also omitted in the framework (although climate induced changes in energy demand, such as for space heating and cooling, are incorporated in the Energy Demand and Supply sectoral study, see Appendix B for details). Also as discussed in the Uncertainties section above, the FrEDI framework does not yet incorporate the feedback impact of income growth over time on adaptive capacity.
- **Path Dependency:** Sectors where the impacts are a function of cumulative exposure can be more challenging to represent in a temperature binning context. For example, sea level rise is a function of the integration of heat absorption by the ocean and melting of land ice, and so is a more complex function of temperature over time, compared to health impacts from heat stress that occur in direct response to local ambient weather. There are also potential irreversible effects which might accumulate dynamically and lead to cascading or indirect effects, such as impacts on accumulated human and physical capital over time. There are approaches to addressing some of these difficulties: for example, financial smoothing is applied in the framework for one-time adaptation

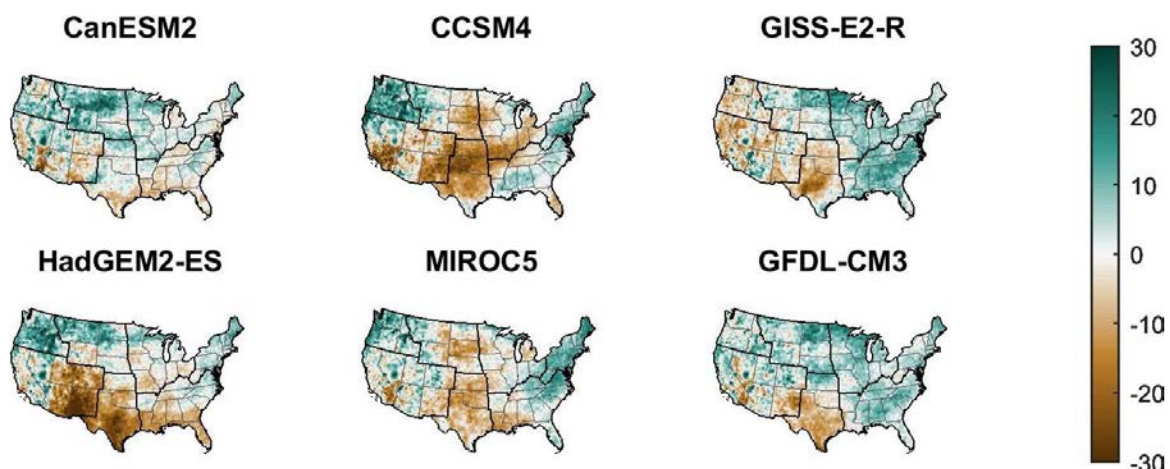
⁴¹ See both (Jacobs et al., 2018; Maxwell et al., 2018)

costs or threshold damages to avoid discontinuities in the relationship between temperature and damages.

- **Geographic Coverage:** The primary geographic focus of this framework is the contiguous U.S., excluding Hawai'i, Alaska, and the U.S. territories – reflecting the geographic focus of the available underlying economic impact studies. This omission is particularly important given the known unique climate change vulnerabilities of these high-latitude and/or island locales.
- **Variability in Societal Vulnerability Characteristics:** The results from the framework do not separately report impacts for overburdened populations for all sectors, only for the six sectors analyzed in EPA's Climate Change and Social Vulnerability report, nor does the framework analyze how individual behavior affects vulnerability to climate. Results are aggregated across demographic groups.
- **Population Migration and Urbanization Effects:** FrEDI cannot account for any assumed changes in population migration within the U.S. as compared to the default ICLUS dataset. Any more spatially resolved population distribution factors are defined by the socioeconomic scenarios used in the underlying studies, which for many sectors is the ICLUS population scenario. Recent demographic and migration trends reflect increasing urbanization in the U.S., and recent literature suggests that climate change impacts and vulnerabilities could be a driver of migration. For the Temperature-Related mortality sector in particular, urban areas display a pronounced heat island effect, which may be incorporated in the framework, to the extent the underlying studies rely on local, urban-scale temperature data (as the Mills et al. 2015 study does) and the projected changes in broader scale temperature changes from GCM reflect a similar absolute increase in temperature at urban-scale. Increased urbanization also could lead to increased impacts – or migration away from climate hazards, such as extreme temperature and coastal flooding, could decrease impacts. These types of impacts will need to be assessed in the underlying demographic and sectoral impact literature before they can be reflected in impact estimates from FrEDI.
- **Changes in Non-Climate Drivers:** Some sectors in this analysis have significant non-climate drivers. For example, changes in land use and forest management could have substantial implications for the climate response of impacts such as wildfires or fugitive dust. If the underlying study did not consider such sensitivity analyses, the framework cannot yet consider them.
- **Co-benefits and Ancillary Benefits and Costs of Climate Policy:** This framework only examines the direct impacts of climate change. It does not, for example, estimate the benefits of reducing co-emitted air pollutants such as nitrogen oxides, volatile organic carbons, or particulate matter due to climate policy. As such, this framework does not address the costs of reducing emissions, which have been well-examined elsewhere in the literature (e.g., "Energy Modeling Forum," n.d.).

Similarly, the health benefits associated with reductions in other co-emitted air pollutants, beyond the two conventional pollutant emission scenarios considered in the Air Quality sector that are not tied to GHG mitigation, are beyond the scope of this framework. FrEDI also does not capture interactions between sectors (such as the land-energy-water nexus), including the potential for compounding or cascading effects across sectors.

- Representation of Temperature Patterns:** FrEDI relies on estimation of impacts based on annual CONUS temperature indexing. An infinite combination of daily or even hourly temperatures, varying spatially across CONUS, can reach the same average annual temperature nationally. FrEDI is calibrated to these variations as represented in the GCMs used in the underlying sectoral impact models. Input temperature scenarios may have, for example, a different distribution of heat across states or a different distribution of extreme high and low temperature days than any of the GCMs that were considered, which could have implications for some sectoral impacts categories (e.g., temperature-related mortality) however the specifics of this detailed pattern of temperatures related to the input scenario would not be captured in FrEDI. That is not to say extreme temperatures are not represented in the framework; they are present as defined by the underlying climate models. More detail on this point can be found in Sarofim et al. (2021). Additionally, if global temperatures are input to FrEDI rather than CONUS temperatures, the translation from global to CONUS temperatures is fixed based on the estimated relationship described in Section 2.4 and does not take into account how that relationship might vary by GCM and over time, for example with stabilization.
- Representation of non-temperature climate stressor patterns:** The same limitations described in the previous bullet apply to non-temperature stressors. For example, precipitation patterns, in terms of intensity, frequency, and location of events, vary by GCM, and therefore precipitation driven impacts represented by degrees of CONUS temperature change developed for each FrEDI damage function reflect the precipitation patterns present in the GCMs used in the underlying sectoral impact models. For precipitation-driven impact sectors, this can result in larger variations between GCM-specific impacts by degree compared to temperature-driven sectors. **Figure 3** shows the percent change in precipitation compared to baseline for the six GCMs at two degrees of warming. The adopted method in this framework is to calculate impacts using several GCMs and use the average for interpretation. An alternative method could be to rely upon results from a subset of GCMs that are known to have similar climate patterns to the scenario of interest. For example, if there is interest in the implications of a relatively wet future, an analysis using the CMIP5 CanESM2 GCM, the wettest of the ensemble, could provide insights.

FIGURE 3. PERCENTAGE DIFFERENCE IN PRECIPITATION FOR THE 2-DEGREE TEMPERATURE BIN


Maps of the differences in annual mean precipitation (%) from 1986-2005 average baseline annual mean precipitation at 1/16th degree for six GCMs used across a number of underlying sectoral impact models.

- Rate of Change and Direct Effects of GHGs:** This approach does not capture impacts that are a function of rate of change, rather than absolute change (though there is a paucity of studies on that topic in general). Nor does it capture impacts that are a direct function of greenhouse gas concentrations, such as ocean acidification, CO₂ fertilization, or ozone resulting from methane oxidation in the atmosphere.⁴² Impacts that are sensitive to non-GHG factors, such as aerosol emissions or land-use changes, continue to be challenging to emulate. Inter-sectoral interactions (such as the land-water-energy nexus) and cascading risks would also be difficult to capture in this framework. Some of these challenges are surmountable – for example, (Schleussner et al., 2016) shows temperature slices for coral reefs under assumptions of coral adaptation for both 2050 and 2100 in order to account for the ability of coral to adapt to slower rates of change, and (O’Neill et al., 2017) created reasons for concern figures for rate-of-change and CO₂ concentration as a complement to the temperature-based reasons for concern – but require more complexity in approach.

