Chapter 1

The Ocean in the Earth System

Learning Objectives

- Describe the meaning of an Earth system perspective.
- Identify and describe the major subsystems of the Earth system.
- Provide some examples of how Earth's major subsystems interact with one another.
- Describe the global water cycle.
- Define the processes whereby water cycles between Earth's surface and atmosphere.
- Present the major implications of the global water budget for the flow of water between land and ocean.
- Explain the significance of the electromagnetic spectrum.
- Distinguish between geostationary satellites and polar-orbiting satellites.
- List the advantages of remote sensing of the ocean by satellite versus ship-based investigations.
- Identify the principal limitation of remote sensing of the ocean by an Earth-orbiting satellite.
- Distinguish among conceptual, graphical, physical, and numerical models.
- Identify the advantages and potential shortcomings of models used for scientific investigations.

Central Question

What is the Earth System perspective for studying the ocean?

Case-in-Point

The Japan and Indian Ocean Tsunamis

On 11 March 2011, a succession of tsunami waves struck the northeast coast of Japan's main land mass and largest island, Honshu, decimating the city of Sendai and numerous other coastal communities. The tsunami was caused by the largest earthquake to affect Japan since instrumental recording began 130 years ago and the fourth largest earthquake in the world since 1900. There were 15,890 deaths and approximately 2500 missing in Japan. Another very powerful tsunami devastated coastal areas around the Indian Ocean on 26 December 2004. This event claimed 227,898 dead and missing from 14 countries. The difference in mortality rates between these tsunamis reflects, in part, the benefits of understanding how tsunami waves are generated and move, and educating citizens to make scientifically sound and potentially life-saving decisions.

A tsunami is a series of rapidly propagating, shallow-water ocean waves that develops when a submarine earthquake, landslide, or volcanic eruption displaces a large volume of water. Powerful earthquakes, with magnitudes of 9 or greater, caused both the 2004 and 2011 tsunamis. The earthquakes resulted from the movement of large tectonic plates. The 11 March 2011 earthquake occurred at 32 km (20 mi.) deep in Earth's crust about 130 km (81 mi.) east of the city of Sendai. This location is on the boundary between two tectonic plates—the Pacific plate to the east and North American plate to the west. This boundary fractured, releasing energy that was transmitted through the rocks and elevated portions of the ocean floor. This drastic movement transmitted energy to the overlying ocean water, which generated tsunami waves that radiated outward. The waves washed over the nearby coastlines and were felt around the globe within hours (Figure 1.1).

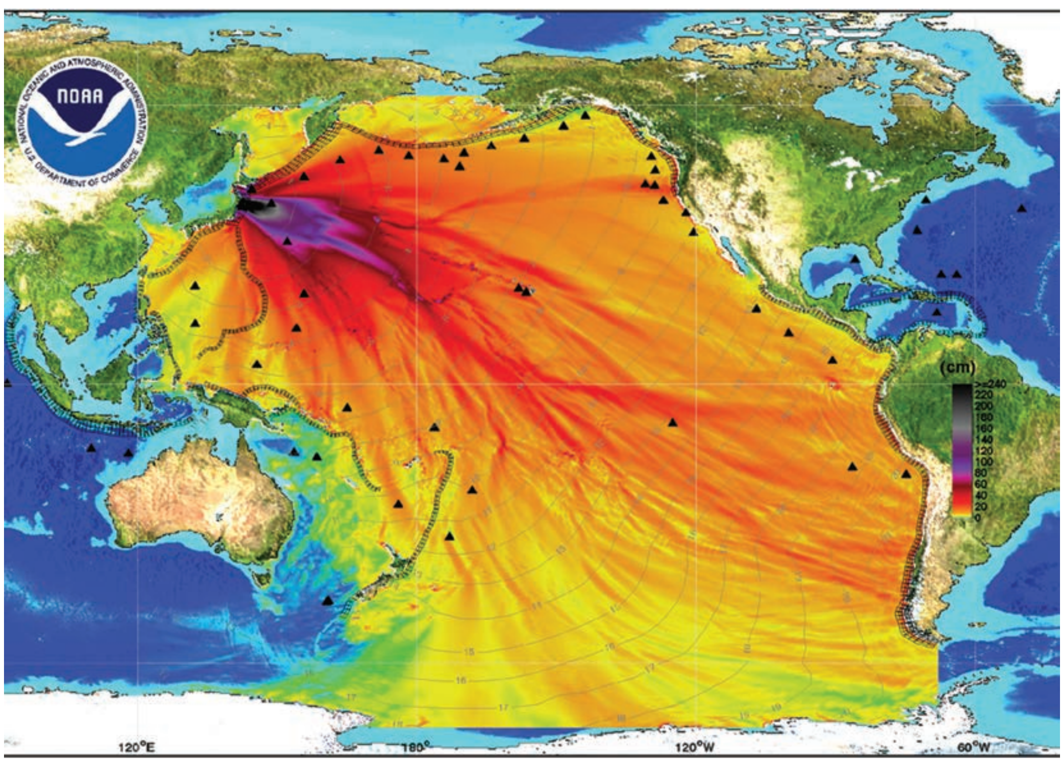


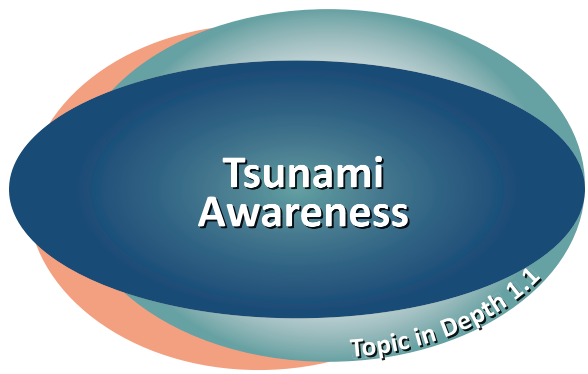
Figure 1.1
The MOST (Method of Splitting Tsunami) model simulation of maximum 11 March 2011 tsunami amplitude in cm during 24 hours of wave propagation after the earthquake occurred near Sendai, Japan. [Courtesy of NOAA Center for Tsunami Research]

Residents of Japan's coastal communities only had minutes to evacuate to higher ground because tsunami waves travel quickly, about 500 to 1000 km per hr (300 to 600 mph). As each wave approached the shallow coastal water, it crested, forming a wall of water up to 10 m (33 ft.) high as it pushed inland. These waves traveled as far as 10 km (6 mi.) inland. In comparison, the tsunami that devastated Sumatra's Aceh Province exceeded 30 m (100 ft.) high, the height of a 10-story building.

In 2004, there was no tsunami warning system operating in the Indian Ocean. The citizens living in the region had no advanced warning that a tsunami wave was approaching. For those living along the Pacific Ocean, the *Intergovernmental Coordination Group for the Pacific Tsunami Warning System*

(ICG/PTWS) was established in the 1960s to provide an early warning. The Japanese people are also trained, starting in elementary school, on what to do when a tsunami warning is given. These precautionary measures saved many lives during the 2011 tsunami.

Understanding tsunamis and underwater earthquakes, as well as volcanoes, is the first step for effective planning for these disasters, but there is always room for improvement. Only by studying the processes and consequences, and the interactions across the entire ocean system, can future tragedies be mediated. Achieving this goal calls for a perspective enveloping not only oceanographic and geological processes, but also humans and their lifestyles, an *Earth system perspective*.



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1.1 Introduction

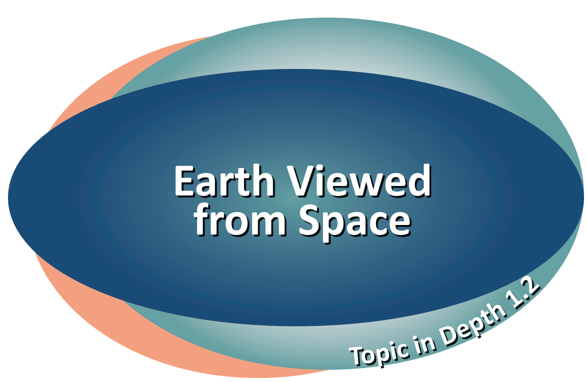
This book examines all aspects of Earth's oceans from why ocean water is salty to the role organisms, both large and microscopic, play in many aspects of human lives. The book also examines how ocean water moves through the vast basins of the world ocean and the role of the ocean in transferring heat and matter around the planet and modulating global climate. The ocean interacts with many other components in the Earth system. It is essential to understand these interactions to truly appreciate the roles the ocean plays in the condition of the planet. To reach such an understanding, each of Earth's subsystems (or spheres) and their complex interactions must be examined. The book explores the hydrosphere (Earth's water and ice, including the ocean), atmosphere (its gaseous envelope), geosphere (Earth's solid portion), and biosphere (all living organisms); and the flow and transformations of matter and energy within and among these subsystems. Chapter 1 lays the groundwork to appreciate the role of each sphere in studying the Earth system.

1.2 Earth as a System

The Earth can be described as a **system**, an interacting set of components that behave in an orderly way according to the laws of nature. Scientists conduct extensive observations to understand and assess how the system and its components are likely to respond to changing conditions. This approach provides the background leading to better understanding of global climate change and its potential impacts on the planet. The Earth system consists of four spheres: the hydrosphere, atmosphere, geosphere, and biosphere. In order to study Earth, it is important to understand how the spheres interact. Viewed from space, all of the major subsystems of Earth can be seen (Figure 1.2). The most prominent feature of

Earth is the blue of the ocean. Landmasses, part of the geosphere, appear strewn across the planet. Polar regions are white, revealing the ice sheets of Antarctica and Greenland and the sea ice in the Arctic Ocean, which is partially hidden by clouds. The ever changing clouds of the atmosphere swirl across much of the planet and the green hues of parts of the landmasses are vegetation, part of the biosphere.

Figure 1.2
Planet Earth viewed from space appears as a "blue marble" with its surface mostly ocean water and partially obscured by swirling cloud masses. The Moon, appearing in the upper left limb of the Earth, is the planet's only natural satellite and exerts a major influence on the ocean through tides. [Courtesy of NASA, Goddard Space Flight Center]



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1.2.1 Hydrosphere

The existence of life on Earth is believed to depend on water. Earth's position relative to the Sun permits water to be found in three phases (solid, liquid, and gas) on the planet's surface. Earth's **hydrosphere** is dynamic as water moves continually among its three phases. The ocean is the ultimate destination of water moving on or beneath the land surface. Water flowing in river or stream channels may take a few weeks to reach the ocean. Groundwater moves more slowly through fractures and tiny openings in subsurface rock and sediment, which ultimately feed into rivers, lakes, or directly into the ocean. Water in large lakes also moves slowly, in some cases taking centuries to reach the ocean.

