Catastrophe and Climate

Integrated Assessment Models

Making sense of economic scenarios for climate systems

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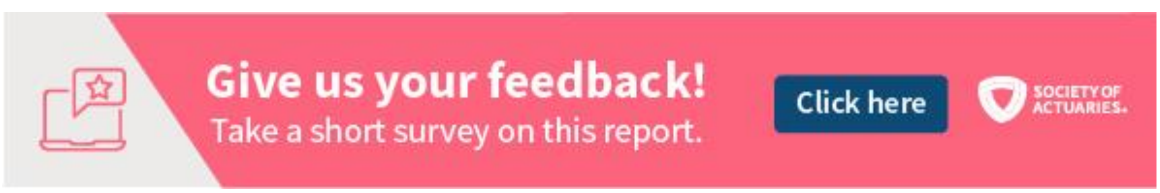

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CONTENTS

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Integrated Assessment Models

Making sense of economic scenarios for climate systems

Executive Summary

Integrated Assessment Models (IAM) combine scientific scenarios that project changes in greenhouse gas (GHG) levels, resulting in global temperature increases and meteorological volatility when GHG increases, with quantitative economic models expanding on an aligned narrative.

The climate system models are directed by the assumed levels of radiative forcing,[1] with resulting changes in the level of GHG. This causes temperature changes and drives variables like population growth, economic growth, education, urbanization and rate of technological development. If a global scenario shows higher GHG and temperatures, this leads to lower global economic growth. Each of these factors will vary regionally, with some results moving in the opposite direction from the global average due to local circumstances.

The Intergovernmental Panel on Climate Change (IPCC) is scheduled to complete their sixth cycle in mid-2022 with a synthesis report summarizing the project's conclusions since their last cycle completed in 2014.

The mathematical models that are used to project future climate conditions can be thought of as simulations. Each of the modeling teams uses probability distributions to develop expectations over various time horizons. Natural forcings include cycles that occur without input or alteration from humans. They include solar energy cycles, earth orbital cycles and large volcanic eruptions that occur periodically but not on a regular cycle.

Actuaries act as interpreters of other scientific topics as the financial implications are determined, whether it is health, social insurance, family security, retirement planning or property damage due to driving a car of building a home near the ocean. This skill set naturally sets up the profession as one that can work with scientists, politicians and other decision makers to analyze problems and develop solutions.

Event attribution compares a distribution of resulting metrics (e.g., temperatures, wind, precipitation) based on these natural forcings against actual results. This is often done for a specific region to estimate how much more likely an event is than would have been expected, and the amount of any additional cost, without fossil fuel use. Hurricane Harvey, a Category 4 hurricane that impacted the U.S. Gulf Coast, including Houston, in 2017 was determined to be three times as likely[2]. Heat related emergency room visits were determined to be 25% higher than

[1] Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of *atmosphere* due to a change in a driver of *climate change*, such as a change in the concentration of *carbon dioxide (CO_2)* or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere. https://www.ipcc.ch/sr15/chapter/glossary/ IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. *World Meteorological Organization, Geneva, Switzerland, 32 pp.*

[2] Otto, Friederike. 2020. *Angry Weather*. Greystone Books.

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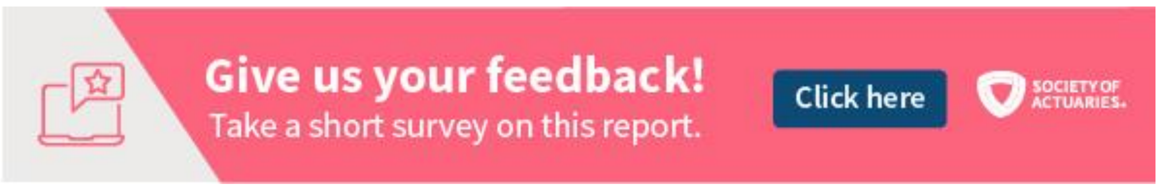
would have previously been expected.[3] These are unknown knowns, where historical data is no longer predictive. Actuaries need to adjust their assumptions for trends, looking for feedback loops and being aware of potential tipping points.

Wayne Gretzky, the Hall of Fame hockey player, talks about skating “to where the puck is going, not where it has been.” That’s similar to the goal here, to identify the economic impacts of climate change using a time-step process that ties together current conditions (analogous to a balance sheet) with future conditions using incremental changes (similar to a cash flow statement). Each stage of this process is evolving. As computers get faster more detail can be added and similar time intervals processed for both the climate (e.g., reduce the size of each grid “square” or add greater breakdowns of ocean depths) and economic components (e.g., analyze below the country level). Understanding the nuances, like how changes in climate impact economic damages and how these factors interact, will allow actuaries to remain relevant.



Introduction

Resources are finite. Models of climate systems are incomplete since they don’t reflect the costs associated with addressing historical buildups of greenhouse gases as well as limiting future contributions. Since *Limits to Growth*[4] was published in 1974, attempts have been made to merge climate models and economic growth models to highlight the issues and develop solutions.

Integrated assessment models aggregate scientific information and their financial implications, providing input for decision makers to make choices that can then be monitored. The climate science models generate output showing changes in variables like expected temperatures, wind and precipitation that are used to calculate expected sea levels, amounts of carbon dioxide (and other GHG) in the atmosphere and oceans, and frequency of extreme events like cyclones and tornados. Since they operate in a complex climate system with many interacting parts, a forecast is not possible so a range of climate scenarios is prepared.

Decision makers anticipate adaptation and mitigation efforts that would impact these results and societal and economic narratives are developed for each. Economic growth, population levels by country, education and health scenarios are developed to be consistent with the narrative that can then be used to prioritize efforts.

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[3] Bell et al. 2021. *Determining the Role of Anthropogenic Climate Change on Human Health Outcomes: A Case Study on Heat Related Illness Attribution* https://www.soa.org/resources/research-reports/2021/determining-role-climate-change/

[4] Meadows et al. 1974. *The Limits to Growth: A Report for the Club of Rome’s Project on the Predicament of Mankind.* Universe Books.

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Role of humans

The extraction of fossil fuels from the earth has increased average temperatures. Dr. James Hansen first testified to the U.S. Congress in 1988, tying the levels of carbon dioxide and other greenhouse gases in the atmosphere to global warming. His warnings, along with his projections of continued warming, were quite accurate. Many reports from scientists have proven conservative, understating the impact of climate change, as they required high levels of proof before communicating concerns.

Climate scientists have developed terminology to reflect similar levels of certainty (likelihood of the outcome) in their conclusions. These terms, shown in Table 1, are useful to scientists (and actuaries) but often confuse everyone else. When reading an IPCC report, it can be helpful to keep this table handy.

Table 1
LIKELIHOOD SCALE[5]

Term	Likelihood of the Outcome
Virtually certain	At least 99% probability
Extremely likely	At least 95% probability
Very likely	At least 90% probability
Likely	At least 66% probability
More likely than not	At least 50% probability
About as likely as not	33-66% probability
Unlikely	Less than 33% probability
Very unlikely	Less than 10% probability
Extremely unlikely	Less than 5% probability
Exceptionally unlikely	Less than 1% probability

Table developed by author.

