Chapter 13
Summary and Final Thoughts

In this book, we explained the basic principles behind climate models (Sect. 13.1). We described in a qualitative fashion the mechanics of how the different components of a climate model are constructed (Sect. 13.2). In the process, we focused on critical aspects of the climate system that make the different pieces complex, uncertain, and interesting. For most parts of the earth system, important mechanisms for how climate works are not necessarily intuitive. Finally, we laid out some of the methods for evaluating models, and examined what climate models are good for, and what they are not good for (Sect. 13.3). This included a detailed look at uncertainty, and a look at the applications of models for decision making.

This chapter sets out to synthesize the key points from the preceding chapters. The synthesis includes a summary of what is understood about predicting climate and what is uncertain. We also comment on future directions for climate modeling.

13.1 What Is Climate?

The goal of climate prediction is to be able to estimate and understand the present and future distribution of weather states. This distribution determines the probabilities for a weather state occurring. Climate extremes (high temperatures, periods with low precipitation) are generally low-probability events on the edges of the distribution. Climate extremes are what we really want to know about. Extremes are where the impacts are. No one is killed by the global average temperature. Fundamentally, weather and climate models are similar, but they are aiming at slightly different aspects of the system. For weather models, initial conditions are the key, whereas climate models over long time scales of a century should be independent of the initial conditions.

The climate system is a system of balances of energy and mass of air, water, and important trace compounds. The energy in the climate system ultimately comes

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from the sun. The earth absorbs sunlight mostly as visible light (shortwave energy), and radiates it back to the atmosphere and space as heat (infrared or longwave energy). Greenhouse gases alter the flow of energy in the atmosphere and trap some of this radiated heat. Water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4) are critical greenhouse gases. Humans affect water vapor only indirectly. Water and carbon flow through the components of the earth system, and much of the complexity of the climate system comes from the fact that these compounds (CO_2, H_2O) also directly alter the total energy input of the earth. Interactions and transformations of compounds across the climate system lead to many cycles. These cycles evolve on many timescales from seconds to millions of years. These cycles involve feedbacks where changing one part of the system, such as temperature, affects another part of the system, such as the amount of water vapor in the air. The reaction then alters the system, since water vapor is a greenhouse gas that further changes temperature.

Understanding the coupling of the different parts of the climate system with feedbacks is critical to understanding the future evolution of the earth's climate. Feedbacks are a key feature of large climate models. By including representations of critical processes, we try to represent these feedbacks and hence project the future state of the climate system.

The climate system is changing, and it is changing due to human activity. Greenhouse gases, mainly CO_2 and CH_4, have been increasing over the past 60 years observed from direct measurements, and for the past 150 years or so from observations of air trapped in ice cores. The chemical (isotopic) composition of the CO_2 in the atmosphere tells us that the additional CO_2 comes from fossil fuels, because the atmospheric composition of carbon (the balance of carbon isotopes) is looking more like dead plant material.

Since increasing greenhouse gases trap more energy in the system, the energy has to go somewhere. By understanding and representing the energy flows in the climate system, climate models seek to figure out where the energy is going, and what the impact of that change will be on the climate, or distribution of weather.

13.2 Key Features of a Climate Model

We use models all the time to predict the future. Examples include spreadsheets that try to predict budgets of money or goods. Some of these models are numerical. Climate models are usually not statistical but contain some processes represented with observed climate statistics, and equations built from physical theory. Essentially, a climate model is a giant representation of the "budget" of mass (of water, of carbon) and of energy in the climate system. A climate model is an attempt at representing the critical budgets and flows in the climate system in a way that they obey the basic laws of physics we observe all around us.

One way of describing the philosophy of a climate model is that a global climate model bounds each and every process by physical laws, starting from the conservation of energy and mass. From this constrained set of budget equations, combined with different representations of the processes (like condensation in clouds), complex results emerge. But these results have to be compatible with the physical laws (like conservation of mass, or the equations governing fluid flow on a rotating sphere). The emergent complexity is a reflection of reality.

The physical laws behind climate models are well known and observed. The most recent "new" theories are well over 100 years old. They are also the same physical laws that govern many other fields of science and engineering. The description of the motion of fluids in the atmosphere and ocean are the same equations used to build numerical models of how an airplane will perform. The equations that govern the flow of energy in the climate system from the sun, through the atmosphere to the earth, and then back are the same equations describing how cellular phones and radios work.

