impacts of various sizes on our planet and its life. The poet Robert Frost may have had in mind the vulnerability of life on Earth when he wrote

> Some say the world will end in fire,
> Some say in ice.
> From what I've tasted of desire
> I hold with those who favor fire.
> But if I had to perish twice,
> I think I know enough of hate
> To say that for destruction ice
> Is also great
> And would suffice.

Earth as a System of Interacting Components

Although Earth has cooled down from its fiery beginnings, it remains a restless planet, continually changing through such geologic activity as earthquakes, volcanoes, and glaciation. This activity is powered by two heat engines: one internal, the other external. A heat engine—for example, the gasoline engine of an automobile—transforms heat into mechanical motion or work. Earth's internal engine is powered by the heat energy trapped during the planet's violent origin and generated by radioactivity in its deep interior. The internal heat drives motions in the mantle and core, supplying the energy to melt rock, move continents, and lift up mountains. Earth's external engine is driven by solar energy—heat supplied to Earth's surface by the Sun. Heat from the Sun energizes the atmosphere and oceans and is responsible for our climate and weather. Rain, wind, and ice erode mountains and shape the landscape, and the shape of the landscape, in turn, changes the climate.

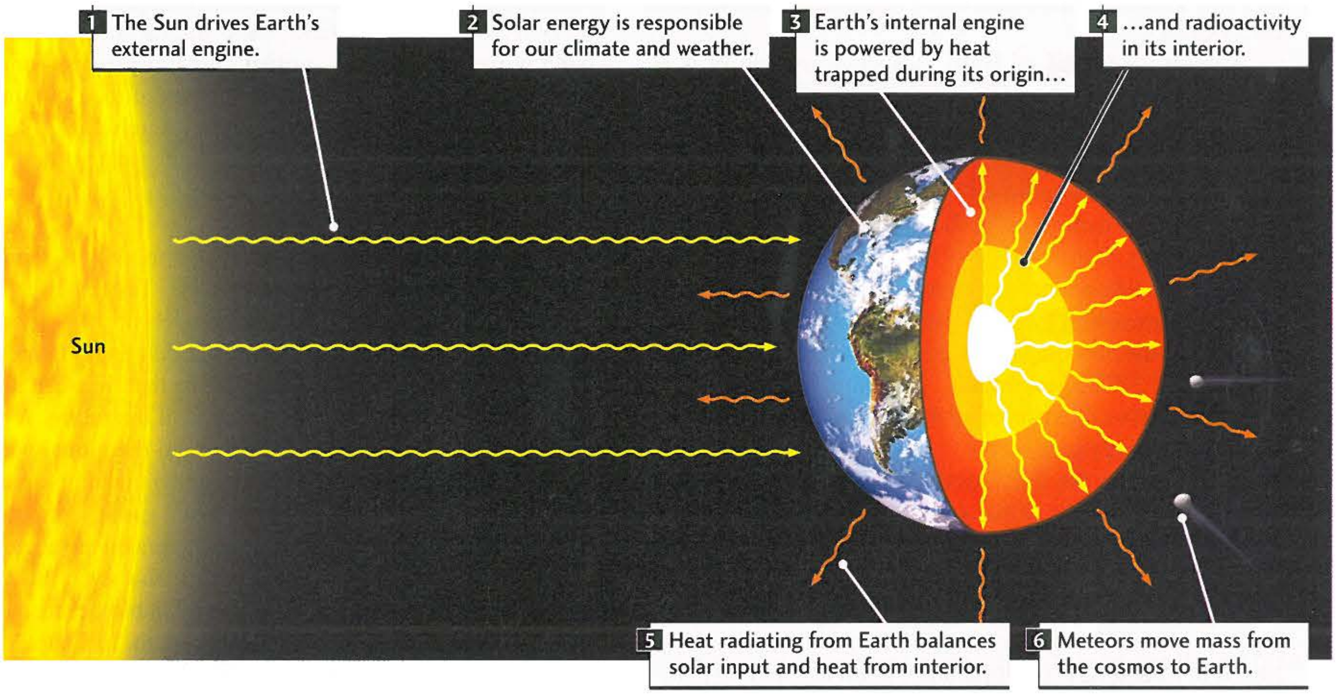
All the parts of our planet and all their interactions, taken together, constitute the **Earth system.** Although Earth scientists have long thought in terms of natural systems, it was not until the latter part of the twentieth century that they were equipped with the tools needed to investigate how the Earth system actually works. Principal among these were networks of instruments and Earth-orbiting satellites to collect information about the Earth system on a global scale and electronic computers powerful enough to calculate the mass and energy transfers within the system. The major components of the Earth system are described in Table 1.2 and depicted in **Figure Story 1.10**. We have discussed some of them already; we will define the others below.

