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Catastrophe and Climate

Climate System

A Primer for Actuaries

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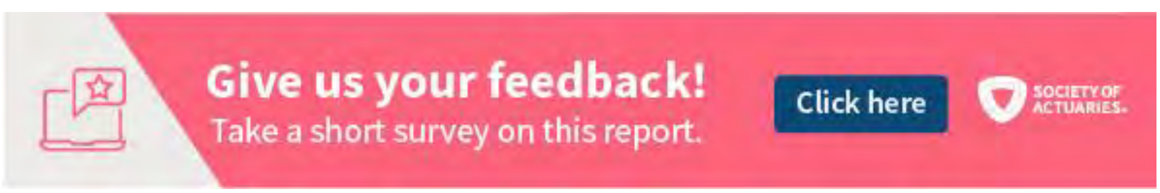

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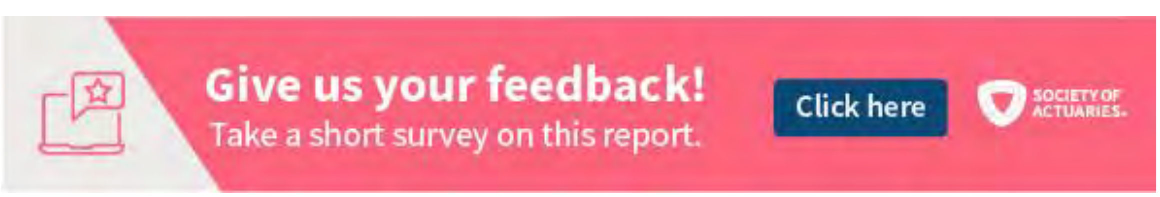
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Climate System

A Primer for Actuaries

Models provide one of the strongest tools in the actuarial toolkit. Many of us have yearned for faster computers so more complex and interactive quantitative models could be completed in a reasonable amount of time. Who hasn't felt the panic induced when submitting the code or pushing the button to start a computer program's overnight cycle while on a deadline? An error meant an entire day was lost so fat fingers, typos and logical flaws all took on increased significance. This is also true for climate scientists. Even today their models require super-computers to run that require shortcuts and simplifying assumptions. It might take a full day to run a decade's climate for a single region. Sound familiar?

The Intergovernmental Panel on Climate Change (IPCC) defines climate system as an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere. The climate system is important for many reasons, but especially due to its interaction with other risks. It acts as a threat multiplier, making risks worse through interaction. Examples include food insecurity, freshwater scarcity, regional tensions and low economic growth.[1] The climate system also shows signs of non-linearity as conditions reach tipping points and variables shift to a new regime of possibilities.[2] Scientists are understanding these interactions better all the time, but the driving factor is the release of additional carbon into the ecosystem. Stories to watch for include permafrost and frozen carbon dioxide on the bottom of oceans melting, or for a conventional war to be fought using fossil fuels.

Actuaries focus on mathematical models, but there is little value without understanding how the underlying climate system works. This paper won't extend all the way to the IPCC assessments of climate change, but it will lay down a foundation for that important work, combining qualitative analysis with scientific climate models.

Complexity models combine the earth's features like atmosphere, oceans, land and cryosphere to simulate larger scale events. These include glacial flows and ocean currents, and cover long periods of time. The impact of the biosphere, including all living organisms, is also modeled.

General circulation models (GCM) are more detailed and are generally what will be discussed here. In a GCM the earth is segmented into a three-dimensional grid, with results calculated at the nodes for each time step of the model. This method is very detailed, so is constrained by computing time as a set of deterministic scenarios take weeks to run even on a super computer.[345]

A model of the climate system is developed in a specific way for a specific purpose. Eventually, scientific results are merged with assumptions about the economy, human developments and societal choices in an integrated assessment model. At times a mean result is the goal, but often the user is interested in extreme events and whether the frequency of such an event has grown relative to pre-industrial trends (attribution).

You will not be able to build your own climate model at the end of this reading. That is not the goal. You will learn the basics of the science behind the climate system and will be able to follow highlights of climate research. You will come away impressed with how far mathematical models have come, while understanding that they produce a distribution of results and are not a prediction. This paper will provide a high-level review of climate models for the actuary and show they are not impenetrable, intriguing the reader enough to seek out additional resources.