13.3 Components of the Climate System

Climate modeling has been enabled by the rapid increase in computer power that permits many of these relatively simple equations to be solved all together on more and more detailed grids of points on the planet. Climate and weather modeling were among of the first uses of digital computers in the 20th century.[1] More computer power has led to increases in complexity and increases in resolution (more points, smaller scale for each one). This evolution will continue into the future (see Sect. 13.5).

In constructing a climate model, a series of individual components, each representing one sphere of the system (atmosphere, ocean, cryosphere) is typically developed. Climate models started with just an atmosphere model and have grown to include oceans, land, and sea ice. Climate models now also typically include chemistry and representations of the flow of nutrients like carbon in the climate system. The flows of energy and mass, particularly of water mass, are critical for understanding climate. Climate models are models of the earth system that solve a set of dynamical equations. But there are also statistical (or **empirical**) models of climate and individual processes in the climate system. Statistical models represent climate-system processes with relationships among variables based on past observations. Representations (or parameterizations) of complex physical processes are often statistical models based on fits to observations. These are also called 'empirical' models. The danger of statistical models is that they are only as good as the observations of the system they seek to represent. If conditions change so that inputs are outside of the

[1]The earliest digital computers were used for estimating artillery firing tables and simulating the physics of the atomic bomb. See Dyson, G. (2012). *Turing's Cathedral: The Origins of the Digital Universe*. New York: Vintage.

observed range on which the model was built, or because of another factor not predicted, the statistical model may not be valid. The risk of going out of bounds of the data set used to develop a model is called extrapolation. As a result, statistical or empirical models are often limited in use to particular processes, or carefully used for relating climate variables to local conditions (statistical downscaling).

In all of the component models, there are equations for different transformations and processes (like clouds), and equations that govern the motion of air or water. A great deal of the complexity and uncertainty in climate models comes from processes at small scales that have to be represented by parameters rather than fundamental equations. These representations are often called parameterizations. The goal is to represent a process or set of processes in a particular component of a climate model. Sometimes parameterizations are tightly coupled to physical equations of the climate system. Other times, they are based on fitting a function to observations. These functional fits are empirical or statistical models described above. One needs to be careful of extrapolation. For example, if the representation of the size of ice crystals in a cloud is based on observations that range from 32 to −4 °F (0 to −20 °C), then when the temperature is below the lower limit (−4 °F or −20 °C), the values are "out of range."

Most of the problems and complexity of parameterization come from variations in the climate system at subgrid scales, that is, those smaller than the size of a single model grid box. In the example of ice crystal sizes, there is not one single size of ice crystals in a 62 × 62 mile (100 × 100 km) grid box: There are many sizes within clouds or a single cloud. The clouds may also not fill a particular volume of grid box. So there are interacting parameterizations (of the microphysical structure of clouds, and of the horizontal extent of clouds). Representing this variability at the grid scale is a central problem of parameterization. Higher-resolution models (smaller grid boxes) seek to get to the scale where the variability is not important: With small grid boxes the size of a football field (about 100 yards or 100 m), a single cloud can probably be assumed in the volume. Another emerging method for parameterization is to recognize that the state itself (i.e., the concentration of cloud drops in a grid box volume) is not constant, and instead of a number it can be a distribution: a probability distribution function of size of ice crystals in clouds in a particular large box, representing many clouds.

13.3.1 The Atmosphere

The atmosphere is the sphere that we live in, and it is highly changeable. There are several types of atmosphere models, from simple reduced-dimension models (a single column model or a simple zero-dimensional box or energy balance model), all the way up to general circulation models (GCMs). GCMs represent the entire atmospheric circulation with only top and bottom boundaries. The goal of global GCMs is to represent each point on a grid by a set of numbers (the state of the system at that point). This is the essence of a finite element model, where each grid point is an element. Ultimately, the description has three dimensions: two horizontal and one vertical. Some models just try to represent a single column, or a single box. A series of equations are solved for each point. These equations represent different processes of the system, like clouds in the atmosphere. Generally, the same concept is used across climate models for the different components, which are generally all finite element models. Atmosphere models must parameterize key processes. Key processes include the transformations of water into clouds and precipitation, the motion of air, and the flow of energy to and from the surface.

In addition to physical processes that are parameterizations, climate models must represent motions and the atmospheric general circulation. The atmospheric circulation can be described by the basic physics of a gas on a rotating sphere, with one extremely important complication: water. Water is a unique substance in the climate system, found naturally in the atmosphere in all three phases: water vapor gas, liquid water, and solid ice. Water is critical in most parts of the climate system. In the atmosphere, it plays a critical role in storing heat used to evaporate it, and releasing heat when it condenses.

