Chapter 8
Bringing the System Together: Coupling and Complexity

Chapters 5–7 focused extensively on what parts of the earth system are being modeled. This chapter brings together the different components of the climate system and discusses how the component models we have described are coupled together to represent the earth system. This chapter is more about the mechanics of models, and how we couple the pieces together. Different components (atmosphere, ocean, ice, terrestrial systems) each have their own complexities, and their own challenges for modeling. Different types of coupled models can be constructed, representing regions, the whole planet, or even focusing on human systems.

Some specific features in the climate system are really the product not just of one component, but of the interaction of different components. One example might be the variability in tropical ocean surface temperatures in the Pacific, called El Niño. Every few years the eastern Pacific water warms up, in an oscillation that has large impacts on global weather patterns. Treating these patterns or modes of variability properly is necessary to properly represent climate.

There are different ways of running different models (e.g., regional or global, full ocean or mixed-layer ocean only). Some important aspects of the coupled system are obvious. For example, the amount and distribution of precipitation from the atmosphere strongly impacts the terrestrial surface. Other aspects of coupling are more complex. A number of them have been described, and we focus here on a few more interactions and challenges, especially those interactions that result in strong feedbacks to the climate system by ultimately affecting the energy in the climate system. We also examine some features of the system, such as the global sea level, that are set by interactions of the ocean, ice, and atmosphere.

8.1 Types of Coupled Models

The traditional models we have described are general circulation models (GCMs), which are dynamical system models of the atmosphere, ocean, and other pieces of the system (e.g., sea ice, terrestrial systems). These are global and three-dimensional models that are designed to represent key earth system processes. But these are not the only kind of climate model.

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Earth Systems Data and Models 2, DOI 10.1007/978-3-662-48959-8_8

Increasingly, climate models are being extended to incorporate other types of models that are of direct relevance to society, such as ocean-wave models, hydrologic models, ecosystem models, and policy-relevant models. The complexity represented by these models is daunting. Some researchers develop local models of high complexity and limited temporal and spatial application. Coupling with these models is sometimes "one-way" in the sense that the global climate model provides information to, but does not receive information from, the detailed process model. Sometimes the coupling is "two-way" so the effect of the detailed model changes (or feeds back on) the global model. These detailed models can be classified as *impacts models*.[1]

An example of an impact model related to a physical process is a global ocean-wave model, which would be expected to have a "two-way" coupling. That is, the climate model surface winds will determine the wave field and the wave field will affect surface characteristics, for example, water and salt exchanges, as well as surface drag. The output of the wave model will influence the climate model. There are also models of economic and technological relationships and responses to climate and climate change, which is a type of integrated assessment model. Below, we focus on a small number of coupled models that have sufficient maturity that they have broad exposure to practitioners interested in applying model projections.

8.1.1 Regional Models

Regional climate models[2] are also three-dimensional dynamical systems models, but with smaller domains. As a result. they often contain often more detailed processes. They are run with boundary conditions from observations or from GCMs (other models) when no observations are available (i.e., in the future). Regional climate models are often used to generate high-resolution and high-frequency weather statistics to understand how broad-scale climate change alters weather patterns. Examples of regions might be Western Europe, the Arctic, or the continental United States. The atmosphere models used are often models that are used for weather prediction, that resolve the scales of weather systems from 3 to 125 miles (5–200 km). These are often called *mesoscale* models (*meso* = medium). These are an effective way to "downscale" the large-scale general circulation (and potential changes) to generate better weather statistics by driving dynamical models at high resolution with the output from a global model (see box in next section).

Why is higher resolution (smaller grid boxes) better? One strong driver for local weather and climate is the physical environment, especially topography (landforms and changes in elevation) that affects both the atmosphere and the ocean. At lower

[1]For more information on such models, see the International Environmental Modeling and Software Society, http://www.iemss.org/society/index.php/scope.

[2]Rummukainen, M. (2010). "State-of-the-Art With Regional Climate Models." *Wiley Interdisciplinary Reviews: Climate Change, 1*(1): 82–96.

resolution, the topography is just not represented correctly because a large grid box at low resolution can have only one elevation: the average of perhaps many mountains or valleys. It is thus hard to represent the climate of California, Chile, Colorado, or Switzerland, without resolving mountains. One way to think about resolution generally is that in regions where there is a lot of variability in any quantity, like elevation (though it could be surface albedo or even atmospheric water vapor), increasing the resolution allows more of the variability to be represented explicitly, and to force the climate directly. From the practitioner's perspective, higher resolution represents features at a geographic scale that is more intuitively relevant, such as more realistic and detailed coastlines and the built environment of cities.

8.1.2 Statistical Models and Downscaling

GCMs and regional climate models are dynamical models. They use the equations of motion and thermodynamics to determine the rates of change of physical quantities (e.g., water vapor, temperature or heat, cloud water, carbon). There are also statistical models of climate. **Statistical models of climate** take observations from the past and try to predict the future with various forms of regression or correlation analysis: fitting past data on temperature and precipitation for example, to a function that is used as a predictor of the future. Usually this is done for **downscaling**, fitting temperature at one point to a larger scale temperature or flow pattern that can be predicted by a dynamical model.

