Deloitte.

The turning point – United States

Technical appendix

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Deloitte Access Economics

Contents

Glossary

Acronym/Abbreviation	Full name
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AR6	Sixth Assessment Report
BEA	Bureau of Economic Analysis
CCUS	Carbon capture, utilization and storage
CGE	Computable general equilibrium
CMIP6	Coupled Model Intercomparison Project Phase 6
CO_2	Carbon dioxide
COP26	Conference of Parties (26th)
DAE-RGEM	Deloitte Access Economics Regional General Equilibrium Model
ERP	Emissions response parameter
GCM	Global climate model
GDP	Gross domestic product
GHG	Greenhouse gas
GSAT	Global-mean surface air temperature
GTAP	Global Trade Analysis Project
GVA	Gross value added
IAM	Integrated assessment model
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate change
LECZ	Low-elevation coastal zone
LULUCF	Land use, land-use change and forestry
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate change
RCP	Representative Concentration Pathway
SAM	Social accounting matrix
SLR	Sea level rise
SSP	Shared Socioeconomic Pathway
WBGT	Wet Bulb Globe Temperature
WGI	Working Group I

Turning point: The economics of climate change

In 1990, the first Intergovernmental Panel on Climate change (IPCC) report concluded that human-caused climate change would become apparent but could not confirm that it was currently happening.

In August 2021, the latest IPCC Sixth Assessment Report provides the most up-to-date physical understanding of the climate system and climate change. In this assessment, the evidence is “unequivocal” that the climate has changed since the preindustrial era and that human activities are the principal cause.[1] With more data and improved models, the Assessment gives improved estimates and narrower ranges compared to previous reports. On this basis, global surface temperature will continue to increase until at least midcentury under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades. There is greater certainty that with every additional increment of global warming, changes in extremes become larger; for example, every additional 0.5°C of global warming causes distinct increases in the intensity and frequency of extreme heat and heavy precipitation and droughts in some regions, among other impacts.

Modeling the economic impacts of the physical risks from climate change, and the economic impacts of mitigation and adaptation pathways, can be fraught but is not insurmountable. The economics discipline has spent several decades debating the benefits and limitations of the established techniques to derive economic estimates. To this day, while there remain many uncertainties and technical limitations on what macroeconomic models can reasonably conclude, economic techniques have improved to integrate views of the physical climate and economies and provide important insights into the choices that can be made to drive prosperity.

The Deloitte Economics Institute recognizes the uncertainties and technical challenges in quantifying relationships between greenhouse gas emissions, global surface temperatures, and economic impacts. The use of integrated assessment modeling (IAMs) presents one framework and approach to addressing these questions but, like any method, comes with limitations (Scenario A, see section 2.). But equally, we recognize that economics can provide useful insights for decision-making today. This study does not discount the pragmatic in pursuit of the perfect.

In this context, the economic modeling conducted in this analysis has several objectives that seek to address those limitations:

- The results provide an order of magnitude impact on gross domestic product (GDP) and other economic variables over the next 50 years. These results should not be interpreted as predictions or “most likely” estimates of climate change impacts. The modeling instead provides a consistent framework through which to understand the economic difference between possible future worlds: one with significant climate change impacts and one with more moderate effects. Establishing a long-term view of impact, albeit limited to precise scenario specifications, enables us to draw conclusions about trade-offs and the direction of change in economies. This is true for both high emissions, high temperature increase pathways and low emissions, lower temperature increase pathways.
- In the absence of transformation, a pathway of higher emissions and higher global surface temperature is the baseline outlook for the world. That in turn creates climate change-induced economic damages. While there are several probable scenarios for emissions profiles and corresponding temperature increases (all of which would result in some climate change damage), we adopt a single, higher-emission and higher temperature future pathway (see section 2.1) that offers the basis for an integrated view of chronic physical damages becoming a trend. This baseline outlook is used to demonstrate that choosing a path of no change from current global emissions

trends is not costless.[2] Economic growth will not occur uninterrupted as the climate changes.

- In reference to this baseline outlook, an assessment of the costs and benefits of mitigation and adaptation can be considered. To inform this, we model a single pathway of economic transformation that decouples emissions from the system of economic production (Scenario B). This pathway decarbonizes economies to reach a near net-zero greenhouse gas emission profile and limits global surface temperature warming to close to 1.5°C, and well below 2°C, compared to preindustrial levels, by 2050. Like the baseline scenario, this decarbonization pathway is taken as a given—we do not assign a probability to it being realized. Rather, the focus is on the sequencing, pace and scale of economic actions that could enable economies to decarbonize within a carbon budget that limits global surface temperature warming to well below 2°C by 2050.

Economic analysis of climate change is important to reframe the debate and inform decision-making today, while being mindful of the limitations of both science and economics.

Governments, businesses, and communities are making choices today about how to address climate change. COP26, the global climate summit in Glasgow, catalyzed enhanced emissions reduction commitments in many major economies. Analysis of these new targets—on top of existing targets—shows that if they are met on time, the stated goals could hold the rise in global temperatures to 1.8°C by the end of the century.[3] This would enable the world to achieve close to what is required and is a significant step-up in ambition to hold global warming below 2°C.

To meet the stated commitments, leaders will be required to make a number of choices, and economic analysis accounting for the climate is a key input into these choices. If we can't reframe the starting point—that inaction comes with significant economic costs—then any action on climate change will always appear as an unnecessary cost to society and economies.

Any economic change will have a cost attached to it—whether that is a change in the climate or a change to decarbonize. It is about how we understand the potential magnitude of those costs, the options to minimize them, and how the choices we all make today determine the extent of them. There is a narrow—and closing—window of time to create a new engine for sustainable economic prosperity while preventing the worst consequences of a warming world.

This technical appendix is a supporting document to *The turning point: A new economic climate in the United States* https://www2.deloitte.com/content/dam/Deloitte/us/Documents/about-deloitte/us-the-turning-point-a-new-economic-climate-in-the-united-states-january-2022.pdf. The modeling and methodology described below underpins a series of reports for the Americas region, including the United States, Canada, and South America. While there is reference to Canada and South America throughout this document, the focus is on the United States.

The IPCC Sixth Assessment and this analysis

The IPCC has released the Working Group I contribution to the Sixth Assessment Report (AR6) as the most up-to-date physical understanding of the climate system and climate change. AR6 describes improved knowledge of climate processes, paleoclimate evidence, and the response of the climate system to increasing radiative forcing (driven by higher greenhouse gas concentrations). AR6 gives a best estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to the previous AR5. In AR6, the global surface temperature will continue to increase until at least midcentury under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades.

This analysis using the D.Climate model does not take a probabilistic approach to the baseline and net-zero scenarios. Rather, it models narrow economic impacts that relate to specific damage functions from the selected emission pathways, without assigning probability to the outcome. This approach is to inform a better framework for decision-making today, based on orders of magnitude of economic trade-offs over time.

① Definitions

1.1 Net zero

Net zero refers to achieving an overall balance between greenhouse gas (GHG) emissions produced and GHG emissions taken out of the atmosphere. Deloitte Economics Institute has modeled a scenario that reflects the world reaching net-zero GHG emissions by 2050. Of this, around 13.4Gt (or around 20%) of CO_2 is expected to be offset or captured via carbon sinks in 2050.[4]

The US offset or captured emissions are benchmarked to feasible land use, land-use change and forestry (LULUCF), natural and human-made carbon sinks by 2050, noting that the likelihood of these becoming viable is enhanced by the modeled carbon price.

1.2 Close-to-1.5°C world

This pathway to net zero for the world limits global average warming to well below 2°C and close to 1.5°C compared to preindustrial levels, in alignment with current Paris Agreement objectives. The precise warming in global average mean surface temperature used in modeling is 1.7°C above preindustrial levels by 2100.

The climatic and economic implications of this global temperature pathway are modeled (Scenario B) as the comparison scenario to a world of climate inaction.

1.3 3°C world

An economic scenario that relates to a pathway of climate inaction (Scenario A). The socioeconomic and emissions pathways underpinning this exercise are broadly consistent with the SSP2-6.0 scenario (see section 2.4).[5] The implied temperature change is 3°C above pre-industrial levels by 2100.

1.4 Turning point concept

Transitioning to a net-zero world and limiting warming to as close to 1.5°C requires an industrial and economic transformation that would typically occur over a century to take place in just three decades. The turning point concept highlights that, despite initial costs, countries and industries will see dividends to rapid decarbonization. It is a climatic and economic turning point in that the worst effects of climate change are avoided, while the economic benefits of new industries and technologies offset the costs of transitioning away from emissions-intensive production processes.

1.5 Deviations from baseline

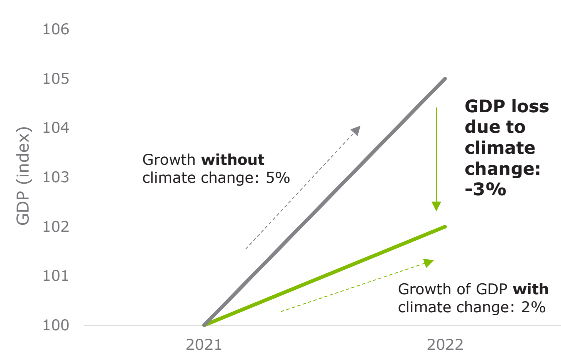
The turning point narrative is based on scenario analysis. The modeling does not provide a forecast of the future, but rather comparisons between possible future worlds. The discussion of modeling results will usually describe the state of the economy in reference to an alternative future or the deviation in a variable (like GDP) from one scenario (i.e., a close-to-1.5°C world, Scenario B) to another (i.e., 3°C world, Scenario A).