The other critical complexity of the atmosphere is the range of scales that are important. The patterns of wet and dry regions are determined at the global scale, but important aspects of how, and when, water condenses occur on scales of a fraction of a millimeter. The range of scales in the atmosphere is a critical problem. The problem is the worst when the scale of interest is close to the grid scale of the model. When the important scale is large, then the model can represent it with one value for each grid box (like the general circulation). When the scale is small, such as a cloud drop, in a large grid box, the billions of drops can be represented statistically (as a distribution of drop sizes). But when the scale is intermediate, such as for clouds and cloud systems that may be 1–20 miles (2–32 km) in size, the scale cannot be represented well statistically. In a single grid box, there are too few clouds to use statistics to represent them, but since a number of different clouds may exist within a grid box, using a single value is not an ideal representation either. Ongoing research is currently underway to better model phenomena at intermediate scales.

13.3.2 The Ocean

The ocean has a similar hierarchy of modeling tools, from simplified versions that just provide a “wet blanket” under the atmosphere to complex models of the ocean general circulation (ocean GCMs). The ocean circulation is driven by surface winds and by buoyancy forces due to changing density (much like the buoyancy in the atmosphere that creates clouds). The density of water changes with the temperature and salt content, so both temperature and salinity can affect the circulation of the ocean. The ocean has a mixed layer that exchanges rapidly with the surface, and a strong density gradient outside of polar regions beneath this mixed layer, which separates the upper ocean from the deep ocean.

The ocean circulation is a complex result of these wind and buoyancy forces, acting on a rotating planet with ocean basin boundaries. The currents we see are a consequence of the combination of these forces. Salt content (salinity) is regulated by evaporation of water in the tropics and the formation of sea ice in the polar regions, leaving the salt behind in the ocean. Salt content is also regulated by the input of fresh water from the land surface (rivers) and directly from precipitation. Sea ice is also important for changing the reflectivity (albedo) of the surface, and insulating the ocean from a cold polar atmosphere. The ocean is a large reservoir of heat and a large store of carbon. These reservoirs play a large role in regulating the climate of the earth on long timescales. Currently, it seems that some of the heat being absorbed by the planet is going into the deep ocean and not warming the surface. That is like a "debt" that will eventually be paid in higher surface temperatures when this heat gets released. The timescales of the ocean circulation are long, and water that sinks to the deep ocean may not see the surface again for many hundreds of years.

Like the atmosphere, parameterization of key processes is important in the ocean, and often hard to represent due to subgrid variability. There is small-scale, buoyancy-driven vertical motion that is hard to represent. And a significant fraction of the oceanic heat transport occurs in small-scale eddies (loop currents) that may not be resolved by global ocean model grid spacing.

13.3.3 Terrestrial Systems

While the ocean is a huge reservoir of heat and a giant regulator of climate, the land surface is where we live, and where most of the impacts of climate are felt. The land surface, or the terrestrial system, is strongly affected by the living things on the surface (the biosphere). As with the ocean and the atmosphere, water is a critical substance for the biosphere and for regulating climate. Water fluxes are strongly affected by plants. Plants use water in respiration, bringing it up into their tissues where some evaporates in the process of photosynthesis, a process called evapotranspiration. Evapotranspiration from plants brings water from the soil up to the leaves of plants, where it can exchange with the atmosphere. This is critical for cycling moisture between the land and the atmosphere.

The growth and decay of plants also depends on critical nutrients such as nitrogen and carbon. In addition to water, carbon is the other interactive component of the terrestrial system, changing forms from solid earth to plant tissue to gas in the atmosphere.

Modeling these cycles in terrestrial systems involves representing the energy and substance (carbon, water) as it flows into and out of the system. Terrestrial models are more stationary than the atmosphere or ocean: They do not move. They describe the physical flows of the system (biogeophysics) and the plants (ecosystems) that govern and alter those flows. Ecosystems can evolve and feedback on the land surface through nutrient cycling and changes to the absorption and retention of water and heat.

