1
The Climate of the Earth

1.1 Introduction

Typically, climate is frequently defined as a description of the climate system which includes the analysis of the behavior of the major components that influence the climate of the Earth: (i) the atmosphere, which is the gaseous envelope surrounding the Earth, (ii) the hydrosphere, which is the liquid water such as the oceans, lakes, underground water and, for the purposes of this text, (iii) the cryosphere, which are those portions of the surface of the Earth where the water is in solid form, including sea ice, lake ice, ice sheets, and glaciers, (iv) the lithosphere, which refers to the crust and upper mantle of the Earth, and (v) the biosphere, which refers to living organisms and the interactions between them [1, 2]. These components interact with one another and with aspects of the biosphere of the Earth to determine not only the day-to-day weather, but also the long-term averages that are referred to as *climate*.

On the other hand, the most general definition of *climate change* is a change in the statistical properties of the climate system when considered over long periods of time, regardless of the cause(s). By this definitions, fluctuations over periods shorter than several decades, such as El Niño, do not represent climate change. A key difference between climate change and climate variability is in persistence of anomalous conditions that used to be rare but occur more frequently (summertime maximum air temperatures increasingly break records each year), or vice versa (duration and thickness of seasonal lake ice decreasing with time). In statistical terminology, the curve of the frequency distribution representing the probability of specific meteorological events occurring is changed. The curve may be modified either in amplitude, or shifted about a new mean, or both [3].

However, care must be taken not to confuse *climate change* and *climate variability*. For the most part, climate variability (that is, variable climate caused by non-anthropogenic sources) relates to the natural processes that affect the atmosphere, such as the North Atlantic oscillation (NAO)

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that refers to anomalous changes in atmospheric pressure at sea level that occur near Iceland. The North Atlantic oscillation phases are often associated with above-average storm counts over parts of Europe and the United States. In addition, there is also the El Niño Southern Oscillation (ENSO) phenomenon near the equatorial Pacific Ocean, where fluctuations of the temperatures of the surface of the sea typically alternate every few years between a warming phase (El Niño) and cooling periods (La Niña), with a neutral phase in between.

By way of clarification, the term *above average* as used above or, for that matter, in any example of climatic conditions, is often difficult to define precisely because it is based on a minimum and a maximum that may be close or far apart. In other words, the limits of the data can give misleading information about the actual conditions that fall into the range of the data limits.

Many regions of the world experience greater variability, climatologically speaking, than do others. In some parts of the world, or in any region for certain time periods or parts of the year, the variability can be weak (i.e., there is not much difference in the conditions within that time period). In other places or time periods, the conditions can swing across a large range, from freezing to very warm, or from very wet to very dry and exhibit strong variability. A certain amount of this is understood and accepted, instinctively, by the people in a region. What are typical normal climatic conditions for Denver (Colorado) in terms of the frequency of precipitation (high variability) would be abnormal for Rome (Italy) (low variability). Thus, any single event, such as a severe tropical cyclone, cannot be attributed to human-induced climate change, given the current status of scientific understanding [3] but it can contribute to the so-called average climate.

Within scientific journals, *global warming* refers to an increase in the surface temperature of the Earth. Global warming is a long-term rise in the average temperature of the climate system of the Earth, which is an aspect of climate change, as manifested by temperature measurement and by multiple effects of the warming. On the other hand, *climate change* is a more all-inclusive term that includes global climate systems on a worldwide basis.

Climate change occurs when changes in the climate system of the Earth result in new weather patterns that last for at least decades, if not millennia [4]. The term *climate change* is often used arbitrarily to refer to climate change caused by human activity as the predominant cause without giving consideration to changes in the climate that may have resulted from the natural processes of the Earth. As a result, especially in the context of modern environmental policy and environmental science, the term *climate change* has unfortunately (and incorrectly) been associated with anthropogenic (human) activities as the causative factor.

The issue of global climate change is often associated with the use of fossil fuels as sources of energy. Of most concern is the increase in emissions of carbon dioxide (CO_2) due to emissions from fossil fuel combustion:

$$C_{\text{fossil fuel}} + O_2 \rightarrow CO_2$$

Other factors, including land use, ozone depletion, animal agriculture, and deforestation, are also of concern in the roles they play – both separately and collectively – in affecting climate, microclimate, and the climatic variables (Chapter 2). This focus is operative even though emissions from other sources such as agriculture, waste management, and biomass burning occur on a regular basis [5].

Chemical compounds released at the surface by natural processes and by anthropogenic processes are oxidized in the atmosphere before being removed by wet or dry deposition. Key chemical species of the troposphere include organic compounds such as methane and non-methane hydrocarbon derivatives as well as oxygenated organic species and carbon monoxide, nitrogen oxides (which are also produced by lightning discharges in thunderstorms) as well as nitric acid. Other chemical species include hydrogen compounds (and specifically the hydroxy radical ($OH\bullet$), and the hydroperoxy radical ($HO_2\bullet$) as well as hydrogen peroxide (H_2O_2), ozone (O_3), and sulfur compounds such as dimethyl sulfide (CH_3SCH_3), sulfur dioxide (SO_2), and sulfuric acid (H_2SO_4). The hydroxyl radical ($OH\bullet$) deserves additional consideration since it has the capability of reacting with and efficiently destroying a large number of organic chemical compounds and, hence, making a direct contribution to the oxidation capacity (reactivity) of the atmosphere [6].

Finally, the release of sulfur compounds at the surface of the Earth surface and the subsequent oxidation of the sulfur compounds in the atmosphere leads to the formation of small liquid or solid particles that remain in suspension in the atmosphere. These aerosol particles affect the radiative balance of the atmosphere directly, by reflecting and absorbing solar radiation, and indirectly, by influencing cloud microphysics. The release to the atmosphere of sulfur compounds has increased dramatically, particularly in regions of Asia, Europe, and North America as a result of human activities, specifically coal combustion [7, 8].

When studying the climate system of the Earth, an area of common confusion that relates to whether climate scientists agree or disagree as to whether or not climate change is happening, or if it is happening, whether or not humans are the primary cause [9]. There are a variety of reasons for this, but (supposedly) a majority of scientists who study climate and publish in peer-reviewed journals agree that human activity is causing the warming of the Earth. But when anthropogenic activities are cited as the *main cause* the cause of the warming there is serious concern because of the other factors that are often ignored.

However, before progressing any further into the changeability of the Earth and the various subsystems, it is also necessary to introduce the terminology applied to the various subsystems to aid in an understanding of the Earth. The climate system itself is often considered as part of the broader Earth system, which includes all the parts of the Earth and not only the elements that are directly or indirectly related to the temperature or precipitation [10].

The following sections of this chapter provide some general information about the components of the Earth system that play an important role in determining climate change. These components are: (i) the atmosphere, (ii) the hydrosphere, (iii) the cryosphere and geosphere, (iv) the lithosphere, and (v) the biosphere.

1.2 The Atmosphere

Physically, the atmosphere is the envelope of air surrounding the Earth that is held in place around the Earth by gravitational attraction and which has a substantial effect on the environment. It is the layer or a set of layers of gases surrounding the Earth that is held in place by gravity. Chemically, dry air contains nitrogen (78.09% v/v), oxygen (20.95% v/v), argon (0.93% v/v), carbon dioxide (0.04% v/v), and small amounts of other gases [11].

The atmosphere contains oxygen used by most organisms for respiration and carbon dioxide used by plants, algae, and cyanobacteria for photosynthesis. Also, the atmosphere helps protect living organisms from genetic damage by solar ultraviolet radiation, solar wind, and cosmic rays. The current composition of the atmosphere is the product of billions of years of biochemical modification of the paleoatmosphere by living organisms [12]. The atmosphere can be divided (atmospheric stratification) into five main layers. Generally, the atmosphere of the Earth has four primary layers, which are (i) the troposphere, (ii) the stratosphere,

(iii) the mesosphere, (iv) the thermosphere, and (v) the exosphere – these layers differ in properties such as composition, temperature and pressure.

1.2.1 Structure

Approximately three-quarters (75% v/v) of the mass of the atmosphere resides within the troposphere, and is the layer within which the weather systems develop. The depth of this layer varies between 548,000 feet at the equator to 23,000 feet over the polar regions. The stratosphere, which extends from the top of the troposphere to the bottom of the mesosphere, contains the ozone layer which ranges in altitude between 49,000 feet and 115,000 feet, and is where most of the ultraviolet radiation from the Sun is absorbed. The top of the mesosphere ranges from 164,000 feet to 279,000 feet, and is the layer wherein most meteors burn up. The thermosphere extends from 279,000 feet to the base of the exosphere at approximately 2,300,000 feet altitude and contains the ionosphere, a region where the atmosphere is ionized by incoming solar radiation.

1.2.1.1 The Troposphere

The troposphere is the lowest layer of atmosphere of the Earth and the layer to which changes can greatly influence the floral and faunal environments. The troposphere extends from the surface of the Earth to a height of approximately 30,000 feet at the polar regions to approximately 56,000 feet at the equator, with some variation due to weather. The troposphere is separated from the stratosphere by the tropopause, which is a boundary marked in most places by a temperature inversion (i.e., a layer of relatively warm air above a colder one), and in others by a zone which is isothermal with height.

Although variations do occur [13], the temperature usually declines with increasing altitude in the troposphere because the troposphere is mostly heated through energy transfer from the surface. Thus, the lowest part of the troposphere (i.e., the surface of the Earth) is typically the warmest section of the troposphere, which promotes vertical mixing. The troposphere contains approximately 80% of the mass of the atmosphere of the Earth. The troposphere is denser than all its overlying atmospheric layers because a larger atmospheric weight sits on top of the troposphere and causes it to be most severely compressed. In the context of water, the majority of the atmospheric water vapor or moisture is found in the troposphere.

1.2.1.2 The Stratosphere

Above the troposphere, the atmosphere becomes very stable, as the vertical temperature gradient reverses in a second atmospheric region – the *stratosphere* – which extends from the top of the troposphere at approximately 39,000 feet above the surface of the Earth to the stratopause at an altitude of approximately 164,000 to 180,000 feet. The atmospheric pressure at the top of the stratosphere is approximately 1/1000 the pressure at sea level.

The stratosphere contains the ozone layer, which is the part of atmosphere that contains relatively high concentrations of that gas. In this layer ozone concentrations are approximately 2 to 8 parts per million, which is much higher than in the lower atmosphere but still very small compared to the main components of the atmosphere. It is mainly located in the lower portion of the stratosphere from approximately 49,000 to 115,000 feet, though the thickness varies seasonally and geographically. Approximately 90% v/v of the ozone in the atmosphere of the Earth is contained in the stratosphere.

The two lowest layers of the atmosphere, the troposphere and stratosphere, are particularly important for climate issues. At ground level, heat is exchanged between the atmosphere and the surface of the Earth. The rays of the Sun strike the surface of the Earth at different angles, and equal areas at different latitudes gain different amounts of heat resulting in equatorial regions being heated up more than the polar regions. Air masses flowing vertically and horizontally act as a regulatory mechanism, preventing the equatorial regions from overheating and the polar regions from excessive cooling. This is achieved by an exchange of warm air and water masses in the tropics and cooler ones at the poles, resulting in a meridional heat transport. This exchange is expressed in the distinctive global wind systems which take the form of large-scale belts encircling the northern hemisphere and the southern hemisphere.

1.2.1.3 The Mesosphere

The mesosphere is the third-highest layer of atmosphere and occupies the region above the stratosphere and below the thermosphere. This layer extends from the stratopause at an altitude of approximately 160,000 feet to the mesopause at approximately 260,000 to 80,000 feet above sea level. Temperatures drop with increasing altitude to the mesopause that marks the top of this middle layer of the atmosphere. It is the coldest place on Earth and has a temperature on the order of -85°C (-120°F).

1.2.1.4 The Thermosphere

The thermosphere is the second-highest layer of the atmosphere and extends from the mesopause (which separates it from the mesosphere) at an altitude of approximately 260,000 feet up to the thermopause at an altitude that ranges from 1,600,000 to 3,300,000 feet. In the thermosphere, the temperature increases to reach maximum values that are strongly dependent on the level of solar activity. Vertical exchanges associated with dynamical mixing become insignificant, but molecular diffusion becomes an important process that produces gravitational separation of species according to their molecular or atomic weight.

The height of the thermopause varies considerably due to changes in solar activity. Because the thermopause lies at the lower boundary of the exosphere, it is also referred to as the exobase. The lower part of the thermosphere, from 260,000 feet to 1,800,000 feet above the surface of the Earth surface, contains the *ionosphere*.

The ionosphere is a region of the atmosphere that is ionized by solar radiation and is responsible for auroras (the *aurora borealis* in the northern hemisphere and the *aurora australis* in the southern hemisphere). The ionosphere increases in thickness and moves closer to the Earth during daylight and rises at night allowing certain frequencies of radio communication a greater range. During daytime hours, it stretches from approximately 160,000 feet to 3,280,000 feet and includes the mesosphere, thermosphere, and parts of the exosphere. However, ionization in the mesosphere largely ceases during the night, so auroras are normally seen only in the thermosphere and lower exosphere. The ionosphere forms the inner edge of the magnetosphere.

The temperature of the thermosphere gradually increases with height. Unlike the stratosphere beneath it, wherein a temperature inversion is due to the absorption of radiation by ozone, the inversion in the thermosphere occurs due to the extremely low density of its molecules. The temperature of this layer can rise as high as 1500°C (2700°F), though the gas molecules are so far apart that its temperature in the usual sense is not very meaningful. This layer is completely cloudless and free of water vapor. However non-hydrometeorological phenomena such as the aurora borealis and *aurora australis* are occasionally seen in the thermosphere.

1.2.1.5 The Exosphere

The exosphere is the outermost layer of the atmosphere (that is, it is the upper limit of the atmosphere) and extends from the exobase, which is located at the top of the thermosphere. The exosphere begins variously from approximately 2,300,000 feet to 3,280,000 feet above the surface, where it interacts with the magnetosphere, to space. Each of the layers has a different lapse rate, defining the rate of change in temperature with height. Initial atmospheric composition is generally related to the chemistry and temperature of the local solar nebula during the formation of the planets and the subsequent escape of interior gases.

The exosphere layer is mainly composed of extremely low densities of hydrogen, helium and several heavier molecules including nitrogen, oxygen and carbon dioxide closer to the exobase. The atoms and molecules are so far apart that they can travel hundreds of kilometers without colliding with one another. Thus, the exosphere no longer behaves like a gas, and the particles constantly escape into space. The exosphere contains most of the satellites orbiting Earth.

1.2.1.6 The Atmospheric Boundary Layer

The atmospheric boundary layer (sometimes referred to as the *boundary layer of the Earth* or the *planetary boundary layer*) is that portion of the atmosphere that is nearest to the ground having considerable variations over the course of a day which is in contrast with the free atmosphere above it, whose diurnal fluctuations are more limited. Also, in the boundary layer the major transfer of momentum, heat, and water vapours with the underlying surface occurs, in the first few centimeters, chiefly by molecular diffusion, but above this area, by turbulent diffusion.