We will talk about many facets of the Earth system in later chapters. Let's get started by thinking about some of its basic features. Earth is an *open system* in the sense that it exchanges mass and energy with the rest of the cosmos. Radiant energy from the Sun energizes the weathering and erosion of Earth's surface, as well as the growth of plants, which feed almost all living things. Our climate is controlled by the balance between the solar energy coming into the Earth system and the energy Earth radiates back into

Table 1.2 Major Components of the Earth System

	Solar Energy Energizes These Components
Atmosphere	Gaseous envelope extending from Earth's surface to an altitude of about 100 km
Hydrosphere	Surface waters comprising all oceans, lakes, rivers, and groundwaters
Biosphere	All organic matter related to life near Earth's surface
	Earth's Internal Heat Energizes These Components
Lithosphere	Strong, rocky outer shell of the solid Earth that comprises the crust and uppermost mantle down to an average depth of about 100 km; forms the tectonic plates
Asthenosphere	Weak, ductile layer of mantle beneath the lithosphere that deforms to accommodate the horizontal and vertical motions of plate tectonics
Deep mantle	Mantle beneath the asthenosphere, extending from about 400 km deep to the core-mantle boundary (about 2900 km deep)
Outer core	Liquid shell composed primarily of molten iron, extending from about 2900 km to 5150 km in depth
Inner core	Inner sphere composed primarily of solid iron, extending from about 5150 km deep to Earth's center (about 6400 km deep)

