Chapter 7
Simulating Terrestrial Systems

We have discussed the atmosphere, the ocean, and the sea ice that floats on top of the ocean. The remaining major component of the earth system is probably the closest to you right now: the surface of the earth (unless you are reading this on a boat or a plane). The earth's surface is certainly closest to home. We can think of all the components of the climate on the (permanent) solid surface of the earth as the terrestrial system. Although this is commonly thought of as just modeling the land surface, it also includes two other important components: the cryosphere (ice and snow) that sits on land and the anthroposphere (the role of humans) in the climate system. We also discuss how human systems are simulated in general, and in climate models. Since all these interactions occur on the surface of the earth, the most useful way to discuss them is by looking at the land, cryosphere, and humans as parts of the *terrestrial system*.[1] Here we review the role of terrestrial systems in climate and discuss how they are simulated.

7.1 Role of the Land Surface in Climate

The surface of the earth plays several important roles in the climate system (Fig. 7.1).[2] Like the ocean surface, the land surface interacts with the atmosphere. The land surface also interacts with water and energy budgets. Land is only 30 % of the surface of the earth, but since humans are a terrestrial species, land has outsized importance to the climate system we experience.

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[1] Lawrence, D., & Fischer, R. "The Community Land Model Philosophy: Model Development and Science Applications." iLEAPS and GEWEX newsletter, April 2013, http://www.cesm.ucar.edu/working_groups/Land/ileaps-CLM.pdf.

[2] For a review of many of these basic concepts, see Schimel, D. (2013). *Climate and Ecosystems*. Princeton, NJ: Princeton University Press; or Bonan, G. B. (2008). *Ecological Climatology: Concepts and Applications*. Cambridge, UK: Cambridge University Press.

A. Gettelman and R.B. Rood, *Demystifying Climate Models*,
Earth Systems Data and Models 2, DOI 10.1007/978-3-662-48959-8_7

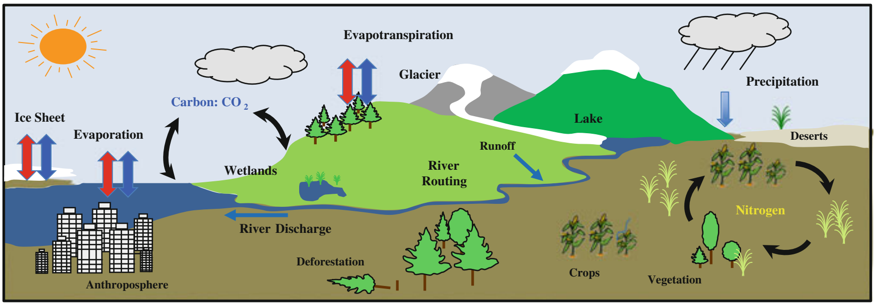

Fig. 7.1 Terrestrial systems and climate. Key processes include exchanges at the surface of water (evapotranspiration, precipitation, and evaporation) and energy (radiation). Key cycles of carbon and nitrogen are illustrated. Land surface processes of the hydrologic cycle are shown (precipitation, glaciers, runoff, and evaporation). Human disturbances (anthroposphere, deforestation, and crops) are also illustrated. Adapted from Lawrence and Fischer (2013)

7.1.1 Precipitation and the Water Cycle

Precipitation falls on the land surface. Some of this water is absorbed by plants and soils, some evaporates back into the atmosphere, and some may become surface water (streams, rivers, and lakes). The latter (runoff) occurs if the total water is greater than the holding capacity (or field capacity) of soil. The type of surface matters a great deal: Different land surfaces have different albedos, so they absorb radiation differently, and different soil types hold different amounts of water. As in the atmosphere, water in the soil is also important in the energy cycle. Heat may go into the land surface to evaporate water rather than heating the surface, and this has profound impacts. The fluxes (movements) of water are very important for recycling moisture back into the atmosphere.

7.1.2 Vegetation

Critical for the land surface is the role of vegetation. Vegetation alters the albedo of the land surface: Trees are darker than grasses, and grasses are usually darker than bare rock or dry soil. Vegetation changes the way that winds interact with the surface. But perhaps most critical are two aspects to vegetation that feed back into the climate system. First is the exchange of carbon, as plants “fix” carbon dioxide (CO_2) from the atmosphere via photosynthesis and incorporate it into organic matter. This fixation of carbon, driven by photosynthesis, is a critical part of the carbon cycle that ultimately helps regulate how much CO_2 is in the atmosphere. Second, plants use water in their tissues and for photosynthesis. In the leaves where photosynthesis occurs, some water leaks out, or “transpires” from the plants in a process called **transpiration** (“plant sweat,” you might call it). Plants thus modulate the flux of water from the soil (where they take water up in their roots) into the canopy (the leafy region), where some of the moisture escapes into the atmosphere. Transpiration of water from plants is a significant fraction of the total evaporation: It is estimated to be a little over half of the total global **evapotranspiration** (the combination of water evaporated from the soil, water intercepted by leaves, and water released from plants via transpiration), and is a very important part of the water cycle. The role of animals in respiration (processing oxygen and CO_2) is too small to directly impact the carbon cycle. Think of the difference between the mass of animals in a square mile of natural land compared to all the plant material.

Changing vegetation can thus change the water available to the atmosphere. The change in atmospheric water can ultimately change precipitation downwind. We discuss the interaction between the land and atmosphere later in this chapter. Vegetation is not static, it will respond to changes in climate over time. The change in vegetation is often called **succession**, as one species or ecosystem gives way to another. The evolution of ecosystems creates a series of different feedbacks: As ecosystems change, the albedo and the ability to take up water and transpire water back to the atmosphere change. The different recycling of moisture can alter total precipitation. Thus, the vegetated land surface plays an important and active role in climate, particularly in the hydrologic cycle. But not all surfaces are vegetated.

7.1.3 Ice and Snow

Some of the most important land surfaces are covered with ice or seasonal snow, and/or contain permanently frozen soil (permafrost). These are the portions of the cryosphere that are on land, and they represent seasonal snow-covered tundra (with and without permafrost), mountain glaciers and the two large ice caps of Greenland and Antarctica. These frozen surfaces are important for a variety of reasons on a number of timescales. We have extensively discussed snow and ice albedo feedbacks, and the sensitivity of high-latitude climate to changes in the surface albedo. The ice sheets are stores of 70 % of the total freshwater on earth. The Greenland ice sheet stores the equivalent water to raise global sea level by 23 ft (7 m). Antarctica contains by itself 60 % of the earth's freshwater, which if it all melted would be equivalent to raising sea level by nearly 230 ft (70 m). These ice sheets are generally thought to be quite stable. The Antarctic ice sheet has been there in some form for millions of years.[3] But Greenland is melting rapidly at the surface and the margins now, and part of the Antarctic ice sheet (the West Antarctic ice sheet) actually rests on land below sea level, making it more susceptible to erosion, flow, and melting. Recent evidence has indicated that warmer water around the edges of the West Antarctic ice sheet (10 % of the total mass of Antarctica, or 23 ft, 7 m of

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[3] Bender, M. L. (2013). *Paleoclimate*. Princeton, NJ: Princeton University Press.

sea-level rise) may be making it unstable.[4] Given the importance of these ice sheets, new modeling tools are being developed to simulate their dynamics.

7.1.4 Human Impacts

Finally, there is one other very important surface type: the regions of the earth' s surface that are affected or regulated by humans. Likely you are in one of those regions now, and, by definition, you live in one of these regions. This includes regions of urbanization, and land use change caused by humans for agricultural use (crops and grazing) and wood harvesting (deforestation). Cropland covers about 10 % of global land area,[5] and pasture another 25 %. This is one-third of the earth's land area. Forests of all sorts are another 30 %. About a third of total land area is tundra, deserts, or mountains. So a significant fraction of the earth's surface is being used intensively by humanity.

Humans have altered about half of the **arable land** (land on which plants grow and animals can find food).[6] The land use by humans affects many of the cycles and feedbacks noted earlier. Shifting from natural vegetation to crops, with their need for additional water (irrigation) and nutrients (fertilizer, mostly nitrogen and some phosphorous) can alter nutrient cycling and can also drastically change the surface albedo as well as surface heat and moisture fluxes. For example, the rainforests in the Amazon, through evapotranspiration, recycle water back to the atmosphere that falls again as rain. Theories (and models) predict that as the rainforest is converted to pasture land (as is happening now), this might reduce the evapotranspiration and reduce rainfall, potentially making the remainder of the forest more vulnerable.[7] Thus, trying to understand the impacts of our actions on the land surface and how that might affect the climate system is important, whether global climate change or local land use change is a driver.

In addition to changes to the physical land surface, humans have significantly altered chemical and nutrient cycles (often called biogeochemistry; see Sect. 7.3)[8] through the activities of organized societies. Humans have perturbed the CO_2 concentration by about 40 % (from 280 to 400 parts per million) over the past

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[4] Alley, R. B., et al. (2005). "Ice-Sheet and Sea-Level Changes." *Science*, *310*(5747): 456–460.

[5] Based on land-use data available from the World Bank, http://data.worldbank.org/indicator/AG.LND.ARBL.ZS, or the *CIA World Fact Book*, https://www.cia.gov/Library/publications/the-world-factbook.