⁴² Note that the air quality estimates for ozone do not consider changes in methane emissions associated with greenhouse gas reduction policies, only the climate penalty on ozone formation associated with changes in meteorology for two overall conventional pollutant emissions scenarios.

THREE | DEMONSTRATION OF THE FREDI FRAMEWORK

This chapter demonstrates how FrEDI can be used to quantify and communicate the annual physical and economic impacts of climate change to the United States under multiple future scenarios. The first example illustrates how detailed output from FrEDI can inform a distributional analysis of climate change impacts under a single hypothetical “baseline” scenario (defined only for purposes of illustrating FrEDI’s capabilities). The second example demonstrates how FrEDI can be run with two climate scenarios to estimate the change in projected physical and economic impacts associated with a temperature change resulting from an illustrative GHG emissions mitigation policy. Both scenarios in this Chapter use FrEDI’s default population and GDP inputs⁴³, as well as the default income elasticity, and include the primary adaptation variants and sectoral studies identified in **Table 1**. Results presented represent the average damages across GCMs.

These examples are not meant to be exhaustive of the types of analyses that can be informed by FrEDI and its results, and are only intended to provide illustrative examples of the types of detailed and customizable analytical capabilities that are unique to FrEDI. Other recent analyses using FrEDI include an assessment of the distribution of climate change impacts across regions, sectors, and populations in over 10,000 probabilistic scenarios of future GHG emissions, U.S. population, and U.S. GDP (Hartin et al., 2023); analyses of marginal emission changes through 2300 to quantify the net present climate damages per ton of CO₂, CH₄, and N₂O emissions (Hartin et al., 2023; EPA, 2023); and an analysis of the projected benefits to the U.S. associated with meeting global temperature targets as part of the 2021 Long Term Strategy of the U.S. (Department of State (DOS), 2021). See the FrEDI [publications page](#) for a current list of published analyses that have used FrEDI results.

3.1 FrEDI Example Application #1: Distributional U.S. Climate Change Impacts

Quantitative evidence of climate change and its impacts overtime is a critical input to decision-making and policy development. In addition to the total magnitude of change, distributional impact analyses also provide unique understanding of the potential risks of climate change and insight into how these risks may be experienced differently across the United States. For example, the impacts of climate change occurring in a particular region or community will be determined by the sensitivities to physical climate stressors in each location (e.g., heat, wildfire, flooding), as well as the ability or capacity of each community to adapt. Outputs from FrEDI provide the information needed to quantitatively assess the total magnitude and relative

⁴³ The default population scenario is based on the national-level UN Median Population projection (United Nations, Department of Economic and Social Affairs, Population Division, 2015), disaggregated to the county-level using EPA’s ICLUSv2 model (Bierwagen et al., 2010; EPA, 2017b) and reaggregated to NCA regions for this analysis. GDP projection is defined by the EPPA, version 6 model (Chen et al., 2015), using the aforementioned UN Median population projection for the U.S. (United Nations, Department of Economic and Social Affairs, Population Division, 2015) and the 2016 Annual Energy Outlook reference case (USEIA, 2016) for the U.S. through 2040.

distribution of future climate change impacts, with flexible post-processing options to tailor the communication of results to users needs and/or interests.

In this first example application, default⁴⁴ FrEDI is run through 2090 using an input of annual CONUS temperature changes (relative to FrEDI 1986-2005 baseline) that increase linearly from 0° C in 2010 to 6° C change by 2090. This scenario is only intended to illustrate an example ‘baseline’ analysis to demonstrate the breadth of FrEDI’s analytical capabilities and is not intended to reflect or endorse a particular scenario. Unlike more complex models that have nonlinear dynamic processes, the impacts-by-degree damage function approach does not include internal variability, which enables the use of FrEDI to analytically assess future climate-related impacts under any level of temperature increase relative to the 1986-2005 baseline. While FrEDI can be applied to any scenario, as described in Chapter 2, FrEDI’s damage functions are calibrated to start at the 1986-2005 baseline, so in a scenario where the climate cools below that baseline temperature, damages in FrEDI are set to zero.

Figure 4 shows the resulting projected climate-related damages to the U.S. in three future years (2050, 2070, and 2090) for this hypothetical 6-degree scenario. These impacts represent both a warming climate and changing socioeconomic conditions. Total annual damages for each year in **Figure 4** are summed across all regions (and states) and 22 default impact category sectors, which are grouped into 6 aggregate categories (**Table 1**). Default options are used for sectors with multiple variant or adaptation options. In this hypothetical 6 degree C warming scenario, FrEDI estimates over \$1 trillion or ~\$2,500/person (2015 USD) of U.S. climate-related damages each year by 2050, which increase by nearly a factor of 5 to ~\$5 trillion or ~\$11,000/person (2015 USD) of damages each year by the end of the century.⁴⁵ While absolute annual U.S. monetized damages will vary strongly with different temperature and socioeconomic input scenarios, the largest share of damages will occur in health category sectors, regardless of scenario. These category impacts are largely driven by the valuation of future changes in premature mortality associated with projected changes in temperature and climate-related changes in air pollution exposure. Impacts to infrastructure and labor categories will also experience the second and third largest share of national annual climate-related damages under most future scenarios. Remaining damages can be expected to occur in sectors in the electricity, agriculture, and ecosystems & recreation categories. These relative rankings reflect damages captured in the current version of FrEDI but are subject to change in future versions, dependent on the availability of new sectoral study information.

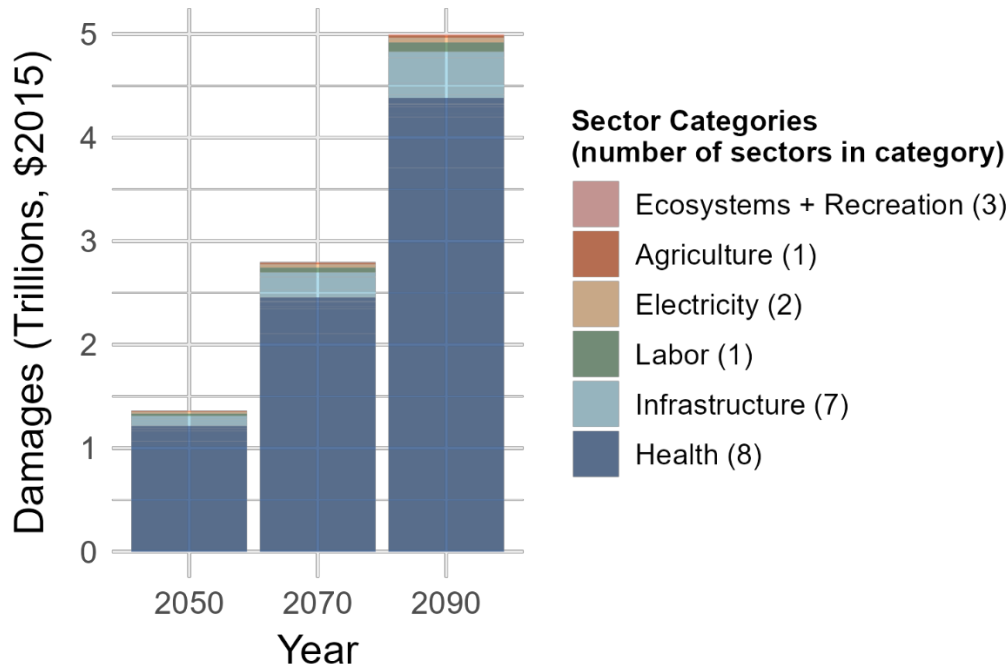
⁴⁴ The `run_fredi()` R code is run with default input options, including an income elasticity of 1.

⁴⁵ The 6-degree illustrative scenario is employed to show results that account for the effects of the damage function extrapolation approach implemented in FrEDI (see Section 2.3). The latest IPCC global temperatures projections range from 2.7°C for a very low emissions scenario to 4.4°C for a very high emissions scenario, equivalent to approximately 3.8°C to 6.2°C CONUS warming by the end of the century. See Section 3.1.1 in the [AR6 Synthesis Report](#) for more details on the likelihood of particular levels of warming (IPCC, 2023).

