Chapter 2
Components of the Climate System

We experience climate generally at the surface of the earth. This is the intersection of a number of different and distinct parts of the climate system. Understanding the different components of the climate system is critical for being able to simulate the system. As we will discuss, the climate system is typically simulated as a set of building blocks, from each individual process (i.e., the condensation of water to form clouds) collected into a model of one part or component of the system (i.e., the atmosphere), and then coupled to other components of the system (i.e., ocean, land, ice). Understanding and then representing in a model the different interactions between processes and then between components is critical for being able to build a representation of the system: a climate model.

In this chapter we describe the basic parts of the earth system that comprise the climate system, some of the key scientific principles and critical processes necessary to simulate each of these components. This forms the background to a discussion of how climate might change (see Chap. 3) and a more detailed discussion of each component and how it is simulated (Sect. 2.2, Chaps. 5–8). We discuss the key components of the earth system, as well as some of the critical interactions (discussed in more detail in Chap. 8).

2.1 Components of the Earth System

Figure 2.1 represents a schematic of many of the important components of the earth system that govern and regulate climate. Broadly, there are three different regions of the planet: the atmosphere, the oceans and the land (or terrestrial) surface. In addition to these general regions, we also speak of a cryosphere, the snow and ice covered regions of the planet. This fourth "sphere" spans the ocean (as sea ice) and the terrestrial surface (as glaciers, snow and ice sheets). We address the cryosphere in discussions of the ocean and terrestrial surface. While modeling the surface of the earth is commonly thought of as just modeling the land surface, it also includes the cryosphere (ice and snow) that sits on land. The term *terrestrial* is used to encompass all these spheres, though the common term *land* is also used.

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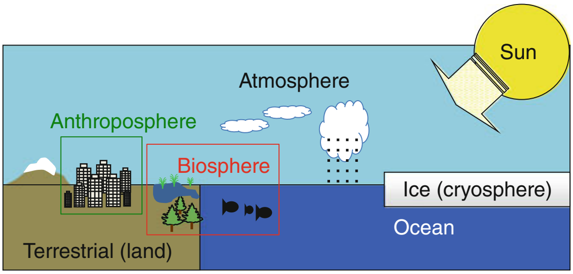

Fig. 2.1 The Earth system. The climate system contains different spheres (components): atmosphere, ocean, terrestrial, cryosphere, biosphere and anthroposphere

These are the traditional physical components of the earth's climate system. We also introduce two more "spheres." An important fifth component of the system is the biosphere: the living organisms on the planet, again, which span the terrestrial surface (plants, organisms in the soil, and animals) as well as the ocean (fish and plants in the ocean). We discuss the biosphere as part of both the ocean and terrestrial surface. Finally, although humans are technically part of the biosphere, our large "footprint" and impact on the global environment and the climate system is large enough that we can define a separate sphere for human activity and impacts called the *anthroposphere* (see Chap. 3).

2.1.1 The Atmosphere

The **atmosphere** is usually the first part of the climate system we naturally think of. It is literally the air we breathe: mostly inert nitrogen (78 %) with oxygen (16 %) and then other trace gases (argon, water vapor, carbon dioxide). The oxygen is a by-product of the respiration ("breathing") of plants and other organisms: It is evidence of life on earth. The oxygen in the atmosphere did not exist before the emergence of living organisms.[1] Oxygen is emitted by plants as an outcome of photosynthesis that removes carbon from carbon dioxide. Oxygen reacts with materials (rock and ore) at the earth's surface (oxidation) and disappears from the atmosphere. One of the most common reactants is iron (iron oxide = rust), which is responsible for the red color of many rocks. Unless organisms continue to produce oxygen, it will disappear from the atmosphere. It would take a long time however: hundreds of thousands to millions of years. But it is the trace species—water vapor, carbon dioxide and methane—known as the **greenhouse gases**, that are most important in understanding the climate system and how climate might change.

[1]Kasting, J. F., & Siefert, J. L. (2002). "Life and the Evolution of Earth's Atmosphere." *Science*, *296*(5570): 1066–1068.