1.5.1 Climate change impacts (Scenario A)

When comparing two alternative futures, a **lower** GDP at the same point in time is not the same as having negative GDP growth. The example in figure 1.1 comparing two GDP scenarios with and without the impacts of climate change shows that both scenarios reflect an economy that is still growing. The impact or "loss" of GDP in 2022 due to climate change is the difference between the two GDP levels.

FIGURE 1.1

Accounting for climate change impacts



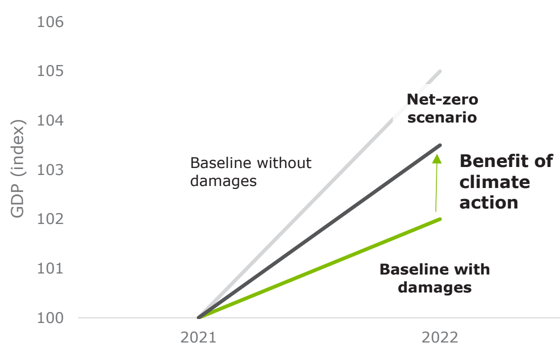
Note: This data is illustrative only.
Source: Deloitte Economics Institute.

1.5.2 Net-zero deviations from a damaged baseline (Scenario B)

When considering the costs and benefits of actions to reduce emissions, an appropriate economic baseline would reflect the damages that would arise under a world that continued to warm due to unconstrained GHG emissions. In simplified form (figure 1.2), the "corrected" growth path represents a baseline against which a net-zero scenario (with lower damages) can be compared. Scenario B (section 3) estimates deviations of a close-to-1.5°C world ***compared to*** a 3°C world.

FIGURE 1.2

Net-zero scenario impacts compared to a climate-damaged baseline



Note: This data is illustrative only.
Source: Deloitte Economics Institute.

1.6 Decarbonization

The process of decoupling emissions from economic growth in our context. The modeling represents decarbonization in a particular way. The emissions intensity of energy commodity use does not change, but industrial composition and production processes adapt to rely less on emissions-intensive energy commodity use, thus making production less emissions-intensive overall.

1.7 Clean energy and electricity

Clean electricity includes solar, wind, nuclear, hydropower, and geothermal production technologies. Zero-emission hydrogen and bioenergy are combined with clean electricity to be described as clean energy (see section 2.3.2).

1.8 Conventional energy and electricity

Includes coal, oil, and gas as fuels and energy production as well as their use in electricity production. Carbon capture, use, and storage is not separately modeled.

② D.Climate modeling

2.1 Overview

To date, most macroeconomic models and economic policy analyses are considered against a “baseline” that assumes economic growth will occur unhindered by rising concentrations of GHGs in the world’s atmosphere. The Deloitte Economics Institute believes that this viewpoint does not hold true in practice—particularly in the long run—and therefore economic analysis and climate policy is informed by a dated theoretical framework.

Climate change impacts should not be considered as a scenario relative to a baseline of unconstrained emissions-intensive growth, because absent fundamental societal and economic shifts, the impacts of unmitigated climate change are the baseline. By excluding the economic impacts of climate change from economic baselines, decision-making misses a fundamental point.

A shift to understand and incorporate this climate-affected baseline into decision-making is gaining momentum. The Network for Central Banks and Supervisors for Greening the Financial System (NGFS), made up of 92 central banks, has been a prominent example, developing guidance and scenarios to assist the financial sector to better understand its climate risks.[6]

The Deloitte Economics Institute has developed an extension of an in-house regional general equilibrium model, DAE-RGEM, giving it the functionality of a full-fledged integrated assessment model (IAM). Unlike many IAMs, this model incorporates multiple economic damages that vary by sector and region, and unlike many regional computable general equilibrium (CGE) models, it has full integration with the global economy through the Global Trade Analysis Project (GTAP) database and a complete set of emissions accounts covering CO_2 and non-CO_2 gases.[7]

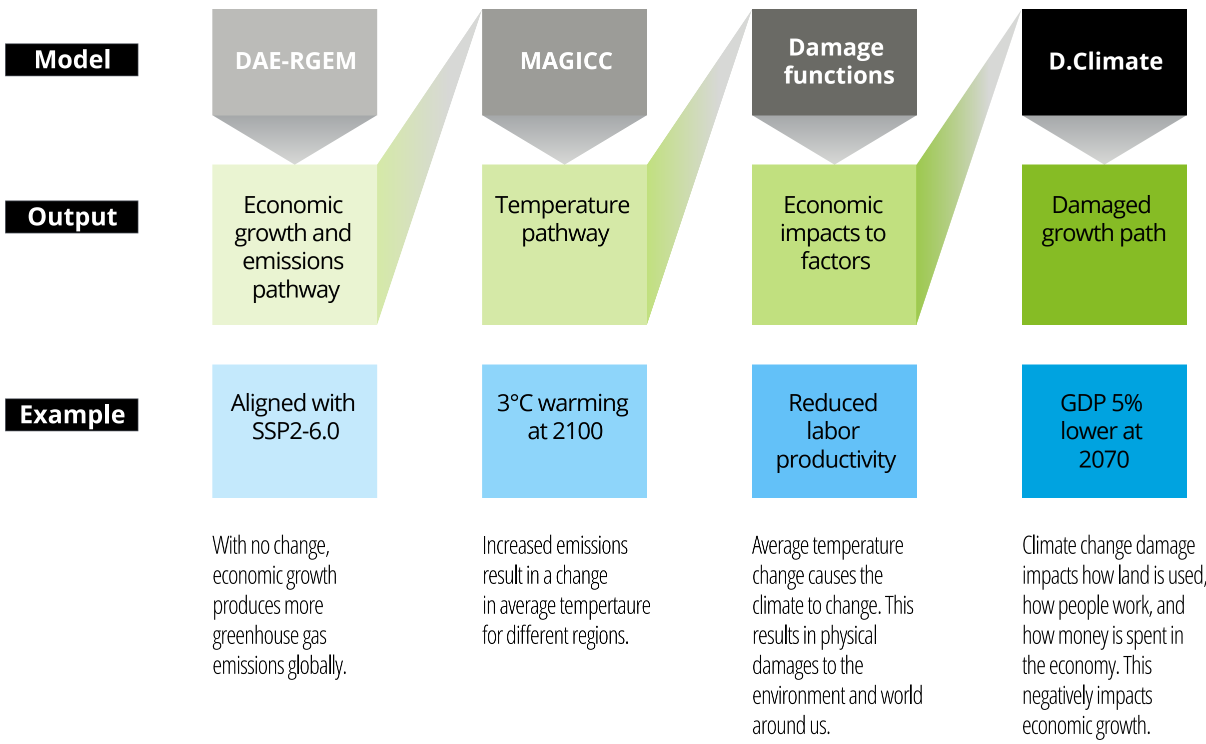
This work draws on, and contributes to, three key streams of research:

- The primary stream is that of advances in CGE models, allowing for modeling of complex and dynamic policies like those required to effect a transition to a low-carbon environment.[8]
- Another stream is advances in IAMs.[9] The IAM stream, in its initial phases, used a more aggregate representation of the economy that allowed for a stylized climate module.[10] These models sought to incorporate potential damages associated with climate change into a model of the economic system to form an integrated (but simplified) framework for assessing the decisions facing policymakers when it came to emissions reduction targets.[11]
- The third and most recent stream seeks to combine the two described above and provide the richer sectoral and policy detail of modern CGE models coupled with climate feedback mechanisms that allow for integrated assessment.[12]

D.Climate is an extension of a well-established modeling methodology and policy analysis technique that seeks to “correct” the typical business-as-usual baseline assumed in most modeling.[13]

FIGURE 2.1

D.Climate framework



Note: The temperature pathways provided by the MAGICC is global-mean surface air temperature. The damage functions estimate regional impacts based on this temperature pathway as well as other regional climate variables (e.g., precipitation), which are not provided by the MAGICC.
Source: Deloitte Economics Institute, Meinshausen et al. (2011, 2020), Nicholls et al. (2021).

D.Climate is built on an economic modeling framework that accounts for the economic impacts of climate change and establishes a reference case that can be modeled out to the year 2100 or beyond. The D.Climate process and logic are as follows:

1. The modeling produces a baseline economic growth path that draws on short- to medium-term global and regional forecasts in combination with a long-run assumption of contraction and convergence.
2. The baseline economic growth path has an associated emissions growth path—derived from the established link between economic activity and emissions—that corresponds to atmospheric GHG concentrations rising in line with a representative concentration pathway (RCP).
3. Rising atmospheric concentrations of GHGs cause global warming above preindustrial levels, as projected by a reduced complexity climate model, the Model for the Assessment of Greenhouse Gas Induced Climate change (MAGICC).[14]
4. Warming causes shifts in global climate patterns and results in damages to the factors of production (capital, labor, and land) and their productivities.
5. Damages to factors of production are distributed across the economy, impacting GDP.
6. These feedbacks are fed back into the model to determine the deviation in economic activity associated with a given level of warming (i.e., the damages).

Translating this concept into a modeling process involves three models that are linked through three key outputs. The Deloitte Economics Institute's approach extends methods adopted by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), the IPCC, and other research organizations. The method is extended by necessity for practical public policy purposes, and the modeling is regionalized—allowing results and insights to be produced at more granular geographic levels (such as countries or subnational regions).

