CHAPTER 13

CLIMATE MODELING FOR HEALTH IMPACTS

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Greenhouse Gases and Radiative Forcing

The global carbon cycle is changing, and that change is accelerating. Humanity emitted about 10 gigatons (Gt) of carbon into the atmosphere from fossil fuel use in 2018, equivalent to 37 Gt of CO_2 (Friedlingstein et al. 2019). These were the global **emissions**, as quantified by an international team of dozens of credentialed scientists and engineers representing governmental and academic institutions, with relatively small uncertainty (±5 percent). It is a couple of percentage points higher than in 2017, which was a couple of percentage points higher than in 2016. Another annual number that we know quite well is the amount by which the global **concentration** of atmospheric CO_2 has increased. In 2018, the concentration of CO_2 in Earth's atmosphere grew by about 3 parts per million (ppm), which is three times the annual growth rate in 1970.

Emissions and concentration are obviously linked, but it is worth appreciating their distinction, where the former is the amount deposited each year and the latter is the account balance. The strength of the greenhouse effect (described later) at a given time is a function of the composition of the global atmosphere at that time, so the total *concentration* of **greenhouse gases** (e.g., 411.44 ppm of CO_2 in 2019) is what the physical climate system responds primarily to. If annual CO_2 emissions were as high as they are but constant year after year, the CO_2 concentration might increase linearly. However, emissions themselves are steadily increasing; hence the concentration is growing exponentially.

The amount by which the atmospheric CO_2 concentration has increased since the beginning of the industrial revolution is not unprecedented. Both the rise in CO_2 concentration over the past 150 years due to anthropogenic emissions and the increases in CO_2 that occur at the termination of a glacial cycle are approximately 100 ppm. The pace of the recent rise in CO_2 concentration, however, is indeed unprecedented in the history of Earth's climate. If one lines up the beginning of the previous two deglaciations (roughly 137,000 and 15,000 years ago) with the year 1851, we can see just how rapidly CO_2 concentration is rising today compared to quite some pivotal climatic shifts in Earth's history (Figure 13.1). During the last two deglaciations, CO_2 concentrations rose by 80 ppm in somewhere between 6,000 and 10,000 years, whereas recent anthropogenic emissions drove CO_2 upward by the same amount in just 150 years (1851–2000). We are conducting a massive, uncontrolled physics experiment on planet Earth. At the present rate of increase (2.5 ppm per year), the next 80 ppm should be added in as little as thirty years.

It is not a coincidence that human activities are emitting CO_2 into the atmosphere and the concentration of CO_2 in the atmosphere is increasing. Apart, they are highly uncontroversial facts both within and outside of the scientific community. However, there are a couple of **attribution** ("cause and effect") cases that must be

KEY CONCEPTS

- **Atmospheric concentrations of greenhouse gases are higher today than any time in at least the past million years, which is rigorously proven to be a result of human activities.**
- **Rising concentrations of greenhouse gases lead to a net energy imbalance in Earth's climate (primarily by reducing how much heat escapes), requiring an increase in global average temperature.**
- **Global climate models (GCMs) are computerized representations of the laws of physics that govern how the atmosphere, ocean, and other features of the climate system operate and interact.**
- **GCMs enable us to attribute the observed global warming over the past century to greenhouse gas forcing and to predict future warming (and other changes in the climate such as rainfall) given assumptions about future rates of greenhouse gas emissions.**
- **Climate modeling for global change science is an international collaboration; considering the dozens of GCMs developed and run at institutions around the world enables quantification of uncertainties in future climate change projections.**

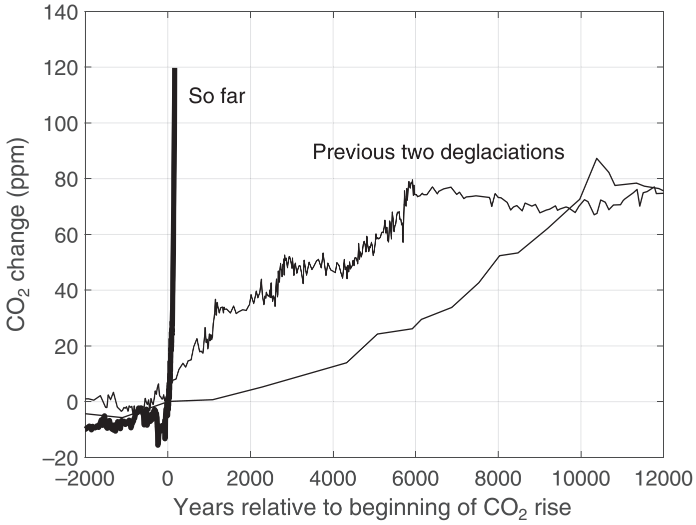

Figure 13.1 Three segments of the full CO_2 concentration (ppm) record shifted such that the beginning of the CO_2 rises associated with the previous two deglaciations and the modern era begin at coordinates (0,0) on the graph. This enables direct comparison of both the amount and rates of change associated with these three time periods. The last and next-to-last deglaciations were taken to start at years −15,410 and −136,900, respectively, and the modern era is aligned such that the year 1851 is at zero on the time axis.
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made in order to bring them together, and although science has made them very well, they are the usual sources of confusion and contention among those whose expertise and life's work may lie outside of the field of climate science. The first is whether CO_2 is rising at the measured rates *because* of human activities. Earth's climate has, after all, changed in the distant past—including the atmospheric CO_2 concentration. For an ironclad case, we must go beyond simply correlation, which—as is often cited—doesn't prove causation.

