Chapter 18
Types of Models

Abstract Climate models range in complexity from very simple to very complex. General Circulation Models are the most complex and most require time on a supercomputer in order to utilize all the required data. Box models, Energy Balance models, Radiative-Convective models, and General Circulation models are all used to allow scientists to vary input and ask "what if" questions about the climate system. Validation of models is necessary in order to have confidence in modeling and for individual models. History matching (or hindcasting) is an integral part of the modeling process. The validation process allows scientists to have greater confidence in model results.

Keywords Hindcasting • Box • Model • Circulation • History • Matching • Grid • Projection • Prediction • Attribution • Validation • Parameterizing • GCMs • EBMs • RCMs • Confidence • Circulation • Trends • CCSM • GCSM • Boundaries

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_18,

Things to Know	
Box models	General circulation models
CCSM	History matching
GCSM	Physical climate models
Chemical climate models	Model grid
Model validation	Boundary conditions
Hindcasting	GEWEX
Energy balance models (EBMs)	UCAR
Radiative-Convective Models (RCMs)	EPRI
Parameterizing	Statistical-dynamical models (SDMs)
CERFACS	General circulation models (GCMs)
Model confidence and validation	

18.1 Introduction

There are various types of climate models. Some focus on certain things that affect climate such as the atmosphere or the oceans. Models that look at only a few variables of the climate system may be simple enough to run on a personal computer but more complex models are run on supercomputers.

All models are simplified versions of more complex systems. Climate models range in complexity from a simple box model to a complex general circulation model. Models must be designed to gain a better understanding of the climate system that is being modeled. Models provide climate change scientists with a quantitative means to obtain projections of what may happen to the climate system in the future.

18.2 Climate Models

Computer models of the coupled atmosphere-solar-land surface-ocean-sea ice system are essential scientific tools for understanding and projecting natural and human-caused changes in Earth's climate. Climate models can be used to map out trends in the climate system. They are not used to reveal specific events, such as a hurricane or a series of floods. Trends are important because they eliminate or smooth out single events that may be extreme.

Climate models allow climate change scientists to ask "what if" questions. They can vary the input and change the outcome to produce results which give an indication of what will happen to the climate if, for example, carbon dioxide is doubled or tripled or even reduced in the future. Climate models may also be used to vary the timeframes of climate change; changes that may take place over months, thousands, or millions of years.

Models are necessary for testing many technological advances before designing and building the real things. Climate modeling gives climate change scientists a means of projecting climate changes into the future. Projecting climate change is not the same as predicting climate change for one cannot predict the future. The most popular use of climate models in recent years has been to project temperature changes resulting from increases in atmospheric concentrations of greenhouse gases, especially carbon dioxide, but other greenhouse gases have been used as well.

A climate model must be compared to observational climate changes of the past (hindcasting or history matching) in order to use the model to project into the future.

18.2.1 Simplifying the Climate System

Before models can be constructed of the climate system, it is necessary to develop the equations that simulate the natural processes and to run tests of the models to determine whether they are correct or not. The development of climate models over the past 35 years is depicted by Fig. 18.1. The calibration of the model must be done using hindcasting or history matching. If the model matches the climate history of the past, it has a good chance of projecting climatic conditions into the future. This process involves several iterations of the model runs as well as numerous tweaks to the model.

The purpose of climate models is essentially to model the response of the climate to changes in the climate system by parameterizing the system and then changing certain parameters to measure the climate response. Parameterizing is simply breaking down the climate system into its individual parameters such as wind directions, ocean currents, etc.

Climate models are systems of differential equations derived from the basic laws of physics, fluid motion, and chemistry formulated to be solved on supercomputers. Some of the simpler climate models have been adapted to personal computers.

Models are constructed so that climate change scientists can vary the parameters to see the response the climate will have to changes in input, e.g., vary the incoming solar radiation at the surface of the Earth to be able to witness the climatic response. For example, climate change scientists need to know what effects the change in solar radiation will have on atmospheric and oceanic currents and where will these changes most likely occur. They often change the input of greenhouse gases to determine their effect on the Earth's temperature.

18.2.2 Boundary Conditions

Boundary conditions are set when the model is designed or redesigned or when the model is run. Boundary conditions may be the thickness of an atmospheric layer and its latitude and longitude. A boundary condition may be the input of carbon dioxide in parts per million or methane in parts per billion. Boundary conditions may be a period of time, decades, years, thousands and millions of years. In the