Figure 1 shows global averages of atmospheric temperature by year, reflecting a clear increase over a 140-year time period relative to a 20th century base.[6] For this author, anecdotally, an additional level of confidence in this chart comes from the temperature increase during World War 2, when fossil fuels were used without constraint. Periods of el Niño have caused surges in temperature used by some to claim warming trends were not occurring (the temperature was so warm in 1997 it was argued we were in a cooling period for the decade that followed). These examples show why you should always view data graphically over a long period, since many have used climate data selectively in an attempt to "lie with statistics."

[5] Ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties

[6] NOAA National Centers for Environmental Information, State of the Climate: Global Climate Report for April 2021, published online May 2021, retrieved on May 30, 2021 from Image provided by NOAA from their web site https://www.ncdc.noaa.gov/sotc/global/202104

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Figure 1

NOAA CHART SHOWING TEMPERATURE ANOMALIES SINCE 1880

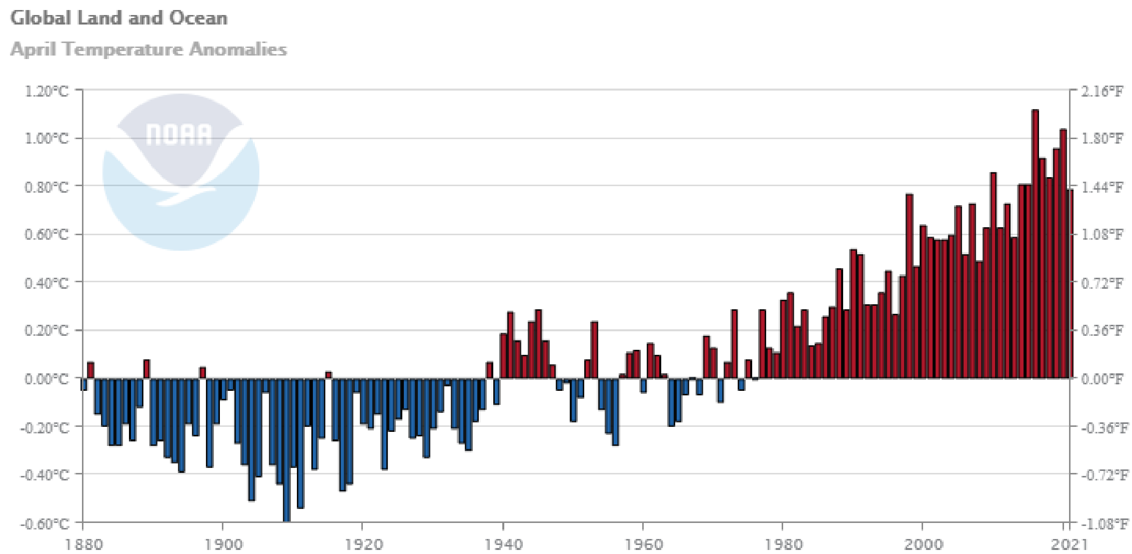
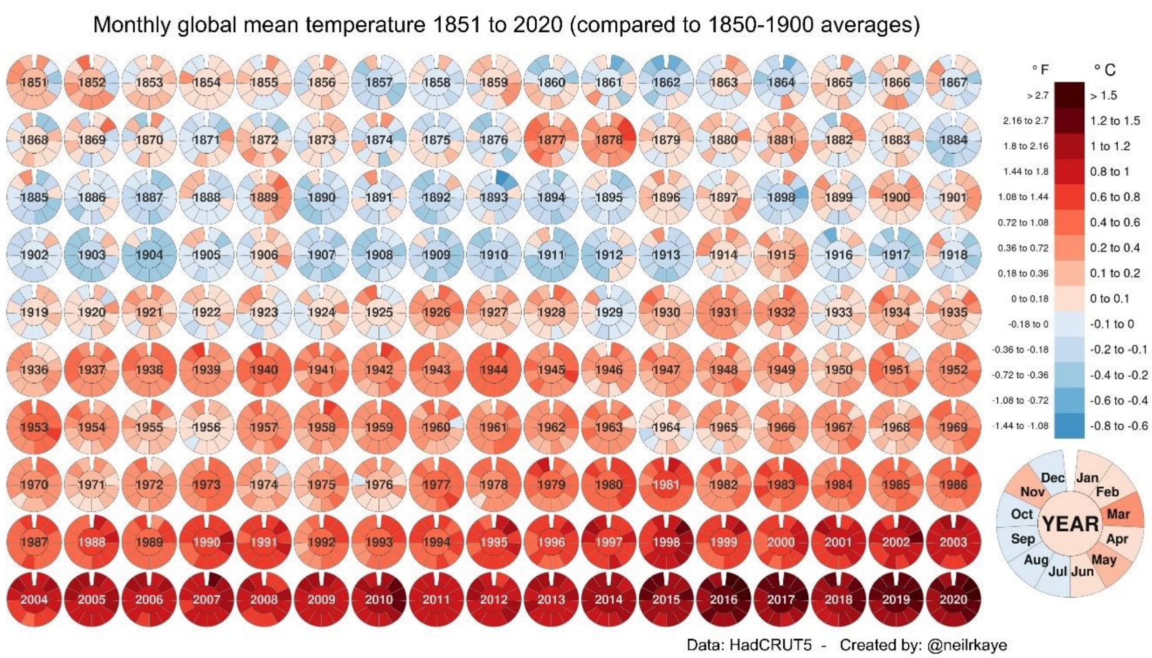


Figure 2 provides another graphic of temperature rise, showing surface temperatures by month for 170 years relative to a base period from the 19th century.

Figure 2

GLOBAL MONTHLY SURFACE TEMPERATURES (1851-2020)[7]



[7] Visual Capitalist. https://www.visualcapitalist.com/global-temperature-graph-1851-2020/

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Scientists have been able to use core samples of Antarctic ice to study the past 800,000 years and use other proxy methods for older periods to determine levels of carbon and temperatures at various times in the earth's history. The core samples recognize recent ice ages and long periods of warmth that correlate with estimated levels of carbon dioxide. Since the last ice age, which ended about 10,000 years ago, the climate has been extremely stable. This has corresponded with the rise of human civilization. Small changes in temperature since then (well below a single degree Fahrenheit) caused material changes and have received names like mini-ice age. These small changes in temperature apparently led to large changes in localized precipitation and temperature in the past, resulting in failed harvests and food insecurity. Longer periods of just a few degrees change to the climate system caused changes to weather patterns, resulting in droughts, changes in the monsoon season and eliminate the stability that allows farmers to manage their crops.

Since the start of the industrial revolution in the mid-1700s, the release of sequestered carbon, mostly from fossil fuel extraction, has added to greenhouse gases (GHG) in the climate system that is highly correlated with the global temperature increases not seen except during five previous mass extinction events.[8] .

External events like wars and volcanic eruptions are excluded from climate system models. This is also true for financial discontinuities such as severe recessions. These can be material and serve as excellent scenario planning sensitivities.