Climate-based computer models are extremely complex, based on differential equations, but the process is very similar to what an actuary would create for a traditional actuarial project. Choices need to be made that balance the level of detail and number of time steps. None create a forecast of what will happen with 100% accuracy. All, through the process used, provide climate scientists and others willing to learn with knowledge that allows better decisions to be made based on science and logic. They aren't perfect but they are transparent. It's not so different after all.

Ecosystem

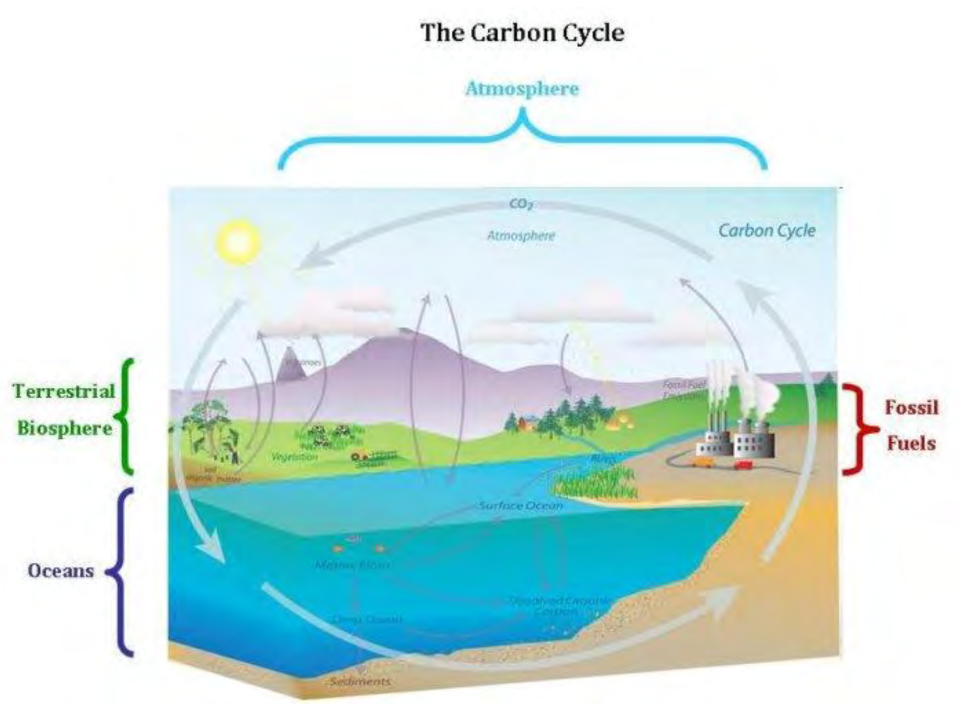
The earth's climate system is an ecosystem, a complex adaptive system, that includes a dynamic network of interactions continually seeking equilibrium. Some of the primary features of earth are the carbon, energy and hydrologic cycles. Our planet does not prefer one state over another but updates its balancing point as new elements are introduced. Humans have impacted this process in recent geologic times, with many defining the Holocene as the era starting just over 10,000 years ago and the Anthropocene following it, starting in the mid-20th century.[6]

Prior to human influences, natural cycles guided the energy that entered the ecosystem in ways generally understood today, causing recurring warming and cooling periods. Massive volcanic events occur periodically, releasing vast amounts of carbon to the atmosphere and warming the planet to levels that depressed biodiversity.[7]

CARBON CYCLE

Figure 1 shows the carbon cycle.[8] Plants sequester carbon through photosynthesis, becoming mostly food or sediment. Animals eat plants and release carbon though respiration. Both decay, releasing carbon. Tectonic activity, either through volcanic eruptions or building mountains as tectonic plates crash into each other, leads to carbon being naturally returned to the atmosphere. Mountains, created when carbon captured in sediment is turned into rock through pressure, release carbon through weathering and send it through the river systems back to the ocean where it settles and repeats the cycle. Fossil fuels, long sequestered, reenter the atmosphere when they are burned, releasing carbon into the air.