The structure of the boundary layer in particular is much dependent on the vertical stability of the layer, including the type of air mass in which it is embedded. The basic stability is related to the temperature lapse rate. The rate at which an atmospheric variable – typically, the temperature – in the atmosphere changes with altitude. Thus, if the temperature increases with height, the air is unstable and convection readily occurs. Conversely, a stable portion of the air mass is one in which an inversion has formed, limiting the upward motions associated with convection. Thus, in a dry air mass without cloud cover, ground cooling leads to strongly stable air which hinders convective activity. On the other hand, in a moist cloudy air mass the usual nighttime ground surface cooling may not occur, tending to destabilize the air in the subcloud layer.

Over land surfaces, the boundary layer often has a well-defined structure – above a very shallow surface layer during the daytime is the mixed layer, developing often as a result of convection related to solar heating of the surface of the Earth. During the course of the first few hours after sunrise, turbulent exchanges form an even distribution heat, momentum, and moisture; such can be seen as constant values of virtual potential temperature, wind, and specific humidity. This mixed layer is at a maximum depth in the late part of the afternoon, and, when convection brings air above the level where condensation takes place, cloud form. After sunset, however, the actions of a radiatively cooled ground change the lowest layer into one with a vertically stable distribution and this stable boundary layer grows between sunset and the first hours after dawn, and its turbulent structures are much reduced compared with those of the mixed layer.

Air in the boundary layer is relatively isolated from the free troposphere and therefore functions like a chamber over the surface of the Earth. The changes in the amounts of water vapor, carbon dioxide, and other chemical constituents in the boundary layer serve as an indicator of the biological and physiochemical processes occurring at the surface. For example, in urban regions, the boundary layer often has higher concentrations of pollutant gases than the cleaner, more stable air above. At night, gases emitted by the surface, such as carbon dioxide in natural ecosystems or pollutants in urban environments, often reach high concentrations because they are concentrated in a shallow boundary layer [1]. The pollutant gases can either be (i) non-indigenous gases (ii) or gases that are present in excessive quantities (i.e., higher than the natural quantities) quantities in the atmosphere.

1.2.2 Gases

The composition and chemistry of the atmosphere is of importance for several reasons, but primarily because of the interactions between the atmosphere and the flora and fauna of the Earth.

The atmosphere possesses a number of properties related to its physical state and chemical composition and undergoes a variety of internal processes and external interactions that can either maintain or alter these properties. The atmosphere is not a closed system, because it exchanges all three of these internally conservative quantities across the boundary of the atmosphere and receives input from regions outside it. Thus surface fluxes of moisture, momentum, and heat occur to and from the underlying ocean and land. The atmosphere exchanges very little mass and momentum with space, although it absorbs directly a portion of the solar radiation energy received from above. The atmosphere exists in a space that has as its lower boundary the land surface geopotential, as the relatively equipotential ocean surface. Thus the local atmospheric surface pressure, and hence the quantity of its mass above any area, varies considerably from one geographical area to another.

The composition of the atmosphere changes as a result of natural processes such as emissions from volcanos and by lightning. It has also been changed by human activity and some of these changes are harmful to human health, crops, and ecosystems. Examples of problems which have been addressed by atmospheric chemistry include acid rain, ozone depletion, photochemical smog, and greenhouse gases.

As an example, carbon dioxide belongs to the group of gases that lie in the transition between the major gases and the trace gases. It is often selected as the most significant gas for causing global warming because it has a long effective lifetime before it is tied down to forms that cannot affect atmospheric concentrations over the time scales of interest and because it has high concentration compared with the other gases involved in global warming. However, water vapor – which is a stronger greenhouse gas than carbon dioxide on a molecule per molecule basis – is often ignored as a major contributor to atmospheric chemistry. However, because of the reliance on fossil fuels, carbon dioxide was the first gas shown to be increasing owing to human activities and was implicated in global warming. Fossil fuels are a reservoir of carbon that would not be released as carbon dioxide to the atmosphere were it not for the burning of fossil for energy [7, 8, 14].

Another example, is methane – the lifetime of methane is only 10 years, compared with a 150- to 200-year lifetime for carbon dioxide. Major sources are the natural wetlands, rice agriculture and domestic cattle. Other sources include biomass combustion, gas produced in landfills, coal mines, termites, sewage disposal, natural gas leakage, lakes, and oceans. The reason for the minor sources being of importance is that there are many of them and together they represent a substantial fraction of the animal emissions. Methane is removed from the atmosphere mostly by reactions with tropospheric hydroxyl radical (OH•). Lesser amounts are removed by dry soils and in stratospheric processes.

Some atmospheric gases are critical for life, such as the photosynthetic organisms use carbon dioxide in the presence of light to produce organic matter that eventually becomes the basic food source for almost all animals and microbes. Most organisms also require oxygen for metabolic respiration. Nitrogen (N_2) makes up 78% v/v of the atmosphere and it is unavailable to most organisms, but nitrogen-fixing bacteria convert it to biologically available nitrogen that is ultimately used by all organisms to build proteins. Other gases, such as carbon monoxide (CO), nitric oxide (NO), nitrous oxide (N_2O), methane (CH_4), and volatile organic carbon compounds like terpenes and isoprene, are the products of plant and microbial activity. Some gases, like tropospheric ozone (O_3), are produced chemically in the atmosphere as products of chemical reactions involving both biogenic (biologically produced) and anthropogenic gases, and can, at high concentrations, damage plants, microbes, and people [1].

1.3 The Hydrosphere

The hydrosphere (also called the aquasphere) is the combined mass of water found on, under, and above the surface of the Earth. The hydrosphere has a direct influence on weather and climate conditions on Earth, with the worldwide oceanic circulation playing a particularly important role. The global distribution of water and land at the surface of the Earth significantly affects the circulations in the ocean and the atmosphere. Thus, plate tectonics contribute to the development of climate and to changes in global environment. Volcanic eruptions, even though local in origin, can affect the Earth system as a whole. They devastate wide areas of land and drastically change the habitat of flora, fauna and humans, and – for climate purposes – the volcanic output reflects in the substance composition of the atmosphere. Some large volcanic events cause eruptions of volcanic ash reaching the stratosphere, where it remains for many years, substantially influencing the radiation balance and the climatic conditions of the Earth.

Although the hydrosphere has been in existence for more than 4 billion years, it continues to change in size. This is caused by sea floor spreading and continental drift, which rearranges the land and ocean. Finally, the lithosphere is the combined land masses of the Earth, the land which is the outermost shell of the Earth and is composed of the crust (which is defined on the basis of its chemistry and mineralogy) and the portion of the upper mantle that behaves elastically during geological time (a time scale of thousands of years to millions of years) (Table 1.1).

The existence of a water system is due to a collection of factors. For example, the pore structure of the soil and the sediment are central influences on groundwater movement. Hydrologists quantify this influence primarily in terms of (i) porosity and (ii) permeability. The porosity is the proportion of total volume that is occupied by voids but it is not a direct function of the size of soil grains. Porosity tends to be larger in well-sorted sediments where the grain sizes are uniform, and smaller in mixed soils where smaller grains fill the voids between larger grains. Soils are less

Table 1.1 The geological timescale.

Era	Period	Epoch	Duration (years × 10^6)	Years ago (years × 10^6)
Cenozoic	Quaternary	Holocene	0.01 to the present	
		Pleistocene	2	0.01
	Tertiary	Pliocene	11	2
		Miocene	12	13
		Oligocene	11	25
		Eocene	22	36
		Paleocene	71	58
Mesozoic	Cretaceous		71	65
	Jurassic		54	136
	Triassic		35	190
Paleozoic	Permian		55	225
	Carboniferous		65	280
	Devonian		60	345
	Silurian		20	405
	Ordovician		75	425
	Cambrian		100	500
Precambrian			3,380	600

porous at deeper levels because the weight of overlying soil packs grains closer together.

The term *permeability* refers to the relative ease with which a formation transmits water and is based on the size and shape of its pore spaces and the interconnectivity of the pores. Formations that have a high porosity and a high permeability produce good aquifers and include sand, gravel, sandstone, fractured rock, and basalt. Formations that have a low-permeability formation which impede groundwater flow include granite, shale, and clay.

Groundwater recharge enters aquifers in areas at higher elevations (typically hill slopes) than discharge areas (typically in the bottom of valleys), so the overall movement of groundwater is downhill. However, within an aquifer, water often flows upward toward a discharge area. To understand and map the complex patterns of groundwater flow, hydrogeologists use a quantity called the hydraulic head which, for a particular location within an aquifer, is the sum of the elevation of that point and the height of the column of water that would fill a well open only at that point. Thus, the hydraulic head at a point is simply the elevation of water that rises up in a well open to the aquifer at that point.

The height of water within the well is not the same as the distance to the water table. If the aquifer is under pressure, or artesian, this height may be much greater than the distance to the water table. Thus the hydraulic head is the combination of two forces: (i) mechanical, which is due to elevation, and (ii) pressure part, which is caused by compression within the formation. Thus, groundwater flow between two points is proportional to the difference in mechanical and pressure forces as well as to the permeability of the medium through which flow is taking place. These proportionalities are expressed in the fundamental equation for flow through porous media (Darcy's Law) which, in the absence of gravitational forces, is a proportional relationship between the instantaneous flow rate through a porous medium of permeabilityk), the dynamic viscosity of the fluid and the pressure drop over a given distance in a homogeneously permeable medium. Thus:

$$Q = [kA(p_b - p_a)]/\mu L$$

In this equation, the total discharge, Q (units of volume per unit of time) is equal to the product of the intrinsic permeability of the medium, k, the cross-sectional area to flow, A (units of area), and the total pressure drop p_b-p_a) divided by the dynamic viscosity, μ and the distance or length, L, over which the pressure drop occurs.

Hydrogeologists collect water levels measured in wells to map hydraulic potential in aquifers. These maps can then be combined with permeability maps to determine the pattern in which groundwater flows throughout the aquifer. Depending on local rainfall, land use, and geology, streams may be fed by either groundwater discharge or surface runoff and direct rainfall, or by some combination of surface and groundwater. Perennial streams and rivers are primarily supplied by groundwater, referred to as base flow. During dry periods they are completely supplied by groundwater; during storms there is direct runoff and groundwater discharge also increases. Thus, it is now possible to understand the overall structure of a water system.

Clean freshwater resources are essential for drinking, bathing, cooking, irrigation, industry, and for plant and animal survival [15]. Without water, most life forms would be unable to sustain themselves and the Earth would be a barren, desert-like place. Due to overuse, pollution, and ecosystem degradation the sources of most freshwater supplies – groundwater (water located below the soil surface), reservoirs, and rivers – are under severe and increasing environmental stress. The majority of the urban sewage in developing countries is discharged untreated into surface waters such as rivers and harbors. Approximately 65% v/v of the global freshwater supply is used in agriculture and 25% v/v is used in industry. Freshwater conservation therefore requires a reduction in wasteful practices like inefficient irrigation, reforms in agriculture and industry, and strict pollution controls worldwide. Aquatic regions house numerous species of plants and animals, both large and small. In fact, this is where life began billions of years ago when amino acids first started to come together. Although water temperatures can vary widely, aquatic areas tend to be more humid and the air temperature on the cooler side.

However, for the present purposes, water supply is generally considered to occur in five accessible locations: (i) groundwater, (ii) wetlands, (iii) ponds and lakes, (iv) streams and rivers, and (v) oceans. Furthermore, a freshwater region is an area where the water has a low salinity (a low salt concentration, usually on the order pf <1% w/w). Plants and animals in freshwater regions are adjusted to the low salt content and would not be able to survive in areas of high salt concentration (such as the ocean). There are different types of freshwater regions: ponds and lakes, streams and rivers, and wetlands. The following sections describe the characteristics of these three freshwater zones.

1.3.1 Groundwater

Groundwater is fresh water (from rain or melting ice and snow) that soaks into the soil and is stored in the tiny spaces (pores) between rocks and particles of soil [16–18]. Groundwater is both an important direct source of supply that is tapped by wells and a significant indirect source, since surface streams are often supplied by subterranean water. More specifically and contrary to the comments of some observers, a groundwater resource is not (and should not be imagined to be) an underground lake! In reality groundwater is rarely a distinct water body (large caves in limestone aquifers are one exception) but it is found in a water-bearing rock formation in which the water typically fills very small spaces (pores) within rocks and between sediment grains and the water can move within the formation due to the permeability of the rock. The packing of the rock particles dictates the amount of water that the rock can hold.

Layers of loosely arranged particles of uniform size (such as sand) tend to hold more water than layers of rock with materials of different sizes. This is because smaller rock materials settle in the spaces between larger rock materials – decreasing the amount of open space that can hold water. Porosity (how well rock material holds water) is also affected by the shape of rock particles. Round particles will pack more tightly than particles with sharp edges. Material with angular-shaped edges has more open space and can hold more water. Groundwater can remain underground for prolonged periods (even hundreds of thousands of years) or the water can rise to the surface and in the form of rivers, streams, lakes, ponds, and wetlands. Groundwater can also come to the surface as a spring or be pumped from a well and either way provides drinking water.

Groundwater is stored in the tiny open spaces between rock and sand, soil, and gravel and is located in two zones: (i) the unsaturated zone, which is immediately below the land surface, contains some water and air in the open spaces, or pores and (ii) the saturated zone, in which all of the pores and rock fractures are filled with water, underlies the unsaturated zone. The top of the saturated zone is called the water table, which may be just below or hundreds of feet below the land surface.

Thus, near the surface of the earth, in the *zone of aeration,* soil pore spaces contain both air and water. This zone, which may have zero thickness in swamplands and be several hundred feet thick in mountainous regions, contains three types of moisture. After a storm, *gravity water* is in transit through the larger soil pore spaces. *Capillary water* is drawn through small pore spaces by capillary action and is available for plant uptake. *Hygroscopic moisture* is water held in place by molecular forces during all except the driest climatic conditions. Moisture from the zone of aeration cannot be tapped as a water supply source.

In the *zone of saturation,* located below the *zone of aeration*, the soil pores are filled with water (*groundwater*). A stratum (layer of rock) that contains a substantial amount of groundwater is the aquifer. At the surface between the two zones (the *water table* or *phreatic surface*) the hydrostatic pressure in the groundwater is equal to the atmospheric pressure. An aquifer may extend to great depths, but because the weight of overburden material generally closes pore spaces, decreasing amounts of water is found at depths greater than 2000 ft. The amount of water that can be stored in the aquifer is the volume of the void spaces between the soil grains. The fraction of voids volume to total volume of the soil (the *porosity*) is derived from the equation:

$$\text{Porosity} = (\text{volume of void space})/(\text{total volume})$$

However, not all of this water is available because it is so tightly tied to the rock particles in the aquifer. The amount of water that can be extracted is the *specific yield,* which is the percentage of total volume of water in an aquifer that will drain freely from the aquifer.

If the groundwater can move rapidly though the rock (such as movement through gravel and sandy deposits) an aquifer can form. In the aquifer, there is enough groundwater that it can be pumped to the surface and used for drinking water, irrigation, industry, or other uses. However, if the groundwater is to move through the rock formation, the pores or fractures in the rock must be connected and the rock will have good permeability. If the pores or fractures are not connected, the rock material cannot produce water and is therefore not considered an aquifer. The amount of water an aquifer can hold depends on the volume of the underground rock materials and the size and number of pores and fractures that can fill with water. An aquifer may be a few feet to several thousand feet thick, and less than a square mile or hundreds of thousands of square miles in area.