The modeling process is summarized as follows:

1. Deloitte's in-house regional general equilibrium model (DAE-RGEM) is used to produce a projected path for economic output and emissions that align with a chosen shared socioeconomic pathway (SSP) and representative concentration pathway (RCP).
2. For each RCP scenario, the associated climate data (global annual surface temperature increases and atmospheric concentrations) is sourced from a climate change model: the MAGICC version 7.[15] Separately, regional average temperature, precipitation, and relative humidity variables are sourced from a synthesis of the models available from the Coupled Model Intercomparison Project Phase 6 (CMIP6).[16]
3. This climate data is then fed into damage functions to inform how shifts in temperature may play out in terms of impacts on the stocks and productivities of factors of production in each sector/region. Unlike most other models, we model multiple damages, including capital damages, sea level rise (SLR) damages to land stock, heat stress damages on labor productivity, human health damages to labor productivity, agricultural damages from changes in crop yields, and tourism damages to net inflow of foreign currency.

2.2 Baseline economic assumptions

The baseline includes a set of assumptions about macroeconomic growth rates and technological improvements between 2015 and 2070. These key variables have been calibrated drawing on historical and forecast time series from a range of reputable sources.

2.2.1 Macroeconomic variables

Macroeconomic variables including GDP (table A.3), population and labor supply (table A.4) and unemployment rate (table A.5) are calibrated for each year over the model period.

Growth rates for GDP are based on data from the International Monetary Fund's (IMF) World Economic Outlook database, which provides historical and forecast GDP growth over the period 1980 to 2025.[17] These growth rates are extrapolated using historical growth rates and assuming a degree of convergence over the long run.

Population growth rates are calibrated using the total population trajectories of the second shared socioeconomic pathway (SSP2) made available by the International Institute for Applied Systems Analysis (IIASA). A linear interpolation is applied to build yearly data.[18] Changes to labor supply are estimated by employing a similar approach and are assumed to broadly reflect trends in population growth.

Unemployment rates are based on short-term forecasts developed by the IMF[19] and extrapolated using a moving average. This approach implicitly assumes a steady-state unemployment rate over the medium to long term.

2.2.2 Emissions, energy efficiency, and productivity improvements

Shocks in the first year of the simulation are used to match the observed energy mix for each region to ensure an accurate reflection of the current state of the energy mix between renewable and traditional sources. Energy mix data is drawn from OurWorldInData.org.[20]

A uniform energy-efficiency improvement (0.5% per annum) is applied across all regions, reflecting a continuation of the long-run improvement observed to date.

2.3 Database: Regions and sectors

The core economic data underpinning DAE-RGEM—the social accounting matrix (SAM)—is sourced from the GTAP database.[21] This economic data is supplemented with specific data on electricity, differentiated by power-generation type (coal, gas, solar, etc.) from the GTAP satellite database, GTAP-Power, as well as CO_2 and non-CO_2 emissions data.[22] The behavioral parameters are also sourced from GTAP for the most part, with some exceptions as discussed next.

2.3.1 Regional aggregation

D.Climate is a global model and can be tailored to a specified regional concordance in line with the GTAP database.[23] For this project, the Americas region was isolated in the model with 11 regional aggregations modeled within this geographical area (table 2.1).

TABLE 2.1.

Regional concordance

Reported subregion name	Country or area	GTAP abbreviations
Canada	Canada	CAN
Greater Rockies	Alaska	USA
	Colorado	
	Idaho	
	Montana	
	North Dakota	
	Utah	
	West Virginia	
	Wyoming	
Southwest	Louisiana	
	New Mexico	
	Oklahoma	
	Texas	
West	Arizona	
	California	
	Hawaii	
	Nevada	
	Oregon	
	Washington	
Great Lakes	Illinois	
	Indiana	
	Michigan	
	Ohio	
	Wisconsin	
Northeast	Connecticut	
	Delaware	
	District of Columbia	
	Maine	
	Maryland	
	Massachusetts	
	New Hampshire	
	New Jersey	
	New York	
	Pennsylvania	
	Rhode Island	
	Vermont	
North Central	Iowa	
	Kansas	
	Minnesota	
	Missouri	
	Nebraska	
	South Dakota	

Reported subregion name	Country or area	GTAP abbreviations
Southeast	Alabama	
	Arkansas	
	Florida	
	Georgia	
	Kentucky	
	Mississippi	
	North Carolina	
	South Carolina	
	Tennessee	
	Virginia	
South America*	**Non-tropical**	
	Argentina	ARG
	Chile	CHL
	Falkland Islands	XSM
	Uruguay	URY
	Tropical	
	Bolivia	BOL
	Brazil	BRA
	Colombia	COL
	Ecuador	ECU
	French Guiana	XSM
	Guyana	XSM
	Paraguay	PRY
	Peru	PER
	Suriname	XSM
	Venezuela	VEN
Rest of world	All others	ROW

Noted: Reported as one South American region, but modeled as two separate regions.
Source: Deloitte Economics Institute.

The United States was grouped into seven smaller regions of similar industry composition and climate (figure 2.2).

These groupings were based initially on the Bureau of Economic Analysis (BEA) Census regions, commonly adopted in regional economic analysis of the United States. Two of these regions were aggregated together, and five states were reorganized between these initial groupings. While the BEA Census regions provide a useful starting point for regional economic analysis, they do not adequately reflect the climatic variation that is relevant for the analysis of climate change impacts on the economy nor the contemporary economic structures of states.

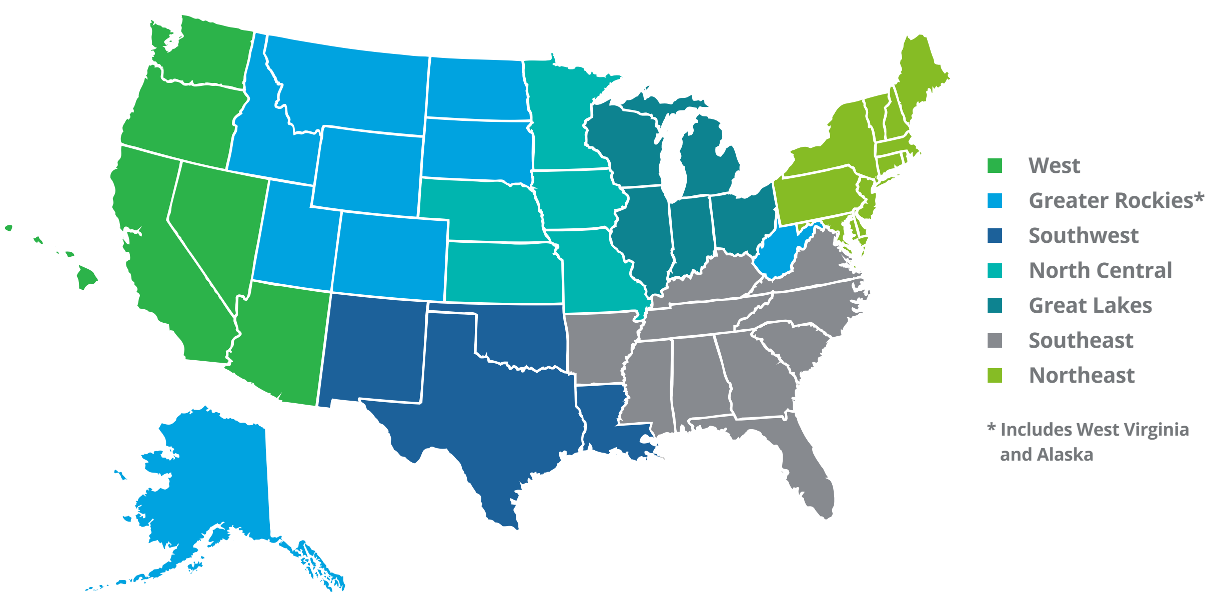
To develop a more up-to-date regionalization that reflects the current composition and industry focus of each state, the BEA Census regions were compared to groupings of individual states found in the economic literature[24] and against 2020 industry gross value-added (GVA) data.[25]

Analyzing industry GVA data provided a greater understanding of the sources of each state's growth, highlighting which states have similar economies from an industry composition standpoint. The groupings were further informed by research on individual state's climates to ensure that subregions have relatively consistent climates and will experience relatively consistent climate damages. Consultation with Deloitte US economists provided assurance on the appropriateness of the final groupings.

South America was modeled as two country-based regions: tropical and non-tropical. Tropical countries were distinguished by their proximity to the Amazon rainforest and their northern latitude.[26] This was done to ensure that the range of climate effects were not averaged for the entire continent, given the variety of climates and economic output across the different countries.

Canada was modeled as a single region, although there may be relevant subnational climatic and industrial variation.

FIGURE 2.2
US subregional map



Note: While most regions represent a contiguous collection of states, some do not follow an intuitive grouping due to differences in climate or industrial structures. West Virginia, for example, has an economic structure more broadly aligned to economies in the Greater Rockies, rather than its surrounding states. As such, it has been included in the Greater Rockies regional grouping, despite being geographically separate.
Source: Deloitte Economics Institute.

2.3.2 Sectoral aggregation

D.Climate can also be tailored to a specified sectoral concordance in line with the GTAP database.[27] For this project, a relatively high-level sectoral aggregation was chosen, given the level of regional detail that was required in the Americas region. However, there was a specific effort made to distinguish two non-GTAP sectors (hydrogen and bioenergy) to aid in the representation of the transition to net zero.

The sectoral concordance for this study is presented in table 2.2.