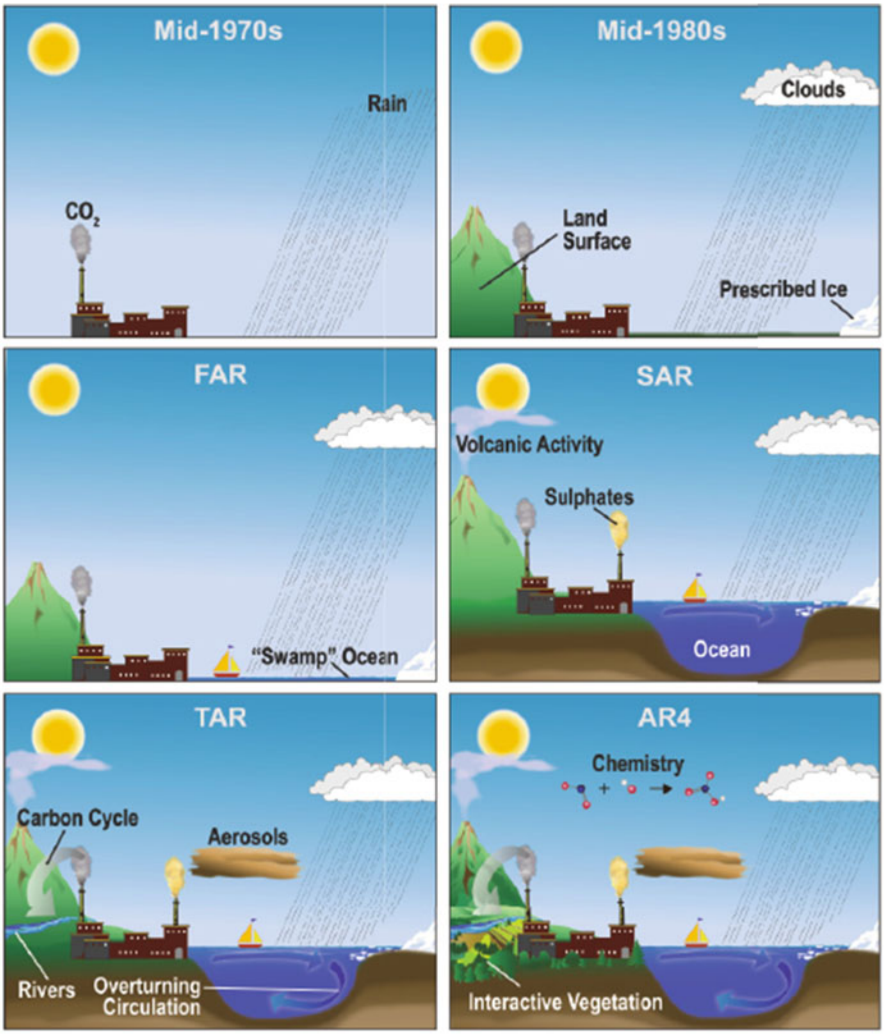

Fig. 18.1 Increasing complexity of climate models. (IPCC AR4 2007, Figure 1.2. The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modeled world). (FAR = First Assessment Report; SAR = Second Assessment Report; TAR = Third Assessment Report; AR4 = Assessment Report 4)

modeling of ancient climates (paleoclimatology), the distribution of land and sea become boundary conditions. The elevation of the land surface where ancient mountains may have been could also serve as a boundary condition.

Boundary conditions must be accurately stated and input for each model run and their details precisely documented.

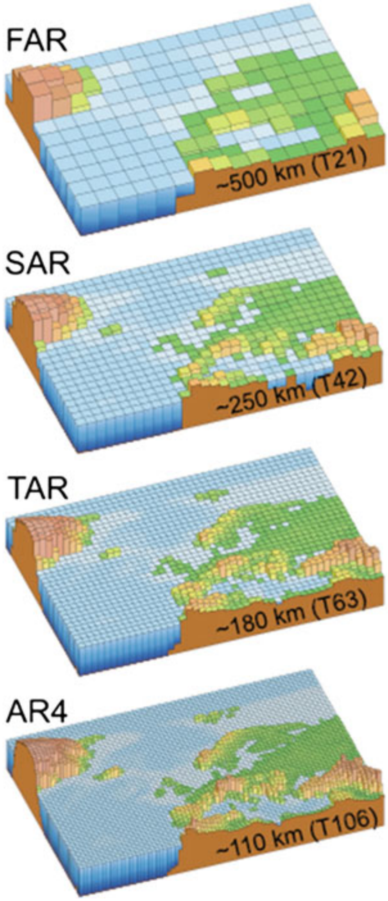

Fig. 18.2 Progression of degree of detail in climate models from the FAR to AR4. (IPCC AR4 2007, Figure 1.4. Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC 1990), SAR (IPCC 1996), TAR (IPCC 2001), and AR4 (2007). The figures above show how successive generations of these global models increasingly resolved northern Europe. These illustrations are representative of the most detailed horizontal resolution used for short-term climate simulations. The century-long simulations cited in IPCC Assessment Reports after the FAR were typically run with the previous generation's resolution. Vertical resolution in both atmosphere and ocean models is not shown, but it has increased comparably with the horizontal resolution, beginning typically with a single-layer slab ocean and ten atmospheric layers in the FAR and progressing to about 30 levels in both atmosphere and ocean)

Climate models take into account many factors of the atmosphere, biosphere, geosphere, hydrosphere, and cryosphere to model the entire Earth system. They take into account the interactions and feedbacks between these different parts of the planet. The evolution or progress in climate modeling is illustrated by Figs. 18.1 and 18.2 that show the increasing level of detail over the time of the four IPCC reporting periods.