The ocean is by far the largest reservoir of water in the hydrosphere. It covers 70.8% of the planet's surface, mostly as ocean. Despite the vast resources of water on and beneath the planet's land surface, most of the water (96.5%) is ocean saltwater (Table 1.1). Ice caps, glaciers, and permanent snow comprise the next largest reservoir in the hydrosphere, making up 1.74% of water in the hydrosphere. Smaller quantities of water occur on land as lakes, rivers, and streams (0.0132%), as well as below ground as soil moisture (0.001%) and groundwater (1.69%). The atmosphere also contains water as water vapor, clouds, and precipitation (0.001%). The biosphere contains water found in plants and animals (0.0001%).

Table 1.1
Distribution of Water on and near Earth's Surface (Total of 1.4 x 10^9 km^3)

Water source	Percent of freshwater	Percent of total water
Oceans, Seas, and Bays	--	96.5
Ice caps, Glaciers, and Permanent Snow	68.7	1.74
Groundwater	--	1.69
Fresh	30.1	0.76
Saline	--	0.93
Soil Moisture	0.05	0.001
Ground Ice and Permafrost	0.86	0.022
Lakes	--	0.013
Fresh	0.26	0.007
Saline	--	0.006
Atmosphere	0.04	0.001
Swamp Water	0.03	0.0008
Rivers	0.006	0.0002
Biological Water	0.003	0.0001

[Source: Data from Shiklomanov, I., 1993: World fresh water resources. *Water in Crisis: A Guide to the World's Fresh Water Resources,* P. H. Gleick, Ed., Oxford University Press, 13–24 and http://water.usgs.gov/edu/watercycle.html]

The ocean and atmosphere are coupled, which means they interact in many ways. For Earth's climate, the most important interaction is that heat from the ocean drives winds, which drive the ocean currents. Wind-driven ocean currents are primarily restricted to a surface ocean layer typically about 100 m (300 ft.) deep and can take as much as a few months to years to cross an ocean basin (Chapter 6). Deep-ocean currents flow at depths greater than 100 m (300 ft.) and are generally much slower than surface currents. These deep-ocean water movements are less well understood than surface currents because of the difficulties in making measurements at great depths in the oceans. Movements of deep-ocean waters are caused primarily by small differences in water density (mass per unit volume) arising from small differences in water temperature and salinity (a measure of dissolved salt content). Cold seawater, being denser than warm seawater of the same salinity, tends to sink whereas warm seawater, being less dense, is buoyed upward by (or floats on) colder seawater. Likewise, saltier water is denser than less salty water of the same temperature and tends to sink whereas less salty water is buoyed upward. Thus, the combination of temperature and salinity determines ocean water density. If water becomes denser than the surrounding water it sinks. If it is less dense than the surrounding water it rises. In each case the water moves vertically until it reaches a level where surrounding water has the same density. The movement of water, regardless of depth in the ocean, plays an important role in the distribution of heat, nutrients, and other matter in the ocean.

The densest ocean waters form in polar or nearby subpolar regions. Salty water becomes even saltier where sea ice forms at high latitudes because dissolved salts are excluded (left behind in the remaining unfrozen water) when ocean water freezes into ice crystals. Near Greenland and Iceland, and in the Norwegian and Labrador Seas, cooling of high salinity surface water increases water density. The water then sinks and forms a deep current that flows southward into the South Atlantic, nearly as far south as Antarctica. Here, this water is joined by high density water (formed by cooling and ice exclusion) that sinks around Antarctica. Branches of that cold bottom current then spread northward into the Pacific, Indian, and Atlantic basins. Eventually, the water slowly moves to the surface, mainly in the Pacific, and travels in surface currents through the islands of Indonesia, across the Indian Ocean, around South Africa, and into the tropical Atlantic. There, intense heating and evaporation make the water both warmer and saltier. This surface water is then transported northward in the Gulf Stream, thereby completing the cycle (Chapter 5). The transport of heat energy and salt in this global ocean circulation is an important factor of climate and plays a role in Northern Europe having a mild climate.

The second largest component of the hydrosphere consists of fresh water locked in large blocks of ice. Known as the **cryosphere**, the frozen fresh water is found in massive glacial ice sheets, glaciers, floating sea ice, and permafrost (permanently frozen ground). A **glacier** is a mass of ice on land that forms where annual snowfall exceeds annual snowmelt. As snow accumulates, the pressure of the new snow transforms underlying snow to ice. Ice sheets, which are found on Greenland and Antarctica, are up to 3 km (1.8 mi.) thick. The Antarctic ice sheet contains 90% of the ice on Earth's surface. Glaciers are much thinner (tens to hundreds of meters thick). At present, glacial ice covers about 10% of the planet's surface area but at times during the past 1.8 million years, glacial ice expanded to cover as much as 30% of the surface area, primarily in the Northern Hemisphere. At the peak of the last major glacial advance, about 20,000 to 18,000 years ago, ice covered much of what is now Canada, the northern tier states of the United States, the British Isles, and parts of northwest Europe.

Under the perpetual pull of gravity, glacial ice flows slowly from sources at higher elevations to lower elevations, where the ice melts and flows into the ocean. Around Antarctica, glacial ice flows to the ocean and, since ice is less dense than seawater, it floats and forms ice shelves (typically about 500 m or 1600 ft. thick) that extend out from the coastline. As ice breaks off the shelf edge, flat-topped icebergs float and are carried in surface ocean currents around Antarctica. Likewise, irregularly shaped icebergs break off the glacial ice streams of Greenland and flow out into the Atlantic Ocean (Figure 1.3). *RMS Titanic* struck such an iceberg and sank in 1912. During summer, most of the sea ice around Antarctica melts whereas in the Arctic Ocean most sea ice melts annually though some multi-year sea ice persist for several years before flowing out through Fram Strait into the Greenland Sea and eventually melting. Since 1979, sea ice cover in the Arctic has been steadily shrinking both in winter and summer coverage; the average thickness has decreased such that near the middle of the present century little or no multi-year ice is expected to remain and the Arctic Ocean could become ice free (having less than 1 million square km or 368,102 square mi. of sea ice) in summer. In contrast, sea ice coverage has remained fairly steady in the Antarctic in recent decades with its 2016 maximum (in September) being very close to the 1981–2010 average. Sea ice in the Antarctic region behaves differently than that in the Arctic because in the Antarctic much of the multi-year sea ice is actually floating glacier attached to the continent of Antarctica. This ice tends to be much thicker than the multi-year ice in the Arctic. Also, there is less ocean water in the Antarctic, so the *positive feedback* (amplification or intensification of the original process) created when reflective ice melts and is replaced by water is less important.

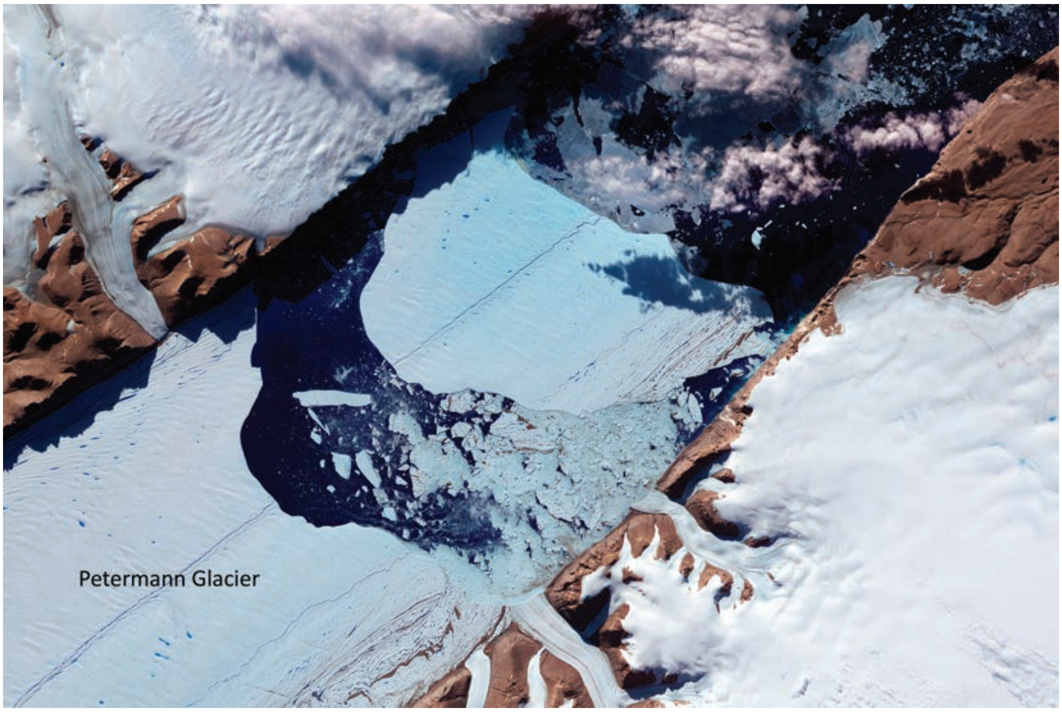

Figure 1.3
A massive iceberg is shown drifting down the fjord in western Greenland in July 2012, following break off (calving) from the Petermann Glacier. The image was obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard NASA's Terra spacecraft. [Courtesy of NASA]

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1.2.2 Atmosphere

Earth's **atmosphere** is a thin envelope of gases surrounding the planet. Compared to Earth's diameter, the atmosphere is like the thin skin of an apple. The total mass of the atmosphere is infinitesimal compared to the mass of the total Earth system, yet the atmosphere is essential for terrestrial life and the orderly functioning of physical and biological processes on Earth. Air pressure is the measurement of the weight of the atmosphere above a unit area, so pressure decreases with altitude as there is progressively less atmosphere above (Figure 1.4). All gases, including air, are compressible: they are squeezed into a smaller volume when pressure increases and expand when pressure decreases. Put another way, the air gets progressively thinner with increasing altitude above Earth's surface. Half of the atmosphere's mass is concentrated within about 5.5 km (3.4 mi.) of Earth's surface and 99% of its mass occurs below an altitude of 32 km (20 mi.). At an altitude of about 1000 km (620 mi.), Earth's atmosphere merges with the highly rarefied interplanetary gases, hydrogen and helium.

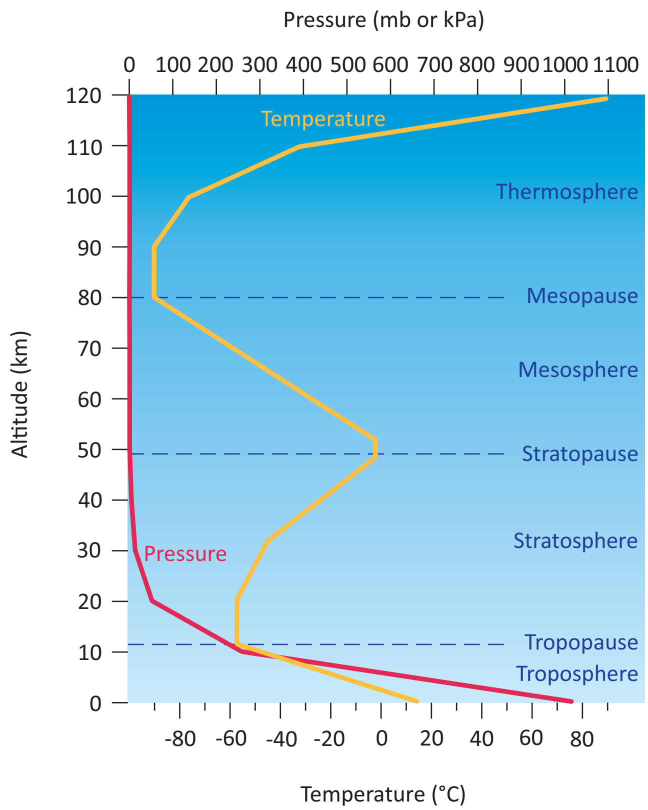


Figure 1.4
Based on variations in average temperature (yellow curve) with altitude, the atmosphere is divided into the troposphere, stratosphere, mesosphere, and thermosphere. Pressure (red curve) decreases as altitude increases since there is progressively less atmosphere above.