Figure 1



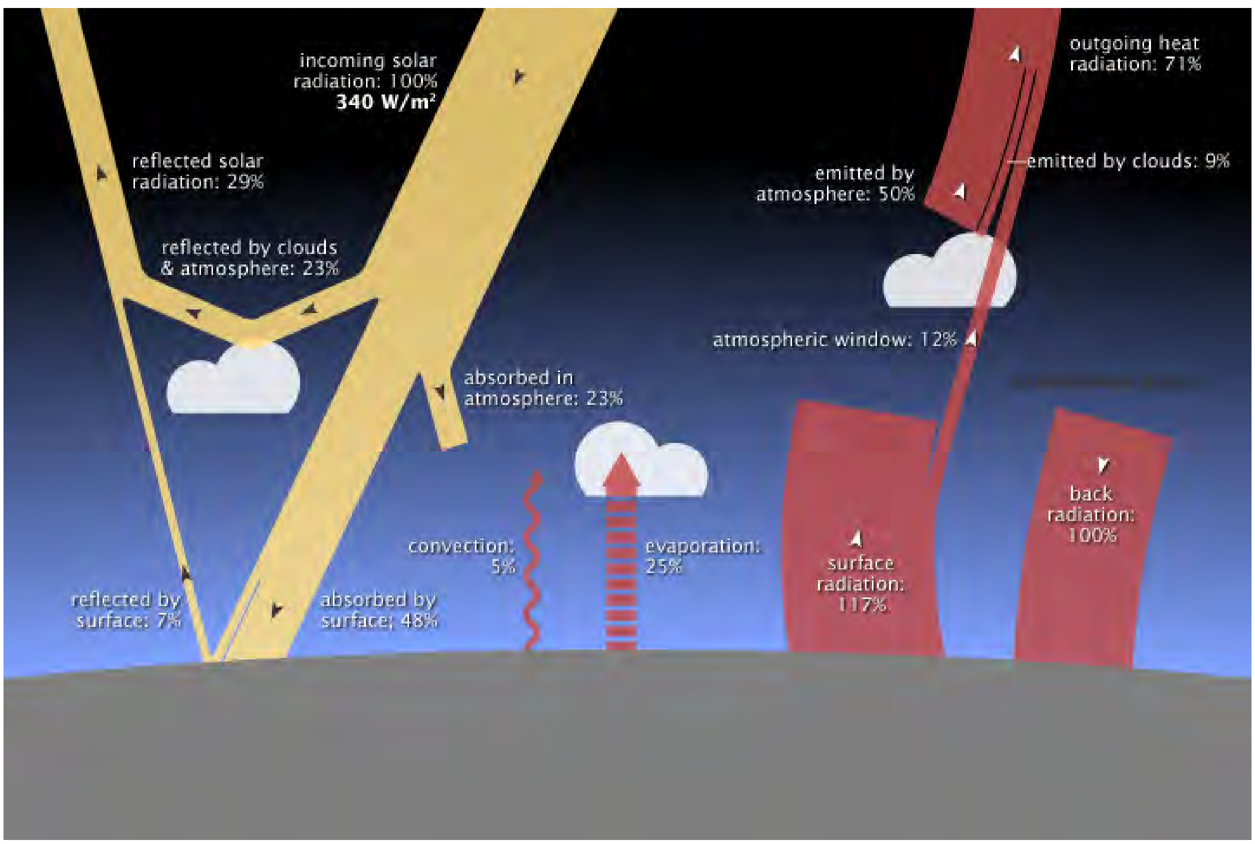
ENERGY CYCLE

Climate models consolidate complexities involved in the underlying process. Energy balance models track changes in energy within an ecosystem, looking at temperature changes driven by changes in absorption of solar energy. One way to think about it is a pinball game, with the sun's radiation bouncing between or absorbed by clouds, land, ice and others. If more (or less) energy is absorbed, equilibrium is fractured and the earth warms (or cools) until a new equilibrium is reached. Figure 2 shows how energy from the sun enters the earth's ecosystem, interacting with clouds and the surface (land, oceans, ice).[9] Some remains in the system, but much eventually escapes back into space.

As energy enters the system, some is absorbed by the atmosphere, clouds, land and oceans but some is reflected back into space. The albedo ratio is high for a feature like sea ice, which has a bright color and reflects much energy, acting as a mirror. It is low for forests and oceans, which are dark and absorb more energy.