Regional Climate Modeling: Downscaling
Use of a regional model at high resolution is an example of at type of analysis called **downscaling**.[3] Downscaling uses finer-resolution information to improve the results of a coarse-scale model. It is effective especially when the improvement in resolution affects the simulation because of small-scale features at the surface: as is the case in regions of varied topography (mountains or coastlines). Use of a regional or local area model is known as **dynamical downscaling**. Downscaling can also be **statistical downscaling**. For example, if you want to know the temperature high on a mountain, you could develop a statistical relationship between the temperature for the whole region and this particular point based on observations over the past 50 years, and then adjust climate model output for the region in the same way to get a simulated record at that station that takes into account the unique local features (high altitude). Both methods of downscaling would be particularly useful for representing climate in regions of variable topography: either at high altitude,

[3]Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J., & Wilks, D. S. (1998). "Statistical Downscaling of General Circulation Model Output: A Comparison of Methods." *Water Resources Research, 34*(11): 2995–3008.

or in mountain valleys and around mountain ranges. Downscaling works best when we have a good physical understanding of the variations, like temperature, than for things like precipitation that are dependent on small-scale atmospheric processes. In mountainous regions, precipitation is also strongly dependent on the flow of air over mountains and its direction.

Downscaling with statistics works only if (a) the statistics are well described, (b) the relationships do not change, and (c) the data do not need to be extrapolated. Statistical models can work for weather events, largely because we have a lot of statistics on daily weather at a particular place, and small-scale details are dependent on large-scale patterns. Note that weather forecasts are *not* done with statistical models: Weather prediction models have more skill than statistical models. But if you want to understand what the climate of a particular place is when all you have is the large-scale flow (from a dynamical GCM), then basing the results on the past may be accurate.

Let's say we have 60 years of daily weather data. Then for any day in a particular month, there are 1800 samples of days (30 days × 60 years) from which to build a statistical model at one place for temperature, or precipitation, or stream flow. The assumption of statistical downscaling is that these samples represent all possible states. The problem in doing this for the future is that if the climate is changing, then by definition the probabilities and statistics are changing. Recall Fig. 1.1, showing the shifting probability distribution function (PDF) of climate. The distribution that defines climate is changing, so the statistics change, and there are extremes that are not in the past statistics (so extrapolation would be necessary).

There exist inherent dangers in statistical downscaling, but the results may be better than just using large-scale dynamical models that miss important local effects. This is true, for example, for places where the climate is affected by topography that is not well resolved by global models with a resolution of 16–65 miles (25–100 km). Practically, the resolved resolution is at least four times the grid resolution, so this means features smaller than about 65–200 miles (100–400 km).[4] Examples would include islands that might not be resolved by large-scale models, and peaks and valleys in mountain ranges that have steep gradients. A very good example of the combination of both would be the local climate on the island of Hawaii: It is dependent strongly on your location on the island, the elevation, and the direction of the prevailing large-scale wind. Here a statistical model of climate may be helpful: If you know the large-scale wind at a given location, you can probably represent the temperature halfway up a mountain pretty well. But in general, even here, dynamical downscaling using regional climate models may be preferred.

[4]Kent, J., Jablonowski, C., Whitehead, J. P., & Rood, R. B. (2014). "Determining the Effective Resolution of Advection Schemes. Part II: Numerical Testing." *Journal of Computational Physics, 278*: 497–508.

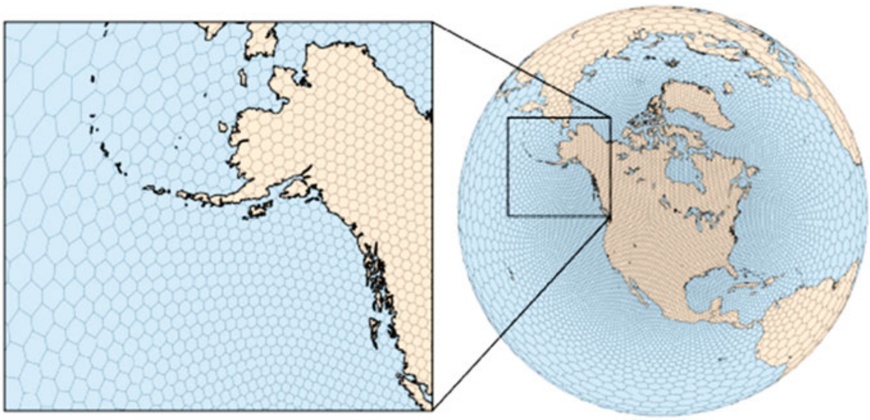

Fig. 8.1 An example of a variable resolution grid from the model for prediction across scales (*MPAS*). The grid gets finer over the continental United States using a grid made up of hexagons. *Source* http://earthsystemcog.org/projects/dcmip-2012/mpas

An active area of work right now is using increased computer power to run GCMs at the resolution of regional models, to have global models capable of producing regional climate statistics. The goal is to focus on representing extremes of weather events (the tails of the PDF). Regional models have typically been run with grid sizes of 3–17 miles (5–25 km). Global model grids have been 30–140 miles (50–200 km). Global models in the range of 5–25 km are now running experimentally, and some are even capable of running with variable resolution grids, where the resolution is finer in one region of the planet than in other regions. An example is shown in Fig. 8.1 (also shown in Chap. 4, Fig. 4.2), where a complex hexagonal grid has fine resolution over North America (10–20 km) and coarse resolution (100–200 km) elsewhere. The resolution inside of the fine mesh is comparable to a regional model. The total number of grid points for which the equations of state must be solved is not much more than a regional model, because the outer grid is sparse. There are difficulties in dealing with the different resolutions for representing both the motion of air and the representation of clouds at different resolutions.