TABLE 2.2
Sectoral concordance

Sector name	Abbreviation	GTAP sector
Agriculture, forestry, and fishing	AGRI	Paddy rice
		Wheat
		Cereal grains
		Vegetables, fruit, nuts
		Oil seeds
		Sugar cane, sugar beet
		Plant-based fibers
		Crops
		Bovine cattle, sheep and goats, horses
		Animal products
		Raw milk
		Wool, silkworm cocoons
		Fishing
Forestry	FORESTRY	Forestry
Coal	COAL	Coal
Oil	OIL	Oil
Gas	GAS	Gas
Other mining	OMIN	Other mining
Food manufacturing	FOODMAN	Bovine meat products
		Meat products
		Vegetable oils, fats
		Dairy products
		Processed rice
		Sugar
		Food products
		Beverages, tobacco products
Light manufacturing	LIGHTMAN	Textiles
		Wearing apparel
		Leather products
		Wood products
		Paper products, publishing
Hydrogen	HYD	Petroleum, coal products*
Bioenergy (carbon-neutral)	BIO	Petroleum, coal products*
Petroleum, coal products	P_C	Petroleum, coal products

Sector name	Abbreviation	GTAP sector
Heavy manufacturing	HEAVYMAN	Chemical products
		Basic pharmaceutical products
		Rubber and plastic products
		Mineral products
		Ferrous metals
		Metals
		Metal products
		Computer, electronic, and optical products
		Electrical equipment
		Machinery, equipment
		Motor vehicles and parts
		Transport equipment
		Other manufactured goods
Electricity transmission and distribution	ELYTND	Electricity transmission and distribution
Conventional electricity	ELYDIRTY	Coal base load
		Gas base load
		Oil base load
		Other base load
		Gas peak load
		Oil peak load
Clean electricity	ELYCLEAN	Nuclear base load
		Wind base load
		Hydro base load
		Hydro peak load
		Solar peak load
Gas manufacture and distribution	GDT	Gas manufacture, distribution
Water	WATER	Water
Construction	CONS	Construction
Retail trade and tourism	TRADE	Trade
		Accommodation, food and service activities
Transport	TRANS	Transport
		Water transport
		Air transport
		Warehousing and support activities
Other services	OSERV	Communication
		Financial services
		Insurance
		Real estate activities
		Business services
		Recreational and other services
		Dwellings
Government services**	GOVSERV	Public administration and defense
		Education
		Human health and social work activities

Note: *The hydrogen and bioenergy sectors are not identified as individual sectors in the GTAP database but have instead been distinctly separated from the petroleum and coal products sector. An explanation of this process is provided in the following section. **Includes federal, state, and local government services.
Source: Deloitte Economics Institute analysis of GTAP database.

2.3.3 Commodity splits

To provide greater granularity representing the transition to net zero, the hydrogen and bioenergy sectors were split from their parent sector of "petroleum, coal products." This process was required, as the GTAP database does not specifically identify either of these emerging energy sectors individually.

The petroleum, coal products sector was targeted as the parent sector due to the similarities in its sales structure to that of hydrogen and bioenergy. This transformation was based on information gathered on the current size of the hydrogen, bioenergy and petroleum and coking sectors, as well as the respective cost and sales structures of each individual sector. The split was executed so as to maintain the following conditions:

- The size of the hydrogen sector is approximately 2% of the parent sector (petroleum, coal products). Its cost structure is different in that it draws more heavily on coal and P_C (the parent sector itself; petroleum, coal products), although there is sufficient flexibility in its production function to allow for a shift toward using zero-emission electricity and primary factors as the main inputs. The sales structure is the same as its parent.
- The size of the bioenergy sector is approximately 1.4% of the parent sector (petroleum, coal products). It relies solely on the output of agriculture and waste as inputs to production in conjunction with primary factors. The sales structure is the same as its parent. This is a subset of the broader bioenergy sector as it is exclusively carbon-neutral.
- The remaining P_C sector is essentially the same as the original GTAP sector, but slightly smaller.

There is scope for further refinement of this process, drawing on more detailed data to help get a better picture of production, consumption, and export, specifically at the detailed regional level.

2.4 Physical climate modeling for D.Climate

The future of climate change contains key uncertainties. The rate at which CO_2 and other pollutants accumulate in Earth's atmosphere could follow a number of trajectories, with each leading to a range of physical climate effects varying in both scope and scale. What is certain, however, is that the average global temperature has been rising and will likely continue to rise until a sustained and concerted effort is made to decarbonize globally.

In 2011, a set of four emissions and warming pathways were published to support consistent scenario analysis in the climate modeling community.[28] These representative concentration pathways (RCPs) were selected as plausible future GHG emissions and atmospheric concentration trajectories extending out to 2100. They are:

- RCP2.6 (assumes stringent decarbonization)
- RCP4.5 and RCP6.0 (two central scenarios)
- RCP8.5 (a high GHG emissions scenario)

The IPCC's Fifth Assessment Report of 2014 adopted these RCPs as core scenarios for long-term projections and assessments.

In 2017, a concurrent research effort sought to develop a similar set of consistent future scenarios for human development—the five shared socioeconomic pathways (SSPs).[29] These include a range of societal factors such as demographics, human development (for example, health and education), economic growth, inequality, governance, technological change, and policy orientations.[30] The five SSPs are:

- SSP1 – Sustainability
- SSP2 – Middle of the Road
- SSP3 – Regional Rivalry
- SSP4 – Inequality
- SSP5 – Fossil-fueled Development

Neither RCPs nor SSPs are "complete" without the other. RCPs generate climate projections that do not correspond to specific societal pathways. SSPs provide alternative societal futures, where climate change impacts and policies are not present. Thus, it is increasingly common to find research, including the IPCC's Sixth Assessment Report (AR6), adopting an integrated SSP-RCP scenario framework.[31] The five core scenarios that feature in the IPCC AR6 Working Group I (WGI) report are:

- SSP1-1.9 (very low emissions)
- SSP1-2.6 (low emissions)
- SSP2-4.5 (medium emissions)
- SSP3-7.0 (high emissions)
- SSP5-8.5 (very high emissions)

The computational demands of the climate models in this report limit a detailed analysis of a wider range of scenarios, although other scenarios feature in certain sections. The feasibility or likelihood of any of these scenarios is not part of the IPCC's assessment.[32]

Following this SSP-RCP framework, data consistent with the SSP2 narrative and RCP6.0 climate scenario were integrated in D.Climate, representing the baseline state in the Turning Point series. The SSP2 narrative reflects a continuation of current social, economic, and technological trends, as well as slow global progress toward achieving sustainable development goals.[33] RCP6.0 represents an economic future with a high rate of GHG emissions, where no significant further action is taken to reduce emissions and radiative forcing stabilizes after 2100. The economic and emissions profile consistent with RCP6.0 has the potential to increase global average temperature by more than 3°C.[34]

While SSP2-6.0 is not one of the five scenarios featured in IPCC AR6 WGI, it aligns best with the Deloitte Economics Institute's view of a baseline of inaction that reflects mitigation action taken to date and the current state of technology. It has also been applied in more than 150 studies between 2014 and 2019 and is one of the more commonly implemented scenarios that reflects continued emissions growth and temperature increase from today.[35]

For SSP2, this assumes socioeconomic trends do not shift markedly from historical patterns, and emissions continue to rise to 2100.[36] The more climatically extreme scenarios include socioeconomic futures: SSP3 Regional Rivalry and SSP5 Fossil-fueled Development as part of SSP3-7.0 and SSP5-8.5, respectively. These socioeconomic futures generate higher global warming outcomes than a "Middle of the Road" (SSP2) scenario would assume and are therefore both relevant for consideration in a review of the physical science of climate change and the risks of higher emissions. These SSPs, however, do not align with the Deloitte Economics Institute view of a baseline future.

The SSP2 scenario featured in IPCC AR6 WGI, SSP2-4.5, projects an emissions pathway that plateaus by midcentury and then declining to 2100. Emissions pathways, like RCPs 6.0, 7.0, and 8.5, continue to rise to the end of the century, consistent with the Deloitte Economics Institute's baseline view of inaction. While RCP8.5 is a possible future emissions scenario, it is considered a high-emissions no-policy future. It relies on a combination of assumptions, such as rapid population growth and a persistent increase in coal use to 2100, that appear increasingly less likely given recent policy and technological developments.[37] Scenarios that use lower RCPs, like 6.0 and 7.0, can therefore be consider more appropriate inaction baselines, noting that worse future scenarios, like RCP8.5, are still possible.

2.4.1 Climate of global average temperature increase—MAGICC

Emissions produced by Deloitte's DAE-RGEM model are translated into global-mean surface air temperature (GSAT) relative to the preindustrial (1750) period based on these emissions trajectories using a reduced complexity climate model. Specifically, the D.Climate framework uses outputs from the MAGICC, as described in Meinshausen et al. (2011) and Meinshausen et al. (2020), and configured by Nicholls et al (2021).[38] Global temperature increases are the main driver of climate impacts and are regionalized via the damage functions. The MAGICC does not provide regional temperature outputs or regional climate impacts.

2.4.2 Other climate variables—CMIP6

Separately, regional average temperature, precipitation, and relative humidity variables—specifically Wet Bulb Globe Temperature (WBGT)—have also been used. The data for each variable is the multi-model mean of 17 global climate models (GCMs) for the modeled SSP-RCP future pathways that are available from the Coupled Model Intercomparison Project Phase 6 (CMIP6).[39] The GCMs output was downloaded from the Earth System Grid Federation portal and then processed into monthly periods per geography/region across the modeled regions in the Americas and the rest of world from present day to 2100.[40]

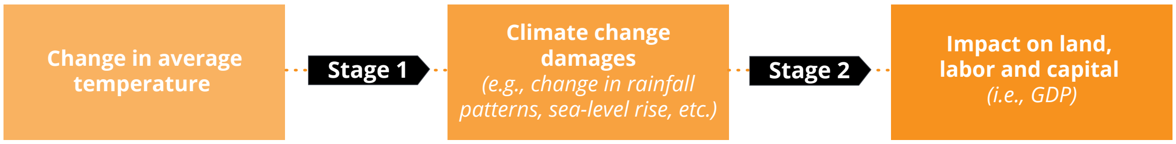
Twenty-year averages of the GCM projections are used here to assess the key signals for future climate change across short- to long-term horizons. Each 20-year averaged period represents the climate of the midyear. For example, the average temperature projection for the period 2011 to 2030 is assumed to represent the climate in the 2020 horizon.

