

CHAPTER 12

THE HYDROLOGIC CYCLE, THE SEDIMENT CYCLE, AND THE CARBON CYCLE

1. INTRODUCTION: SYSTEMS, CYCLES, RESERVOIRS, AND FLUXES

1.1 Thinking about the Earth as a system has become, in recent years, much in vogue. The basic idea of a *system* is that it is *something that consists of a number of distinctive and diverse parts that function together by a variety of interactions and exchanges of energy and matter*. Your motor vehicle is a good example of a fairly small and simple system: it is a machine with a number of moving or nonmoving parts, which consumes motor fuel and emits various exhaust substances as it travels from place to place. The Earth is, of course, a far larger and also far more complicated system, whose component parts operate on time scales from seconds to many millions of years. This is the basis for what is nowadays called *Earth system science*. Here I'm only touching upon some important aspects of Earth systems science that are relevant to this course: the hydrologic cycle and the carbon cycle. A whole course could be devoted to those and certain other cycles that are important in the context of the Earth's surface environment.

1.2 The concept of cycles plays a fundamental role in systems thinking—although it's not easy to frame a suitable definition of such cycles. A *cycle* might best be described as a characteristic succession of events and processes, involving certain kinds of Earth materials, by which the materials reside in certain kinds of places and move among such places in certain ways. Cycles operate through an indefinitely long span of time.

1.3 Much of the material that has been covered so far in this course involve, in one way or another, water and sediment. Earlier chapters have dealt in much detail with the Earth's water and sediment: where they are, and how they move. Now it's time for us to be more integrative in our thinking about the Earth's water and sediment. To that end, the next two sections deal with what are called the *hydrologic cycle* and the *sediment cycle*.

1.4 Geochemists, in particular, are fond of thinking about certain substances from the standpoint of cycles. Such cycles are called *geochemical cycles*. The most important, in the context of the Earth's surface environment, is the *carbon cycle*. The carbon cycle is especially important because carbon is the fundamental basis for life. It is also of great importance for the Earth's climate, because carbon dioxide (CO₂) is the second important of the so-called greenhouse gases, which play a key role in climate. (Water vapor is the most important, but we humans

have virtually no control over the content of water vapor in the atmosphere, whereas we have great influence on the content of carbon dioxide in the atmosphere, owing to the burning of fossil fuels.) The concluding section of this chapter is devoted to some aspects of the Earth's carbon cycle that are most relevant to the Earth's surface environment. Geochemical cycling of certain other elements, most notably nitrogen and phosphorus, have received study because of their role as nutrients.

1.5 What pops into your mind when you hear the word *reservoir*? Probably a body of water, small or large, that is impounded behind a dam. In Earth systems science, the term **reservoir** is used for *a distinctive kind of place where a certain kind of material is stored, or resides, for some period of time*. That definition probably doesn't enlighten you much, so here are some examples of near-surface reservoirs you have encountered earlier in the course: the atmosphere; glaciers; the soil layer; the aggregate of bodies of fresh water on the continents (rivers and lakes).

1.6 Material moves into and out of reservoirs. *The rate at which a given material moves between reservoirs* is called a **flux**. If the flux of material into and out of a given reservoir is the same for some period of time, that reservoir is said to be in a **steady state**. Commonly, however, the flux in and the flux out are not equal.

1.7 Another concept that is useful to know about when thinking about systems is **residence time**. In an earlier chapter you learned about the residence time of water in lakes. The same concept can be applied to any substance that resides in some reservoir for some period of time.

2 THE EARTH'S WATER, AND THE HYDROLOGIC CYCLE

2.1 The earth would be a boring place without water. Fortunately, there's a lot of water on Earth. Table 12-1 gives an approximate accounting of where the earth's water resides. By far the most water is in the oceans. Of the Earth's fresh water, most is tied up in glacier ice, with groundwater a distant second; the fresh water we are most familiar with—streams, rivers, lakes, and what's in the atmosphere in the form of water vapor, clouds, and precipitation—is a tiny part of the Earth's stock of near-surface water.

2.2 The trouble with an accounting technique like that of Table 12-1 is that it doesn't tell anything about *the movements and transformation of the earth's water*. You all know that water on, below, and above the earth's surface is in a continuous state of movements and transformations. The picture of these movements and transformations, viewed in their entirety, is called the **water cycle**, or the **hydrologic cycle**. Figure 12-1 gives one version of the hydrologic cycle. Most of the pathways and processes shown in Figure 12-1 should be easily

understandable to you. They vary a lot in their magnitude (how much water, per unit time on average, is involved in each of them), but that's not shown in the figure. For the purposes of this course, what's most important is evaporation, condensation, and precipitation.