18.2.3 Climate Modeling Centers

Climate modeling is an international endeavor and a massive undertaking at present to build and tweak climate models so they can be as accurate as is humanly possible. There are several centers of climate modeling expertise throughout the world. A few of these centers and their web addresses are listed below:

- Cambridge Center for Atmospheric Science (U.K.) http://www.atm.damtp.cam.ac.uk/
- CERFACS Global Change and Climate Modeling (France) http://www.cerfacs.fr/globc/
- DOE Computer Hardware, Advanced Mathematics and Model Physics Program (CHAMMP) (USA) http://www.esd.ornl.gov/programs/chammp/chammp.html
- National Oceanic and Atmospheric Administration (NOAA) (USA) http://www.nasa.gov
- Climate Research Group University of Illinois (USA) http://crga.atmos.uiuc.edu/
- Climate Research Unit, University of East Anglia (U.K.) http://www.cru.uea.ac.uk/
- Climatic Impacts Centre, Macquarie University (Australia) http://cic.mq.edu.au/
- Colorado State University Department of Atmospheric Sciences (USA) http://www.atmos.colostate.edu/
- Coupled Model Intercomparison Project (CMIP) (USA) http://www-pcmdi.llnl.gov/covey/cmip/cmiphome.html
- Pennsylvania State University Earth System Science Center (USA) http://www.essc.psu.edu/
- German Climate Science Computing Center (DKRZ) (Germany) http://www.dkrz.de/index-eng.html
- Geophysical Fluid Dynamics Laboratory (GFDL) (USA) http://www.gfdl.gov/
- NASA Goddard Institute for Space Studies (GISS) (USA) http://www.giss.nasa.gov/
- Hadley Center for Climate Prediction and Research (U.K.) http://www.meto.govt.uk/sec5/sec5pg1.html
- Laboratoire de Meteorologie Dynamique du CNRS (France) http://www.lmd.ens.fr/english/
- Los Alamos Advanced Computing Laboratory Global Climate Modeling (USA) http://www.acl.lanl.gov/GrandChal/GCM/gcm.html
- Electric Power Research Institute (EPRI) Model Evaluation Consortium for Climate Assessment (MECCA) (USA) http://www.epri.com/Strategic/Environment/MECCA/MECCA.html
- MIT Climate Modeling Initiative (USA) http://geoid.mit.edu/climatemodel/climatemodel.htm
- NASA/GSFC Coupled Climate Dynamics Group (CCDG) (USA) http://pong.gsfc.nasa.gov

- NASA Langley Atmospheric Modeling Group (USA) http://rossby.larc.nasa.gov/
- NCAR Climate and Global Dynamics Division (CGD) (USA) http://www.cgd.ucar.edu/
- NCAR Climate Systems Model (CSM) (USA) http://www.cgd.ucar.edu/csm/index.html
- UCAR GENESIS Earth Systems Modeling Project (USA) http://www.cgd.ucar.edu/ccr/genesis.html
- UCAR Community Climate Model (USA) http://www.cgd.ucar.edu/cms/ccm.html
- Lawrence Livermore National Laboratory Program for Climate Model Diagnosis and Intercomparison (PCMDI) (USA) http://www-pcmdi.llnl.gov/
- University of Wisconsin-Madison Space Science and Engineering Center (SSEC) (USA) http://www.ssec.wisc.edu/
- NCAR Community Climate System Model (CCSM) http://www.cesm.ucar.edu/models/ccsm3.0/

Climate models allow us to test particular hypotheses about climate change. For example, we can use the models to tell us how much warming of the Earth we might expect for a given change in greenhouse gas concentrations; or what effect the slowing of a major ocean current would have on the Earth's temperature. The efficacy of using models is that we can vary the input and look at the effects on various environmental and global warming parameters.

Earth is a complex planet and because of this many of the models are very complex. Many of these more complex models include enough mathematical calculations that they must be run on supercomputers, which can do the calculations quickly. All climate models must make some assumptions about how the Earth works, but in general, the more complex a model, the more factors it takes into account, and the fewer assumptions it makes.

At the National Center for Atmospheric Research (NCAR), researchers work with complex models of the Earth's climate system. Their Community Climate System Model (CCSM) is so complex that it requires about three trillion mathematical calculations to simulate a single day on planet Earth. It can take thousands of hours for the supercomputer to run the model. The model output, typically many gigabytes in size, is analyzed by researchers and compared with other model results and with observations and measurement data.

There are currently several other complex global climate models that are used to project the current climate into climatic changes and they require supercomputers to run. Figure 18.3 below shows the development of complex climate models over the period from the mid-1970s to the early 2000s.

State-of-the-art climate models now include interactive representations of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry. Figure 18.4 shows the features that serve as input to the Community Climate System Model (CCSM) Version 3 computer model designed by UCAR.

