Chapter 4
Essence of a Climate Model

Now that we have described climate, we ask the question, what is a climate model? A climate model is a set of equations that try to represent and reproduce each of the important pieces of the climate system. The model is developed based on everything we know about the world around us. Traditionally and historically, there are different sections in the model (sub-models, or components) for the major spheres we have discussed: atmosphere, ocean, land, cryosphere and biosphere. If these different spheres can interact with each other in a simulation, then we say they are coupled together.

Although a model can sometimes be a physical object (a model airplane, or a physical model of a building), a climate model exists as a conceptual model coded into a computer (think of the drawings of a building's plans on a computer). The structure of the model is a description of the physical laws of the system. It is a series of equations. These equations are a description of the climate system: component by component (e.g., atmosphere, ocean, land), process by process. The set of equations is analogous to the description of a building contained in blueprints that describes the structure, components, dimensions and finishes. This description can be used to simulate the building in three dimensions so that you can see what the building will look like in the future when it is built. Not unlike a climate model, the structure of a building is also governed by fundamental physical laws: We discuss them in Sect. 4.2. However, climate models are dynamic, meaning they change in time. Although a building may seem static, many complex structures, including buildings, are described and subjected to simulated forces (e.g., to simulate earthquake effects) on a computer to understand how they might react.

The equations in a climate model can be (and are) written down on many pieces of paper; description documents run to hundreds of pages.[1] To solve these equations efficiently, a computer is used. A "simple" climate model can be written out in just a few equations and either solved by hand or put into a spreadsheet program to solve. We illustrate the concepts of such simple models below. More complicated

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[1] For example, Neale, R. B., Chen, C. C., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D. L., et al. (2010). *Description of the NCAR Community Atmosphere Model (CAM5.0)*. Boulder, CO: National Center for Atmospheric Research, http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf.

A. Gettelman and R.B. Rood, *Demystifying Climate Models*,
Earth Systems Data and Models 2, DOI 10.1007/978-3-662-48959-8_4

models are essentially giant spreadsheets inside of supercomputers. We also discuss how different types of models are constructed. Finally, we discuss exactly what it means to set these models up and "run" them on large (super) computers. These methods give us are a general way to think about climate models before diving into the details of what the models contain.

4.1 Scientific Principles in Climate Models

Each of the components (submodels) and the individual processes must obey the basic physics and chemical laws of the world around us. An important overlooked fact is that the fundamental principles of climate modeling are not new. Simulating the earth system relies on principles of physics and chemistry that have been known for 100–300 years. The existence of a new subatomic particle does not require us to change our climate models. They contain no complex physics (like presumptions of warping space-time).

The physical laws start with **classical physical mechanics**,[2] developed by Sir Isaac Newton in his *Philosophiæ Naturalis Principia Mathematica* (1687): conservation of mass and momentum (especially Newton's second law of momentum) and gravity. The classical physical mechanics of the atmosphere and ocean (air and water) use equations developed by Claude-Louis Navier and Sir George Gabriel Stokes in the first half of the 19th century, known as the Navier-Stokes equations. The same equations are used to simulate airflow around aircraft, for example, in another type of finite element modeling.

In addition to the motion of parts of the earth system, flows of energy are critical in the climate system. As we discussed earlier, the slight imbalance of energy input and outflow as carbon dioxide concentrations increase gives rise to climate change. The transformation of energy and its interaction with the physical system is known as **thermodynamics**,[3] the principles of which were developed by Nicolas Carnot and others in the early 19th century. Flows of energy are essentially **electromagnetic radiation**, described by the electromagnetic theory of James Maxwell in the 1860s. Important details about how radiation interacts with thermodynamics were added by Jozef Stefan and Ludwig Bolzmann in the 1870s and 1880s. Also in the 19th century, much of the basic work on chemistry was performed, culminating in

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[2] Starting with Newton, there are many books on the subject. Perhaps the best modern reference is still the *Feynman Lectures on Physics*. You can buy them, but they are available online from http://www.feynmanlectures.caltech.edu/. Classical mechanics is Volume 1, mostly Chaps. 1–10.

[3] *Feynman Lectures on Physics* (http://www.feynmanlectures.caltech.edu/), Volume 1, Chaps. 44–45. Or there is always Pauken, M. (2011). *Thermodynamics for Dummies*. New York: Dummies Press.

specific experiments and estimates by the Swedish chemist Svante Ahrrenius in the late 19th century about the radiative properties of carbon dioxide.[4]

In the face of criticism of climate science, it is important to note that the physical science behind climate models and energy is based on physical laws known for several hundred years and is not new or subject to question. If the world did not work this way, cars would not run, airplanes would not fly, and everyday motions that we observe (baseball pitches, gravity) would not happen. As we demonstrate later, these underlying scientific principles are not cutting-edge science. The principles are not open to question or debate, any more than the law of gravity can be debated.

Climate models simply take these basic laws, apply them to a gridded representation of the different pieces of the earth system and connect it all together. The overall philosophy is classic scientific reductionism. The same principles and scientific laws are used in countless other fields. Do we "believe" in climate models? That is a bit like asking if we "believe" that the earth is round, that the sun will rise in the east, or that an airplane will take off when it gets to a certain speed. But if you still don't, please reread the "Models All Around Us" box in Chap. 1. We use physical laws that agree with observed experience to make a prediction. This is a different way to use models than many people are used to (see box on dynamical system models below).

Dynamical System versus Empirical Models

Weather and climate are dynamical systems; that is, they evolve over time. Dynamical system models use equations of relationships between variables to describe the future state of a model. The future state of a dynamical system is dependent on the present state. Scientists in many fields use models that describe dynamical systems with time evolution.

The rules that define the evolution of the Earth's climate rely on physical laws and relationships. So, for example, the speed or velocity (v) of air is defined by the equation that describes the conservation of momentum. The velocity of a "parcel" of air is the existing velocity (v_0) plus the acceleration of the object (a) over a given time interval (t). So $v = v_0 + at$. This is based on Newtonian mechanics, the basic laws of common physics. If the desired output is the velocity v at any time, then the inputs are v_0, a, and t. The equation can be marched forward in time (where at the next time $v_0 = v$ from the previous time). This equation predicts how the state (physical properties: velocity, in this case) of the object changes over time. Climate models have equations of motion for air, water, ice and the biosphere that are integrated forward in time.