FIGURE 4. ANNUAL CONUS CLIMATE-DRIVEN DAMAGES (NOT COMPREHENSIVE)

Annual U.S. Climate-Driven Damages

Mean Damages by Year and Category (Trillions \$)
Subset of Climate-Related Impacts



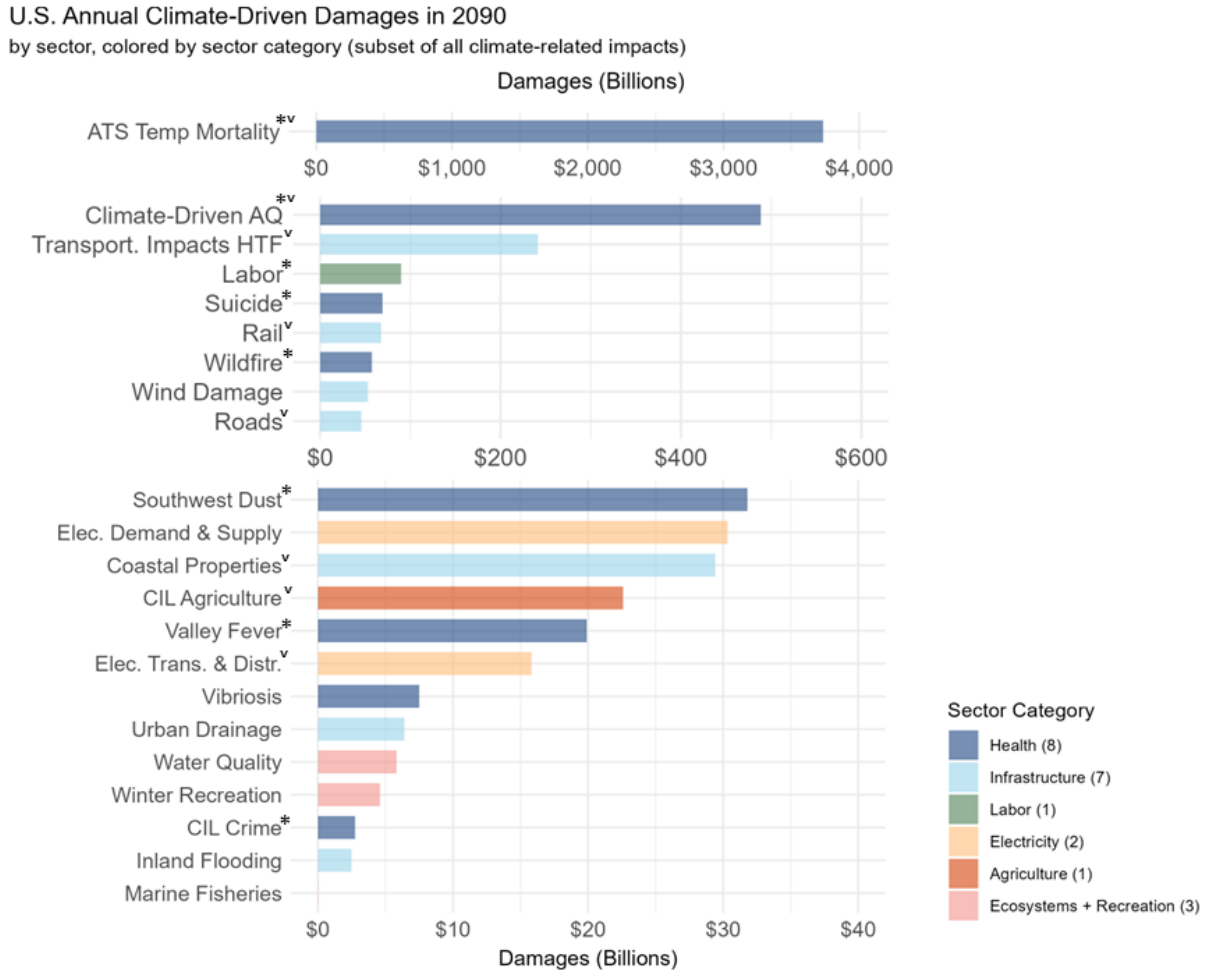
Annual climate-related damages (trillions of 2015\$) to the U.S. in 2050, 2070, and 2090 for a hypothetical climate scenario reaching 6 degrees of warming by 2090. Impact sectors are grouped into six aggregate categories for visual purposes. The number of impact categories included in each sector is given in parentheses in the legend. See Table 1 for identification of impact categories by sectors. Damages reflect the sub-set of climate-related damages currently included within FrEDI and do not provide a comprehensive accounting of all climate-related damages to the U.S.

Figure 5 shows the distribution of annual monetized climate-related impacts in the year 2090 in each FrEDI impact sector for the hypothetical 6-degree scenario. Sectors in **Figure 5** are listed in order of decreasing annual national total damages in 2090. Temperature-related mortality is the largest single impact sector and accounts for approximately three quarters of the total annual damages in 2090. The remaining top 10 sectors projected to experience the largest national-level damages in 2090 include climate-driven changes in air quality-related mortality, transportation impacts from high tide flooding, impacts to labor hours, suicide incidence, rail transportation, wildfire health impacts and response costs, wind damage from tropical cyclones, impacts to roads, and mortality and morbidity from dust exposure in the Southwest. Like the aggregate national totals in **Figure 4**, the absolute magnitude of impacts in each sector are expected to vary with temperature and socioeconomic input scenarios, however the relative sectoral contributions are expected to remain similar across scenarios.

In addition to monetized damages, sectors with [*] in **Figure 5**, include annual estimates of both physical and monetized damages. Physical damages include, for example, counts of premature mortality or morbidity, number of labor hours lost, or the number of crime incidents. See **Table 1** for more details. For

sectors with [*] in **Figure 5**, FrEDI also includes multiple adaptation variant options, with results in **Figure 5** illustrating monetized damages from the default adaptation option (**Table 1**).