8.1.3 Integrated Assessment Models

Models relevant to society and decision making represent another class of models that might be coupled with climate models. This class of models might be focused on local adaptation or global mitigation. Of specific note, here, are integrated assessment models (IAMs).[5] As noted in Chap. 7, these models are focused on the anthroposphere, the human part of the terrestrial and climate systems. These models have a societal component that resembles a macroeconomic model (see Sect. 8.6 for an application of such models). Macroeconomic models are dynamical systems models in which the grid points are locations like countries, or groups of countries, with a single economic system. There are still linkages between the grid points (trade flows). Then this economic model is coupled in some way to a simplified representation of the physical system. The land surface component (natural ecosystems) could have a grid corresponding to the economic model, and the ocean model might simply be a basin model. Sometimes the atmosphere is represented as a one-dimensional energy balance model at each grid point, sometimes the world is a simplified circulation model with low resolution, sometimes a series of statistical relationships.

Integrated assessment models can have an economic component coupled to a full climate model, but generally the climate system is substantially simplified. The goal of an IAM is to determine the broad-scale climate impact of the economic system, project that forward, and then allow the social system to adjust, perhaps changing itself in the process (e.g., new policies), then projecting the climate again. The result is a co-evolution of climate and society.

A number of efforts are being conducted to couple economic models to full climate models. One hybrid would be a climate model with an anthroposphere in the terrestrial system. These models are designed to generate self-fulfilling prophecies: Rules are set for policies that react and change as the climate changes. The policies adjust and then adjust the climate, and so on. The goal is to estimate economic policies, and the costs of the outcomes. The complexity of these models is that IAMs have very different time horizons than dynamical models. Typically, an economic model would be run for 100 years forward with a simple "projection." That projection would affect policies in the model, and then the physical and economic system would run 1 year forward. Then the IAM would run an adjusted scenario again for 100 years.

8.2 Coupling Models Together: Common Threads

For GCMs, there is quite a bit of complexity in coupling the different components we detailed in Chaps. 5–7. The creation of a coupled system model proceeds by improving each component (e.g., atmosphere, terrestrial surface, ocean), as well as trying to put the components together and make them work together. Improving each component means improving the representation (parameterization) of each process, as well as improving the coupled system as a whole. Ultimately, the processes that provide the rates of change for the state of the system then affect the

[5]"Integrated Assessment Modeling: 10 Things to Know," http://sedac.ciesin.columbia.edu/mva/iamcc.tg/mva-questions.html.

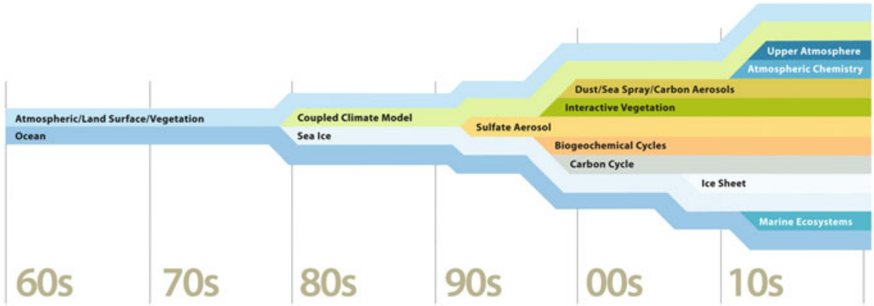

Fig. 8.2 Schematic of components. Evolution of the parts of the earth system treated in climate models over time. Figure courtesy of UCAR (same as Fig. 4.8)

whole system. For example, clouds affect the radiation absorbed and emitted as well as precipitation, and this then strongly affects the underlying land or ocean surface.

The coupling of different components is achieved in a coupling layer that is a bit like a clearing-house for financial trades. Changes to financial positions come in (e.g., stock trades). The changes are settled between the accounts of the buyer and the seller, their accounts updated, and the stock changes hands. In a similar way, each component model has changes in their state (e.g., precipitation from the atmosphere hitting the surface). Mass and energy budgets need to be conserved in the same way that stock certificates and money have to be accounted for. And, like a modern financial market, there are lots of traders (one for every grid box), trading different stocks (the different states of the system, like mass of water, or carbon or the energy in a region). And all this happens over and over again. There is a regulator that ensures all this runs smoothly. In a model, the regulator checks the mass and energy to ensure conservation. Fortunately, the physical equations in a climate model are usually not prone to the self-criticality ("crashes") of financial markets. That is because there are lots of negative feedbacks in the system that damp out the changes. For example, if the temperature rises because there is a lot of sunlight, then more energy is radiated to space. Or warmer temperatures might cause upward air motion, condensation, and the formation of clouds, shading the surface.

Coupling the components we have described began slowly, as illustrated in Fig. 8.2. Coupling, of course, occurs at the interfaces of the components, and this mostly means coupling at the surface of the earth. As circulation models of the atmosphere and ocean were developed, the atmosphere generally had a specified land surface. Initially, each model received specified surface exchanges of energy and heat based on observations. In the late 1960s,[6] about 10 years after the first models were developed, the atmosphere and ocean were coupled together, with the

[6]Manabe, S., & Bryan, K. (1969). "Climate Calculations With a Combined Ocean-Atmosphere Model." *Journal of the Atmospheric Sciences, 26*(4): 786–789.