Aquifers receive water from precipitation (rain and snow) and from water from surface waters like lakes and rivers that filters through the unsaturated zone. When the aquifer is full, and the water table meets the surface of the ground, water stored in the aquifer can appear at the land surface as a spring or seep. A recharge area is an area where the aquifer takes in water and a discharge area is the point where the groundwater flows to the land surface. Water moves from higher-elevation areas of recharge to lower-elevation areas of discharge through the saturated zone.

The groundwater and other surface water systems are part of the hydrologic cycle, which is the constant movement of water above, on, and below the surface of the Earth (Figure 1.1). The water cycle is the result of a collection of connected processes that distribute water and energy throughout the Earth system in cyclic patterns. Over time, ongoing and repeated change in the distribution and form of water and energy around the globe is caused by processes like evaporation, condensation, freezing, melting, convection currents and infiltration.

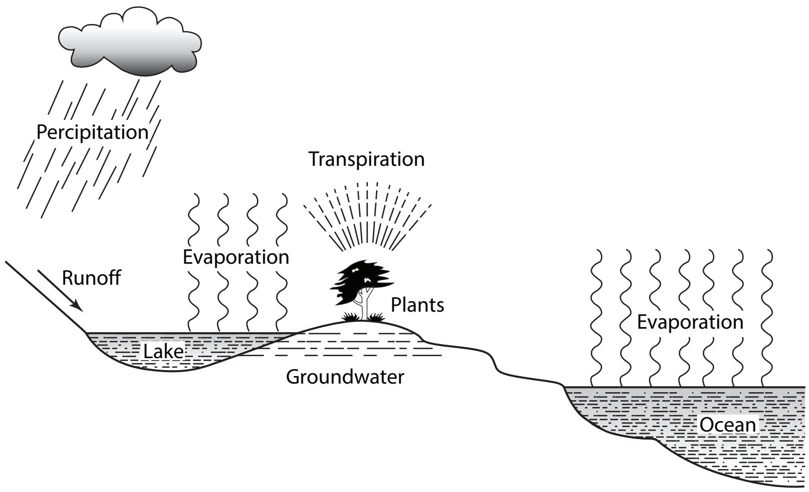


Figure 1.1 The hydrogeological cycle (the water cycle).

A cycle has no beginning and no end, but a water cycle is understood to commence at the precipitation stage. Selecting the beginning of the cycle as the water from precipitation (i.e., rain, snow, or hail), the water then soaks into the soil, while water that cannot soak into the soil collects on the surface, forming runoff streams. When the soil is completely saturated, additional water moves slowly down through the unsaturated zone to the saturated zone, replenishing or recharging the groundwater. Water then moves through the saturated zone to groundwater discharge areas. Evaporation occurs when water from such surfaces as oceans, rivers, and ice is converted to vapor. Evaporation, together with transpiration from plants, rises above the surface of the Earth, condenses, and forms clouds. Water from both runoff streams and from groundwater discharge moves toward streams and rivers and may eventually reach the ocean where water can also evaporate.

Groundwater can become contaminated in many ways, such as when polluted surface water recharges an aquifer, the groundwater will also become contaminated. Groundwater can also become contaminated when liquid hazardous substances soak down through the soil into groundwater. Contaminants that can dissolve in groundwater will move along with the water, potentially to wells used for drinking water. If there is a continuous source of contamination entering moving groundwater, an area of contaminated groundwater (a plume) can form. A combination of moving groundwater and a continuous source of contamination can, therefore, pollute very large volumes and areas of groundwater.

When hazardous substances seep into the groundwater, some may remain in liquid form. If the liquid is less dense than water, it will float on top of the water table, like oil on water – light non-aqueous phase liquids (LNAPLs) – but if the liquid is denser than water, the pollutants are called dense non-aqueous phase liquids (DNAPLs). Dense non-aqueous phase liquids sink to form pools at the bottom of an aquifer which continue to contaminate the aquifer as they slowly dissolve and are carried away by moving groundwater.

1.3.2 Wetlands

It is appropriate at this point to mention another surface water system that is often ignored in many presentations of water systems, and that is the system known as the wetlands system.

A wetland is a place where the land is covered by water, either salt, fresh or somewhere in between [19]. Wetlands vary widely and are difficult to classify because of regional and local differences in soils, topography, climate, hydrology, water chemistry, vegetation and other factors, including human disturbance. Wetlands are often located alongside waterways and in floodplains and it is not surprising that there is a classification that is based on location in which wetlands are subdivided into five general types: (i) marine or ocean wetlands, (ii) estuary wetlands, (iii) river wetlands, (iv) lake wetlands, also called lacustrine wetlands, and (v) marsh wetlands, also called palustrine wetlands. Common names for wetlands include marshes, estuaries, mangroves, mudflats, mires, ponds, fens, swamps, deltas, coral reefs, billabongs, lagoons, shallow seas, bogs, lakes, and floodplains. A large wetland area may be comprised of several smaller wetland types.

Tidal wetlands are, as the name suggests, found along coastlines and are often linked to river estuaries where seawater mixes with freshwater to form an environment of varying salinity. The salt water and the fluctuating water level (due to tidal action) combine to create a rather difficult environment for most plants. Consequently, many shallow coastal areas are non-vegetated mud flats or sand flats. Some plants, however, have successfully adapted to this environment. Certain types of grasses and grass-like plants that are able to adapt to the saline conditions form the tidal salt marshes that are found along a coastline. Moreover, mangrove swamps, with salt-loving shrubs or trees, are common in tropical climate areas. Some tidal freshwater wetlands form beyond the upper edges of tidal salt marshes where the influence of salt water ends.

Non-tidal wetlands are most common on floodplains along rivers and streams (riparian wetlands), in isolated depressions surrounded by dry land, along the margins of lakes and ponds, and in other low-lying areas where the groundwater intercepts the soil surface or where precipitation sufficiently saturates the soil (vernal pools and bogs). Inland wetlands include marshes and wet meadows dominated by herbaceous plants, swamps dominated by shrubs, and wooded swamps dominated by trees. Wetlands may support both aquatic and terrestrial species.

Water saturation (hydrology) largely determines how the soil develops and the types of plant and animal communities living in and on the soil. The prolonged presence of water creates conditions that favor the growth of specially adapted plants (hydrophytes) and promote the development of characteristic wetland (hydric) soils. Wetlands vary widely because of regional and local differences in soils, topography, climate, hydrology, water chemistry, vegetation and other factors, including human disturbance. Indeed, wetlands are found from the tundra to the tropics and on every continent except Antarctica. Two general categories of wetlands are recognized: coastal or tidal wetlands and inland or non-tidal wetlands.

Thus, marshes and ponds, the edge of a lake or ocean, the delta at the mouth of a river, low-lying areas that frequently flood all fall into the definition of wetlands. Wetlands are some of the most productive habitats on the Earth and often support high concentrations of animals such as mammals, birds, fish and invertebrates, and serve as nurseries for many of these species. Wetlands also support the cultivation of rice, a staple in the diet of the population in many countries. Also, wetlands provide a range of ecosystem services that benefit human populations, including water filtration, storm protection, flood control and recreation.

Wetlands act as natural water filters, but they can only do so much to clean up the fertilizers and pesticides from agricultural runoff, mercury from industrial sources and other types of pollution. There is growing concern about the effect of this pollution on the supply of drinking water and the biological diversity of wetlands. Climate change brings a variety of alterations to patterns of water and climate. In some places, rising sea levels are swamping shallow wetlands and drowning some species of mangrove trees while in other locations, droughts are destroying estuaries, floodplains and marshes. Also, dams alter the natural flow of water through a landscape. There are possibilities for building dams or locating them in more sustainable ways that limit impact on existing ecosystems, but many have been very destructive to wetlands.

Many wetlands are seasonal (they are dry one or more seasons every year), and, particularly in the arid and semiarid areas, may be wet only periodically (i.e., less than seasonal). The quantity of water present and the timing of its presence in part determine the functions of a wetland and its role in the environment. Even wetlands that appear dry at times for significant parts of the year – such as vernal pools (temporary pools of water that provide habitat for distinctive plants and animals) – often provide critical habitat for wildlife adapted to breeding exclusively in these areas.

Thus, wetlands are areas of standing water that support aquatic plants – marshes, swamps, and bogs are all considered wetlands. Plant species adapted to the very moist and humid conditions (hydrophytes) include pond lilies, cattails, sedges, tamarack, and black spruce as well as marsh flora which include species such as cypress and gum. Wetlands have the highest species diversity of all ecosystems and are attractive to many species of amphibians, reptiles, birds (such as ducks and waders), and furbearers can be found in the wetlands. Wetlands are not considered freshwater ecosystems as there are some, such as salt marshes, that have high salt concentrations and which support different species of animals, such as shrimp, shellfish, and various grasses.

Wetlands – in which high rainfall, appropriate topography, or low evapo-transpiration lead to permanent or seasonal flooding – are an exception to the relationship between emissions and climatic conditions. Wetlands are disproportionately found in cooler latitudes, and northern wetlands are thought to share in importance with methane emissions over tropical wetlands simply because of the greater area (albeit with lower fluxes) of northern wetlands. These areas become anoxic (deficient in oxygen) because microbial activity consumes all the oxygen – anoxic conditions lead to reduced productivity, reduced organic matter decomposition, and greatly enhanced methane production. Wetlands may also contribute significant amounts of reduced sulfur-containing gases to the atmosphere.

1.3.3 Ponds and Lakes

Ponds and lakes vary on aerial extent (without placing hard and fast boundaries on such waters) from just a few square yards to many square miles. Scattered throughout the surface of the Earth, several are remnants from the last ice age, after which the ice melted – approximately 10,000–12,000 years ago. The final part of the Quaternary glaciation lasted from approximately 110,000 to 12,000 years ago and occurred during the last 100,000 years of the Pleistocene epoch.

Many ponds are seasonal, lasting just a couple of months (such as sessile pools) while lakes may exist for hundreds of years or more. Ponds and lakes may have limited diversity of floral and faunal species since they are often isolated from one another and from other water sources, such as rivers and oceans, which have a larger floral and faunal diversity. Lakes and ponds are divided into three different zones, which are usually determined by depth and distance from the shoreline.

The topmost zone near the shore of a lake or pond is the *littoral zone*. This zone is the warmest since it is shallow and can absorb more of the heat of the Sun, and it sustains a fairly diverse community, which can include several species of algae (like diatoms – algae in which the cell walls composed of transparent, opaline silica and which are found in the oceans, waterways, and soils), rooted and floating aquatic plants, grazing snails, clams, insects, crustaceans, fishes, and amphibians. The vegetation and animals living in the littoral zone are food for other creatures such as turtles, snakes, and ducks. The near-surface open water surrounded by the littoral zone is the *limnetic zone*.

The limnetic zone is well-lighted (like the littoral zone) and is dominated by plankton, both phytoplankton and zooplankton. Plankton are small organisms that play a crucial role in the food chain. Without aquatic plankton, there would be few living organisms in the world, and certainly no humans. A variety of freshwater fish also occupy this zone. Plankton have short life spans and when plankton die, the remains fall into the deep-water part of the lake/pond, the *profundal zone*. This zone is much colder and denser than the other two and little light penetrates all the way through the limnetic zone into the profundal zone. The fauna are heterotrophs – organisms which eat other dead organisms and use oxygen for cellular respiration.

A lake is an area filled with water, localized in a basin – often referred to as a structural bas, which is a large-scale structural formation of rock strata formed by tectonic warping of previously flat-lying strata – that is surrounded by land, apart from any river or other outlet that serves to feed or drain the lake. Lakes are temporary deposits of water on continental depressions and are supplied with water by watercourses (tributaries). The water flows into the out-flowing streams, streams or rivers that originate from the lake. Lake water has a low salinity, but has plenty of suspended material, and its temperature depends on local climate conditions. Also the water of big lakes can move and originate variations called seiches, due to differences in atmospheric pressure.

Lakes lie on land and are not part of the ocean, and therefore are distinct from lagoons, and are also larger and deeper than ponds, though there are no official or scientific definitions. Lakes can be contrasted with rivers or streams or which are usually flowing. Most lakes are fed and drained by rivers and streams. In some parts of the world there are many lakes because of chaotic drainage patterns left over from the last ice age. All lakes are temporary over geologic time scales, as they will slowly fill in with sediments or spill out of the basin.

Natural lakes are generally found in mountainous areas, rift zones, and areas with ongoing glaciation. Other lakes are found in endorheic basins or along the courses of mature rivers – an endorheic basin is a limited drainage basis that normally retains water and allows no outflow to other external bodies of water. In some parts of the world, a water contained in an endorheic basin (with no outflow to other external bodies of water) is often referred to as a *pond*.

A phenomenon that needs to be addressed because it can affect the survival and distribution of pollutants is the stratification of a lake, which is the separation of the lake into three layers: (i) the epilimnion, which is the top of the lake, (ii) the metalimnion or thermocline, which is the middle layer and which may change depth throughout the day, and (iii) the hypolimnion, which is the bottom layer (Figure 1.2).

The thermal stratification of lakes refers to a change in the temperature at different depths in the lake, and is due to the change in the density of the water with temperature. Cold water is denser than warm water and the epilimnion generally consists of water that is not as dense as the water in the hypolimnion but the temperature of maximum density for freshwater is 4°C (39°F). In temperate regions where the lake water warms up and cools through the seasons, a cyclical pattern of overturn occurs that is repeated from year to year as the cold dense water at the top of the lake sinks. For example, in dimictic lakes, the lake water turns over during the spring and the autumn. This process occurs more slowly in deeper water and as a result, a thermal bar may form. If the stratification of water lasts for extended periods, the lake is meromictic. Conversely, for most of the time, the relatively shallower meres are unstratified; that is, the mere is

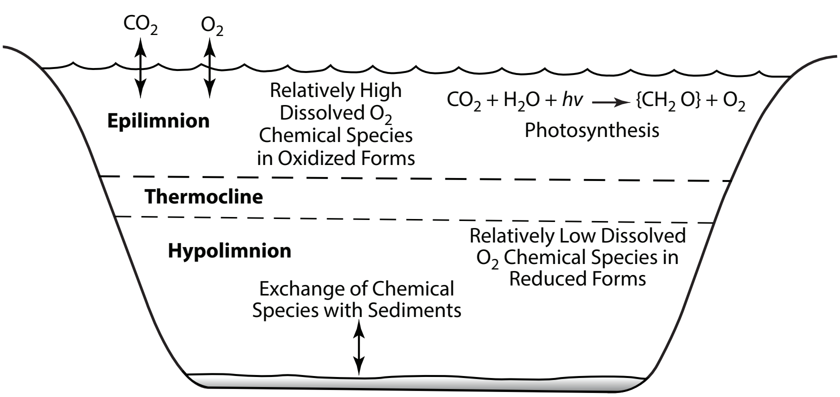


Figure 1.2 Stratification of a lake.

considered all epilimnion. If a lake is triggered into limnic eruption (a natural disaster in which dissolved carbon dioxide suddenly erupts from deep lake waters, forming a gas cloud) the carbon dioxide can quickly leave the lake and displace the oxygen needed for life by people and animals in the surrounding area.