FIGURE 5. ANNUAL CONUS CLIMATE-DRIVEN DAMAGES IN 2090 BY IMPACT CATEGORY

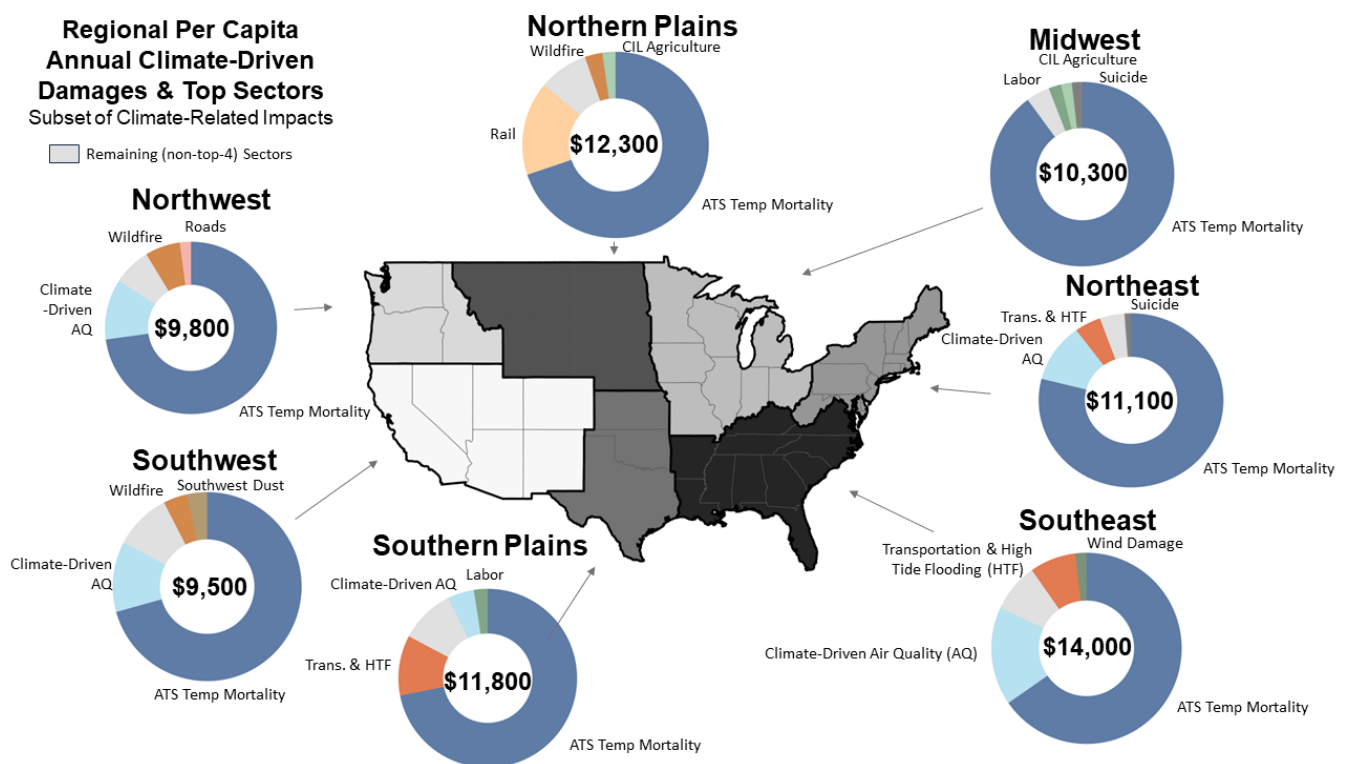


Annual damages in 2090 (billions of 2015\$) for the hypothetical 6-degree scenario. Sectors are ordered by decreasing damages—note the use of different x-axis scales in each panel. Impact sector bars are colored by aggregate categories. Note, Marine Fisheries impacts are visually indistinguishable from zero. * symbol indicates sectors that are output from FrEDI with both physical and monetized annual impacts. v symbol indicates sectors that include multiple adaptation options. Damages reflect the sub-set of climate-related damages currently included within FrEDI and do not provide a comprehensive accounting of all climate-related damages to the U.S.

FrEDI also outputs sectoral impact information at the sub-national level, which helps inform potential adaptation planning and improves understanding and communication of future climate change risks to specific communities. For example, **Figure 6** presents 2090 annual damages per capita, by region and by sector for the hypothetical 6-degree scenario. The map shading indicates the relative total damages per capita in each region in the year 2090, also shown by the value in the center of each donut chart. The regional donut charts also illustrate the relative share of damages in the four largest individual impact sectors within each region (share of damages from all remaining 18 sectors in gray). For example, the Southeast is projected to experience the largest climate-change damages in 2090 compared to other

CONUS regions, and these damages are projected to be driven by changes in temperature-related mortality (dark blue), climate-related changes in air quality mortality (light blue), transportation impacts from high tide flooding (orange), and wind damage (dark green). The share of total damages in this region from all remaining 18 sectors are given in light gray. In contrast, the Southwest is projected to experience the smallest climate-related per capita damages relative to other CONUS regions, with the largest damages also driven by temperature- and air-quality-related mortality, as well as wildfires and exposure to southwest dust. **Figure 6** illustrates that while temperature-related mortality is the single sector with the largest share of 2090 damages at both the national and regional levels, other sectors have important regional impacts, such as wildfires having relatively greater damages in the Northwest, Southwest, and Northern Plains, high-tide flooding damages having greater impacts in coastal regions such as the Southeast, Southern Plains, and Northeast, and sectors like agriculture and rail having relatively larger damages in the Midwest and Northern Plains. As with national damages, the relative distribution of damages across each region and sector are expected to be similar across different input scenarios, while the absolute magnitude of impacts will change.

FIGURE 6. ANNUAL CONUS CLIMATE-DRIVEN DAMAGES PER CAPITA IN 2090 BY REGION



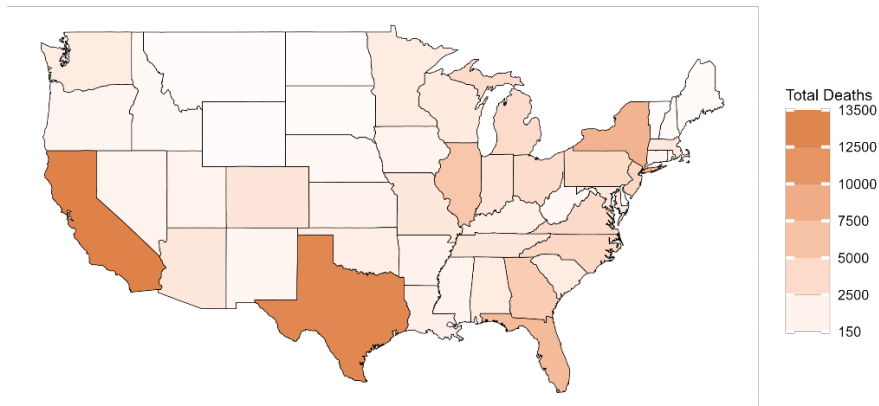
Per capita annual damages (2015\$) in 2090 under the hypothetical 6-degree scenario. Donut charts show the annual per capita damages (center) and identify the share by impact category for the four largest impact sectors per region. Total damages from all remaining 18 sectors in each region are shown in light gray. The shading in the map represents the magnitude of per capita damages across regions. Damages reflect the sub-set of climate-related damages currently included within FrEDI and do not provide a comprehensive accounting of all climate-related damages to the U.S.

State-level damage information from FrEDI provides even more detail relevant to climate change risk analysis and communication. For example, **Figure 7** explores the distribution of the number of temperature-

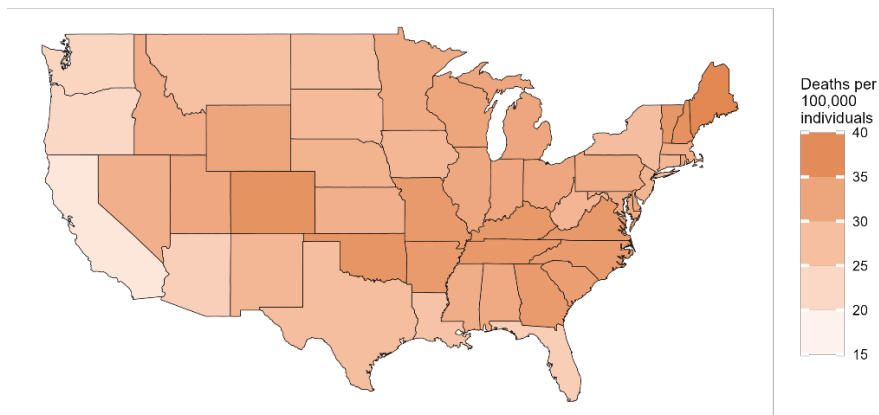
related premature deaths in each state in 2090 in the hypothetical 6-degree scenario. The two panels in **Figure 7** shows absolute premature mortality counts (top) and counts per 100,000 people (bottom). While temperature-related mortality is the sector with the largest damages in each region, **Figure 7** shows that the mortality counts (and their monetization) also vary within these regions. For example, in the Southeast, the absolute greatest increases in mortality are projected to occur in Florida (top panel), however, when normalizing for differences in population, the increases in the temperature-related deaths per capita are relatively larger in Tennessee and Georgia (bottom). Results in the top panel largely reflect the distribution of total population within the CONUS, however the per capita results are driven by the distribution of the levels of warming in each state relative to a global change in temperature (e.g., northern latitudes warm faster than southern latitudes, etc.). While the state-level distribution of damages within many other FrEDI sectors (e.g., health category sectors) also track with total population, damages in sectors that are not dependent on population (e.g., agriculture) have different relative spatial patterns than those in **Figure 7**.