2.4.3 Damage function overview

The fundamental driver of economic damages is rising temperature. As rising temperature induces climate change, economic output (as measured by GDP) is impacted by the physical damages that affect productivity and/or the stock of production factors (figure 2.3).

FIGURE 2.3

Two-stage economic damages relationship



Source: Deloitte Economics Institute.

This study includes six regionalized damages:

1. Heat stress damages to labor productivity
2. Human health damages to labor productivity
3. Sea level rise damages to land and capital stock
4. Capital damages
5. Agricultural damages from changes in crop yields
6. Tourism damages to net inflow of foreign currency

The following section outlines each damage and how each affects the economy.

2.4.4 Heat stress damages on labor productivity

A working environment that is sufficiently hot can negatively affect the health and safety of workers, as well as restrict their ability to perform tasks and limit their productive capacity.[41] For jobs where tasks are performed outdoors, it can be difficult for workers to moderate their heat exposure. The same can be true for indoor jobs where air conditioning is not readily accessible.

Rising average global temperatures lead to shifts in the distribution of daily peak temperatures and relative humidity. Heat waves are likely to become more frequent and increasingly extreme for many countries.

When workers exert energy to perform physical tasks, their bodies produce thermal energy and begin to heat up internally. For body temperature to be maintained at a healthy level, thermal energy needs to be transferred to a cooler external environment. If body temperature exceeds 39°C, an individual can suffer heatstroke. Temperatures exceeding 40.6°C can be fatal. However, at lower levels of heat exposure, workers can still experience diminished work capacity or mental task ability and increased accident risk.

To continue functioning at elevated body temperatures, workers can take instinctive actions to reduce their work intensity or increase the frequency of short breaks. This slowing down of activity (whether it occurs through self-instinct or occupational health management interventions) results in reduced "work capacity" and lower labor productivity.[42]

This analysis estimates the effect of rising temperatures and changing relative humidity levels on labor productivity using Wet Bulb Globe Temperature (WBGT) as a measure of heat stress. Analysis is conducted at a regional level. It is assumed that changes in labor productivity (an economic concept) are equal to changes in estimated work capacity (a physiological concept).

The methodology follows an approach proposed by Kjellstrom et al. (2017), which uses a series of functions describing the relationship between WBGT and labor productivity across three different work intensities: 200W (equivalent to light manual labor, such as office work), 300W (equivalent to moderate manual labor, such as manufacturing), and 400W (equivalent to high-intensity manual labor, such as farming). Relationships have been determined by Kjellstrom et al. (2017), based on a review of epidemiological datasets.

Workers in each GTAP sector are assumed to perform tasks at one of the three work intensities specified above. GTAP sectors have been allocated to specific work intensities based on internal advice from Deloitte subject-matter experts.

Consistent with the approach proposed by Kjellstrom et al. (2017), it is assumed that a geography or region's WBGT varies over three 4-hour intervals comprising the approximate 12 hours in a working day:

1. Early morning and early evening: 4 hours at WBGT mean (calculated using average monthly temperature)
2. Middle of the day: 4 hours at WBGT max (calculated using average monthly maximum temperature)
3. Hours in between: 4 hours at WBGT half (calculated as the midpoint between WBGT mean and WBGT max)

These three variants of WBGT have been projected at monthly intervals using the simplified WBGT index—sWBGT—based on surface temperature and water vapor pressure (developed by the Australian Bureau of Meteorology).[43] Water vapor pressure was derived using estimates of relative humidity and the corresponding surface temperature.

Labor productivity is then estimated for each geography/region at monthly intervals, across each of the three 4-hour intervals assumed to comprise the working day. The mean of these three estimates is then taken to represent the average labor productivity for workers throughout the working day. Workers are assumed to maintain the same level of productivity for all days contained within each month. Monthly labor productivity estimates are then averaged to give an aggregate measure of labor productivity for each year in the modeling period.

2.4.5 Human health damages to labor productivity

The impacts of climate change on human health are many and complex.[44] Increasing temperatures can increase heat-related health problems, particularly for those with preestablished cardiovascular and respiratory disorders.[45] Increasing temperatures can also reduce cold-related health problems.[46]

Climate change can impact the range, abundance, and dispersion of species-carrying diseases. Studies generally agree that the prevalence of malaria increases with an increase in temperature. Other vector-borne diseases may increase or decrease.[47] Climate change would allow diseases to invade immunologically naïve populations with unprepared medical systems and would affect food- and waterborne diseases, with cholera and diarrhea being potentially most problematic.[48]

As extreme weather events become more severe and frequent, so too does the threat they present to human populations. Climate change can affect air quality, leading to greater incidence of diseases caused by air pollution. Climate change may also affect human health indirectly, through changes in food production, water resources, migration, and economic development.[49]

Human health is therefore prominent in estimates of future climate change impacts. The welfare costs (or benefits) of health impacts contribute substantially to the total costs of climate change. Many estimates of economic damages rely on direct costs methodologies (i.e., price times quantity). With regard to human health, the price is typically equal to the value of a statistical life, based on estimates of willingness to pay to reduce the risk of death or diseases, or the willingness to accept compensation for increased risk.[50] However, these methods ignore the human health impacts on labor productivity and the demand for health services.

The approach adopted for this analysis is based on the work undertaken by Roson and Sartori (2016), which in turn is based on Bosello et al. (2006), by considering some vector-borne diseases (malaria, dengue, schistosomiasis), heat- and cold-related diseases, and diarrhea. It does not consider other diseases and impacts mentioned in the IPCC Fifth Assessment Report (2014), such as the effects of extreme events, heat exposure effects on labor productivity (separately considered), hemorrhagic fever with renal syndrome, plague, chikungunya fever, Japanese and tick-borne encephalitis, cholera and other (nondiarrhea) enteric infections, air quality and nutrition-related diseases, allergic diseases, and mental health.[51]

The starting point of the analysis presented in Bosello et al. (2006) is a meta-analysis of the epidemiological, medical, and interdisciplinary literature to achieve the best estimates for the additional number of extra cases of mortality and morbidity associated with a given increase in average temperature.[52] The information obtained in this research has been combined with data on the structure of the working population to infer the number of lost working days. The changes in morbidity and mortality are interpreted as changes in labor productivity.

Roson and Sartori (2016) update the work of Bosello et al. (2006) to account for recent literature on health impacts and studies mentioned in IPCC (2014), scaling up or down the variations in labor productivity.

The results of these studies are expressed as changes in average labor productivity for a 1°C increase in temperature (implicitly assuming that the relationship is approximately linear). For the purposes of this analysis, and to understand the relationship between human health impacts, an increase in average temperature, and time, we regressed the variables to find an equation with a satisfactory fit for the relationship.

The analysis estimates the higher-order economic effects (or indirect costs) of human health impacts and variations in labor productivity. It is important to note that this methodology excludes induced demand for health care.

2.4.6 Sea level rise damages to land and capital stock

As average global temperatures continue to rise, glaciers and polar ice are melting, and water bodies are experiencing thermal expansion. Together, these factors cause sea level rise (SLR).

SLR can impact a geography's total stock of land (an economic factor of production) through a combination of erosion, inundation, and salt intrusion along the coastline. As the global stock of land declines due to SLR, productive activity that would otherwise occur on that land is also foregone.

The extent of land lost to SLR will depend on several geography-specific characteristics, including (i) the composition of the shoreline (cliffs and rocky coasts are less subject to erosion than sandy coasts and wetlands), (ii) the total length of the coastline, (iii) the share of the coast that is suitable for productive purposes (e.g., in agriculture or urban land), and (iv) the vertical land movement (e.g., coastal subsidence or uplift).[53]

This report estimates land area lost due to SLR using a methodology proposed by Roson and Sartori (2016), who estimated the mean SLR (in meters) associated with global-mean surface temperature change from a series of regressions based on data within the IPCC Fifth Assessment Report (AR5), while also accounting for vertical land movement.

The proportion of agricultural land lost per meter of SLR is then estimated based on the findings of Roson and Sartori (2016), as well as World Bank data describing the extent of low-elevation coastal zones (LECZ) for each geography or region. The proportion of LECZ used for agricultural production in each geography is assumed to be equal to the proportion of total land area used for agriculture in that same geography.

This analysis extends the Roson and Sartori (2016) methodology to also capture urban land area lost due to SLR, again leveraging World Bank data describing the extent of urban area in LECZ. In low-lying and seacoast urban areas, residential and commercial properties may incur physical damages. Economic activity that would otherwise occur in these urban areas will also need to transition to other geographies.

The process for estimating both components is as follows:

- The percentage of effective land area lost per meter of SLR is calculated by multiplying the following factors: the percentage loss in coastal wetland (a proxy for loss of land due to SLR, estimated by the HadCM3 climate model under the A1b SRES scenario),[54] the LECZ area, and the percentage of erodible coast and relevant coastline.
- Considering which proportion of total coast is suitable for agricultural (productive)/urban purposes, the percentage of effective land change is adjusted by agricultural land area/urban land area.
- The percentage change in agricultural and urban land stock is computed by multiplying the percentage of effective land change by meter of SLR and the estimated SLR.