The term *greenhouse gas* refers to gases that are transparent to visible light emitted from the sun, but opaque (absorptive) to the "infrared" radiation emitted by the earth. This follows from fundamental physical principles described by the Boltzmann law, after Ludwig Boltzmann, a 19th-century Austrian physicist. All mass radiates energy, depending on temperature. The hotter a body (could be your body, the earth, or the sun), the more energy it radiates: and the peak energy occurs at different wavelengths. The peak radiation of the sun (surface temperature = 6,000 Kelvin[2] [K] or 10,000 °F: very hot either way) radiates a lot of the light we call visible. It is no accident our eyes evolved to be able to 'see' in the visible where the maximum solar emission is. Objects with cooler temperatures such as the temperature of the earth at about 300 Kelvin (80 °F) radiate in the infrared (longer wavelengths with much lower energy). These objects include our bodies, the earth itself, the ocean surface or clouds.

Greenhouse gases, like the glass in a greenhouse, allow in visible light from the sun, but absorb (and re-emit back down) the infrared energy from the earth.[3] The higher the concentration of these gases in the atmosphere, the greater the warming effect. The most important greenhouse gas is water vapor. Water vapor also has some other important effects in the climate system. The second most important gas is carbon dioxide.

The basic picture of the flows of energy in the atmosphere is illustrated in Fig. 2.2. The arrows represent approximate sizes of the **energy flows**[4] in the energy budget. Solar energy comes in; the atmosphere, clouds and the earth absorb some and reflect some. The technical term for the ratio of reflected over total energy is **albedo**. White/light surfaces reflect a lot and have a high albedo: snow, ice, bright sand. Black/dark surfaces absorb a lot and have a low albedo: dark green trees, the ocean, asphalt. This is why a black car is hotter than a white car or asphalt is hotter than concrete in the sun. The energy absorbed warms the object (clouds, atmosphere, surface of the earth/ice/ocean) and it 're-emits', but now at longer wavelengths and lower energy since the temperature of the surface is much lower than the sun. For common temperatures at the earth's surface (0–100 °F, –20 to 40 °C), this emission occurs in the infrared. Infrared radiation is absorbed in the atmosphere by greenhouse gases and clouds, and some returns to the earth. The earth warms the atmosphere above it in two ways. The direct conduction of heat from a warm

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[2]The Kelvin temperature scale has the same increment as the Celsius scale but starts at absolute zero, while Celsius starts at the freezing point of water and can be negative. The Fahrenheit scale has a smaller increment and the freezing point of water is 32 °F. So 1 °K = 1 °C = 9/5 °F. Scientists use °K, the United States uses °F and most other countries use °C. We will typically provide °F and °C.

[3]Strictly speaking, the analogy is not correct: The glass in a greenhouse also prevents air from escaping, and simply being transparent in the visible and restricting air motion is sufficient to keep a greenhouse warm. The actual "greenhouse" effect for glass is a small part of it.

[4]For a more detailed treatment of the energy budget, see Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009) "Earth's Global Energy Budget." *Bulletin of the American Meteorological Society, 90*(3): 311–323.

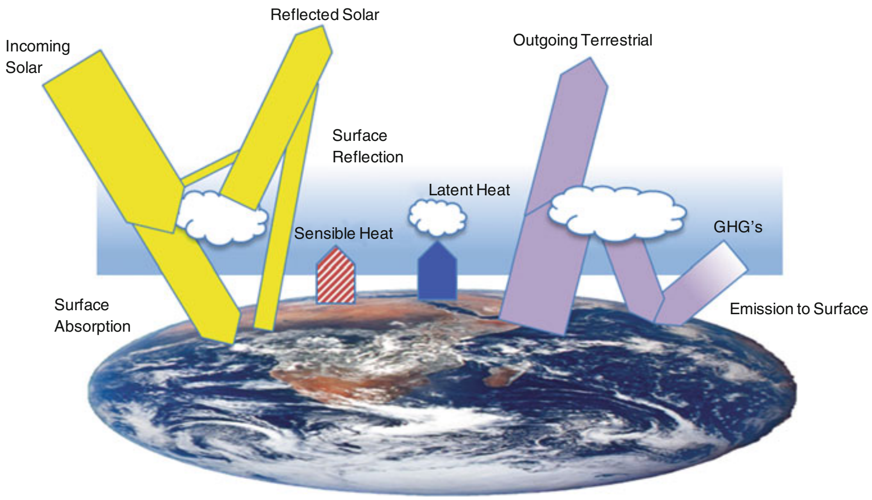

Fig. 2.2 Energy budget. Solar energy, or shortwave radiation (*yellow*) comes in from the sun. Energy is then either reflected by the surface or clouds or absorbed by the atmosphere or surface (mostly). The surface exchange includes sensible heat (*red striped*) and latent heat (*blue*) associated with water evaporation and condensation. Terrestrial (*infrared*, longwave) radiation (*purple*) emitted from the earth's surface is absorbed by the atmosphere and clouds. Some escapes to space (outgoing terrestrial) and some is re-emitted back to the surface by clouds and greenhouse gases (GHGs)

surface occurs by sensible heat. The energy hitting the surface, particularly the ocean surface, also can evaporate water vapor. Since this water vapor contains the energy used to evaporate it, it also is a way of transmitting 'heat' (energy), without changing the temperature. The energy in water vapor is called "latent heat".