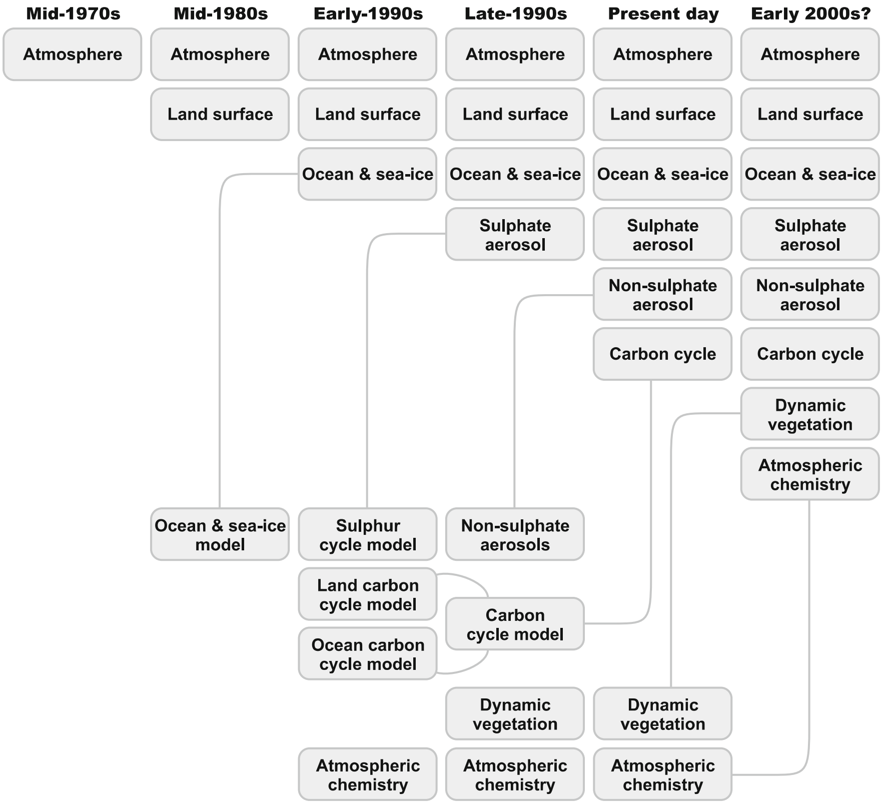

Fig. 18.3 Development of complex climate models. The figure illustrates the development of comprehensive climate models over the 25 years before the IPCC 2001 report showing how different components are first developed separately and later coupled together (Credit: Intergovernmental panel on Climate Change, Third Assessment Report, Technical Summary of Working Group I Report 2001)

For each grid point in a general circulation model, calculations are done for the atmosphere as follows:

- Motion of the air (winds);
- Heat transfer (thermodynamics);
- Radiation (solar and terrestrial);
- Moisture content (relative humidity); and
- Surface hydrology (precipitation, evaporation, snow melt and runoff).

These physical factors are calculated as are the interactions of processes among neighboring grid points. The computations are stepped forward in time from seasons to centuries depending on the timeframes of the studies.

Figure 18.5 illustrates the type of grid system utilized in the more complex GCMs.

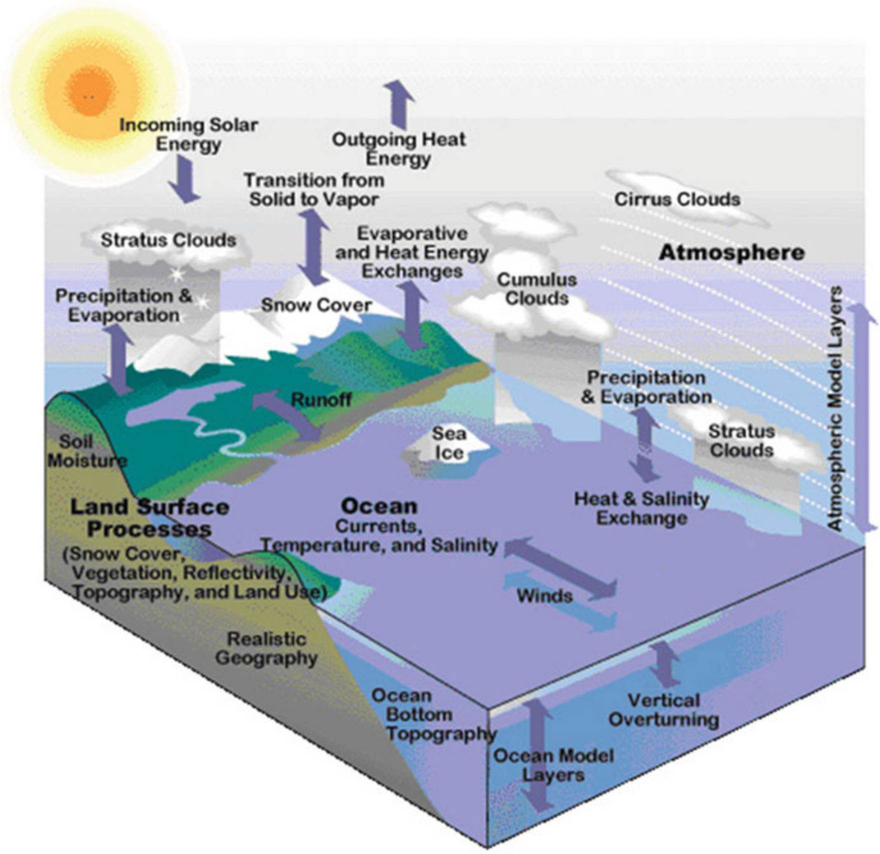

Fig. 18.4 Features represented by input to climate models. The Community Climate System Model (CCSM version 3) that is run with the supercomputer at the National Center for Atmospheric Research (NCAR) incorporates data about all of the natural processes shown in this diagram to simulate Earth's complex climate system (From UCAR)

State-of-the-art climate models now include interactive representations of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry and motion.