Also with severe thermal stratification in a lake, the quality of drinking water can be adversely affected. In addition, the spatial distribution of fish within a lake is often adversely affected by thermal stratification and in some cases may indirectly cause large die-offs of recreationally important fish. One commonly used tool to reduce the severity of these lake management problems is to eliminate or lessen thermal stratification through aeration which has met with some success, but is not always the cure-all for such a problem.

Temperature varies in ponds and lakes seasonally. For example, during the summer, the temperature can range from 4°C (39°F) near the bottom of the pond or lake to 22°C (72°F) at the top. During the winter, the temperature at the bottom of the pond or lake can be 4°C (39°F) while the top is 0°C (39°F). In between the two layers, there is a narrow zone (the *thermocline*) where the temperature of the water changes rapidly. Outside of the summer and winter season (during the spring and autumn/fall seasons), there is a tendency for the top layers and the bottom layers to mix, usually due to winds, which results in a uniform water temperature of around 4°C (39°F), but this is very dependent upon the climatology of the region. This mixing also circulates oxygen throughout the lake but if the lake or pond did not freeze during the winter, the top layer can be expected to be warmer than the bottom of the pond or lake.

1.3.4 Streams and Rivers

Streams and rivers are bodies of flowing water that are ubiquitous throughout the surface of the Earth and which naturally move predominantly in one direction (unless there are upsets such as earthquakes). These water courses start at the headwaters which arise from springs, from snowmelt, or even from lakes, after which the water flows to the mouth (or delta) of the river into another water channel, typically the ocean.

The characteristics of a river or stream change during the journey from the source to the mouth. For example, the temperature of the water is cooler at the source than it is at the mouth – the water is also clearer, has higher oxygen levels, and freshwater fish such as trout and heterotrophs can be found there. Towards the middle part of the stream/river, the width increases, as does species diversity—numerous aquatic green plants and algae can be found. Toward the mouth of the river/stream, the water becomes murky from all the sediments that it has picked up upstream, decreasing the amount of light that can penetrate through the water.

A river is a natural flowing watercourse, usually freshwater, flowing towards another river, a lake, a sea, or an ocean. In some cases a river flows into the ground and becomes dry at the end of its course without reaching another body of water. Small rivers are often referred to using names such as stream, creek, brook, rivulet, rill (a shallow channel cut into soil by the erosive action of flowing water), and *beck* in northeastern England where remnants of a Saxon-related dialect (with the insertion of some Old Norse words) remain.

Rivers are part of the hydrological cycle (Figure 1.1) – water generally collects in a river from precipitation through a drainage basin from surface runoff and other sources such as groundwater recharge, springs, and the release of stored water in natural ice and snow packs (e.g., from glaciers). Every river is part of a larger system—a watershed, which is the land drained by a river and its tributaries. Rivers are large natural streams of water flowing in channels and emptying into larger bodies of water. This diagram shows some common characteristics of a river system. Every river is different, however, so not all rivers may look exactly like this illustration.

The river source (the headwaters) is the beginning of a river and is often located in mountains; the source may be fed by an underground spring, or by runoff from rain, snowmelt, or glacial melt. Other terminology related to rivers includes: (i) the main river, which is the primary channel and course of a river, (ii) a tributary, which is a smaller stream or river that joins a larger or main river, (iii) a meander, which is a loop in a river channel – a meandering river winds back and forth, rather than following a straight course – and the meander may be referred to as an ox-bow, (iv) upstream, which is the opposite direction from that in which a stream or river flows, nearer to the source – the converse is downstream, and (v) the floodplain, which is relatively flat land stretching from either side of a river, which may flood during heavy rain or snowmelt – the floodplain consists of materials deposited by a river and is often rich in nutrients for plants.

Rivers contain a relatively small share of fresh water, but the flux of water down rivers is a large part of the global hydrologic cycle and they are centrally important in shaping landscapes. The flow of rivers erodes solid sediment and carries it toward the sea, along with dissolved minerals. These processes shape land into valleys and ridges and deposit thick layers of sediment in flood plains – over geologic time the erosion caused by rivers balances the uplift driven by plate tectonics.

1.3.5 The Oceans

The oceans (sometimes referred to as *marine regions*) cover approximately 75% of the surface of the Earth and also (under the general term *marine regions*) include coral reefs, and estuaries – estuaries are areas where freshwater streams or rivers merge with the ocean. This mixing of waters with such different salt concentrations creates a very interesting and unique ecosystem. Microflora (such as algae) and macroflora (such as seaweeds, marsh grasses, and mangrove trees), can be found here. Estuaries support a diverse fauna, including a variety of worms, oysters, crabs, and waterfowl. Marine algae supply much of the oxygen supply of the Earth and, at the same time, remove a substantial amount of carbon dioxide from the atmosphere. In addition, the evaporation of the seawater provides rainwater for the land.

Life began in the ocean, and the ocean remains home to the majority of floral and faunal species of the Earth, extending from tiny single-celled organisms to animals as large as the blue whale, which is the largest living animal on the Earth. However, most of the plant life of the ocean consists of microscopic algae (phytoplankton) that float at the surface and through photosynthesis produce approximately half of the oxygen that humans and all other terrestrial creatures breathe. Seaweed and kelp are big algae easily visible to the naked eye. Marine plants with roots, like seagrasses, can only survive as deep as the rays of the Sun can support photosynthesis – approximately 650 feet (200 meters). Ocean depths vary but can go down to 9,800 feet.

The largest of all of the marine region ecosystems sand are very large bodies of water that dominate the surface of the Earth. Like ponds and lakes, the ocean regions are separated into separate zones: intertidal, pelagic, abyssal, and benthic. All four zones have a great diversity of species – often claimed (with some justification) to be the richest diversity of species even though the oceans may contain fewer species than exist on land-based ecosystems.

The ocean is coupled to the atmosphere from both a physical and a biogeochemical perspective. The basic structure of the ocean is set by the geographic patterns of surface heating and freshwater input (precipitation – rainfall, snowfall – minus water lost due to evaporation), which influences the salinity distribution in the ocean. In general, there is net warming of the ocean surface in the tropics and subtropics and net cooling of the oceans in the temperate and polar latitudes.

In addition, the ocean can be divided into two general regions: (i) a warm, surface pool – typically 18°C (64°F – that is approximately 3280 feet thick and (ii) the deep water – typically: 3°C (37°F) – that outcrops to the surface at high latitudes and forms the bulk of the ocean volume. Unlike the atmosphere, heating of the ocean surface stabilizes the water and also prevents rapid exchange (or mixing) between the surface and deep water. In fact, contact between the surface and deep waters is limited to localized polar regions where losses of heat and freshwater lead to sinking and deep water formation. The resulting thermohaline circulation (part of the large-scale ocean circulation that is driven by global density gradients that are created by surface heat and fresh-water flow) is especially important over long timescales (such as glacial cycles).

The other component of the ocean circulation is produced by the drag of the surface winds on the ocean. The zonal wind patterns over the ocean result in rotating circulation patterns in the subtropical and sub-polar regions and are also responsible for the circumpolar current in the southern oceans (i.e., oceans to the south of the equator). Typically, the wind-driven surface currents move heat and trace species (such as organic chemical compounds) from the tropics to the poles, and approximately an equal amount of solar energy received in the tropics is transported toward the pole by oceanic and atmospheric circulations. Wind forcing also causes divergence of the surface water and upwelling along both the equator and coastal regions on the eastern margin of ocean basins. The upwelling of cooler, nutrient-rich waters in these areas greatly enhances ocean productivity, which affects the climate [20]. The ocean circulation, which exhibits variations on different timescales (including perturbations such as the El Niño events that occur in the equatorial Pacific on an average of four years and produce massive warming of the coastal waters off Peru and Ecuador with torrential rainfall in the region), greatly affects biogeochemical cycles as well as the global climate..

Briefly, a biogeochemical cycle is a pathway by which a chemical substance moves through the components of the climate system of the Earth, i.e., the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere [21, 22]. Ecological systems (ecosystems) have many biogeochemical cycles operating as a part of the system, such as the water cycle, the carbon cycle, the nitrogen cycle [23]. There are biogeochemical cycles for a variety of chemical elements as well as for anthropogenic cycles for human-produced chemicals. In addition to occurring in living organisms, these chemical elements also cycle through the various abiotic factors of ecosystems such as the air (the atmosphere), the water (the hydrosphere), and the land (the lithosphere). In some cycles there are *reservoirs* where a chemical can remain for a long period of time (such as an ocean or lake for water).

The biogeochemical cycles link the most important reservoirs of these elements: the hydrosphere, components of the solid Earth, the biosphere and the atmosphere. The processes which mainly drive these cycles include the constant oxidation of living and dead biomass by atmospheric oxygen. On the one hand these processes result in carbon dioxide, which may then be used in photosynthesis; on the other hand energy is released by these processes which is used for the growth and the development of living organisms. These processes cause rapid circulation of nutrients in the Earth system unless they are stored in living organisms, organic soil matter or in the decayed biomass on land or in the ocean. Biogeochemical cycles thus comprise physical, chemical and geological processes on Earth and largely determine boundary conditions for the development of ecosystems.

Biogeochemical cycles are also a prerequisite for the variety of species in flora and fauna and for the number of individuals within each species. In the course of evolution new species have always developed, the number of which has constantly fluctuated. However, due to human interference these changes are occurring at an ever-increasing rate. A visible sign of this human influence is the rapid decrease in the variety of species, particularly in the tropical rain forests.

An ocean is a body of saline water that composes much of a hydrosphere of the Earth. The word *ocean* is often used interchangeably with *sea* but, more specifically, an ocean is a large area of salt water between continents while a sea is a body of saline water partly or fully enclosed by land. The main characteristics of ocean water (sea water) are: (i) salinity, (ii) gases, (iii) temperature, and (iv) light.

The salinity of a water system refers to the total salt content in 1000 grams of water and for seawater the value is on the order of 35 grams per 1000 grams of water (3.5% w/w salt). The percentage of the different substances that are present in the solution depends on the river contribution, on chemical reactions that occur in sea sediments, on volcanic activity and on the decomposition of organisms. In fact, the quantity of salt is stable only at a certain depth, while on the surface and coastal areas it is also subject to seasonal variations.

Gases such as oxygen and carbon dioxide are necessary for the life of water organisms. Oxygen is largely present on the surface, since water is in contact with the atmosphere and where photosynthetic organisms live, and deep underwater, where water temperature is very low. Carbon dioxide is a water-soluble and can easily spread from the atmosphere into seawater, transported by river water to the sea, and which derives from decomposing organic materials.

The temperature influences the chemical and physical characteristics that are responsible for the vertical movement of water masses. In some water systems (such as in an ocean or lake or in the atmosphere), a thermocline (also known as the *thermal layer* or the *metalimnion* in lakes) is a distinct layer in which temperature changes more rapidly with depth than it does in the layers above or below. In the ocean, the thermocline divides the upper mixed layer from the calm deep water below. Depending on the season, the latitude and wind turbulence, a thermocline may be a semi-permanent feature of the water system or may form temporarily in response to phenomena such as the radiative heating of the water during the day and the cooling of the water during the night. In the thermocline layer, the temperature rapidly diminishes; on the deep layers it keeps on diminishing, but very slowly. The thermocline is an important surface as far as the spreading of organisms in the oceans is concerned.

Brightness is a subjective attribute/property of an object being observed and refers to an absolute term and should not be confused with lightness. It depends on the ability of the light to penetrate in the water and light up only the superficial part even though the water is clear. This area (the photic zone, approximately 0 to 550 feet of depth) is where most of marine life and phytoplancton are concentrated. The photic zone (also called the *euphotic zone*, *sunlight zone*, *sunlit zone*) is the uppermost layer of water in a pond, lake, or ocean that is exposed to intense sunlight. It corresponds roughly to the layer above the compensation point which is the depth where the rate of carbon dioxide uptake, or equivalently, the rate of photosynthetic oxygen production, is equal to the rate of carbon dioxide production, equivalent to the rate of respiratory oxygen consumption, i.e., the depth where net carbon dioxide assimilation is zero. Since the photic zone is where almost all of the photosynthesis occurs, the depth of the photic zone is generally proportional to the level of the primary production that occurs in that area of the ocean.

Approximately 90% of all marine life lives in the photic zone while a small amount of primary production is generated deep in the abyssal zone in the area of the hydrothermal vents which exist along some mid-ocean ridges. In the disphotic zone, which extends from the base of the euphotic zone, there is some light but it is insufficient for photosynthesis, or at least insufficient for photosynthesis at a rate greater than respiration. The euphotic zone together with the disphotic zone coincides with the epipelagic zone and most deep ocean waters belong to the zone bottom-most zone – the aphotic zone.

The ocean is a continuous body of saltwater that covers more than 70% of the surface of the Earth. On a geographical basis, the oceans can be divided into four major sections: (i) the Pacific Ocean, (ii) the Atlantic Ocean, (iii) the Indian Ocean, and (iv) the Arctic Ocean. Smaller ocean regions typically fall under the names: seas, gulfs, and bays, such as the Mediterranean Sea, Gulf of Mexico, and the Bay of Bengal but standalone bodies of saltwater such as the Caspian Sea and the Great Salt Lake are distinct from the oceans. The ocean water is approximately 3.5% w/w salt and contains traces of all of the chemical elements found on Earth (Table 1.2). The oceans absorb the heat from the Sun and transfer this heat to the atmosphere and distribute it around the world via the ever-moving ocean currents as well as carrying various forms of pollutants from one continent to another; they have a major effect on the climate of the Earth by transferring heat from the tropics to the polar regions.

Huge masses of water displace for long distances due to the wind action. The direction of the movement is determined by the Earth rotation (Coriolis force), which creates circular movements. In the Atlantic Ocean, regular and constant winds, the trade winds, move superficial water masses towards the equator where they are diverted to the west by the Coriolis force (North-Equatorial current); when they reach the American continent they are pushed to the north and accumulate in the Gulf of Mexico. The water continues to flow towards the Atlantic Ocean and forms the Gulf current along the coast of the United States, and then divides into two: (i) one current goes towards the Canary Islands and starts the tour again,

Table 1.2 Elements in the crust of the Earth.

Element (symbol)	**% w/w***
Oxygen (O)	46.6
Silicon (Si)	27.7
Aluminum (Al)	8.1
Iron (Fe)	5
Calcium (Ca)	3.6
Sodium (Na)	2.8
Potassium (K)	2.6
Magnesium (Mg)	2.1
Titanium (Ti)	0.4

*Approximation

and (ii) the other current moves to the northeast, reaches the northwestern coasts of Europe and mitigates their climate.

In polar areas the water cools, becomes denser, falls deep down and moves to the Equator. As it gets warmer, it becomes less dense and lighter and tends to rise to the surface. This movement, which forms deep sea currents, is very slow: it takes even a thousand years for a water mass to go back to the surface. Transferring warm or cold air and precipitation to coastal regions, winds may carry them inland. Surface heat and freshwater fluxes create global density gradients that drive the thermohaline part of large-scale ocean circulation. Changes in the thermohaline circulation govern the rate at which deep waters reach the surface; it may also significantly influence the concentration of carbon dioxide in the atmosphere. These vast bodies of water surrounding the continents are critical to human life but overfishing and global warming threaten to leave this vital habitat barren.