This is the cycle of radiative energy in the earth system, flowing through the atmosphere. The ultimate source of the energy is the sun. One of the biggest complications is water, in all its forms: from the oceans, to water vapor in the atmosphere, to clouds. Put a cloud over a dark surface (ocean or forest), and you change the energy in the system. The energy changes by reflecting solar energy from the top of the cloud back to space (cooling). Then energy also changes by absorbing infrared energy radiated from below in the cloud and sending some of it back down to the surface (warming).

The movement of water through the atmosphere, the surface and the ocean is called the **hydrologic cycle** (Fig. 2.3), which is also important for moving energy in the atmosphere. Solar energy hitting the ocean causes **evaporation** of vapor into the atmosphere, and plants also move water from liquid phase in the soil through their leaves, back into the atmosphere in a process called **transpiration**. This water carries the energy necessary for evaporation in the form of latent heat. The energy is used to make water molecules in liquid move fast enough to separate from each other into a gas. They conserve this heat of evaporation as the water vapor moves through the atmosphere. This heat of evaporation is released when water vapor undergoes **condensation** into cloud drops (or ice crystals). This can happen a long way from the

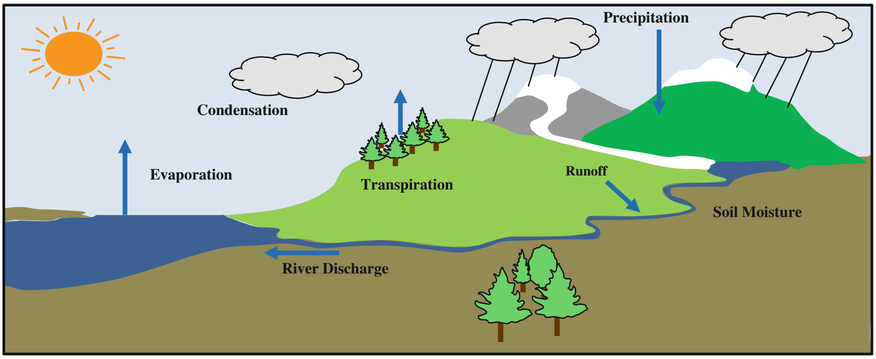

Fig. 2.3 The Hydrologic cycle. Water evaporates from the ocean and is carried in the atmosphere as vapor. It condenses into clouds, and precipitates to the surface, where it can become soil moisture, glaciers, or runoff as surface water into lakes and back to the ocean. Plants move soil water back to the atmosphere through transpiration

liquid source (oceans), and clouds eventually form enough drops that they get heavy and fall (precipitate). The water thus completes a cycle, landing back on the surface.

Water then enters other components of the earth system, such as glaciers, snow, soil or rivers. Soil moisture can go through plants to get back into the atmosphere by transpiration. Or it can saturate the soil, become runoff and eventually get back into the ocean, where the cycle repeats. The key is that water changes the energy budget because it forms clouds, because it is a greenhouse gas and because it moves heat around. Water evaporated in the tropics moves as water vapor with the winds to higher latitudes (see Chap. 5), where it condenses as clouds and deposits heat there. Water is magical stuff in the earth system. The cycle of water is linked to the energy budget (through latent heat), and it links the atmosphere to other pieces of the system.

2.1.2 The Ocean and Sea Ice

We have discussed the ocean briefly as a source of water. The world's oceans (or combining them into a single "ocean") are a critical part of the climate system.[5] The ocean is a tremendous reservoir of heat and holds a lot more mass than the atmosphere. Water is denser than air, and the mass of the top 30 feet (10 m) of ocean is equal to the mass of the atmosphere above it (90 % of the atmosphere is in the first 55,000 feet or about 17 km). The ocean is critical as a very large store of heat that can move around and come back into contact with the surface after long periods of time.