There is much humans can do to reduce our carbon footprint, moving beyond carbon offsets that may do more to make the participant feel good than to reduce GHG emissions. In addition, geoengineering solutions are being developed that use technology to sequester carbon already in the climate system. Some would like to try to simulate a volcanic eruption, since sulfur is known to initially cool the planet slightly for several years after an event. Naysayers worry that these solutions, even if they initially work, could become a crutch that allows fossil fuel use to continue unabated, and that there may be unintended adverse consequences. Although carbon capture would avoid some of these concerns, current processes are too expensive for the volume of capture needed to significantly impact the problem and the process can create carbon emissions that offset the savings.

COMPLEX ADAPTIVE SYSTEMS

The climate system, along with the geopolitical and financial systems of humans, is a dynamic network of interactions that reacts differently at each time step based on conditions prevalent at that point. If something works, we keep doing it. If it doesn't, we pivot to try something else. Representations of these types of systems are mathematically complex and don't result in closed form solutions or optimized outcomes. Models must utilize simulations, with each time step using assumptions that are consistent with and build off the output from the previous cycle. Such a process is similar to modeling a universal life insurance product, where interactions between the product's crediting strategy and investment strategy change regularly and influence future results.

Fertilizer provides a good example of this type of pivot strategy. Civilization developed in the Fertile Crescent as a stable climate allowed nomads to settle down and cultivate crops. Over time, crop rotations returned nutrients to the soil and animal power was added that secondarily provided natural fertilizer. In China, crop rotation and a simple transport system operated symbiotically between farms and cities, with crops carried to cities for sale while those returning to the farms carried human waste to use as fertilizer. Later pivots included bat guano, extracting nitrogen from the air chemically and genetically manipulated seeds. Each was successful until resources dwindled or a better approach was developed.[9] As populations grew, Robert Malthus hypothesized that agricultural yields would

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[8] Kolbert, Elizabeth. 2015. *The Sixth Extinction*. Picador.
[9] DeFries, Ruth. 2014. The Big Ratchet. Basic Books.

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grow linearly but population exponentially. So far, these pivots have provided adequate food, but each pivot makes it more likely that over a long time horizon he will be proven correct.[10] The risks present today can be modeled using a range of deterministic scenarios that tie climate systems to migration and finance, with scenarios tested to see which we should pursue.

Representative Concentration Pathways (RCP)

For the IPCC fifth iteration, published in 2013, a set of four scenarios was developed. While earlier scenario sets were designed around socioeconomic assumptions, these are based on radiative forcings driven by carbon dioxide equivalent additions to the climate system. These are mostly from fossil fuels, but include other greenhouse gases as well. Each RCP must be plausible, internally consistent and must transition smoothly from historical data. For AR5 (Fifth Assessment Report) the transition date was 2007. These deterministic scenarios, described in Table 2, were chosen as representative from those developed by modeling teams around the world.

Table 2
RCP SCENARIOS IN AR5[11]

Radiative Forcings by 2100	CO_2 Equivalent by 2100	Temperature change by 2100 (°C)
8.5 W/m^2 by 2100 and still growing due to population growth	1,370	4.9
6.0 W/m^2 stabilized by 2100	850	3.0
4.5 W/m^2 stabilized by 2100	650	2.4
2.6 W/m^2 (peaks 3.1 then declines) by 2100	490	1.5

Table developed by author.

These scenarios are known as RCP8.5, RCP6.0, RCP4.5 and RCP2.6. The Paris Agreement, an international climate change treaty adopted in 2015, set a goal to limit global warming to less than 2°C. This makes RCP2.6 of great interest as it is the only scenario that accomplishes this goal. RCP8.5, with no attempted mitigation or adaptation,[12] presents a scenario that is hard to build a narrative around given recent results, expected feedback loops and tipping points of the climate system. It represents an extreme scenario.

The scenario naming convention can be confusing since radiative forcings are correlated with temperature increases. While the temperature increases are in the same relative number range as the forcings, the reader should note that they are not the same.

Without human activity, natural forcings would not be expected to cause increases in temperatures or carbon dioxide equivalents over long time horizons.[13] Models are run using these assumptions when analysis attributing results to human actions is completed.

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[10] Rudolph, Max. 2018, *Was Malthus Right, Just Early?* From SOA Environmental Sustainability 2017 Call for Essays https://www.soa.org/globalassets/assets/files/static-pages/research/opportunities/environmental-essays.pdf
[11] Moss et al. February 11, 2010. *The Next Generation of Scenarios for Climate Change Research and Assessment*. https://www.nature.com/articles/nature08823
[12] Rudolph, Max. April 2021. *Focus on Terminology: Baseline Scenario – Are we Talking past each other?* From SOA Catastrophe and Climate Research Program Newsletter. https://www.soa.org/globalassets/assets/files/resources/research-report/2021/2021-04-cat-climate-newsletter.pdf
[13] Please use the following reference to the whole report: IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

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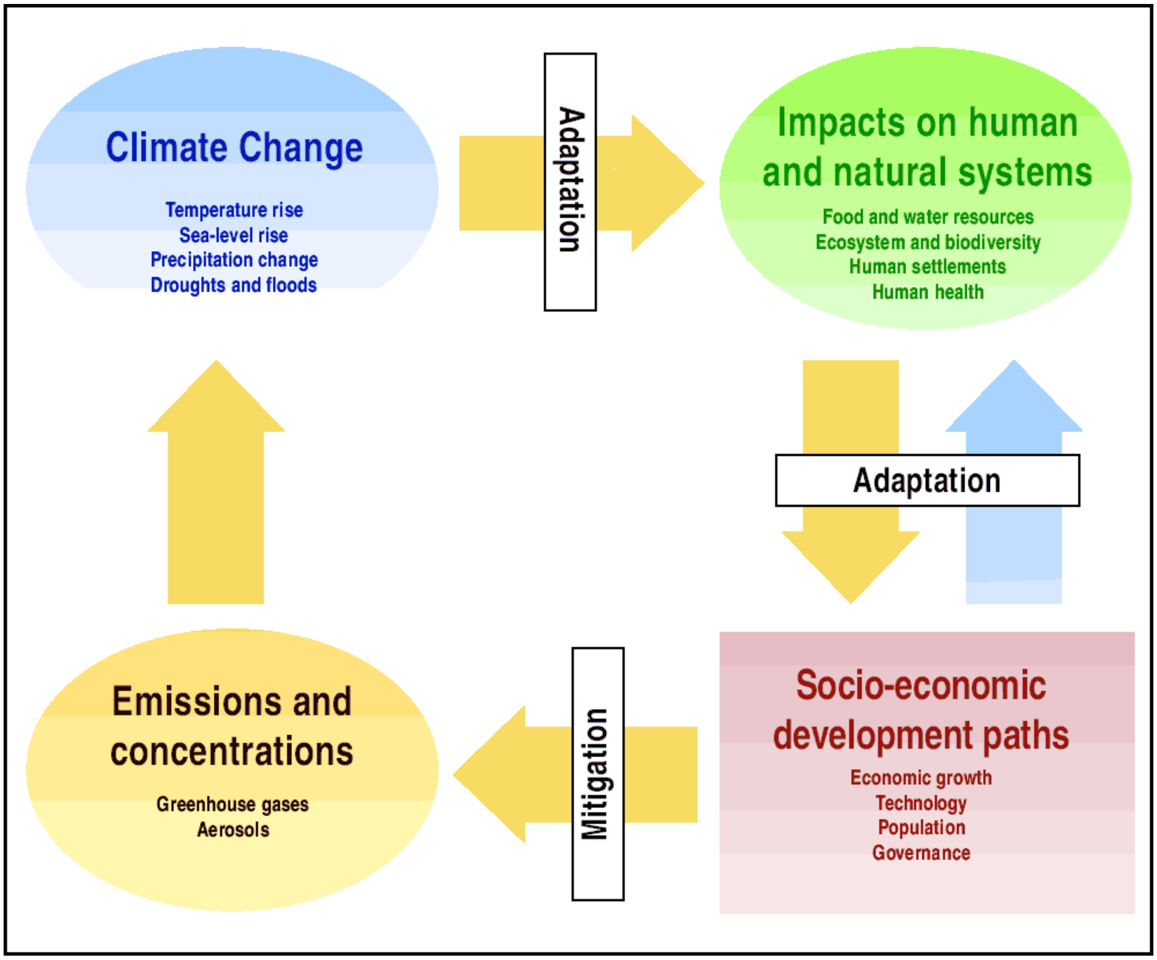
CURRENT CYCLE: RCP SCENARIOS AND SHARED SOCIOECONOMIC PATHWAYS (SSP)