Clouds have very complex interactions and feedbacks due to constantly changing shape and small-scale fluid dynamics that are impossible to model at the grid scale of a climate model. They both warm and cool, with low clouds reflecting and high clouds both reflecting and retaining energy in the system, but net out to a cooling impact. Higher model resolution can improve results, like when a mountain peak is in the middle of a grid that represents both arid and wet climates. Regions where tropical activity is strong often have more detailed models to reflect the importance of weather phenomenon in that region.

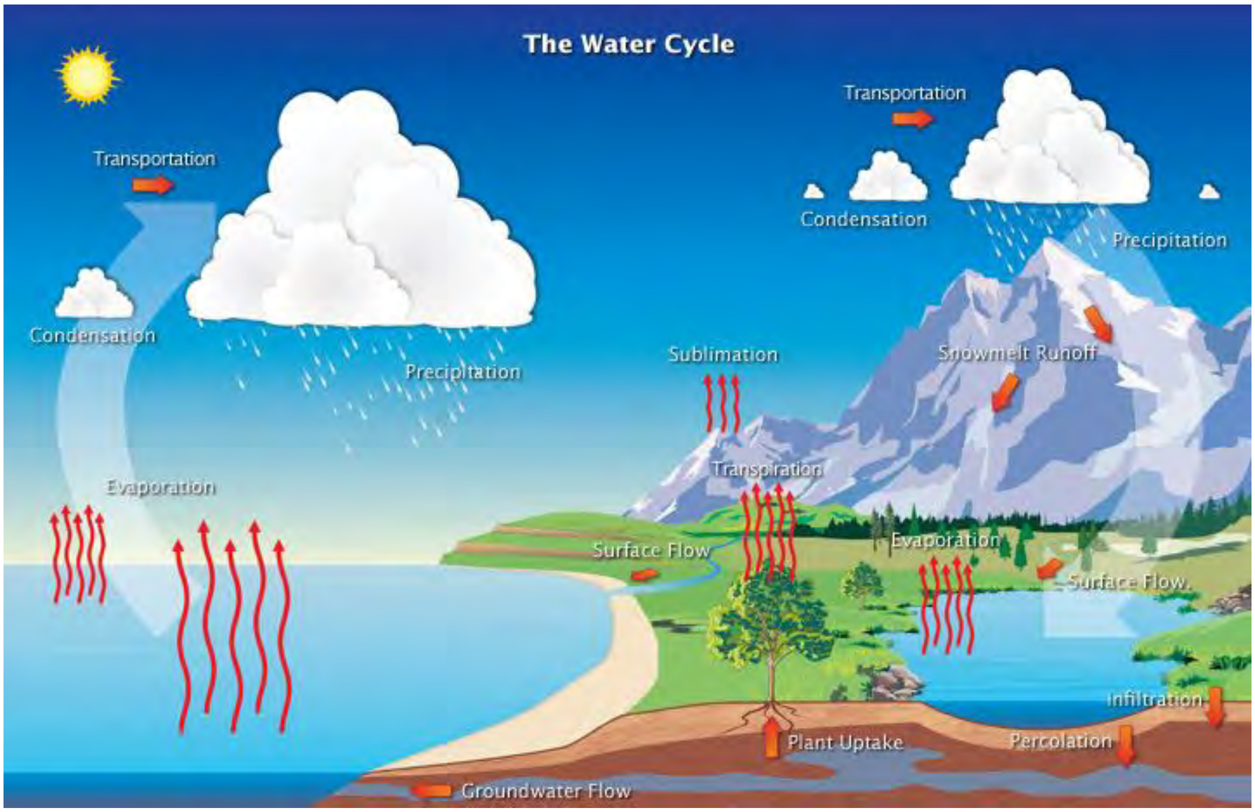
Figure 2



HYDROLOGIC CYCLE

The hydrologic cycle, in Figure 3, demonstrates the sources and uses of water.[10] The cycles must all work in equilibrium as they interact. Water, energy and carbon must all be conserved within a climate model at each time step. Burning fossil fuels releases carbon, increasing temperatures in a way that is mathematically understood. That leads to expanded water volume in oceans and lakes and increased humidity. The cycles are complex, and both positive and negative feedback loops are found.