The field of geochemistry has developed an extraordinary tool for detecting the fingerprint of fossil fuel combustion: isotopic fractionation. When humans engage in fossil fuel combustion, we are burning plant matter that has been buried in layers beneath the surface of the Earth and has become fossilized (Figure 13.2). When those plants were living and photosynthesizing, they were fixing carbon in the form of atmospheric CO_2. However, not all carbon atoms are the same. There are three naturally occurring carbon isotopes, which differ only in how many neutrons are present (as all isotopes do). Carbon–12 (^{12}C) and carbon–13 (^{13}C) are stable, meaning they do not decay radioactively like carbon–14 (^{14}C). When plants photosynthesize, they may use either ^{12}C or ^{13}C, but their physiology is able to discriminate between isotopes and they strongly prefer the lighter isotope, ^{12}C. Tracking the ratio of one isotope to the other in the atmosphere ($^{13}C/^{12}C$ or simply $\delta^{13}C$) thus enables us to determine *why* CO_2 started rising as rapidly as it did in the nineteenth century. By extracting long ice cores from the Antarctic ice sheet and examining air bubbles trapped inside of them, we have detected a precipitous drop in atmospheric $\delta^{13}C$ (higher ^{12}C relative to ^{13}C), which happens to be timed very well with the increase in *total* atmospheric CO_2 concentration, confirming that the modern rise in CO_2 is attributable to fossil fuel combustion (Francey et al. 1999; Rubino et al. 2013). Have anthropogenic emissions been *enough* to account for the atmospheric concentration passing 400 ppm in 2015? Unfortunately, we have emitted way more than enough to account for that. Had all of the CO_2 emitted into the atmosphere *stayed* in the atmosphere rather than some being absorbed by the ocean and land, we would have met the 400–ppm milestone about twenty years earlier (Denman and Brasseur 2007). About half of the CO_2 emitted by fossil fuel combustion so far has already been drawn out of the atmosphere, and that burden has been shared about evenly between the ocean and terrestrial biosphere.

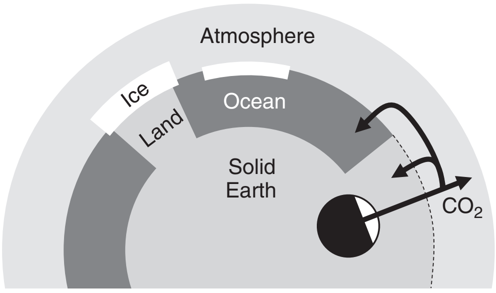

Figure 13.2 Illustration of carbon reservoirs and components of earth's climate system, including the atmosphere, ocean, cryosphere, and solid earth

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Note: Black arrows represent anthropogenic carbon dioxide emissions, indicated as a flux from the solid Earth into the atmosphere, and subsequent fluxes of anthropogenic CO_2 from the atmosphere to the terrestrial biosphere and ocean.

The other question of attribution concerns whether the increasing concentration of CO_2 (which is definitely due to human activities) is in fact causing the climate changes that we have been observing. Even when one accepts that the global average surface temperature on Earth has risen by about 1.3°C (2.4°F) over the last century, firmly establishing cause and effect entails some basic understanding of the expected thermodynamic response of the climate system to increasing greenhouse gas concentrations. Building those laws into comprehensive Earth system models, we may show that the actual CO_2 emissions indeed account for the observed warming. The laws of thermodynamics in fact *require* the climate to warm when additional molecules of CO_2 are added to the atmosphere. CO_2 is regarded a greenhouse gas because of how it interacts with thermal radiation attempting to pass through it. Consider one molecule of CO_2 as comprised of three marbles (two oxygen atoms and one carbon in the middle) connected by two springs (covalent bonds); there are several ways for such a contraption to bend, wiggle, and vibrate. Like other greenhouse gases, including methane, nitrous oxide, and water vapor, the geometry of these molecules is well suited to intercepting thermal radiation, converting it to kinetic energy (i.e., raising their own temperature), and reemitting that thermal radiation at a rate proportional to their temperature to the fourth power (à la Stefan-Boltzmann Law).

A greenhouse is therefore not a bad analogy for this process; solar radiation passes through these molecules in the atmosphere to heat the surface (like sunlight passing through glass walls), but most of the thermal radiation emitted by the surface is intercepted by greenhouse gases on its way out and returned to the atmosphere. If Earth's atmosphere contained no greenhouse gases whatsoever, its equilibrium temperature would be a miserable −18°C. It is perhaps obvious that greenhouse gases are not just lining the floor; they are generally mixed throughout the lower layer of the atmosphere (called the **troposphere**). So, when greenhouse gases absorb and reemit thermal radiation, the fraction of that reemitted energy that is escaping to space has been reemitted on average by molecules with a *lower* temperature than that of the surface because they reside in a colder part of the atmosphere! It is both the radiative properties of greenhouse gases *and* their vertical distribution in the troposphere that allow them to reduce the amount of thermal radiation escaping to space. Because they do not change the amount of incoming energy (solar radiation), the incoming radiation in the presence of greenhouse gases exceeds the outgoing radiation. Given such a net energy imbalance, the fundamental laws of thermodynamics for a closed system guarantee that a new equilibrium will be reached after the temperature increases until the outgoing energy (thermal radiation escaping to space) exactly balances the incoming energy (solar radiation). With the presence of greenhouse gases in Earth's atmosphere, such equilibrium is (or was) achieved with Earth's average surface temperature set at about 15°C (59°F).

Today, we are maintaining a perpetual *disequilibrium* between the incoming and outgoing energy because each additional molecule of a greenhouse gas emitted to the atmosphere by human activity ensures that more of the thermal radiation emitted by Earth's surface is intercepted in the atmosphere and re–radiated at a lower temperature. This energy imbalance currently amounts to a **radiative forcing** of 1–2 W/m^2, and meanwhile we witness the guaranteed consequence of an upward trend in global average surface temperature. Recent studies have unambiguously detected the fingerprints of radiative forcing in measurements of the *decreasing* trend of thermal radiation escaping to space (Harries et al. 2001) and of the *increasing* trend of thermal radiation reaching Earth's surface (Feldman et al. 2015). The greenhouse effect works, and we are making it stronger. As the greenhouse effect and the laws of thermodynamics in general are quite well known, they constitute an important function within the models that are discussed in the next section, and which we use both to attribute past changes in climate and to project future changes given various assumptions about how much CO_2 will be emitted throughout the remainder of this century.

What Is a Global Climate Model?