[6] For arable land trends over time, see United Nations Food and Agriculture Organization Statistics division (FAOSTAT), http://faostat3.fao.org/home/E.

[7] Malhi, Y., et al. (2009). "Exploring the Likelihood and Mechanism of a Climate-Change-Induced Dieback of the Amazon Rainforest." *Proceedings of the National Academy of Sciences*, *106*(49): 20610–20615.

[8] For a detailed background, see Charlson, R. J., Orians, G. H., & Butcher, S. S. (1992). *Global Biogeochemical Cycles*, ed. G. V. Wolfe. New York: Academic Press.

several centuries. But we have also perturbed the cycle of fixed nitrogen (an important nutrient and the primary nutrient in fertilizer) by at least 100 %. The particles we emit from industry or as by-products of energy use may affect how clouds form and how much energy is absorbed in the atmosphere, and chemical perturbations (air pollution or smog) damage animals and plants. So our economic systems are coupled to the climate system.

There are models that try to simulate these human systems and their two-way interactions with climate. For example, as temperature rises, humans use more energy to cool their societies (think of Arizona or Athens on a hot day). This increased energy use will have economic costs and environmental impacts (more energy, more CO_2 emissions). More CO_2 emissions will further impact climate. So coupling models of economic systems to climate is also critical, and the land surface is where that happens.

7.2 Building a Land Surface Simulation

The terrestrial surface is simulated by representing a series of these critical processes, on the surface of the earth. The discussion also tracks the history of development of land surface models. First comes the treatment of exchanges with the atmosphere and ocean: surface fluxes and heat, and also a discussion of **hydrology** (the water cycle). This includes the water in the soil, and how it evolves. Together, these heat and moisture fluxes are often called **biogeophysics** (*bio* = living things, *geo* = earth). The critical *bio*-part of biogeophysics includes how vegetation alters fluxes of heat and moisture through evapotranspiration. Surface waters (rivers, lakes, and wetlands) are also important for hydrology.

The next phase of terrestrial system modeling involves nutrient cycles, chiefly of carbon and nitrogen, but also some minor species important for plant growth. In addition to these nutrient cycles comes a representation of the dynamic land surface: changing land cover types including cropland, simulating disturbances (deforestation or fires), and even models of the urban system.

The cryosphere is also important in terrestrial systems. Snow is an important surface type. Recently climate models have started to develop new models for “land ice” (glaciers and ice sheets). Finally, we mention models of human social and economic systems.

7.2.1 Evolution of a Terrestrial System Model

Terrestrial system models generally began as a set of parameterizations to consistently supply energy and moisture fluxes to the atmosphere. A basic land surface model contains timescales and efficiencies (often characterized as resistances to flow, as in an electric circuit) for water and energy. Basic models also include simple representations of how much water the soil can hold, and its exchange into the atmosphere.

The next step in complexity is to treat soil and plant systems in more detail, with representations of different soil and plant types. This is important for representing the effect of plants through evapotranspiration. Soil and plant submodels have been extended so that the vegetation can evolve over time in response to nutrients (biogeochemistry) and climate, so that the vegetation becomes dynamic. What is dynamic vegetation? It means the type of vegetation is not fixed and can evolve as the climate changes. For example, if precipitation changes, rainforests can turn into grassland.

The last stages of complexity are to also simulate the effects of humans, and a complete land cryosphere. Human perturbation to climate can be integrated into the system with economic models coupled to the physical models. Attempts to represent more completely glaciers and ice sheets are also under way.

It is clear that a terrestrial system model is really a system of coupled submodels (land ice, human systems, vegetation types, soil, hydrologic cycle) that represent key processes that occur on the land system.

One important requirement of terrestrial system models is the ability to represent the different impacts of small-scale features—such as forests versus grasslands versus lakes—within a large-grid cell. One advantage of terrestrial system models is that generally soil and plants do not move in the horizontal. Only water really moves rapidly in the terrestrial system. This improves the computational efficiency of terrestrial models. It also helps that land represents only 30 % of the area of the earth.

Land models have a different approach to subgrid variability than do models of the ocean, atmosphere, or sea ice. While things like clouds in part of a grid cell are ephemeral and change rapidly, the proportion of a part of the earth's surface (say, 62 miles or 100 km on a side) covered with a given type of soil and/or vegetation does not change much. So land models often split up each grid cell into the different vegetation and surface types (lakes, urban areas, and glaciers) that might be present at any location. Fluxes of water, energy, and carbon are then calculated separately for each surface type and then the grid-cell fluxes are calculated via a weighted average based on the proportion of each surface type within the grid. The distribution of surface types remains relatively fixed, evolving only slowly over time due to human alterations of the land surface or through vegetation disturbances due to fire or a response to a climate shift. Unlike the atmosphere, there is very little communication between different grid points or even subregions of the grid at the surface. Generally there is only runoff of surface water. Conduction of heat and subsurface flow is not treated in most large-scale terrestrial system models. Mostly individual land units exist independent of the others, as if the model were an atmospheric general circulation model (GCM) with no dynamics (i.e., no general circulation) and advection, and just a series of columns with a list of different surface types in each column.

Topography, defined as the change in elevation, generates additional complexity in terrestrial system modeling. When subgrid variations of the surface are considered for different surface types (soil or vegetation) on scales of hundreds of kilometers, there are also elevation changes to consider. This requires addressing variations in temperature and precipitation, and the treatment of the angle and slope of terrain. As an example, a grid box with a mountain range will have very different land cover types as altitude increases from forest to alpine to snow/ice or bare rock. Also, the windward side of the range (facing the prevailing wind) will generally have more precipitation and different vegetation types than the leeward (downwind) side, which often sits in a “rain shadow.” Fortunately, many of these topographic features are fixed, so relationships for these distributions can be designed (parameterized). For example, the mean surface temperature of a grid box can be distributed so that some regions have warmer and some colder temperatures depending on elevation. Precipitation can be distributed unevenly based on the direction of the wind. These complexities are necessary for getting local climates and land surface types correct.

7.2.2 *Biogeophysics: Surface Fluxes and Heat*

Atmosphere models have a bottom boundary, and the first terrestrial system models were really just surface flux parameterizations that represented the heat exchanged at the surface. Radiation impinges on the surface both as direct solar radiation and

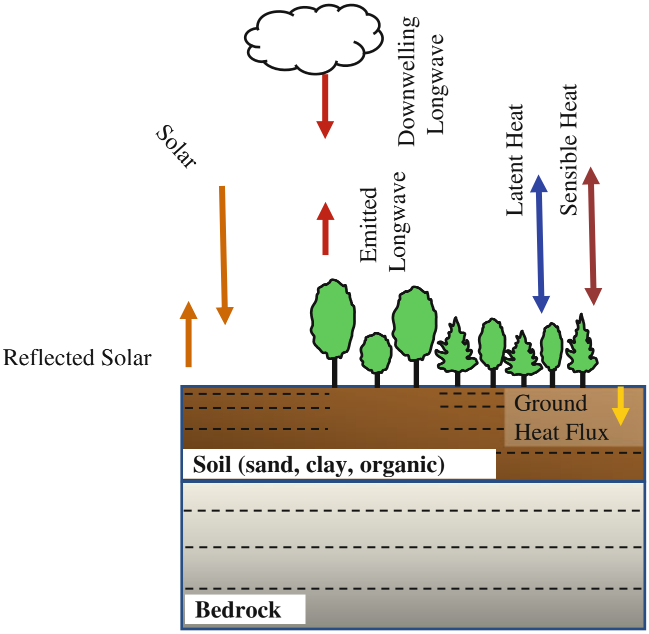

Fig. 7.2 Surface energy fluxes. Key surface fluxes into and out of the land surface. Radiation from the sun (solar) is in *orange*. Infrared (longwave or terrestrial) radiation is *red*. Fluxes of water (latent heat, precipitation) are *blue*. Sensible heat exchange is *magenta* and the heat into the soil is *yellow*. Adapted from Lawrence and Fischer (2013)

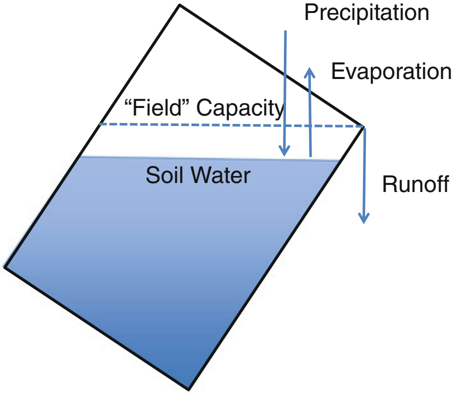

Fig. 7.3 Bucket model. Soil can hold water based on precipitation input and evaporation loss up to its field capacity. Water in excess of the field capacity becomes runoff

as more diffuse (backscattered) solar and longwave (terrestrial) radiation. Some of this energy is not just in the form of heat, but also energy that comes from the potential to condense water (called **latent heat**), which ties the **energy budget** to the hydrologic cycle. Figure 7.2 illustrates the absorption and reflection of energy, and the latent and sensible heat. These surface fluxes then send heat into (and out of) the ground and soil as the ground heat flux.