The Pacific Ocean, the largest of the oceans, also reaches northward from the Southern Ocean to the Arctic Ocean. It spans the gap between Australia, Asia, and the Americas and meets the Atlantic Ocean south of South America at Cape Horn. On the other hand, the Atlantic Ocean, the second-largest ocean, extends from the Southern Ocean between the Americas, Africa, and Europe to the Arctic Ocean. The Atlantic Ocean meets the Indian Ocean south of Africa at Cape Agulhas.

The Indian Ocean, the third largest, extends northward from the Southern Ocean to India, the Arabian Peninsula, and Southeast Asia and, in Asia, between Africa in the west to Australia in the East. The Indian Ocean joins the Pacific Ocean to the east, near Australia. The Arctic Ocean is the smallest of the five oceans and joins the Atlantic Ocean near to Greenland and Iceland and joins the Pacific Ocean at the Bering Strait. The Arctic Ocean overlies the North Pole and touches North America in the Western Hemisphere and Scandinavia and Siberia in the eastern hemisphere. The Arctic Ocean is partially covered by sea ice, the extent of which varies according to the season. The Southern Ocean is the general name given to the waters that surround Antarctica and is partially covered by sea ice, the extent of which varies according to the season. The Southern Ocean is the second smallest of the five oceans.

From a chemical point of view, the ocean influences the atmosphere through the exchanges of trace gases across the air-sea interface. The transfer of carbon dioxide from the atmosphere to the ocean is controlled by the two competing factors of temperature: warming of surface waters, which releases carbon dioxide to the atmosphere, and biological productivity. Photosynthesis by marine phytoplankton converts dissolved carbon dioxide into organic carbon, leading to a reduction in surface carbon dioxide values and a carbon dioxide flow into the ocean. The amount of carbon dioxide dissolved in seawater is quite large due to its high solubility and its reactivity with water to form carbonic acid and its dissociation products. The ocean, therefore, serves as a major reservoir for carbon dioxide, approximately 65 times larger than the atmosphere, and oceans have played an important role in the evolution of atmospheric carbon dioxide over the geological history of the Earth and are a primary sink for anthropogenic carbon dioxide.

Other chemical species are released by the ocean, such as reduced sulfur, certain hydrocarbon derivatives, and carbon monoxide. The largest oceanic source of sulfur is provided by dimethyl sulfide (CH_3SCH_3), which is produced by various, but specific, types of phytoplankton. These emissions appear to be most intense in regions where the net primary productivity of the ocean is highest, modified somewhat by poorly understood large-scale patterns in the distribution of phytoplankton species.

The *intertidal zone* is where the ocean meets the land – sometimes this zone is a submerged zone and at other times exposed, as the ocean ebbs (outgoing tide) and flows (incoming tide). Because of this, the floral and faunal communities are constantly changing. For example, on rocky coasts, the zone is stratified vertically and, where only the highest tides reach, there are only a few species of algae and mollusks. In those areas usually submerged during high tide, there is a more diverse array of algae and small animals, such as herbivorous snails, crabs, sea stars, and small fishes. At the bottom of the intertidal zone, which is only exposed during the lowest tides, many invertebrates, fishes, and seaweed can be found. The intertidal zone on sandier shores is not as stratified as in the rocky areas – wave action maintains the mud and sand in a state of constant motion and, thus, very few algae and plants can establish themselves – the fauna includes worms, clams, predatory crustaceans, crabs, and shorebirds.

The *pelagic zone* includes those waters further from the land and the open ocean. The pelagic zone is generally cold though it is hard to give a general temperature range since, just like ponds and lakes, there is thermal stratification with a constant mixing of warm and cold ocean currents. The flora in the pelagic zone include surface seaweeds. The faunal animals include many species of fish and some mammals, such as whales and dolphins. Many feed on the abundant plankton.

The *benthic zone* is the area below the pelagic zone, but does not include the very deepest parts of the ocean. The bottom of the zone consists of sand, slit, and/or dead organisms and the temperature decreases as depth increases toward the abyssal zone, since light cannot penetrate through the deeper water. Floral species are represented primarily by seaweed while the fauna, since it is very nutrient-rich, include various types of bacteria, fungi, sponges, sea anemones, worms, sea stars, and fishes.

The deep ocean is the *abyssal zone* and in this region is very cold (typically: 3°C, 347°F), highly pressured, high in oxygen content, but low in nutritional value – the abyssal zone supports many species of invertebrate species and fishes. The mid-ocean ridges (spreading zones between tectonic plates), often with hydrothermal vents, are found in the abyssal zone along the ocean floor. Chemosynthetic bacteria thrive near these vents because of the large amounts of hydrogen sulfide and other minerals produced from the vents. These bacteria are thus the start of the food web as they are eaten by invertebrates and fishes.

Coral reefs are widely distributed in warm shallow waters and can occur as barriers along continents, such as the Great Barrier Reef located in the Coral Sea off the coast of Queensland, Australia. The Great Barrier Reef is the largest coral reef system in the world and is composed of over 2,900 individual reefs and 900 islands stretching for more than 1,400 miles over an area of approximately 133,000 square miles. The dominant organisms in coral reefs are corals. Corals are interesting since they consist of both algae and tissues of animal polyp. Since reef waters tend to be nutritionally poor, corals obtain nutrients through the algae via photosynthesis and also by extending tentacles to obtain plankton from the water. Besides corals, the faunal animals include several species of microorganisms, invertebrates, fishes, sea urchins, octopuses, and sea stars.

The different processes in the ocean run on a broad range of time scales and although the interactive processes in the upper part of the ocean, the so-called mixed layer, take place within a matter of days, weeks or months, the redistribution processes between the warm equatorial water masses and the cold water of the polar regions in the deep ocean take decades or centuries.

The oceans of the world (sometimes referred to as the World Ocean) play a twofold role in the climate system of the Earth: (i) climate fluctuations are caused by long-term changes in the heat distribution of the ocean and (ii) the thermal inertia of these large water masses slows down climatic changes. The close link between ocean and atmosphere is also effective on shorter time scales and is manifested by the close correspondence between the surface temperature of the ocean and the air temperature close to the ground. Surface winds also strongly contribute to changes in the oceanic circulation and thus regional weather conditions. Since such changes prevail for longer times in the oceans compared to the atmosphere, the ocean can be regarded as a long-term memory system which imposes events from previous climate conditions on future climate.

There is, however, also another factor which underlines the importance of the ocean for the global climate system – the oceans form one of the largest carbon reservoir on the Earth and play an important role in the carbon cycle through biological and chemical exchange processes. A small quantity of this carbon is deposited on the sea floor through dead organisms and their calcific shells but a much larger part of this carbon is given off again into the atmosphere. The ocean reacts relatively inertly to an increase in the carbon dioxide concentration in the atmosphere but the carbon dioxide content in the water close to the surface remains in a quasi-equilibrium with the atmosphere. Carbon dioxide is only withdrawn permanently from the atmosphere when the carbon, which is chemically or biologically bound in the surface water, sinks to lower levels in the ocean (biological pump) and is buried in the sediments.

1.4 The Cryosphere

Another term, the *cryosphere*, is used to describe those portions of the surface of the Earth where the water is in solid form, including sea ice, lake ice, ice sheets, and glaciers [24]. The cryosphere is an integral part of the global climate system with important linkages and through its influence on surface energy and moisture fluxes, clouds, precipitation, atmospheric circulation, and oceanic circulation. The cryosphere also exists in places far away from the cold poles, at high elevations. Frozen soil can be found high in the mountains of the Earth. The cryosphere expands during the cold winter months. Seasonal areas of the cryosphere include places where snow falls, and where soil, rivers, and lakes freeze.

Water (as water vapor) is also present in the atmosphere and other water is contained as ice and snow in snowpack, glaciers, and the polar ice caps. Snow, ice, or both are key ingredients in every aspect of the cryosphere, including sea ice, glaciers, ice shelves, icebergs, and frozen ground. The cryosphere forms the most important fresh water reservoir of the Earth.

Ice forms when temperatures drop below the freezing point and liquid water becomes a solid, creating a tightly bonded substance. Ice is a key ingredient in glaciers, sea ice, ice shelves, icebergs, and frozen ground. Naturally occurring ice exists all over the world, but mostly forms in the high latitudes, at high elevations, or at night when temperatures cool.

1.4.1 Ice Sheets

Ice sheets form in areas where snow that falls in winter does not melt entirely over the summer (Table 1.3) [25–27]. Over thousands of years, the layers of snow pile up into thick masses of ice, growing thicker and denser as the weight of new snow and ice layers compresses the older layers. Because of their height, ice sheets help to maintain cold conditions on the surface. The presence of cold air on the ice sheet also has a regional influence, cooling the surrounding areas.

Ice sheets are constantly in motion, slowly flowing downhill under their own weight. Near the coast, most of the ice moves through relatively fast-moving outlets (often called ice streams, glaciers, ice shelves) [28]. As long as an ice sheet accumulates the same mass of snow as it loses to the sea, it remains stable. The ice sheets of the Earth constantly expand and contract as the climate fluctuates. During warm periods ice sheets melt and sea levels rise, with the reverse occurring when temperatures fall. Water may remain locked in deep layers of polar ice sheets for hundreds of thousands of years.

Table 1.3 General descriptions of glaciers, ice shelves, and icebergs.

Glaciers	Thick masses of ice on land.
	The ice has built up from many seasons of snowfall
	Move downhill very slowly
	Cover 10% of the land
	Store 75% v/v of the fresh water of the world
Ice shelves	Platforms of ice
	Form where ice sheets and glaciers move out into the oceans
	Exist mostly in Antarctica and the Arctic
	Break off and melt as temperatures rise
Icebergs	Large pieces of ice that break off glaciers and ice shelves
	Drift in the oceans.
	Ice shelves and icebergs:

Ice sheets store large amounts of water on land and, thus, any change in the volume has a significant effect on the sea level. It is estimated that, if all the ice sheets melted completely, considering the fact that some ice sheets are grounded below sea level, the sea level would rise by more than 200 feet. On the other hand, if the effect of dilution on sea water density and volume is neglected, the melting of sea ice and ice shelves does not influence sea levels. Indeed, because floating ice displaces its own weight of seawater (of Archimedes' principle), the meltwater simply replaces the volume of ice previously below sea level.

The majority of the ice present on the Earth is located in two big ice-sheets: (i) the Greenland ice sheet and (ii) the Antarctic ice sheet. The Antarctic ice sheet is itself commonly divided into two parts, East Antarctica and West Antarctica, roughly corresponding to the eastern and western hemispheres relative to the Greenwich meridian. The thickness of ice on these ice sheets can reach several miles. Ice sheets are formed by the accumulation of snow layers over tens of thousands of years. As snow falls at the surface, the pressure on the older snow layers increases, transforming them into ice. Ice sheets (like glaciers) are not stagnant and generally flow slowly towards their margins. However, in some regions (called ice streams), the flow is much faster than in other parts of the ice sheet, sometimes reaching several miles per year.

1.4.2 Glaciers

A glacier is a persistent body of dense ice that is constantly moving under its own weight; it forms where the accumulation of snow exceeds its ablation (melting and sublimation) over many years, often centuries. Glaciers form above the permanent snow line due to the accumulation of water at a solid state (snow that transforms into ice). The line varies according to the latitude on which continental glaciers (that uniformly cover wide areas) and mountain glaciers (that occupy mountain valleys) form. However, below the permanent snow the ice melts and the water is present in a liquid state.

Glaciers are categorized by the morphology, thermal characteristics, and behavior. *Cirque glaciers* form on the crests and slopes of mountains, whereas a glacier that fills a valley is called a *valley glacier*, or alternatively an *alpine glacier* or *mountain glacier*. A large body of glacial ice astride a mountain, mountain range, or volcano is termed an *ice cap* or *ice field*.

Glaciers slowly deform and flow due to stresses induced by their weight and also abrade rock and debris from their substrate to create landforms such as moraines. Glaciers form only on land and are distinct from the much thinner sea ice and lake ice that form on the surface of bodies of water. Ice sheets and glaciers are not always thought of as freshwater sources, but they account for a significant fraction of world reserves. Glacial ice is the largest reservoir of fresh water on Earth. Many glaciers from temperate, alpine and seasonal polar climates store water as ice during the colder seasons and release it later in the form of *meltwater* as warmer summer temperatures cause the glacier to melt, creating a water source that is especially important for plants, animals and human uses when other sources may be scant. Within high-altitude and Antarctic environments, the seasonal temperature difference is often not sufficient to release meltwater.

Snow is precipitation that falls to the ground as ice crystals. When cold temperatures and high humidity levels combine in the atmosphere, snow crystals form. As long as the air temperature remains below freezing, the crystals will fall to the Earth as snow. Snow can be found all over the world, even near the equator at high elevations, and also provides a habitat for some animals and plants.

The perennial ice of glaciers is an important part of the water cycle in cold regions. It represents a storage component with strong effects on river discharge and freshwater supply. Such effects indeed make high mountain chains water sources for many areas and climatic change will lead to pronounced changes in this system. Considering time scales of tens and hundreds of millennia, the growth and decay of continental ice sheets, large ice caps and glaciers during periodical ice ages profoundly affect the global water cycle. Within annual cycles of temperature and precipitation, glacial meltwater feeds rivers during the warm/dry season. This contribution to river flow is the predominant source of freshwater for large regions surrounding the corresponding mountain areas. Meltwater from glacierized mountain chains with rugged topography is also intensively used for hydropower generation [29, 30].

1.4.3 Sea Ice

Sea ice is an important element in the climate system of the Earth, in addition to the atmosphere and ocean [24]. Since ice reflects solar energy much more efficiently than open water, the radiation balance of the Earth is significantly affected by the presence of sea ice, which is a moving medium formed when sea water freezes, generally does not cover the whole oceanic surface in a region. Relatively narrow elongated areas of open water inside the pack are called *leads*, while larger areas of open water are called *polynyas*. The sea-ice concentration is defined as the fraction of the surface of interest that is effectively covered by sea ice. A concentration of ice of 1 (or 100%) thus corresponds to a continuous ice pack, while a value of 0 corresponds to open ocean.

In contrast to temperature latitudes, in which moisture and heat are exchanged directly between the ocean and atmosphere through evaporation and precipitation, it is the seasonal freezing and melting of sea ice which causes the exchange in the polar regions. The formation of ice causes seawater to release most of the salts it contains. Some of the resulting heavier surface water sinks to the sea floor. In response, warmer, less heavy water from the deeper ocean layers rises to the surface. Thus there is an exchange between surface and bottom leading to the formation of deep water in the polar oceans. Traces of this water can be found throughout the world ocean. It supplies the surrounding water with oxygen and nutrients.

1.4.4 Permafrost

A permafrost area is an area of soil, rock, or sediment that remains frozen for more than two consecutive years – in practice, this means that permafrost occurs at a mean annual temperature of below 0°C (32°F). Most permafrost areas are located in and around the Arctic and Antarctic regions as well as at higher elevations (alpine permafrost). Ground ice is not always present, as may be in the case of non-porous bedrock, but it does occur and it may be in amounts exceeding the potential hydraulic saturation of the ground material. The formation of permafrost has significant consequences for ecological systems because of limitations on rooting zones as well as on the faunal den and burrow structures. The Arctic region is one of the many natural sources of the greenhouse gas methane [31]. Global warming accelerates its release, due to both release of methane from existing stores, and from methanogenesis in rotting biomass [32].