Notably, there are a number of limitations involved with this methodology of measuring SLR. One is the assumption that the area of LECZ in each region is used for agricultural or urban purposes. This will not be true of all regions, some of which have large areas of unproductive coastal areas.

Further, the method used focuses primarily on the loss of total land stock. The method does not explicitly consider damage to labor productivity due to forced displacement and SLR damage to infrastructure, which is generally established to be higher than damage to land stock.[55] However, it is widely assumed that submergence by SLR does not lead to damages to capital, because it is a slow process, and by the time SLR arrives the capital stock will have fully depreciated and property markets will have adjusted.[56]

Further, as average SLR increases (a gradual process), the impact of extreme or acute SLR (e.g., king tides and storm surges) will cause damage that may not be fully reflected in this function.[57] Financial and asset value shocks of SLR to coastal property will also not be captured through this damage but may represent a significant economic risk if warming continues.[58]

2.4.7 Capital damages

This study captures climate-induced capital damages as a function of global-mean surface air temperature (GSAT).

Capital damages, in this context, are "measured as a reduction in capital productivity across sectors"—that is, the output produced per unit of capital input. Reducing the productivity of capital as a result of climate change represents a need for firms to spend more on capital to achieve the same amount of output in every period. This effectively acts as depreciation and diverts investment from otherwise productive applications.

Accounting for capital damages in this way represents a departure from existing economic impact modeling and integrated assessments of climate change. In some cases, capital damages are included but at a highly aggregated level that limits regional analysis. Often, reports discuss the exposure or risk of geographies to capital damages but do not attempt to monetize an impact.

The relationship between GSAT and capital productivity is parameterized using projected data estimated by Neumann et al. (2020). This data provides projections of estimated temperature-denominated damages (in millions of dollars) to capital that would occur across 15 sectors in the United States due to climate change.[59] Damages are aggregated to three impact categories: health damages, infrastructure and electricity losses, and natural or managed ecosystem effects.[60] The sectoral damage functions modeled in this analysis informed the US Fourth National Climate Assessment released by the US Environmental Protection Agency in 2018.[61]

The Neumann et al. (2020) study uses average surface air temperature and annual precipitation data from five global climate models (GCMs) for two emissions scenarios, RCP8.5 and RCP4.5, to provide temperature-denominated annual damages for capital in the infrastructure sector.[62] This capital includes infrastructure such as roads, bridges, rail, urban drainage, and coastal properties. Since the effects of sea level rise are captured in the SLR damage function (described in section 2.4.6), the capital impact on coastal properties from this study is excluded from this specific damage function to avoid double counting. The projections are available for the years 2030, 2050, 2070, and 2090 and are provided at the regional level.[63]

The relationship between temperature increase and estimated annual damage in the Neumann et al. (2020) analysis is used as a proxy for the annual change in capital productivity in the D.Climate model, by country and region. This effectively smooths a stochastic process of natural-disaster impacts over time into an average annual damage estimate captured by a reduction in capital productivity.

This damage estimate **does not measure** the direct impact of any particular temperature increase to a particular location at a particular time in future modeled periods. Nevertheless, the implied relationship between temperature change and capital damage in Neumann et al. (2020) indirectly and implicitly reflects the fact that, as global temperatures continue to increase above preindustrial levels, the frequency and intensity of natural hazards will rise in aggregate, and the productivity of capital will fall, on average.

2.4.8 Agricultural damages from changes in crop yields

Climate change will see rising temperatures, higher concentrations of CO_2 in the atmosphere, and different regional patterns of precipitation.[64] These factors all affect crop yields and agricultural productivity.

The effects of climate change on agricultural productivity are one of the most studied areas of climate change impacts. Yet, despite the many existing studies and the extensive empirical evidence, it is still difficult to identify a "consensus" on the impacts of climate change on agricultural productivity. There are many factors at play, including the role of adaptation behavior by farmers, firms, and organizations, including variety selection, crop rotation, sowing times, the amount of fertilization due to higher CO_2 concentration, the actual level of water available for irrigation, and irrigation techniques.[65]

Modeling the economic consequences of yield changes to understand the consequences of climate change impacts on agriculture is important for two main reasons. First, varying levels of agronomic and economic adaptation exist in the agricultural sector; farmers can adjust how they grow a particular crop, the location and timing of crop growth will shift in response to climate change impacts; trade in agricultural commodities will adjust; and consumers will be able to substitute goods as prices adjust.[66] Each of these adaptive responses will mediate the impacts of yield changes. Second, climate change impacts will vary by crop and by region, changing the comparative advantage of countries, and creating winners and losers in global agricultural markets.[67]

The approach undertaken in this analysis provides an estimate of productivity changes for the whole agricultural sector across the modeled regions. The methodology is based on Mendelsohn and Schlesinger (1999) and Cline (2007), where the variation in output per hectare is expressed as a function of temperature, precipitation, and CO_2 concentration.[68]

One disadvantage of this approach is that adaptation is not incorporated within the function. Studies that include an agronomic adaptation do, on average, report higher yields than those that don't; however, recent research has noted that the effects of agronomic, on-farm, within-crop adaptations (principally changes in crop variety and planting date) are small and statistically insignificant.[69] Additional economic adaptations such as crop switching, increasing production intensity, substituting consumption, or adjusting trade relationships are captured within the computable general equilibrium (CGE) model.

A further constraint of this approach to note is that the methodology is not as thorough as the Agricultural Model Inter-Comparison Project (AgMIP). AgMIP has used both partial and general equilibrium models to examine the economic implications of climate-induced yield shocks, determined using a number of process-based crop models (Nelson et al., 2014). Modeling based on AgMIP explicitly accounts for regional variation resulting from soil type, irrigation, baseline temperature, and nutrient limitations.

2.4.9 Tourism damages to net inflow of foreign currency

Climate-induced economic tourism damages are driven by changes in net visitor flows and expenditure. In D.Climate, changes to net visitor flows and expenditure are fundamentally driven by the exposure of each region to climate change. However, the impacts can be varied. Countries with lower current temperatures can experience a beneficial net inflow of foreign currency as temperatures rise and tourism increases in the region. Conversely, for countries with high current temperatures, further temperature rises mean the economy could experience a net outflow of foreign currency as tourism spending is reallocated to other regions.

The functional relationship of the tourism damages means that in a region, there is a point where rising temperatures reach a threshold, and the relationship between temperature and net flow of foreign currency switches from a net inflow to a net outflow.

To estimate tourism damages in D.Climate, functions that relate visitor arrivals and departures to average temperature are employed. These functions are consistent with those employed by Roson and Sartori (2016) and are derived from econometric models expressed in terms of land area, average temperature, length of coastline, per capita income, and the number of countries with shared land borders.[70]

Existing inflows and outflows of tourism expenditure for Canada and South American countries are based on data collected from the World Bank.[71] Existing inflows of foreign currency from tourist expenditure in states within the United States are based on data collected from the US Travel Association.[72] For number of visitors, the top four states (California, Florida, New York, and Texas) are based on state government agency data, while the remaining number of inbound tourists across the United States were proportionately allocated based on magnitude of inbound expenditure.[73] Tourism outflows across the United States are based on international tourism data from the World Bank and domestic travel data from the US Travel Association, with the proportion of spending and visitors to states based on Tourism Intelligence International for the top 10 outbound travel states and the remaining states proportionate to their population size.[74]

Projected average temperatures are used as inputs to these functions to determine a resulting net flow of foreign currency.

The magnitude and persistence of tourism damages are also a function of the economic structure of each region's economy. Regions with more diverse economic structures are less likely to experience persistent economic damages as industries are less reliant on tourism and more malleable and adaptable.

2.4.10 Benchmarking climate change impacts

There is a wide range of estimates of the relationship between climate change and economic outcomes. Consensus has formed, however, around a negative relationship between global GDP and more than 2°C of warming.[75] This negative relationship also holds for most regions in the world, while some regions (e.g., Asia Pacific and Africa) are likely to be more negatively affected than others (e.g., Europe).[76]

For the United States, the overall effect of the impact channels described in section 2.4 can be situated within a literature of similar estimates for a sense of "reasonableness" (table 2.3).[77] There are a range of damage function specifications and impact channels adopted within the literature as well as other scenario (emissions, temperature, and time horizon) and methodological differences,[78] so the figures in the tables below are not necessarily like-for-like comparisons.

The standard approach to valuing climate damages describes average impacts across large regions (e.g., national impacts such as for the United States as a whole). Examining more regional-level impacts (such as the regions undertaken in Deloitte's modeling for the United States, described in section 2.3.1), reveals more nuanced impacts of climate change on some regions and sectors that are not captured by more aggregated averages (including a number of those listed below). More regionally detailed modeling can reveal impacts not precisely captured with national aggregations, as aggregating climate variables (such as temperature increases across regions) will minimize extremes.

It's important to note that while Deloitte's estimates sit at the higher end (larger estimates) of the range of damage estimates across the literature (table 2.3), with the regional breakdown in D.Climate likely contributing to this outcome, further regional dissection (e.g., at a state or county level) and taking a "bottom-up" analytical approach to modeling the impacts on the United States could provide further nuance regarding the regional cost of climate damages.