7.2.3 Biogeophysics: Hydrology

In addition to surface energy fluxes, the flow of water in and out of the soil is represented. One common form of hydrology, originally conceptualized in the late 1960s in the Soviet Union, is to treat the soil column as a "bucket" that can hold a given amount of water. The precipitation, minus the evaporation, is used to fill or empty the bucket, and if the bucket of soil gets to a threshold where it cannot hold any more water (the soil's **field capacity**), the water runs off. Figure 7.3 illustrates a **bucket model**.[9]

Soil moisture is a critical part of the climate system. It regulates what happens to precipitation, and how it gets recycled into the atmosphere, stays in the soil where it is available for plants to use, or becomes surface runoff. There are important feedbacks between the atmosphere and the soil moisture as well.[10] Wetter conditions (more precipitation) mean more evaporation, and a wetter atmosphere above the land. Evaporation is latent heat: Energy goes into evaporating water rather than increasing temperature, and this latent energy dominates in wet conditions. With

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[9] The original treatment of the Budyko bucket model is reviewed in Budyko, M. I. (1974). *Climate and Life*. New York: Academic Press.

[10] For a review of soil moisture feedbacks, see Seneviratne, S. I., et al. (2010). "Investigating Soil Moisture—Climate Interactions in a Changing Climate: A Review." *Earth-Science Reviews*, *99*(3–4): 125–161.

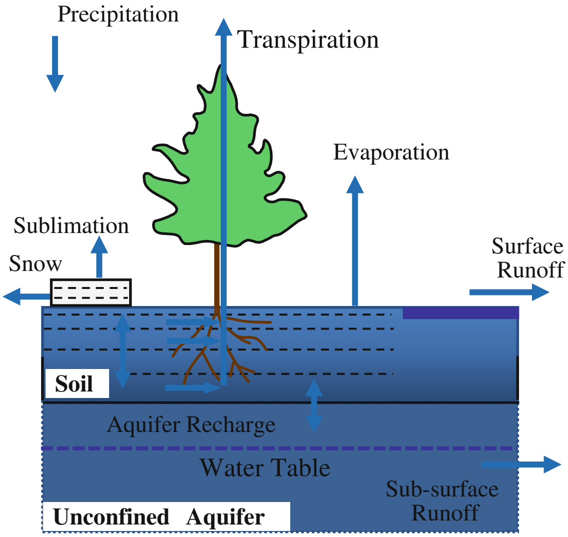

Fig. 7.4 Hydrology of the terrestrial model. Precipitation comes from the atmosphere. Evaporation, sublimation (evaporation directly from snow), and transpiration (from plants) returns water to the atmosphere. Water also goes into soil and surface runoff. The soil water can also recharge an aquifer in the deep soil layer. Adapted from Lawrence and Fisher (2013)

wetter conditions, the surface is energy limited (more energy is needed to evaporate water). The only way that water can evaporate is by adding more energy to the system. In wet conditions, adding more energy does not necessarily increase the temperature; rather it can just go into latent heat, evaporating more water.

Drier conditions are often water limited, meaning there isn't enough water to satisfy the energy demands. In dry regions, there is basically very little vegetation and little transpiration. In between, in semi-arid regions, the transpiration (evaporation from plants) is important. Transpiration can be dependent on soil moisture. Less soil moisture means more sensible heat and larger increases in temperature for a given energy input. Thus, the surface properties and biogeophysics of soil moisture and total evapotranspiration, even diagnosed with a simple model, show the importance of the land surface for local climate.

The simple bucket approach is quite useful, but it has many limitations. It is basically the simplest approach to capture some of these atmospheric feedbacks with the surface. More modern treatments of the soil include multiple layers, and water transport across those layers, in the subsurface soil. Many of these processes are illustrated in Fig. 7.4. Having multiple layers and different pathways through the soil for local hydrology allows for a better representation of the variability in soil environments: from permafrost (with variable frozen layers), through to tropical wetlands with saturated soils. The **tiled approach** allows many soils to be present in a single grid box with varying fractions and effects, for example, like only part of the grid box's being saturated.

When the soil becomes saturated with more water than can be absorbed, runoff occurs, generating lakes, rivers, and wetlands. The bucket model is a simple illustration of this. Surface water has often not been treated extensively in terrestrial system models. But of course lakes and rivers are important for climate. Rivers move freshwater into the oceans. They also move nutrients into the oceans (see Sect. 7.2.4). Lakes and wetlands, with potential large area coverage, are also important for providing regions of large-scale evaporation, with significant effects on climate: Surface water can readily evaporate back into the atmosphere. Regionally this can be a dominant source of water for precipitation. This is familiar to anyone who lives to the east (downwind) of the Great Lakes region of North America (e.g., western Michigan, parts of New York state), where "lake effect" snow storms result from moisture picked up as cold air flows over large lakes that are relatively warm. Lake water evaporates into the air and then this water is deposited downstream as snow when the air cools. Representing lakes in climate models is critical for getting regional climate correct. Human modifications of surface water systems, via dams and reservoirs, also create such lake effects from evaporation, and may modify local or regional climate. Though human-made lakes are usually much smaller than the Great Lakes, the effects can still be important locally. Plus, these reservoirs store and evaporate water, thereby altering river flow.

The deepest piece of the land hydrology is the storage of water in aquifers beneath the soil. **Aquifers** are regions of permeable rock containing groundwater that can be extracted with a well. A common analogy is digging a hole in the sand at a beach: When water is reached, it flows into the hole (a well). The level of the water is the **water table** and the moist sand the aquifer. Geology creates these regions with permeable soils, and they are "recharged" by seepage of groundwater into them from precipitation. Representing "stored" water, aquifers are an important part of the hydrologic cycle: They can be used to provide water when no surface water or precipitation is available. Most regions of the earth have some sort of aquifer beneath them. Aquifers are critical for human populations. Many human settlements coalesced around wells, and a lot of agricultural areas are dependent on groundwater for irrigation. Aquifers typically interact with the soil in land models, forming a deep storage region for water that penetrates the soil. Simulating aquifers is important for understanding the low-frequency behavior of hydrology and the interaction of hydrology with humans on climate scales.

7.2.4 Ecosystem Dynamics (Vegetation and Land Cover/Use Change)

Representing vegetation is an important part of modern terrestrial system models. Proper representation of vegetation is important for biogeophysics: heat and moisture fluxes between the atmosphere and the surface. As we have seen, this is particularly because of transpiration from plants. The structure of a vegetation canopy also is important for regulating how surface radiation fluxes filter between the top of the canopy and the surface. Vegetation creates its own near-surface boundary layer that modifies surface fluxes. And vegetation also is important for nutrient cycles, including the cycling of carbon between organic matter in the land surface and the atmosphere (see Sect. 7.3).

Vegetation also has subgrid-scale variation. Typically a model will have different vegetation classes, or **plant functional types**, in a single grid cell. These are probably best thought of as simple representations of different ecosystems. For example, a grid cell might contain forest, grassland, cropland, and/or tundra. The characteristics might be more detailed: There may be several different types of forest (e.g., broad-leaf deciduous forest, evergreen forest). Different plant types behave differently with respect to the properties of transpiration, leaf area, canopy height, and so on, so it makes sense to have different "tiles" or units that can represent the different ecosystems. Modern terrestrial system models can have 10–15 of these plant functional types. The types classify an ecosystem of plants by plant traits both above ground (height, flammability, leaf area, and nutrient content) and below ground (root depth, nutrient uptake). Plants are also classified by their different physical traits: their ability to grow and use nutrients and water (called plant **phenology**).

A great deal of detail in current terrestrial system models is being added at the fundamental level of understanding plant physical traits. This is the description of the physical nature of plant characteristics for things like transpiration, growth (uptake of carbon), even their albedo. Properly describing these traits and then having multiple plant types enable a complex treatment of the land surface with quite a bit of diversity. These plant characteristics are typically based on direct observations of plant types. The goal of the description of the plant functional types is to represent how the environment affects plant growth, and how plants in turn affect the environment.

When vegetation and vegetation characteristics were first introduced into surface models, the description of the vegetation was taken to be static: not unlike the topographic conditions describing the arrangement of the land surface and its elevation. Similarly, the first atmospheric models (in the 1960s and 1970s) had fixed cloud distributions (see Chap. 5). Even a static distribution of vegetation, with different properties for on the order of 10 different ecosystems, is a significant improvement compared to no vegetation. It allows for a more complete representation of important properties of the surface system (like evapotranspiration). But vegetation is not static, and vegetation health and distribution can evolve in response to disturbances (natural or human caused) and due to climate change. Disturbances include occurrences such as fire, disease or insect outbreaks, and drought. Climate changes can make the present distribution of vegetation unable to survive, and cause succession of one plant type into something else. The representation of dynamic vegetation in terrestrial systems is often called **ecosystem dynamics**. In this context, dynamic means change in a temporal sense: changes over time.