There are many pathways and manifestations of climate change in the real world, both past and future. In most cases, there is a common tool that is used for projecting the future impacts and regional expressions of climate change: **global climate models** (GCM)—that is, comprehensive models of the global climate system that incorporate the atmosphere *and* ocean, as well as other realms of the Earth system like the cryosphere (including sea ice, ice sheets, snow, and glaciers) and even the biosphere to a varying extent. The latest generations of GCMs are actually *combinations* of atmospheric general circulation models (AGCMs), ocean general circulation models (OGCMs), and other submodels, like ones that predict how ice sheets and fields of sea ice change and how terrestrial vegetation responds to climate (Figure 13.3). GCMs are also useful for investigating climate variations of the recent past, as certain experiments can be designed to estimate how much *natural* variability we might expect to see in various aspects of the climate system, and to attribute observed long-term changes in the climate to particular forcings. Those experiments will be discussed here as well.

What is a GCM? To the newcomer, the answer can take a while to sink in, particularly because of how tempting it is to conflate climate models with climate observations. In the most general sense of the word, *observations* of the natural world have led us to theories that explain in a universal sense how it all works. Think of Newton's *Principia* of 1687. He observed the proverbial apple falling from the tree, and following much more careful observation and consideration, the laws of classical mechanics, gravitation, etc. were developed. Most of the equations and other theoretical material comprising physics textbooks were inspired at some point in time by a set of such observations that made someone ask "why?" The various models (of the atmosphere, ocean, etc.) that make up a complete GCM are merely the laws of physics that govern those realms of the climate system, all packed into a computer program that solves those equations at every location on Earth and on any date (past or future) that is of interest to the researcher. Notice that the "observations" that were important in the development of GCMs were actually important in the development of their precursors—the laws of physics. GCMs are *not* observations of climate change. Climate change is the thing we want to diagnose and predict with GCMs, so observations *of* climate change are not fed into GCMs, and for some very good reasons that will become clear as we explore how GCM experiments are conceived. To summarize, GCMs are large collections of equations whose outputs have an impact on each other's inputs, and we know those equations largely because of systematic observations of the natural world—they are then translated from mathematical notation into computer code.

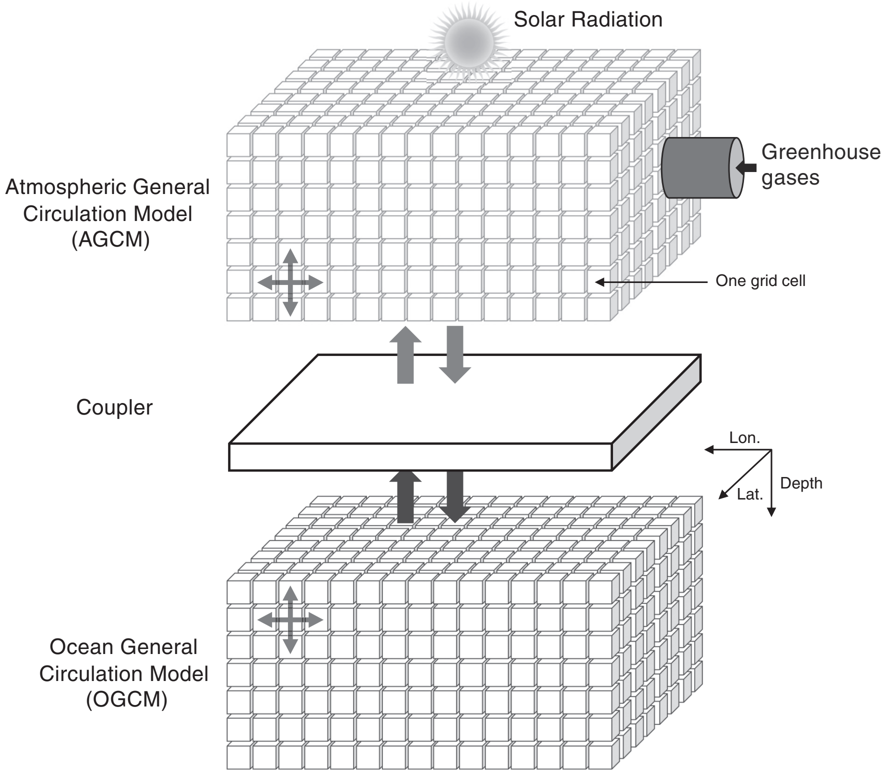

Figure 13.3 Anatomy of a GCM as a coupled model including component models representing the global atmosphere (AGCM), global ocean (OGCM), and other components such as ice and the terrestrial and/or marine biosphere (not pictured). The component models discretize their global realm with finite-sized grid cells whose size is a function of model resolution. Grid cells must communicate with each other (transparent arrows), and a coupler serves to exchange information (forcing) between the component models. Typical prescriptions during coupled GCM experiments include solar radiation and the concentration of greenhouse gases.
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Given this general description of GCMs, you may be wondering why we need supercomputers the size of large classrooms to run climate simulations with them. The answer has less to do with the number of equations that constitute a GCM and more with how big Earth is and how far out the end of the twenty-first century still is (a conventional time frame to predict using GCMs). If you imagine all of the equations in a meteorology textbook, plus all the equations from books that similarly describe the behavior of the ocean, sea ice, ice sheets, and terrestrial biosphere, you can now imagine how simulating the time evolution of the climate system actually means solving those equations *everywhere!* It may also be obvious that those equations at one location cannot just be considered in isolation from neighboring locations, nor can a single time step be simulated in isolation of all of the previous times. It gets complicated and expensive, but fortunately there is some compromise that takes place by approximating "everywhere" with a reasonable number of volumes connected to one another.