Location	surface area		water volume		percent of total
	sq mi	sq km	cu mi	cu km	
SURFACE WATER					
fresh-water lakes	330,000	860,000	30,000	125,000	0.009
saline lakes and inland seas	270,000	700,000	25,000	104,000	0.008
average in stream channels	—	—	300	1,250	0.0001
SUBSURFACE WATER	50,000,000	130,000,000			
soil moisture and intermediate zone (vadose) water			16,000	67,000	0.005
ground water within 0.5 mi (0.8 km) depth			1,000,000	4,170,000	0.31
ground water, deep-lying			1,000,000	4,170,000	0.31
total liquid water in land areas			2,070,000	8,637,000	0.635
GLACIERS	6,900,000	18,000,000	7,000,000	29,200,000	2.15
ATMOSPHERE	197,000,000	510,000,000	3,100	13,000	0.001
WORLD OCEAN	139,500,000	360,000,000	317,000,000	1,322,000,000	97.2
Totals (rounded)			326,000,000	1,360,000,000	100

Figure by MIT OCW

Table 12-1. An accounting of where the Earth's water resides. (From Strahler, 1975.)

2.3 Here's one interesting fact that underlines the "activeness" of the hydrologic cycle: *the mass of water vapor plus condensed water in clouds plus precipitation that's in the process of falling to the ground, at any given time, amounts to only about one week's worth of global precipitation.* This means that there must be very rapid recycling of water between the liquid reservoirs at the earth's surface, on the one hand, and the stock of water in the atmosphere, on the other hand.

2.4 Two incidental notes:

- The major player in evaporation is the ocean surface: the ocean surface accounts for about 85% of total average evaporation, and the continents account for only about 15%.

- Evaporation of the ocean exceeds precipitation over the ocean, and precipitation over the continents exceeds evaporation. The balance is maintained mainly by *runoff of water from the continents*, in the form of rivers and streams, although in certain places large glaciers deliver water to the oceans, as they calve directly into the ocean.

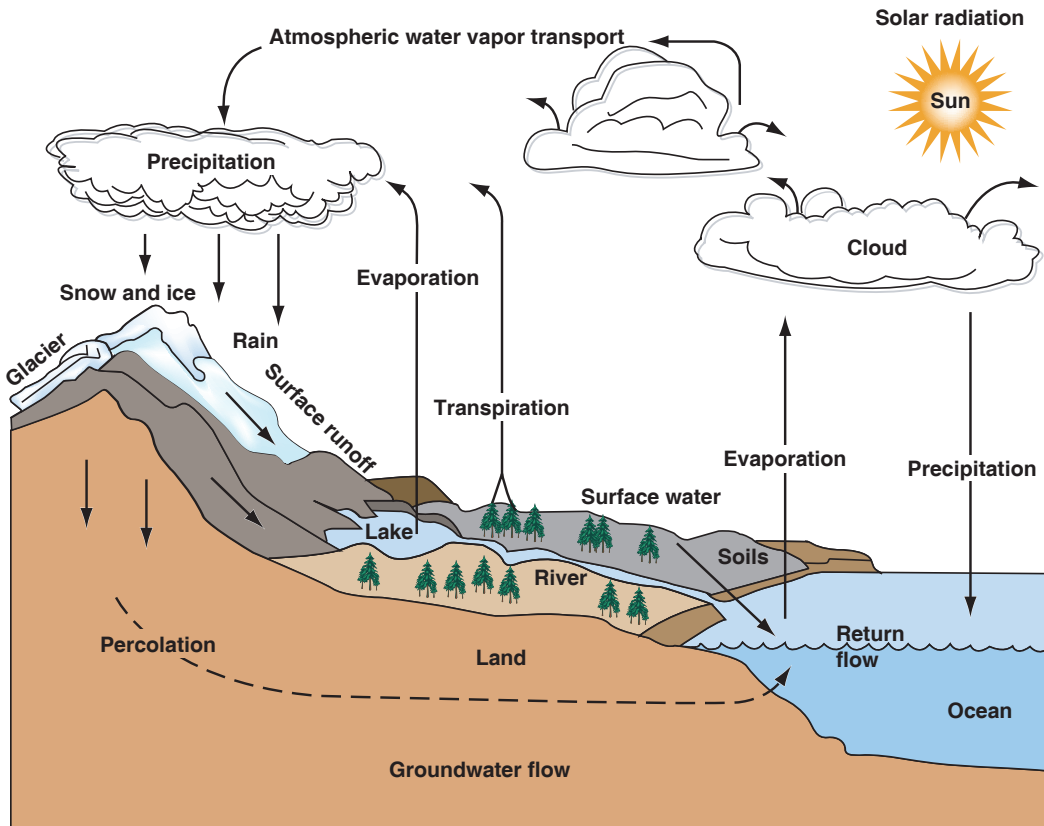


Figure by MIT OCW

Figure 12-1. The hydrologic cycle. (From Water, The Yearbook of Agriculture 1955.)