EARTH IS AN OPEN SYSTEM THAT EXCHANGES ENERGY AND MASS WITH ITS SURROUNDINGS



THE EARTH SYSTEM IS ALL PARTS OF OUR PLANET AND THEIR INTERACTIONS

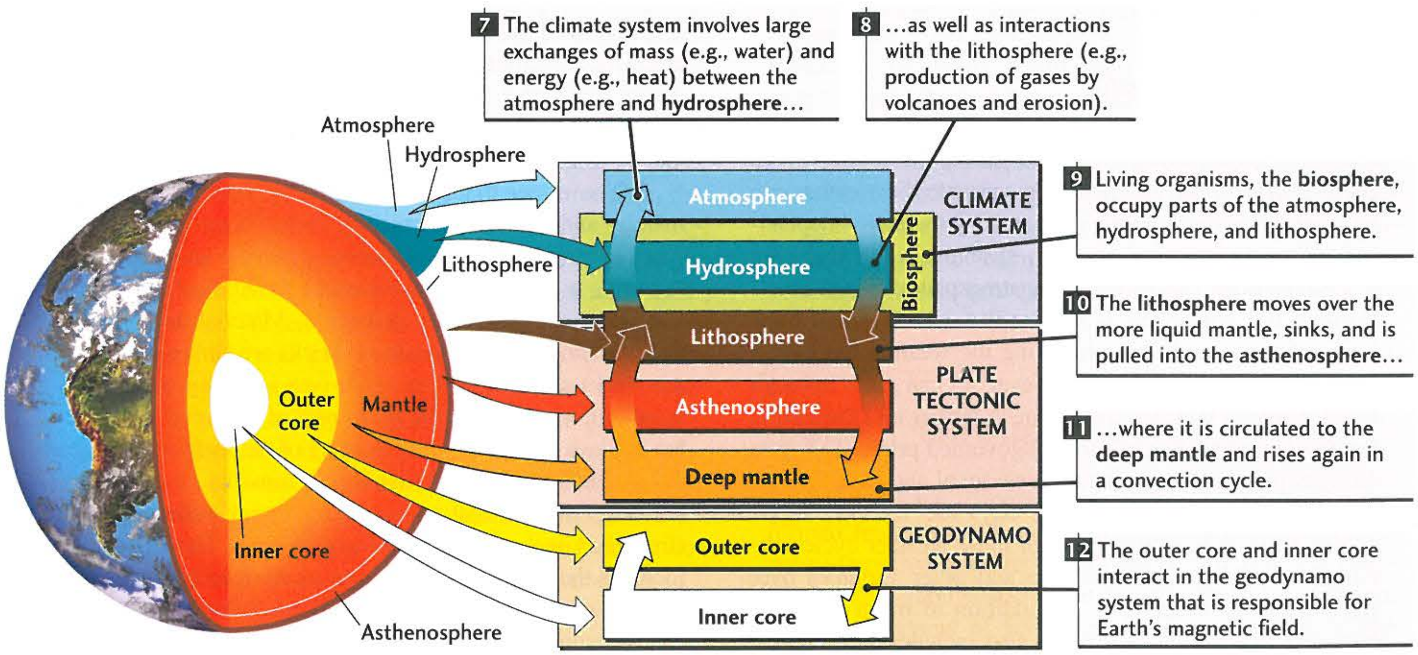


Figure Story 1.10 Major components and subsystems of the Earth system (see Table 1.2). Interactions among the components are powered by energy from the Sun and the planetary interior and organized into three global geosystems: the climate system, the plate tectonic system, and the geodynamo system.

space. The mass transfers between Earth and space decreased markedly after the Heavy Bombardment period, but they still play an active role in the Earth system—just ask the dinosaurs!

Although we think of Earth as a single system, it is a challenge to study the whole thing all at once. Instead, we will focus our attention on parts of the system we are trying to understand. For instance, in the discussion of recent climate changes, we will primarily consider interactions among the atmosphere, hydrosphere, and biosphere that are driven by solar energy. Our coverage of how the continents formed will focus on interactions between the crust and the deeper mantle that are driven by Earth's internal energy. Specialized subsystems that encompass interesting types of terrestrial behavior are called **geosystems**. The Earth system can be thought of as the collection of all these open, interacting (and often overlapping) geosystems.

In this section, we will introduce two important geosystems that operate on a global scale: the climate system and the plate tectonic system. A third global system is the geodynamo, which is responsible for Earth's magnetic field. It is an important part of how Earth works as a planet and a key tool for exploring the interior. The geodynamo is discussed in Chapter 21. Its importance to understanding plate tectonics is discussed in Chapter 2. Later in the book, we will have occasion to discuss a number of smaller geosystems. Here are three examples: volcanoes that erupt hot lava (Chapter 6), hydrologic systems that give us our drinking water (Chapter 13), and petroleum reservoirs that produce oil and gas (Chapter 22).

The Climate System

Weather is the term we use to describe the temperature, precipitation, cloud cover, and winds observed at a point on Earth's surface. We all know how variable the weather can be—hot and rainy one day, cool and dry the next—depending on the movements of storm systems, warm and cold fronts, and other rapidly changing atmospheric disturbances. Because the atmosphere is so complex, even the best forecasters have a hard time predicting the weather more than four or five days in advance. However, we can guess in rough terms what our weather will be much farther into the future, because the prevailing weather is governed primarily by the changes in solar energy input on seasonal and daily cycles: summers are hot, winters cold; days are warmer, nights cooler. *Climate* is a description of these weather cycles obtained by averaging temperature and other variables over many years of observation. In addition to mean values, a complete description of climate also includes measures of how variable the weather has been, such as the highest and lowest temperatures ever recorded on a given day.