GCMs divide the world into three-dimensional volumes called **grid cells**. If it is decided that each grid cell in the *atmosphere* component of the GCM is 0.5° latitude by 0.5° longitude by 100 meters in height, then we end up with about thirty million grid cells for the troposphere alone. Such numbers define the **resolution** of the GCM. In reality, a GCM's resolution can be different in different regions, depending on what the modeler thinks is going to be important to resolve in greater detail. For example, the atmospheric component of GCMs (or AGCMs) usually have finer vertical resolution packed into the lower altitudes of the troposphere to better resolve the detailed interactions with the surface. In addition, many OGCMs have "stretched" resolution such that grid cells are smaller (~0.2° latitude) but more numerous within a few degrees of the equator, and finer vertical resolution (1–10 m) in the upper ocean. The former is in recognition of how important the coupled dynamics in the deep tropics are in determining the evolution of the global climate system (e.g., **El Niño**). Finally, an important component of a GCM known as the “coupler” translates everything that is happening within the AGCM that matters to the ocean into a direct *input* (also referred to as forcing) to the ocean model (solar radiation, surface winds, etc.). At the same time, the coupler must also round up all of the variables from the OGCM that should affect the atmosphere and pass it along as forcing along the bottom of the AGCM. So, a GCM is truly a set of multiple submodels, each of which are responsible for simulating their own jurisdiction within Earth’s climate, but exchanging information frequently along the way so that the overall climate evolution is determined by their *coupled* interaction—just like in the real world. Because GCMs are *coupled* models, there is no way to guarantee that the basic climatology that emerges in such simulations is perfect. Each model has mean state **biases**, meaning a little too much rainfall here, not enough there, this part of the ocean is too windy, or not enough low cloud cover over there. GCM biases are acceptable within reason and generally do not prevent us from using them to make predictions of *change*, but it is still the ambition of model developers to reduce biases with each new generation of GCMs.

The amount of computer time required for a GCM to complete a simulation is known as “wall clock” time—how long the climate modeler will actually have to wait for an experiment to finish and obtain the results. Wall clock time depends on many characteristics of the GCM and the experimental design including the spatial resolution and number of years to be simulated. The wall clock time also depends on the computer! Drawing on the comparison between the size of a supercomputer and a large classroom, a supercomputer is not unlike a classroom full of students, each with their own basic calculator. The supercomputer takes the whole Earth full of grid cells as defined by the modeler, splits it up into a number of tiles (similar to broad, rectangular regions), and assigns each tile to an individual processor to work on—a computing strategy known as **parallel processing**. The large number of calculations needed just for a single time step in the model simulation is thereby shared across a large number of processors that work on them simultaneously. When the first time step is finished (say 0 UTC [coordinated universal time] on January 1, 1900), all of the processors move on to the next time step (6:00 UTC), solve the equations for each grid cell in their assigned segment of the world, and so on. Eventually, 0 UTC on January 1, 2000 is reached and *voilà*, a retrospective simulation of last century has finished. For modern GCMs running on state-of-the-art supercomputers, such a simulation might take several days if not weeks or more, depending on the aforementioned characteristics of the GCM and experimental design and how many other climate modelers you are sharing the computer with.

Global Climate Models and Global Change Science

Although running a one–off GCM experiment for an esoteric problem might be a relatively solitary pursuit achievable by a single or small group of climate scientists, climate modeling for the purpose of global change science is a truly collaborative and international enterprise. There are dozens of GCMs that have been developed and are run on supercomputers at various research, academic, and governmental institutions around the world. Major centers in the United States, for example, include the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), National Center for Atmospheric Research (NCAR), and the NASA Goddard Institute for Space Sciences (GISS). To put it mildly, these are incredibly sophisticated computer models, and *within* each of these institutions are large and diverse teams of climate scientists (as well as computer scientists, data scientists, and engineers) whose full-time jobs are to work on a single *component* of the full GCM (such as the AGCM or the coupler).

When it comes time to conduct the climate change experiments that inform the assessment reports issued periodically by the Intergovernmental Panel on Climate Change (IPCC), a special team must be assembled to coordinate *across* institutions. This coordinating effort is called the Coupled Model Intercomparison Project (CMIP). Just as the latest Assessment Report of the IPCC was AR5 (IPCC 2013), the most recent CMIP was CMIP5. The coordination achieved by CMIP is essential to ensure that, although each of the international modeling institutions may have its own GCM(s), the experiments are being conducted in a consistent manner. In other words, each GCM simulation uses the same prescribed historical greenhouse gas forcing, the same time periods being simulated, and the same assumptions about possible *future* CO_2 concentrations. The latter of course, depends critically on how society evolves in the coming decades, but at least the same **representative concentration pathways** (**RCPs**) are simulated by each model. This coordination and controlling for as many confounding variables as possible lead to a uniformity of experiments that enables teams of IPCC authors to merge the results from all models into one picture, ensuring that any differences between results from different institutions must be the result of their *models themselves* being different, not, say, because they used different historical records of nitrous oxide concentration.

Each time a new IPCC assessment report is on the horizon (every 5–7 years), several types of GCM experiments are conducted under the auspices of CMIP. GCM simulations in which the radiative forcing (greenhouse gases, volcanic aerosols, solar radiation) are held constant for a thousand years or more are known as **control experiments**. Control experiments yield insight into how much the climate system varies without any perturbation by humans or other external factors, which is important to know when determining whether a trend is undoubtedly due to radiative forcing or might just be a perfectly natural wiggle. **Attribution experiments** are two otherwise–identical GCM simulations conducted with and without "something," where that something is usually one or more of the anthropogenic forcings. These are counterfactual experiments from which we can estimate how the past century of climate would have unfolded *without* fossil fuel combustion simply by keeping the atmospheric CO_2 concentration set at its preindustrial level. Here's why observations of climate change (beyond the *forcing* like CO_2 concentration) are not just fed into the models! Because one of these GCM simulations represents the model's best attempt to reproduce the historical changes in global average temperature (and other changes mediated by warming) and the other excludes the greenhouse gases, we can *compare* both of them with the observational records and soundly establish attribution—we *cannot* explain the observed global warming unless we include the effect of greenhouse gases (Figure 13.4). It is not just a natural wiggle or due to some other natural forcing like volcanic aerosols or variations in the solar radiation emitted by the sun. We humans are responsible for the rise in greenhouse gases, which explains the observed warming; therefore we are responsible for the observed warming—we have now come full circle.