FIGURE 7. ANNUAL TEMPERATURE-RELATED PREMATURE DEATH OUTCOMES IN 2090 BY STATE

Annual Temperature-Related Premature Mortality in 2090 by State



Per 100,000 people



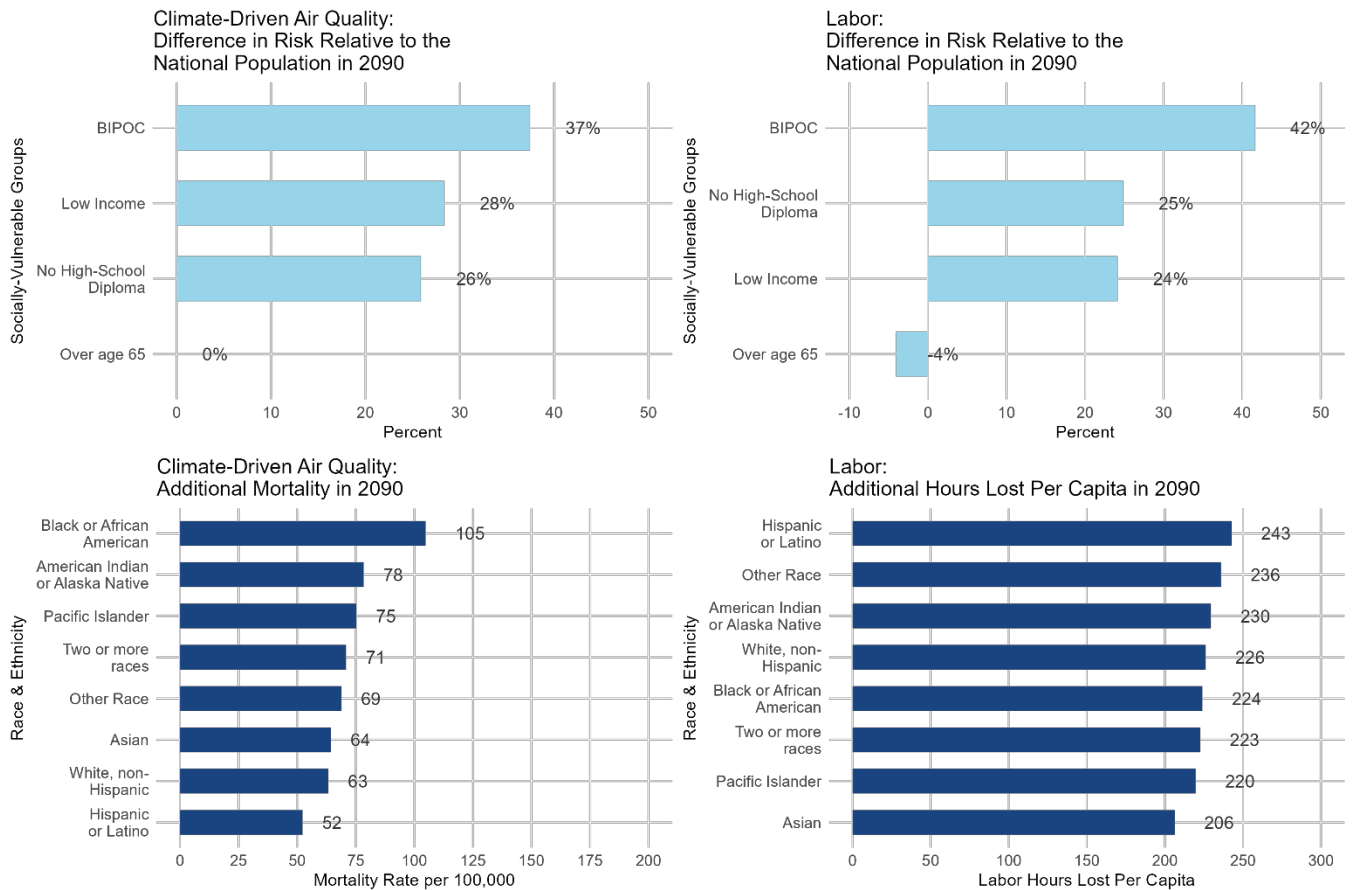
Distribution of temperature-related mortality counts in 2090 across 48 CONUS states. The top panel shows absolute total premature deaths in 2090 under the hypothetical 6-degree scenario. The second panel shows premature deaths per capita, using 2090 population.

Lastly, results from the FrEDI SV module can assess how future climate-change risks may be experienced differently across different population groups of concern: (1) individuals with low income (below two times the national poverty line), (2) those identifying as Black, Indigenous, or people of color (BIPOC), (3) those that are without a high school diploma, and (4) those that are 65 years of age or older (described in Chapter 2). Understanding differences in risks across different populations is critical for developing effective and equitable strategies for responding to climate change.

Figure 8 presents example results from the FrEDI SV module for two sectors in the hypothetical 6-degree scenario: climate-related air quality mortality and labor sector damages. The top two panels (light blue) shows the difference in risks in each sector in 2090 for individuals in each of the four population groups of concern, relative to the risk of those in each reference population (i.e., everyone not in the defined group). In this analysis, risk is defined as the likelihood of living in areas that are projected to experience the largest climate-related damages in a given sector. In this hypothetical scenario, **Figure 8** shows that individuals in three of the four population groups (race & ethnicity, income, and education) are projected to be at least 20% more likely to live in areas that will experience the largest impacts from climate-related air quality mortality and labor hour losses. For example, those with low income are projected to be over 25% more likely to experience the largest damages from air quality-driven mortality than those who are not low income (reference population). As another example, individuals with no-high school diploma are projected to be about 25% more likely to experience the largest damages in the labor sector compared to those with a higher education attainment level (reference population).

The bottom two panels of **Figure 8** illustrate a more detailed view of the difference in impact rates by individuals of different races and ethnicities. For example, individuals who identify as Black or African Americans are the most likely to be impacted by climate-driven changes in air quality, while individuals who identify as Hispanic and Latino Americans are most likely to experience lost labor hours relative to individuals of other races and ethnicities. Appendix D provides additional information on how both these risk and rate metrics are derived from output of the FrEDI SV module.

FIGURE 8. PROJECTED DISTRIBUTION OF ANNUAL IMPACTS PER CAPITA IN 2090 BY POPULATION GROUP



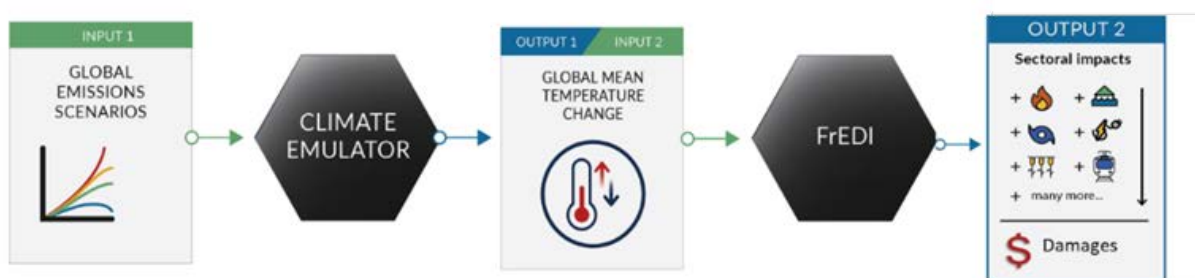
Vulnerability to climate-related changes in air quality mortality and labor hours lost in 2090 in the hypothetical 6-degree scenario. (top) Differences in risk in 2090 for four population groups of concern, (bottom) impact rates by race and ethnicity. Note that the Air Quality metric in FrEDI SV is only calculated for people over the age 65, therefore “Over age 65” relative risk is not applicable.

3.2 FrEDI Example Application #2: Climate-Driven Benefits of Marginal Emissions Change

This second example demonstrates how FrEDI can be applied to quantify the physical and economic benefits of a hypothetical GHG emissions reduction policy. In this example, we use a hypothetical ‘mitigation’ scenario where temperatures increase linearly from 0 degrees C in 2010 to 5.9999 degrees C in 2090. This scenario is designed to illustrate the anticipated changes in CONUS temperature relative to the 6-degree scenario from Example #1, which corresponds to an example GHG emissions reduction policy. While changes in emissions from individual policies may be expected to have marginal impacts on global temperature (illustrated by this scenario), all future “climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States” (USGCRP, 2018). Therefore, the approach using FrEDI outlined in this section can be used with any level of relative temperature change to better understand how specific policies may mitigate the magnitude and distribution of future climate-related damages across different populations within the United States.

First, if a user would like to use FrEDI to assess a custom GHG emissions trajectory or proposed GHG emissions policy (global, national, local), FrEDI should be coupled with output from a climate emulator, such as the Finite amplitude Impulse Response (FaIR) (Smith et al., 2018) model, as shown in **Figure 9**. The climate emulator can first relate projected GHG emission changes to trajectories of global mean temperature change, which can then be re-based to changes relative to FrEDI’s 1986-2005 baseline warming and passed as input to FrEDI to calculate the damages associated with these specific emission-driven temperature changes. By leveraging these flexible capabilities, FrEDI can offer additional context for specific policies to help better understand the magnitude and distribution of potential environmental impacts, avoided damages, or changes in relative risks in the U.S. associated with specific GHG policies.