Terrestrial system models now commonly include representations of how vegetation distributions could evolve. This is illustrated in Fig. 7.5. Some changes are natural, or a response to climate: Plants will die off or grow better depending on climate changes. If the planet warms or cools, certain vegetation classes will

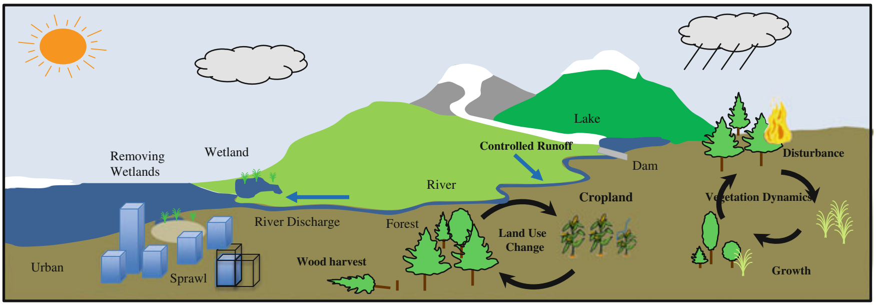

Fig. 7.5 Ecosystem dynamics. Ecosystems can be disturbed (e.g., from fire), and they evolve and change ecosystem type. Ecosystems can have humans change their type (e.g., to cropland or through deforestation). Runoff and rivers can be controlled, wetlands can be altered, and urban landscapes expand. Adapted from Lawrence and Fisher (2013)

populate different regions. This can also occur due to disturbance. **Natural disturbances** can be fires or floods. **Human disturbances** are often called “land use change,” such as forest conversion to crop or pastureland, or even conversion to urban environments. For natural changes (responses to climate change, for example), rules can be developed for the success or failure of each plant functional type for different climate regimes, and the evolution (or succession) of those types. One example might be the disturbance of a forest by fire, and the conversion of the forest to grassland, then to a deciduous forest and then to an evergreen forest over time. While we generally think of human land use change as something we must impose, there are ways to try to simulate the evolution of human systems (Sect. 7.6) and how they might alter land use (Sect. 7.7). Thus, ecosystem dynamics is also the link to human systems and their impact on the land surface.

7.2.5 Summary: Structure of a Land Model

The structure of a land model grid cell describes how the model interacts with the atmosphere above it, through exchanges of heat and moisture (see Sect. 7.2.2). Generally, the land surface will be broken up into different surface types, or ecosystem types, such as desert, grassland, or forest. Multiple types can exist in the same grid cell. The model will have a description of the characteristics for the soil properties in each grid cell, and possibly for each surface type. This includes a description of the hydrology of the soil: how much water it can hold (the field capacity; see Sect. 7.2.3). It also accounts for excess water that may run off.

Each surface or ecosystem type will have a description of the plants on the surface (see Sect. 7.2.4). The description includes a description of how an ecosystem of plants (like the trees in a forest) moves water into the atmosphere through evaporation, reacts to precipitation, and grows and decays. This helps to determine the surface exchanges of heat and moisture and also allows a description of the carbon content of the soil and plants.

All of these characteristics are input to the model. The plant responses to the environment are usually derived from observations of actual plants: either single plants or detailed measurements of entire ecosystems such as forests or grasslands. The data are distilled down into relationships. If the rainfall is W and there is at least X amount of nitrogen and water in the soil, then the plants will grow in that ecosystem and they will take Y amount of carbon from the atmosphere and Z amount of carbon from the soil. This is calculated for every ecosystem type in a grid cell, and for every grid cell in the land model. The moisture in the soil is estimated from a hydrology model. Excess surface water becomes runoff that flows into the next (downhill) grid box.

Now we focus on some of the key nutrients that limit plant growth, and on the flows of carbon that go into plants. Carbon is of concern because it exchanges between the soil, plants, and the atmosphere. In the atmosphere, carbon is CO_2, the greenhouse gas.

7.3 Biogeochemistry: Carbon and Other Nutrient Cycles

Plants affect the water and energy fluxes at the surface through transpiration, and through canopy absorption and emission of radiation. These are immediate effects that affect weather as well as climate scales. Plants are also important for cycling nutrients: key chemicals in the earth system on which life depends. Nutrients cycle through the earth system, and understanding the flow of these nutrients is called **biogeochemistry** (a complement to biogeophysics).

The role of **nutrient cycling** is important for two reasons: Some of these chemicals directly affect climate, and others affect plant growth in the ocean and on land. The critical nutrients we focus on are carbon and nitrogen. Carbon is an example of a chemical that affects climate as carbon dioxide (CO_2) or methane (CH_4) in the atmosphere. Nitrogen is an example of a critical chemical affecting plant growth. Phosphorous is also an important nutrient for plant growth, especially in tropical ecosystems.

Biogeochemical cycles describe what happens to key nutrients in the earth system. The key concept is a cycle: There are a series of **reservoirs** in which carbon exists in different forms. The **carbon cycle** is illustrated in Fig. 7.6.[11] Carbon reservoirs include rocks and minerals (including geological storage of carbon in fossil fuels), the ocean (where carbonate minerals and CO_2 are dissolved in the water column), vegetation and soil, and the atmosphere. The figure also indicates the exchange between the reservoirs, and the changes to the exchange between

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[11] An accessible introduction to the carbon cycle is Archer, D. (2010). *The Global Carbon Cycle*. Princeton, NJ: Princeton University Press.

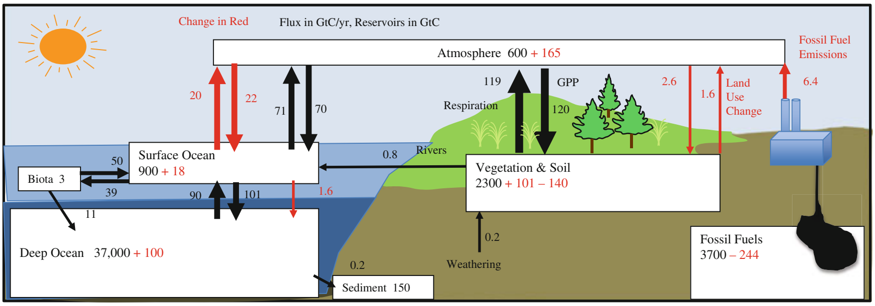

Fig. 7.6 The carbon cycle. The largest climate system reservoirs for carbon include the deep ocean, soil and vegetation, surface ocean, and atmosphere. The approximate size of annual carbon fluxes is given by the width of the *arrows*; *red arrows* indicate perturbations by humans. *Black arrows* are natural exchanges. Quantities are in gigatons (10^9 tons) of carbon (GtC) and gigatons of carbon per year (GtC/yr)

reservoirs induced by human activity. With all biogeochemical cycles, it is important to understand not just the size of the reservoirs, but also the fluxes between them and the "lifetime" of the reservoir turnover. That is why a "small" increase in CO_2 from fossil fuels (1 % per year increase) can build up in the atmosphere. Similar cycles can be drawn for a number of different important nutrient species.[12] Earth system models are now starting to represent these reservoirs and fluxes in the various components.

The terrestrial biosphere (soil and vegetation) is the largest gross exchange of carbon (often called the **gross primary productivity**, or GPP) with the atmosphere. The sink of carbon from the atmosphere to the land cannot be measured but is typically calculated as a residual. Nearly half of the CO_2 we emit from fossil fuels and land use change (deforestation) stays in the atmosphere. Observations indicate that a bit less than one-quarter of the additional CO_2 is going into the ocean.[13] This leaves about one-quarter of human emissions to go into the land surface. Thus, half the additional CO_2 is flowing through the carbon cycle and leaving the atmosphere (where it does not function as a greenhouse gas to warm the planet). One of the big outstanding scientific questions in the field of biogeochemistry is whether this partitioning of the **carbon sink** from the atmosphere will continue. If forests die, or if the carbon trapped in

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[12] An overview of other trace element cycles is found in Jacobson, M., Charlson, R. J., Rodhe, H., & Orians, G. H. (2000). *Earth System Science: From Biogeochemical Cycles to Global Changes*, Vol. 72. New York: Academic Press.

[13] Takahashi, T., et al. (2002). "Global Sea—Air CO_2 Flux Based on Climatological Surface Ocean pCO_2, and Seasonal Biological and Temperature Effects." *Deep Sea Research Part II: Topical Studies in Oceanography, The Southern Ocean I: Climatic Changes in the Cycle of Carbon in the Southern Ocean, 49*(9–10): 1601–1622. doi:10.1016/S0967-0645(02)00003-6. For a classic overview of the carbon cycle and sinks, see Siegenthaler, U., & Sarmiento, J. L. (1993). "Atmospheric Carbon Dioxide and the Ocean." *Nature*, *365*(6442): 119–125.

permafrost is released, the carbon budget may change. One of the key goals of land models is to simulate the carbon cycle and predict whether and how it might change.

The land surface is an important part of the carbon cycle that helps determine atmospheric CO_2 levels (and hence climate). Organic matter contains a great deal of carbon. Organic molecules generally contain a ratio of carbon to hydrogen to oxygen (C:H:O) of 1:2:1. Understanding and representing the biogeophysics of plants and soil is the first step to determine the temperature, moisture, and plant types, from which the carbon contained in plants can be estimated, and its evolution through soil and exchanges with the atmosphere can be modeled. The reason why plants transpire water is because their stomata (like pores, but in leaves) open to allow the exchange of CO_2 and oxygen for photosynthesis, and some water is lost. Increasing concentrations of CO_2 in the atmosphere can reduce the need for plants to open their stomata and lose water, because it is easier for the plant to collect CO_2 from the atmosphere. The change in plant physiology with higher CO_2 can change the growth rate of plants, and their primary productivity, thus changing the sink of carbon.