The accuracy of climate models is limited by grid resolution and our ability to describe the complicated atmospheric, oceanic, and chemical processes mathematically. Despite imperfections, models simulate current climate and its variability remarkably well. More capable supercomputers enable significant model improvements by allowing for more accurate representation of the physics and chemistry of the climate system.

Component-level evaluation of climate models is common. Numerical methods are tested in standardized tests, organized through activities such as the quasi-biennial Workshops on Partial Differential Equations on the Sphere. Physical

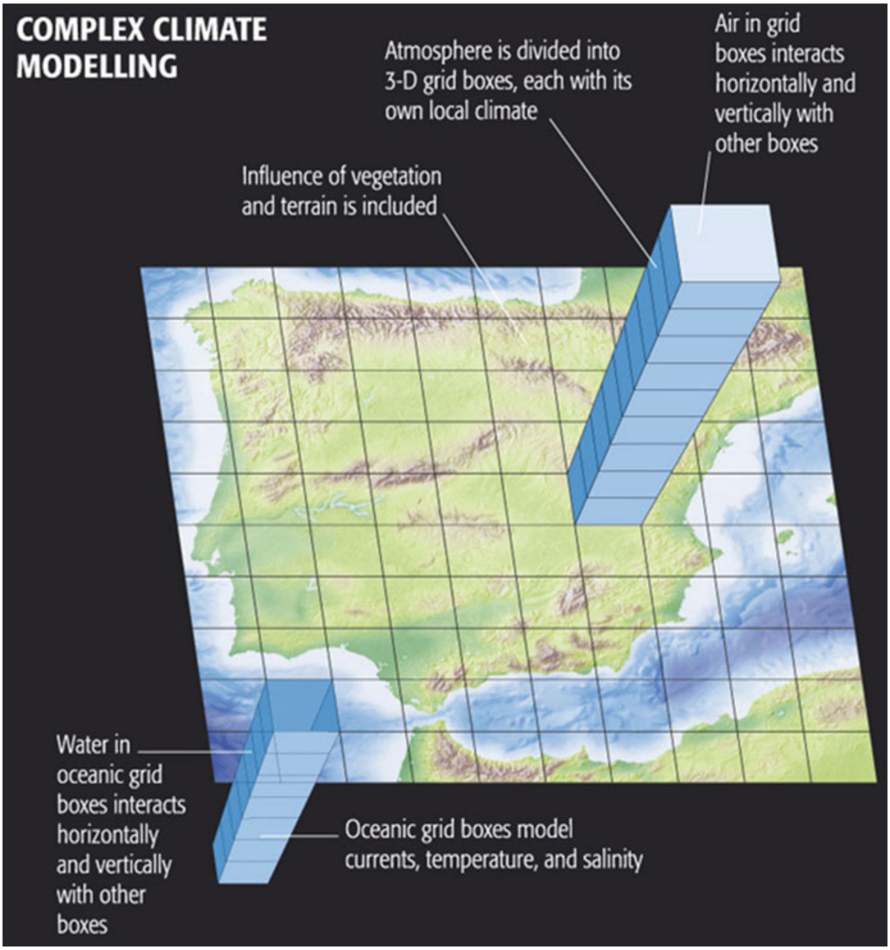

Fig. 18.5 A climate model showing the horizontal and vertical grids and the physical processes in a global circulation model (GCM) (From Mann and Kump, *Dire Predictions,* supported by the National Science Foundation, Public Domain)

parameterizations used in climate models are being tested through numerous case studies, some based on observations and some idealized, organized through programs such as the Atmospheric Radiation Measurement (ARM) program, EUROpean Cloud Systems (EUROCS), and the Global Energy and Water cycle Experiment (GEWEX) Cloud System Study (GCSS). These activities have resulted in a large body of published results.

System-level evaluation focuses on the outputs of the full model, i.e., model simulations of particular observed climate variables.

18.3 Types of Climate Models

There are two main types of models used by climate change scientists; physical climate models and chemical climate models, and there are several variations of each. Physical models simulate the parameters of atmospheric physics. Chemical models simulate changes in composition of atmospheric constituents. Both kinds of models can be combined to simulate how the climate will respond to changes in the physics or chemistry of the climate system.

Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To run or use a model, scientists divide the planet into a 3-dimensional grid (as in Fig. 18.5), apply the basic mathematical equations, and evaluate the results. Supercomputers can do more than 80 million math calculations in less than an hour. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid point and evaluate interactions with neighboring points on the grid. The grid may have thousands of points.