A different way to represent a dynamical system is with a statistical or empirical model. Empirical models define mathematical relationships

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[4] The original paper: Arrhenius, S. (1896). "XXXI. On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground." *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *41*(251): 237–276.

between independent variables (inputs) and dependent variables (outputs). For example, if you measure the speed of an object at different points in time, you can develop a relationship based on those observations. If you are dropping the object with no air resistance, so the acceleration is gravity, you can develop a relationship between the velocity and the time. For the surface of the earth, you would get (in metric units) $v = v_0 + 9.8\ t$, where t is measured in seconds, and v is in meters per second. This is an approximate form of the equation of motion, which might work very well for similar cases, but would not work for a different situation.

Physical laws contain more information than statistical or empirical methods and, therefore, are more suitable for dynamical systems where the environment for statistically based parameters might be different. For example, the gravitational acceleration is dependent on the mass of the object that is doing the attraction and the distance from the center of that mass (Earth, in this case). So the dynamical system approach works on the moon: You can calculate different acceleration (a) based on the lunar mass. But the empirical result (using 9.8) would not work on the moon.

The danger with statistical or empirical models is being “out of sample”: There is some condition where the model does not work. This may be obvious in our example, but it is not always obvious.

So are dynamical models always better? Only when a good description of the system can be made. For many processes, we turn to empirical or statistical relationships. Even many fundamental properties of the world around us are made up of many different conditions at the molecular or atomic level, so we have to describe the process empirically. As an example, the chemical properties of a substance, like the freezing temperature and pressure of water, are related to small-scale motions of molecules (all governed by our velocity equation), but we cannot measure each molecule. So we measure the collected behavior of all the molecules in a sample and build an empirical model of the freezing point of water as a function of temperature and pressure.

Thus climate models do contain empirical models of processes, coupled together in a dynamical system. They contain a representation of the freezing point of water, for example. These processes are tied together using physical laws, which help us to make sense of the interconnection between the processes. Some processes are simple or well described (like water freezing), and some are very complex. But these statistical models are sometimes necessary. Tying them together with physical laws (like conservation of energy and mass) is an important constraint on climate models. These conservation constraints help to reduce uncertainty.

4.2 Basic Formulation and Constraints

Ultimately a climate model is a series of interlinked *processes* and a set of equations or relations: physical laws that control how the system evolves. These different laws are solved for each different location in the model: a finite element. Let's describe how we break up a model into different pieces, what each of these pieces does and why. This will define the basic formulation of a climate model.

4.2.1 Finite Pieces

The physical laws (see below) are solved at each physical location (**point**, **cell**, or **grid box**) defined in a model. The physical points are illustrated in Fig. 4.1. Most models also have a vertical dimension (whether in the atmosphere, the ocean, or through the thickness of sea ice or soil), making a **column**. This has one dimension: in the vertical. Columns are generally on a regular **grid**, so each location is a grid point. *Grid* comes from a regular lattice of points, usually equally spaced, but they can be irregular (different arrangements of points), which we discuss later. Thus, a model (like the reality it represents) has three dimensions: one horizontal and two vertical (Fig. 4.1c). Each individual vertical location in a column is called a grid box, or cell. Each of these cells is a "finite element" for which a model defines different processes, usually representing a given region with a single "finite" value.

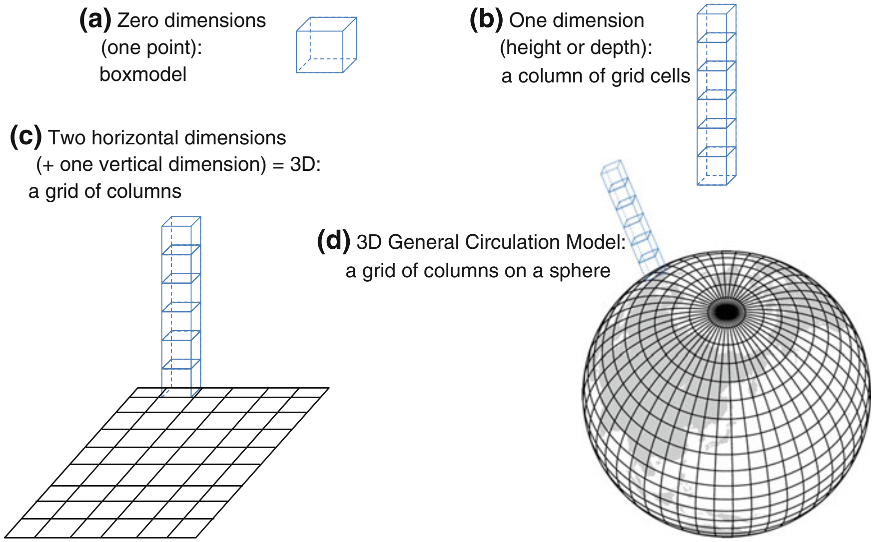

Fig. 4.1 Dimensions of models and grids. **a** Point or box model (no dimensions). **b** Single column (one dimension in the *vertical*). **c** Three dimensional (3D) model with *two horizontal* dimensions and *one vertical* dimension. **d** 3D grid on a sphere

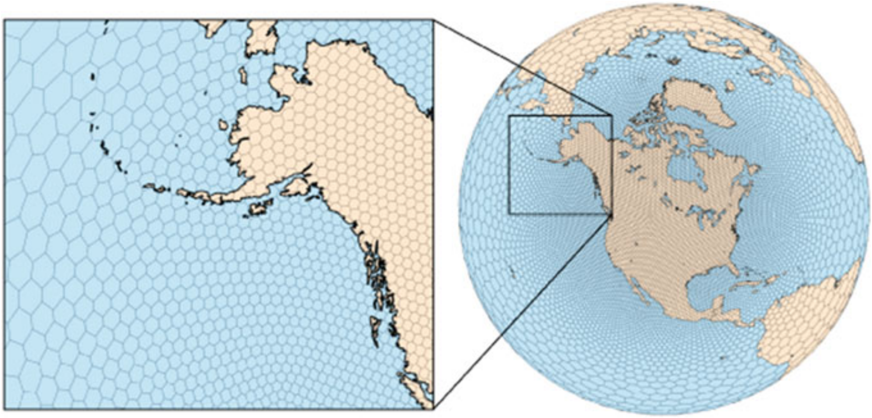

Fig. 4.2 An example of a variable resolution grid from the model for prediction across scales (*MPAS*). The grid gets finer over the continental United States using a grid made up of hexagons. *Source* http://earthsystemcog.org/projects/dcmip-2012/mpas

When we talk of the **resolution** of a model, we mean the size of the horizontal boxes or, equivalently, the space between the centers of different grid boxes. So a model with horizontal resolution of one degree of latitude has grid boxes that are 68 miles (110 km) on a side.