An integrated framework aligns climate change, human and natural systems, paths of socio-economic development and emissions. Figure 3 shows how the IPCC views these interactions.[14] They are not linear, with adaptation and mitigation working throughout the process.

Figure 3

INTEGRATED FRAMEWORK OF CLIMATE CHANGE



Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. https://www.ipcc.ch/report/ar5/wg1/anthropogenic-and-natural-radiative-forcing/

[14] AR3 Climate Change 2001: Impacts, Adaptation and Vulnerability. Figure SPM-1. https://www.ipcc.ch/report/ar3/syr/summary-for-policy-makers/figspm-1/

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Shared socioeconomic pathways (SSPs) development process[15]

The SSPs are a key component of the scenario development framework currently in use for the IPCC sixth cycle and the climate research communities for evaluating climate risk and climate policy. The scenario development framework replaced the prior sequential scenario development framework with a parallel process. The framework is intended to capture global and local effects, with most projections available at the country level.

Scenario development begins with a set of greenhouse gas concentration scenarios (the Representative Concentration Pathways, or RCPs), representing a wide range of potential concentration and radiative forcing futures from the existing scientific literature. The scenarios are sufficiently comprehensive to provide full inputs into the climate models. Next, in parallel, the climate modeling community develops a set of climate change projections for each scenario. The Integrated Assessment Modeling (IAM) community develops the SSPs as a set of reference socioeconomic scenarios representing plausible global socioeconomic futures. They included projections of greenhouse gas concentrations but do not incorporate the effects of climate change or associated mitigation and adaptation responses. The RCPs and the climate projections based on the RCPs are then combined with the SSPs to generate full IAM projections for each of the SSPs, both with and without mitigation measures.

The Coupled Model Intercomparison Project (CMIP) then selects deterministic scenarios from this grid of possibilities. The SSP reference scenarios themselves were initially described qualitatively as a set of narrative scenarios that describe a range of potential socioeconomic futures. Then, selected groups of experts are tasked with developing quantitative projections of various socioeconomic elements—including population, urbanization and gross domestic product (GDP)—consistent with these narratives.

Brief descriptions for five SSP storylines follow:

SSP1, sustainability: Reasonably good progress toward sustainability. Declining resource intensity and fossil fuel dependency driven by rapid environmentally-friendly technological development and increasing awareness of environmental damage. Low-income countries develop rapidly through open economies, improved governance and global institutions focused on the Millennium Development Goals, resulting in reduced poverty and inequality. Low population growth and significant investment in education.

SSP2, middle of the road: Continuation of recent trends. Slow progress in reducing resource intensity and fossil fuel dependence. Development in low-income countries is uneven, with partially connected markets and relatively weak global institutions. Medium growth in per capita income with slow convergence. Educational improvement is slow, and population growth continues to be relatively high.

SSP3, regional rivalry: Globalization is reversed, resulting in a number of closed regions with widely divergent paths ranging from moderate wealth to extreme poverty. There is little progress in meeting Millennium Development Goals, reducing resource intensity or reducing fossil fuel dependence. Global institutions are weak, economies are closed, and adaptive capacity to address climate change and other challenges is low.

SSP4, inequality: The world is highly unequal, both within and among countries. A small, rich elite controls wealth and resources. Emissions are relatively low because the poor majority lacks sufficient wealth to generate significant emissions, and the elites can relatively easily invest in mitigation technology for their emissions. Global institutions work effectively only for the elite who control them, but adaptation barriers are high for the vast majority of the population affected by climate change.

SSP 5, conventional development: World is focused on economic growth as the solution to all socioeconomic problems, with conventional development fueled by fossil fuels and high resource utilization. Climate mitigation is difficult due to high emission levels, but the benefits of strong economic growth support strong progress toward Millennium Development Goals and reduced challenges to climate change adaptation.

[15] Adapted from Alberts, Mark and Rudolph, Max. 2019. *A Low Growth World : Implications for the Insurance Industry and Pension Plans.* https://www.soa.org/resources/research-reports/2019/low-growth-world/