TABLE 2.3

Select damage estimates from comparable studies (US)

Report	Damages (GDP deviation)	Scenario (°C)	Year
Deloitte (2021)	**-3.7%**	**3**	**2070**
Network of Central Banks and Supervisors for Greening the Financial System (2021)	-3.9%	3	2070
Kompas, Pham, and Che (2018)	-0.6%	3	2067
Fernando, Liu, and McKibbin (2021)	-1.0%	3	2070
Swiss Re (Guo, Kubli, and Saner) (2021)	-1.2%	3.2	2050
Hsiang et al. (2017)	-3.5%	4	2100
IMF (Kahn et al.) (2019)	-6.5%*	RCP8.5	2070

Note: *Measured in GDP per capita.

Source: Deloitte Economics Institute.

③ Scenario modeling

3.1 Emissions abatement drivers: Scenario inputs and assumptions

A number of high-level emissions abatement drivers are included to reflect a possible path to global net zero by 2050. A summary of the differences between Scenarios A and B is presented in table 3.1. Note that the Scenario B does not model in detail the current policies of jurisdictions in the Americas, but a set of drivers that enable the Americas and the world to rapidly reach net zero by 2050.

TABLE 3.1
Summary of emissions pathways and drivers in both scenarios

Scenario	Drivers
Scenario A (3°C world)	• RCP6.0 emissions pathway, reflecting global inaction on climate change mitigation • 3°C of warming and a range of climate damages by region and industry
Scenario B (1.5°C world)	• RCP2.6 emissions pathway, reflecting significant global climate action • 1.5°C of warming and "locked-in" climate damages • Global economy emits net-zero emissions in 2050 • Productivity improvements to clean electricity driven by cost reductions to renewable energy in excess of those in the base case • Transition assistance by governments to support industries and regions that face higher transition costs

Source: Deloitte Economics Institute.

There are four steps implemented in Scenario B: an emissions constraint, "locked-in" climate damages in a close-to-1.5°C world, clean electricity productivity improvements, and transition assistance.

3.1.1 Emissions constraint

The transition to a low-carbon economy has been modeled as one in which policymakers set clear and ambitious targets. These are implemented as constraints on the total level of emissions in each region such that global and regional emissions are reduced at a rapid rate over the next 30 years in line with the budget prescribed in the RCP2.6 scenario.

The emissions constraints form a shadow price on carbon such that processes that have associated emissions—like the combustion of coal to produce electricity—become more expensive. Those processes that do not have associated emissions—such as the generation of electricity from renewables—do not face this price increase. Relative price changes like these lead to changes in behavior, such as switching from fossil fuel-based electricity generation to renewables. As these changes aren't seamless, the combined effect of them is to impose an aggregate cost on each economy which is known as the shadow price of carbon. This isn't the same as a legislated carbon tax, or a traded emissions price, but it is analogous in that it represents the projected price at which a given reduction in emissions can be achieved.

Reductions in fugitive and industrial process emissions, which cannot be achieved via switching to alternative fuel sources, are modeled using emissions response parameters (ERPs), which allow for the gradual adoption of low-emissions processes or technological alternatives, as they become more viable over time, in response to a rising shadow price on carbon.

To inform the emissions constraint parameterization, existing commitments and targets on emissions reduction across the United States, Canada, and South America were consulted. For many parts of the Americas regions, contributing to a global goal of net-zero emissions by 2050 will go beyond current commitments.

Net-zero emissions and GHG reduction targets are determined at the state and country level across these regions. Some targets are mandated as part of legislation (e.g., in California). However, the majority of targets are set by strategic policy direction. For the United States, net-zero targets are largely determined at the state level. As of November 2021, the United States had an overarching goal to achieve 50% GHG reduction relative to 2006 levels by 2030. For South America and Canada, as of November 2021, net-zero targets are determined at the country level.

Canada, Argentina, Chile, and Uruguay are the only countries where 100% of the economy has both a net-zero target and GHG reduction target. A large share of the West region also has both targets, largely driven by California (which makes up 80% of the West regional economy).[79] No states in the North Central region contain net-zero targets; however, 30% of the regional economy is subject to GHG targets, based on Minnesota's target of a 30% GHG emissions reduction compared to 2005 levels by 2025 (table 3.2).[80] GHG emissions targets range between 26% of 2005 levels by 2030 (several states in the Great Lakes and Greater Rockies regions) to 81% GHG emissions reduction compared to 1990 levels by 2030 (California in the West).

TABLE 3.2

Share of D.Climate regional economies with net-zero targets

D.Climate region	2020 GDP ($ billions)	Share of region with net-zero target (% GDP)
Canada	1,979	100
South America	2,986	72
West	4,620	86
Northeast	4,859	69
Southeast	4,170	63
Great Lakes	2,784	19
Southwest	2,307	11
Greater Rockies	945	5
North Central	1,257	0
Total	**25,907**	**58**

Source: Deloitte Access Economics.

3.1.2 Locked-in climate damages under a close-to-1.5°C world

The combined effect of warming driven by historical emissions already in the atmosphere and the amount that will be emitted under the emissions path described in 3.1.1, means that some amount of climate damage is unavoidable. This is incorporated into the 1.5°C world Scenario B.

One component of the benefits of climate action in the close-to-1.5°C world Scenario B is the avoided damage—the difference between damages under a 3°C world and a close-to-1.5°C world.

3.1.3 Clean electricity productivity improvements

Projections of reductions to the levelized cost of electricity to 2050 for wind and solar, combined with the rising share of wind and solar in clean electricity sector generation (different shares in Scenarios A and B) will drive cost reductions per unit of outputs.[81] A share of this productivity improvement to these technologies is included in the 3°C world Scenario A, reflecting the fact that these cost reductions will likely continue irrespective of policy, driven by learning by doing, economies of scale, and supply chain efficiencies.[82] An incremental productivity improvement driven by policy is included in the close-to-1.5°C world Scenario B, reflecting the fact that the share of solar and wind in electricity production will grow more rapidly, lowering production costs within this industry.

3.1.4 Transition assistance

Scenario B incorporates coordinated government investment to offset structural adjustment costs in industries and regions as decarbonization accelerates. Coordinated government transition assistance reflects economic and regulatory settings that create new economic activity for economies *to transition into*—in general, targeted to industries that are neither emissions-intensive nor in high demand as the world decarbonizes.

This means coordinated government effort does not generally go toward emissions-intensive conventional energy, or emerging clean energy, as they primarily respond to price and changing demand. For example, in an emissions-intensive region such as the Greater Rockies, government transition assistance is targeted to diversify economic activity into areas such as construction, private-sector service industries, retail, and public services. This smooths the structural disruption to economies and their workforces, resulting in increased job creation earlier in the phases of decarbonization.

Government investments are implemented through effective tax reductions and/or subsidies on capital and labor within targeted industries and are constrained at the national level by government revenue that is collected during transition. At the subregional level within the United States, investments are distributed across regions according to the relative costs incurred through transition. The transition assistance implementation is representative of a federal government role, although levels of government are not explicitly defined within the model.

A failure to provide coordinated transition assistance increases the cost of the transition for industry, and most significantly for those employed in those industries. There are no new or emerging job opportunities for workers to transition into, resulting in reduced job creation and significant dislocation for workforces, particularly in some regions. Transition assistance is necessarily simplified in the modeling. In practice, the US public sector will need coordinated action and effective policymaking across federal, state, and local governments to minimize the costs of transition.

3.2 Emissions abatement results: Scenario outputs

3.2.1 Emissions pathways

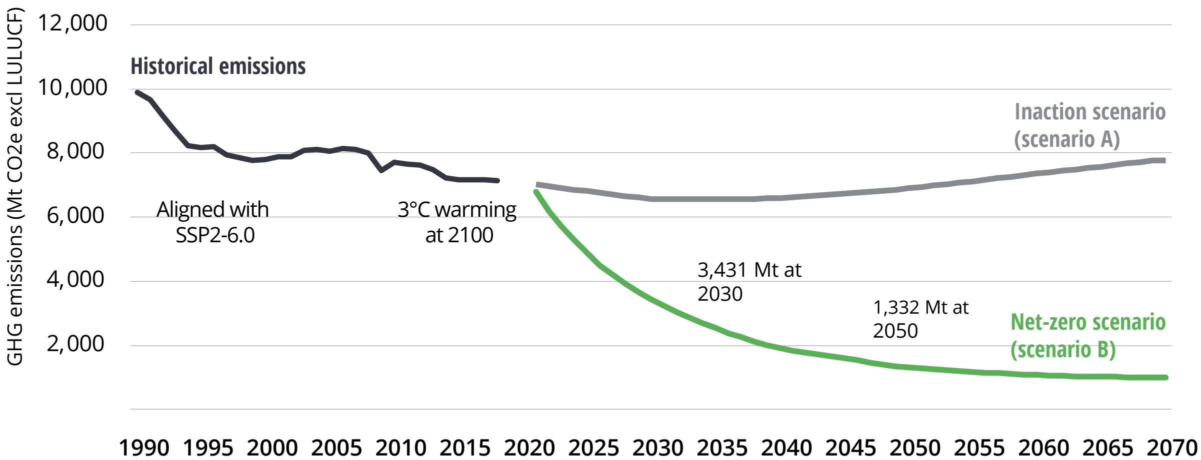
The emissions reduction pathway in figure 3.1 reflects rapid decarbonization across the Americas region as firms, households, and governments respond to the drivers described in section 3.1. Although the Americas region does not have a single emissions reduction target, of those countries that have adopted 2030 and 2050 targets, these pathways are in line with and, in some cases, exceed those aspirational rates of change.

This pathway reflects gross emissions excluding LULUCF, human-made, and natural negative emissions technologies. By 2050, it is assumed that 2,735 Mt CO_2e will be captured by these sources across the region, although they are not explicitly modeled. Within the modeling framework, a shadow carbon price that reaches an average US$190/ton across the region by 2070 is thought to make a number of these currently less economical abatement options viable.