The global grid in Fig. 4.1d is along latitude and longitude lines. It has the same number of boxes in longitude (around the circle) at any latitude. Since the circumference of the earth is smaller at higher latitudes, the grid has unequal areas. This is a problem for several types of model (see Chap. 5, on the atmosphere, and Chap. 6, on the ocean). Some models use other grids to make the different boxes have nearly equal area (e.g., a grid of mostly hexagons). Other grids are designed with higher resolution (smaller size grid cells) in a particular region. This provides benefits of a higher resolution model, but with lower computational cost. Figure 4.2 shows an example of a variable resolution grid.

Motions in the climate system are both horizontal and vertical. Climate models need to represent processes in both directions. Horizontal processes include the flow of rivers, wind-driven forces on the ocean surface, or the horizontal motion of weather systems in the atmosphere. Many features of the climate system vary in the horizontal. The ocean surface is pretty uniform, but the terrestrial surface is not: Vegetation and elevation change. Figure 4.3 illustrates horizontal grids in a climate model, illustrating with horizontal resolutions of about 2° of longitude (124 miles, or 200 km), ~1°, ~0.5°, and ~0.25° (the latter is 16 miles, or 25 km). The color indicates the elevation, showing that, as the resolution gets finer, more realistic features (like the Central Valley of California) can be resolved. For the terrestrial surface, this also means that the land surface (soil, vegetation) can also vary on smaller scales.

There are also many vertical processes: like the rising or sinking of water in the ocean, the movement of water through soil, or the vertical motion of air in a

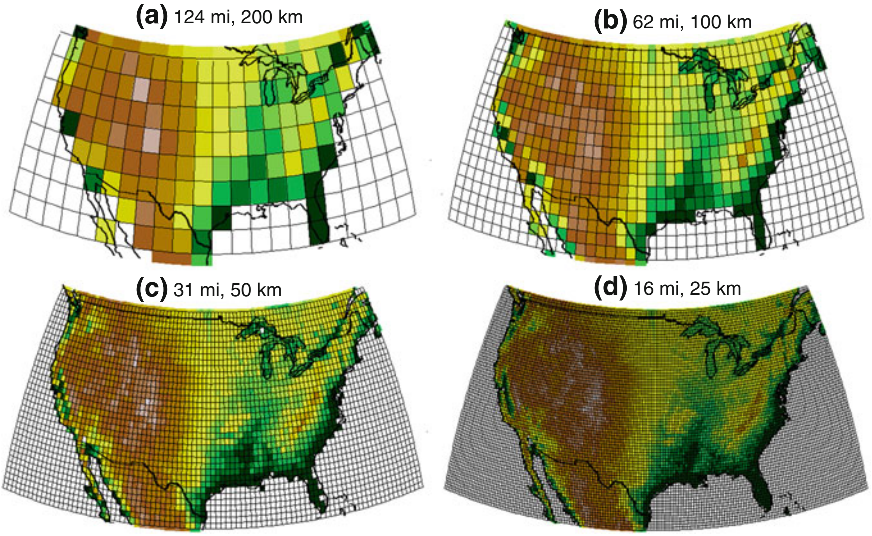

Fig. 4.3 Example of a model with different horizontal resolutions on a latitude and longitude grid over the continental United States. Resolutions are **a** 2° latitude, **b** 1° latitude, **c** 0.5° latitude, and **d** 0.25° latitude. Elevation shown as a color

thunderstorm. These vertical processes feel the effects of gravity and the effects of buoyancy. Buoyant objects are less dense than their surroundings (air or water) and tend to rise. There are also forces like pressure that act both vertically (pressure decreases as you get farther from the bottom of the atmosphere or ocean) and horizontally (wind tends to blow from high to low pressure).

4.2.2 Processes

It seems natural to be able to break down the problem into a series of boxes in physical space for each component, as in Fig. 4.1. But what is in these boxes? Each box tracks the properties of the physical **state** of the system: a collection of variables representing the important physical conditions at a location and time. These are the physical properties and energy in the box: like the temperature of the air in the box. The physical properties include the mass of water or ozone molecules in a box of air, the salt in a box of ocean, the soil moisture and vegetation cover of a box on the land surface. The "state" also records the total energy in a grid box. The total energy has several parts, including the **kinetic energy** (winds, currents, stream flow) of the air or water or ice in motion, and the **thermal energy**, usually represented by temperature. Each of these quantities can be represented by a number for the box: the number of molecules, the temperature, the wind speed, and the wind direction. This set of numbers is the state of box. Figure 4.4 indicates how these

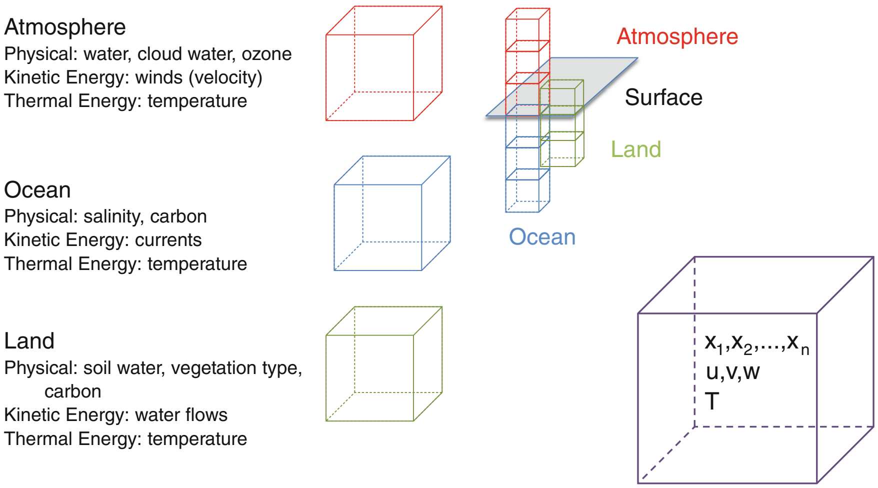

Fig. 4.4 State of the system. Different grid columns for the atmosphere (*red*), ocean (*blue*) and land (*green*) with description of contents. Also a grid box (*purple*) with a 'state' vector of temperature (T), wind in 3 dimensions (U, V for *horizontal* wind and W for *vertical* wind) and the mass fraction of compounds like water (X_n)

components are described by a series of numbers grouped into physical quantities (x_1, x_2, … x_n for *n* tracers like water), kinetic energy (u, v, w for wind vectors in three dimensions), and thermal energy (T for temperature).