Based on the average vertical temperature profile, the atmosphere is divided into four layers. The **troposphere** extends about 11 km (6.8 mi.) above sea level and is where weather takes place. It also is where the atmosphere interfaces with the hydrosphere, geosphere, and biosphere. In the troposphere, the average air temperature decreases with increasing altitude. This is why it is usually colder on mountaintops than in valleys. The troposphere contains 75% of the atmosphere's mass and 99% of its water. The *stratosphere* extends from the base of the troposphere at 10 km (6 mi.) to 50 km (30 mi.) above Earth's surface. The stratosphere contains the *ozone shield*, which protects organisms from exposure to potentially lethal levels of solar ultraviolet radiation. The *mesosphere* extends above the stratosphere and is where the average temperature generally decreases with altitude. Above the mesosphere, the *thermosphere* is where the average temperature increases with altitude while being particularly sensitive to variations in incoming solar radiation.

Nitrogen (N_2) and oxygen (O_2) are the most abundant gases in the atmosphere. The two gases are mixed in uniform proportions up to an altitude of about 80 km (50 mi.). Nitrogen occupies 78.08% by volume of the lower atmosphere (below 80 km), and oxygen is 20.95% by volume (Table 1.2). The next most abundant gases include argon (0.93%) and carbon dioxide (CO_2) (0.04%). Many other gases occur in the atmosphere in trace concentrations, including ozone (O_3) and methane (CH_4). Unlike nitrogen and oxygen, the percent volume of some of these trace gases varies with time and location. In addition to gases, minute solid or liquid particles of various compositions, collectively called **aerosols**, are suspended in the atmosphere. Aerosols can function as nuclei that promote formation of the tiny water droplets seen as clouds. Certain aerosols, such as volcanic dust and sulfurous particles, interact with incoming solar radiation and influence air temperatures. A flashlight beam in a darkened room reveals an abundance of tiny dust particles floating in the air. Individually, most atmospheric aerosols are too small to be visible but in aggregates, such as the water droplets and ice crystals composing clouds, they may be visible. Most aerosols occur in the lower atmosphere, near their sources on Earth's surface. They are derived from sources such as wind erosion of soil, ocean spray, forest fires, volcanic eruptions, industrial chimney exhausts, and the exhaust of motor vehicles. Although the concentration of aerosols in the atmosphere is relatively small, they participate in some important processes. Aerosols function as nuclei that promote the formation of clouds, essential for the global water cycle. Depending on their composition, including products from the burning of fossil fuels and other human activity, they can combine with cloud droplets to produce acid rain.

Table 1.2
Gases Composing Dry Air in the Lower Atmosphere (below 80 km)

Gas	% by volume	Parts per million
Nitrogen (N_2)	78.08	780,840.0
Oxygen (O_2)	20.95	209.460.0
Argon (Ar)	0.93	9,340.0
Carbon dioxide (CO_2)	0.04	400.0
Neon (Ne)	0.0018	18.0
Helium (He)	0.00052	5.2
Methane (CH_4)	0.00014	1.4
Krypton (Kr)	0.00010	1.0
Nitrous oxide (N_2O)	0.00005	0.5
Hydrogen (H)	0.00005	0.5
Xenon (Xe)	0.000009	0.09
Ozone (O_3)	0.000007	0.07

The significance of an atmospheric gas is not necessarily related to its concentration. Water vapor, which has a highly variable concentration, is confined primarily to the lowest kilometer or so of the atmosphere and is never more than about 4% by volume even in the most humid places on Earth, such as tropical rainforests. Water vapor is essential for the water cycle, which produces the fresh water that falls as snow or rain on Earth's surface. Water vapor is also important in Earth's heat cycle and climate, as water vapor evaporated from the oceans carries heat into the atmosphere where it is later released. Water vapor is an important greenhouse gas that prevents the planet from becoming too cold. Carbon dioxide accounts for 0.04% of the lower atmosphere and is essential for photosynthesis. Without carbon dioxide, plants and the food webs they support could not exist. Although the atmospheric concentration of ozone (O_3) is minute, it is formed and found in elevated concentration in a layer called the ozone layer in the stratosphere. Ozone in this layer absorbs ultraviolet light and shields organisms on Earth's surface from potentially harmful levels of exposure.

The atmosphere is dynamic; it is always circulating. On an average annual basis, Earth's surface experiences net radiational heating (more heating than cooling mainly due to the Sun) at the tropics and the atmosphere undergoes net radiational cooling (to space) at the poles. Variations in heating and cooling give rise to *temperature gradients*, that is, differences in temperature from one location to another. In response to temperature gradients, the atmosphere (and ocean) circulates and redistributes heat within the Earth system. This redistribution controls regional climates, but more importantly it transfers heat from the tropics toward the poles to balance the excess heat gained in the tropics with the excess heat lost near the poles.

1.2.3 Geosphere

The **geosphere** is the solid portion of the planet consisting mostly of rocks, minerals, and sediments. Earth's interior cannot be observed directly. Scientists have learned about the planet's interior by studying seismic waves generated by earthquakes and explosions. From these studies, they have determined that Earth's interior consists of four spherical shells: the crust, mantle, outer core, and inner core (Figure 1.5). Earth's interior is mostly solid and accounts for much of the planet's mass. The densest spherical shell is the inner core. The outermost solid skin of the planet, called the **crust**, ranges in thickness from only about 8 km (5 mi.) under the ocean to about 70 km (45 mi.) in some mountain belts. The continental crust is thicker and composed of lighter density rock, like granite, compared to ocean crust that is thinner and composed of greater density rock, like basalt. The crust is the source of nearly all rock, mineral, and fuel resources. Between the core and the crust lies the mantle, a solid to semi-molten mass of rock that moves plastically (flows extremely slowly and can be deformed without rupture). The **lithosphere** is the rigid uppermost portion of the *mantle* plus the overlying crust. The lithosphere averages about 100 km (62 mi) thick and changes through time by slow processes on the planet's surface and deep in its interior.

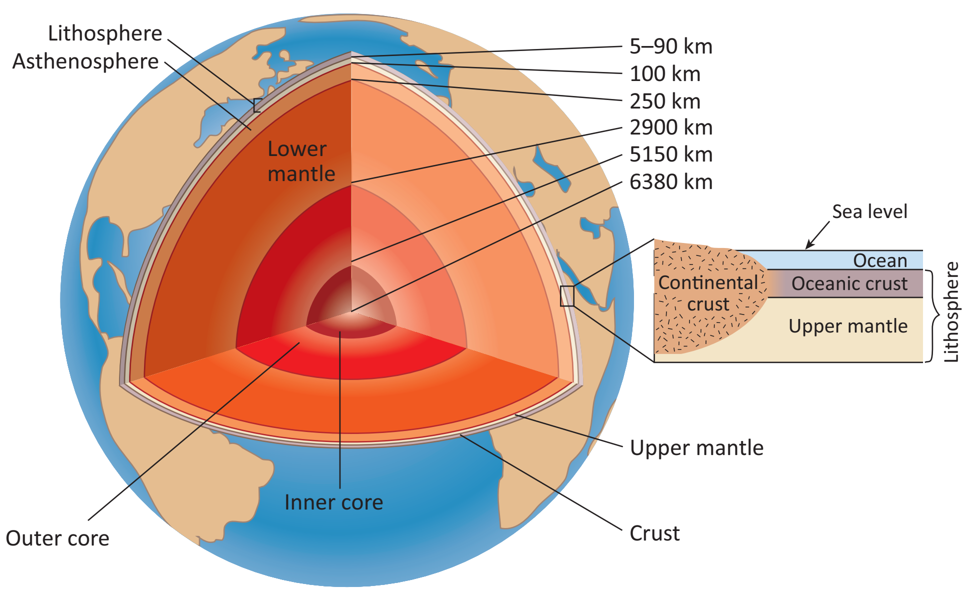


Figure 1.5
A cross section of the Earth showing its layers. Note that the thickness of the lithosphere has been greatly exaggerated in this diagram. If it were drawn to the correct scale, the lithosphere would appear as just a thin line at the Earth's surface. [From Segar, D. A., 2018: Introduction to Ocean Sciences, Fourth Edition. [Available online at http://www.reefimages.com/oceansci.] Used with permission.]

Surface geological processes include weathering, erosion, and deposition. **Weathering** includes the physical processes that degrade or disintegrate the exposed surface of a rock. Water plays an important role in the weathering process. It dissolves soluble rock and minerals through various chemical reactions that decompose the rock's surface. Water also breaks rock down into sediments by physical processes. Water seeps into cracks and pore spaces in the rock and freezes when temperature falls below 0°C (32°F). As ice forms it expands, pushing the rock apart. Fragments of rock, including particles of organic material, such as shells of tiny ocean animals, are known as *sediments*.

Erosion is the removal and transport of sediments by gravity, moving water, glaciers, and wind. Erosive agents transport sediments from source regions, usually highlands to low-lying depositional environments, such as oceans and lakes. Weathering aids erosion by reducing massive rocks (through physical, chemical, or organic processes) to particles that are small enough to move by wind, water, or ice. Erosional processes remove the products of weathering and expose fresh surfaces of rock to the atmosphere and weathering processes. Together, weathering and erosion slowly reduce the elevation of the land.

Internal geological processes uplift the land through tectonic activity, including volcanism and mountain building. Most tectonic activity occurs at the boundaries between lithospheric plates. The lithosphere is broken into a dozen massive plates that move slowly (typically less than 20 cm per year, with 5 cm per year as the average) across the face of the planet following large convection currents in Earth's mantle.

The movement of plates across the planet's surface is called **plate tectonics**. This process changes the configuration of land and ocean on the planet. At several times in Earth's past, continents merged to form one, massive continent, called a supercontinent, only to break apart again. The most recent supercontinent, called *Pangaea* (Greek for "all land"), began breaking apart about 200 million years ago. Since that time, the fragments of Pangaea, the continents, have been moving to their present location. Plate tectonics explains many seemingly out of place scientific discoveries, such as glacial sediments in the Sahara Desert of Africa and ancient tropical coral reefs in the Canadian Arctic.