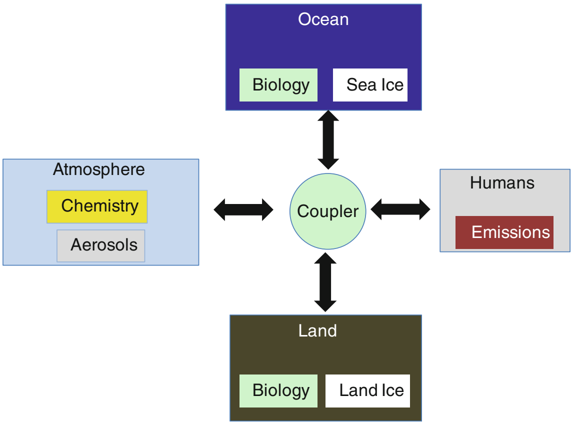

Fig. 8.3 Coupled climate model. Schematic of the component models and subcomponents of a climate model program. The coupler code ties together different spheres (ocean, atmosphere, land, biosphere, and anthroposphere) that then contain smaller parts (like aerosols, chemistry, or sea ice)

first real geographically resolved simulations in the mid-1970s.[7] The coupling was fairly crude, with the models not really run together. The ocean model was run to provide forcing for the atmosphere, and then the atmosphere model was run to provide forcing for the ocean, and so on. The ocean models were usually not models with a deep ocean circulation. Figure 8.2 illustrates the timing of this evolution. Sea-ice models were added to ocean components in the 1980s. In the 1990s, detail began to be added to the land surface, and the first simulations of some of the biogeochemical cycles were attempted.

Now, the coupling of the model components is more synchronous, with atmosphere, land, and ocean models running with the same time resolution: several steps forward at a time, with coupling occurring each day, or several times a day. The coupling of the components illustrated in Chap. 4 (Fig. 4.9) is illustrated again here in Fig. 8.3. The different model components (many with different submodels for processes) all are coupled together, and are integrated forward (run) at the same time.

One of the major problems with this approach has been that errors in the different processes and different components resulted in consistent and significant errors in the surface fluxes or exchanges passed to other models. Think of having the wrong cloud cover in a region: Significant errors would mean too much or not enough solar energy reaching the surface and going into the land or atmosphere. An analogy would be an imbalance in financial flow. If a stock trader consistently took

[7]Manabe, S., Bryan, K., & Spelman, M. J. (1975). "A Global Ocean-Atmosphere Climate Model. Part I. The Atmospheric Circulation." *Journal of Physical Oceanography, 5*(1): 3–29. See also Bryan, K., Manabe, S., & Pacanowski, R. C. (1975). "A Global Ocean-Atmosphere Climate Model. Part II. The Oceanic Circulation." *Journal of Physical Oceanography, 5*(1): 30–46.

part of the trade proceeds, and did not return it to the client, the money flows returned would be too small to keep accounts in balance. Up until about the year 2000, many climate models adjusted their coupling to correct for systematic errors. A model was run uncoupled, and the biases compared to observations were adjusted away by a fixed “flux adjustment” of heat and/or moisture. Of course, flux adjustment assumes that the biases are systematic, and that these are constant. Like statistical models, this adjustment works if the climate changes are assumed to be small perturbations of a basic state.

Fortunately, the use of flux adjustments has largely been eliminated in most coupled models. The removal of flux adjustment has occurred because better representations of the components of the system have smaller systematic errors. Flux adjustment is like correcting the steering of a vehicle for a lack of alignment in the wheels. With better alignment, it is no longer necessary. Another advance that has helped is to integrate climate models for longer periods of time with steady forcing applied, usually representing a pre-industrial state of the 19th century, before carbon dioxide (CO_2) levels began to rise. This allows all the components to come into balance (equilibrium) with each other.

8.3 Key Interactions in Climate Models

Once components are coupled, there are a number of key interactions that are critical for the earth’s climate. We have talked about critical processes in each component: water or latent heat in the atmosphere and land as a mechanism of heat transport, salinity in the oceans, transpiration on land. Let’s look at some different couplings of processes in the system and how they are simulated. Many of these are really feedbacks that cause one component to affect another.

8.3.1 Intermixing of the Feedback Loops

All of these feedbacks are playing out in the climate system at the same time. The intermixing of the feedback loops makes simulations incredibly complex and is one of the reasons we turn to finite element models constrained by energy and mass balance for simulation. For example, it is the change in forcing from the sun as the earth’s orbit changed that likely ended the last ice age: warming the Northern Hemisphere. This would be amplified by the ice albedo feedback from melting land glaciers, but it also may have changed the ocean carbon cycle, resulting in more CO_2 getting into the atmosphere, and accelerating the warming trend, which melted more snow and ice, and so on. But these feedbacks would work very differently now, because of a different ocean circulation and a different distribution of ice sheets on land. There are also feedbacks associated with biological cycles of methane (natural gas, CH_4), another greenhouse gas.

So positive and negative feedbacks act on the earth system, regulating and changing the response of climate to forcing. On the scale of human systems (a century or so), cloud feedbacks are critical. Clouds respond quickly to changes in their local environment, such as altered surface temperature or altered temperature profiles, and this environment is affected by climate change. Cloud feedbacks are thought to be positive in the current climate (warming makes clouds get thinner and/or less extensive, and this reduces the cooling effect of clouds). Ice- and snow-related albedo feedbacks are important at high latitudes and are probably large now, as ice and snow disappear rapidly.

Uncertainties in climate feedbacks drive our uncertainty about the sensitivity of the current climate. The larger the sum of the feedbacks, the greater the climate response to a given forcing. A larger positive albedo feedback means a higher surface temperature for a given forcing. Since we can estimate the radiative forcing for increasing amounts of CO_2, the climate response is due to the combination of feedbacks. Longer-term feedbacks with the carbon cycle make that trajectory even more uncertain as we extend to centuries, because now the change in climate will affect how much CO_2 is in the atmosphere, which alters the radiative forcing. Cloud feedbacks are confined to the atmosphere. But there are other feedbacks like carbon cycle feedbacks that cross boundaries of components of the climate system, and can be understood only with coupled climate models.