The basic goal of a climate model is to take these physical quantities (the state) at any one time in each and every grid cell and then to figure out the processes and physical laws that will change these quantities over a given time interval (called a **time step**) to arrive at a new state in every grid cell. Figure 4.5 illustrates the different parts of a time step in a model. A time step involves several different processes. (1) Calculating the rates of processes that change the different quantities with sources and loss of energy or mass and their rearrangement. (2–3) Estimating the interactions between all the boxes (2) in one model column and (3) between different component models. (4) Solving physical laws that govern the evolution of the energy and mass. (5) Solving physical laws for motions of air and everything moving with the air on a rotating planet.

First, processes that change the state of the system are calculated. This might include, for example, the condensation of water into clouds, or freezing of ocean water to sea ice. This is illustrated in (1) in Fig. 4.5. As part of this endeavor, exchanges between boxes in a column are often calculated (2). These steps define the sources and loss terms for the different parts of the state: the quantity of water precipitating, or the quantity of salt expelled by newly formed sea ice. These terms are used in (3) to exchange substances with different components: for example, precipitation hitting the land surface. Then, all these terms for the mass changes in substances and the energy changes are added to the basic equations of thermal

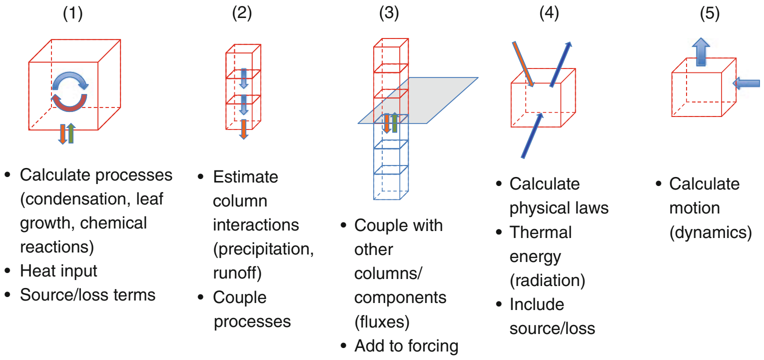

Fig. 4.5 Changing the state: one time step. Climate model calculations in a time step that change the state of a model. *1* calculate processes, *2* estimate column interactions like precipitation, *3* couple with other columns and components, *4* calculate physical laws like radiation, *5* estimate motions

energy (4). Finally, these terms are used as inputs to the equations of motion to calculate the changes to wind and temperature (5).

The physical laws are the fundamental **constraints** on the model state. The constraints are rules set in the model that cannot be violated. In classical physics, mass is not created or destroyed. If you start with a given number of molecules of water, they all have to be accounted for. This is called **conservation of mass**. There is usually an equation for each substance (like water). It has terms for the motion of water in and out of a box and for the processes that transform water (sources and loss terms).

Energy is also conserved. There are equations for the kinetic energy (motion) and for the thermal energy (temperature). There is also potential energy (work against gravity). The total conserved energy includes all these kinds of energy. There can be transformations of this energy that seem to make it go away: Heat is needed to evaporate water and change it from a liquid to a gas. The heat energy becomes part of the chemical energy of the substance. Temperature or heat energy is the kinetic energy of the molecules of a substance moving around, so evaporating water into vapor adds energy to the water, which must come from somewhere. The heat is released when the water condenses to liquid again. This is **evaporative cooling** when you evaporate liquid (and **latent heating** when it condenses). It is also what happens when you compress air (it gets warmer). But the processes will reverse their energy, conserving it. These constraints are quite strict for climate models: If you start with a certain amount of air or water, it has to go somewhere. The transformations and transport (motion) of mass and energy must be accounted for. These properties of physics (at the temperatures and pressures of the earth's atmosphere and climate system) do not change, and these laws cannot be repealed.

Finally, all of these terms are balanced between the grid boxes. This is illustrated in step (4) in Fig. 4.5. Typically, models are used to calculate how the system would change due to different effects. Then these effects are added up. For example, the land surface has water evaporate from it and plants that take up water. The amount of water in the soil column (a box of the land surface) is a result of precipitation falling from the atmosphere, runoff at the surface, and the motion of water in the soil column. These boxes also then exchange their properties with other boxes, such as water filtering deeper into the soil, or runoff going to an adjacent piece of the land surface. In addition, exchanges can occur with other pieces of the system: The precipitation falls onto the land from the atmosphere, evaporation goes into the atmosphere, and runoff goes into the ocean. These interactions can all be described at a particular time, and the effects can be calculated and used to update the state of the system.

Key to this system are the descriptions of each process. Some examples of *processes* are the condensation of water vapor to form clouds, carbon dioxide uptake by plants, or the force on the ocean from the near-surface wind. Each of these processes introduces a forcing on the climate system. As we will learn, many of these processes are hard to describe completely, particularly for processes that occur at scales much less than the typical size of one grid box in a model. A climate model usually has one value for each substance (like water) or the wind speed in each large location, and it has to represent some average of the process, often by approximating key parameters.

Parameterization is a concept used in many aspects of climate models (see box). The basic concept is like that of modeling itself: to represent a process as well as we can by approximations that flow from physical laws. Many of the approximations are required because of the small-scale nature of the processes. The goal of a parameterization is not to represent the process exactly. Instead, it is to represent the *effect* of that process at the grid scale of the model: to generate the appropriate forcing terms for the rest of the system and the rest of the processes.

Parameterization

Representing complex physical processes (clouds, chemistry, trees) in large-scale models is in some sense impossible. The French mathematician Laplace articulated a thesis of the reductionist worldview in the early 19th century: If one could have complete knowledge of every particle in the universe and the laws governing them, the future could simply be calculated. Of course, we cannot do that, so we seek to represent what we know about the behavior of particles, based on physical laws and empirical observation. For some processes, we can refer to the basic physical laws, which often have little uncertainty in them. The laws of how photons from the sun move through a well-mixed gas such as air are an example. Other processes are more complex, or variable on small scales. It is hard to derive laws from these processes. For instance, the flow of low-energy photons from the earth through air is somewhat uncertain because the laws governing how the energy interacts with water vapor are very complex. In the case of water vapor, the way the molecule is constructed it can absorb and release energy at many different wavelengths. For these processes, we often must use statistical treatments to match observations to functions that can be used to describe the behavior. Some processes can be represented by basic laws, other processes must (at the scale of a climate model) be represented by statistical relationships that are only as good as our observations (see box on dynamical vs. empirical models earlier in this chapter).