FIGURE 9. MODEL OF EMISSION SCENARIO TO SECTORAL IMPACT CALCULATION



Flow diagram of the inputs and outputs needed to evaluate the economic damages associated with specific emission-driven temperature scenarios within the U.S., beginning with a custom emissions scenario and resulting in associated sectoral impacts.

In this example scenario, the climate-related benefits (or avoided climate-related damages) are calculated as the difference in damages estimated by FrEDI for the hypothetical 6-degree scenario from Example #1 and the damages estimated by FrEDI from the second scenario that reaches 5.9999 degrees C by 2100 (e.g., net avoided damages = scenario #1 damages – scenario #2 damages). **Figure 10** presents the resulting net⁴⁶ avoided climate-related damages at the national level in the years 2050, 2070, and 2090, based on this hypothetical reduction in warming. While FrEDI is capable of quantifying the net impacts in any year after 2010, results here focus on results in the second half of the century to better illustrate the impacts from avoided long-term climate-related damages. This approach is complementary to an analysis of net present damages, which alternatively aggregates and discounts all impacts that result from a single year of emissions change, through the year 2300.⁴⁷

FrEDI results in **Figure 10** demonstrate that the U.S. is projected to experience net benefits (or net avoided damages) each year from reduced warming in the hypothetical mitigation scenario, with annual end of

⁴⁶ The metric of annual net impacts captures both positive and negative impacts from climate change and is consistent with the approach used in the climate impacts literature, including the U.S. NCA (USGCRP, 2018) and IPCC (IPCC, 2022) assessments

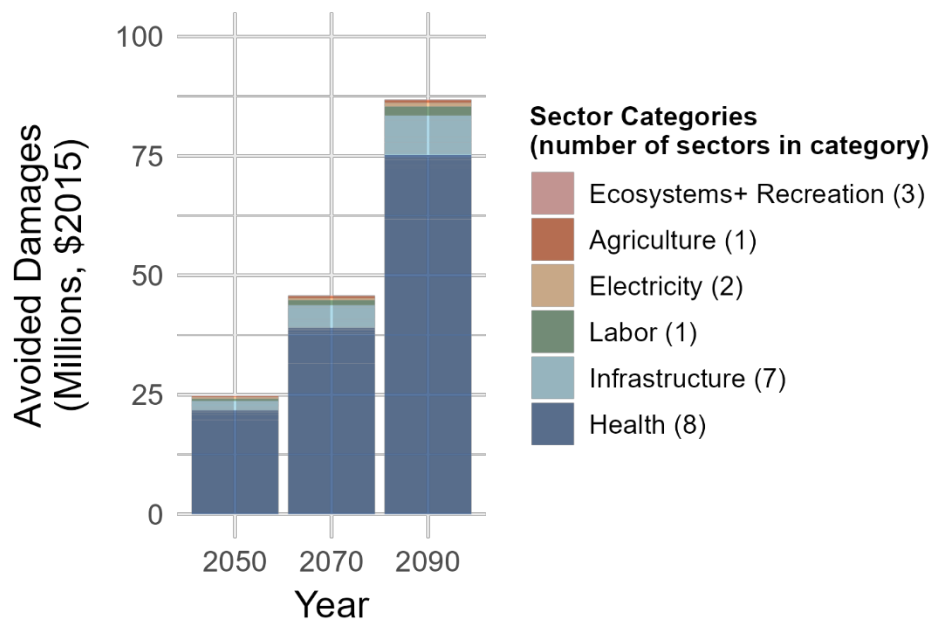
⁴⁷ The FrEDI 2300 module enables users to use FrEDI for a domestic net present damage analysis, as in Hartin et al., 2023.

century benefits over 3x greater than those projected in 2050. The majority of these benefits are projected to occur within sectors that impact human health, including reductions in mortality from temperature changes, mortality from climate-driven changes in air pollution (ozone and ambient fine particulate matter), suicide incidence, exposure to wildfire smoke, Southwest dust, Vibriosis, and Valley fever, as well as reductions in lost labor hours and infrastructure-related impacts such as avoided transportation impacts from high-tide flooding, reduced property damage from hurricane winds, and avoided damages to roads and rail (see **Figure 11** for a breakdown by impact category).

FIGURE 10. NET ANNUAL U.S. CLIMATE-RELATED MITIGATION BENEFITS (SUBSET OF IMPACTS)

Net Annual U.S. Climate-Related Benefits

Net damages avoided from a 0.0001°C decrease in warming by 2090
Subset of climate-related impacts

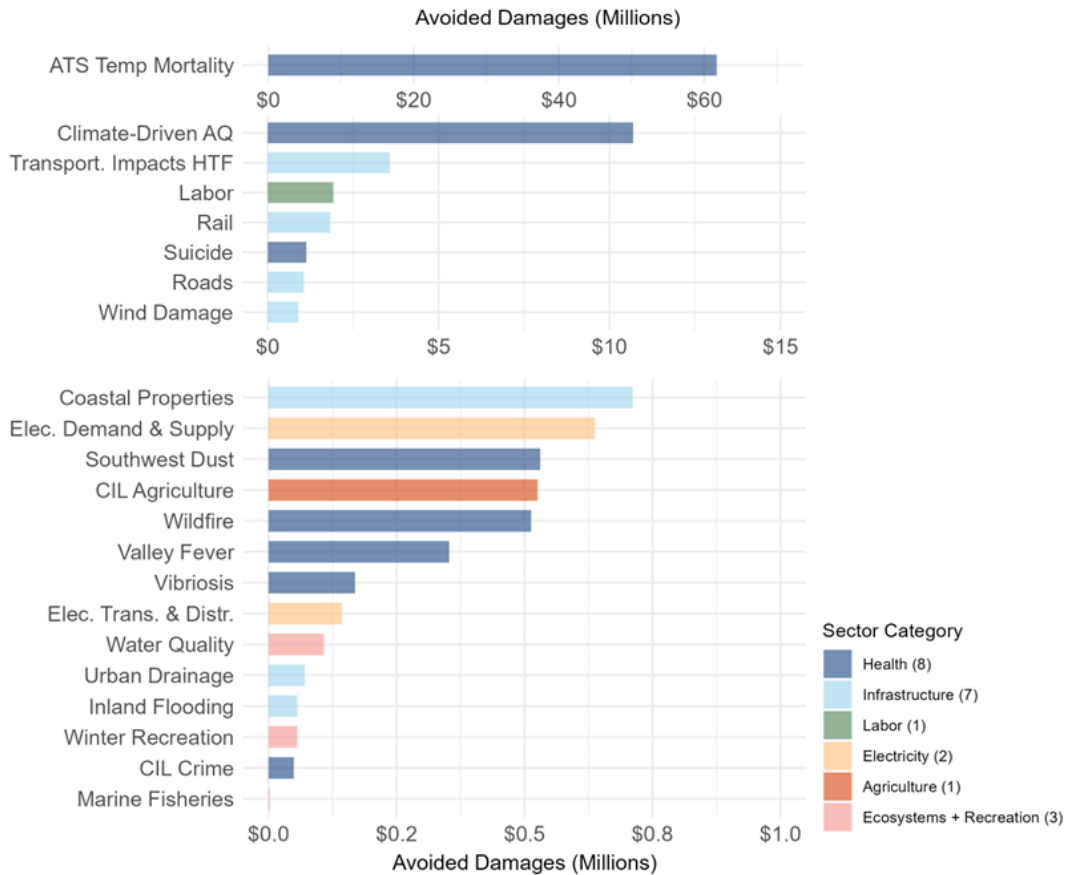


Net annual avoided climate-related damages (millions of 2015\$) to the U.S. in 2050, 2070, and 2090 associated with a hypothetical climate scenario that has a decrease of 0.0001C by 2090 relative to the baseline scenario. Impact sectors are grouped into six aggregate categories for visual purposes. The number of impact categories included in each sector is given in parentheses in the legend. See Table 1 for identification of impact categories by sectors. Benefits reflect the sub-set of climate-related impacts currently included within FrEDI and do not provide a comprehensive accounting of all climate-related impacts to the U.S.