Subsea permafrost formed during glacial periods, when lower sea levels exposed large areas of the polar continental shelves. The cold air temperatures and long periods of exposure allowed permafrost to grow there to great depths. Thicknesses of several hundreds of meters are known to exist in these shelves and, at present, this permafrost is slowly degrading beneath the relatively warm and salty ocean. However, several tens of thousands of years are required to thaw it completely.

The distribution and thickness of permafrost are controlled by factors that influence its heat balance and heat flow within it. Since pore spaces in permafrost are generally blocked by ice, heat flow is by conduction. While the presence of permafrost is due primarily to climate, considerable modification of the temperature between the atmosphere and permafrost may occur, owing to vegetation, energy exchanges at the snow–ground surface, transfer of heat through the active layer, and local geological and hydrological conditions.

1.5 The Lithosphere

The lithosphere (the land, sometimes referred to as is the *geosphere* and sometime as the *terrestrial biosphere*) is the solid, outer part of the Earth, including the brittle upper portion of the upper mantle and the crust of the Earth that behaves elastically on time scales of thousands of years or greater [1]. The outermost shell of the Earth, the rocky crust, is defined on the basis of its chemistry and mineralogy.

The internal structure of the Earth structure is subdivided into crust, mantle and core and was formed very early during the evolution of the Earth into a solid mass. Beneath the lithosphere is the asthenosphere, a relatively low-viscosity layer on which the lithosphere is supported. Within the crust, there are 12 major plates and these crustal segments drift away from or towards each other at rates of up to 1.5 inches a year. The continents are constituent parts of these drifting plates. Compared to the Earth radius, the crust is extremely thin, only two to four miles under the oceans and approximately 60 miles under the continents. At the mid-ocean ridges, which can be described as a series of active magma chambers, new oceanic crustal rock is created each year.

The crust of the Earth is subject to changes due to the uplift and subsi dence of its parts. This gives rise to material being constantly eroded from higher areas by water, ice and air and being deposited again in subjacent areas. The extent of erosion and sedimentation depends on the prevailing topography and climatic conditions. The continual deposition of loose material in sedimentation basins over long geological periods leads to a gradual consolidation of the sedimentary layers. Ultimately, this leads to the formation of sedimentary rocks. These deposits reveal climate fluctuations way back in the past. The oldest sedimentary rocks date back some 3.5 billion years and show signs of weathering. Also, portions of the older crust disappear on the active continental margins (the subduction zones) and returned to the Earth mantle.

Subduction is a geological process that takes place at convergent boundaries of the tectonic plates where one plate moves under another (subducts) and is forced to sink due to gravity into the mantle – the rates of subduction are typically in inches per year. Plates include both the oceanic crust and the continental crust. Stable subduction zones involve the oceanic lithosphere of one plate sliding beneath the continental or oceanic lithosphere of another plate due to the higher density of the oceanic lithosphere.

Both processes – the formation of new oceanic crust at the mid-oceanic ridges and the simultaneous subduction of older oceanic crust at the active plate margins – are accompanied by intensive volcanism and increased earthquake activity in these regions. The movement of the plates is the response of the outer crust to convective motion in the Earth mantle in which hot deep material rises and cooler surface material sinks. The formation of mountain ranges as well as the creation and disappearance of ocean basins are the result of plate-tectonic processes – these processes play a role in the distribution of water and land over the surface of the Earth.

Also, the magnetic field of the Earth does not remain static over time and the polarization of the magnetic field changes direction by nearly 180°C (field reversal) in a quasi-periodic fashion. In fact, over the past 100 years the magnetic field has been constantly decreasing and the next field reversal (which could take place in approximately 1,500 years) could have considerable consequences for the biosphere.

The crust of the Earth is also subject to changes due to the uplift and subsidence which gives rise to material being constantly eroded from higher areas by water, ice, and air after which it is deposited again in subjacent areas. The extent of erosion and sedimentation depends on the prevailing topography and climatic conditions. The continual deposition of loose material in sedimentation basins over long geological periods leads to a gradual consolidation of the sedimentary layers, which ultimately leads to the formation of sedimentary rocks. Soil is a degradation product consisting of rocks and organic substances formed on the surface of the land by the reaction of water, air and organisms in conjunction with environmental influences. It is the basis of life for flora, fauna (including humans) and an area in which the geosphere, hydrosphere, atmosphere and biosphere interact.

The distribution of water and land on the surface of the Earth has a significant effect on the circulations of water (in the oceans) and gases (in the atmosphere). Thus, plate tectonics contribute to the development of climate and to changes in global environment. Volcanic eruptions, even though local in origin, can affect the Earth system as a whole – they devastate wide areas of land and drastically change the habitat of flora, fauna and man – and, in terms of climatic effect, the volcanic output is reflected in the composition of the atmosphere. Some large volcanic events cause eruptions of volcanic ash reaching the stratosphere, where it remains for many years, substantially influencing the radiation balance of the Earth.

1.5.1 Types

There are two types of lithosphere: (i) the continental lithosphere, which is associated with the continental crust of the Earth and (ii) the oceanic lithosphere, which is associated with the oceanic crust and exists in the ocean basins. The thickness of the lithosphere is considered to be the depth to the isotherm associated with the transition between brittle and viscous behavior. The oceanic lithosphere is approximately 30 to 80 miles thick crust. The oceanic lithosphere thickens as it ages and moves away from the mid-ocean ridge. This thickening occurs by conductive cooling, which converts hot asthenosphere into lithospheric mantle and causes the oceanic lithosphere to become increasingly thick and dense with age. The thickness of the mantle part of the oceanic lithosphere can be approximated as a thermal boundary layer that thickens as the square root of time.

The oceanic lithosphere consists mainly of mafic (rich in magnesium and iron) crust and ultramafic (in excess of 90% w/w mafic) mantle and is denser than continental lithosphere where it thickens as it ages and moves away from the mid-ocean ridge. This thickening occurs by conductive cooling, which converts hot asthenosphere into lithospheric mantle. It was less dense than the asthenosphere for tens of millions of years, but after this becomes increasingly dense. The gravitational instability of mature oceanic lithosphere has the effect that when tectonic plates come together, oceanic lithosphere invariably sinks underneath the overriding lithosphere. New oceanic lithosphere is constantly being produced at mid-ocean ridges and is recycled back to the mantle at subduction zones, so oceanic lithosphere is much younger than its continental counterpart. The oldest oceanic lithosphere is approximately 170 million years old compared to parts of the continental lithosphere which are billions of years old.

The terrestrial lithosphere is important to environmental chemistry as a source and sink for many compounds – a major activity within atmospheric chemistry has been (and remains) the determination of such flows. The structure of the biosphere is controlled by the interaction of climate with the patterns of soils and topography resulting from geological processes on a range of time scales, and further modified by the biogeographic distribution of organisms. Climate patterns are reflected in productivity (annual carbon fixation through photosynthesis), with warmer and wetter regions having higher productivity – the rate of nitrogen cycling follows similar trends – and as a result, trace gas emissions are usually higher (in some cases higher by one or more orders of magnitude) in the tropics than in the mid-to-high-latitude regions. This is clearly true for all soil trace gas fluxes, and may be true for plant-mediated fluxes.

For example, large quantities of hydrocarbon derivatives such as isoprene (C_5H_8) are produced by the foliage of the abundant vegetation in productive ecosystems. Biomass burning fluxes are highest in tropical savanna ecosystems, which are warm and have sufficient rainfall during the wet seasons to accumulate significant biomass, which burns readily during the dry seasons. Large quantities of atmospheric carbon dioxide, carbon monoxide, hydrocarbon derivatives, and nitrogen oxides (NO_x) are produced as a result of the combustion of biomass. Soil and nitrogen oxide relationships are enhanced when the soil is rapidly wetted, dried, and wetted again in succession, and so may be higher in regions of sporadic rainfall, despite higher overall rates of nitrogen cycling, and nitrogen oxide emissions in moist areas.

Soil, a mixture of mineral, plant, and animal materials, is essential for most plant growth and is the basic resource for agricultural production. In the process of developing the land and clearing away the vegetation that holds water and soil in place, erosion has caused devastation on a worldwide scale. The rapid deforestation taking place in the tropics is especially damaging because the thin layer of soil that remains is extremely fragile and quickly washes away when exposed to the heavy tropical rain storms.

Technically, soil is a mixture of mineral constituents – the inorganic components of soil are principally produced by the weathering of rocks and minerals – plant materials, and animal materials, that forms during a long process that may take thousands of years and is an unconsolidated, or loose, combination of inorganic and organic materials. Soil is necessary for most plant growth and is essential for all agricultural production. The organic materials are composed of debris from plants and from the decomposition of animals as well as the many tiny (microscopic) life forms that inhabit the soil. The chemical composition and physical structure of soils is determined by a number of factors such as: the kinds of rocks, minerals, and other geologic materials from which the soil is originally formed. The vegetation that grow in the soil are also important.

Food sources grown on soils are predominantly composed of carbon, hydrogen, oxygen, phosphorous, nitrogen, potassium, sodium and calcium. Plants take up these elements from the soil and configure them into the plants that are recognized as food-plants. Each plant has unique nutritional requirements that are obtained through the roots from the soil. Nutrients are stored in soil on "exchange sites" of the organic and clay components. Calcium, magnesium, ammonium, potassium and the vast majority of the micronutrients are present as cations in soils of varying acidity and alkalinity (varying under most soil pH).

1.5.2 Ecosystems

The term ecosystem describes the total of floral and faunal organisms in a specified spatial unit, their physical conditions and the numerous interactions between the living and non-living components of the system. An ecosystem can either be an isolated pool within an arid region or a whole ocean and the general assumption is that each element in the ecosystem is linked directly or indirectly with the other elements and influences them.

Ecosystems develop in two phases, (i) in the early stage, the growth phase, the system is characterized by a small number of species, short food chains and relative instability, and (ii) in the second phase, at the end of its development, the ecosystem is more complex and consists of a large number of species but is a more stable system. Developments are also disturbed by environmental pollution which leads to changes in natural habitats. As a consequence, forms of vegetation disappear, changing the physical characteristics of the surface of the Earth which directly affects the radiation and moisture balances and thus the weather and climatic conditions of a region.

1.5.3 Composition of Soil

Soil is a mixture of organic matter and minerals that support the floral and faunal species of the Earth. Soil, also called the pedosphere, has four important functions: (i) as a medium for plant growth, (ii) as a means of water storage, water supply, and water purification, and (iii) as a habitat for various life forms and all of these functions, in turn, modify the soil. Soil consists of a solid phase of minerals and organic matter (the soil matrix), as well as a porous phase that holds gases (the soil atmosphere) and water (the soil solution). Accordingly, soil scientists can envisage soils as a three-state system of solids, liquids, and gases. In addition, soil continually undergoes development by way of numerous physical, chemical and biological processes, which include weathering and the associated erosion.

Soil is a major component of the ecosystem of the Earth and, with respect to the carbon cycle of the Earth, soil is an important carbon reservoir, and it is potentially one of the most reactive to the effects of humans. A typical soil is approximately 50% w/w solids (45% w/w mineral and 5% w/w organic matter), and 50% v/v voids (or pores) of which half is occupied by water and half by gas. Networks of pores hold water within the soil and also provide a means of water transport. Oxygen and other gases move through pore spaces in soil and the pores also serve as passageways for small animals and provide room for the growth of plant roots.

The proportion of soil mineral and soil organic content can be treated as a constant (in the short term), while the proportion of soil water and gas content is considered highly variable whereby a rise in one is simultaneously balanced by a reduction in the other. The pore space allows for the infiltration and movement of air and water, both of which are critical for life existing in soil. Compaction, a common problem with soils, reduces this space, preventing air and water from reaching plant roots and soil organisms.

The mineral component of soil consists of an arrangement of particles that are less than 2.0 mm in diameter. Technically, soil is composed of particles that fall into three main mineral groups (i) sand, (ii) silt, and (iii) clay, each of which is determined by particle size: sand, 0.05 to 2.00 mm. silt 0.002 to 0.05 mm, and clay, less than 0.002 mm. Depending upon the parent rock materials from which these mineral were derived, the assorted mineral particles ultimately release the chemicals on which plants depend for survival, such as potassium, calcium, magnesium, phosphorus, sulfur, iron, and manganese.

Organic materials constitute another essential component of soils. Some of the organic material arises from the residue of plants, such as the remains of the roots of plants deep within the soil, or materials that fall on the ground, such as leaves on a forest floor or even a dead animal. These materials become part of a cycle of decomposition and decay, a cycle that provides important nutrients to the soil. In general, soil fertility depends on a high content of organic materials.

Soils are also characterized according to how effectively they retain and transport water. Once water enters the soil from rain or irrigation, gravity comes into play, causing water to trickle downward. Soil differs in the capacity to retain moisture against the pull exerted by gravity and by plant roots. Coarse soil, such as soil consisting mostly of sand, tends to hold less water than do soils with finer textures, such as those with a greater proportion of clays. Water also moves through soil pores by capillary action, which is the type of movement in which the water molecules move because they are more attracted to the pore walls (adhesion) than to one another (cohesion). Such movement tends to occur from wetter to drier areas of the soil. The attraction of water molecules to each other is an example of cohesion.

Water is a critical agent in soil development due to its involvement in the dissolution, precipitation, erosion, transport, and deposition of the materials of which a soil is composed. Soil water is never pure water, but contains dissolved organic and mineral substances. In fact, water is a critical agent in soil development due to its involvement in the dissolution, precipitation, erosion, transport, and deposition of the materials of which a soil is composed. Water is central to the dissolution, precipitation, and leaching of minerals from the soil profile. Finally, water affects the type of vegetation that grows in a soil, which in turn affects the development of the soil.

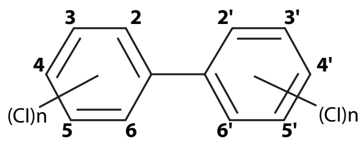
In terms of the floral constituents that grow in the soil, climate is quite sensitive to regional variations in vegetation and water content at the surface of the Earth. The fraction of the incident shortwave radiation reflected from the surface determines the quantity of solar energy absorbed by the surface, which is subsequently available for transfer to the atmosphere as longwave radiation and turbulent fluxes of sensible and latent heat. Water generally has a low fraction of incident shortwave radiation reflected from the surface lakes and the ocean absorbs considerable solar energy. At the opposite extreme, snow and ice have a high fraction of incident shortwave radiation reflected from the surface and, hence, absorb little solar radiation, contributing to the cold conditions required for their persistence. Vegetation has an intermediate fraction of incident shortwave radiation reflected from the surface with values generally decreasing from grasslands, with their highly reflective standing dead leaves, to deciduous forests to dark conifer forests [1]. Land-use changes have substantially altered the fraction of the incident shortwave radiation reflected from the surface by increasing the area of exposed bare soil. Furthermore, the fraction of the incident shortwave radiation reflected from the surface of soil depends on soil type and wetness but is often higher than that of vegetation in dry climates.