What processes to represent and at what level of detail are other critical choices. Herein lie decisions that require a rigorous attention to the scientific method: Hypotheses must be developed and tested against observations to ensure the results of the parameterization match observations of the process being represented. To some extent, the complexity may be dictated by the available inputs: If the inputs are only crude and broad in scale, or uncertain, then it may not make sense to have complex processes acting on bad inputs if simpler solutions are possible. But if a lot of information is available, it should be used.

Another determinant is how important the process is to the desired result. Climate modelers worry quite a bit about having detailed descriptions of the flows of energy and mass, especially of water mass (which, by carrying latent heat, affects both energy and mass). Small errors in these terms over time might result in large biases (if energy is “leaking” from the system). So conservation is enforced. But this does not constrain important effects. For example, while total precipitation might be constrained, some of the details of precipitation, such as timing and intensity, are not well represented. Weather models, however, focus much more on the timing and intensity of precipitation by having more detailed descriptions of cloud drops and their interactions, but they often do not conserve energy and mass perfectly over the short period of a forecast.

Putting the processes together seems like a daunting task. It would also seem that one simply is multiplying uncertainty by taking one uncertain process after another. But in fact the physical laws are strong overall constraints on climate models. If each process is bounded and forced to be physically reasonable—starting with the conservation of energy and mass, but usually extending to other fundamental observations—then it is expected the whole climate system being simulated will be constrained but still have the interconnectedness needed to generate the complex and chaotic couplings that we see in the real world around us. The danger is that the complexity gets large enough that we cannot understand it in the model. The rationale is that by interlocking the carefully designed and constrained parameterizations in a sensible way, like putting bricks together, we can build the **emergent** whole of the climate system. The whole “emerges” from a series of processes tied together.

The emergent constraints arising from conservation is where “art” seems to come into climate modeling. How can a crude representation of processes possibly represent the complexity of climate? The constraints drive simulations toward reality. Hence, climate modeling is often called an art, but in a derogatory way, to imply that it does not follow the scientific method. But parameterization development is a series of hypothesis-testing exercises, forming and testing hypotheses for representing processes in the earth system and the connecting of the processes together. The problem is that our incomplete knowledge and imperfect observations permit multiple states of the system that behave similarly: More than one description may match current observations of the earth.

Consider this simple example: Viewed from a satellite in space, the Arctic Ocean appears white. But is it covered by clouds, or just by sea ice? Either option would fit the observation, as both clouds and sea ice are white. But clouds in the atmosphere and ice at the surface are very different and will respond differently to changes in winds and temperatures. If you assume that the "average" condition, or the distribution of how often clouds and ice are present, is not known, then we cannot determine the present climate state from observations. In this case, very different climates with different clouds and ice are possible. The different climates may respond to climate changes in different ways.

The goal of modeling is to try to reduce these uncertainties by careful application of numerical tools to represent climate processes and continual testing against observations. Multiple models and multiple approaches in the global scientific enterprise are competing in this context to see which representations seem to work the best.

It all comes down to representing processes.

But the compensation in a climate model is the conservation laws: Energy and mass must be conserved. Each process at each time step must be limited to what is possible. For example, the amount of water that can rain out of a cloud is limited by the total water in the cloud.

The respect for these fundamental laws and the equations that describe the motion provide strong constraints. If each process is limited and each set of processes in the atmosphere and ocean are limited, then the emergent whole of the sum of those processes is constrained by known physical laws. The complex interactions are constrained by those laws. The model cannot go "out of bounds" for any process, or for the sum of any processes at any time step. This requires the model to be "realistic": resembling the laws of the physical world and the observations of the world. There is no guarantee or theory that prescribes this at the scale of a climate model yet, but energy and mass conservation are powerful constraints.

As we shall discover, there are many different possible representations of processes and their connections in the climate system that are physically realistic. We do not understand the whole climate system well enough to make unique models of each process: Multiple different models are possible. This yields multiple ways to develop and construct a climate model. Different representations will yield different results, sometimes importantly different results. But it also means a "hierarchy" of models is possible: from simple models that try to simulate just the global average temperature, to detailed regional models that try to represent individual processes correctly. These different models are used for understanding different parts of the climate system.

4.2.3 Marching Forward in Time

The reductionist approach to individual effects or processes and discrete time steps is an important part of understanding finite element models such as climate models. For climate models, many decisions can be made, starting with which processes to include and how to represent them.

Figure 4.6 illustrates one method of taking the different physical processes and equations in Fig. 4.5 and marching forward in time. It is drawn as a loop, because where one time step ends another begins. Here the processes and exchanges are highlighted. They occur at every point in every column on the grid for each component model. First shown are (1) the physical (including chemical) processes in each grid box. These interact in the column (2) for example: precipitation falling. There are (3) exchanges between components–like precipitation hitting the surface. Then there is the application of the physical laws. Conservation of mass is applied throughout. Conservation of energy happens in the thermodynamic equation when

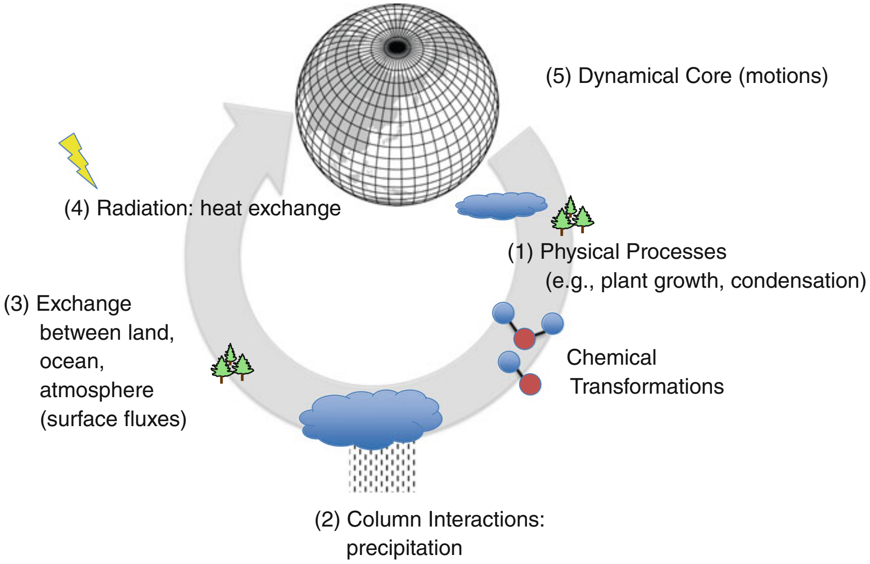

Fig. 4.6 Marching forward in time within a climate model. Time step loop typical of a climate model. Processes are calculated in a sequence at each time. *1* Physical processes and chemical transformations, *2* column interactions, *3* exchange between different components, *4* radiation and heat exchange, *5* dynamics and motion

radiation is calculated (4). For models with a moving fluid or solid like the atmosphere, ocean and sea ice, the equations describing motion (kinetic energy) are solved in the *dynamical core* (5) of the model. The dynamical core solves the equations of motion to determine how substances (water, air, ice, chemicals) move between columns.