Geological process occurring at plate boundaries form landscape and ocean bottom features, including mountain ranges, volcanoes, deep sea trenches, and the ocean basins themselves. Enormous stresses at plate boundaries bend and fracture bedrock. Magma (hot molten rock) wells up from deep in the crust or upper mantle and migrates along sub-surface rock features. Magma can solidify and form the core of mountain ranges or new oceanic crust. It also feeds volcanoes and flows through fractures as lava, which cools and solidifies. Volcanism is concentrated along most plate boundaries, but also occurs at a limited number of locations within a plate.

1.2.4 Biosphere

All living organisms on Earth are components of the **biosphere** (Figure 1.6). They range in size from organisms so small that they can only be seen through the most powerful microscopes (or are only detectable by their genes) to the largest plants and animals, like the redwood tree and blue whale. While massive plants and animals are impressive, and plants and animals large enough for us to see are familiar, the majority of all animals in the oceans are about the size of a mosquito. Even more important, bacteria, and other single-celled organisms including archaea dominate the biosphere, both on land and in the ocean. Microscopic bacteria, algae, and archaea are far more abundant than the animals and constitute the majority of the biomass (total weight or mass of living matter) in the oceans. Larger, complex multi-cellular organisms, such as humans, are actually relatively rare on Earth.

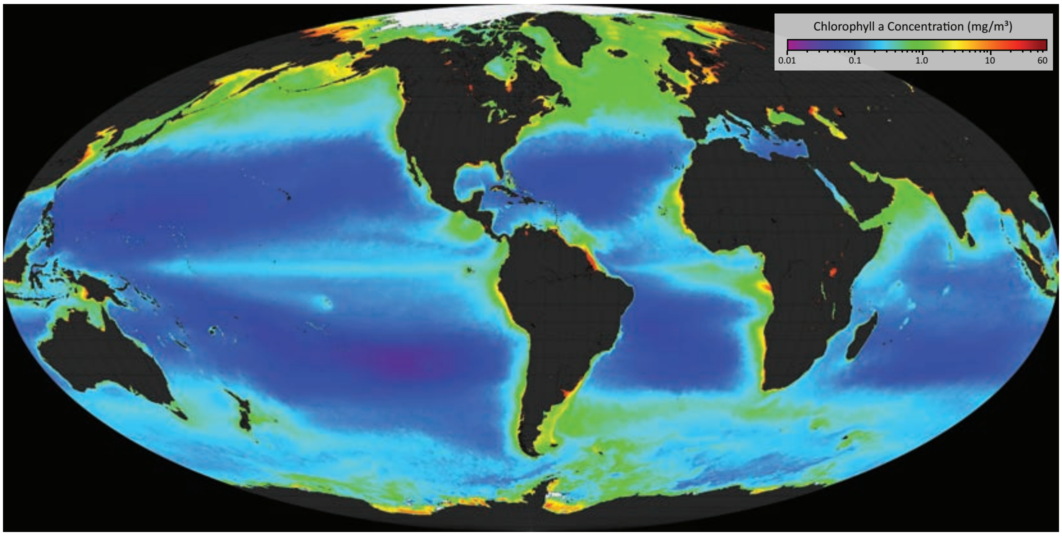


Figure 1.6
A view of Earth's biosphere using ocean chlorophyll data provided by NASA's SeaWiFS (Sea-viewing Wide Field-of-view Sensor) project. Chlorophyll concentration is highest where the ocean displays orange and red shadings. [Courtesy of NASA]

Photosynthesis and cellular respiration are the basis for most life that is known to exist. All known animal life, including humans, would not be present on Earth if photosynthesis had not developed first. **Photosynthesis** is the process where green plants, algae, and photosynthetic microbes use light energy from the Sun to combine carbon dioxide from the atmosphere with water and nutrients to produce sugars, a form of carbohydrate containing a relatively large amount of energy. Oxygen is an important byproduct of photosynthesis. It took photosynthetic microbes a billion years to build atmospheric oxygen concentration to the present day level. Prior to that, there was almost no free oxygen in the atmosphere or oceans. Animals require free oxygen for **cellular respiration**, the process whereby they convert organic matter (food) into energy to fuel their life processes – maintenance (activities such as movement), growth, reproduction, and waste. Respiration is not restricted to animals; all known life forms from the smallest bacteria to the largest plants use respiration to fuel their life process. Photosynthesis consumes carbon dioxide and releases oxygen, while respiration consumes oxygen and releases carbon dioxide. The balance between these two processes, which has remained stable for about one billion years, maintains the free oxygen level in the ocean and atmosphere within the range of concentrations that supports animals.

Adequate oxygen concentrations in the atmosphere are essential to land animals. They are equally important to marine animals, especially those that live in the ocean deep layers. Photosynthesis only occurs where there is sunlight, but respiration occurs wherever there is life. On land and in the surface layers of the oceans, sunlight is available, and both photosynthesis and respiration occur. Below the upper few hundred meters of ocean water, sunlight does not penetrate so there is no photosynthesis. However, respiration does still occur. The oxygen concentration in these deep waters is fixed at the time the water sinks below the surface layers, where it can also exchange oxygen with the atmosphere at the sea-air interface. After sinking below the surface layers there is no photosynthesis, but there is still respiration, so the dissolved oxygen concentration steadily declines as it is used up by respiration. Additionally, the decomposition of organic matter consumes dissolved oxygen, lowering oxygen concentration. The longer the water stays away from the surface layers, the lower the oxygen concentration becomes. If it becomes too low, it is insufficient to support animal life. The oldest (away from the surface layer the longest) water in the oceans today is just below the surface layer in the North Pacific Ocean. Oxygen concentrations in this water are too low to sustain animal life. In the past, the low oxygen pool has varied in size and has, at times expanded so far that it is thought to have contributed to at least one or more of Earth's mass extinctions.

Photosynthesis had long been thought to be the only, or at least major, mechanism whereby living organic matter can be created. In recent years, it has been discovered that many species of bacteria, archaea, some species of microscopic algae, and even some viruses in the oceans contain genes that allow them to use sunlight as an energy source and to grow without the use of photosynthesis. While the extent to which this non-photosynthesis light driven mechanism contributes now or in the past to the production of ocean biomass is not yet known, the existence of this mechanism and the widespread distribution of the relevant gene hint that photosynthesis may not be as essential to life in the oceans as was once believed. The microbial community may be far more dominant than currently thought and also resilient to even massive climate or ocean chemistry changes.

Microbes known to be capable of growing in environments where there is no light use chemical energy as an energy source, a process known as **chemosynthesis**. These chemosynthetic organisms have been found in a number of lightless environments. These organisms derive energy from substances such as hydrogen sulfide (H_2S) or methane (CH_4) originating in Earth's interior. Studies of the genetics of ocean microbial species, including bacteria and archaea, show that many species may be capable of switching between energy sources by turning on or off appropriate genes or by transferring the needed genes from other microbes.

The biosphere is composed of **ecosystems**, communities of living organisms that interact with one another, together with the physical conditions and chemical substances in a specific geographical area. Deserts, tropical rainforests, tundra, estuaries, marshes, lakes, streams, and coral reefs are examples of natural ecosystems. Most people live in highly modified terrestrial ecosystems such as cities, towns, farms, or ranches.

Within an ecosystem, some species are producers (also called *autotrophs* for "self-nourishing"), usually plants or bacteria. They use sunlight, or another energy source, to create living organic matter. Other species are consumers (also called *heterotrophs*), usually animals, bacteria, or fungus. Consumers eat producers or other consumers. The transfer of food and energy from producer to consumer to another consumer and yet another is called a **food chain**. In practice, food chains are not simple since, for example, one consumer may eat both other consumers and producers or consumers from two or more different levels in the sequence so the term **food web** is more often correct (Figure 1.7). After producers and consumers die, they are eaten by decomposers, usually bacteria, archaea, or fungi. Decomposers break down organic matter to release carbon dioxide and other nutrients that are essential to producers, completing the ecosystem cycle.

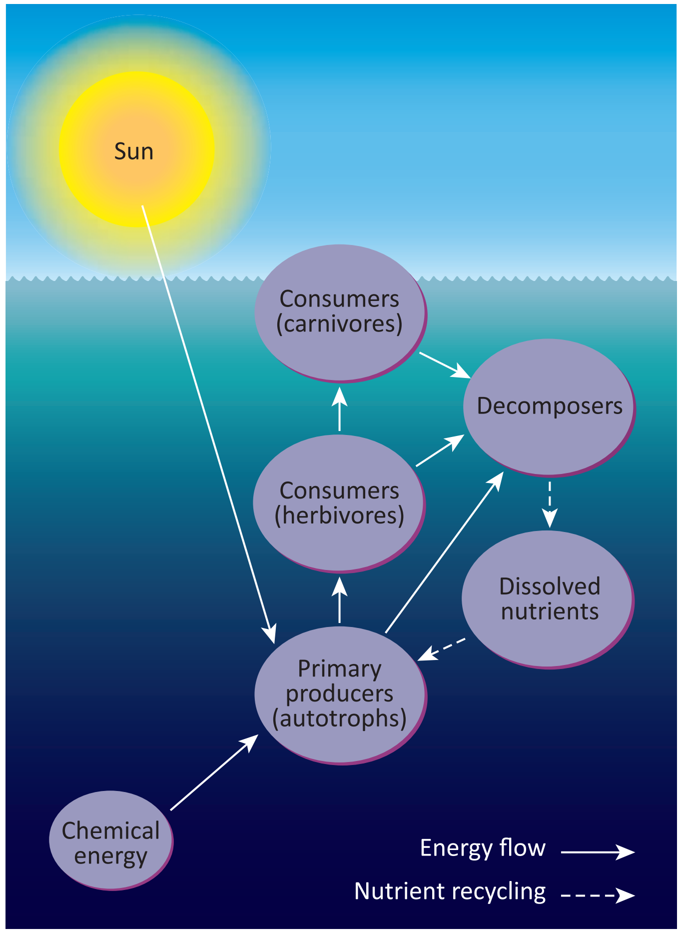


Figure 1.7
Schematic diagram of a marine food web in which solar radiation powers photosynthesis and chemical energy enables chemosynthesis. The majority of ocean primary production is fueled by solar radiation. Some of the energy generated is conveyed to successively higher trophic (feeding) levels.

Within a food chain or web, the steps are called trophic levels. Producers are at the first trophic level, consumers that eat producers are at the second trophic level, consumers that eat second level consumers are at the third level, and so on (Figure 1.8). Only about 10% of the energy at one trophic level is transferred to the next higher level. The remaining 90% is used for growth, respiration, reproduction, and mobility, while some is lost as waste. The total weight or mass of organisms (*biomass*) is used to describe the transfer of energy in food chains.