Finally, **future experiments** are conducted by running GCMs from the present to the year 2100 (or beyond) and introducing additional CO_2 into the atmosphere according to an assumption of how much humans will continue emitting the gases over that interval. This is where the coordinating role of CMIP is especially crucial for efforts to provide useful predictions for policymakers via IPCC. Rather than allowing every nation or modeling institution to use its own projection of CO_2 emissions, which is highly dependent on assumptions about population, technology, energy policy, international relations, national politics, etc., a set of four RCPs were agreed upon by CMIP and IPCC stakeholders, and each modeling center conducted GCM experiments using those RCPs so that, again, all of the model results could literally be combined onto a single graph and enable us to judge not only the consensus predictions but

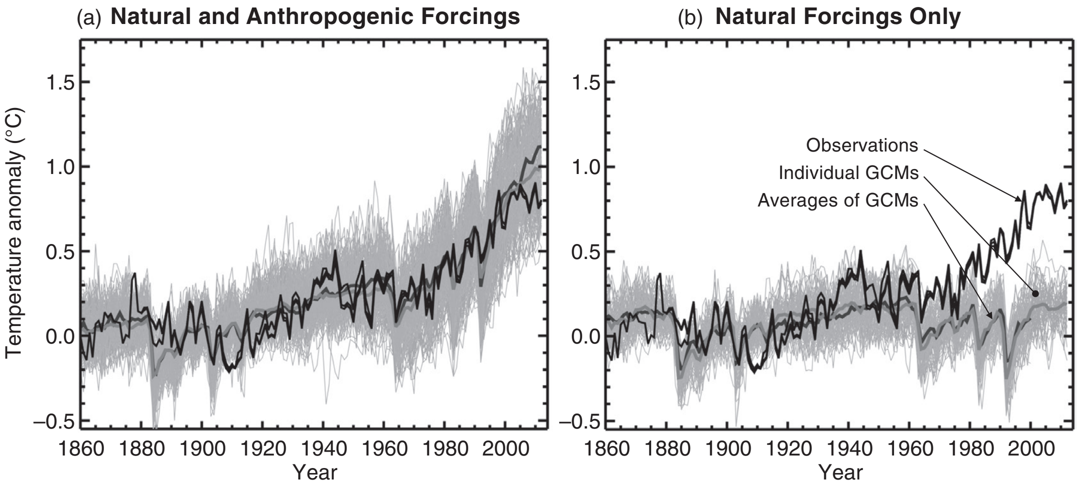

Figure 13.4 Historical simulations by ensembles of GCMs of the CMIP3 and CMIP5 generation of global mean surface temperature (°C) with natural (e.g., volcanic) and anthropogenic (e.g., greenhouse gases) forcings (a). The plot in (b) is the same except that only natural forcings were included in the model simulations, thus attributing the observed temperature change to anthropogenic forcings.

Note: Three different observational records are shown in thick black lines. Individual model simulations are shown in thin light gray lines, and the multimodel averages are indicated by thick dark gray lines.

Source: Adapted from IPCC AR5 WG1, Figure 10.1 (IPCC 2013) and reproduced from Kris Karnauskas, *Physical Oceanography and Climate*, 2020, © Kris Karnauskas 2020, published by Cambridge University Press, with permission.

the range of uncertainty. The most severe RCP is RCP8.5 (where 8.5 refers to 8.5 W/m^2 of radiative forcing due to the climatic energy imbalance at year 2100). RCPs of lesser end-of-century radiative forcing lie somewhere below RCP8.5: RCP6 and RCP4.5 may still be reasonable scenarios, whereas RCP2.6 sits so close to the year 2019 concentration by 2100 that one can only imagine the severity of policy changes required for it to be plausible. In most peer-reviewed studies considering future climate changes, and in the fifth IPCC assessment report itself, the most common comparison is between RCP8.5 and RCP4.5 as something of a comparison between unmitigated or "business-as-usual" versus "policy-mitigated emissions" scenarios, although even the term business as usual makes strong (and actively debated) assumptions about just what that means and of what we as a global society are capable.

Although it has been the norm to express the results of future experiments by GCMs as the change of a variable (such as rainfall) at a specific future time horizon (such as 2070) given a specified forcing scenario (such as RCP4.5) and perhaps compare that result with those from RCP8.5 simulations, a clever alternative is growing in popularity as a way to make GCM results more relevant to ongoing international climate policy discussions such as the 2°C target associated with the Paris Agreement. Rather than a *time horizon*, results can be portrayed for a particular *global warming threshold*. For example, the resulting illustration might be a map of the rainfall change that we expect if and when global average surface temperature reaches 2°C (3.6°F), which can be compared with the change expected for 1.5°C and 3°C (2.7°F and 37.4°F) to weigh the costs and benefits of meeting such targets through mitigation strategies. Although this might not satisfy the stakeholder who *is* interested in a particular time period, when averaging multiple models (as is usually the case in climate modeling for global change science), it does have the clear advantage of removing the confounding factor that every GCM might have a different **climate sensitivity**. If a GCM developed and run by NOAA GFDL reached 2°C global warming by 2030 under RCP8.5 forcing, but the one at NASA GISS didn't reach a global warming of 2°C under the same forcing until 2070, does it make sense to pull out the climate at year 2050 to compare between both models? Again, it depends on whether the stakeholder using the GCM results is interested in adaptation measures that must be in place by 2050 or understanding the climate impacts that can be expected, given different levels of global warming.

All of the coordination by CMIP and IPCC to ensure uniformity across climate change simulations carried out at modeling institutions around the world has paid off, especially in terms of our ability to characterize the uncertainties in future climate change predictions. If the world only had one GCM, and we ran only one future experiment once, we would be in a situation even worse than having uncertainty: We would not even know what the uncertainty is. Although there are probably many segments of computer code that may be shared between GCMs or at least descended from a common ancestor, each GCM is a little different from the others. As you may suspect, the attributes they share in common are the aspects of the climate system we understand the best (i.e., basic thermodynamics and force balances driving the wind and ocean currents), and where they differ the most are in those aspects that are either difficult to simulate or are heavily **parameterized** because we cannot explicitly resolve them. Examples of the latter include clouds and rainfall, as well as turbulence in the atmosphere and ocean). Simply put, they are driven by processes occurring at spatial (or temporal) scales smaller than the GCM's grid cells, so each model development team employs its own approaches and innovations to represent them since they could matter in the global or long-term sense. These challenges, either to our scientific understanding of the climate system or to our technical capabilities to run models of high enough resolution, has led to a useful diversity of GCMs. The same prescribed CO_2 forcing in thirty different GCMs leads to thirty different simulations of the future evolution of Earth's climate. We refer to this spread as the **scientific uncertainty** associated with GCM simulations. Climate scientists who gather observations and attempt to understand the essential nature of how the system works are working very hard to reduce this source of uncertainty with each successive generation of GCMs.