But decisions involving which processes to calculate first and how to put them all together, are not always obvious. This is one of the inherent complexities in finite element models. Some choices matter for the results and a lot of research has gone into understanding these choices and the range of solutions that result. One goal is to develop formulations so that the solutions do not depend on the ordering of processes. Fortunately, many of the basic scientific principles used limit the realistic choices, as we have already seen above with the conservation of energy and mass.

4.2.4 Examples of Finite Element Models

Global climate models are made up of a series of component models (e.g., atmosphere, ocean, land). Each component model has a series of grid boxes or cells, on a regular grid. The solution of all the processes and transformations is carried out at each time step, for each one of these finite elements (grid cells) in the model. The concept of a finite element model is used in many other scientific and engineering endeavors. The flow of air over the wing of an airplane is a close analog of many of the concepts used in modeling the atmospheric part of the climate system. Fluid flow in a pipe is another example of finite element modeling. Such models are used for a water treatment plant, a chemical plant, an oil refinery, or the boiler in a coal-fired power plant. Finite element models are also used to understand how engines work in cars and trucks, or how materials perform under different forces (stress), whether an individual part of a device, or an entire structure (a building, an engine block, etc.). These models are used all the time in engineering things in the world around us. The fact that planes fly, cars run, and all our electronic and mechanical devices work is testament to the power of finite element modeling. It includes whatever electronic machine you are reading this on, or whatever machine printed the words in ink on the page you are reading. Numerical modeling works in many fields, and includes many of the same scientific concepts, as in climate modeling.

4.3 Coupled Models

Currently, all the components of the climate system have also been included in earth system models. Generally, the process started with representing the atmosphere (see below for more discussion of model evolution). Representations of the land surface and the ocean were added next and then coupled to the atmospheric model to make a **coupled climate system model**. A climate system model does not include a comprehensive and changeable set of living components in the biosphere. The biosphere contains the flows of carbon in land-based plants and in small organisms in the ocean (phytoplankton). Including the biosphere allows these stocks of carbon to affect the carbon dioxide in the atmosphere. This is a more complete description of the system usually termed **earth system models**. We refer to these models simply as climate models. So where the scientific literature says "earth system," we use the term "climate system."

The components of the earth's climate system (atmosphere, ocean, land) are each coupled to the others as physically appropriate. Figure 4.7 shows a simple schematic of the arrangement. The bottom of the atmospheric model is the top of the ocean and land models, for example. Information is exchanged across the components at these natural boundaries. The exchanges are critical to the operation of the system. Rain falling out of the atmosphere is critical for the state of the land (determining soil moisture, runoff, plant growth, and the like). The interaction of floating sea ice with the surface ocean is critical for the density of the ocean at high latitudes (since when ice freezes the salt is expelled and the water becomes saltier and denser). And the atmospheric winds drive ocean currents and move the sea ice around.

Many of these interactions are illustrated in Fig. 4.7. These interactions are critical for understanding how the climate system evolves and how it responds to changes in the interactions. Small changes in one component have ripple effects on other components. Note how the arrows in Fig. 4.7 can circle back: changing temperatures can melt sea ice. The melting sea ice exposes darker ocean. The darker ocean absorbs more energy. The absorbed energy changes temperature further. These are expressions of feedbacks in the system (see Chap. 5). Each of these component models contains a certain amount of complexity related to the respective piece of the system that a given model illustrates. We address those complexities in later chapters. In this chapter, we are concerned with understanding the essence of these models.

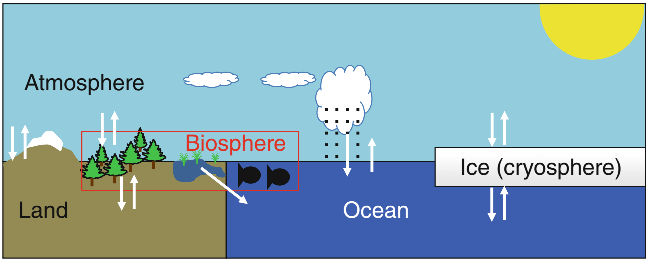

Fig. 4.7 Schematic of earth system coupling. The basic coupling between different components of a climate model

4.4 A Brief History of Climate Models

So how did we get to breaking up the planet into tiny boxes on massive numerical computers humming away in air-conditioned rooms? Climate predication is an outgrowth of wanting to know more about the fundamental and long-term implications of daily weather phenomena.[5] It arose in the 1960s in parallel with the development of weather prediction. Weather prediction actually started well before electronic computers. As mentioned earlier, in the 19th century, scientists speaking as philosophers, such as Simone Laplace, articulated the idea that if we knew where every particle in the universe was and we knew the laws governing them, we could calculate the future. That remains a philosophical statement more than anything else, especially since quantum physics has shown that you cannot measure the characteristics of a particle without affecting them (Heisenberg's uncertainty principle).

Early experiments with forecasting the weather, for example, by Vilhelm Bjerknes in the early 20th century, articulated that with a sufficiently accurate (but not perfect) knowledge of the basic state and reasonably accurate (but not perfect) knowledge or approximations of the laws of the system, prediction was possible for some time in the future. During World War I, a British scientist (working as an ambulance driver) named Lewis Richardson attempted to write down the laws of motion and, using a series of weather stations, calculated the future evolution of surface pressure. These equations were correct but virtually impossible to solve practically by hand. Approximations for the equations, developed by Carl Gustav Rossby in the 1920s and 1930s, enabled some measure of the evolution of the system to be described and enabled some rudimentary attempts at predicting the evolution of weather systems. Electronic computers were developed during and after World War II. One of the first was developed to calculate the tables for the trajectory of artillery shells. After the war, other computers were applied to solve Rossby's simpler set of equations, among others by a group at Princeton led by John von Neumann.[6]

The use of electronic computers to solve the equations of motion describing weather systems led to actual numerical forecasts. So where does climate prediction come in? In the mid-1950s, several experiments took rudimentary weather forecasts, added some of the forcing terms for energy and radiative transfer, and tried to run them to achieve some sort of statistical steady-state independent of the initial conditions. These experiments were able to represent important aspects of the

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[5] A good overview of the co-evolution of weather and climate models is contained in: Edwards, P. N. (2010). *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press. Another good reference is the description of the history of General Circulation Models in Spencer Weart' online book *The discovery of Global Warming*, Harvard University Press, 2008. Available at: https://www.aip.org/history/climate/GCM.htm.