8.3.2 Water Feedbacks

Some of the most important couplings have to do with water. The most obvious is the flow of water through the atmosphere (as clouds and precipitation) to the land surface (soil moisture, runoff, lakes and rivers), to the oceans (inflow from rivers and glaciers), and then back into the atmosphere through evaporation. This is the hydrologic cycle, and it pervades every part of the climate system. Because of the complexity of this system, significant processes are still either missing or uncertain. Recently, terrestrial systems have sought to include detailed models of runoff and transport. Atmosphere models still struggle with representations of clouds and humidity. And observations of the hydrologic cycle are still uncertain, so that there is limited quantitative information to constrain the hydrologic cycle in some regions.

Water is fundamental, not just for moisture as precipitation, but for changing the energy and physical state of the system, often through changes of phase. Water is one of the few substances that can be found naturally on the earth as a gas, liquid, or solid. The changes of phase can have interesting consequences: Changes from vapor to liquid or solid in the atmosphere (the formation of a cloud) suddenly have large impacts on the solar radiation at the surface (one feels immediately cooler when the sun goes behind a cloud). Formation of sea ice expels salt, making the remaining ocean water denser. Water is also an important contributor to the energy budget through latent energy: the energy needed to evaporate water back to vapor, or the energy released during condensation. Latent heat energy in water is an efficient mechanism to move heat around as water vapor, and cloud systems move with the general circulation. Plants as well as animals use evaporative cooling (sweat in animals, transpiration in plants) for cooling. Water vapor is also released by plants as a side effect of photosynthesis.

Also important at the surface, and related to water, is the coupling of soil moisture and evapotranspiration (evaporation including evaporation from plants) with precipitation.[8] Increases in soil moisture increase evapotranspiration, at least in semiarid environments: Wet environments are energy limited (there is plenty of water to evaporate, but not enough energy for it), and arid environments are too dry (there is not enough water). But in semiarid regions, increases in soil moisture increase evapotranspiration, which reduces soil moisture, thus shutting off the coupling (a negative feedback). But the increased moisture in the atmosphere may lead to more precipitation, starting the cycle again.

8.3.3 Albedo Feedbacks

Surface albedo feedbacks allow more heat to be absorbed at the surface, but there are special feedbacks with sea ice.[9] Melting of sea ice changes the albedo of the surface to a dark ocean, but it also changes the surface exchanges of heat and moisture, as it is easier to evaporate water from the ocean than to sublimate (transfer from the solid to vapor phase without liquid) from ice. The result also impacts the atmosphere, and the extra fluxes or exchanges of heat and moisture can either reduce clouds if heating dominates or increase them if moisture dominates. Much depends on how the surface and the atmospheric boundary layer above it are coupled. The results are critical for assessing the feedbacks and the energy budget at high latitudes. These couplings are inherently present in models, but only in models with active and detailed ocean and ice components, combined with a good representation of Arctic clouds (sometimes ice, sometimes both ice and liquid). Needing so many processes, along with sparse observations, makes this coupling hard to reproduce. Complicating the modeling of the Arctic is limited observations. There are now only 5–10 years of high-frequency and high-quality satellite cloud observations in the Arctic after limited long-term records from individual sites.[10]

[8]Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., et al. (2010). “Investigating Soil Moisture–Climate Interactions in a Changing Climate: A Review.” *Earth-Science Reviews, 99*(3–4): 125–161.

[9]Hall, A. (2004). “The Role of Surface Albedo Feedback in Climate.” *Journal of Climate, 17*: 1550–1568. doi:10.1175/1520-0442.

[10]For more on the Arctic and climate, see Arctic Climate Impact Assessment, http://www.acia.uaf.edu.

8.3.4 Ocean Feedbacks

There is also coupling between the atmospheric winds and the ocean circulation. Particularly around Antarctica, the wind flowing off the continent pushes ice off shore, forming leads (open water). The open water cools due to the exposure to the cold atmosphere and forms more ice. The salinity increases from salt expelled from ice that is forming. This makes the remaining water denser. The cold and salty (dense) water sinks. Antarctic bottom water is some of the coldest and densest water in the oceans, and it flows into the Atlantic and Indian Oceans (the formation regions are not on the Pacific side of the continent). Wind stress also affects other areas of the ocean, such as along ocean boundaries and along the equator. These are just two examples of the coupling of the atmosphere and ocean. If the atmospheric circulation changes, it alters the ocean circulation. The same may also happen in reverse, as the ocean circulations move heat around. Changes in the North Atlantic western boundary current (the Gulf Stream) will change the heat transport into the North Atlantic.[11]

8.3.5 Sea-Level Change

The change in sea level experienced in any location results from several factors, many of which must be simulated to properly understand how sea level may vary. First, and rather obviously, the sea level depends on the amount of water in the ocean. As ice sheets melt (or grow), they change the total water in the ocean. This changes the sea level. During the last ice age 20,000 years ago, the sea level was 400 ft (120 m) lower.[12] But there are other factors that change sea level, and many of them are local. Since the density of water can change, its volume changes, too. If the ocean warms up and warmer water is less dense, it expands and raises the sea level as well.

These processes affect global sea level. But the sea level does not change the same everywhere on the earth. Why not? Small, localized changes in the height of the land surface occur over time due to the shifting of the land surface itself. The most important of these changes is the result of large ice sheets having been on many regions of the Northern Hemisphere until 10,000 years ago. The weight of these ice sheets pushed down the land surface. When the ice sheets receded, the land surface began to recover and rise. This rebound (technically, **isostatic rebound)** reduces any impact of sea-level rise from increasing volume of the ocean (due to more water or warmer and less dense water) because the land is rising locally.

[11]For a review of the ocean circulation and the North Atlantic in Climate, see Vallis, G. K. (2011). *Climate and the Oceans*. Princeton, NJ: Princeton University Press.