Terrestrial systems also include a frozen portion: snow cover and ice sheets on land, known as the cryosphere. The cryosphere is important for altering absorption of solar radiation and changing surface fluxes. Snow cover is also an important seasonal part of the climate system for the water available to humans: Snow changes the timing of runoff by storing water on the land that can be released later. Ice sheets also store water that affects sea level. Greenland represents 23 feet (7 m) of sea-level-equivalent water, and Antarctica ~230 feet (70 m). That matters a lot to the 600 million people living in low-lying coastal zones.[2]

Finally, terrestrial systems also include human systems. Some physical climate models (especially simple ones) are being coupled to economic models that can simulate human systems, and so generate predictions of future climate that include the feedbacks of human societies on the climate system. One of the biggest human feedbacks is how much CO_2 we emit to the atmosphere. Another human feedback is changes that society makes to the land surface (e.g., removing forests for cropland).

13.3.4 Coupled Components

All of these components are coupled together in a comprehensive climate model. Coupling involves testing component models with observations (see below) and then attempting to put them together. The coupling layer is sort of a clearinghouse that passes information between components and reconciles their "accounts" of mass and energy. For example, a model of the ocean is usually developed by forcing with observed winds and temperatures at the ocean surface. An atmosphere model is usually developed with fixed-surface ocean temperatures. If coupling is done appropriately, then the climate should not have surface temperatures that drift over time, if energy and mass are conserved. This has taken a while to get to work properly, and one of the big advances of climate modeling in the past 20 years has been the ability to couple appropriately the atmosphere and ocean and achieve a balanced and stable global climate. The complex interactions among components of the climate system make diagnosis of coupled models difficult. But the coupling also enables evaluation of coupled phenomena across components, like the atmosphere-ocean interactions that result in phenomena like the El Niño Southern Oscillation: a pattern of changing sea surface temperatures with large-scale effect on the global distribution of precipitation. These emergent coupled behaviors are strict tests of the fidelity of models. Climate models do not parameterize phenomena like El Niño; they arise from representing basic processes (e.g., clouds, atmospheric and ocean motions) in the climate system.

[2]McGranahan, G., Balk,D., & Anderson, B. (2007). "The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones." *Environment and Urbanization, 19*(1): 17–37. doi:10.1177/0956247807076960.

Different types of climate models can also be coupled to each other. This is often done to use a high-resolution model in a limited area to generate high-resolution and high-frequency statistics. Variables that are outside of the limited-area model are described by a coarse model. Coupling a high-resolution model inside of a coarser (usually global) model is also called *nesting*. Nesting is often done to achieve high-resolution simulations in a particular region with limited computer resources.

13.4 Evaluation and Uncertainty

For the consumer of model output, quality is a critical question. How good is a climate model? What is a good model? Ultimately, models are fit for purpose. A good model is a model that is fit for its purpose.

13.4.1 Evaluation

So how is a good model determined? Models of all sorts are usually evaluated against some set of observations. A climate model should reproduce the present climate. Evaluation against observations is a necessary, but not sufficient condition for predicting the future. Evaluation of a model against a set of observations also requires a good knowledge of the magnitude of the uncertainty in the observations, and how comparable are the model and the observations. Evaluation also requires using the right observations and right processes to make sure the model is salient (relevant) for the intended purpose.

But reproducing observations does not guarantee a model can reproduce the future. The future response of a model may be outside of the range currently seen in the observations. This means the present is not a sufficient condition to constrain the future. A central problem of climate modeling is that we do not yet know what a sufficient condition is. We test models against observations of the recent past and present. We also continue to look for records of past climates that are preserved in various records: whether in gas bubbles from ancient atmospheres in ice cores, or in the width of tree rings over time, or in the fossilized creatures in ocean sediments. We try to expand the range of possible observations, but since the direction the climate is going now has not been seen on the planet in millions of years, inevitably we are going to have some extrapolation.

Ultimately, climate models are evaluated and compared extensively to different observations from the past: the last 100 years, all the way up to recent weather events. Climate models have a fundamental constraint on conservation of energy and mass. The global constraints, with a single boundary of the system at the top of the atmosphere model, provide powerful constraints on climate models. Few other models have these constraints (weather models usually do not). If a model conserves energy and mass, then the energy from the sun put into the system has to go somewhere. Most of the energy escapes again, but if mass is conserved, then the difference between the energy into the system and out represents energy available in the system. Figuring out where the energy goes is complex, but it is necessary to make sure energy is conserved. This also allows us to move “off scale” of current energy inputs and have some confidence that we are not accidentally gaining or losing energy in the simulated climate system.

The concept of evaluation and the energy and mass constraints can also be used to describe how a climate model is able to represent the complex earth system with complex interactions of processes occurring on many scales. If each process or parameterization or set of processes (such as a cloud model, or a biogeophysical model of how plants move water and carbon) can be evaluated against observations, and also is bounded by physical constraints, then the resulting combination of these processes should be able to represent important features of the climate system.