The **climate system** includes all the properties and interactions of components within the Earth system needed to determine the climate on a global scale and discover how the climate changes with time. The problem is incredibly complicated because climate is not a behavior of the atmosphere alone. It is sensitive to many processes involving the hydrosphere, biosphere, and solid Earth (see Figure Story 1.10). To understand these interactions, scientists build numerical models—virtual climate systems—on big computers, and they compare the results of their computer simulations with observed data. (In March 2002, Japan unveiled the world's largest and fastest computer, the Earth Simulator, dedicated to modeling Earth's climate and other geosystems.)

Scientists gain confidence in their models if there is good agreement with the observed data. They use the disagreements to figure out where the models are wrong or incomplete. They hope to improve the models enough through testing with many types of observations that they can accurately predict how climate will change in the future. A particularly urgent problem is to understand the global warming that might be caused by human-generated emissions of carbon dioxide and other "greenhouse" gases. Part of the public debate about global warming centers on the accuracy of computer predictions. Skeptics argue that even the most sophisticated computer models are unreliable because they lack many features of the real Earth system. In Chapter 23, we will discuss some aspects of how the climate system works and the practical problems of climate change caused by human activities.

The Plate Tectonic System

Some of Earth's more dramatic geologic events—volcanic eruptions and earthquakes, for example—also result from interactions within the Earth system. These phenomena are driven by Earth's internal heat, which escapes through the circulation of material in Earth's solid mantle, a process known as *convection.*

We have seen that Earth is zoned by chemistry: its crust, mantle, and core are chemically distinct layers that segregated during early differentiation. Earth is also zoned by strength, a property that measures how much an Earth material can resist being deformed. Material strength depends on chemical composition (bricks are strong, soap bars are weak) and temperature (cold wax is strong, hot wax is weak). In some ways, the outer part of the solid Earth behaves like a ball of hot wax. Cooling of the surface forms the strong outer shell or **lithosphere** (from the Greek *lithos,* meaning "stone") that encases a hot, weak **asthenosphere** (from the Greek *asthenes,* meaning "weak"). The lithosphere includes the crust and the top part of the mantle down to an average depth of about 100 km. When subjected to force, the lithosphere tends to behave as a rigid and brittle shell, whereas the underlying asthenosphere flows as a moldable, or ductile, solid.

According to the remarkable theory of **plate tectonics,** the lithosphere is not a continuous shell; it is broken into about a dozen large "plates" that move over Earth's surface at rates of a few centimeters per year. Each plate acts as a