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[5]For a good basic overview of the ocean and climate, see Vallis, G. K. (2012). *Climate and the Oceans*. Princeton, NJ: Princeton University Press.

The ocean has currents that are both shallow (near the surface, the first few hundred feet of depth) and deep (the rest of the ocean). Unlike the atmosphere, the ocean has "edges": Land sticks up in places, dividing the seven seas into, well, seven seas (actually five ocean basins). The ocean surface currents are forced by the rotation of the earth and winds. These currents are constrained by the topography in ocean basins and generate **circulation patterns** of surface currents.

In addition to the near surface ocean, there is a complex vertical structure to the ocean. The ocean is divided into a near surface region that is generally warmer and less salty (fresher) than the deeper ocean below it. Colder and saltier water is denser, so it tends to sink. The process often is self-reinforcing and is seen in lakes as well: The surface warms, gets less dense and mixes less with the deeper water, thus warming more over time (this is called stratification). Density is a critical part of the structure of the ocean because of changes in density due to heat and salinity, which do not change very quickly in the ocean. Density helps control the deep ocean circulation. The deep ocean has one large circulation globally, driven by the sinking of surface water that gets saltier and colder (denser) until it sinks from the surface to the deep ocean. This **thermohaline circulation** (*thermo* = heat, *haline* = salt) has sinking motion in small areas of the North Atlantic and the Southern Ocean near Antarctica, where water is cooling as it moves poleward, and where salt is expelled from formation of sea ice, increasing salinity. Both processes make the surface water denser than the water beneath it, causing it to sink.

The ocean also contains parts of two other spheres. The ocean has a biosphere, consisting of plants and animals living in the ocean and nutrients that flow through the ocean. Most of the biosphere in the ocean is composed of small organisms, mostly small floating plants (phytoplankton, algae) and animals that form the basis of the marine food chain. The ocean is an important part of the flows of carbon through the earth system as well. The ocean also holds (or supports) part of the cryosphere as sea ice.[6] Sea ice forms in winter in high latitudes in the Arctic Ocean and in the Southern Ocean. The sea ice moves around and can grow and melt. The ice may last several years and is a year-round feature in most of the Arctic today.

2.1.3 Terrestrial Systems

Most of the land surface is not covered by ice, however. Most of it is covered by plants: the **terrestrial biosphere**. There are also lakes and rivers that channel precipitation and return it to the ocean. The atmosphere and ocean cause changes over time in the composition of the land by erosion and processing of rock material. Water, wind, and waves break up rock. The rock reacts with the atmosphere (oxidation) and with water: Sometimes minerals in rocks dissolve in water. The land

[6]For a primer on sea ice, see Marshall, S. J. (2011). *The Cryosphere*. Princeton, NJ: Princeton University Press.

evolves by moving slowly as it floats over the crust. For purposes of climate, the land is often considered static, but we know it changes over long timescales. Volcanoes and earthquakes are evidence of this motion.

The terrestrial surface is intimately connected with the plants and the biosphere that lives on it: Dead plant (and a bit of dead animal) material makes up a significant part of the soil. Plants regulate the water in the soil through uptake into plant structures and release water into the atmosphere. Plants also can be darker or lighter than the surface soil, thus absorbing (and reflecting) a different amount of energy than in their absence. Plants react to their environment (rainfall), but plants and the biosphere also create their environment. Plants cycle water vapor back into the atmosphere from the soil by moving water from the soil into the plant, where it is lost in the process of photosynthesis back to the atmosphere. Plants also change the reflectance of the surface, altering the energy absorbed in the system, and the temperature of the surface. The biosphere cycles nutrients used by plants from the soil into plant material and back again, sometimes also into the ocean. Central to the biosphere are nutrients, and the elements that make up the structure of organic molecules: oxygen (O) and hydrogen (H) and carbon (C).