If the scientific uncertainty is essentially the *spread* about the average of model results for the same RCP, the **societal uncertainty** is the opposite—the difference between the average results associated with different RCPs. In other words, even if we had perfect GCMs, they would still predict different outcomes for different assumptions about future CO_2 emissions. No matter how hard we try, we will always have a considerable amount of societal uncertainty. The final major source of uncertainty is only recently becoming widely recognized as a substantial gap in our understanding of uncertainties. As each *coupled* GCM simulation steps forward in time from one year to the next, it is free to evolve its own **internal variability** (Figure 13.5). In other words, an enormous El Niño event might happen in the winter of 2059 in one GCM, but there is no reason such an event should occur in that year in any other model simulation. This is because the only thing being prescribed in such simulations is the CO_2 forcing, and El Niño events are not *forced* by gradually trending CO_2 concentration. At regional scales, internal variability can be a significant impediment to identifying anthropogenic trends compared to when quantities such as surface temperature are averaged over the entire globe.

The framework described here clearly places GCM experiments in the class of **boundary value problems**. The key constraint on the model solution is the *boundary* forcing, or in this case the amount of radiative forcing present. The key constraint of such GCM experiments as those described is *not* the initial state of the climate system—that is what short-term weather forecasts rely on. In fact, running so many GCMs so many times, each with ever-so-slightly different **initial conditions**, is the idea behind the new wave of large **ensembles**. When an ensemble of simulations by the *same* model is run on the *same* supercomputer, where the only difference is minute changes in the weather on the first day of the model simulation, that is enough of a butterfly effect that each simulation (even by the same model, on the same supercomputer) will evolve completely differently in terms of *internal* climate variability. This is analogous to diagnostic tests (e.g., blood tests) in a clinical setting; taking a sample on a few different days (and a few different times of the day) averages out the random effects that may obfuscate the underlying problem—what the patient was recently exposed to, what they just

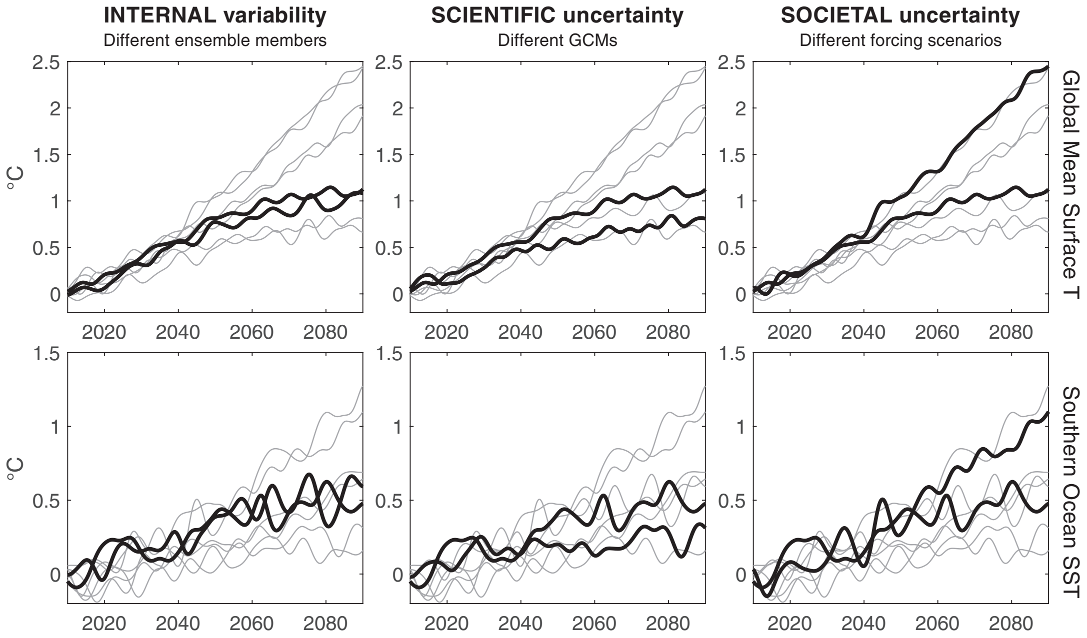

Figure 13.5 Schematic illustration of the major sources of uncertainty in future climate projections by GCMs. Top row for global mean surface temperature, bottom row for southern ocean sea surface temperature. The same eight simulations are repeated across each row (2 GCMs, 2 RCPs, 2 ensemble members). The first column highlights uncertainty due to internal variability by contrasting two ensemble members of the same GCM and subject to the same future radiative forcing scenario (RCP4.5). The only difference between ensemble members is the initial conditions (weather on day one of the experiment). The second column highlights scientific uncertainty by comparing two different GCMs subject to the same forcing scenario (RCP4.5). The third column highlights societal uncertainty by contrasting projections by the same GCM but under two different forcing scenarios (RCP4.5 and RCP8.5).

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ate, or how much they slept the night before. So, too, in climate modeling, averaging an ensemble of experiments allows us to tease out what all of these seemingly different predictions actually have in common—that is, the inherent response to anthropogenic forcing.