The response of plants to increasing CO_2 is often called **CO_2 fertilization** or the **carbon cycle feedback**. One hypothesis regarding increased land uptake of carbon is that plants are more efficient at growing with higher CO_2 concentrations and can grow more, pulling more carbon into their tissues. But increasing temperatures and changing precipitation are confounding factors that may limit the efficiency of plant growth. Thus,

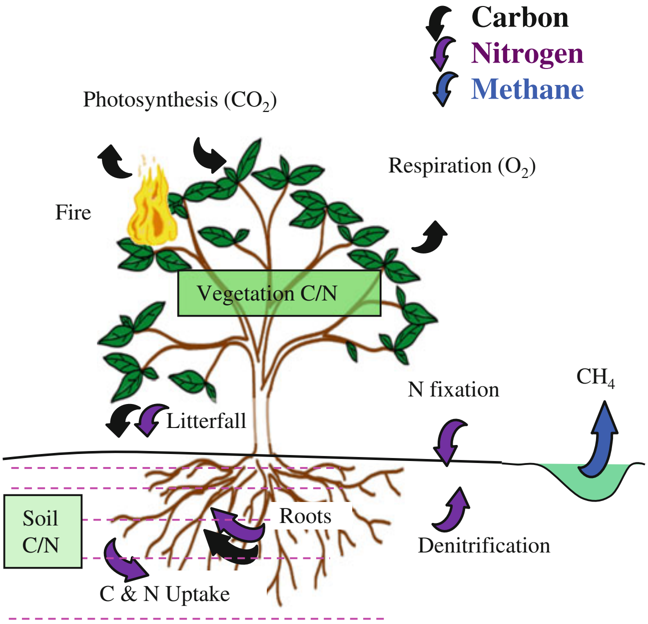

Fig. 7.7 Biogeochemical cycles in a terrestrial system model. Vegetation carbon and nitrogen go into the soil or the atmosphere. Carbon is produced in plants from photosynthesis. It leaves plants when they burn or decay, the latter carbon going mostly into the soil. Nitrogen is fixed and removed (denitrification) from the soil. Methane is produced in wet (anoxic: no oxygen) environments. Adapted from Lawrence and Fisher (2013)

understanding the carbon cycle, and representing it, becomes critical for the evolution of atmospheric CO_2 and the climate system. The cycle is built up from careful measurements of how plants grow and process nutrients (physiology), how they compete and evolve, and then how they respond to climate and climate changes. Chapter 11 discusses some of the predictions of the carbon cycle from current climate models.

Terrestrial models are now including representations of the transport of carbon in the system with representations of the carbon cycling, sometimes called biogeochemistry. An example is shown in Fig. 7.7. Vegetation and soil carbon are primary reservoirs. Key processes for carbon are photosynthesis, respiration by plants, and decay in the soil. Methane (CH_4) is important in aquatic or inundated ecosystems, where methane is produced by bacteria in the absence of oxygen.

But carbon is not the only biogeochemical cycle that is important for climate. Organic matter contains and requires other elements as well. After carbon, organic matter contains nitrogen, in a ratio varying from C:N of 106:16 in the ocean to 160:1 for plants, and 15:1 for soil organic matter. Nitrogen gas is the largest component of air, but it is inert and can be converted for organic use ("fixed") by only a few plants and microbes in soil, symbiotically living with plants, or some algae. Specifically, atmospheric nitrogen (N_2) is converted into ammonia (NH_3) by an enzyme. The absence of this fixed nitrogen can limit plant growth. Hence, representing nitrogen is important for understanding how plants will use water and carbon. Figure 7.7 also shows some important terrestrial processes for the **nitrogen cycle**,[14] including fixation (making nitrogen into forms used by plants) and uptake in soil, and leaching and loss of fixed nitrogen in soils. There are a whole host of other nutrients that play a role in the growth of ecosystems in small concentrations. Phosphorous and iron are the next most important elements, and iron may be a limiting nutrient in some ocean ecosystems, as it can arrive only by dust deposition to the ocean surface.

The Carbon Cycle

Carbon is magic stuff. It makes up organic matter, whether living plants (including algae in the oceans), organic matter from dead plants (or algae) in the soils or on the sea floor, or animal tissue (our bodies, or plankton in the ocean). The carbon that is in our bodies or in plants comes ultimately from minerals in the earth, but it often arrives by being a gaseous species in the atmosphere. The carbon dioxide and methane that are greenhouse gases regulate and alter the radiative energy leaving and entering the earth system. Carbon dioxide is used by plants in photosynthesis and is a by-product of the respiration process used by animals for energy, returning to the atmosphere or mineral form when we are done using it (and plants or animal tissues decay). This cycling is critical for understanding how the climate evolves on long timescales. And by long, that can mean geological timescales (up to millions of years).

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[14] Galloway, James N., et al. (2008). "Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions." *Science, 320*(5878): 889–892.

The carbon cycle is one reason that climate change is a difficult problem to understand, predict, and simulate. For many environmental issues, a human-induced chemical, compound, or process is introduced into the earth system that did not exist before, for example, the refrigerants called **chlorofluorocarbons** (CFCs) that cause depletion of stratospheric ozone, or chemicals like Dichloro-diphenyl-trichloroethane (DDT) that cause cancer in humans and animals. These chemicals do not even sound natural. But with climate change, the "culprits" are a part of the system itself: Carbon dioxide is literally the breath of life for plants, and it is part of our bodies and the food we eat. Like many things, it is the change in natural cycles, "too much of a good thing," that potentially alters the system. And because the systems are delicately balanced and coupled (carbon dioxide affects transpiration, which alters water fluxes at the surface; e.g., see Fig. 7.6), large climate changes can result.

The carbon cycle is in a delicate balance, and is coupled to the climate system on many timescales. Because the two most important greenhouse gases after water vapor are part of the carbon cycle (carbon dioxide and methane), carbon has a very direct effect on the radiation absorbed and emitted by the earth, and hence the global climate.

The different reservoirs in the carbon cycle (see Fig. 7.6) have different timescales: from days to years in the case of plants and soil, to hundreds of years for the atmosphere and deep soil, to thousands of years for the ocean, and millions of years for weathering and sediments. The feedbacks in the system are complex. Carbon moves in and out of the atmosphere, and into other reservoirs. Slow feedbacks from weathering and burying carbon in sediments are different than many of the faster feedbacks between land and atmosphere. The ocean and land are currently thought to be taking up more carbon than they release because of the increase in atmospheric carbon dioxide. The land can change much faster than the ocean, because it is more prone to disturbance, and the ocean acts as a big damper on the system. A key current goal of earth system models is to represent flows and reservoirs of carbon in the earth system. In the atmosphere, it is fairly simple to represent carbon containing gases and particles. The land surface and ocean require extensive treatment of their biology to cycle carbon through the systems and determine its fate. These biological cycles and models are some of the most important and uncertain parts of earth system models, and representing their feedbacks becomes important on long (century or more) timescales.

7.4 Land-Atmosphere Interactions

From the descriptions in Sect. 7.3, you can see that there are several important ways in which the land surface is coupled to the atmosphere and can affect the atmosphere directly. The effect can certainly be on climate scales, such as the scale of the carbon cycle and the CO_2 fertilization effect. But the coupling can be short term and more process based, such as the land surface cycling and processing of water through the surface hydrologic cycle. Precipitation falls on the land surface, and can take several pathways. Surface water can evaporate back into the atmosphere. This changes the climate in some regions by providing a water source. But subsurface water in the soil (soil moisture) can be recycled back into the atmosphere by transpiration from plants. This can directly affect the low-level atmospheric humidity, and recycle humidity, for example, back into the lower atmosphere, where it can alter cloud formation. The humidity and soil moisture can also alter the partitioning of surface fluxes between sensible heat (increasing temperature) and latent heat (increasing evaporation).

Altering the local hydrologic cycle can affect short-term weather systems, or long-term climate. One storm may moisten part of a land surface. The runoff or soil moisture provides future evaporation back to the atmosphere, but it also can reduce temperatures when that evaporation occurs. On the climate scale, the moisture recycling of terrestrial systems may maintain certain climate zones. The Amazon rainforest is often called the **green ocean**. This is partially because rainforest plants provide a large additional source of humidity back into the atmosphere that can rapidly recycle rain back into the system. Many models do not capture this effect fully. If the Amazon exists because of these couplings between land and atmosphere, it may not be stable to large-scale disruption. Many coupled climate models have trouble maintaining the Amazon rainforest: It tends to dry out and turn to grassland if precipitation is a little too low. This highlights the importance of understanding and representing land-atmosphere coupling in global climate models.

7.5 Land Ice

Snow- and ice-covered surfaces are other large and long-lived parts of the terrestrial system with important implications for climate.[15] Ice sheets include Antarctica and Greenland but also some small ones in Iceland and other regions. There are also numerous glaciers in high latitudes and high altitudes distributed around the planet. But it is really Greenland and Antarctica that contain large amounts of ice. The cryosphere on land, like that contained in sea ice, is important for its effect on the earth's albedo. The land-based frozen water is also important for the storage of freshwater and regulation of sea level. In addition to the rapid decrease in Arctic sea ice and seasonal snow cover, there is increasing evidence of surface melting and increased glacier flow in Greenland. The increased awareness of the potential risk of significant melt, or catastrophic collapse (which would raise sea level, and change the ocean density in a region of deep water formation), has motivated detailed observations and modeling studies. The simulation of ice sheets on land is

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[15] An overview of the role of the cryosphere in climate is contained in Marshall, S. J. (2012). *The Cryosphere*. Princeton, NJ: Princeton University Press.