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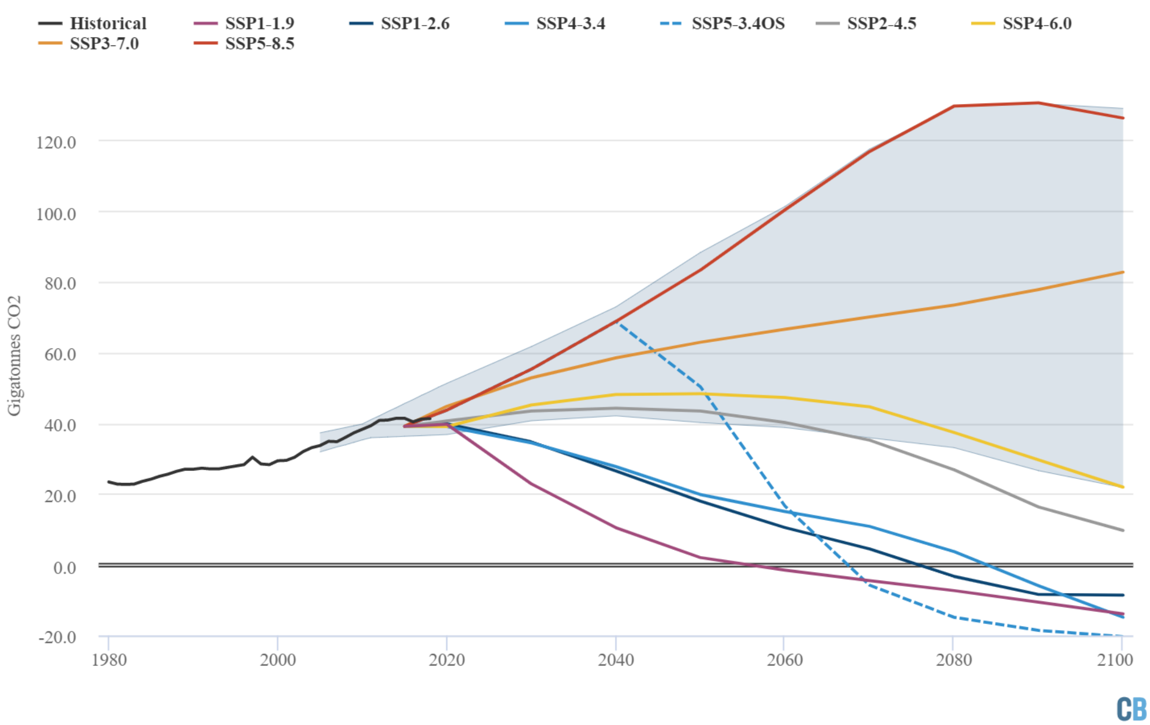
For the sixth IPCC report cycle, the transition from historical data has been set to 2014 and the models enhanced from the previous cycle. The SSPs work with the RCPs, combining greenhouse gas emission scenarios with different climate policies. These integrated scenarios anticipate technological advances, including effective carbon capture systems, that can reduce total carbon in the climate system. In addition to updated scenarios SSP1-2.6, SSP2-4.5, SSP4-6.0 and SSP5-8.5 (with similar radiative forcing levels in 2100 as those in the previous cycle), it is anticipated that CMIP6 (Coupled Model Intercomparison Project, 6th cycle) has added a number of scenarios using the same naming convention tied to radiative forcing in 2100. SSP1-1.9, SSP4-3.4, SSP5-3.4 and SSP3-7.0 are additional scenarios being tested. Figure 4 shows the expected CMIP6 scenarios.

Figure 4
CMIP6 SCENARIOS[16]



Economic growth metric

The economic output of these scenarios is measured using GDP. Other economic growth scenarios have been developed based on specific narratives, but CMIP6 does a good job of putting together a story consistent with the underlying climate science. The problem for actuaries is that we don't tend to think of GDP growth as an explicit pricing metric. We will need to develop our own assumptions for interest rates, inflation and equities that align with these scenarios. For the most part low growth would be expected to lead to low interest rates, but a stagflation scenario with a double digit increase in rates/inflation should also be considered.

[16] Courtesy of Steve Bowen; Head of Catastrophe at Aon. The black line reflects historical CO_2 emissions. The label OS stands for overshoot scenario, where the scenario exceeds the goal temperature before stabilizing by 2100 at that level. Emissions follow SSP5-8.5 until 2040; extreme decline w/ negative emissions after that.

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UNKNOWN KNOWNS

Of concern to analysts is the possibility that historical data will not be predictive of the future, as unknown known conditions, events or trends, using the terminology made famous by Donald Rumsfeld.[17] In contrast, an actuary can confidently work in a known known environment, with historical data that can be used to project a stable distribution of expected results into the future. Especially over short time horizons, assumptions can be used with reasonable confidence that they represent reality.

Climate change creates a more uncertain environment in multiple ways. Assumptions may trend consistently in ways that can be anticipated, but they may also represent tipping points driven by feedback loops where the assumption is discontinuous. This requires a margin of safety to be built into profit models. Especially over long-time horizons these margins can be material.

GROWTH RATES

There are a few sources where modelers can find long-term growth scenarios or forecasts. Some are predictions, but most are considered what-if scenarios. The most useful and robust scenarios start qualitatively as a narrative or story that captures likely consequences, feedback loops and responses to a set of specific conditions. Quantitative modeling of a scenario can be useful to explore feedback loops and interactions among variables while avoiding a false sense of precision.

The Pardee Center for International Studies at Denver University provides a useful and transparent resource. Its International Futures model[18] considers the physical, human and economic worlds in complex and interrelated ways.

Figure 5 combines the results of 20 global long-term economic growth projections, generated by multiple authors,[19] comparing projected growth rates for the United States, China and the world for the period 2010-2060 against historical growth rates for the period 1960-2010.

[17] Shermer, Michael. September 1, 2005. *Rumsfeld's Wisdom*. Scientific American. https://www.scientificamerican.com/article/rumsfelds-wisdom/
[18] http://pardee.du.edu/access-ifs
[19] More information about the IFs scenarios, and Figure 5, can be found at https://www.soa.org/resources/research-reports/2019/low-growth-world/ Alberts, Mark and Rudolph, Max. 2019. *A Low Growth World : Implications for the Insurance Industry and Pension Plans.*

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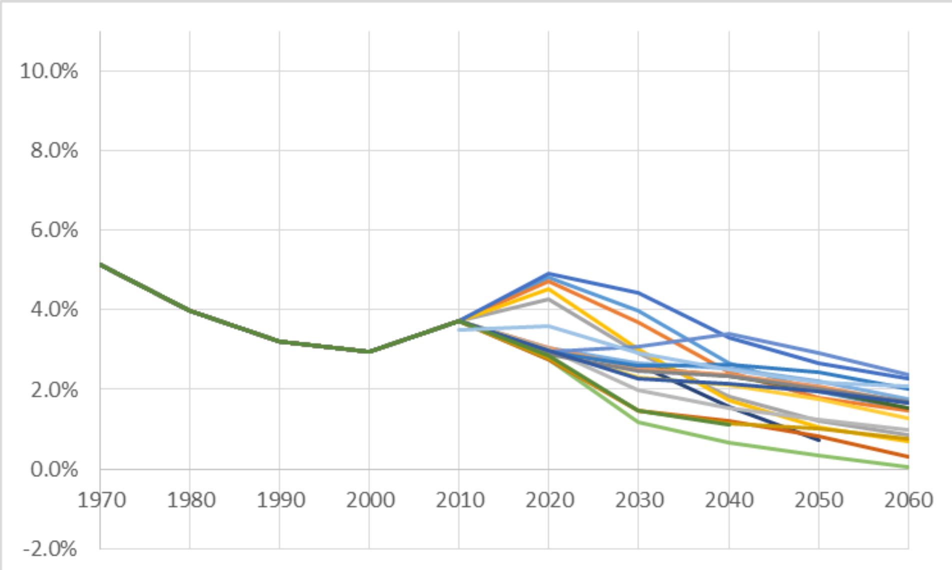
Figure 5

SUMMARY OF GROWTH SCENARIOS, 2010-2060; GLOBAL ANNUALIZED GROWTH RATES BY DECADE VERSUS ACTUAL, 1960-2010



These scenarios include a full range of expectations—high growth, medium growth and low growth. As seen in Table 3, even high-growth scenarios exhibit growth rates generally lower than historical results during the period studied. The medium range results show both aggregate and per capita growth rates for the U.S. and China roughly half historical rates. The lowest of these scenarios shows global growth rates of 1 percent on an aggregate basis and 0.3 percent on a per capita basis—effectively a return near preindustrial-era growth levels.