The global potential for negative emissions sources is assumed to be 13.4 Gt CO_2e by 2050 (see section 1.1). Globally, there is a wide range of uncertainty around the potential for human-made negative emissions technologies. The IPCC SR1.5 scenarios that reach net zero by 2050 have a median level of carbon capture, utilization, and storage (CCUS) of 15 Gt CO_2 and a range of carbon direct removal (bioenergy with carbon capture and storage and direct air carbon capture and storage) of 3.5–16.0 Gt CO_2.[83] The International Energy Agency (IEA) net-zero report includes a less optimistic projection of 7.6 Gt CO_2 in 2050 being captured by a range of negative emissions technologies.[84] Despite the wide range of uncertainty, the assumption of 13.4 Gt CO_2e being removed from the atmosphere by 2050 appears feasible.

FIGURE 3.1

Emissions pathway under Scenarios A and B



Source: World Resources Institute (2021) and Deloitte Economics Institute.

3.2.2 Energy mix transition

The global transition to net zero will require a total transformation of the current energy system. There is no single path along which that may occur. The energy mix in 2050 has been benchmarked to two prominent transition scenarios (table 3.3). While these employ different modeling approaches and assumptions, they nevertheless demonstrate alignment on the broad energy transition narrative: a significant reduction of fossil fuel use, a scale-up of clean electricity, and a wider adoption of clean fuels in sectors and applications where electrification is not possible.

Certain energy sources, such as bioenergy, have definitions that vary across sources and are not directly comparable. D.Climate's bioenergy source is limited to carbon-neutral varieties. Bioenergy associated with positive emissions will be partly captured within the oil category. Of the oil energy source that remains in 2050, this will include hard-to-abate applications, such as jet fuel, and as inputs into specific chemicals manufacturing (known as feedstock). As described in section 3.2.1, the emissions from these sources will be removed from the atmosphere through negative-emissions technologies.

TABLE 3.3

Global energy mix—percentage share of total final energy demand

Time period	2020	By 2050		
Source	Historical	D.Climate	IEA net-zero scenario[1]	BNEF (green and red scenario)[2]
Clean electricity	7%	56%	51%	48%
Conventional electricity	19%	~0%	1%	1%
Oil	46%	30%	13%	7%
Gas	18%	1%	6%	5%
Coal	10%	~0%	3%	1%
Hydrogen	0%	12%	10%	22%
Bioenergy	0%	0%	15%	11%
Other*	N/A	N/A	N/A	4%

Note: IEA – International Energy Agency. BNEF – Bloomberg NEF. *The "other" category is exclusive to Bloomberg NEF modeling and likely includes sources such as heat. Shares will not necessarily sum to 100% due to rounding.
[1] Ibid.
[2] Seb Henbest et al., *New energy outlook 2021*, BloombergNEF, July 2021.

Source: Deloitte Economics Institute.

In the United States, Larson et al. (2021) review five net-zero scenarios to assess potential energy transition pathways, infrastructure required, and impacts on industries and communities.[85] In 2050, renewable energy, particularly solar and wind, as a share of the total final energy demand ranges between 62% and 100%. This is higher than the D.Climate modeled outcome of 52% clean electricity as a share of total final energy demand (which also includes nuclear energy). The persistence of conventional fuels, such as oil and gas, is expected to reflect hard-to-abate energy use sectors such as air travel. In D.Climate, emissions from these fuels are assumed to be captured by negative emissions sources.

In the same study, Larson et al. (2021) estimate the share of electricity generation from carbon-free sources is expected to more than double, from 37% today to between 98% and 100% by 2050. Wind and solar play a dominant role in 2050 electricity generation, with between 85% and 90% of total electricity supply. D.Climate has 100% clean electricity as a share of generation by 2050, which is a feasible outcome compared to Larson et al. (2021).

FIGURE 3.2

On a net-zero pathway, US' energy mix would rapidly shift toward clean sources

Within the modeled pathway, nearly all electricity will be clean after 2040, and by 2070 would be 62% of the total energy consumed. It's the electrification of the economy that makes the deeper structural changes possible.

Source: Deloitte Economics Institute.

④ Discounting the future

It is inherently difficult to "discount" the future, particularly concerning an issue as socially and economically complex as global climate change.

In considering this issue, it is important to recognize the intergenerational impact of climate change on society and in doing so, how to value "income," "consumption," "utility," or "well-being" at one point in time relative to another. In comparing these conditions across generations, the discount rate must reflect a preference for short-term consumption over the long term and the opportunity cost of saving.

In determining the rate, the question is, *What rate is appropriate to embody these preferences in estimating the net present value of impacts to economies and societies from climate change and various climate change policy responses?*[86]

GHG emissions have a long residence time in the atmosphere, which means that the value of the impacts of today's emissions must be considered for future generations. Equally, policy responses regarding mitigation and adaptation to altered climatic conditions impact future generations significantly.

In this context:[87]

- The use of a "high discount rate" implies that society puts less weight on future impacts and therefore less emphasis on guarding against such future costs.
- The use of a "low discount rate" highlights the importance of future generations' well-being.[88] Society should act now to protect future generations from climate change impacts.

A discount rate of 2% has been used by the Deloitte Economics Institute in this analysis, after considering the differing perspectives within literature, the economic framework adopted for analysis in D.Climate, and broader policy actions modeled.[89] This rate reflects a view consistent with social discounting in other climate change economic analyses.

Further, the results of a survey of economists in the *American Economic Journal: Economic Policy* (the sample contains more than 200 academics who are defined as experts on social discounting by virtue of their publications) indicates that most favor a low discount rate, with more than 75% comfortable with a median discount rate of 2%.[90]

⑤ Limitations

Modeling the full physical consequences of climate change on the global economic system and the economic impacts of mitigation and adaptation pathways can be fraught, but not insurmountable. The approach outlined in this paper provides a detailed view of the literature and science that underpins our analysis. There nevertheless remain many uncertainties, technical limitations, and areas of future research that will benefit from recognition and separate discussion.

The Deloitte Economics Institute recognizes that there are legitimate critiques and limitations of IAMs, as well as the complexity involved in determining relationships between GHG emissions, global surface temperature, and economic impacts.[91] But equally we recognize that such a framework can provide useful insights for policymakers who are making a choice today that will have far-reaching consequences. We should not discount the pragmatic in pursuit of the perfect. There is value that these frameworks provide in their capacity to consistently model such complex relationships, policies, and technologies.[92] Our approach is to incrementally improve and build upon previously identified limitations in these modeling frameworks, rather than dispensing with their use altogether.

In particular, a key area of earlier criticism—the damage function—has benefited from a rapidly expanding econometric literature, which has enabled the parameterization of plausibly causal relationships that more accurately capture relationships between climate and the economy.[93] We have incorporated these into a more disaggregated, multi-sectoral view of damages and have updated damage estimates based on more recently available science and research.[94] For example, a number of our damage functions reflect a core finding that temperature increases have a nonlinear relationship with economic outcomes.[95] We nevertheless recognize there are a range of impact channels that are not explicitly modeled here. In this sense, this work can be considered a conservative estimate of impacts, and ongoing model development will look to incorporate these channels over time. A selection of these includes:

- Individual natural disasters and extreme events[96]
- Changes in household energy demand[97]
- Water availability[98]
- Crime and other social impacts[99]
- Ocean acidification[100]

An extensive literature focuses on climatic nonlinearities that are not captured in this framework. Within climate-economic modeling, the most renowned argument for considering these impacts is made by Martin Weitzman.[101] These "tipping points" include events such as the partial disintegration of ice sheets, biosphere collapses, or permafrost loss that pose a threat of abrupt and irreversible climate change. Positively, the most recent IPCC report argues that there is growing confidence that taking action to reduce emissions will significantly lower the likelihood of certain tipping points being reached.[102] AR5 was more pessimistic about the range of tipping points that are at risk of being crossed regardless of abatement and mitigation action. Once again, given these uncertainties, we consider our analysis of primarily chronic impacts of warming to underestimate the potential future damages of climate change.

Economic modeling of climate impacts is not only interested in the direct effects of climate outcomes on physical spaces, but also the behavioral responses that occur in response to those changes.[103] These can variously be referred to as adaptation responses.[104] D.Climate considers adaptation in two main ways:

1. The damage functions are informed by empirical relationships that reflect long-term, ongoing adaption processes that are already embedded in underlying data.
2. The computable general equilibrium (CGE) component of the model captures decision-making by firms and households that are able to switch between consumption sets and inputs based on relative prices and productivity changes in the economy. This flexible switching is akin to adaptation.

There will be some adaptation that is not able to be explicitly modeled; in particular, adaptation that seeks to reduce the marginal damage caused by warming beyond that which is already captured by the damage function parameters (e.g., the building of sea walls or other technological change). The advantage of the D.Climate approach is that some adaptation and dynamic economic change does take place in response to a changing climate, which improves upon approaches that project historical patterns forward. Improving the ability of the model to account for a wider range of adaptive responses is the focus of ongoing work.

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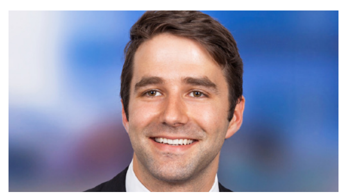

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The pace and scale of global economic, social, environmental, and digital disruption is rapid, and we all now operate in a world that we no longer readily recognise. This creates a need to understand how structural economic change will continue to impact economies and the businesses in them, and the livelihoods of the world's citizens.

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