3. THE SEDIMENT CYCLE

3.1 You learned earlier that sediment is material, in either particulate or dissolved form, that is produced by weathering of rocks on the continents and then transported, by some agent (water is by far the most important, in general, but wind and moving glacier ice are important as well, at certain times and places) to come to rest as a sediment deposit. A whole field of Earth science, *sedimentary geology*, is devoted to the study of sediments, as well as the sedimentary rocks that are formed when sediment is buried and becomes lithified.

3.2 In a sense, the sediment cycle is simpler than the water cycle, because after sediment is formed it inevitably moves downhill toward places of rest. From the perspective of the Earth's surface, sedimentary processes are basically a matter of source, transport, and sink. (Scientists like to use the term *sink* for a kind of place to which matter moves and accumulates, or a kind of place to which energy flows and is there stored or dissipated.)

3.3 To have a full appreciation of the sediment cycle, you need to think beyond the Earth's surface and the processes and kinds of environments of reservoirs associated with it. Although sediment can be stored in lakes and in river valleys for geologically long periods of time, and become buried deeply enough to be converted to sedimentary rocks, most sediments end up in the world's oceans. The oceans don't fill up, though: plate tectonics operates, in ways that are beyond the scope of this course, to recycle the sediments and sedimentary rocks back to the continents, there to be exposed once again to weathering and transport, to complete the cycle.

4. THE CARBON CYCLE

4.1 Introduction

4.1.1 The element carbon holds a distinctive place among the chemical elements: it can form covalent bonds with itself (these are called carbon-carbon double bonds and carbon-carbon triple bonds, depending upon how many of the bonding positions are involved) as well as with other elements, especially hydrogen, to form an enormous number of chemical compounds, called *organic compounds*.

4.1.2 The term "organic" here is a bit misleading: great numbers of such compounds are synthesized by organisms, but even greater numbers can be synthesized in the laboratory, from inorganic raw materials, without the involvement of organisms, living or dead. The field of chemistry devoted to the study of organic compounds is called *organic chemistry*.

4.1.3 Carbon also forms various *inorganic compounds*. In such compounds, carbon bonds covalently with oxygen. The two most important kinds of such carbon-containing inorganic compounds are carbon dioxide (CO_2), invariably a gas under Earth-surface conditions, and carbonate minerals, mainly calcite, CaCO_3 , and dolomite, $\text{CaMg}(\text{CO}_3)_2$.

4.1.4 Carbon, as both organic compounds and inorganic compounds, is present at and near the Earth's surface in a great variety of environments. The study of where carbon resides in and on the Earth, together with the modes and rates at which carbon moves from one to another of such environments, is known as the *carbon cycle*.

4.1.5 The concept of a “cycle” here carries the implication that there is an unceasing movement of carbon, in all of its various forms, in and on the Earth. In this respect the Earth can be viewed as a closed system with respect to carbon, in the sense that although the carbon undergoes a great variety of transformations the total amount does not change with time.

4.1.6 A full consideration of the Earth’s carbon cycle would necessitate casting a wide net: we would need to consider not only the Earth’s surface environment, including the atmosphere, the land surface, and the oceans, but also the Earth’s deep interior—because, by various processes, carbon becomes buried within the Earth, and, by various other processes, it is released from deep storage back into the surface environment. The carbon cycle is truly integrative, in the sense that its study draws upon a wide range of scientific disciplines: geology, biology, and climatology. Here we’ll concentrate on the Earth-surface part of the carbon cycle.

4.2 Elements of the Carbon Cycle

4.2.1 There are many reservoirs of carbon at and near the Earth’s surface. Table 12-2 shows the important carbon reservoirs, along with rough estimates of the mass of carbon in those reservoirs. (In ecology, the term *biomass* is used for *the total mass of living material, in plants and animals*. It can be expressed as mass per unit area in a particular region of the Earth’s surface, or as the total over the entire Earth.) You can see that the mass of carbon in the atmosphere, the oceans, and biomass is tiny in comparison to the carbon that resides in sedimentary rocks in the earth’s crust. Note also from Table 12-2 that the mass of carbon in the atmosphere is approximately equal to total biomass carbon.

4.2.2 In Figure 12-2 you can see the distinction between organic carbon and inorganic carbon. It’s useful to consider these two forms of carbon separately. It’s easier to deal with the latter than with the former.

4.2.3 As noted earlier, the two important forms of inorganic carbon are carbon dioxide and carbonate minerals and rocks. Carbon dioxide is present in the Earth’s atmosphere in an average concentration of close to 0.4 percent by volume.