FIGURE 11. U.S. ANNUAL CLIMATE MITIGATION BENEFITS IN 2090 BY IMPACT SECTORS

U.S. Annual Climate-Mitigation Benefits in 2090

by sector, colored by sector category (subset of all climate-related impacts)

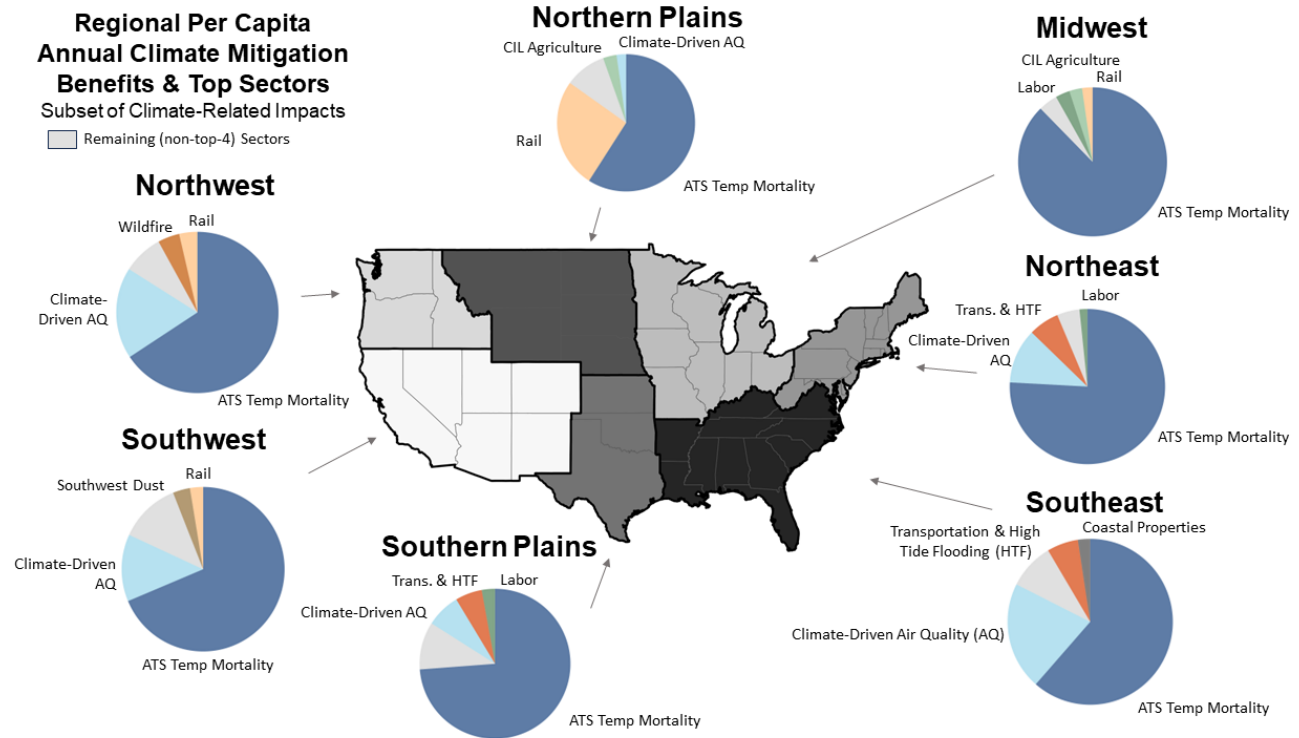


Annual net benefits in 2090 for the hypothetical 0.0001 degree C mitigation scenario, relative to the baseline. Sectors are ordered by decreasing benefits —note the use of different x-axis scales in each panel. Impact sector bars are colored by aggregate categories. Benefits reflect the sub-set of climate-related impacts currently included within FrEDI and do not provide a comprehensive accounting of all climate-related impacts to the U.S.

At the regional level, **Figure 12** provides a more detailed breakdown of how net climate-related benefits in 2090 are expected to vary across seven regions within the contiguous U.S., and which of FrEDI’s sectors are projected to experience the largest share of benefits in each region. The map in **Figure 12** first illustrates that all regions within the contiguous U.S. are projected to experience net reductions in climate-related damages (or net climate-related benefits). The regional pie charts secondarily show that the largest share of benefits in each region are from reduced mortality due to avoided warming. All regions except for the Midwest are also projected to experience large improvements due to reductions in climate-related air quality mortality (2nd largest sectors at the national level) relative to other sectors. There are, however, also notable differences in the sectoral share of regional benefits, including relatively larger benefits from reduced agriculture and rail transportation impacts in the Northern Plains and Midwest, larger benefits from reduced wildfires in the Northwest, and larger benefits from reduced transportation impacts from high tide flooding in the Southern Plains, Southeast, and Northeast regions. As with the results in Example

#1, the magnitudes of projected benefits in each region are expected to vary with custom inputs, but the relative distribution of regional and sectoral benefits is expected to be more similar across scenarios.

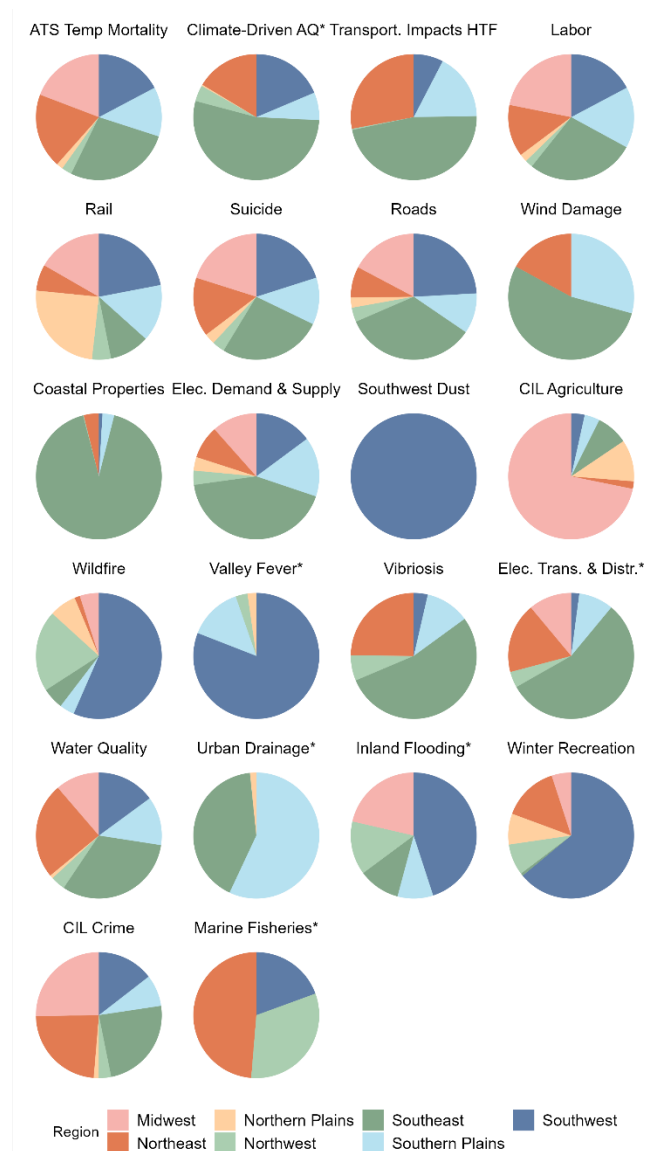
FIGURE 12. DISTRIBUTION OF PER CAPITA MITIGATION BENEFITS BY REGION AND RELATIVE CONTRIBUTIONS FROM TOP SECTORS IN 2090



Distribution of per capita annual mitigation benefits in 2090 under the hypothetical 0.0001C mitigation scenario. Pie charts identify the share of net benefits for the four largest (and remaining, in gray) impact sectors in each region. Benefits reflect the sub-set of climate-related impacts currently included within FrEDI and do not provide a comprehensive accounting of all climate-related impacts to the U.S.

For a more detailed sector-specific perspective, **Figure 13** provides an additional breakdown of the share of benefits occurring within each region for each of FrEDI’s sectors. The pie charts in **Figure 13** illustrate that for some sectors, benefits are only expected to occur in select regions. Examples include reductions in climate-driven changes in dust and Valley fever primarily in the Southwest, reductions in tropical wind damage and transportation impacts from high-tide flooding largely occurring along coastlines of the Southeast, Southern Plains, and Northeast regions, agricultural losses in the Midwest and Northern Plains, and wildfire cost in the Northwest and Southwest regions.