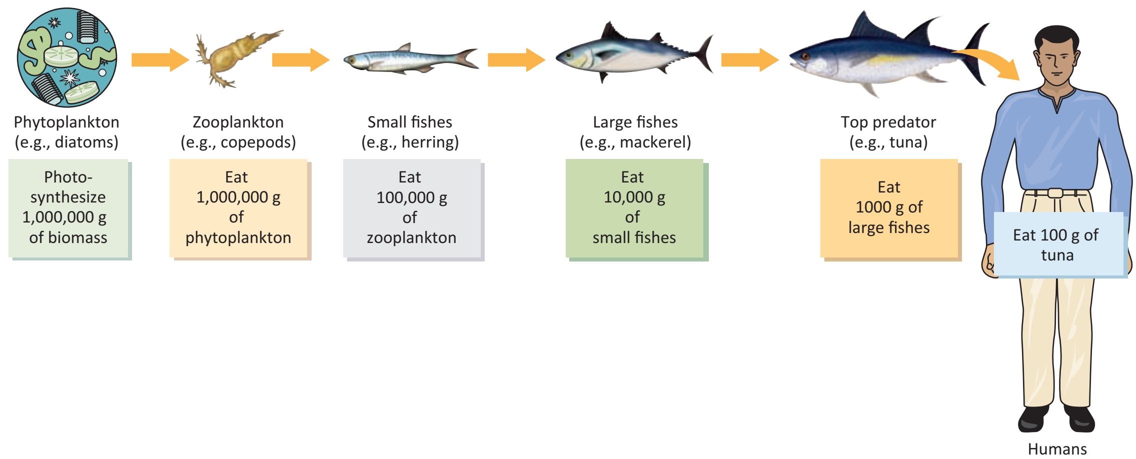


Figure 1.8
The food chain leading to tuna and humans, assuming that the trophic efficiency at each trophic level is 10%. [Modified from Segar, D. A., 2018: Introduction to Ocean Sciences, Fourth Edition. [Available online at http://www.reefimages.com/oceansci.] Used with permission.]

An example of an ecosystem that is particularly important in the coastal zone is an **estuary**. This region is where the hydrosphere, lithosphere, and biosphere interact in special ways. An estuary forms where fresh and salt water mix, usually in rivers as well as in tidal marshes and bays. In some estuaries, tides and tidal mixing extend far inland and almost all estuaries include parts of the coastal ocean where fresh water influence can be detected. For example, the San Francisco Bay estuary stretches from Sacramento, CA almost 160 km (100 mi.) inland to the Farallon Islands about 43.5 km (27 mi.) offshore. A special combination of biological and physical characteristics makes estuaries among Earth's most productive ecosystems. Estuaries support luxuriant plant and algae growth, such as phytoplankton, sea grass, and marsh grasses, as well as large populations of animals that feed on detritus (dead or partially decomposed remains of plants and animals). Water in an estuary undergoes one or two tide cycles per tidal day. *Tides* are the periodic rise and fall of sea level in response to the gravitational attraction of the Moon and Sun. The circulation of water in estuaries tends to trap and recirculate nutrients and detritus. This explains why estuaries are especially favored places for juvenile fishes and other marine animals to feed and grow and why estuaries are especially vulnerable to the buildup of contaminants.

Organisms living in an estuary are adapted to frequent fluctuations in water depth, temperature, salinity, and the concentration of suspended sediment. Among the nation's best-known estuaries, other than San Francisco Bay, are Chesapeake Bay and Puget Sound. Estuaries are very productive ecosystems that support a diverse array of plant and animal life. Estuaries are also frequently the locations of large cities and ports, so ecosystem management issues often abound.

1.3 The Ocean in the Global Water Cycle

Biogeochemical cycles describe the pathways of solids, liquids, and gases among the reservoirs of Earth's spheres. Examples include the global water cycle, carbon cycle, oxygen cycle, and rock cycle. These cycles follow the law of energy conservation, meaning that energy is neither created nor destroyed, although it is converted from one form to another. Biogeochemical cycles also follow the law of conservation of matter, which states that matter can neither be created nor destroyed, but can change chemical or physical form.

Based on available evidence, the total amount of water in Earth's biogeochemical cycle has not changed significantly over long periods of geological time. Volcanic activity is more or less continuous on Earth and adds to the supply of water. Water vapor typically accounts for 70% or more of all gases emitted during a volcanic eruption; at least some of this water originally was held in magma and solid rock. A portion of this water is recycled as it originated in rocks and sediments earlier subducted during plate tectonics (Chapter 2). A minute amount of water is contributed to Earth by meteorites and other extraterrestrial debris continually bombarding the upper atmosphere.

Water in Earth's system is distributed in all three phases (solid, liquid, and gas) among the hydrosphere, lithosphere, atmosphere, and biosphere. Natural processes continually move water through the different spheres on the planet. The ceaseless movement of water among its various reservoirs at the planetary scale is known as the **global water cycle** (Figure 1.9). In brief, water vaporizes from the surface of the ocean and land to the atmosphere where winds transport water vapor thousands of kilometers. In the atmosphere, clouds form and produce rain, snow, and other forms of precipitation that fall as fresh water from clouds to Earth's surface. This fresh water recharges the ocean and the terrestrial reservoirs of water. From terrestrial reservoirs, water seeps and flows back to the ocean through rivers and rocks.

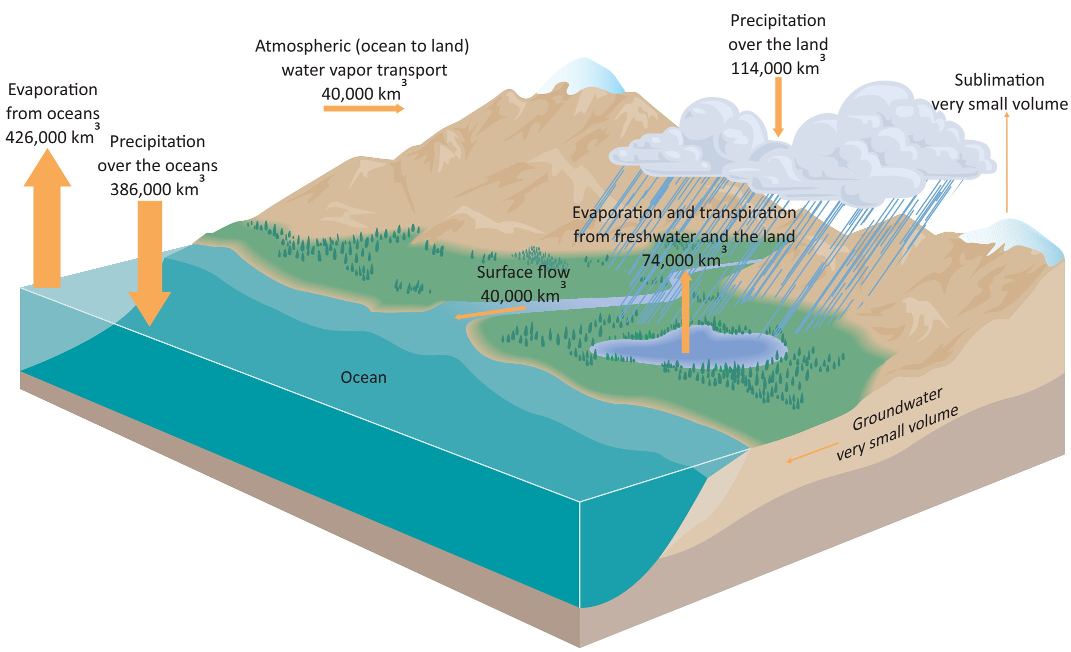


Figure 1.9
Schematic representation of the global water cycle. [Modified from Segar, D. A., 2018: Introduction to Ocean Sciences, Fourth Edition. [Available online at http://www.reefimages.com/oceansci.] Used with permission. Updated transport data from Trenberth, K. E., J. T. Fasullo, and J. Mackaro, 2011: Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Climate*, **24**, 4907-4924, doi:10.1175/2011JCLI4171.1.]

http://ametsoc.org/amsedu/OTIDS/1.4.html

The change of phase that involves water changing from liquid to gas is important to Earth's climate. Water transitions from liquid to gas by evaporation and transpiration, both of which require heat. **Evaporation** is the process where water absorbs heat energy and changes from a liquid to a vapor. Water evaporates from the surface of bodies of water, including the ocean, lakes, and rivers, as well as from soil and the surfaces of plant leaves and stems. About 85% of the total annual evaporation in the Earth system takes place at the ocean surface so the ocean is the principal source of water in the atmosphere. **Transpiration** is the process where water that is taken up from the soil by plant roots eventually escapes as vapor through the tiny pores (called stomates) on the underside of green leaves. During the growing season, transpiration is more effective than evaporation at delivering water vapor from the land surface of the planet to the atmosphere. A single hectare (2.5 acres) of corn typically transpires 28,000 to 38,000 liters (7400 to 10,000 gallons) of water per day. Transpiration accounts for about 10% of the water vapor component of the atmosphere.

Ice can melt and the resulting liquid can evaporate, but it can also change phase directly from solid to vapor by **sublimation**, which requires heat. Sublimation is the process by which snow banks shrink and patches of ice on sidewalks and roads disappear even while the air temperature remains below freezing. However, sublimation accounts for only a very small amount of atmospheric water vapor.

Water moves from the atmosphere to land and ocean via condensation, deposition, and precipitation. **Condensation** is the process where water changes phase from vapor to liquid in the form of small droplets; this phase change releases heat to the atmosphere. Water droplets forming on the outside surface of a cold can of soda on a warm, humid day is an example of condensation of water vapor. **Deposition** is the process where water changes directly from vapor to solid (ice crystals) without first becoming a liquid. Appearance of frost on an automobile windshield is an example of deposition of water vapor. Condensation or deposition within the atmosphere produces clouds. **Precipitation** is water in liquid (rain or drizzle) or frozen (snow, ice pellets, or hail) form that falls from clouds to Earth's surface.

The processes of evaporation, transpiration, and sublimation followed by condensation or deposition purify water. As water vaporizes, essentially all suspended and dissolved substances, such as sea salts, are left behind. Through this natural cleansing mechanism, ocean water that originally was too salty to drink eventually falls as freshwater precipitation to Earth's surface. (Purification of water through phase changes is known as **distillation**.) As precipitation falls through the atmosphere, it dissolves or captures gases and dissolves small amounts of some chemicals from suspended particles. Return of water from the atmosphere to Earth's surface via condensation, deposition, and precipitation completes the global water cycle.

Over the course of a year, the total mass of water that falls as precipitation (rain plus melted snow) on land exceeds the total mass of water that vaporizes through evaporation, transpiration, and sublimation from land by about one-third. Over the same period, the total mass of water falling as precipitation on the ocean is less than the total mass of water that evaporates from the ocean. The global water budget reveals an annual net gain of water mass on the continents and an annual net loss of water mass from the ocean. The annual excess of water that falls as precipitation on the continents equals the water that evaporates. This process is balanced by the excess water on land that flows back to the ocean. The balance sheet for inputs and outputs of water to and from the various global reservoirs is the *global water budget* (Table 1.3).