Figure 3



GREENHOUSE GASES

Most of the gases in the atmosphere are nitrogen (nearly 80%), oxygen (just over 20%) or argon (under 1%). Trace gases from human activity with aggregate totals under 1% include carbon dioxide,[11] methane, nitrous oxide and sulfur hexafluoride. These gases, even though they occur in small amounts, absorb radiation from the sun's rays and reflect a percentage back to the earth as energy seeks to escape into space. This causes them to act like a greenhouse, warming the earth, and so are called greenhouse gases (GHG).

Water vapor (about 0.4% of the atmosphere) is the most common GHG, creating a natural feedback loop as the atmosphere warms. It serves an important role in both the carbon and energy cycles.

Carbon dioxide is created when a carbon compound like wood or coal is burned, or through respiration, while it is naturally captured through sinks using plant photosynthesis on land and sea (it also makes the oceans more acidic). It remains in the atmosphere up to 1,000 years. Methane sources include burning natural gas, decomposing organic matter, cows belching or flooded rice fields. It lasts in the atmosphere less than 10 years, encouraging some (not all) to think of natural gas as a transition fossil fuel, but it can initially be nearly 100 times as potent as carbon dioxide. Nitrous oxide occurs naturally, but is also created from using fertilizer. It lasts over 100 years in the atmosphere and is 300 times as potent as carbon dioxide, while also depleting the ozone layer. The final GHG of concern due to human activity is sulfur hexafluoride, which remains in the atmosphere for over a thousand years and is over 20,000 times as potent a GHG as carbon dioxide. Man-made, it is used in high voltage circuit breakers and elsewhere in industry. These excess GHGs take time to build up in the atmosphere and oceans, but also create momentum for hotter scenarios as it takes time to flush them from the system.

Scientists chart carbon dioxide in the atmosphere using the Keeling curve. The correlation between temperature and the greenhouse gas has proven strong.

The best solution would be for humans to reduce all types of greenhouse gases, but the overall impact today and in the future should be considered when shifting between them. A higher impact today, say from methane, could take the ecosystem past a tipping point that is hard to recover from, like Arctic sea ice melt or a change in timing of the monsoon season that impacts agriculture.

What drives a model of the climate system?

ANTHROPOSPHERE

Homo sapiens left an imprint on the planet as we evolved and spread around the earth. Biodiversity has been reduced and increased agricultural land use has driven deforestation. Large fish and mammals have been mostly eradicated, and overfishing has nearly exterminated some species. Construction along coasts has reduced resilience even as sea levels are rising due to global warming.

Long before fossil fuels became the driver of climate change, humans evolved from hunter/gatherer to farmer. This altered natural cycles through our use of irrigation and fertilizers, changing the surface albedo and flows of heat and moisture.

Humans broke the carbon cycle equilibrium with the advent of the Industrial Revolution, extracting coal, natural gas and oil from previous reservoirs and releasing carbon back into the atmosphere and oceans. This created a carbon imbalance that has interacted with the energy cycle to warm the planet.

WEATHER AND CLIMATE

It is said that weather tells you what clothes to wear today, while climate tells you what clothes to have in your closet. A meteorologist forecasts the weather, with accuracy beyond a few days considered unlikely. But the goal differs. A weather forecast aims to keep its listeners or readers safe and aware of events that will impact tomorrow's ball game or trip to the grocery store. A climate forecast sets a target date along with its location. It is the distribution of possible states of weather at that time, in that region. Variables include measurement of wind, temperature, clouds, ice, precipitation and humidity. Science-based uncertainty is reflected by running many stochastic scenarios and examining the distribution of results. Climate is measured over long temporal scales (time horizons).

SIMILARITIES TO ACTUARIAL MODELS

There are many similarities between a climate model and a traditional actuarial model. An actuary thinks of the starting point of a financial model as an inventory of assets and liabilities. The model marches through time as it generates periodic cash flows and income statements. Similarly, the climate scientist starts with initial conditions at a specific point in time for each section of the spatial grid and advances in time step increments. Both define a model and scenario distributions, generating random sequences to determine interactions between variables and reflect uncertainty.

Understanding the details of a climate system model

Climate is a dynamical system; it evolves over time. Climate models simulate the movement and interaction of fluids, both air and water, how they exchange heat and cycle carbon. Mathematics require simulations using differential equations and probability. No closed form solutions exist. A climate model can be wrong due to uncertainty of the model, of the scenario and of the initial conditions. Using multiple teams of global modelers across generations of research improves the uncertainty of forecasts.