Table 3

GROWTH RANGES IN PARDEE CENTER SCENARIOS COMPARED WITH 1960-2010

	Historical 1960-2010	Low	Medium	High
World aggregate	3.8%	1-2%	2-2.5%	2.5-3.5%
World per capita	2.1%	0-1%	1-2%	2-3%
U.S. aggregate	3.2%	0-1%	1-2%	2-3%
U.S. per capita	2.1%	1-2.5%	1-1.5%	1.5-2%
China aggregate	8.1%	1-2.5%	2.5-3.5%	3.5-4.5%
China per capita	6.5%	1-2.5%	2.5-3.5%	3.5-4.5%

Table developed by author.

HOW AN ACTUARY CAN UTILIZE CLIMATE SCENARIOS

Each SSP scenario maps to a narrative that aligns with a specific RCP scenario of radiative forcings. They produce a lot of useful information about GDP growth, population, policies, technology and other assumptions. There are several issues for actuaries to consider when using these deterministic scenarios.

- These specific IAM scenarios produce GDP as the output metric. For short-duration insurance contracts that are re-priced annually like homeowner's insurance or Annual Renewable Term life insurance, GDP growth can be used to drive an inflation assumption. For products with longer time horizons, discount rates

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are needed to align with the GDP growth rate and other assumptions. Since discount rates do not follow directly from GDP, it is appropriate to consider the SSP scenario narrative and be internally consistent with it. It may be viewed as being more art than science. Regulators may require specific scenarios, in part to ensure consistency and ability to compare results. Voluntary scenarios can better reflect unique risk exposure and planned responses.

- Climate science scenarios like the RCP set generally do not reflect significant discontinuities or regime shifts. This is useful for projecting trends, but additional stress tests should be considered that incorporate a specific feedback loop and tipping point for conservatism. Typical interest rate scenarios under a low growth narrative anticipate low rates due to factors like climate and demographics, but policy reactions mean a stagflation scenario should also be considered.
- Climate change inevitably leads to a changing environment, creating stresses for animals, plants, property and business plans. Biodiversity can also be at risk. These stresses test the fragility of the climate system. Interest rates will generally have downward pressure due to these stresses and the government's attempts to stimulate the economy. Interest rate guarantees may be hard to meet with available investments, so products would be expected to evolve.
- Actuaries should build in margins of safety for situations where they are unsure that assumptions will remain stable over the product's lifetime. For products like payout annuities, medical malpractice, long-term care or whole life, it has often been difficult to match cash flows with investments due to a long liability time horizon. This will be almost impossible if interest rates are low and long assets come to be in short supply.
- The actuary should consider the time horizon over which parameters are stable. If investments like commercial loans are likely to change credit quality due to climate change before maturity, how can liabilities be sold profitably that extend beyond that period?

Attribution science

When looking at assumption trends and discontinuities, it is helpful to know where extreme events are more likely to occur. An attribution method is being used increasingly often that compares a statistical distribution of regional weather over the past 30 years (recently updated to a base period of 1991-2020) with an expected distribution had the industrial revolution not occurred with its release of sequestered fossil fuels. An actual event or condition can then be placed on the distribution and compare its likelihood.

Attribution science was pioneered in part by Dr. Friederike Otto and a team that looked at Hurricane Harvey, the Category 4 hurricane that hit Houston with 39 inches of rain over 3 days in 2017.[20] Prior to the first industrial revolution (starting about 1750) this type of event would have been expected to occur only once in 9,000 years at this location. The basic concept is that, prior to human extraction of fossil fuels, a given event (e.g., hurricane, tornado) and location had a specific probability distribution and distribution of financial impacts (think of a normal distribution with fat tails) consistent with pre-industrial revolution temperatures and type of damages. The probability distribution based on recent data can be compared to one using the natural forcings model. The difference between expected likelihood pre- and post-GHG increase generates an event attribution. One might say there is a XX% greater chance of a Category 4 hurricane hitting Miami today than in the past.

[20] Otto, Friederike. 2019. *Angry Weather*. Greystone. 2019.

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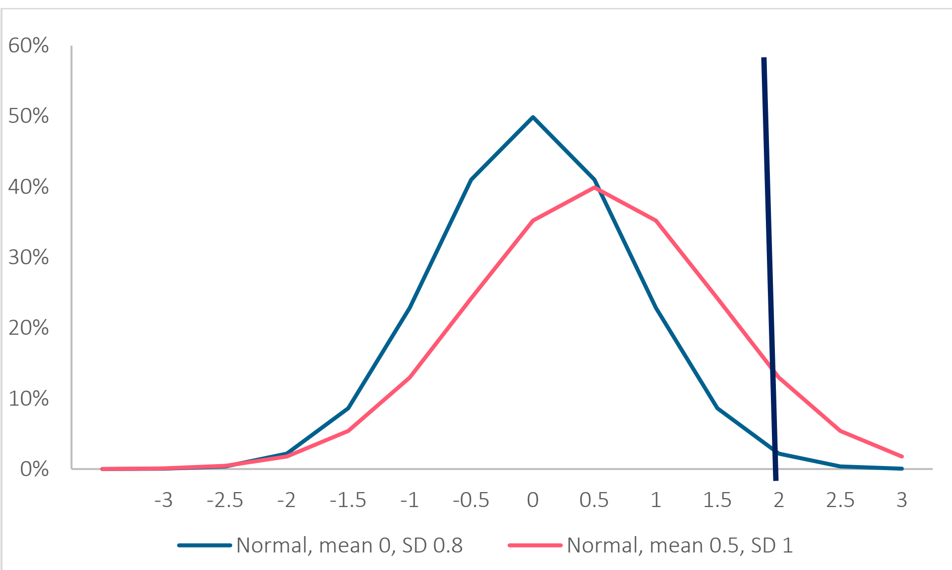
ATTRIBUTION EXAMPLE

The best way to understand this method is through an example. Figure 6 shows two distributions, each one representing the likelihood of a weather event in a specific region. One represents the actual record over the most recent 30 years, while the other is a model of the expected likelihood distribution had only natural forcings occurred and fossil fuels remained in the ground. The variable could be related to wind, precipitation, temperature or other weather phenomena. Limited data points are included to show the value added even from an elementary illustration since extreme events may take thousands of years to occur. While alternative distributions can be used, for this example the base distribution, assuming natural forcings since 1750, is represented by a normalized curve with mean 0 and standard deviation 0.8. A second curve is developed using recent data ('actual'), often collected over the most recent 30 years. The shape of the curve tends to be wider, with a higher mean and variance. In this case the likelihoods are represented by a normalized curve with mean 0.5 and standard deviation 1.

Figure 6 shows the probability distribution function (PDF) for the actual and theoretical distributions, while Figure 7 is the inverse of the cumulative distribution function (CDF). You can tell from Figure 6 that an event consistent with 2 on the X-axis, under the curve showing what probabilities would have been, has a likelihood of at least 0.6%, or every 161 years. That would have been an unlikely event, but anecdotally about once per century. Today, a similar or worse event may have a 6.7% likelihood and could occur every 15 years, or once per generation. Thus, such an event is now approximately 10 times more likely than it was prior to our actions since the start of the industrial revolution. Expected costs associated with such an event can be compared between the two distributions.