What does this basic physical constraint mean? For a cloud model (or cloud parameterization in an atmosphere component of a climate model), there are a series of descriptions of evaporation, formation of cloud drops, how rain begins to fall, freezing, and the like. But the overall cloud can have only as much water as is available to condense, and the energy of that condensation and/or evaporation has to go somewhere. These constraints act at every point in space and time in a model, and require all clouds in a model to meet these constraints and be physically realistic. Add up many processes pushing and pulling on the system, and climate models actually do a pretty good job of getting a decent climate for the present based on detailed comparisons to observations. The constraints of energy and mass also allow for some confidence in prediction. Another method of evaluation is to use a climate model with appropriate initial conditions to simulate individual weather events. Many models are moving to “unified” weather and climate models for this reason (see below).

13.4.2 Uncertainty

Prediction has different uncertainties over different time and spatial scales, and this distinction is critical for understanding how to use climate model output. Predicting the near term is a similar exercise to weather prediction, even if it is considered on a timescale of a season or several seasons in advance. In the short term, prediction is dominated by the uncertainty in the present state, or initial condition uncertainty. This is true on the course of a few days for weather, and maybe a few years in the atmosphere with longer-term variations in El Niño and in ocean circulation patterns. On scales of 20–50 years, the structural uncertainty in a model is important. Structural uncertainty is what we usually think of in terms of model errors. These are errors in the formulation of the model processes (parameterizations) or the interactions between processes. On spatial scales smaller than global and timescales smaller than a century, model uncertainty tends to dominate: If a model represents a process badly that is important in a particular region (like ice clouds in the Arctic), then the model is likely to have a structural bias in that region.

On longer timescales of a century, the uncertainty in human aspects of the system such as emissions of greenhouse gases dominates. The climate of 2100 is more dependent on how much we choose to emit than on the differences between different models. This is known as scenario uncertainty. That means that the climate of the end of the century is really dominated by human system uncertainty, not by uncertainty in the physical climate system. Put another way: It is our future to determine, and we do not need better climate models to make a decision on what future we want. However, to adapt to the impacts of climate change, we need to know local impacts, and local impacts are dominated by model uncertainty even at long timescales.

A common way that models are used for broad climate projections is to create a set (an ensemble) of possible realities that can be used to describe the internal variations of a model or a set of models. Ensembles can be used to provide a range of predictions or projections. A projection is dependent on things outside of the model that must be specified (such as greenhouse gas emissions). Different sets or ensembles of model simulations use different inputs, scenarios, or models. Ensembles can be used then to understand this range of uncertainties. Ensembles can be conducted with a single model. Single-model ensembles eliminate model uncertainty and explore either scenario uncertainty by performing simulations with multiple scenarios, or internal variability by focusing on a single scenario and different initial conditions. Ensembles can also be from multiple models, to focus on the model uncertainty and remove the scenario uncertainty and minimize initial condition uncertainty.

13.5 What We Know (and Do not Know)

So what do the models tell us? There are varying degrees of confidence in climate model projections. We are unlikely to be wrong on large-scale effects that are constrained by conservation of energy and mass. We are less certain of processes that do not have strict limits of energy and mass conservation. Thus, we are less certain of climate change at regional scales. If one region warms more and the next less, the average of the two may be constrained by the energy budget. But the individual regions may change a lot. Other impacts also are not constrained by conservation. One example is precipitation frequency and intensity, which are not dependent on large-scale energy and mass conservation. To produce the same amount of rain (required by conservation of water and energy) in a location, it can rain a little for a long time, or a lot for a short time. The precipitation frequency and intensity can combine in different ways to generate the same total rainfall and result in a very different climate. The least certain aspects also relate to extreme or infrequent events such as floods (local extreme precipitation), droughts (extreme periods without water), or heat waves (extreme duration of high temperatures). We are less certain about extreme events such as tropical cyclone precipitation and intensity. We are also less certain and likely to be surprised by effects with thresholds like sea-level rise to ice-sheet melting.