[12]Fairbanks, R. G. (1989). "A 17,000-Year Glacio-Eustatic Sea Level Record: Influence of Glacial Melting Rates on the Younger Dryas Event and Deep-Ocean Circulation." *Nature, 342*(6250): 637–642.

In addition, there is an important "tilt" to ocean heights caused by the motion of the ocean. When water moves (due to wind stress), the forces on it cause variations in pressure across the flow. This pressure difference allows water to stack up where there is lower pressure, tilting the ocean surface slightly. When the circulation changes, the tilt of the ocean changes. This is important locally. For instance, the Gulf Stream current off the east coast of the United States causes a tilt of the ocean surface to lower the ocean along the coast. If the circulation weakens, the ocean tilt will relax, causing the coastal sea level to rise even more in regions near the circulation.

8.4 Coupled Modes of Climate Variability

The couplings described in the preceding sections are critical emergent properties of the climate system that depend on other components. Their coupling can change the mean state of the system. Some couplings, however, give rise to different patterns and timescales of variability. These couplings have significant impacts on weather and climate scales. Here, we discuss small and fast timescale processes of tropical cyclones (hurricanes), seasonal monsoon circulations, tropical oscillations of El Niño, drought and precipitation linkages, and the enhanced efficiency of CO_2 uptake at higher CO_2 concentrations.

8.4.1 Tropical Cyclones

Tropical cyclones, known as hurricanes in the Atlantic and as typhoons in the western Pacific, are a critical and extreme weather event with climate implications. Although individual storms are definitely short-lived weather phenomena, climate patterns affect storm formation, intensity, and frequency. The climate impact of tropical cyclones, and how changes to climate will impact cyclones, is an area of active research.[13] Tropical cyclones exist by a coupling between atmosphere and ocean. Cyclones get their energy from the ocean surface, through evaporation of moisture and release of the latent energy in deep cloud systems. The vertical motion in these clouds organizes into spiral bands of clouds and a large-scale flow through and out the top of the storm. This is hard to represent without the correct coupling between the surface and the ocean. Tropical cyclones are very destructive and disruptive to societies where they make landfall. They may also be important for large-scale transport of moisture both in the vertical to the upper troposphere and in the horizontal to higher latitudes.

[13]For a recent summary, see Knutson, T. R., et al. (2010). "Tropical Cyclones and Climate Change." *Nature Geoscience, 3*(3): 157–163.

Tropical cyclones are barely resolved in global climate models at high resolution (25 km, 16 miles), and usually without the correct intensity (they are too weak). Some of the efforts to make variable resolution models are driven by a desire to have high resolution in tropical cyclone active basins.

8.4.2 Monsoons

The seasonal **monsoon** circulations are giant sea breezes that provide seasonal moisture to many regions of the planet.[14] The South Asian or Indian Monsoon is one of the most important: providing a lot of the seasonal rainfall that feeds a billion people. The South Asian summer monsoon is a consequence of heating of the land mass of South Asia (the Indian subcontinent), causing onshore flow from the surrounding oceans. The convergence and uplift from mountains cause significant precipitation. This releases latent heat, causing more upward motion, and thus feeds on itself. The flow over the ocean is strong enough to affect ocean currents. The topography of the Indian subcontinent, the Himalayan plateau, and even the East African highlands contribute to the development and evolution of the monsoon. The process is a seasonal combination of the atmosphere, ocean, and land surface in the tropics, driven by seasonal radiative processes. Monsoons exist in other regions as well (Africa and even southwestern North America), with similar processes, but smaller magnitude. The monsoons are seasonal and occur every year. They are affected by longer-term climate patterns as well. Monsoons are critical, because most monsoon regions have societies that have grown to depend on them, and failures of the monsoon rains can be disastrous.

Monsoons are affected by ocean currents and by topography. Both of these are difficult to represent in the coupled climate system at large scales, and many global models struggle with the details of the South Asian Monsoon. In particular, the biases in ocean circulation and lack of resolution of mountains can contribute to different strengths of the monsoon, different convergence over India, and hence very different rainfall.

8.4.3 El Niño

One of the best known interannual patterns of climate variation is the **El Niño Southern Oscillation (ENSO)**, named for the warm waters that occur off the coast of South America every other December or so (around Christmas: *El Niño* means "the boy" in Spanish, referring to the Christ child).[15] The warm water is a consequence of a coupling between the ocean and atmosphere in the tropical Pacific.

[14]The World Climate Research Program (WCRP) has a good factsheet on monsoons; see http://www.wcrp-climate.org/documents/monsoon_factsheet.pdf.

[15]A good El Niño overview with current state, forecasts and factsheets on what El Nino is available from the U.S. National Oceanic and Atmospheric Administration, http://www.elnino.noaa.gov.

Normally, winds blowing westward along the equator push warm water into the western Pacific, and causing cold upwelling of deep ocean water near South America (see Chap. 6, Fig. 6.2). The atmosphere responds with rising motion over the warm water in the west, with formation of clouds and rain, while air descends in the east.

During an El Niño event, the westward wind is disrupted and the warm water flows east to South America. The pattern of rainfall moves toward the central Pacific. The mechanisms for this are complex; they have to do with a combination of winds in the atmosphere and slow motions of the mixed layer in the ocean. When too much water piles up in the west, and the thermocline (the bottom of the mixed layer) gets too "tilted" from west to east, internal ocean waves can result. The waves are also affected by wind patterns. The tropical Pacific is a giant bathtub that sloshes around with wind blowing intermittently over the top: When the wind hits the sloshing wave just right, it can amplify and reinforce the wave. The opposite phase, with cold water near South America and warmer water in the western Pacific, has been termed *La Niña* ("the girl" in Spanish). La Niña brings more rain to the western Pacific.