Summary and Closing Remarks

In this chapter, we examined the scientific case—from physics to empirical evidence—attributing observed climate change to human activities. Greenhouse gases in the atmosphere are more abundant today than any time in at least the past million years, which is rigorously proven to be a result of human activities. This relatively abrupt shift in the composition of Earth's atmosphere has led to a net energy imbalance in Earth's climate (primarily by reducing how much heat escapes), requiring an increase in global average temperature—which we have indeed witnessed. We then delved into the mechanics of global climate models, which are a vitally important tool in the international enterprise of global change science, including efforts to understand the specific manifestations of climate change that may impact human health. GCMs are computerized renditions of the laws of physics that govern how the atmosphere, ocean, and other features of the climate system operate and interact. They enable us to attribute the observed global warming over the past century to **greenhouse gas** forcing, and to predict future changes in the climate given assumptions about future rates of greenhouse gas emissions. Climate modeling for global change science is an international collaboration; considering the dozens of GCMs developed and run at institutions around the world enables rigorous quantification of uncertainties in future climate change projections. Just like in a clinical setting, uncertainty may be inevitable, but knowledge of the uncertainties is helpful in making an informed decision.

For better or worse, the GCMs described in this chapter have been quite accurate in their future projections of global temperature change thus far, especially when accounting for the fact that our assumptions of future CO_2 emissions are always imperfect (Hausfather et al. 2019). Therefore, the predicted climate impacts described here are both serious and credible. Other studies have established that the imprint of anthropogenic radiative forcing on global climate will be detectable for thousands of years (Clark et al. 2016) because of the natural lags built into the ocean, and that with every year that passes before emissions begin to decline, the path to limiting global warming to 1.5°C (2.7°F) or even 2°C becomes less likely or feasible. Climate change and its growing influence on human health represents one of the grand challenges of our generation, and it will take more than just scientists working alone to solve it. A broader understanding of GCMs including how to interpret their results and uncertainties *across* these disciplines will lead to a deeper and more reliable diagnosis of the climate impacts on human health.

DISCUSSION QUESTIONS

1. Identify two lines of scientific evidence that support the notion that increasing concentrations of greenhouse gases in the atmosphere are causing the observed warming since the nineteenth century. Which line do you think makes a stronger case, and why?
2. Say you are interested in a future prediction of the change in a physical climate variable of relevance to health (e.g., temperature, humidity, rainfall). Compare the pros and cons of expressing this prediction as a function of time horizon (e.g., 2050) depending on emissions scenario (RCP4.5 or RCP8.5), or as a function of global warming threshold (e.g., 1.5°C or 2°C). What is more useful from a health outcome perspective, and does it depend on the particular health or social context?
3. Identify one disease or negative health outcome that is believed to be mediated in some way by climate. What is the spatial scale of predictions you would need for them to inform stakeholders interested in the future prevalence of that disease?
4. Compare and contrast the blend of uncertainties between GCM future projections of Arctic sea ice and ocean pH. For the latter, you will need to consult the Summary for Policymakers (Figure SPM.7) of the Fifth Assessment Report of the IPCC, available online at https://www.ipcc.ch/assessment-report/ar5/. Which projection has greater scientific uncertainty? Which has greater societal uncertainty relative to scientific uncertainty?

KEY TERMS

Attribution: The process of proving that a response is actually a direct result of a forcing, beyond simply observing a correlation between cause and effect. For example, see **attribution experiment**.

Attribution experiment: In the context of climate modeling, an attribution experiment is one in which a known forcing agent is withheld to determine the degree to which the result is a direct result of that forcing agent. For example, using a GCM to simulate the twentieth century with and without the observed increase in CO_2 concentration—the latter experiment not resulting in global warming attributes the global warming to the CO_2 increase.

Bias: In the context of GCMs, a bias is a discrepancy between today's climate as simulated by the GCM and that observed in real data (*in situ* measurements, satellite observations, etc.). A typical GCM bias might be that India does not receive enough rainfall or that the eastern Pacific Ocean is too cold. Some GCM biases are systemic (i.e., common across most of the GCMs from around the world) or vary enough from GCM to GCM that they effectively cancel out in the ensemble average of GCMs.

Boundary value problem: A model experiment in which the results will be strongly influenced by factors external to (or literally at the boundaries of) the system being modeled. This is the case in future climate change experiments (see **Future experiment**). For example, consider a GCM simulation of the period 2020 through 2100. The result in the year 2050 will be a function of the greenhouse gas concentrations at that point, rather than whatever the *initial* weather was on January 1, 2020. The opposite of a boundary value problem is an initial value problem. A five-day weather forecast is an initial value problem because the weather a few days from now is determined by how weather systems that are present right now continue to evolve; global concentrations of greenhouse gases will not change very much in that time frame.

Climate sensitivity: How strongly the global climate system responds to a given amount of forcing (see **Radiative forcing**). For example, how much will the global average surface temperature rise if the concentration of CO_2 in the atmosphere is doubled? Different GCMs have slightly different climate sensitivities. For example, given the same future greenhouse gas forcing scenario (say, RCP8.5), one GCM might reach 2°C of global warming by 2050 whereas another GCM has only warmed by 1.7°C at that point in the experiment (and doesn't reach 2°C until 2065). The first GCM in this example has the higher climate sensitivity. See **Representative concentration pathways**.

Concentration: The amount of a substance present in the medium, for example, carbon dioxide of methane in the atmosphere, usually expressed as parts per million. Contrast this definition to the closely related **Emissions**.

Control experiment: A "long" GCM simulation (typically simulating a time period of 1,000 years or more) in which greenhouse gas concentrations (and other facts such as solar output) are held constant. Year-to-year and even decade-to-decade climate fluctuations can still arise in such GCM simulations due to the internal dynamics of the climate system (i.e., ocean–atmosphere interaction) and due to random weather ("noise"), but there are no "external" influences (such as humans) on the climate that would lead to robust long-term trends. Control experiments can be used to determine how large an externally forced trend (in a different experiment) should be in order to be "detectable" amid the background, natural climate variability.

El Niño: A natural climate phenomenon in which the temperature of the surface of the eastern equatorial Pacific Ocean warms by a few degrees Celsius. El Niño is the warm phase of a cycle between abnormally warm and cold conditions in this region; the cold phase is called La Niña. This cycle is somewhat cyclical, but still irregular enough (with a period of 2–7 years) to be a challenge to predict more than a few months in advance. The broader cycle, referred to as El Niño–Southern Oscillation (ENSO), is entirely a result of internal climate dynamics—a manifestation of *coupled* ocean–atmosphere interactions.