Practically, what does all this mean? In fits and starts, the planet should continue to warm up. Not every year or every day will be warmer than the last (because of internal variability of weather states), but over decades it will get warmer. It is hard to make the heat go away. Thus “global warming” will be nonuniform: High latitude cold regions will likely warm more because of surface albedo feedbacks resulting from melting of snow and ice cover. And there will likely be significant changes in regional patterns of precipitation. We are less certain of how this will occur, but the prediction is for very small changes in the regions of upward and downward motion, leading to more intense precipitation in the tropics, and an expansion of the semiarid regions astride the deep tropics. We also know that scenario uncertainty will start to dominate in the latter half of the 21st century, and the different path we choose for emissions (even if that path is a choice of not making a decision and doing what we are doing now) will be clear. The degree of climate change is unknown mostly because of forcing uncertainty regarding how much humans choose to emit.

Models can also be used in a more focused way to attempt to understand the smaller-scale local effects, and to provide representations of what might occur, given the above-mentioned uncertainties. The conditional forecast is a projection, rather than a prediction. Given a scenario (the condition), climate models can provide a projection. The usability of a model for a particular problem or particular impact estimate depends on whether the forecaster is “legitimate,” or trusted, whether the model yields credible results compared to observations for a particular problem, and whether the results are salient, or relevant, for the problem. The latter implies “fit for purpose”: The global average temperature is not a good estimate of whether a model is fit for a particular application. The ability of a model, for example, to reproduce tropical cyclones is likely a better measure of salience for projecting possible changes in tropical cyclones (but not for Arctic climate).

Climate models are just one piece of information for decision making. Climate models are one input for a knowledge system, such as a precipitation or stream flow record for a water management system that has to simulate water storage and runoff, with both physical assets (like rivers, canals, dams, and drainage basins) and human requirements for water storage and water flow. In practical terms, climate model projections are a small piece of a complicated puzzle. When they are a very different or uncertain piece, the models become difficult to use. Understanding the uncertainty in model results is critical for making them usable and relevant. Focusing on a particular result and the processes that drive the result is one way to reduce the many dimensions of uncertainty.

Planners and decision makers need interpreters or translators for climate models who can assist them in understanding the usability of particular types of model for a particular problem. Think of it as shaping the model output to fit as a piece of the overall puzzle. One goal of this book is to engage the reader to learn more about climate models, enough to be an interpreter for a set of disciplines to help shape the interpretation of model output.

13.6 The Future of Climate Modeling

We have discussed what climate models are, and what climate models can do and cannot do. Where is the development of climate models headed? Climate-model development is an iterative process. Models respond to scientific questions and needs of users, or in the absence of proper interpreters, to perceived needs of users.

The current generation of climate models typically has a series of components coupled together in various ways for various scientific tasks. The core models of the atmosphere and ocean are run at different resolutions, and with different additional components as different science questions are needed. For example, detailed models of chemistry may be run to understand air quality near the surface, or to study the evolution of the stratospheric (upper-atmosphere) ozone layer. Greenhouse gases like CO_2 are often specified by concentration over time in scenarios. But detailed carbon cycle models can be used to simulate future emissions and flows of carbon and predict, instead of specify, greenhouse gas concentrations. It is rare that all model components are turned on at once, and not every model has all the pieces. This means that particular models and particular configurations of models are most relevant for different problems.

So where are climate models headed? Increased computational power drives the ability to do more computations. There is an ongoing tension between using these computations to have higher resolution and smaller grid spacing, or adding processes and components to the model to represent more processes or improve the representation of existing processes. Process improvement means representing individual climate processes (clouds) better, and this requires improved understanding and improved observations. This also applies to additional processes that need to be represented in models.

Over time, models have grown in complexity as new processes are understood, and as computational power has increased. Adding complexity and resolution requires more computational power. And because models are multidimensional, performing calculations in three spatial dimensions and the time dimension (four dimensions, total), increasing resolution by a factor of 2 means a factor of 2×2 in the horizontal, and often a factor of 2 in time. Vertical resolution may also change, adding another multiplier. So doubling resolution often requires a factor of 8 or more in computer power just because of the increasing number of grid points in all directions, and the need to take smaller steps forward in time.

13.6.1 Increasing Resolution

Models are typically run at different scales: Finer-scale models, sometimes regional climate models, are used to try to represent extremes better with fine resolution. Global models have the benefit of a self-consistent energy balance. Currently, models are typically run for century timescales at about 62 miles (100 km) horizontal grid spacing. Shorter runs for climate (many years, occasionally a century) can be run at 15-mile (25-km) scales. In a few years from 2015, the 15-mile spacing will be more typical. Current model experiments are being run for short periods or for forecasts at ranges as small as 1–8 miles (3–12 km). These experiments are often short (or just weather forecast experiments of a few days) and experimental for now. This is the range of scales at which weather forecast models are typically run.