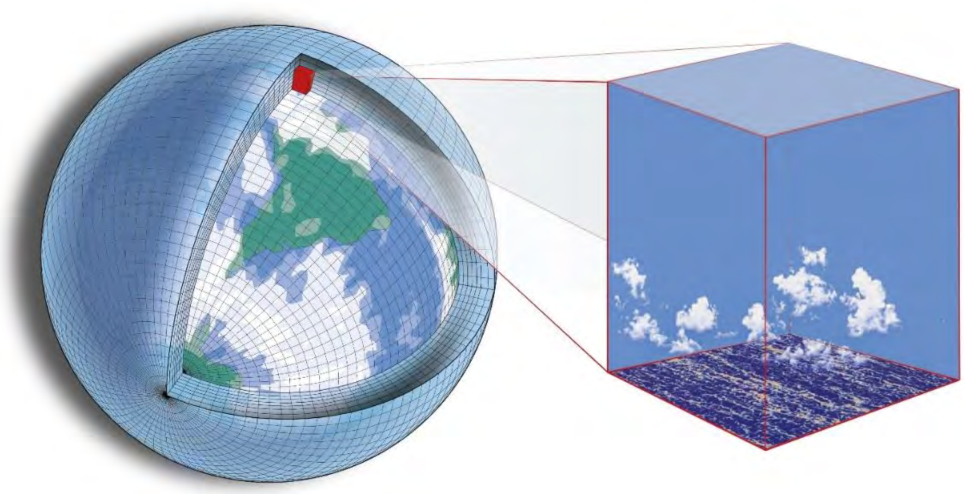
REGIONS

Models are built by dividing up the earth into regions with similar characteristics in a grid pattern, much like an actuarial model will stratify by variables like product, issue year, age and sex. It is useful to understand the difference between spatial and temporal scales. A spatial scale will look at a specific location and compare results such as temperature or precipitation between times, often color coding a map to show where the impact lies. A temporal scale, in contrast, looks at the duration of a specific event. For example, a drought can last months or years while a storm lasts hours.

Regions are defined based on goals of the model and constraints set by computational power, but the primary components of a mathematical climate model are atmosphere, ocean/sea ice and terrestrial (land). Models capture the distinctive characteristics of each while minimizing computer constraints. For example, as shown in Figure 4, atmosphere is split into cube-like three dimensional blocks that may segment by height as well as latitude and longitude. Since the earth is a near-sphere this presents challenges, especially near the poles. Programs ensure conservation of energy, water and carbon for the ecosystem in each region and at each time interval.[12] Similar grids have been developed for some ocean models, while others look only at surface conditions.

Just like a stratified actuarial model built for life insurance or auto coverage needs assumptions (e.g., claims, expenses) to reach the next node, each region of a climate model will start with initial conditions for the period and use assumptions (e.g., atmosphere would consider changes like wind, precipitation, cloud cover) to move to through the next time step.

Figure 4



These models continue to improve as they evolve. Ocean models have various levels of sophistication. Some include topographical features and ocean circulation at all depths (ocean general circulation models), while others simplify using regional models or focus only on surface properties. Sea-ice models struggle with initial observations of ice thickness. This can be a challenge, for example, when feedback loops in Greenland occur as temperatures warm and melting ice uncovers land that is much more conducive to absorbing radiation.

Localized interactions can cause problems in a general model. There are many, and they continue to be discovered. For example, the Norfolk, Virginia area is impacted by general sea level rise due to its location on the U.S. east coast, but the land is also sinking due to overuse of groundwater. An anomaly in the Antarctic, where freshwater melt is changing salinity and circulation patterns was recently described in a research paper. The result in the short term appears to be a colder region, with more snow, but it also results in a thinning ice sheet as the warmer ocean melts it from below.[13]

Events such as drought, fire, water and wind provide complex interactions that can cause feedback loops related to climate. Forced climate migration has already caused population increases in other areas where cultures must merge.[14] Climate solutions must be managed to a future point in time rather than attempt to revert to previous periods of stability. The amount of carbon present today will take centuries to naturally leave the ecosystem. The earth cannot be managed back to a time before the industrial revolution.