18.3.1 Box Models

Box models are simplified versions of complex systems. Within a box in a climate system model, concentrations of atmospheric constituents of the climate system are assumed to be homogeneous but can be changed with time. More complex box models use numerical techniques to solve concentration problems. Box models can be written to treat flows across and within ocean basins. Other types of modeling can be interlinked with box models, such as land use, allowing researchers to predict the interaction between climate and ecosystems. Box models may consist of more than one box and they may all be linked. Box models are used extensively to model environmental systems or ecosystems and in studies of ocean circulation and the carbon cycle. Simple box models are often used to derive analytical formulas. More complex box models are usually solved using numerical techniques.

18.3.2 Energy Balance Models

Energy balance models (EBMs) estimate the changes in the climate system from an analysis of the energy budget of the Earth. An Energy Balance Model does not attempt to resolve the dynamics of the climate system, i.e., large-scale wind and atmospheric circulation systems, ocean currents, convective motions in the atmosphere and ocean, or any number of other basic features of the climate system. Instead, it focuses on the energy and thermodynamics of the climate system. Energy

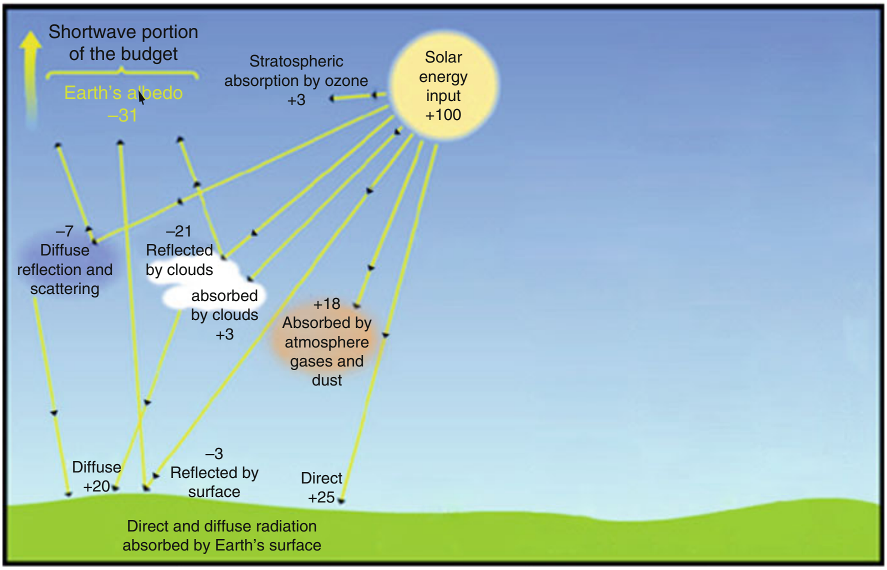

Fig. 18.6 Energy balance of Earth's climate system using a packet of 100 units of solar energy as input to the climate system. This input is shortwave or ultraviolet radiation (From https://www.e-education.psu.edu/meteo469/?q=node/202), (Used with permission)

balance models have proven useful in understanding mechanisms and feedbacks in the climate system. In their simplest form, they do not include any explicit spatial dimension, providing only globally averaged values for the computed variables.

In the illustrations (Figs. 18.6 and 18.7), 100 units of solar energy enter Earth's atmosphere as shortwave ultraviolet (UV) radiation. We will track these and see what happens to the 100 units throughout the climate system. Of these 100 units, 21 are reflected by clouds, 7 are diffused by scattering, and 3 are reflected by Earth's surface totaling 31 parts reflected or diffused. This number is the same as Earth's average albedo at ~31%. This leaves 69 of the packet of 100 still in the Earth system; 25% is directly absorbed by the Earth's surface, 3% is absorbed by clouds, 3% is absorbed by stratospheric ozone, 20% is diffused by the Earth's surface, and 18% is absorbed by greenhouse gases and aerosols in the atmosphere.

As the Earth's surface warms by shortwave ultraviolet radiation, it radiates heat in the form of longwave or infrared radiation (IR). The surface heat generates 45%, the atmosphere generates 21%, and 3% is generated by the ozone layer to space. This is the 69% that was left within the Earth system after 31% of the original 100% of solar input was reflected as albedo. Of the 69, 19% is given off by the surface as evapotranspiration, 4% is given up from the surface by convection, 14% is re-radiated by greenhouse gases, 8% is direct heat lost to space, 21% is atmospheric heat, 3% is heat from the ozone layer, equaling 69% that was in the climate system after the 31% of UV portion of the energy budget lost to space.