Emissions: The amount of a substance added to the medium in a given time period. In the context of climate change, emissions refers to the amount of greenhouse gases added to the atmosphere per year (e.g., ~19 Gt of C per year). The relationship with concentration in terms of climate change mitigation strategies is important; for example, reduction of emissions does not necessarily lead to a decline in concentration.

Ensemble: In the context of climate modeling, an ensemble is a group of different GCMs that have conducted an otherwise identical experiment. Their results can be averaged to produce a multimodel ensemble mean; their spread or variance is a measure of the scientific uncertainty associated with that prediction. An ensemble may also be composed of an experiment conducted several times by a *single* GCM conducting an experiment several times, identical in every way except for the weather on the first day of the experiment (i.e., the **initial conditions**). In that case, the ensemble mean can be used to isolate the true forced response (according to that GCM) whereas the variance likely represents internal variability.

Future experiment: GCM experiments that simulate a future period of time (say, out to the year 2100) given a prescribed scenario of future greenhouse gas scenarios (see **representative concentration pathways**). These are, mathematically speaking, boundary value problems because the initial conditions (weather) on the first day of the experiment is essentially "forgotten" by the GCM after just a very short time into the experiment—perhaps after a few weeks. Such experiments are conducted by dozens of GCMs around the world; the collection of output from those GCMs constitutes an international ensemble of results whose average and spread can be examined to understand the various uncertainties.

Global climate model: A computerized representation of the laws of physics that govern how the atmosphere, ocean, and other features of the climate system operate and interact.

Greenhouse gas: Atmospheric constituents such as CO_2, methane, etc. whose molecular geometry render them particularly effective at intercepting thermal radiation (emitted by the surface of Earth) and reemitting it to the atmosphere rather than allowing it to escape into space. Rising concentrations of greenhouse gases lead to a net energy imbalance in Earth's climate, requiring an increase in global average temperature (hence the widely used term *greenhouse effect*).

Grid cell: The basic unit of space in a GCM. GCMs divide the global climate system into a large number of discrete cells, and the governing equations of the atmosphere, ocean, etc. are all solved for within each of these grid cells. The size of a grid cell is a function of the GCMs resolution and can vary from GCM to GCM depending on scientific objective and/or computer resources available.

Initial conditions: In the context of climate modeling, the particular state of the climate system at the first time step of a GCM simulation. In other words, the weather. In weather forecasting, initial conditions are crucially important; in general, the better we know the state of the atmosphere *now*, the better our forecast of the weather in forty-eight hours will be. In climate modeling, the initial conditions are long forgotten before the time period attempting to be predicted (decades in the future). In fact, it is becoming commonplace for GCM experiments to be run many times with extremely slight random noise added to the initial conditions to *ensure* that the initial conditions are not influencing the long-range climate change projection.

Internal variability: Loosely synonymous with *natural* climate variability, internal variability refers to the fluctuations in climate that are not driven by changes in *external* forcing agents such as greenhouse gases, volcanic eruptions, and solar output. Internal climate variability arises in the real world and in GCMs due to the coupled interactions between the atmosphere, ocean and other realms of the Earth system. El Niño (or ENSO) is a prime example of internal climate variability. Internal variability is relevant to climate change, particularly in efforts of detection and attribution, as internal variability introduces a source of noise that can obfuscate externally forced trends such as those arising due to increasing concentrations of greenhouse gases.

Parallel processing: The computation strategy often employed in climate modeling wherein the world is split into a number of tiles (each tile containing many grid cells), and the equation solving within those tiles is distributed across a number of individual computer processors. Parallel processing significantly speeds up a GCM experiment that needs to simulate a long time period (say, 2006 through 2100) at a reasonable spatial resolution.

Parameterization: The implementation of a real physical process in the climate system into a GCM without directly simulating that physical process. Rather, the process is implemented by way of its relationship with other *parameters* that *are* more confidently solved for by the GCM. A classic example for GCMs is clouds; one puffy cloud might be too small for a GCM to resolve, but we know the conditions in which different types of clouds are likely to form. Small-scale mixing and turbulence in both the atmosphere and ocean are also parameterized; they are surely important process in climate dynamics, but we do not know enough about them yet and/or do not have enough computer power to directly simulate them in global simulations.

Radiative forcing: The planetary energy imbalance (incoming minus outgoing) due to a particular forcing agent. Some anthropogenic forcings can result in a negative radiative forcing, such as aerosols (as they reflect incoming solar radiation). Anthropogenic greenhouse gas forcing currently amounts to a net 1–2 W/m^2 of radiative forcing.

Representative concentration pathway: Future trajectories of **greenhouse gas concentrations** (out to 2100) that may be used as forcing for GCM future experiments. Four RCPs are widely used in climate modeling for global change science; RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The number following RCP indicates the radiative forcing (in W/m^2) at 2100.

Resolution: In the context of GCMs, the size of a grid cell. A "higher resolution" GCM has smaller grid cells and, consequently, more of them (so as to completely cover the planet). Higher resolution requires exponentially greater computer resources but may enable smaller-scale (and potentially important) physical processes to be directly simulated rather than relying heavily on parameterizations.

Scientific uncertainty: In the context of GCMs, the uncertainty due to imperfect scientific knowledge of the physics of the climate system (manifest as imperfect GCMs). The scientific uncertainty associated with future experiments is generally characterized by the *spread* among an ensemble of GCM results. Each GCM may be subject to the same assumptions about future greenhouse gas forcing, yet each GCM yielded slightly different results.

Societal uncertainty: In the context of future experiments, the uncertainty due to the fact that we cannot predict exactly how much greenhouse gases will continue to increase over the course of this century. Even if there was no scientific uncertainty, societal uncertainty would be inevitable. Societal uncertainty is built into the enterprise of climate modeling for global change by simulating four different RCPs—to account for a wide range of possible futures in terms of population, economics, technology, policy, etc.

Troposphere: The lowest layer of the atmosphere, in which the air temperature decreases with height. The depth of the troposphere is roughly 11 km on average, but with considerable geographical and seasonal variation. The boundary between the troposphere the next layer above, the stratosphere, is called the tropopause; above this altitude, temperature begins to increase with height.

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