[6] For a detailed description of the origin of digital computers, focused on von Neumann and the Princeton group (with cameo appearances by climate models), see Dyson, G. (2012). *Turing's Cathedral: The Origins of the Digital Universe*. New York: Vintage.

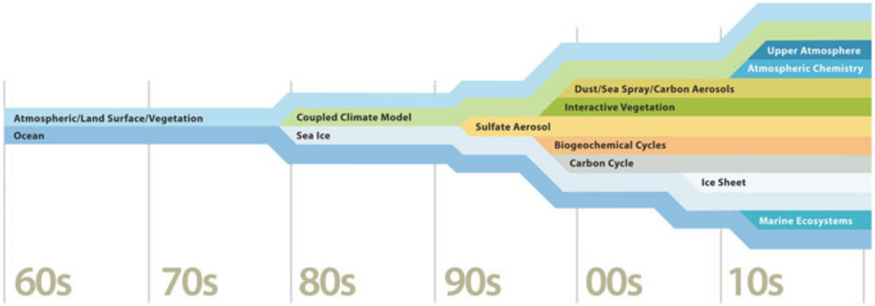

Fig. 4.8 Schematic of components. Evolution of the parts of the earth system treated in climate models over time. *Source* Figure courtesy of UCAR

general circulation, and from there, climate models (originally General Circulation Models) were born. Initial development as a separate discipline evolved in the 1960s. As computers got faster and techniques got better, more realistic simulations evolved. Since then, there has been a co-evolution of climate and weather models with improved computational power.

This co-evolution led to the expansion of climate models from just models of the atmosphere, to coupled models of the entire climate system. Figure 4.8 illustrates how climate models have evolved from simple atmospheric models and ocean models, to coupled models with land and sea ice by the 1980s, to adding particulates and chemistry in the atmosphere, dynamical vegetation and chemical cycles on land, and marine ecosystems and climate in the early 21st century.

4.5 Computational Aspects of Climate Modeling

Climate models are naturally computer codes. They are run on supercomputers. What does it actually mean to *run* a climate model code? What does it entail?

4.5.1 The Computer Program

A climate model is a computer program. Generally each component, such as the atmosphere, can be run as a separate model, or coupled to other components: often a coupled climate model. Figure 4.9 illustrates a schematic of a coupled climate model. The figure is really an abstraction from Fig. 4.7: without the trees and fish pictures. A coupled climate model program features separate model components that interact, usually through a separate, master, control program called a coupler. Each component is often developed as an individual model (like the atmosphere). The coupler or control program handles the exchanges between the different

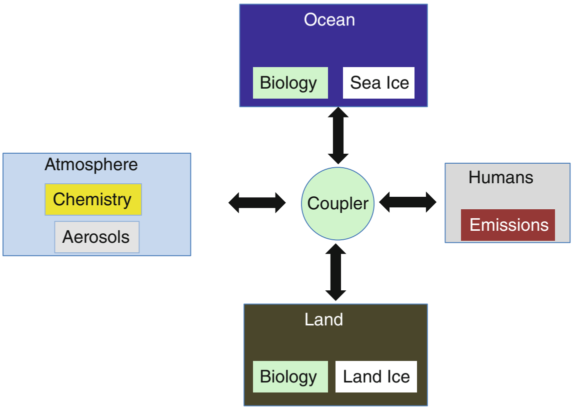

Fig. 4.9 Coupled climate model. Schematic of the component models and subcomponents of a climate model program. The coupler code ties together different spheres (ocean, atmosphere, land, biosphere, and anthroposphere) that then contain smaller component submodels (like aerosols, chemistry, or sea ice)

models. In idealized form, different versions or different types of component models can be swapped in and out of the system. These can include data models where, for example, instead of an active ocean, just specified ocean surface temperatures are used to test an atmospheric model.

The different components of the system, the different boxes in Fig. 4.9, can each be thought of as a separate computer program. There are often subprograms for different sets of processes, such as atmospheric chemistry or ocean biology. Each of these boxes can often be constructed as a series of different processes (individual boxes). The deeper one goes, the more the individual models are a series of processes.

This software construction is modular. A process is represented mathematically by a program or subroutine. It is coupled to other similar processes, like a model for clouds, or a model for breakup of sea ice. These similar models at each step are constrained for mass and energy conservation. The cloud model may consist of different processes, down to the level for a single equation, such as the condensation or the freezing of water. The processes and sub-models may be tested in some of the simple frameworks discussed earlier, and then often they are coupled with other physical processes into a component model. As shown in Fig. 4.9, the atmosphere model typically contains a set of processes for clouds, radiative transfer, chemistry, and the dynamical core that couples the motion together, as in Fig. 4.6. This is a sequence of computer codes: a set of equations, tied together by physical laws of conservation and motion.

How complicated does this get? Current climate models have about a million lines of computer code. This is similar to a “simple” operating system like Linux, but far less than a more “complex” operating system (50 million lines of code for

Windows Vista) or a modern web browser (6 million lines for Google Chrome).[7] So models are complex, but still quite compact, compared to other large-scale software projects. Of course, this level of complexity and complication means that there are always software issues in the code, that is, potential “bugs.”[8] How do we have any faith in a million lines of code? Scientifically, the conservation of mass and energy is enforced at many stages: If the model is well constrained, then even a bug in a process must conserve energy and mass. Let’s say that a process evaporating water is “wrong.” It still cannot evaporate more liquid than is present, limiting the impact of the mistake.

From a software perspective, climate model code must be tested the same way as any large-scale piece of software. There are professional researchers whose sole job is to help manage the software aspects of a large climate model.