Figure 6

ATTRIBUTION PROBABILITY DISTRIBUTION FUNCTIONS



In Figure 7 the inverse of the CDF is shown to focus on the extreme events of interest.

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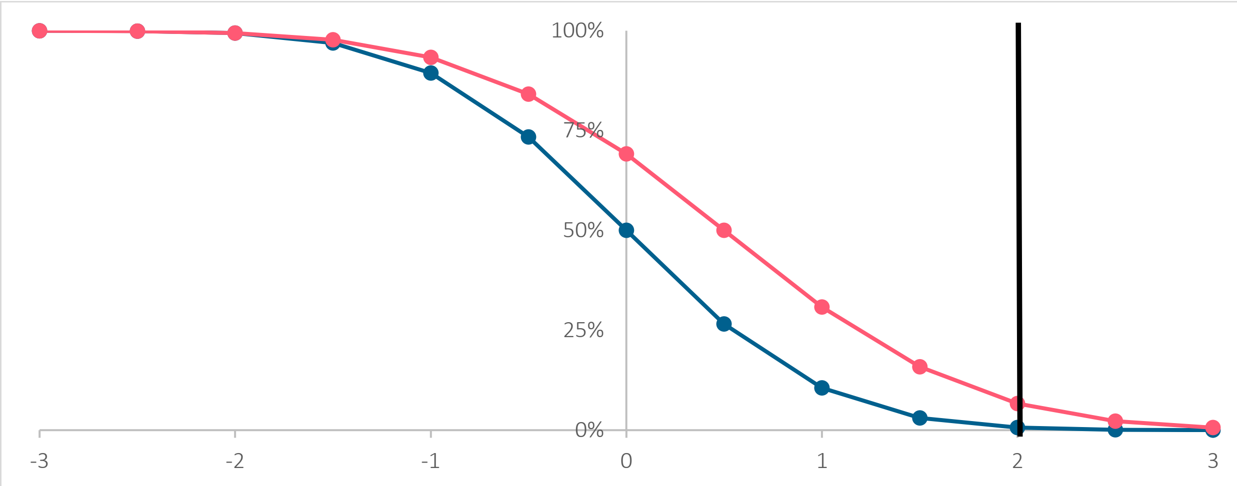
Figure 7
ATTRIBUTION CUMULATIVE DISTRIBUTION FUNCTIONS



HOW WOULD AN ACTUARY USE ATTRIBUTION ANALYSIS?

Visual representation of the higher likelihood of many events due to climate change is very useful in developing educational material about such an issue, but what could an actuary do with the information? Anticipating trends in extreme events can aid in calculating premiums or a distribution of events greater than a specific amount. For years, the wildfire risk in California has been growing as a drought grew more, but premiums reflected only prior claims. When the wildfires finally created extreme events, the initial reaction of insurers was to raise premiums or leave the market. Proactive products could be developed and presented to regulators that act like participating policies and return premiums as a dividend over a rolling 5- or 10-year period if an event does not occur. Hurricane risk could develop similar reserves that would be available during extreme events. These risks could be supported by investments that pay off only when a Category 3 hurricane (or above) makes landfall in the county of interest, like a parametric catastrophe (Cat) bond.

Another tool an actuary could develop would be to anticipate feedback loops that quickly change the claims distribution. Anticipating that the climate system is close to a regime shift, an actuary could petition the regulator to approve an increased premium, but there may need to be additional reserves set up, investment hedges purchased, or product changes before approval is granted.

EMERGENCY ROOM VISITS CAUSED BY HEAT

In a report authored by a team at the University of Nebraska-Medical Center led by Dr. Jesse Bell, extreme temperatures (over 95°F) in North Carolina were compared to local emergency room visits. Over 25% of heat-related illness (HRI) emergency room visits were able to be attributed to anthropogenic climate change. This is the difference between what would have occurred under natural forcings and what was actually observed. As in the previous generic example, in Figure 8 the area under the Observed data under the curve to the right of the 95°F is compared against the same for the "Natural" curve and then adjusted for the cost per emergency room visit.[21] The region is getting hotter at a faster pace than the human body can adapt. This rate of change is the key to

[21] Bell, Jesse et al. 2021. *Determining the Role of Anthropogenic Climate Change on Human Health Outcomes: A Case Study on Heat Related Illness Attribution* https://www.soa.org/resources/research-reports/2021/determining-role-climate-change/

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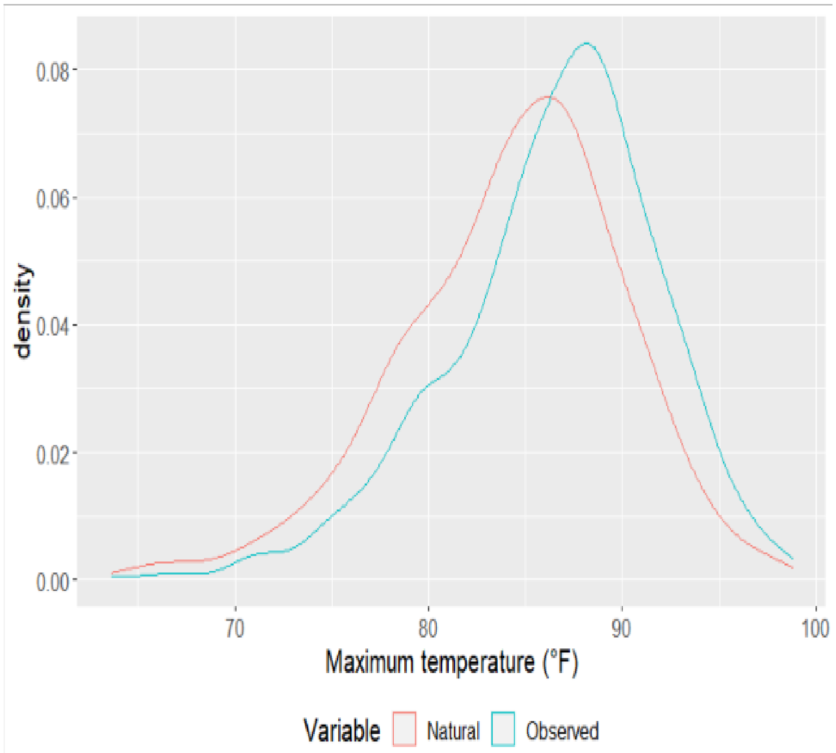
understanding the challenges associated with climate change. The ability to adapt is strong if plants and animals are given sufficient time, but this is rarely the case today. The climate system is a complex adaptive system that interacts with each component to support the whole.