1.5.4 Soil Pollution

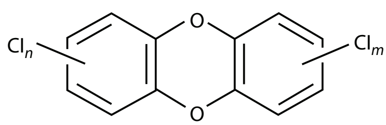
Unhealthy soil management methods have seriously degraded soil quality, caused soil pollution, and enhanced erosion. In addition to other human practices, the use of chemical fertilizers, pesticides, and fungicides has disrupted the natural processes occurring within the soil resulting in soil pollution. Soil pollution is a buildup of toxic chemical compounds, salts, pathogens, or radioactive materials that can affect plant and animal life. The concern over soil contamination stems primarily from health risks, both of direct contact and from secondary contamination of water supplies. All kinds of soil pollutants originate from a source. The source is particularly important because it is generally the logical place to eliminate pollution. After a pollutant is released from a source, it may act upon a receptor. The receptor is anything that is affected by the pollutant. The following subunit describes some of the most common sources of soil pollution.

Some of the most common toxic soil pollutants include organic chemicals, oils, tars, pesticides, biologically active materials, combustible materials, asbestos and other hazardous materials. These substances commonly arise from the rupture of underground storage tanks; application of chemical fertilizers, pesticides, and fungicides; percolation of contaminated surface water to subsurface strata; leaching of wastes from landfills or direct discharge of industrial wastes to the soil. Pesticides that are used in agricultural practices pollute the soil directly by affecting the organisms that reside in it. Pesticides include many types of chemicals that are spread around in the environment to kill some specific sort of pest, usually insects (insecticides), weeds (herbicides), or fungi (fungicides).

Organic pollutants enter the soil via atmospheric deposition, direct spreading onto land, contamination by wastewater and waste disposal. Organic contaminants include pesticides and many other components, such as oils, tars, chlorinated hydrocarbon derivatives, such as polychlorobiphenyl derivatives (PCBs) and dioxins.



PCB derivatives

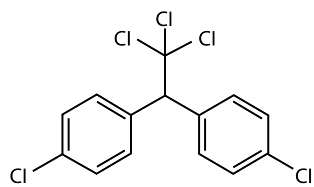


Dioxin derivatives

The use of such pesticides can lead to: (i) destruction of the microflora and fauna of the soil, leading to both physical and chemical deterioration, (ii) severe yield reduction in crops; and (iii) leaching of toxic chemicals into groundwater and potentially threatening drinking water resources.

Existence of the ecosystems requires existence of plants. Humans and animals cannot survive without plants. Soil is not only a source of nutrition but also a place for plants to stand. Pollution of agricultural soils is known to reduce agricultural yield and increase levels of these toxic heavy metals in agricultural products, and thus to their introduction into the food chain. Vegetables and crop plants grown in such soils take up these toxic elements and pose health risk to humans and animals feeding on these plants. The major concern regarding soil pollution is that there are many sensitive land uses where people are in direct contact with soils such as residences, parks, schools and playgrounds. Other contact mechanisms include contamination of drinking water or inhalation of soil contaminants which have vaporized. There is a very large set of health consequences from exposure to soil contamination depending on pollutant type, pathway of attack and vulnerability of the exposed population.

Organic pollutants which are directly applied into soils or deposited from the atmosphere may be taken up by plants or leached into water bodies. Ultimately they affect the health of humans and animals when taken up through the food they eat and the water they drink. More recently research has revealed that many chemical pollutants, such as DDT (dichlorodiphenyltrichloroethane) and polychlorobiphenyls (PCBs), mimic sex hormones and interfere with the reproductive and developmental functions of the human body – the substances are known as *endocrine disrupters*.



DDT

Although soil might be affected less by pollution compared to water or air, cleaning polluted soil is more difficult, complex, and expensive than cramming water and air.

1.6 The Biosphere

The biosphere is the layer of the Earth where life exists (and, therefore, is often defined to include the atmosphere, the hydrosphere and the lithosphere) which ranges from heights of up to several miles above sea level to the depths of the ocean. In general, the layer of the Earth containing life is thin: the upper atmosphere has little oxygen and very low temperatures, while ocean depths are dark and cold. More specifically, the biosphere (also known as the ecosphere) is the worldwide sum of all ecosystems and is the zone of life on the Earth, the global ecological system that refers to all living organisms in their various interrelationships. This also includes the interaction of the living organisms with the elements of the atmosphere, the hydrosphere, the cryosphere, and the lithosphere. The biosphere is unique insofar as life on Earth depends on the Sun. Energy, provided as sunlight, is captured by plants and various microorganisms through the process of photosynthesis.

As part of the biosphere, forests are very important for maintaining ecological balance and provide many environmental benefits. In addition to timber and paper products, forests provide wildlife habitat, prevent flooding and soil erosion, help provide clean air and water, and contain tremendous biodiversity. Forests are also an important defense against global climate change. Forests produce life-giving oxygen and consume carbon dioxide, the compound that is claimed to be the most responsible for global warming through photosynthesis, thereby reducing the effects of global warming.

The biosphere also has a clear impact on the hydrological cycle insofar as water storage is generally greater in soil covered by vegetation than on bare land where direct runoff often follows precipitation. Stored water can later be taken up by plant roots and transferred back to the atmosphere (evapotranspiration). A third effect of the vegetation cover is related to the surface roughness that influences the stress at the atmosphere-land interface and the turbulent exchanges at the surface.

The biosphere is one of the most critical and complex components of the climate system, regulating fluxes of energy, water and aerosols between the Earth surface and atmosphere. Also, the biosphere is central to the biogeochemistry of the Earth, particularly with regard to the global carbon and nitrogen cycles. Prediction or assessment of future Earth system change will always be limited, to some degree, by the ability to define how the terrestrial biosphere will respond to altered climatic forcing, and how this response will express itself as biophysical and biogeochemical feedbacks.

The biosphere plays an important role in the global carbon cycle during evolution of the Earth. In particular, the biosphere has a significant influence on the silicate rock weathering by amplifying the processes. Furthermore relatively inert organic carbon is built up from the decay of organic matter, which contributes 10 to 20% to the present surface reservoirs of carbon. The buildup of this storage of reduced carbon is complemented by the rise of oxygen in the atmosphere. The biosphere is ultimately what ties the major systems of the Earth together. The biosphere plays more central roles in the health of the Earth by means of biodiversity and ecosystem services but the exact dimensions of these roles are difficult to define. There is, however, no doubt that a premium must be placed on maintaining biodiversity, as well as the health of ecosystems critical for human sustainability [33].

As part of the biosphere, the anthrosphere is that part of the environment made or modified by humans and used for their activities. The biosphere is key to the existence of life on the Earth. The life forms (including human life forms) that exist in the biosphere are adapted to make a variety of complex and specialized chemical products for which it is essential to have adequate supplies of water, which emphasizes the important connection between the biosphere and the hydrosphere.

The biosphere is one of the most critical and complex components of the climate system, regulating fluxes of energy, water and aerosols between the Earth surface and atmosphere. The biosphere also is central to the biogeochemistry of the Earth, particularly with regard to the global carbon and nitrogen cycles. Prediction or assessment of future Earth system change will always be limited, to some degree, by the ability to define the manner in which the biosphere will respond to altered climatic forcing, and how this response will express itself as biophysical and biogeochemical feedbacks. In fact, the biosphere represents an immense equilibrium system of chemical reactions. Perturbation of the equilibrium at one site may provoke uncontrolled change in the whole system, in spite of the fact that there are different compensating mechanisms.

Within the biosphere, there is a variety of ecosystems which are self-sustaining structural and functional units of the biosphere and, in the biosphere, several ecosystems can coexist. Usually there is exchange of material and energy between adjoining ecosystems and which may be terrestrial as well as aquatic. Land ecosystems include forests, grasslands, deserts and hillsides. Aquatic ecosystem includes ponds, rivers, lakes, seacoasts and oceans. Artificial ecosystems that are man-made are croplands, gardens, parks, kitchen gardens and aquariums. As mentioned earlier, an ecosystem consists of two major components, (i) abiotic components and (ii) biotic components. The abiotic components are of three kinds: (i) inorganic substances, (ii) organic substances, and (iii) climatic factors.

Abiotic components refer to non-living physical and chemical elements (typically inorganic substances) in the ecosystem and abiotic resources are usually obtained from the lithosphere, atmosphere, and hydrosphere. Inorganic substances are various chemical substances found in the ecosystem such as carbon, nitrogen, sulphur, phosphorous, oxygen and compounds like carbon dioxide, and water. A vital balance among these components in the environment should be maintained and nature plays an important role in doing this through cycles such as the carbon cycle, water cycle, and the nitrogen cycle.

On the other hand, biotic components are living or the remains of once-living organisms in the ecosystem. These are obtained from the biosphere and are capable of reproduction. Examples of biotic components include organic substances (such as floral and faunal organisms); various chemical substances found in the ecosystem but they are organic in nature. They form the greater part of the living organism and form a link between the abiotic compounds and the biotic compounds such as proteins, carbohydrates, fats (sometime referred to as lipids), and humic substances. Typically, both the abiotic systems and the biotic systems exist in a beneficial relationship with each other.

1.7 Interrelationships

In terms of the interrelationships of the subsystems of the Earth, there is a strong connection between all of the components of the climate system of the Earth (i.e., the atmosphere, the hydrosphere, the lithosphere, and the biosphere) (Table 1.4). For example, disturbance of land by conversion of grasslands or forests to agricultural land or intensification of agricultural

Table 1.4 All components of the climate system of the Earth are interrelated.

Atmosphere	↔	Hydrosphere
	↔	Lithosphere
	↔	Biosphere
Hydrosphere	↔	Atmosphere
	↔	Lithosphere
	↔	Biosphere
Lithosphere	↔	Atmosphere
	↔	Hydrosphere
	↔	Biosphere
Biosphere	↔	Atmosphere
	↔	Hydrosphere
	↔	Lithosphere

production may reduce vegetation cover, decreasing transpiration (loss of water vapor by plants) and affecting the microclimate; the result is increased rain runoff, erosion, and accumulation of silt in bodies of water. The nutrient cycles may be accelerated, leading to nutrient enrichment of surface waters. This, in turn, can profoundly affect the chemical and biological characteristics of bodies of water.

The biosphere presently serves as a major net sink of atmospheric carbon and because of the size of the terrestrial carbon pool, any change in the biosphere has the potential to play an even larger role in global carbon cycle dynamics in the future, especially in terms of the response of the biosphere in the face of climate change. However, the growing focus of attention on the biosphere must reach beyond carbon dioxide, to the role of terrestrial vegetation in a range of climatically sensitive biogeochemical and biophysical processes.

However, all the systems and cycles described above are subject to changes – the only constant in the system is change! For a certain period, an average state (e.g., the state of the climate) but going back or ahead to other time intervals there are different states and their temporal sequence of events can be deduced from a number of natural archives. These archives are documentary evidence of changes which took place on the Earth without interference by man. They indicate the range of fluctuations in the past, give clues to the sequence of warm and cold cycles and can serve to test working hypotheses about vital processes in the Earth system.

For example, the climatic conditions prevailing in previous eons of the history of the Earth have been recorded in ice and sediment cores, tree rings and coral deposits. In addition, the continental drift can be deduced from the rock succession of the crust of the on the continents and at the bottom of the oceans.

Thus, the former state of the biosphere can be traced at many points of the Earth in fossils, witnesses of the ancient living world embedded in sediment. In fact, the characteristics of the natural water that is available for human use and consumption are the outcome of the interaction of the hydrosphere with the geosphere. For example, the hardness of water is generally ascribed to the soluble calcium ion (Ca^{2+} ion) while the alkalinity of water is generally ascribed to dissolved bicarbonate ion $\left(HCO_3^- \text{ ion}\right)$. Both of these ions are present in water that is in content with limestone ($CaCO_3$) formations and/or dolomite ($CaCO_3.MgCO_3$) formation. In the latter case (i.e., dolomite formations, magnesium ions (Mg^{2+} ions) will also be present in the water. Other elements (particularly trace elements) are also present in groundwater having been extracted from mineral formations.

Thus, water is a complex system of chemical species that has received considerable study because of a series of environmental issues that have been raised [34–37]. In fact, throughout history, the quality and quantity of water available to humans have been vital factors in determining not only the quality of life but also the existence of life [38, 39]. However, in many parts of the world, water pollution is a major issue.

By means of clarification, water pollution refers to any change in natural waters which may impair their further use, caused by the introduction of organic or inorganic substances with undesirable properties for the ecosystem (Table 1.5), or a change in temperature of the water [40]. Furthermore, water – preferably clean and unpolluted water – is essential to all living organisms. Precipitation and evaporation rates, humidity, and available soil moisture are factors governing water availability for various life forms. Precipitation varies in relation to the position and movement of air masses and weather system, location relative to mountain ranges (rain shadow effect), and altitude. Seasonal distribution of rainfall is as important as the total amount; rainfall evenly distributed throughout the year usually results in greater availability. The water that humans use is primarily fresh (but treated) surface water and groundwater. In arid regions, a small fraction of the water supply comes from the ocean, a source that is likely to become more important as the supply of fresh water available to the Earth

Table 1.5 Key properties of wastes that will be harmful to water systems.

Property	Comments
Ignitable	Waste that will ignite; includes liquids with a flash point below 60°C (140°F), non-liquids that cause fire through specific conditions, ignitable compressed gases and oxidizers.
Corrosive	Waste that is corrosive; includes corrosive waste which include aqueous wastes with a pH of less than or equal to 2, a pH greater than or equal to 12.5 or based on the liquids ability to corrode steel.
Reactive	Waste that is reactive and which may react with water, may give off toxic gases and may be capable of detonation or explosion under normal conditions or when heated.
Toxic	Waste that is toxic when ingested or absorbed; may be able to leach from deposited waste and pollute groundwater.

dwindles relative to demand. Saline or brackish groundwater may also be utilized in some areas.

Obviously, humans have also been polluting water since the early days of civilization. The development of towns and cities in close proximity to rivers also caused the rivers to become polluted by human waste and *effluents*. Indeed, whole civilizations have disappeared not only because of water shortages resulting from changes in the climate but also because of water-borne diseases, such as cholera and typhoid [41]. In fact, in medieval times when a castle was protected from invaders by the moat (which tended to be the dumping area for all type of castle waste), one can wonder whether or not the castle moat actually protected the inmates from the attackers, although it is more likely that the disease-ridden moat was fatal to both sides!

Serious epidemics of waterborne diseases such as cholera, dysentery, and typhoid fever were caused by underground seepage from privy vaults into town wells [42]. Such direct bacterial infections through water systems can be traced back for several centuries, even though the germ or bacterium as the cause of disease was not proved for nearly another century. In the modern world, the indirect reuse of wastewater that has been discharged into rivers is common around the world, and it is acceptable as long as the discharges are treated and contamination from chemical waste is avoided [43]. Less acceptable is the direct reuse of wastewater for potable use, even after a high level of treatment; the major concern in such cases is the possibility of an outbreak of disease initiated by the use of incorrectly treated or untreated water.