FIGURE 13. DISTRIBUTION OF MITIGATION BENEFITS IN EACH SECTOR BY REGION IN 2090



Regional share of annual U.S. climate-related benefits in 2090 in 22 FrEDI sectors in the hypothetical mitigation scenario. Pie charts are ordered (left-to-right, top-to-bottom) by decreasing net national impacts avoided within U.S. borders, such as temperature-related mortality has the largest and marine fisheries have the smallest. Sectors marked with an () have net damages in some regions, which do not appear in the pie charts. Net benefits reflect the sub-set of climate-related impacts currently included within FrEDI and do not provide a comprehensive accounting of all climate-related impacts to the U.S.*

State-level information from FrEDI also allows users to better understand and communicate how the climate-related benefits from specific policy actions are projected to occur in different communities. For example, **Figure 14** explores the distribution of temperature-related premature deaths avoided in each state in 2090 in this hypothetical mitigation scenario. The two panels in **Figure 14** show that absolute premature deaths avoided (top) and deaths avoided per 100,000 people (bottom). Similar to results from Example #1, the top panel in **Figure 14** shows that absolute benefits from temperature-related mortality in 2090 are projected to occur in states with relatively larger shares of the CONUS population. When

normalizing for differences in state populations, the bottom panel of **Figure 14** alternatively shows that temperature-related mortality benefits are more evenly distributed per capita, but that the share of benefits does still vary across states within each region. For example, in the Southeast (the region with the largest benefits), the absolute greatest benefits within this sector are projected to occur in Florida (top), while the per capita benefits are comparatively larger in Tennessee and Georgia (bottom). Similar to Example #1, the relative distributions in the bottom panel are driven by differences in the levels of avoided warming in each state relative to avoided global changes. Damages in FrEDI sectors that are not dependent on population (e.g., agriculture) are projected to have different relative spatial patterns of benefits.

FIGURE 14. AVOIDED PREMATURE DEATHS FROM MITIGATION BY STATE

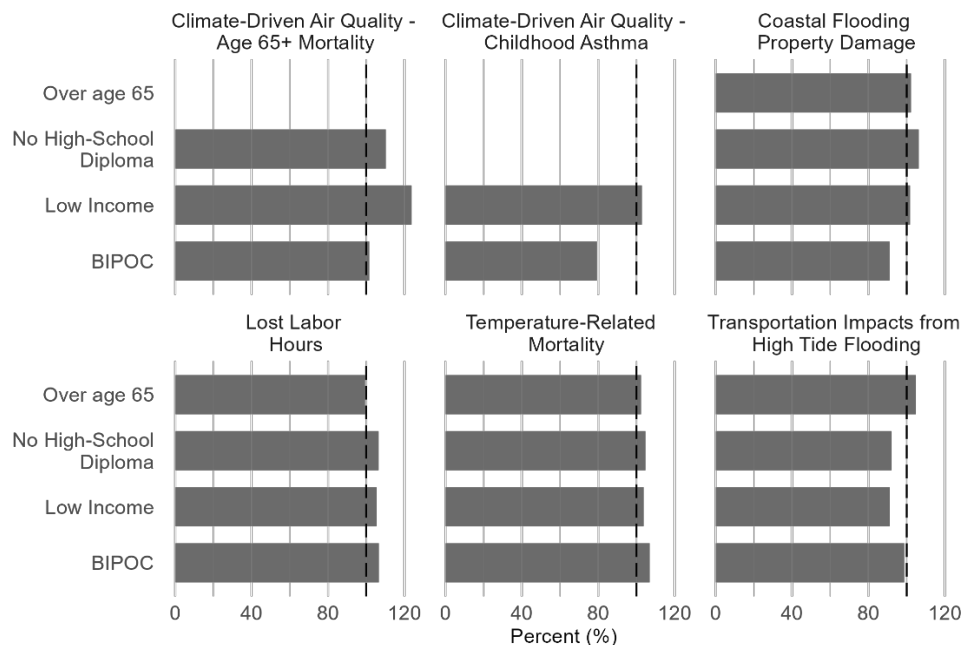


Distribution of avoided temperature-related mortality counts in 2090 across 48 CONUS states. The top panel shows the absolute number of total premature deaths in 2090 under the hypothetical mitigation scenario. The bottom panel shows the avoided premature deaths per capita, using 2090 population.

As in Example #1, the FrEDI SV module can also be used in a mitigation context to examine the distribution of benefits in the hypothetical mitigation scenario across different populations. Avoided damages for

impacts included in the SV module, are distributed across populations of different population groups of concern, including age, education, income, and race and ethnicity. First, **Figure 15** shows that all groups are projected to see an absolute reduction in climate change impacts under the hypothetical mitigation scenario (all bars are greater than zero). However, some populations may see more benefits than others. Populations with greater than 100% differential improvements (right of the dashed lines) are projected to experience relatively larger reductions in long-term climate-driven damages under the example scenario, compared to their reference populations. Those groups with changes of less than 100% (left of the dashed lines) are still expected to see improvements but are projected to experience relatively smaller damage reductions than their reference populations. For example, **Figure 15** shows that BIPOC individuals age 65 and older are 13% more likely to see larger reductions in air quality attributable mortality relative to the white, non-Hispanic reference population. In addition, those in the low-income group are more likely (6%) to see larger reductions in lost labor hours than those not in the low-income group. Example calculations for this type of analysis are provided in Appendix D. Users can alternatively apply output from the FrEDI SV module to assess the changes in rates by region, rates relative to national populations (instead of reference populations), or the relative rates for individuals of different races and ethnicities.

FIGURE 15. DISTRIBUTION OF REDUCED IMPACTS BY POPULATION GROUPS



Differential reductions in per capita climate-driven impacts in 2090 across socially vulnerable groups, normalized to the changes in their reference populations. Dashed gray lines represent 100% of the annual avoided impacts that are experienced by the reference population for each sector. Bars greater than 100% indicate that a group is projected to experience more impact reductions under the mitigation scenario than the reference population. Bars less than 100% indicate that a group is projected to experience fewer impact reductions than the reference population. No bars indicate there are no impacts considered in that group.

As shown in **Figures 10-14**, the share (or distribution) of relative benefits across each sector, region, and population group are similar to the relative shares of climate-related damages in the hypothetical baseline scenario from Example #1. These comparisons illustrate that states, regions, and sectors that are projected

to have the largest damages from future climate change, are also projected to experience the largest climate-related benefits from emissions and temperature mitigation.

Lastly, the FrEDI output from the SV module (impact counts and per capita impact rates) can also be used to analytically quantify the extent to which disproportionate impacts may be created or mitigated under custom temperature (or emissions) mitigation scenarios. In contrast to **Figure 15**, which demonstrates the extent to which net absolute benefits in each sector are experienced by each group relative to each reference population, this second calculation assesses how different groups may be disproportionately impacted relative to their reference populations under a baseline scenario and how that disproportionality may increase or decrease as the result of specific policy actions. This second approach is consistent with the framework for analyzing the effects of a regulatory action on population groups of concern, as discussed in *EPA's Technical Guidance of Assessing Environmental Justice in Regulatory Analysis*. For this calculation, users should compare the per capita impact rates or absolute impacts output for each population group relative to those in each reference group and how these ratios (e.g., the level of disproportionality) change between a baseline (i.e., Example #1) and policy (i.e., Example #2) scenario. Note that while each group may be projected to experience net climate-related benefits under a mitigation scenario (e.g., **Figure 15**), that same mitigation scenario may actually exacerbate the level of disproportionality a group experiences if a reference population experiences a larger *relative* reduction in impacts (e.g., 30% vs. 20% reduction) than the specific population group of concern. Also note that there are many impacts of climate change and additional dimensions of vulnerability that are not incorporated into this analysis, and therefore these FrEDI results only reveal a portion of the potential unequal risks to socially vulnerable populations. In addition, the FrEDI SV module does not consider how changes in future demographic patterns in the U.S. could affect risks to these populations, nor how climate change may affect socially vulnerable populations living outside the contiguous United States.

In summary, the two illustrative FrEDI applications presented in this chapter are intended to demonstrate examples of the types of analyses that can be informed using the current capabilities within the model. FrEDI was developed using a transparent process, peer-reviewed methodologies, and is designed as a flexible framework that is continually refined to reflect the current state of climate change impact science. While FrEDI does not provide a complete and comprehensive accounting of all potential climate change impacts relevant to U.S. interests, and is subject to uncertainties (such as future levels of adaptation), these examples demonstrate how FrEDI can provide the most detailed and complete illustration to date of the distribution of climate change impacts within U.S. borders.

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