Figure 8
ATTRIBUTION PROBABILITY DISTRIBUTION FUNCTION – HRI EMERGENCY ROOM VISITS



IPCC6 reports and further reading

The sixth cycle of the IPCC is scheduled to conclude in 2022 with publication of the AR6 Synthesis Report: Climate Change 2022. At the time this paper was written, each of the three working groups are scheduled to release reports in 2021 (The Physical Science Basis, Mitigation of Climate Change and Impacts, Adaptation and Vulnerability). The pandemic has caused delays and timelines may be pushed back.

Several special and methodology reports have already been published as part of IPCC6. They include

- Global Warming of 1.5°C (SR15)[22] – this 630-page report, published in October 2018, compares the impact of warming above pre-industrial levels

[22] IPCC, 2018: Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. *World Meteorological Organization, Geneva, Switzerland, 32 pp.* https://www.ipcc.ch/sr15/

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  - In this report IPCC recognized with at least medium confidence climate change influences on various climate and weather extremes (Summary Report, page 7)
- Climate Change and Land (SRCCL)[23] – this 874-page report, published in August 2019, considers climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial systems.
- The Ocean and Cryosphere in a Changing Climate (SROCC)[24] – this 765-page report, published in September 2019, focuses on water. This includes ice in all its forms and locations, along with all depths of the ocean (rivers, lakes and atmospheric moisture are covered in other reports).

OTHER REPORTS THE READER MAY FIND USEFUL

In 2019 a report titled Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[25] was published, improving on methodologies developed earlier. The United Nations Framework Convention on Climate Change (UNFCCC) has met many times since 1992, developing the Kyoto Protocol and Paris Agreement at their meetings that informally committed countries to climate change. Its Council of Parties (COP) meets annually, with COP26 scheduled for November 2021 in Glasgow, Scotland.

An IPCC report published in 2012,[26] *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), does a nice job bringing risk management into the discussion. Contributions were received from multiple professions to look at physical risk and exposure, potential impacts, and proactively planning and managing a disaster. Seeking out vulnerable areas provides more information and allows better decisions to be considered.

Published in 1918 by the UN Environment Programme, *The Adaptation Gap Report*[27] notes earlier and larger impacts, especially on extreme heat events, than previously included in global modeling studies. Climate scientists have traditionally been very conservative in their statements so it will not be surprising to see asymmetric changes that tend toward negative outcomes.

Actuaries around the world are working to solve these climate challenges. In 2020 the IFoA published *Climate Scenario Analysis for Pension Schemes*.[28] Economic growth and various economic indicators of interest to actuaries are discussed.

There are a growing number of groups reviewing company sustainability practices. One gaining momentum is the Task Force on Climate-related Financial Disclosures (TCFD), [29] formed by the Financial Standards Board, that has

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[23] IPCC, 2019: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press. https://www.ipcc.ch/srccl/
[24] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press. https://www.ipcc.ch/srocc/
[25]IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/
[26] IPCC, 2012 – Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.) Available from Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU ENGLAND, 582 pp. Available from June 2012 https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/
[27] UNEP 2018. The Adaptation Gap Report 2018. United Nations Environment Programme (UNEP), Nairobi, Kenya A digital copy of this report is available at: https://www.unenvironment.org/resources/adaptation-gap-report
[28] Bongiorno et al. 2020. *Climate scenario analysis*. https://www.actuaries.org.uk/system/files/field/document/Climate%20scenario%20analysis%20for%20pension%20schemes%20-%20An%20illustration%20of%20potential%20long-term%20economic%20%26%20financial%20market%20impacts.pdf
[29] Gutterman et al. 2020. *The Task Force on Climate-Related Financial Disclosures (TCFD) : What Actuaries Need to Know*. https://www.soa.org/globalassets/assets/files/resources/research-report/2020/task-force-climate-financial.pdf

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relied upon peer pressure from investors, regulators and financial institutions to create voluntary standard reporting on climate change. Another is a United Nations-supported network of investors that has created the Principles for Responsible Investment (PRI) that asset managers can sign on to.[30] Regulators and rating agencies are likely to support relevant standards like these rather than developing another set of standards.

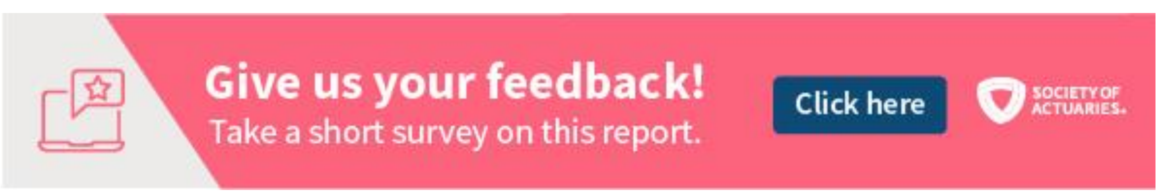
Conclusion

The world is changing and the actuary must adapt. By gaining a basic understanding of the underlying science we can better interpret future impacts on actuarial parameters and assumptions. Insurance products that are repriced every year were once thought to be exempt from this concern, presuming that change would be gradual. However, the California wildfires have shown that decisions to build a home should reflect future claims expectations and not rely on historical data when it is not predictive.

The IPCC reporting cycle provides an opportunity for actuaries to learn from international modelers of weather and climate about what they expect. Their models are quite detailed and are enhanced in each cycle. But there are many public and private models, often with dissimilar results. It is worth thinking about the differences and why they occur. The median and mean will not be the best representations for the most extreme (but possible) events.

The shared socioeconomic pathways (SSP) provide narrative around integrated assessment models that provides a story of how deterministic radiative forcing scenarios might play out in real life. Again, this is very helpful but incomplete. The economic metric most often used is, appropriately for many users, gross domestic product (GDP). The factors used in the scenarios grow smoothly with no discontinuities, consistent with the objectives of ultra-long modeling but missing out on information collected at tipping points and regime shifts. The growth scenarios over the next 50 years used by many modelers are expected to be about half that of the previous 50 years, which could pressure human behavior and economic systems like capitalism and socialism in ways that are difficult to model. Actuaries will need to go back to the narrative behind each SSP/RCP combination used and consider what each one means for an interest rate, inflation or equity scenario. Unfortunately, many processes will result in low rates and low returns over longer time horizons for both, with an occasional period of stagflation.

It will be important to review all assumptions and their interactions. Climate change will lead to changes in product design, investment strategy or looking at time horizon in new ways. The team that considers climate change and its implications will have a competitive advantage versus those who do not.



[30] Principles for Responsible Investment (PRI). www.unpri.org

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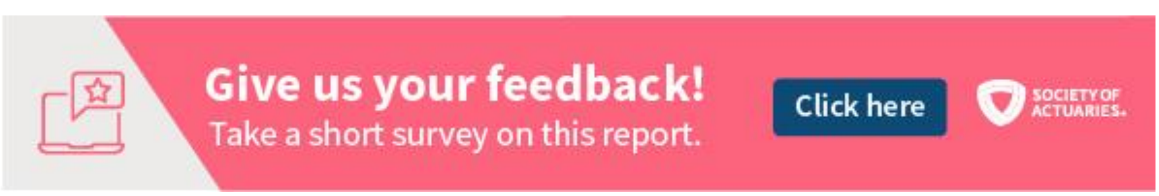

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