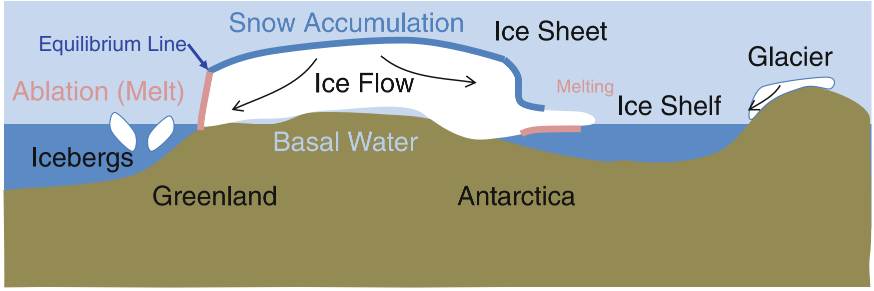

Fig. 7.8 Glaciers and ice sheets. Greenland (*left side*) has ablation (melt) on the lower parts and accumulation on the upper parts. Basal (base) water lubricates ice flow. Antarctica (*right side*) has ice shelves with melting beneath, and some of the ice sheet is grounded below sea level. Glaciers (*far right*) have similar processes including ice flow

still evolving rapidly, and many climate models do not fully treat ice sheets. Glaciers are typically not treated at all. In the absence of an ice sheet model, the ice-covered regions are just treated as (permanently) snow-covered land.

Terrestrial systems often have fairly sophisticated models of snow that falls on land, ice, and sea ice. This is because snow serves as an intermediate layer that mediates surface energy and water fluxes between the atmosphere and land or ice surface. Snow has a different albedo from land or ice, and the albedo can change over time as the snow crystals “age.” Snow models generally have several layers and a complex representation of radiative fluxes. Snow models also treat deposition of particles on their surface: Particularly important in some regions is soot (black carbon) particles from fires and industrial activity, or mineral dust from far-away deserts. These dark particles can significantly lower snow albedo, resulting in more absorption of solar energy. This means more snow melt, and it can accelerate albedo feedbacks at high latitudes. Snow also acts as a strong insulator, keeping high-latitude soils much warmer through the winter when snow is present than when it isn’t. In fact, changes in snow depth due to climate change can have as big an impact on soil temperatures as climate warming itself (either amplifying or offsetting climate change, depending on whether snow depths increase or decrease).

Glaciers and ice sheets have many of the same surface properties, and indeed, a snow model would commonly also run where there is an ice sheet or glacier (annually retained ice at the surface). But ice sheets and glaciers have other components of surface melting and accumulation in addition to radiative fluxes at the surface. Ice sheets can also be present for a long and stable period of time. Ice cores dating back 800,000 years and over 2 miles (3 km) deep have been retrieved from Antarctica.[16] Ice sheets and glaciers also move slowly. Simulating ice sheets requires simulating the accumulation and melting process as well as the ice flow.

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[16] There is an 800,000-year record from the “Dome C” ice core. Original results are reported in Lüthi, D., et al. (2008). “High-Resolution Carbon Dioxide Concentration Record 650,000–800,000 Years Before Present.” *Nature, 453*(7193): 379–382.

Simulating the flow is critical and difficult, because ice sheet and glacier flow depends strongly on the melting and the pressure on the bottom (bed) of the glacier.

Antarctica and Greenland have slightly different processes, illustrated in Fig. 7.8. Greenland has a large region at lower altitude where the ice is melting (ablation) for part of the year. Greenland also has ice streams that run into the sea and calve (creating icebergs) at isolated points around the edge. There is also significant melting that flows down into the ice sheet forming "basal water", potentially lubricating the base for faster flow. The overall balance of an ice sheet depends on the balance between the accumulation (snow) on one hand and flow and melt on the other. There is an "equilibrium line" where the accumulation balances melt. Usually, melt dominates at lower elevations, and accumulation dominates at higher elevations (see Fig. 7.8). For Greenland, this line appears to be rising (more melting over more of the ice sheet).[17]

Antarctica is different. Temperatures are cold enough so that accumulation occurs across the entire ice sheet. In fact, warmer temperatures due to increased greenhouse gases will not bring the temperature above freezing. But they will allow more water vapor in the air, which will still fall as snow, and potentially lead to more net accumulation over the ice sheet. Antarctica has large ice shelves and even portions that are grounded below sea level, held in place by the weight of ice above. Ice sheets are supplied by flow from the interior, and they lose mass by iceberg calving at their face, but also by subglacial melting. If warmer water occurs underneath the ice shelf, this can erode the shelf in a sudden collapse, increase the flow, or even make the grounding line retreat (so that more of the ice sheet is floating and less stable). Recent analysis of the West Antarctic ice sheet indicates that such melting may already be happening. Recall that the West Antarctic ice sheet accounts for about 10 % of the Antarctic total ice mass, or about 23 ft (7 m) of sea-level rise. The only good news is that this may take several centuries to happen.[18]

The equations to model all of these ice sheet processes are relatively straightforward applications of **deformable solid mechanics**, the description of how a solid material acts when force is applied or the temperature changes. They must also represent the different processes that occur, including subglacial water and melting from the bottom of ice shelves. Land ice models typically are simulated with long time steps (a season or a year) so that they can be run for thousands of years.

Including these ice sheet models in global climate models has begun recently and is an ongoing task, made urgent by the continued buildup of greenhouse gases and warming high latitude (especially Arctic) temperatures, combined with observations of significant increases in melting for Greenland. This all adds up to potentially large changes in sea level over the 21st century, hence, the desire to include ice sheets in climate models as a key part of the terrestrial system.

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[17] Van den Broeke, M., et al. (2009). "Partitioning Recent Greenland Mass Loss." *Science, 326* (5955): 984–986.

[18] For a summary of the West Antarctic ice sheet, see Oppenheimer, M. (1998). "Global Warming and the Stability of the West Antarctic Ice Sheet." *Nature*, *393*(6683): 325–332.

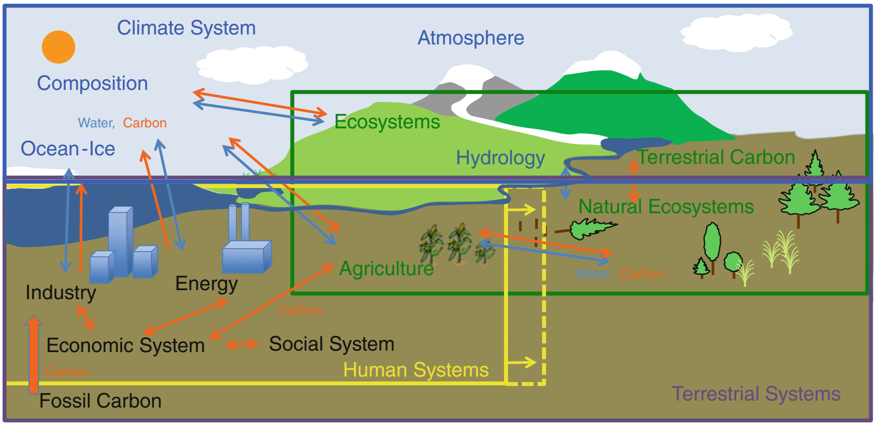

Fig. 7.9 Humans and integrated assessment. Interactions between human and natural systems. Human systems are outlined in *yellow*; interactions with terrestrial systems, in *purple*; natural ecosystems, in *green*; and the climate system, in *blue*. Fluxes of water (*blue arrows*) and carbon (*orange arrows*) occur, starting with fossil fuel carbon being added to the human economic system, then being released into the atmosphere or onto the land surface

7.6 Humans

Finally, we come back to look in the mirror at the last, and perhaps most significantly altered, part of the terrestrial surface, the anthroposphere[19]: the realm of human systems and their effect on climate. As is clear, this goes well beyond just the emissions of CO_2 from burning fossilized carbon fuels. We have already discussed several aspects of human influence: Cropland as a plant functional type and deforestation are examples of human-caused land use change, with subsequent effects on the carbon cycle and regional climate. But human systems also respond to climate, and our economies and underlying social systems are also affected by the climate changes we unwittingly produce. Thus, the anthroposphere is not just a simple flux of "stuff" (whether fossil fuel emissions or acres of cropland), as illustrated by the one-way arrow from the power plant in the carbon cycle schematic of Fig. 7.6. Instead, it is tied to the terrestrial and earth system. Models of how human systems react to climate are now starting to be coupled into terrestrial system components of earth system models. Here, we discuss some of these important feedbacks and how they are simulated.

Figure 7.9 attempts to describe the anthroposphere in the context of terrestrial systems and the climate system. Industrial emissions and emissions from our energy system flow into the atmosphere. But the climate system also forces changes in the energy system: Hotter climates increase demand for energy used in cooling.

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[19] Also called the anthrosphere. The term also has a companion for a geological epoch, *the Anthrocene*. See Crutzen, P. J. (2002). "Geology of Mankind." *Nature*, *415*(6867): 23.