But some of the terrestrial surface, particularly at high latitudes, is frozen. This, of course, brings us to a discussion of ice and snow at high latitudes and altitudes: the **cryosphere**. Snow may be present seasonally on land at high latitudes or high altitudes. If snow lasts over the summer, and continues to pile up, it compacts into ice and forms glaciers. If glaciers get big enough, they merge into ice sheets, ranging in size from small ice sheets filling a few valleys in New Zealand or Alaska, to ice sheets covering entire land masses (Greenland) or continents (Antarctica). The Greenland and Antarctic ice sheets are up to 10,000 feet thick; 99 % of the fresh water on earth is in ice sheets. Greenland holds enough frozen water to raise the sea level 20 feet (6 m). Antarctica holds enough frozen water to raise the sea level 200 feet (60 m).[7]

Finally, while physically humans are part of the biosphere, our impact on the planet is large enough that they are often treated as a separate sphere, the **anthroposphere**. Human emissions as a by-product of our societies now play a significant role in the climate system. Humans alter the structure of ecosystems on continent wide scales (deforestation, and subsequent afforestation). By-products of our societies add to the greenhouse gas loading of the atmosphere, and change atmospheric chemical processes near the surface (creating extra ozone, which is bad for humans, plants and animals). In the upper atmosphere some of these compounds destroy ozone in the stratosphere necessary to block ultraviolet radiation from reaching the surface. These human actions are often modeled using economic models, or models of entire societies and their emissions. These models are sometimes now treated as part of the climate system because the outputs from societies can alter the climate system.

[7]Values are from the National Snow and Ice Data Center (NSIDC). http://nsidc.org/cryosphere/quickfacts/icesheets.html.

2.2 Timescales and Interactions

There is a huge variety of timescales to these cycles: from seconds to millions of years. Evaporation and precipitation formation take seconds to minutes to days to cycle water through the atmosphere, but water that falls onto ice sheets may remain there for hundreds of thousands of years. The energy budget changes throughout the course of the day as the sun moves across the sky and throughout the course of a year as the sun varies its position at any place. Many of the cycles are regulated by the motion of the earth relative to the sun. Plant growth and decay cycles follow the annual cycle. On even longer timescales of thousands to tens of thousands of years, the earth wobbles a bit on its tilted axis (and the tilt changes) and in its orbit. The wobbles alter the seasonal intensity of sunlight at any given location and also alter the distance between the earth and the sun. The result is a slow change in the amount of sunlight hitting the top of the atmosphere. These orbital cycles make it warmer or colder at higher latitudes, enhancing or retarding the presence of snow and ice on the ground, ultimately leading to ice ages.[8] The motion of the plates, the slow tectonic shifts that alter the terrestrial surface and expose new land over millions of years, will change the ocean basins, as well as changing the supply of raw carbon from rocks into the system, or the amount of volcanism that puts new rock onto the surface (and gases from the earth into the atmosphere).

The interplay of cycles such as flows of water and carbon alters many aspects of the climate system. Changing the amount of carbon dioxide in the atmosphere changes the greenhouse effect and the temperature. The temperature change alters water vapor concentrations, potentially further altering the temperature. The coupled nature of the earth's climate system gives rise to a constantly evolving series of interacting processes between the different components. The interplay of forces and pieces is a slowly evolving system with very different interactions and timescales. The climate system is a dynamical system, meaning it can be altered in many ways, and the climate will evolve or change over time. How it will change (or not change) is of critical importance to ourselves and society, and why we try to build models to understand it.

Some of the most critical interactions and flows in the climate system concern carbon, as carbon dioxide (CO_2), and water (H_2O). Both CO_2 and H_2O are critical for life and the biosphere. They are the building blocks of organic molecules, but CO_2 and H_2O are also part of the atmosphere, and make up the largest greenhouse gases, along with methane (CH_4). This is another example of the connections and interactions in the climate system. These connections are one of the reasons why climate change is hard to understand: Carbon dioxide is bad? Not always: Plants need it for their "breathing" (respiration). Carbon dioxide is used in photosynthesis, and for that more CO_2 makes photosynthesis more efficient. Water and carbon flow through the climate system and link the different components.

[8]Hays, J. D., Imbrie, J., & Shackleton, N. J. (1976). "Variations in the Earth's Orbit: Pacemaker of the Ice Ages." *Science*, *194*(4270): 1121–1132.