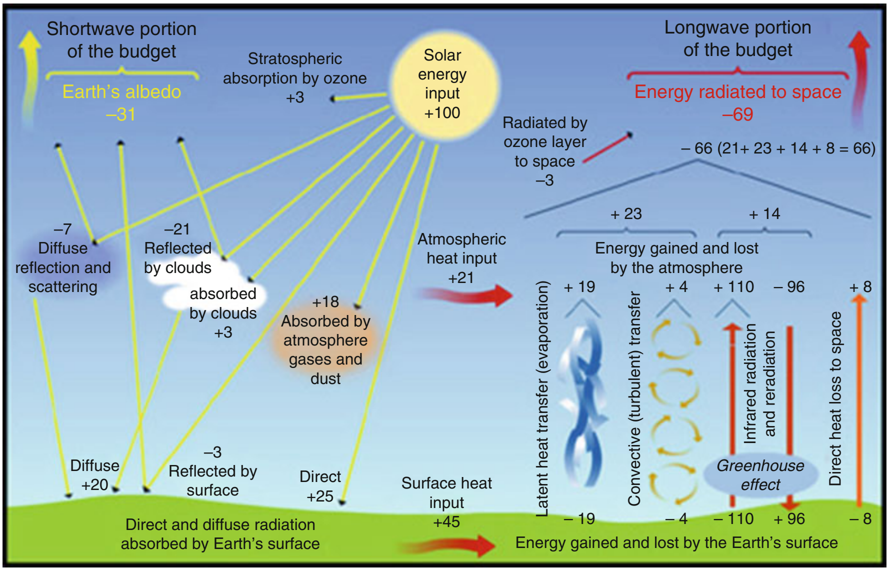

Fig. 18.7 Distribution of the 100 packet of ultraviolet solar radiation within the Earth's climate system and the longwave or infrared radiation of Earth's energy budget (From https://www.e-education.psu.edu/meteo469/?q=node/202) (Used with permission)

Energy balance models describe the climate system in terms of thermodynamics (e.g., heat, temperature). They have been used to show how energy enters and leaves the Earth's climate system and achieves equilibrium. By modeling the energy flow one can compute the effective temperature of Earth as well as the temperature at the surface.

Energy balance models simulate the global radiation balance between incoming solar radiation and outgoing terrestrial radiation. They also are used to simulate the latitudinal energy transfer within the Earth system. EBMs may be 0-dimensional or 1-dimensional. The zero dimensional EBM simply models the balance between incoming and outgoing radiation at Earth's surface. This balance is in reality quite complicated, and we have to make a number of simplifying assumptions if we are to obtain a simple conceptual model that encapsulates the key features. In zero dimensional models, Earth is considered a single point in space and only the global radiation balance is simulated. In 1-dimensional EBMs latitudinal differences, usually temperatures are modeled.

In 1-D models, temperature for each latitudinal band is calculated using a global average temperature compared to a latitudinal temperature. EBMs may also simulate energy transfers between the ocean and atmosphere.

Most energy balance models are not global models, but zonal or latitudinal models. As such, we must have an equation or part of an equation that accounts for the transfer of energy from one latitudinal zone to the next.

18.3.3 Radiative-Convective Models

Radiative-Convective models (RCMs) may be 1- or 2-dimensional. Height is the dimension added in both. RCMs simulate the transfer of energy through the atmosphere, the role of convection, energy transfer, and radiative differences that occur as energy moves vertically through the atmosphere (1-dimensional) and horizontally (2-dimensional). Radiative-convective models have advantages over the simple model; they can determine the effects of varying greenhouse gas concentrations on effective emissivity and therefore the surface temperature. But added parameters are needed to determine local emissivity and albedo and address the factors that move energy within Earth's climate system.

RCMs must contain information about radiation fluxes throughout the atmosphere including fluxes of land and solar radiation. They measure parameters such as surface albedo, clouds, and atmospheric turbidity and the effects in the different layers of the atmosphere. Heating rates of atmospheric layers are calculated based on the imbalance between the top and bottom of each layer. Vertical profiles, lapse rates, are calculated as is convection within the atmosphere.

RCMs are most important in measuring changes in forcing that have their origins in the Earth-atmosphere exchanges such as volcanic eruptions.

18.3.4 Statistical-Dynamical Models

Statistical-dynamical models (SDMs) are mainly 2-dimensional (2-D) models with one horizontal and one vertical dimension. Standard SDMs combine horizontal energy transfer with the radiative-convective transfer of RCMs. Wind speed and direction are modeled based on statistical relationships. Laws of motion are used to calculate the diffusion of energy through the climate system.

Statistical-Dynamical models are used mainly in investigations of horizontal energy transfer and the processes that affect that transfer. These are generally 2-D, with one horizontal and one vertical dimension, although there are some models with two horizontal dimensions.

They combine the horizontal energy transfer of EBMs with the radiative-convective functions of RCMs. However, the equator-pole transfer is more accurately simulated than in EBMs, based on theoretical and empirical relationships of the cellular flow between latitudes.

These models are useful for simulating and studying horizontal energy flows, and processes that disrupt them.

18.3.5 General Circulation Models

The first general circulation climate model that combined both oceanic and atmospheric processes was developed in the late 1960s at the NOAA Geophysical Fluid

Dynamics Laboratory. By the early 1980s, the United States' National Center for Atmospheric Research (NCAR) had developed the Community Atmosphere Model; this model has been continuously refined into the 2000s. Coupled ocean–atmosphere climate models such as the Hadley Centre for Climate Prediction and Research's HadCM4 model are currently being used as inputs for climate change studies.

General Circulation models (GCMs) are the most complex models used in climate change science. They are 3-dimensional and are based on the laws of physics. They include each of the following:

- Conservation of energy;
- Conservation of momentum;
- Conservation of mass; and
- The Ideal Gas Law.

GCMs are used to calculate global factors, not regional ones, and they use tremendous amounts of computer time. They must calculate each parameter for each node point over the entire globe and this requires use of a supercomputer.