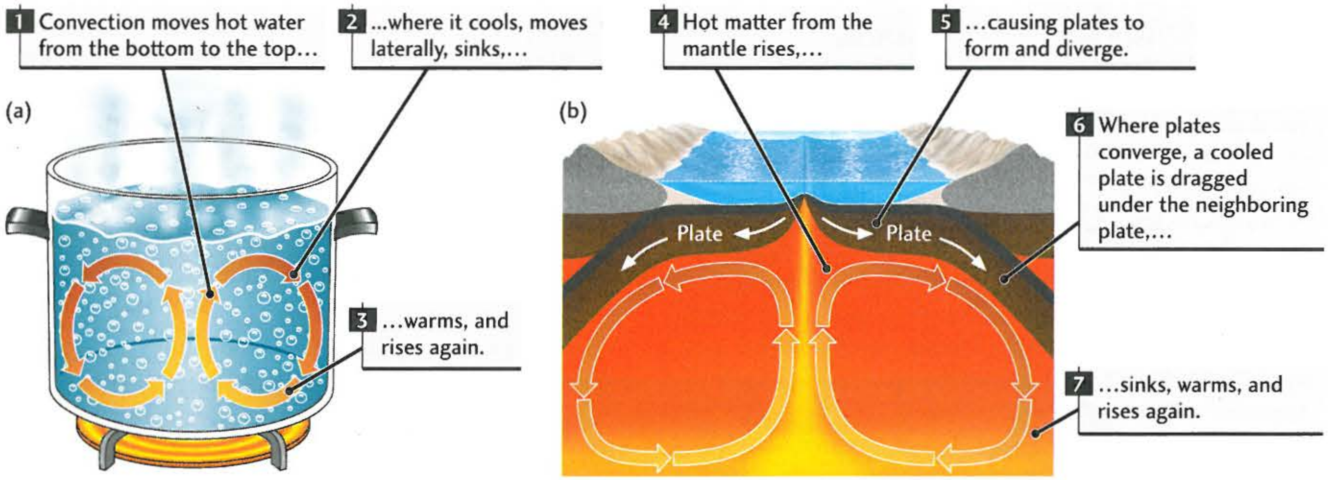


Figure 1.11 (a) Boiling water is a familiar instance of convection. (b) A simplified view of convection currents in Earth's interior.

distinct rigid unit that rides on the asthenosphere, which also is in motion. The lithosphere that forms a plate may be just a few kilometers thick in volcanically active areas and perhaps 200 km thick or more beneath the older, colder parts of the continents. The discovery of plate tectonics in the 1960s furnished scientists with the first unified theory to explain the worldwide distribution of earthquakes and volcanoes, continental drift, mountain building, and many other geologic phenomena. Chapter 2 will be devoted to a detailed description of plate tectonics.

Why do the plates move across Earth's surface instead of locking up into a completely rigid shell? The forces that push and pull the plates around the surface come from the heat engine in Earth's solid mantle, which causes convection. In general terms, convection is a mechanism of energy and mass transfer in which hotter material rises and cooler material sinks. We tend to think of convection as a process involving fluids and gases—circulating currents of water boiling in a pot, smoke rising from a chimney, or heated air floating up to the ceiling as cooled air sinks to the floor—but it can also occur in solids that are at high enough temperatures to be weak and ductile. We note that the flow in ductile solids is usually slower than fluid flow, because even "weak" solids (say, wax or taffy) are more resistant to deformation than ordinary fluids (say, water or mercury).

Convection can occur in a flowing material, either a liquid or a ductile solid, that is heated from below and cooled from above. The heated matter rises under the force of buoyancy because it has become less dense than the matter above it. When it reaches the surface, it gives up heat and cools as it moves sideways, becoming denser. When it gets heavier than the underlying material, it sinks under the pull of gravity, as depicted in **Figure 1.11**. The circulation continues as long as enough heat remains to be transferred from the hot interior to the cool surface.

The movement of the plates is the surface manifestation of convection in the mantle, and we refer to this entire system as the **plate tectonic system.** Driven by Earth's internal heat, hot mantle material rises where plates separate and begins to gel the lithosphere. The lithosphere cools and becomes more rigid as it moves away from this divergent boundary. Eventually, it sinks into the asthenosphere, dragging material back into the mantle at boundaries where plates converge (Figure 1.11b). As with the climate system (which involves a wide range of convective processes in the atmosphere and oceans), scientists study plate tectonics using computer simulations to represent what they think are the most important components and interactions. They revise the models when their implications disagree with actual data.

Earth Through Geologic Time

So far, we have discussed two major topics: how Earth formed from the early solar system, and how two global geosystems work today. What happened during the intervening 4.5 billion years? To answer this question, we begin with an overview of geologic time from the birth of the planet to the present. Later chapters will fill in the details.

An Overview of Geologic Time

Comprehending the immensity of geologic time can be a challenge for the uninitiated. The popular writer John McPhee has eloquently noted that geologists look into the