Why the drive to increase resolution? One goal is to reduce the variations within a grid box. As the scale gets smaller, there are fewer sources of variability. One known source is terrain. Higher resolution models can better represent complex terrain and even the subtle effects of gentle terrain (which may preferentially organize thunderstorms, for example). Another goal of higher resolution modeling is to reduce the number of processes that need to be parameterized because their scale is smaller than the grid spacing, and to represent those processes more explicitly. A smaller grid box of 1–8 miles may not need to be "partly cloudy"; perhaps it can be all cloudy, and the adjacent box clear, while a larger region representing both boxes would be "partly cloudy."

Some processes will remain parameterized (like the distribution of cloud drops whose size is the width of a human hair), but it is hoped that many of these processes are well separated from the grid scale and can still be treated statistically. Other processes, like the dynamic updrafts in clouds, or the organization of such updrafts into large storm systems, have scales from 1 to 8 miles. As models get to higher resolutions, these processes approach the grid scale, where they may not be well represented explicitly but they are hard to parameterize. This has become known as the "gray zone," because how to treat many important processes is not clear. There are many gray zones in climate modeling, but perhaps the one most people refer to is the regime between 1 and 8 miles (3–12 km), which corresponds to a complex cloud scale.

Higher spatial resolution enables unification of regional climate models and global climate models: Regional scales can be simulated with high-resolution global models. These can be either uniform-resolution or variable-resolution grids that focus on a particular region. These variable-resolution grids can be nesting two separate models, where one is on the large-scale grid and is used to force boundaries of a finer-scale model. Or the variable resolution can be a single uniform grid that changes its horizontal extent in different regions.

Improvement in climate models is driven by computational power. Faster computers enable more computations, with either more detailed processes or finer resolutions.

13.6.2 New and Improved Processes

Some newly developed parameterizations are evolving rapidly. Other processes have been represented in models for 30 years or more, and methods are fairly well explored. But new methods are developed all the time either for the "bulk" representation of a process in a grid cell or with a "variance" approach that seeks to represent the subgrid variability found in models. One of the simplest examples is "partial cloudiness" or cloud fraction, whereby a grid box can be "partly" cloudy, and values are kept for a clear and cloudy part. There can be multiple such sub-columns within the column of a grid box, and this can be used to explicitly represent the variability at small scales.

Models are adding new processes as they are identified and described with theory and observations. Starting from just an atmosphere, then adding an ocean and more processes, then a land surface, then sea ice, there is a constant evolution and expansion of the scope of climate models as new questions can be asked. One recent advance into a new area is the inclusion of models of land-based ice sheets coupled into climate models. This is driven by a desire to understand the rapid rates of recent ice melt. "Disturbance" models (such as the occurrence of wildfires) are being added to terrestrial systems. And there is a desire to use computational power to add complexity to representations of clouds, or chemistry in the atmosphere, and the chemistry of carbon throughout the earth system.

Another aspect of additional complexity in climate prediction is coupling with the human system. The treatment in this book is focused deliberately on the physical (and biological) climate system. Typically, humans have been seen as a forcing agent. But the scenarios to run the models need to reflect the possibilities of the human system. This is what actually moves the predictions more into forecasts. We cannot really forecast the future evolution of climate unless we can estimate the human emissions into the atmosphere. That requires predicting the future energy and transport system. To do so basically requires predicting the future human economic system. One approach to reducing scenario uncertainty is to build the carbon cycle into a model and also to build human systems into a model for a more self-consistent treatment of the atmospheric CO_2 concentrations and resulting forcing for climate models.

13.6.3 Challenges

In all of these configurations of climate models, there are challenges. The challenge for representing motions in the atmosphere is a consistent treatment as the scale varies. This is even harder for representing processes like clouds. Often, as the resolution gets finer and the grid size decreases, different approaches to representing processes are used. This usually occurs when the process in question has a scale not far from the grid scale: like large cloud systems or thunderstorms. In many cases, climate models rely on methods used for smaller-scale weather models to improve their process representations (parameterizations).

One ongoing trend is to make unified models for weather and climate prediction, using the same parameterizations and processes, but running the model in different ways for weather or climate. For weather, a system is used to initialize the model carefully with current observations, and the model is run forward for a few days.

For climate, the initialization does not matter, and the model is run for a long time. There are benefits of unified models, both to weather forecasting and climate prediction. Climate prediction benefits from the constant verification and testing against weather events (including extremes) in weather forecast models. Weather models benefit, too. They are forced to make improvements in conservation of energy and mass to run in climate mode. As weather models are starting to be run for seasonal prediction over months rather than days, conserving energy and mass and having a proper energy budget is critical.