GCMs must be tested at the systems level by running the entire model and comparing the results with observations. Models are also tested at the components level, i.e., by isolating components and testing them independently.

Models used by the IPCC are tested by climate scientists and programmers worldwide prior to being used by the IPCC. Bugs are worked out and errors are corrected and various groups throughout the world are conducting climate model intercomparisons. This work has been going on since the 1980s. There are now several dozen intercomparison groups covering all climate model components and coupled model configurations (Fig. 18.8).

18.4 Confidence and Validation

Confidence in a climate model can be gained through simulations of the historical record (history matching or hindcasting), but such opportunities are much more limited than are those available through weather prediction. These and other approaches are discussed below.

Validation of climate models involves a comparison of the model output with observations of changes in the atmosphere. There are some climate scientists that believe that models are validated by the climate scientists and programmers who build and run the models and that there is no need for independent validation. However, with the public perception of climate models being what it is, it is certainly suggested at this time in climate change science to go through an independent validation process and the modeling groups do just that. Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) serves as a validation source for international groups and a clearinghouse for models used to model current and project future climate change.

Confidence in climate models increases with independent validation, history matching, and comparing model results with observations.

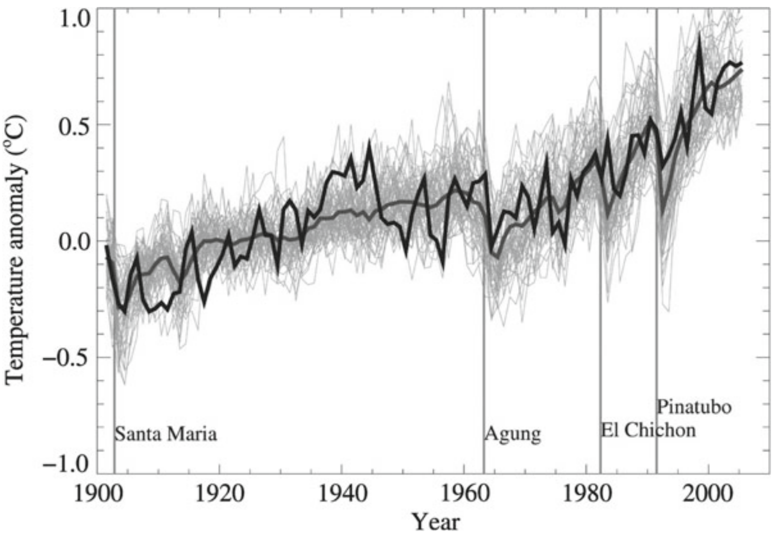

Fig. 18.8 Global mean near-surface temperatures over the twentieth century from observations (*black*) and as obtained from 58 simulations produced by 14 different climate models driven by both natural and human-caused factors that influence climate (*light grey thin lines*). The mean of all these runs is also shown (*thick grey line*). Temperature anomalies are shown relative to the 1901–1950 mean. *Vertical grey lines* indicate the timing of major volcanic eruptions. (IPCC AR4 2007; redrawn by John Cook)

Additional Readings

Archer, D. (2011). *Global warming: Understanding the forecast* (2nd ed.). Hoboken: Wiley. ISBN-10: 0470943416; ISBN-13: 978-0470943410.

Archer, D., & Pierrehumbert, R. T. (Eds.). (2011). *The warming papers: The scientific foundation for the climate change forecast*. Hoboken: Wiley-Blackwell.

Bolin, B. (2007). *A history of the science and politics of climate change. The role of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Houghton, J. (2009). *Global warming: The complete briefing* (4th ed.). Cambridge: Cambridge University Press.

IPCC, in IPCC TAR SYR. (2001). In Watson, R. T., The Core Writing Team (Eds.), Climate change 2001: Synthesis report. *Contribution of working groups I, II, and III to the third assessment report of the intergovernmental panel on climate change*. Cambridge University Press, ISBN 0-521-80770-0 (pb: 0-521-01507-3).

Jin, M., & Liang, S. (2006). An improved land surface emissivity parameter for land surface models using global remote sensing observations. *Journal of Climate, 19*(12), 2867–2881. doi:10.1175/JCLI3720.1.

Meehl, G. A., et al. Climate change 2007 Chapter 10: Global climate projections, in IPCC AR4 WG1 (2007). Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., et al. (Eds.). Climate change 2007: The physical science basis. *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7).

Pierrehumbert, R. T. (2011). *Principles of planetary climate*. Cambridge: Cambridge University Press.

Soden, B. J., & Held, I. M. (2006). An assessment of climate feedbacks in coupled ocean–atmosphere models. *Journal of Climate, 19*, 3354–3360. doi:10.1175/JCLI3799.1.

Sokolov, A. P., et al. (2009). Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate, 22*(19), 5175–5204. doi:10.1175/2009JCLI2863.1.

Wang, W. C., & Stone, P. H. (1980). Effect of ice-albedo feedback on global sensitivity in a one-dimensional radiative-convective climate model. *Journal of the Atmospheric Sciences, 37*(3), 545–552. doi:10.1175/1520-0469(1980)037<0545:EOIAFO>2.0.CO;2. Bibcode 1980JAtS…37..545W.