4.2.4 Carbon is *put into* the atmosphere, in the form of carbon dioxide, mainly from respiration by organisms and by decomposition of organic matter, and also by burning of plant matter. Before the discovery of fire by human beings, burning was ignited by lightning strikes. Nowadays, of course, enormous quantities of carbon are put into the atmosphere by burning of fossil fuels. Carbon is also put into the atmosphere in the form of carbon dioxide released during volcanic eruptions.

4.2.5 Carbon is *removed from* the atmosphere mainly by photosynthesis by plants and by becoming dissolved in the oceans. Some of the added carbon dioxide from burning of fossil fuels results in increase in the concentration of carbon dioxide in the atmosphere, but that increase is in part offset by dissolution into the oceans and in part by increase in total plant biomass.

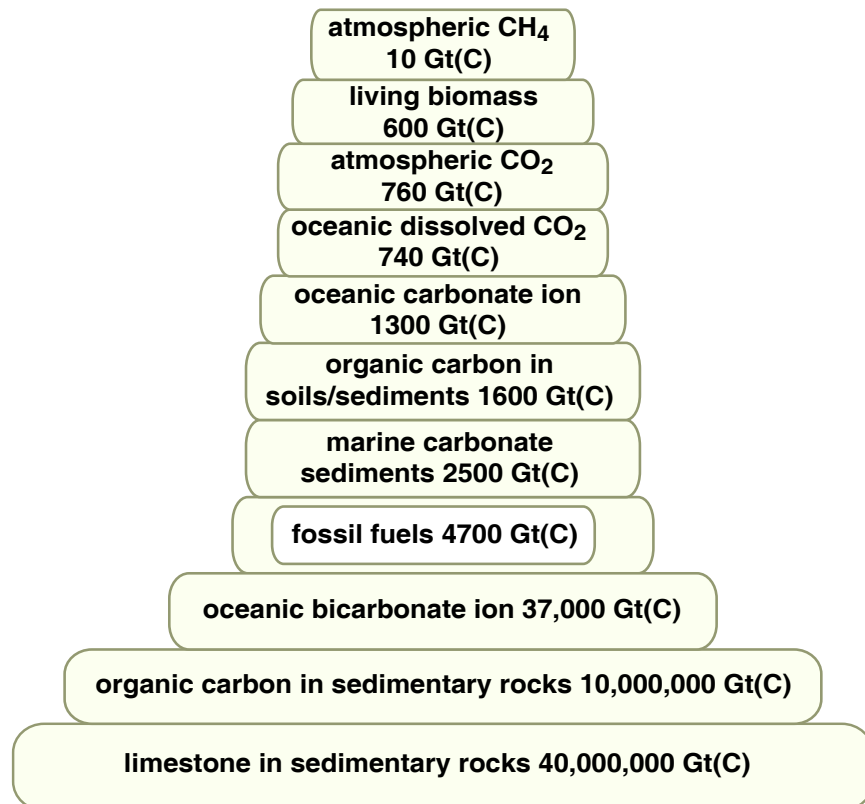


Figure by MIT OCW

Figure 12-2. The Earth's carbon reservoirs. (From Kump, Kasting, and Crane, 2004.)

4.2.6 Incidentally, not all of the carbon in the atmosphere is in the form of carbon dioxide. Methane, CH₄, is present in the atmosphere in concentrations of about 1.7×10^{-4} percent by volume. Methane is added to the atmosphere in two ways, mainly: upward seepage from shallow and deep subsurface, where methane is generated both from by the activity of microorganisms at shallow depths, and by complex reactions involving deeply buried organic matter at greater depths. Methane is unstable chemically in the atmosphere: it is converted to carbon dioxide and water vapor.

4.2.7 Inorganic carbon in the Earth' crust is largely in the form of carbonate minerals calcite, aragonite, and dolomite. Enormous volumes of carbonate rocks, mainly limestone and dolostone, reside in the crust. As you learned in an earlier chapter, carbon in the form of carbon dioxide is released as carbonate rocks are weathered at the Earth's surface. At the same time, carbonate minerals are precipitated, mainly in the shallow ocean, in places where the ocean water is oversaturated with respect to calcium carbonate. Most of that precipitation is in the tissues of a great variety of carbonate-secreting organisms, although some is precipitated inorganically.

4.2.8 The *residence time* of carbon in the atmosphere is about thirteen years. To figure that out, you need to know, in addition to the 760 Gton of carbon that's present in the atmosphere, that the inflow of carbon into the atmosphere, and the outflow of carbon from the atmosphere, which from year to year are not far from being the same, is about 60 Gton carbon.