Changing water availability affects industry and also affects agriculture. Agricultural land (pasture and cropland) has very different surface properties than natural vegetation, which can result in significant differences in evapotranspiration, affecting precipitation, and albedo, affecting surface temperature. Changes in precipitation and temperature in turn feedback on crops: requiring changes to crop types or additional irrigation water if available. All of these feedbacks can be predicted and modeled, with varying degrees of fidelity. Ultimately, human systems like industry, energy, and agriculture respond to price signals from the economic system. The costs of energy and agriculture are affected by the natural environment. This is most obvious with agriculture: Rrain and temperatures strongly affect crop yields and the necessity for irrigation. Then crop yields in different regions affect overall prices for crops, the mix of crops, and ultimately the economic system.

Many terrestrial systems models are starting to include complex representations of the physical side of the anthroposphere: agriculture and urban environments. Agriculture is a significant fraction (one-third) of total land area,[20] so it has a large physical effect. The effect of urban areas is significant as well due to significantly different albedo and evaporation characteristics of hard (nonporous) surfaces common in densely built-up areas (roofs and roads). The extent of urban area (less than 0.5 % of the total land area) is small. However, cities have a large impact because of the intensity and magnitude of their emissions. It is also important to simulate urban areas because cities are home to half of the global population. Simulation of urban environments generally starts as a discrete land surface type in a model, but it may evolve to have its own emission characteristics as well.

There are many varieties of economic models. Economic models range from simple supply-and-demand curves (an economic model of a single product in a spreadsheet), to complex models of entire economies or even the global economy. Such macroeconomic or sectoral models typically have similar supply-and-demand curves for different regions of the planet and different economic activities that are interdependent, and can be solved for a solution to all these supply-and-demand equations that end up yielding predictions of economic output and prices. These **economic system models** encompass the Industry, Energy, and Agricultural sectors of the Human Systems box in Fig. 7.9.[21]

Economic models can also be coupled with the climate and environmental factors. Climate factors can alter supply-and-demand curves (crop yields based on weather, for example). The result of these feedbacks is ultimately to alter the trajectory of human systems to react to changes in the environment: If climate changes, crops may not be viable in certain regions, and the economy and society will adapt. Some regions will suffer, but other regions may benefit from increased crop yields in colder climates that have warmed, and this also needs to be factored

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[20] Data from UN Food and Agriculture Organization (FAO) Statistics Division (FAOSTAT), http://faostat3.fao.org/.

[21] An economic system model is another name for a macroeconomic model, a model tool designed to simulate a country or region. Many different types, descriptions, and simple models are available on the web.

in. There are basic empirical economic relations that are applied (supply and demand). Then when climate affects human systems, the systems will respond by altering their outputs: including altering their emissions of greenhouse gases. Thus, instead of specifying levels or emissions, such models can attempt to predict emissions by simulating the economic results. They can also attempt to look at the future state of the economy as it co-evolves with climate. When used for assessing future economic states and different economic policy options, these are termed *integrated assessment models.*

7.7 Integrated Assessment Models

Integrated assessment models are generally macroeconomic models that include some linkage to the earth system, and some relationships for the feedbacks in Fig. 7.9 between the physical and human climate systems.[22] Traditionally, such models have a simplified representation of climate (often an energy balance model, or a simple regionally average climate) to represent the physical part of the system. With increases in computing power, however, key parts of these models are increasingly being coupled to full climate system models (see Chap. 8). Essentially, the macroeconomic component is a big series of linked supply-and-demand curves. Supply and demand curves indicate what products are delivered and services produced for demand for different economic sectors. Construction demand is fueled by the need for houses, this causes demand for materials, and the people who receive money for the materials and houses they build then buy cars and houses themselves, etc. These economic equations are coupled to the physical system and is discrete geographically (usually by country, but often with some distribution of effects based on physical distributions of population). There are several challenges to this approach, however.

Humans are unique in that they (sometimes) plan for the future. Coupling of integrated assessment models tries to reflect this. An integrated assessment model would be run every time society wants to adjust for the future. This might be the end of every 10 years of a climate model run. The assessment model might run forward 100 years, and the new trajectory of emissions used for the next 10 years in the climate model. Predicting what will happen in an economy for the next decade includes projecting out the economy for many years and deciding if policies and laws should change, then stepping forward with the altered economy, and then doing it again next decade. This is very different from the physical system, and it makes coupling of economic models and physical models difficult.

Another challenge is inherent to economic simulation itself: The “laws” of economics are merely empirical results. There is no conservation of energy and mass in economies to guide a model. Money and people can be “created” or

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[22] Parson, E. A., & Fisher-Vanden, A. K. (1997). “Integrated Assessment Models of Global Climate Change.” *Annual Review of Energy and the Environment, 22*(1): 589–628.

"destroyed" in the human system at will. The laws of economics work, until they don't, and appropriate economic theory is often contradictory, and melded with politics. A simple example is whether countries with economies in recession (not growing) should borrow money for the government to spend to grow out of the recession, or reduce spending by the government to give people more money. For the latter effect, some economists claim that reducing government revenue (taxes) adds to economic activity, while others claim it does not. The economic debate on this issue is raging in the second decade of the 21st century.

Furthermore, the economic relationships vary over time. The supply-and-demand curve for gasoline will change as technology for both extraction and use changes. Predicting the future for these models is fraught with the problem of being forced to project the past into the future. Usually technological change is treated as incremental improvements/changes to processes or consumption. But technology is not smooth: It is often disruptive. What would an economic simulation of the news and media (or book publishing) business from 1990 look like today, over 20 years later? The 1990 prediction might estimate printing presses would have gotten more efficient, but it would certainly not "predict" the impacts of the Internet or electronic music players, smartphones, and tablets on consumption of books and music. Or consider the example of energy system models, which tend to react from crisis to crisis, and do not see sudden changes well. The rise of hydraulic fracturing technology, which allows fossil fuels to be extracted more economically from different types of geology, has drastically reshaped energy markets and the relative cost of different fuels just in the period 2007–2013. We return to these issues in Section III, on uncertainty.

7.8 Challenges in Terrestrial System Modeling

There are many challenges and complexities in modeling the different parts of the terrestrial system. Some challenges are related to modeling of specific pieces (e.g., land ice), and some are challenges that integrate across the different pieces of the terrestrial system (biogeophysics, hydrology, humans, and nutrient cycles).

7.8.1 Ice Sheet Modeling

Ice sheet models are still developing rapidly. Their development has been spurred by recent observations of significant changes to the ice sheets that raise concerns about changes in global sea level (see Chap. 8). There are several ongoing challenges in developing ice sheet models. First is uncertainty in the complex topography of the base (bottom) of ice sheets. Not surprisingly, often the topography is not fully detailed, as it must be sensed through miles of ice. In addition, there exist uncertainties in some of the dynamic processes that occur, such as the water that lubricates glacial flow. So the problem becomes similar to the complexity and heterogeneity of the land surface, but now the whole surface model is in slow motion. Another issue is subglacial melting from ice shelves. Melting from contact with ocean water underneath floating ice sheets or shelves is strongly dependent on ocean circulation. This problem is critical for Antarctica.

Land ice models must also be run with relatively long time steps for thousands (or hundreds of thousands) of years, making the simulation of ice sheets in the coupled climate system very challenging. Because of the complex topography under the ice sheets (and limited area), they are often run with small grid sizes (high horizontal resolution). These models are challenged also by the lack of key data, such as the detailed topography under the ice sheet, and especially limited observations of surrounding oceans underneath thick floating ice shelves. Thus dynamic simulation of ice sheet processes is a challenging task.

7.8.2 Surface Albedo Feedback

The albedo feedback hinges on sudden changes at the terrestrial surface. Albedo is the "absorption fraction" of the surface and depends on the color: Dark surfaces such as the oceans, or a dark green forest, absorb more light (and have a high albedo, close to 1). Light surfaces, such as snow, ice, and light, bare soil as found in deserts, have a low albedo (close to zero). Albedo can refer to any wavelength, but here we refer to solar wavelengths (visible light from the sun). Reflecting solar energy from light surfaces tends to cool; absorption by dark surfaces warms.

This make a classic positive feedback: If sea ice over the dark ocean or snow over darker vegetation melts, then the albedo goes up, the absorption of energy goes up, and the temperature goes up, melting more snow and ice and exposing more dark ocean. Conversely, if the temperature drops, ice and snow expand, reflecting more light and cooling the surface, resulting in more snow and ice. Note that a positive feedback amplifies both ways; it amplifies cooling and warming. A negative feedback damps both ways, causing changes to be minimized.

The connotation of feedbacks in terms of climate change is actually the *opposite* of common usage: Negative feedbacks are usually "good" (they damp changes), whereas positive feedbacks cause larger changes (bad, especially if you are a polar bear). When you receive negative feedback from your boss, however, it is usually *not* good. The snow-ice albedo feedback is a big amplifier of climate changes in snow- and ice-covered regions, and it is a reason why the Arctic has warmed more than other regions recently. It is also a mechanism that naturally comes into play during ice age cycles, as advancing glaciers and sea ice cool the planet. The feedback depends on exactly how much snow and ice there is: If the snow is too thick to melt at some point in the annual cycle, then the albedo doesn't change much for a given heat input. Also, if there is little snow left to melt, there is not much temperature change with more heat. This means that the ice-albedo feedback contribution to the climate sensitivity is variable with the current climate state. As a practical matter, this makes looking into the past for paleoclimate records of previous ice ages not that useful (and potentially misleading) for understanding the present sensitivity of the system.