Climate models are often tested using hindcasts, looking backward from known extreme events to see how well they predict the actual event. This is similar to the actuarial practice of back casting.

TIME STEP INTERVALS

A climate model starts by taking an inventory of conditions at a specific point in time. These conditions are then iteratively moved forward using assumptions developed from the cycles described earlier. Most are interested in what the climate will be like in 10, 25, 50 or 100 years. Many changes take time to develop, so signal is distinguished more easily from noise when looking to 2050 or later for many variables and events (e.g., drought), but model uncertainty and small assumption errors makes it hard to completely rely on results as far in the future as 2100. Small initial changes in conditions, missed independent variables and assumptions that reach tipping points during the period being modeled can build up over time. These risks might be hidden in earlier iterations by offsetting factors, and when one is updated to a better result it can reveal an issue.[15]

FORCING THE CLIMATE SYSTEM

If the climate was stable the modeling focus would be entirely on weather, but externalities due to humans are changing the earth's climate. This allows groups modeling weather and climate to learn from each other. The amount of carbon added to the system through the use of fossil fuels over the past 250 years rivals some of the largest additions from volcanic activity historically, and each previous time the earth warmed and biodiversity plummeted.[16] Not all regions will react the same as the average. In the northern latitudes, temperature changes have been higher than average, replacing Arctic sea ice with open water that absorbs more radiation from the sun and decreases ocean salinity. This creates a feedback loop that weakens the Gulf Stream[17] that much of Europe relies on for its temperate climate.

COUPLED MODELS

Once models by component and region have been generated, they are combined in a highly complex model that maintains conservation principles and is consistent.[18]

Two cycles have combined to define the increasing levels of detail for these models. The IPCC is now in its sixth assessment cycle, with results expected as early as 2022. This creates a holding pattern for many of the 50 worldwide groups with models that will be combined in the report. As each generational cycle of super computers improves computational speed, this allows smaller “cubes” and shorter incremental time periods. It encourages modeling teams to cover greater regions in a single simulation.

A benefit of the many teams, from various countries, building models in each IPCC cycle is that they are not seeking consensus. Much like a Delphi study,[19] the focus is on transparency that allows each team to see methods other teams have utilized.

DATA QUALITY ISSUES

Data quality is a concern due to uncertainty of the assumptions, tipping points for non-linear factors, and complex variables that challenge modelers and programmers. No one knows for sure what actual GHG emissions will look like or the future socioeconomic development of each region. Some of the processes challenging modelers involve cloud formation, localized weather and weather features of the tropics, jet streams and ocean depths. As the models evolve, especially with a large number of modeling teams, these improve and the results strengthen.

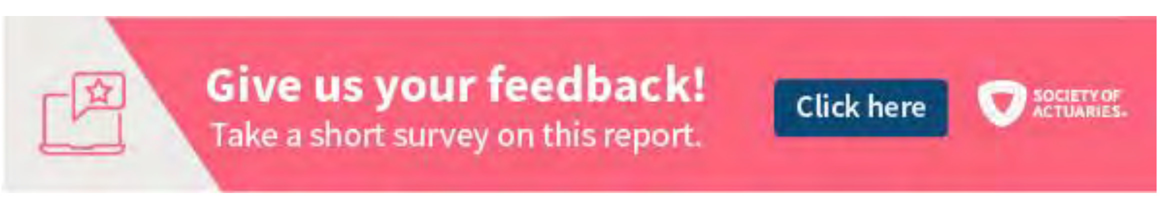
Conclusion

The impact of humans on the climate system goes well beyond the use of fossil fuels, and these impacts also need to be incorporated into climate models. Population growth, especially near oceans, often leads to replacing habitat that moderated storms with buildings susceptible to damage from those storms, while also increasing the risk to buildings that are farther inland. Humans are depleting forests for palm oil plantations, cattle grazing and other agricultural purposes. The Amazon basin is nearing a tipping point that may turn the area from an area of carbon sequestration to one that is a carbon emitter. Growing populations can create spillover events, where pathogen reservoirs are released to human populations (e.g., Ebola, influenza) and biodiversity necessary for stability is reduced (e.g., pesticides and bee population). Many of these changes destroy resilience and change the interactions between variables in a climate model.