Table 1.3
Global Water Budget

Source	km^3 per year
Precipitation on the ocean	+386,000
Evaporation from the ocean	-426,000
Net loss from the ocean	**-40,000**
Precipitation on land	+114,000
Evaportranspiration from land	-74,000
Net gain on land	**+40,000**

[Source: Data from Trenberth, K. E., J. T. Fasullo, and J. Mackaro, 2011: Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Climate*, 24, 4907-4924, doi: 10.1175/2011JCLI4171.1.]

The flow of excess surface and subsurface water from the continents to the ocean has important implications for the composition of ocean water and the global distribution of environmental contaminants. As water flows over land or as groundwater, it dissolves ions from the soil and rock. These dissolved ions contribute to the 'saltiness' of ocean water. The ocean also is the destination of contaminants carried by rivers, streams, and canals. These contaminants primarily end up in estuaries and other coastal waters, which are highly productive areas of the ocean. Not surprisingly, considerable debate centers on the capacity of the ocean to assimilate waste, especially toxic and hazardous industrial waste. The oceans can safely disperse and recycle (decompose) many types of waste materials. However, its assimilative capacity is different for each type of waste and also differs with the location of its entry into the oceans. Assimilative capacity for a given waste can be much less if the contaminant enters a bay or other coastal region where the residence time of the water is long.

When rain or snow falls, it can follow one of several pathways. Some precipitated water evaporates or sublimates directly back into the atmosphere. Some of the water is temporarily stored in lakes, snow and ice fields, or glaciers. Some water either flows as rivers or streams (*runoff component*) or seeps into the ground as soil moisture or groundwater (*infiltration component*). Rivers and streams plus their tributaries drain a fixed geographical area known as a *drainage basin* (or watershed). The quantity and quality of water flowing in a river depends on the climate, topography, geology, and land use in the drainage basin. A drainage basin also may include lakes, glaciers, or temporary impoundments of surface water.

The amount of water that infiltrates the ground compared to the amount that runs off depends on rainfall intensity, vegetation, topography, and physical properties of the land surface. For example, rain falling on frozen ground or city streets mostly runs off whereas rain falling on unfrozen, unsaturated, sandy soil readily soaks into the ground. This water is called *groundwater*. In most environments, groundwater flows very slowly in the subsurface from recharge areas at Earth's surface toward discharge areas including wells, springs, rivers, lakes, and the ocean. Some groundwater finds its way to deep aquifers where interaction with the water cycle is severely limited.

1.4 Observing the Ocean

Scientists observe the ocean not only out of curiosity but also to better understand the ocean's role in the Earth system. Scientists want to know, for example, the physical, chemical and biological factors governing the distribution of marine life and how the ocean influences seasonal and long-term variability in climate. Answers to these and other questions require observational data on the ocean's properties and processes. Today, in addition to obtaining samples to study in the laboratory, scientists observe the ocean using both in situ and remote sensing techniques. With an **in situ measurement**, the sensor measures a property directly in the ocean water. **Remote sensing** refers to determining ocean properties from a distance using sensors aboard floating platforms or on satellites.

1.4.1 In Situ Monitoring of the Ocean's Depths

In situ measurements of ocean properties are made using buoys, floats, gliders, piloted submersibles and vehicles, and undersea observatories. Many ocean observations are conducted from ships (Figure 1.10). Other techniques are necessary to examine the ocean with depth. Instruments lowered from ships are used to sample ocean water and sediments. Instruments moored on the sea floor monitor properties of the ocean beneath the surface waters.

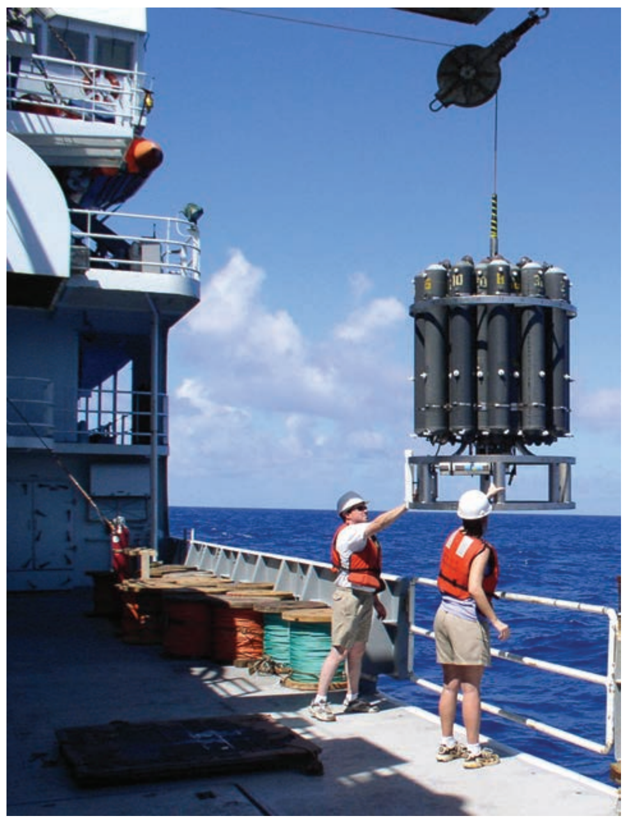


Figure 1.10
Launch of a CTD mounted below a rosette water sampler over the side of the R/V Thompson. The CTD measures conductivity (salinity), temperature, and depth of the water. [Courtesy of NOAA Ocean Explorer]

One in situ method uses the sound waves in water to make various measurements of the deep regions of the ocean. Ocean water is highly transparent to sound, just as the atmosphere is nearly transparent to visible light. A sound pulse from a transmitter on one side of the ocean can be detected by a sensitive receiver thousands of kilometers away on the other side of the ocean. Sound is particularly useful in the oceans since water absorbs almost all wavelengths of electromagnetic radiation. Radio, radar, and most other electromagnetic remote sensing tools used in the atmosphere and in space cannot be used in the oceans.

A **profiling float** may contain many instruments capable of monitoring and measuring the vertical distribution of a variety of ocean properties, like temperature and salinity in the water column (Figure 1.11). In 1998, scientists from more than 30 nations plus the European Union began deploying Argo floats throughout the global ocean. More than 3700 free-drifting floats now provide coverage of about one sensor per 3 degrees latitude and longitude. Argo floats are programmed for a 10-day cycle. For the first nine days, the float sinks to a depth of 1000 m (3300 ft.) and drifts following the prevailing water current. On the tenth day, the float sinks to a maximum depth, typically about 2000 m (6600 ft.). From that maximum depth, sensors measure temperature and conductivity (a measure of salinity) through ocean layers as the float ascends to the surface. At the surface, the float transmits to a communications satellite its location and data, which the scientific community and the public can access using the Internet.

Figure 1.11
Curran Fey of the TAO project and Shawn Gendron of the NOAA Ship Ka'imimoana prepare to deploy a PMEL Argo float in the Tropical Pacific. [Courtesy of NOAA]

The Argo float has proven its value in many ways, including increasing the accuracy of estimates of ocean heat storage. Heat storage is an important factor in predicting future changes in climate and sea level. These data have also improved climate forecasts from coupled ocean/atmosphere computer models. Finally, Argo float data provide insights on the dynamics of air-sea interaction during hurricanes and tropical storms. Argo floats are detailed later in the book. The text also describes Autonomous Underwater Vehicles (AUVs), unpiloted and remotely controlled vehicles that also measure ocean water properties.

Argo Profiling Floats

Topic in Depth 1.5

http://ametsoc.org/amsedu/OTIDS/1.5.html

1.4.2 Remote Sensing by Satellite

Earth-orbiting satellites routinely monitor the ocean's surface waters, the atmosphere, and other components of the Earth system. Powerful computers collect, process, and analyze enormous quantities of satellite-acquired environmental data. In only minutes, sensors onboard an ocean-observing satellite collect as much data as can an ocean-research vessel operating at sea continuously for a decade or longer. Instruments observing Earth from orbiting spacecraft measure selected wavelengths (or frequencies) of electromagnetic radiation reflected or emitted by the various components of the Earth system. **Electromagnetic radiation** describes both a form of energy and a means of energy transfer. Energy spans the **electromagnetic spectrum** from short wavelengths (gamma, X-ray, ultraviolet, and visible) to long wavelengths (infrared (IR) radiation, microwaves, and radio waves) (Figure 1.12). *Wavelength* is the distance between successive wave crests or troughs whereas *frequency* is the number of wave crests or troughs passing a point during a period of time, usually a second (Figure 1.13). All types of radiation travel as waves at the speed of light and the different segments of the electromagnetic spectrum are differentiated by wavelength or frequency.

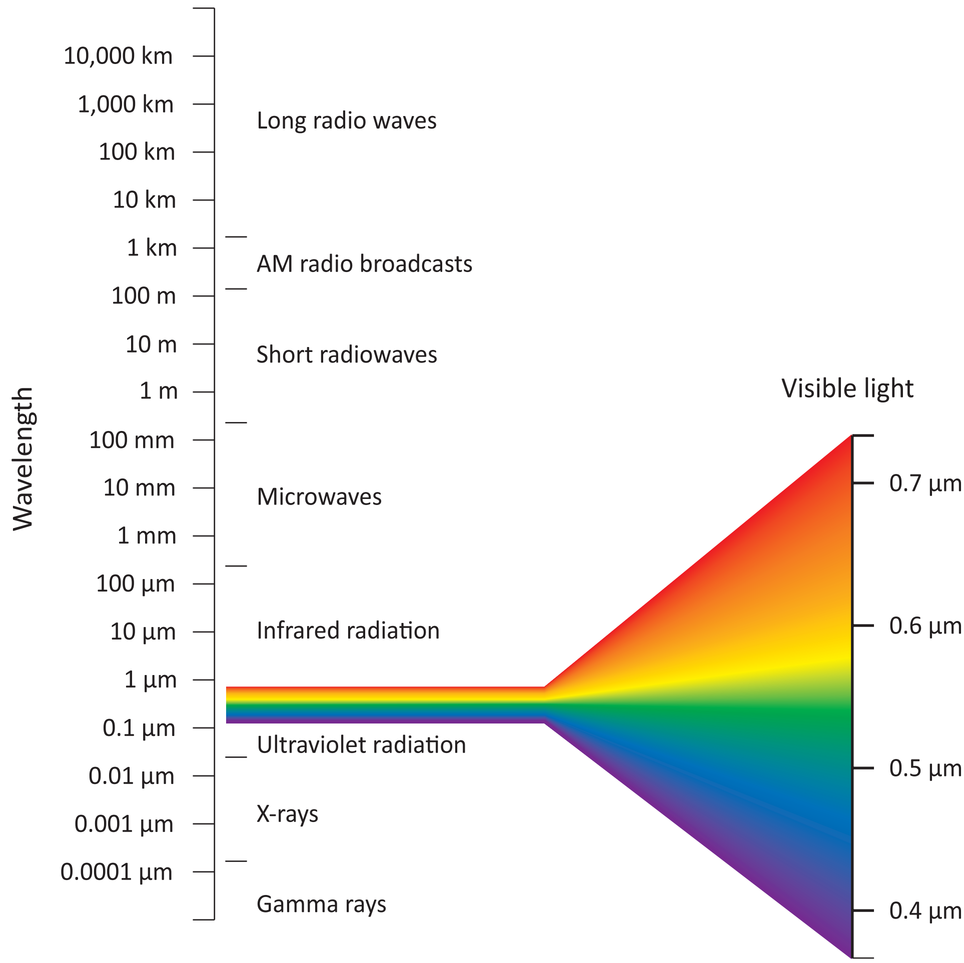


Figure 1.12
The Electromagnetic spectrum. The various forms of electromagnetic radiation are distinguished by wavelength in micrometers (µm), millimeters (mm), meters (m), and kilometers (km).