Representing this coupling between atmosphere and ocean has been a difficult task for coupled models. To get the period right, slow and large-scale wave motions in the ocean need to be simulated, and their effects on the atmosphere represented.

8.4.4 Precipitation and the Land Surface

Another significant climate coupling involves relationships between rainfall and surface conditions. Precipitation is coupled to evaporation: Water has to come from somewhere to get into the atmosphere. In coastal regions, this is from the ocean, but in continental regions far from the oceans, water is recycled. The land surface brings water back to the atmosphere through evaporation and transpiration from plants. Precipitation is most tightly coupled to the surface in semiarid regions, where there is enough energy to evaporate water and enough water in the soil to be released by plants (transpiration) and evaporation. Drought can result from this system's being out of balance: Less rainfall can dry the soil and damage the ability of plants to return the moisture to the atmosphere, creating a cycle that may lead to drought. Many regions of the world are prone to such couplings and multiyear droughts, including the Sahel of Africa (south of the Sahara) and southwestern North America.

8.4.5 Carbon Cycle and Climate

On timescales longer than a few years, there are significant couplings between the carbon cycle and climate.[16] The carbon cycle governs the sources and sinks of

[16]For more on carbon-climate coupling, see Archer, D. (2010). *The Global Carbon Cycle*. Princeton, NJ: Princeton University Press.

atmospheric CO_2, which is a greenhouse gas. On the scale of decades to centuries, increasing CO_2 can cause enhanced plant growth, which may damp increases in CO_2 by fixing more of it in the terrestrial biosphere. Enhanced plant growth is dependent on water and nutrient availability, so the coupling is also dependent on the hydrologic cycle and other biogeochemical cycles.

On timescales of thousands of years, carbon in the ocean adjusts to the ocean circulation. It is thought that the carbon cycle amplified the forcing from the sun that ended the last ice age by a change in ocean circulation. A perturbed ocean circulation near the end of the last ice age resulted in more carbon being released to the atmosphere. Simulating these effects is possible in climate system models, but it requires long simulations. Understanding these couplings of the past carbon cycle is critical for testing climate models and enhancing confidence in future predictions.

8.5 Challenges

There remain many challenges in coupling together the different components of the earth system. The difficulties with coupling components into a system that accurately represents the earth's climate system are really a combination of uncertainty in process representation, and uncertainty from observations (How do we know when the system is "right"?). The strategy has generally been to develop and test component models (e.g., atmosphere, sea ice, terrestrial system) with "observations" until good solutions are achieved, and then to couple them together. If the models are not able to reproduce observations (of their respective spheres) with the right boundary conditions, coupling will be hard. But even if they do reproduce observations, small inconsistencies in the observations can result in systematic errors in the coupled system.

A variety of different complexities and challenges have been detailed in the coupled system. Some of the hardest complexities are those processes and features that extend across different components, and where the interactions between different components are critical. Some of these interactions are at the small scale, such as feedbacks between precipitation and the land surface. Some are on short timescales, such as coupling between the surface ocean and the atmosphere that helps cause tropical cyclones.

Getting these coupled processes correct is an important prerequisite for understanding and simulating how such processes will change. Getting present coupled processes correct is not a guarantee of predicting their future. It is sometimes called a necessary but not sufficient condition. Sometimes models show projected changes as differences from the present day, such as the change in surface temperature in a region. But if the surface temperature has a systematic error in the present in the model, especially if the error is larger than the projected change, then caution is warranted.

Some of the processes have medium timescales: seasonal, like the monsoon, or every few years, like El Niño. El Niño is a coupled atmosphere-ocean mode with a

3–5 year timescale. And some of these processes act on climate change scales of centuries, such as sea-level changes and ocean feedbacks. Finally, some processes like the carbon cycle have important interactions on geologic timescales.

Naturally the development of coupled models has shifted from asking shorter-term to now longer-term questions. Basic issues of interactions and coupling to maintain a stable climate have been achieved in most models, and they are now trying to simulate coupled modes of variability and to understand the longer-term evolution of the climate system on the century scale. This is the scale of climate change over a human lifetime or several generations, and it is where climate models are being used, and where their uncertainty is being assessed. Of course, these predictions rely on representing coupling processes correctly (such as surface exchanges between the ocean or land and atmosphere).

Of these predictions, sea-level rise and carbon cycle changes present some of the biggest challenges. Many of the processes for simulating ice sheets are not well understood (see Chap. 7), and these models are still fairly new. This means a great deal of uncertainty exists, and this is an area where projections are still changing. In addition, the feedbacks between climate and the carbon cycle on century timescales are uncertain: In principle, plants will take up more CO_2, reducing any increase in the atmospheric concentration that creates a radiative forcing. But because in practice plant growth may be limited by the availability of water and nutrients, plants may not take up more CO_2. Uncertainties in future sea level, and uncertainties in the uptake of CO_2 in the carbon cycle, are dominated by specific processes. This is actually a good thing. Attention is focused on understanding and simulating specific processes in the climate system. This is one way climate models can be used to explore specific predictions and help improve understanding.

8.6 Applications: Integrated Assessment of Water Resources

This case study explores coupling models of the earth's climate with models of human activities. This type of coupling takes place at many spatial and temporal scales with many coupling strategies. The coupling of climate models with models from other disciplines is often called integrated assessment modeling[17] and integrated environmental modeling.[18]

Integrated assessment models provide information that helps guide decision making; they are also used to investigate the consequences of decisions. The process brings together many disciplines. Integrated assessment modeling increases

[17]The Royal Society, London, "Modeling Earth's Future," October 1, 2013, https://royalsociety.org/policy/publications/2013/modeling-earths-future/.