Models of the climate system continue to evolve, yet challenges remain. Temperatures seem easier to model than precipitation. Some regional models reflect reality better than others. Feedback loops and tipping points are impacting the results. Improvements are needed on oceans and sea-ice, impacting expected sea levels, temperatures and ocean humidity. These models need to be interpreted by an expert who understands their shortcomings and their interactions with the economy. Actuaries could fill this role of climate interpreter, especially as integrated assessment models add economic ramifications and social developments to specific climate scenarios.

Climate models provide a tool that shows what might happen across a set of future scenarios. It is up to us to decide what we want that future to be and to take steps to achieve it. The models show that the status quo option, where we continue down the path of increasing fossil fuel use, does not have a happy ending for humankind.

Feedback



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[2] NOAA. Climate change and feedback loops. https://www.esrl.noaa.gov/gmd/education/info_activities/pdfs/PSA_analyzing_a_feedback_mechanism.pdf

[3] General circulation models are often tested on other planets to provide a useful test of the basic physics being modeled.

[4] This paper has used several general resources for background. This includes *Demystifying Climate Models: A Users Guide to Earth System Models* by Andrew Gettelman and Richard B. Rood under open access. 1st edition. 2016. Springer Open.

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[8] Image provided by NOAA, U.S. Department of Commerce from their web site at https://www.noaa.gov/education/resource-collections/climate/carbon-cycle

[9] Image provided by National Aeronautics and Space Administration (NASA) from their web site at https://earthobservatory.nasa.gov/features/EnergyBalance/page1.php

[10] Image provided by National Aeronautics and Space Administration (NASA) from their web site at https://earthobservatory.nasa.gov/features/Water

[11] We think of carbon dioxide as "bad" in the context of climate change, but it is good from other perspectives. For example, it is a key input of plants during photosynthesis, which captures carbon and releases oxygen during the process.

[12] Image provided by National Aeronautics and Space Administration (NASA) from their web site at https://climate.nasa.gov/news/2936/clouds-arctic-crocodiles-and-a-new-climate-model/

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[17] Thermohaline circulation details how the ocean circulatory patterns occur. The Gulf Stream creates a good example of this process. As water moves north it cools and expels salt as it forms ice. This increases the ocean's salinity, causing it to sink in areas near the poles where water temperatures vary little from surface to bottom. This differential causes warmer water to travel at the surface north toward England and cooler water to travel south to be warmed near the equator. The Gulf Stream also causes the ocean surface to tilt down toward the east coast of the U.S. If the circulation weakens it will reverse this effect, increasing sea levels further.

[18] Interactions between these cycles reflect complexity as components must stay in equilibrium; neither carbon, water or energy can be created or destroyed.

[19] Real time Delphi Study of Four Economic Variables. Society of Actuaries. 2020. https://www.soa.org/resources/research-reports/2020/real-time-delphi-study/

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With roots dating back to 1889, the Society of Actuaries (SOA) is the world's largest actuarial professional organizations with more than 31,000 members. Through research and education, the SOA's mission is to advance actuarial knowledge and to enhance the ability of actuaries to provide expert advice and relevant solutions for financial, business and societal challenges. The SOA's vision is for actuaries to be the leading professionals in the measurement and management of risk.

The SOA supports actuaries and advances knowledge through research and education. As part of its work, the SOA seeks to inform public policy development and public understanding through research. The SOA aspires to be a trusted source of objective, data-driven research and analysis with an actuarial perspective for its members, industry, policymakers and the public. This distinct perspective comes from the SOA as an association of actuaries, who have a rigorous formal education and direct experience as practitioners as they perform applied research. The SOA also welcomes the opportunity to partner with other organizations in our work where appropriate.

The SOA has a history of working with public policymakers and regulators in developing historical experience studies and projection techniques as well as individual reports on health care, retirement and other topics. The SOA's research is intended to aid the work of policymakers and regulators and follow certain core principles:

Objectivity: The SOA's research informs and provides analysis that can be relied upon by other individuals or organizations involved in public policy discussions. The SOA does not take advocacy positions or lobby specific policy proposals.

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Relevance: The SOA provides timely research on public policy issues. Our research advances actuarial knowledge while providing critical insights on key policy issues, and thereby provides value to stakeholders and decision makers.

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