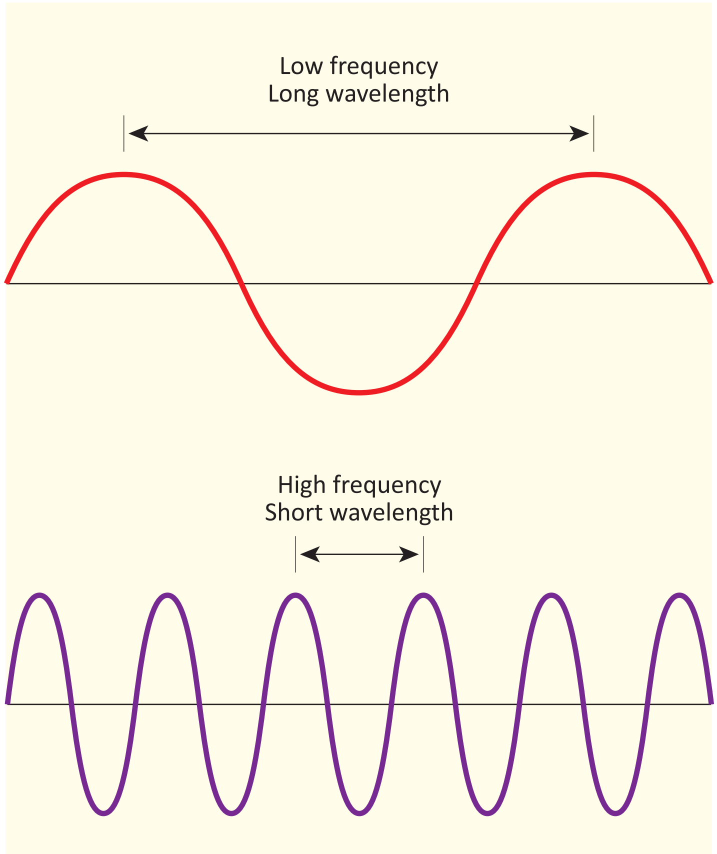


Figure 1.13
Wavelength is the distance between two successive crests or, equivalently, the distance between two successive troughs. Wave frequency is the number of wavelengths passing a point per second. Wavelength is inversely related to wave frequency.

The clear atmosphere is essentially transparent to visible light and is selectively transparent by wavelength to other types of radiation, such as infrared. Satellite-borne sensors monitor the different forms of radiation to gather information on atmospheric processes and properties. Ocean water is much less transparent to electromagnetic radiation than is the atmosphere so that remote sensing by satellite is essentially limited to obtaining data on surface or near-surface ocean processes and properties. Some properties such as ocean depth and internal waves can be studied indirectly by measuring their effect on sea surface properties.

The earliest ocean observations from space came from sensors on meteorological satellites orbiting the planet in the 1960s. Beginning in 1978, satellites were launched specifically to monitor the ocean. Now instruments flown on Earth-orbiting satellites routinely provide global images of ocean conditions, which are typically summarized and updated every few days. Satellites that monitor Earth's atmosphere and ocean are in either geostationary or polar orbits. A **geostationary satellite** is at a high altitude (36,000 km or 22,300 mi.) (Figure 1.14) and revolves around Earth at the same rate and in the same direction as the planet rotates, therefore sensors monitor the same portion of Earth's surface. Five geostationary satellites can provide complete and overlapping global coverage between 60 degrees N and 60 degrees S. A **polar orbiting satellite** is in a relatively low orbit (800 to 100 km or 500 to 600 mi.) that passes near the north and south poles (Figure 1.15) and provides needed coverage of ocean surface areas at latitudes poleward of 60 degrees. Earth rotates eastward under the satellite whose orbit is fixed in space, so that sensors view successive strips of Earth.

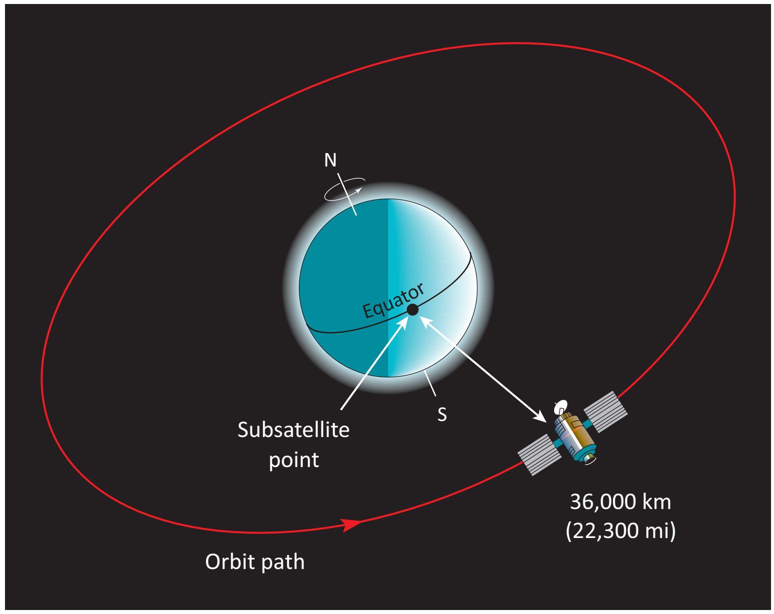


Figure 1.14
A satellite in geostationary orbit about the Earth.

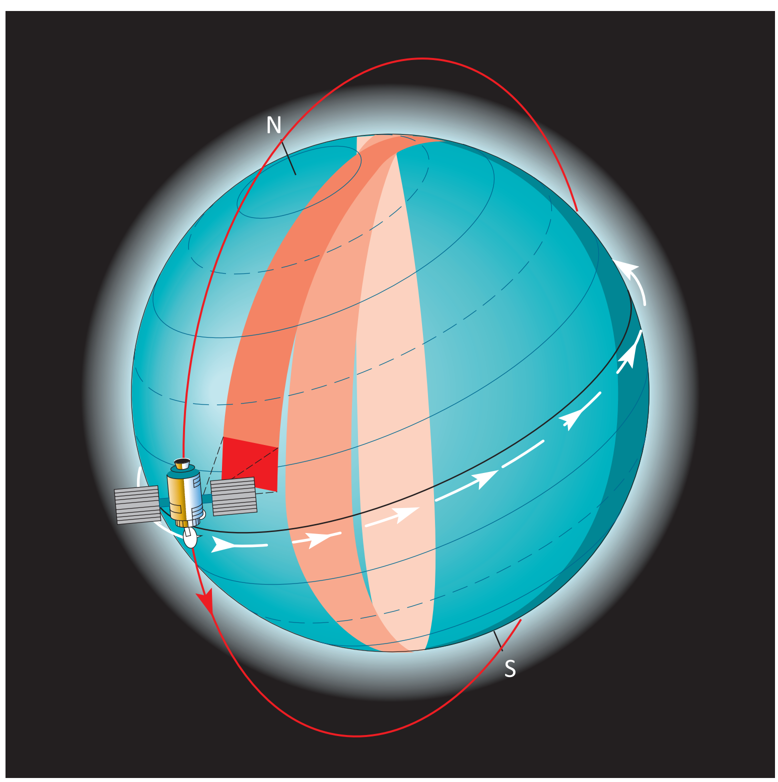


Figure 1.15
A satellite in polar orbit around the Earth.

Passive satellite sensors measure visible solar radiation reflected by the ocean surface and invisible infrared radiation emitted by the surface. Sea-surface temperatures (SST) and ocean color (color can be used as a measure of marine productivity or sediment concentration) are among the properties measured by passive sensors. The intensity of radiation emitted by an object increases rapidly as the surface temperature of the object rises. By calibrating temperature against infrared emission, a satellite sensor measures SST to distinguish between warm and cold ocean currents. Figure 1.16 is an infrared satellite image of the world ocean SST, color coded so that oranges and reds represent the highest temperatures. Satellite images of "ocean color" show the distribution and abundance of chlorophyll (pigments used in photosynthesis), providing an estimate of the concentration of phytoplankton in the surface ocean. Phytoplankton form the base of much of the ocean food web and vary with time and space; therefore these measurements allow large areas of Earth's marine ecosystems to be routinely studied.

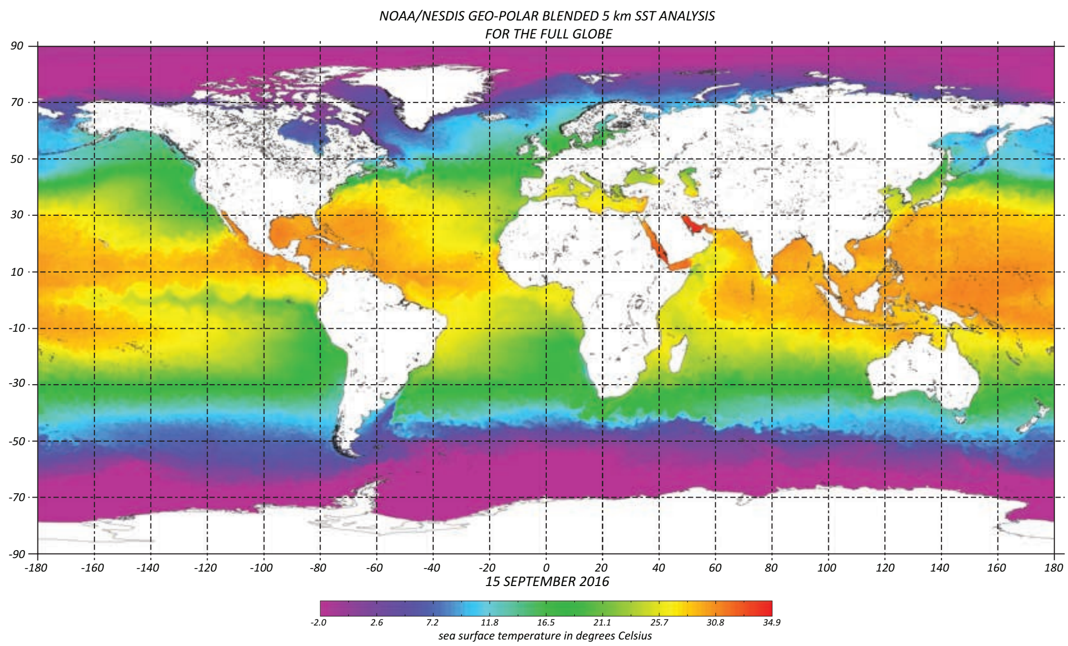


Figure 1.16
Satellite-derived sea-surface temperatures (SST) color coded in °C on 15 September 2016; highest temperatures are shown in orange and red. [Courtesy of NOAA/NESDIS]

Active satellite sensors include radar instruments that emit pulses of microwave radiation and then record the reflected signal. Radar measures surface roughness (an indicator of surface wind speeds and wave heights) and ocean surface elevation used to map bottom topography, surface currents, and, indirectly, some aspects of deep ocean currents. The flood of observational data from satellite-based sensors is analyzed and stored by computers. Internet websites now make details of ocean surface properties available that were impossible to obtain at the start of the 21st century.