In considering water pollution, it is useful to keep in mind an overall picture of possible pollutant cycles which involve the major routes of pollutant interchange among the biotic, terrestrial, atmospheric, and aquatic environments. Problems with water supply quantity and quality remain and in some respects are becoming more serious. These problems include increased water use due to population growth, contamination of drinking water by improperly discarded waste materials, and destruction of wildlife by water pollution.

Water pollutants can be divided into a series of general chemical types (Table 1.6) and water pollution control is closely allied with the water supplies of communities and industries because both generally share the same water resources [44]. There is great similarity in the pipe systems that bring water to each home or business property, and the systems of sewers or drains that subsequently collect the wastewater and conduct it to a treatment facility. Treatment should prepare the flow for return to the environment so that the receiving watercourse will be suitable for beneficial

Table 1.6 Water pollutants and the effects on water systems.

Pollutant type	**Effect***
Trace elements	Health, aquatic biota
Metal-organic combinations	Metal transport
Inorganic pollutants	Toxicity, aquatic biota
Algal nutrients	Eutrophication
Radionuclides	Toxicity
Acidity, alkalinity, salinity (in excess)	Water quality, aquatic life
Sewage	Water quality, oxygen levels
Biochemical oxygen demand	Water quality, oxygen levels
Trace organic pollutants	Toxicity
Pesticides	Toxicity, aquatic biota
Crude oil, crude oil products, crude oil wastes	Effect on water biota
Detergents	Eutrophication
Sediments	Water quality, aquatic biota

*Will also affect land-based wildlife (including humans) that consume the water.

uses such as general recreation, and safe for subsequent use by downstream communities or industries.

Water supply can be considered to be one part of a hydrogeological cycle (also called the water cycle and the hydrological cycle) in which a major portion of the water occurs in the oceans [45–47]. In the present context, the hydrogeologic cycle is a useful starting point for the study of water supply. This cycle (Figure 1.1) includes precipitation of water from clouds, infiltration into the ground or runoff into surface water, followed by evaporation and transpiration of the water back into the atmosphere. The rates of precipitation and evaporation and/or transpiration help define the baseline quantity of water available for human consumption.

Precipitation is the term applied to all forms of moisture (rain, ice, snow) falling to the ground. *Evaporation* and *transpiration* are the movement of water back to the atmosphere from open water surfaces and from plant respiration. The same meteorological factors that influence evaporation are at work in the transpiration process: solar radiation, ambient air temperature, humidity, and wind speed. The amount of soil moisture available to plants also affects the transpiration rate. Evaporation is measured by measuring water loss from a pan. Transpiration can be measured with a *phytometer,* a large vessel filled with soil and potted with selected plants. The soil surface is hermetically sealed to prevent evaporation; thus moisture can escape only through transpiration. The rate of moisture escape is determined by weighing the entire system at intervals up to the life of the plant. The data from a phytometer can be used as an index of water demand by a crop under field conditions, and thus relate to calculations that help an engineer determine water supply requirements for that crop. Because it is often not necessary to distinguish between evaporation and transpiration, the two processes are often linked as *evapotranspiration,* or the total water loss to the atmosphere.

An aquifer is a geologic formation consisting of porous and permeable rocks, material such as sand, gravel, or sandstone, through which water flows and is stored. An artesian aquifer is a confined aquifer containing groundwater under positive pressure and is, essentially, trapped water, surrounded by layers of impermeable rocks or clay minerals, which applies positive pressure to the water contained within the aquifer. If a well is drilled into an artesian aquifer, water in the well-pipe will rise to a height corresponding to the point where hydrostatic equilibrium is reached, i.e., the hydrostatic pressure is equal to atmospheric pressure. A well drilled into such an aquifer is called an *artesian well*, and if water reaches the ground surface under the natural pressure of the aquifer, a *flowing artesian well*.

Groundwater is a vital resource that plays a crucial role in geochemical processes, such as the formation of secondary minerals. The nature, quality and mobility of groundwater are all strongly dependent upon the rock formations in which the water is held. Groundwater is the part of the hydrosphere (also called the aquasphere, or the region of the Earth that consists of the various water systems) most vulnerable to damage from chemical waste materials. Although surface water supplies are subject to contamination, groundwater can become almost irreversibly contaminated by the improper land disposal of chemicals.

Once there is penetration into aquatic systems, chemical species are subject to a number of chemical and biochemical processes. These include acid-base, oxidation-reduction, precipitation-dissolution, and hydrolysis reactions, as well as biodegradation. Under many circumstances, biochemical processes largely determine the fates of chemical species in water. The most important such processes are those mediated by microorganisms. In particular, the oxidation of biodegradable organic wastes in water generally occurs by means of microorganism-mediated biochemical reactions.

Bacteria produce organic acids and chelating agents, such as citrate, which have the effect of solubilizing heavy metal ions. Some mobile methylated forms, such as compounds of methylated arsenic and mercury, are produced by bacterial action.

Physically, an important characteristic of such formations is the porosity, which determines the percentage of rock volume available to contain water. A second important physical characteristic is permeability, which describes the ease of flow of the water through the rock. High permeability is usually, but not always, associated with high porosity – a serious fracture in a rock formation may give the impression that the formation is highly permeable but the remainder of the formation may be impermeable to the water and other fluids. However, clay minerals tend to have low permeability even when a large percentage of the volume is filled with water. Most groundwater originates from precipitation in the form of rain or snow.

Water from precipitation that is not lost by evaporation, transpiration, or to steam runoff, may infiltrate into the ground. Initial amounts of water from precipitation on to dry soil are held very tightly as a film on the surfaces and in the micropores of soil particles. At intermediate levels, the soil particles are covered with films of water, but air is still present in larger voids in the soil. The region in which such water is held is called the unsaturated zone or zone of aeration (the vadose zone) and the water present in it is vadose water.

At lower depths, in the presence of adequate amounts of water, all voids are filled to produce a zone of saturation, the upper level of which is the water table. The water table is crucial in explaining and predicting the flow of wells and springs and the levels of streams and lakes. It is also an important factor in determining the extent to which pollutant and hazardous chemicals are likely to be transported by water. The water table tends to follow the general contours of the surface topography and varies with differences in permeability and water infiltration. The water table is at surface level in the vicinity of swamps and frequently above the surface where lakes and streams are encountered. The water level in such bodies may be maintained by the water table. In-flowing streams or reservoirs are located above the water table; these water systems lose water to the underlying aquifer and cause an upward bulge in the water table beneath the surface water.

Groundwater flow is an important consideration in determining the accessibility of the water for use and transport of pollutants from underground waste sites. Various parts of a body of groundwater are in hydraulic contact so that a change in pressure at one point will tend to affect the pressure and level at another point. For example, infiltration from a heavy, localized rainfall may affect water level at a point remote from the infiltration. Groundwater flow occurs as the result of the natural tendency of the water table to assume even levels by the action of gravity. Also, the flow of groundwater is strongly influenced by the permeability of the stratum (or strata, if there are several such formations) through which the water flows rock permeability. Porous or extensively fractured rock is relatively highly pervious. Because water can be extracted from such a formation, it is commonly referred to as an aquifer.

Briefly, an aquifer is a subsurface zone that yields economically important amounts of water to wells. The term is synonymous with water-bearing formation. An aquifer may be porous rock, unconsolidated gravel, fractured rock, or cavernous limestone. Economically important amounts of water may vary from less than a gallon per minute for cattle water in the desert to thousands of gallons per minute for industrial, irrigation, or municipal use. Also, an artesian is a confined aquifer containing groundwater that will flow upwards out of a well without the need for pumping. Two other terms that are worthy of definition at this point are (i) permeability and (ii) porosity.

The permeability of a formation is a measure of the ease with which water and other fluids migrate through geological strata or landfill liners. For example, a sandstone formation may have very high permeability (i.e., water or other fluids, such as crude oil, flow relatively easily though the formation) while a shale formation or a clay formation will typically have very low permeability (i.e., water or other fluids, such as crude oil, flow with difficulty or not at all through the formation) [14].

Aquifers are important reservoirs storing large amounts of water relatively free from evaporation loss or pollution. If the annual withdrawal from an aquifer regularly exceeds the replenishment from rainfall or seepage from streams, the water stored in the aquifer will be depleted. Lowering the pressure in an aquifer by overpumping may cause the aquifer and confining layers of silt or clay to be compressed under the weight of the overburden. The resulting subsidence of the ground surface may cause structural damage to the aquifer and to surface buildings, damage to wells, and other problems.

By contrast, an aquiclude is a rock formation that is too impermeable to yield groundwater. Impervious rock in the unsaturated zone may retain water infiltrating from the surface to produce a perched water table that is above the main water table and from which water may be extracted. However, the amounts of water that can be extracted from such a formation are limited and the water is vulnerable to contamination.

A river is a natural, freshwater surface stream that has considerable volume compared with its smaller tributaries. The tributaries are known as brooks, creeks, branches, or forks. Rivers are usually the main stems and larger tributaries of the drainage systems that convey surface runoff from the land. Typically, a river flows from the headwater areas of small tributaries to their mouth of the river, where they may discharge into the ocean, a major lake, or a desert basin. Rivers flowing to the ocean drain approximately two-thirds of the land systems. The remainder of the land either is covered by ice or drains to closed basins (common in desert regions). Regions draining to the sea are termed exoreic while those regions which drain into interior closed basins are endoreic. Areic regions are those which lack surface streams because of low rainfall or lithologic conditions.

Groundwater and surface water have different characteristics: substances either dissolve in surface water or become suspended in it on their way to the ocean. Surface water in a lake or reservoir that contains the mineral nutrients essential for algal growth may support a heavy growth of algae. Surface water with a high level of biodegradable organic material, used as food by bacteria, normally contains a large population of bacteria. All these factors have a profound effect upon the quality of surface water. Groundwater may dissolve minerals from the formations through which it passes. Most microorganisms originally present in groundwater are gradually filtered out as it seeps through mineral formations. Occasionally, the content of undesirable salts may become excessively high in groundwater, although it is generally superior to surface water as a domestic water source. The movement of water from waste landfills to aquifers is also an important process whereby pollutants in the landfill leachate may be adsorbed by solid material through which the water passes.

Natural waters have a broad range of total dissolved solids (TDS). Some fresh mountain streams might have a low content of total dissolved solids whilst sea water has a high content of the solids. Extreme amounts of total dissolved solids are found in highly evaporated lake water or isolated seawater basins and in the deep subsurface water (so-called formation water).

Flowing water, whether in aquifers or streams, interacts with rocks and soils and slowly dissolves some of their chemical constituents. The pH (hydrogen ion activity) of the water determines the rate of dissolution and solubility of many chemical species. Some chemical substances, particularly redox-sensitive trace metals (e.g., Fe, Mn, Pb, As, and others), are more soluble when natural waters are depleted in dissolved oxygen. Most chemical species in natural waters arise from both natural and pollutant sources of many types (Table 1.7).

Table 1.7 Chemical species commonly occurring in water.

Chemical	Natural source	Other source
Sodium (Na^+)	Sea salt, soil dust	biomass burning
Magnesium (Mg^+)	Sea salt, soil dust	biomass burning
Potassium (K^+)	Sea salt, soil dust,	biomass burning, fertilizers
Calcium (Ca^+)	Sea salt, soil dust	biomass burning, cement manufacture
Hydrogen (H^+)	Gas emissions	fuel combustion
Chloride (Cl^-)	Sea salt	Industrial chemicals
Sulfate $\left(SO_4^{2-}\right)$	Sea salt, soil dust, biological decay, volcanic activity	biomass burning, fuel combustion
Nitrate $\left(NO_3^{2-}\right)$	Lightning, biological decay	biomass burning, fuel combustion, automobile emissions, fertilizers
Ammonium (NH_4+)	Biological decay	fertilizers, biological decay
Phosphate $\left(PO_4^{3-}\right)$	Soil dust, biological decay	biomass burning, fertilizers
Bicarbonate $\left(HCO_3^{2-}\right)$	Carbon dioxide in the air	volcanic activity, biomass burning, automobile emissions, fuel combustion
SiO_2, Al, Fe	Soil dust	fuel combustion

Natural waters also contain dissolved gases, such as carbon dioxide from the atmosphere which, when dissolved in water, contributes through a series of chemical reactions, contributes to the total dissolved carbon in waters – primarily bicarbonate $\left(HCO_3^{2-}\right)$. Also, the solubility of a gas is inversely proportional to temperature and the amount of total dissolved solids but natural waters can have low concentrations of dissolved oxygen concentrations as the result of biological activity such as the metabolism of water inhabitants, including bacteria.

Moreover, the photosynthetic activity of algae and aqueous plants can add oxygen to the water in which these primary producers grow but the breakdown of organic material by bacteria consumes dissolved oxygen.

Thus, in waters below the surface wind-mixed layer (usually tens of meters or more) or in stably stratified lakes or bays, for which rates of oxygen replenishment to deeper depths are slow, deficiencies in dissolved oxygen can develop, with anoxia (total depletion of dissolved oxygen) at the extreme and excess nutrient supply can have the same impact on a water body.

Finally, the key to understanding global climate change is to first understand the nature and components of the global climate system and how the system operates. On Earth, the global climate is regulated by how much energy the Earth receives from the Sun. However, the global climate is also affected by other flows of energy which take place within the climate system itself. This global climate system is made up of the various Earth systems, i.e., (i) the atmosphere, (ii) the hydrosphere, (iii) the cryosphere, (iv) the lithosphere, and (v) the biosphere, which all affect, to a greater or less extent, the movement of heat around the surface of the Earth. None of these systems operate as an isolated system. Flows of energy take place between the atmosphere and the other parts of the climate system, most significantly the oceans of the Earth. For example, ocean currents move heat from warm equatorial latitudes to colder polar latitudes. Heat is also transferred via moisture – water evaporating from the surface of the oceans stores heat which is released when the vapor condenses to form clouds and rain. The significance of the oceans is that they store a much greater quantity of heat than the atmosphere. Therefore, flows of energy between the oceans and the atmosphere can have dramatic effects on the global climate.

The cryosphere, which includes Antarctica, the Arctic Ocean, Greenland, Northern Canada, Northern Siberia and most of the high mountain ranges throughout the world where sub-zero temperatures persist throughout the year, also has a significant impact on the climate of the Earth. Snow and ice reflect most of the sunlight, instead of absorbing it. Without the cryosphere, more energy would be absorbed at the surface of the Earth rather than reflected, and consequently the temperature of the atmosphere would be much higher.

All land plants make food from the photosynthesis of carbon dioxide and water in the presence of sunlight. Through this utilization of carbon dioxide in the atmosphere, plants have the ability to regulate the global climate. In the oceans, microscopic plankton utilize carbon dioxide dissolved in seawater for photosynthesis and the manufacture of their tiny carbonate shells. The oceans replace the utilized carbon dioxide by dissolving or absorbing the gas from the atmosphere. When the plankton die, their carbonate shells sink to the seafloor, effectively locking away the carbon dioxide from the atmosphere. Such a "biological pump" reduces by at least fourfold the atmospheric concentration of carbon dioxide, significantly weakening the natural greenhouse effect of the Earth and reducing the temperature of the surface of the Earth.

As this book progresses, it will be seen that there is no one effect that is the major cause of climate change; in reality, it is a sequence or collection of effects (many of them natural) that play a role in the changing climate This book suggests that there should be more focus on these natural effects.

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