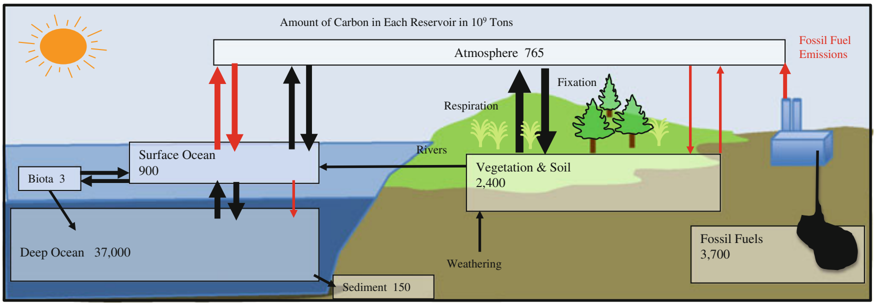

Fig. 2.4 The Carbon Cycle. The largest climate system reservoirs include the deep ocean, soil and vegetation, the surface ocean and the atmosphere. The approximate size of exchanges (fluxes) between boxes is given by the width of the arrows; red arrows indicate perturbations by humans

The cycle of carbon is illustrated in Fig. 2.4. Carbon dioxide in the atmosphere is a greenhouse gas that affects the energy budget, but it may also get taken up by plants (**fixation**) and form part of their structure (leaves, stems, roots). When the plant material dies, carbon enters the soil. Carbon may be broken down by microbes and get back into the atmosphere (**respiration**) as a carbon-containing gas (e.g., CH_4, also a greenhouse gas). It may be dissolved into water and carried into the ocean by rivers, where it also may get taken up into plant or animal tissue (oceanic biota), or remain in the water column. Oceanic biomass "rains" down to the deep ocean when parts of the oceanic biosphere die, and this carbon forms sediments on the bottom of the sea. Some of the carbon dissolves in the water column, where it comes into balance (**equilibrium**) with the atmosphere. The sediments under the ocean eventually get compacted by sediments above, and shifted around over millions of years by tectonic plate motions, where they come back onto land, and rock is exposed to the atmosphere, where it is broken up by wind and water (**weathering**), and the carbon can be dissolved again in water, and react to release the carbon back into the air. This completes a cycle that might take millions of years. The cycle moves carbon in the earth's climate system and through the biosphere. The carbon cycle contains carbon that makes up our living tissues: literally our blood.

As noted in Fig. 2.3, water flows throughout the climate system in the hydrologic cycle. Water evaporates from the ocean into the atmosphere, forming clouds and affecting atmospheric and surface energy transport. It may fall on the land as rain (or snow). Snow affects the energy budget by reflecting more sunlight to space. When snow melts, the water can go into rivers or the soil, where it can be taken up by plants, and then released to the atmosphere as a side effect of pores in leaves opening up to allow carbon from the atmosphere in for photosynthesis. The water may then form a cloud and precipitate, perhaps back into the ocean. The precipitated water is fresh water, lowering the salt content and density of the surface ocean, and affecting the ocean circulation.

2.3 Summary

The earth's climate system is driven by the sun. The atmosphere mediates the flow of energy between the sun and the earth, through the action of clouds and greenhouse gases. There are several different components of the earth's climate system, usually divided into "spheres": atmosphere, terrestrial surface, ocean, cryosphere, biosphere and even anthroposphere (the sphere of human effects). In addition to energy, several critical substances flow through the earth system. Two of the most important and unique are water and carbon. They are important for climate, and they are important for life: Almost all living things contain and use carbon in different forms for our bodies and as part of the cycle of energy (either photosynthesis in plants or respiration in animals).

Both carbon and water have important cycles in the earth's climate system. In the atmosphere they are greenhouse gases. Water is important for life and also as a mechanism for moving heat from where it evaporates (taking up the heat to evaporate water) and releasing it on condensation. Carbon is stored in soils and rocks, and dissolved as a gas in the ocean. We will learn more about the carbon cycle in Chap. 7. One of the reasons the climate system is complex, and comprehensive models are necessary, is because these greenhouse gases (carbon dioxide and water vapor) are critical for understanding the energy budget, but they also flow through the whole climate system.

Thus many interactions between parts of the climate system are critical for describing how climate works and how it evolves. The cycles work on many different timescales. The motion of the earth is a good example: It causes day and night, it causes the seasons, and variations in the earth's orbit over thousands of years alter the conditions at the earth's surface. The slow drift of continents and variations in weathering can alter the climate on even longer timescales. These pieces, and timescales, are critical for understanding how climate may change, the subject of Chap. 3.

Key Points

- The energy in the climate system comes from the sun.
- Greenhouse gases alter the flow of energy in the atmosphere.
- Water vapor, carbon dioxide and methane are critical greenhouse gases.
- Carbon and water flow through the components of the earth system.
- The climate system has cycles that evolve on many timescales from seconds to millions of years.