Climate models are constructed by teams of scientists. The teams have specialties in different parts of climate system science: oceans, atmosphere, or land surface. There are social dimensions to model construction and evolution. Some models share common elements in various degrees. This is important when constructing an ensemble of models, as one has to be careful of picking models that are very similar and treating them as independent. Models with similar pieces (e.g., the same parameterizations) may share similar structural uncertainty. Most modeling centers have a specific “mission” related to their origin and history. They focus on excellence in particular aspects of the system, or on simulating particular phenomena. It should be no surprise that model groups in India worry very much about the South Asian Summer Monsoon, or that a model from Norway has a very sophisticated snow model. This is natural. Model codes are generally quite complex. Some climate models are designed and run only on particular computer systems. Some climate models are used by a wide community. Climate model development teams typically work with friendly competition and sharing between them. Climate model developers are continually trying to improve models and always looking over their shoulder at other models. There is a negative aspect to this community, and that is “social convergence”: Sometimes things are done because others are doing them. There is a desire not to be too much of an outlier.

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[7] See the infographic http://www.informationisbeautiful.net/visualizations/million-lines-of-code/ contained in McCandless, D. (2014). *Knowledge Is Beautiful*. New York: Harper Design.

[8] The first “bug” was thought to be a result of a moth being smashed in an electromechanical relay in the Harvard Mark II computer in 1947, according to Walter Isaacson in Chap. 3 of *The Innovators: How a Group of Hackers, Geniuses, and Geeks Created the Digital Revolution*. New York: Simon & Schuster, 2014. This of course would be considered a hardware, not a software, bug but the name stuck.

4.5.2 Running a Model

So how is a model run to produce "answers" (output)? Complex climate models are designed to be able to run in different ways. Climate models can be run in a simplified way, as a single column in the atmosphere, for example. This can be done on a personal computer. But the real complexity is running every single column of atmosphere on the planet. For this, large computers with many processers are used. These are supercomputers, and they typically have many processors. How many? The number increases all the time. As of 2015, the largest machines had a million processors, or computing cores.[9] Usually a model will run on part of a machine. Since a model with resolution of one degree of latitude ($\sim$62 miles or $\sim$100 km) would have about 180 × 360 = 64,800 columns, models have several atmospheric columns calculated on one core. Note that for 15 mile (25 km) resolution, this number goes up to approximately one million columns. The atmosphere would have a certain number of cores, the ocean a given number, and so forth for all the component models. The speed of each calculation is not as important as how many cores can be used to process computations "in parallel." The total cost of a model is the time multiplied by the number of cores. More cores mean that a larger number of computations can be done in the same amount of time: The total run time gets shorter. The cost of running a climate model depends on the number of columns, and this depends on the resolution. As computers get faster and especially bigger (see below), higher resolution simulations, or more simulations, or longer simulations become possible.

The need to communicate between columns makes climate models suitable for only a special class of computer hardware. A climate model column calculated on a computer core needs to talk to the next column when the calculation of the time step is done. Thus, the system must be designed to rapidly collect and share information. Most commercial "cloud" computing systems are not designed like this. A Google search, for example, requires a computer node to query a database and then provides an answer to a single user, without communication to other cores. So only certain types of computer systems (usually supercomputers designed for research) are capable of running complex climate models efficiently.

The supercomputers used to run climate models are common now with the rise of computational science in many disciplines. Many universities maintain large machines for general use. Weather forecast centers also typically have their own dedicated machines for weather forecasts that climate models are run on. And they run on some of the largest machines hosted by government laboratories. In the United States, these machines are often found at national laboratories run by the Department of Energy. Their primary use is to enable finite element simulations of nuclear weapons: similar to the first electronic computers. These machines use on the order of 1,000–5,000 kW.[10] A watt is a rate of energy use: a Joule per second.

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[9] An updated list is maintained as the "Top 500" list: http://www.top500.org.

[10] Data from the Top 500 list, November 2014.

A bright incandescent light is 60–100 W. Note that 1 kW = 1000 W (so we're talking about 1–5 million watts). For comparison, a large household with many appliances might barely approach 1 kW at peak consumption. Thus, the power requirement of the largest machines is the scale of a town of maybe 2000–10,000 people (assuming about two people per house). The machines themselves live in special buildings, with separate heating and cooling (mostly cooling) facilities.

For very large machines and high-resolution simulations, data storage of the output also becomes a problem, requiring large amounts of space to store basic information. Currently processing power is often cheaper than storage: It is easier to run a model than it is to store all the output. This means sometimes models are run with limited output. If more output is needed, they are run again.

So who runs climate models? Usually the group of scientists who develop a model also run the model to generate results. The groups of scientists who develop coupled climate models have grown with the different components. These groups are usually part of larger research institutes, universities, or offshoots of weather forecast agencies. The work is mostly publicly funded. These research groups are usually called modeling centers. Often, standard simulations are performed (see Chap. 11). The output data are then made publicly available. So use of model output is not restricted to those who can run the models.

4.6 Summary

Based on the fundamental principles that work every day in the world around us, a climate model seeks to represent each part of the system (e.g., atmosphere, ocean, ice, land) and each critical process in these parts of the system. Some examples include the conditions when water vapor condenses to form clouds, how much sunlight is absorbed by a given patch of land, or how water and carbon dioxide flow in and out of leaves. Each process can be measured. Each process can be constrained by fundamental physical laws. We describe many of these processes in the detailed discussion of models in Sect. 4.2 (Chaps. 5–7). The hope is that after each process is properly described and constrained, the emergent complexity of the earth system is in some way represented. With more computational power, more processes can be included. Finer grids (more boxes) can be simulated. But the broad answers should not change. As we will see in Sect. 4.3 of this book, the "hypothesis" of climate models' validity is being tested repeatedly and in many different ways.

The uncertainty that remains is considerable and is discussed in Sect. 4.3. We have discussed fundamental constraints (fundamental transformations and physical laws) on the climate system. But these constraints do have uncertainty in the complex climate system. The emergent complexity means that there are many possible states of the climate system. Just like weather can have many states in a distribution, climate is simply the average (the distribution) of those states realized in a particular finite time. The different states may evolve in response to different forcing and to uncertainties in how processes are represented in the system. We return to these uncertainties later, but now it is time for a slightly more detailed discussion of how we simulate the different major components of the climate system. Time to follow the White Rabbit a bit farther down the rabbit hole before it gets too late.[11]

Key Points

- Climate models are based on known physical laws.
- Basic processes describe the source and loss terms in equations, subject to basic laws of conservation.
- Uncertainty lies in how processes are represented (parameterized) and coupled.
- Simple to complex models exist.
- Climate models have and continue to push the limits of computers.

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[11] See Carroll, L. (1865). *Alice's Adventures in Wonderland*. New York: Macmillan.