[18]The International Environmental Modelling and Software Society, http://www.iemss.org/society/index.php/scope.

the complexity of the modeling environment by adding different disciplines. This can be thought of as adding more detail to the human sphere, or adding other spheres to a coupled model. In the process, the representation of the human-natural system is simplified relative to physical models or economic models on their own. Not only is the range of disciplines increased when human systems are simulated, but uncertainty sources become larger and are influenced by intentional and unintentional decisions of humans.

Human system models are much less constrained than climate models of the physical earth system. Modeling assumptions do not have the definitive cause-and-effect relationship of physical principles: Money is not conserved like energy and mass, and the range of possible outcomes is constrained not by physical laws, but by economic principles. Thus, the ability to apply integrated assessment models directly in deterministic decision making is even more difficult than the application of physical climate models. There is argument about just how useful global integrated assessment models focused on energy, economics, and agricultural are for decision making.

Perhaps the best way to use an integrated assessment model is not to generate a specific answer to a policy question, but to provide insight about crucial interactions and uncertainties between human and natural systems.[19] In other words, integrated assessment models highlight (a) specific climate impacts that might drive societal responses, (b) what aspects of society are affected by different climate impacts, and (c) the relative sensitivity of human systems to different factors. Described later in this section is a specific example of water resource management.

Integrated assessment and integrated assessment modeling is broader than the coupling of climate models with macroeconomic models mentioned in the chapter body. The National Research Council defines integrated assessment as "a collective, deliberative process by which experts review, analyze, and synthesize scientific knowledge in response to user's information needs relevant to key questions, uncertainties or decisions.[20]" Integrated assessment is a problem-solving methodology to bring together natural science, social science, and policy to support knowledge-based decision making.[21] It is a form of participatory, iterative problem solving, as discussed in Chap. 12. From the perspective of the climate scientist, integrated assessment is a structured process that inserts knowledge and consideration of climate change into decisions such as building and maintaining infrastructure; forest management; and water resources for agricultural, industrial, and human consumption. Climate change is often placed into the context of existing policy, built infrastructure, and known weather vulnerabilities; hence, climate

[19]Morgan, G. quoted in "Modeling Earth's Future," Royal Society, London, 2013, https://royalsociety.org/policy/publications/2013/modeling-earths-future/, p. 22.

[20]NRC. *Analysis of Global Change Assessments—Lessons Learned*. National Academies Press, 2007.

[21]Graham Sustainability Institute, "Integrated Assessment," http://graham.umich.edu/knowledge/ia.

change provides an incremental alteration of an existing end-to-end system already in place.

Integrated assessment is frequently applied to water resource management and has been used widely to consider changes in vulnerability to water resources in the western United States. An example is the *California Integrated Assessment of Watershed Health*, sponsored by the Environmental Protection Agency.[22] This study considered four vulnerability factors associated with watersheds: climate change, land cover change, water use change, and fire vulnerability. With regard to climate change, vulnerability indicators are developed for precipitation, mean temperature, minimum temperature, maximum temperature, snowpack, minimum flow (or baseflow), and surface runoff. These indicators show the requirements of the climate model to provide not only direct measures of climate change (temperature and precipitation) but also derived integrated parameters (snowpack, baseflow, and surface runoff).

Climate-change vulnerability is mapped spatially, from low to high, on a 2050 time frame and then considered in context with other vulnerabilities noted above. Climate-change vulnerability is highest in the northern third of California, where temperature increases cause large alterations to snowpack, minimum flow, and surface runoff. A conclusion from this work is that preventing landscape degradation in relatively unpopulated areas at the headwaters of rivers increases the resilience of both ecosystems and human systems to climate change.

8.7 Summary

The climate system can be simulated in many ways with different types of models. Some of these models are dynamical: what we commonly think of as climate models, models that look and work like weather forecast models. There are also statistical models of climate. These are often used for downscaling projections of a large-scale model to smaller scales. Downscaling can also be dynamical. Regional climate models are examples of smaller-scale dynamical models used to generate more detailed statistics, and run with boundary conditions from larger-scale models. Coupling components of the climate system has evolved over the past 40 years or so. First, separate component models are run with fixed other parts of the system, such as running an atmosphere with fixed sea surface temperatures. Coupling is the process of trying to tie component models together. Errors are now small enough that such coupling does not generally cause the climate system to drift, but there are still uncertainties in observations that go into evaluation of the coupled system.

[22] U.S. Environmental Protection Agency. *California Integrated Assessment of Wathershed Health*, November 2013, http://www.mywaterquality.ca.gov/monitoring_council/healthy_streams/docs/ca_hw_report_111213.pdf.

The climate system is full of interactions between the different components. Coupled systems collect and pass the information around, and they ensure energy and mass conservation. These interactions are manifest especially in the hydrologic cycle and the carbon cycle.

On the one hand, these complex coupling mechanisms make it difficult to simulate the earth system. On the other hand, representing these phenomena correctly can be a strict test of climate models. Proper simulation of the carbon cycle, tropical cyclones, and the right period and amplitude of El Niño events are all strong indications that climate models can represent various modes, timescales, and important processes in the earth system. In Part III, we further examine uncertainty in the models and ask how good they are at these various processes, and why should we trust them for the future.

Key Points

- Climate models can be global or regional.
- In addition to dynamical system models, statistical models of climate can be used.
- There are complex interactions in the climate system, including for water.
- Coupled effects such as sea-level rise are difficult to simulate.
- There are many timescales of interactions between component models.