7.8.3 *Carbon Feedback*

In Chap. 5, we discussed cloud feedbacks, and in this chapter we discussed surface feedbacks with ice and snow. Cloud feedbacks are "fast" (minutes to hours) and ice and snow feedbacks are "slow" (decades to centuries for ice sheets). There are also a spectrum of slow feedbacks related to the cycling of carbon in the climate system. The simple example is the land carbon in soils and plants. Changing the level of CO_2 makes plants grow more efficiently. With more CO_2 in the atmosphere, plants open their pores less to let in CO_2, which reduces water loss and makes them more efficient. An analogy would be what happens to humans going from higher to lower altitudes: As oxygen increases, breathing is more efficient (though we usually experience this in reverse when we go to higher altitudes).

So what happens if CO_2 increases (if all else is equal, which is a big "if")? Plants would tend to grow more, and this would increase their CO_2 uptake, reducing atmospheric CO_2 (a negative feedback). This assumes that plants are "limited" by CO_2 and not by water and nutrients. It may not work if nutrients or water are limited. For a human, more oxygen will make you more efficient at breathing, but you still need enough food and water. In addition, warmer temperatures may increase the decay of plant material (e.g., dead leaves) that returns CO_2 to the atmosphere and leaves less in soils. There are many feedbacks with the land surface that, rather than changing the energy budget, directly change the partitioning of carbon between land (or even the ocean) and the atmosphere. The change in CO_2 in the atmosphere changes the energy budget.

These carbon feedbacks may be important on long timescales and would modulate the fast feedbacks in the atmosphere, making them critical to understand for long-term climate change. In addition, storage of carbon in the ocean and ocean ecosystems can also affect atmospheric CO_2, and the global carbon cycle.

7.9 Applications: Wolf and Moose Ecosystem, Isle Royale National Park

This case study demonstrates the methodology of participatory scenario planning for a terrestrial system and how consideration of a specific application defines the role of uncertainty (a point made again in Chaps. 11 and 12). Isle Royale is a small national park in Lake Superior, the largest of the U.S.-Canadian Great Lakes. A unique and valued attribute of the park is a precarious balance between the wolf and moose in the park: a predator-prey ecosystem. The existence of the ecosystem with both animals is generally attributed to sporadic formation of an ice bridge between the island and the Canadian mainland. With the dependence on an ice bridge, there is an explicit relationship between sustaining the populations of these species and maintaining a diverse gene pool by communication with the mainland. This communication is dependent on the climate that creates this ice bridge.

This case study involves a scenario-planning process where plausible, not probable, futures are developed to facilitate investigation of management decisions and develop preparedness.[23] Physical climate projections of temperature and precipitation from climate models have been used to describe projected changes in the environment for a time range in which management decisions are consequential (decades). The focus is on the projection with the "least change" from the present. Though more extreme projections are considered, the least change projection lies at the foundation of the formation of scenarios. The scenarios are formed through a participatory process where, for example, an extreme event (e.g., a wind storm) is conjectured with ecological consequences (e.g., trees blow down). Multiple scenarios are considered, with the responses framed by management priorities, which might include conservation requirements, wilderness management, infrastructure, or visitor experience.

Isle Royale is a small park (about 250 square miles, or 650 km^2), smaller than the resolution of global land models used in climate models. Though large, Lake Superior is not represented with fidelity in global climate models, often treated as a land-surface type. The local, lake-influenced weather processes, responsible for the park's climate, are not represented well in current climate models. Moreover, physical processes such as summertime convective precipitation have large regional biases in models. Therefore, there are substantial barriers to direct, credible application of climate model projections.

In addition to the structural shortcomings of climate models, parameters important to the park, and in particular to the wolf and moose ecosystem, are not directly simulated. An overt example is lake ice, fundamental to the existence of the wolf and moose populations by connecting the island to the mainland. Other parameters include snow cover and winter melt, which directly influence access to moose browsing habitat (food). Decadal trends in observed lake ice cover indicate up to 70 % reductions, with this trend interrupted by extremely cold winters (e.g., 2013–2014) with high amounts of lake ice. This brings attention to variability and in this instance focuses the discussion on questions of changes in variability hypothesized as a possible response to long term changes in the high Arctic.[24]

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[23] Details and results of this case study can be found in "Using Climate Change Scenarios to Explore Management at Isle Royale National Park," http://www.nps.gov/isro/learn/nature/using-climate-change-scenarios-to-explore-mangement-at-isle-royale-national-park.htm.

[24] The possibility that changes in the Arctic might have strong influence on mid-latitudes was proposed by Francis, J. A., & Vavrus, S. J. (2012). "Evidence Linking Arctic Amplification to Extreme Weather in Mid-Latitudes." *Geophysical Research Letters, 39*: L06801. doi:10.1029/2012GL051000. This is an active research area.

Climate observations and climate projections provide a background for discussion. Essential in the application was evaluation of local weather processes and whether or not models represented these processes. This helped to develop trust of the expert guidance to interpret model information. Attention is naturally drawn to recent extreme events and whether or not these extremes are consistent with projections, for example, more precipitation occurring in extreme events. Warm and dry spells in the winter and spring that alter greening of forests, followed by damaging cold, is another example. Convolution of climate, extreme events, and ecological responses sit at the foundation of plausible futures. For example, if there is large-scale disruption of forests by drought, fire, or wind that leads to the death of many trees, then the future forest will be recovering in a much different mean climate than in which it originally evolved.

Since Isle Royale's forests are at the southern extent of the subarctic (or boreal) forest, and that extent may well move northward in a warmer climate, it is unlikely that a boreal forest disrupted by drought, fire, or wind will be regenerated. Given the importance of specific tree species to moose food supply, this would be a negative indicator for moose populations. Evaluation of the combined influence of climate drivers was largely negative for maintaining the wolf-moose ecosystem. Though climate change is only part of the portfolio of factors in the decision-making package, it demonstrates that in the future it will be even more difficult to sustain this precarious ecosystem. A driving conclusion from this exercise is the need to plan for best possible futures rather than manage toward preservation or conservation of the past.

7.10 Summary

Modeling the earth's surface means modeling a complex set of coupled terrestrial systems. The surface fluxes that occur in the climate system are strongly affected by key properties of the surface: Water fluxes are affected by transpiration from plants. The presence of water is also important for moving energy around and releasing it as latent heat (analogous to the role of water in the atmosphere). This is very important in semiarid regions with dry soils. Transpiration of water from plants is an important part of surface processes. And since plants and ecosystems are dynamic and respond to climate, representing different plant types and the ecosystems that support them is critical. Furthermore, the growth and decay of plants in ecosystems depends on critical nutrients, such as carbon and nitrogen. Carbon is the common lifeblood of the earth system, changing forms from the solid earth and sediments, to biological tissue on land, in soils and in the ocean, to a greenhouse gas in the atmosphere. Understanding carbon couples terrestrial systems to climate as well. These systems include the cryosphere (snow and ice) and the anthroposphere (agricultural land, urban areas).

Modeling terrestrial systems involves several components. The biogeophysics of the system is described by a model of energy and water flows, including the absorption and emission of radiation. The hydrology of the land and the terrestrial water cycle is also simulated: Precipitation is input; evaporation, transpiration, and storage in soil moisture occur; and the remainder becomes runoff.

Terrestrial systems generally include a description of the type of ecosystems (plant types) on the surface and soil properties in the subsurface, often in detailed small-scale tiles. The descriptions of the plant types are typically based on climate effects and are not necessarily considered a "detailed" description by an ecologist. Descriptions of plant types represent the effects of ecosystems, or a population of plants, not individual plants. This is similar to parameterizations of clouds in the atmosphere designed to represent a distribution of clouds and their effects, not a single cloud. Different ecosystems have very different properties (height, leaf area, root depth, and transpiration) that affect surface fluxes. The ecosystem descriptions can be dynamic and evolve over time.

Key nutrient cycles, usually carbon and then nitrogen, are often added to land surface models to improve the ability to simulate changes in terrestrial carbon budgets. Changes to the land surface cycling of carbon can alter CO_2 storage and emission.

Ice sheets and snow are an important land cover type for altering albedo and solar energy absorption at the surface. And ice sheets are important for storing water that affects global sea level. There are many complex and incompletely observed processes that determine the balance of ice sheets between accumulation, melting and flow. The Antarctic and Greenland ice sheets have different characteristics and critical uncertainties. The Antarctic ice sheet is sensitive to ocean processes beneath ice shelves and at the edges. The Greenland ice sheet is sensitive to melting on the surface and lubrication at the base.

Finally, many of these land properties are affected by human systems, and these human systems are tightly coupled to the climate system in two-way interactions between the climate system and human industrial, energy, and agricultural uses. Macroeconomic models can simulate these human systems and can be coupled to physical climate models to try to provide possible future "predictions" or scenarios of the co-evolution of natural and human terrestrial systems.

Key Points

- Plants play a large role in climate by moving moisture through transpiration.
- Land surface models represent soil and soil water, and many plant types.
- Nutrient cycles, like carbon and nitrogen, are important at longer timescales in the climate system.
- There are many challenges in modeling ice sheets in climate models.
- Human system models (economic models) can also be coupled to the climate system.