One final note is that improvements must balance where to put increased computer power. Should a model be run with more advanced processes or finer resolution? It depends on decisions made in the development of a model, and what the aims of a model are, and the deficiencies. Different models will make different choices. When selecting climate model projections for applications, some care should be taken to select those climate models that perform well on evaluation of specific processes that are relevant to the application. Some applications benefit from high spatial resolution, and some do not.

13.7 Final Thoughts

Climate models are representations of the complex climate system. They are themselves complex constructions of the interactions of many individual processes. A typical climate model now contains as many lines of computer code as a computer operating system. The processes in climate models are governed by basic physical laws. These laws are applied at the process level, the sum of processes (component level), and the coupling between components in the climate system. The result is an emergent complexity from the interaction of these bounded processes and then the interactions between the different spheres of the climate system. Climate models attempt to represent a complete and consistent earth system and thus benefit from fundamental constraints on energy and mass. This last benefit is often unique to climate models. Climate models are therefore complex, but they are built from basic physical laws, and they do a remarkable job of simulating many aspects of the earth's climate. One of the continuing challenges is representing the many different scales of variations in the climate system that are too small to represent with a single number in a large grid box.

Sometimes, climate modeling is derided as an *art*. The term is derogatory, intended as the opposite of *science*. The implication is that climate models are a hopeless tangle of competing equations that make no sense in the whole, and that cannot hope to represent the key processes that will determine the magnitude of climate change. In particular, since the models contain numerous uncertain parameters, it is argued that there is a "hidden art" to adjusting these parameters in any model and that the process of adjusting these parameters (often called *tuning*) does not follow the scientific method.[3] But this is not really true. The laws of physics and fundamental constraints of conservation bound each process. As models get more complex, parameterizations represent processes more explicitly and are described in ways closer to physical laws, using parameters that can be constrained by observations.

The adjustment or tuning process of a set of parameters to match a set of observations is an optimization problem that can also be completed objectively. Recent attempts at quantifying uncertainty in climate model adjustment have shown that an objective algorithm reproduces the intuition of model developers.[4] This evaluation is important for putting climate models on a sound scientific footing. There is also proof of the utility of climate models from past climate model predictions. Predictions from climate models nearly 30 years ago follow well the trajectory the climate has taken,[5] much better than any economic model has done with the global economy over the past 30 years.

We are more certain of what will happen at longer time scales and larger spatial scales (global). This arises from the nature of the problem, and the transient effects of internal variations in the system. Much of the remaining global uncertainty focuses on clouds, since the response of clouds to climate changes (cloud feedback) affects the total net energy in the earth system. The role of the ocean is also critical. It is a huge reservoir of heat, and it controls where that heat goes and how much goes into the surface or how much heat the system "saves" for later.

The consequence of analyzing the uncertainty in climate model projections in this way is surprising. If we use the global-scale average surface temperature as the defining metric of *global warming*, then projections of global warming are uncertain mostly because we do not know the quantity of human greenhouse gas emissions in the future, not because of uncertainty in climate models. This is scenario uncertainty. The goal of climate models is to minimize model uncertainty to be able to make more confident projections about regional scales with high-resolution climate models or limited-area (regional climate) models.

Using climate models appropriately requires understanding many of these subtleties. Most of all, it requires an understanding of uncertainty and how to assess uncertainty in climate model projections (and the difference between predictions and projections) for a particular problem, recognizing that uncertainty will vary with the application. We hope in the end that the reader is now a more competent interpreter or translator when confronted with climate model output to use.

[3]For a good discussion of the methodology of model optimization, see Schmidt, G. A., & Sherwood, S. (2014). "A Practical Philosophy of Complex Climate Modelling." *European Journal for Philosophy of Science* (December 9). doi:10.1007/s13194-014-0102-9.

[4]Zhao, C., Liu, X., Qian, Y., Yoon, J., Hou, Z., Lin, G., et al. (2013). "A Sensitivity Study of Radiative Fluxes at the Top of Atmosphere to Cloud-Microphysics and Aerosol Parameters in the Community Atmosphere Model CAM5." *Atmospheric Chemistry and Physics, 13*(21): 10969–10987. doi:10.5194/acp-13-10969-2013.

[5]Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., et al. (1988). "Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model." *Journal of Geophysical Research, 93*(D8): 9341–9364. doi:10.1029/JD093iD08p09341.