NASA's Earth Observing System

Topic in Depth 1.6

http://ametsoc.org/amsedu/OTIDS/1.6.html

1.5 Modeling the Ocean

A **model** is an approximate representation or simulation of a real system. It incorporates only the essential features (or variables) of a system while omitting details considered non-essential. Models are widely used to investigate the Earth system and its components, including the ocean. Models can be conceptual, graphical, physical, or numerical.

A *conceptual model* is a statement of a fundamental law or relationship. Such a model is used to organize data or describe the interactions among components of any system. For example, conceptual models are used to explore linkages among physical and biological subsystems in the ocean and enable scientists to understand why and how ocean water circulates. A *graphical model* compiles and displays data in a format that readily conveys meaning. For example, ocean scientists make extensive use of bathymetric charts, maps of sea floor elevations, and the variations in water depth (Figure 1.17). A *physical model* is a small-scale (miniaturized) representation of a system. Prior to the availability of powerful computers, scientists used physical models to study the flow of water in harbors and estuaries. A *numerical model* consists of mathematical equations that simulate the processes under study. Observational data are used as initial or boundary conditions, guiding and verifying model predictions. Usually, a numerical model is initialized using current observational data. A projection of future conditions is made using the current state of the ocean and/or atmosphere as a starting point. By running the model many times, a numerical model projects the future state of a complex system and the probability that the projection will be correct is assessed. To obtain high probabilities, models must be tested and validated using a completely different set of data than what was used to create them, a requirement that can be difficult to meet.

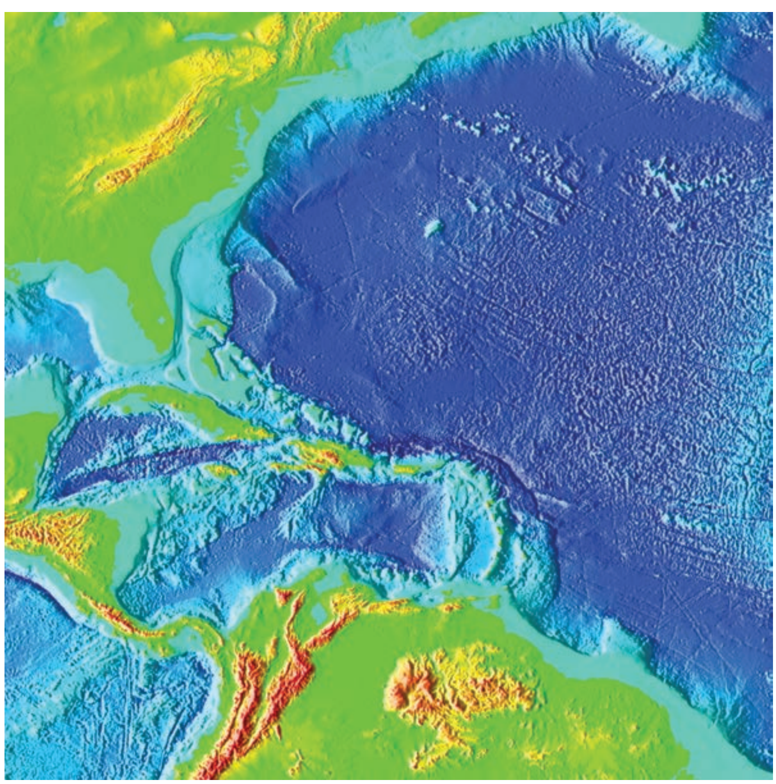


Figure 1.17
A color-coded bathymetric chart of the Atlantic Ocean off the East Coast of the U.S. and the Caribbean Sea. [Courtesy of National Centers for Environmental Information (NCEI), NOAA]

Today, computers are readily available, and numerical models have essentially replaced physical models in investigating the Earth system. Weather forecasts are the most familiar products of numerical models; in fact, numerical models of the Earth-atmosphere system have been used to forecast weather since the 1960s. Very powerful computers are needed to handle the complex mathematics and huge data sets required for ocean, atmosphere, or coupled ocean-atmosphere numerical models. A single set of complex calculations may require hours to a day to run.

Conclusions

The Earth system consists of several subsystems: the hydrosphere, atmosphere, geosphere, and biosphere. These subsystems adhere to natural laws as they interact globally over time scales ranging from seconds to hundreds of millions of years. Matter and energy cycle through the Earth system through global biogeochemical cycles.

Scientists study each subsystem by observation and application of the natural laws of physics to understand, model, and project future conditions. In situ methods include instruments monitored from ships. Remote sensing is monitoring different subsystems using satellites in Earth's orbit. The huge quantity of environmental data that is collected using Earth-orbiting satellites is fed into computer models that generate forecasts of the future state of components of the Earth system.

Basic Understandings

- A system is an interacting set of components that behaves in an orderly way according to natural laws. The Earth system consists of four major interacting subsystems: the hydrosphere (including the ocean and cryosphere), atmosphere, geosphere, and biosphere.

- The hydrosphere encompasses water in all three phases (solid, liquid, and vapor), which continually cycles from one reservoir to another in the Earth system. The ocean is the largest reservoir in the hydrosphere, containing 97.2% of all water on the planet and covering 70.8% of Earth's surface. The hydrosphere is dynamic, with water flowing at different rates through and between reservoirs within the Earth system. It can take days to weeks for water to reach the ocean in river channels and millennia for water locked in ice sheets. Surface ocean currents are primarily wind-driven while deep ocean currents are mainly driven by density differences caused by slight differences in temperature and salinity.

- The cryosphere consists of the frozen portion of Earth's hydrosphere, including mountain glaciers, permafrost, sea ice, and ice bergs. Glacial ice sheets make up the second largest reservoir of water on the planet. The cryosphere contains the most freshwater on Earth's surface. Ice sheets cover much of Antarctica and Greenland.

- Earth's atmosphere is a relatively thin envelope of gases that surrounds the planet and interfaces with the other Earth subsystems. Based on the vertical temperature profile, it can be divided into the troposphere, stratosphere, mesosphere, and thermosphere. Most weather takes place within the troposphere. Nitrogen (N_2) and oxygen (O_2), the principal atmospheric gases, are mixed in uniform proportions to an altitude of 80 km (50 mi.). The significance of atmospheric gases is not determined by concentration. In fact, some of the essentials for life occur in very low concentrations: water vapor (for the water cycle), carbon dioxide (for photosynthesis), and stratospheric ozone (for protection from ultraviolet radiation). The atmosphere is dynamic and circulates in response to temperature gradients that arise from radiational heating and cooling within the Earth system.

- The geosphere is the solid portion of the planet composed of rocks, minerals, and sediments. The lithosphere is the section of the geosphere containing the rigid uppermost portion of Earth's mantle plus the overlying crust. The lithosphere is continually modified by surface geological processes (weathering and erosion) and internal geological processes (plate tectonics).

- Weathering refers to the physical and chemical breakdown of rock into sediments. Rivers, glaciers, wind, and gravity erode the products of weathering and deposit them elsewhere.
- The biosphere encompasses all life on Earth and is dominated by bacteria and other single-celled organisms. Photosynthesis is powered by sunlight to produce sugars (glucose) that form the base of food webs. The opposite process is called cellular respiration. Chemosynthesis, driven by chemical energy rather than sunlight, also contributes to primary production in a few ocean environments.
- The biosphere is composed of ecosystems, which are communities of organisms interacting with each other and the physical and chemical conditions around them. These organisms include producers (plants), consumers (animals), and decomposers (bacteria, fungi) that occupy different trophic levels in food webs.
- Biogeochemical cycles describe the paths of solids, liquids, and gases among the reservoirs of Earth's subsystems. These cycles follow the law of conservation of matter, which states that matter can neither be created nor destroyed but can change chemical or physical form.
- The movement of water through the reservoirs in the hydrosphere is powered by the energy from the Sun. The movement of water is called the global water cycle. Water enters the atmosphere from the ocean and continents through evaporation, sublimation, and transpiration and leaves by condensation, deposition, and precipitation. The net flow of water is from ocean to atmosphere, atmosphere to land, and land to ocean.
- Scientists observe the ocean using techniques both in situ and remotely. In situ techniques, such as instrumented floats, ships, and buoys, are used to monitor ocean properties at depth while remote sensing techniques, such as satellite sensors, can only directly observe the ocean's surface.
- Satellites orbiting the planet are platforms for sensors that monitor the Earth system, including reflected or emitted electromagnetic radiation. Electromagnetic radiation is both a form of energy and a means of energy transfer, distinguishable based on wavelength and frequency.
- A geostationary satellite orbits the planet matching Earth's rotation so it is always positioned above the same spot on Earth's equator. A polar-orbiting satellite travels along relatively low north-south trajectories that take the satellite across the equator and over polar areas.
- A model is a simulation of a real system that includes only variables considered essential to the system. Conceptual, graphical, physical, and numerical models are used to simulate the Earth system and its component spheres.

Enduring Ideas

- Earth's subsystems, the hydrosphere, atmosphere, geosphere, and biosphere, are linked by biogeochemical cycles that are governed by natural laws.
- Water is found in three phases (solid, liquid, and gas) on and near Earth's surface and is distributed among oceanic (the largest), terrestrial (land-based), atmospheric, and biological reservoirs. The constant movement of water among these reservoirs constitutes the global water cycle. The net flow of water in the atmosphere is from above the ocean to above land; at Earth's surface and below the flow is directed from land to sea.

- The ocean is studied using in situ methods and remote sensing. In situ methods include instrumented buoys, floats, ships, piloted submersibles, and undersea observatories. Remote sensing by Earth-orbiting satellites can directly monitor only the ocean's surface waters, because water is nearly opaque to electromagnetic radiation.
- A scientific model is designed to simulate a real system. Conceptual, graphical, physical, and numerical models are widely used in ocean studies, incorporating essential features while omitting non-essential details.

Key Terms

system

hydrosphere

cryosphere

glacier

atmosphere

troposphere

aerosols

geosphere

crust

lithosphere

weathering

erosion

plate tectonics

biosphere

photosynthesis

cellular respiration

chemosynthesis

ecosystems

food chain

food web

estuary

biogeochemical cycles

global water cycle

evaporation

transpiration

sublimation

condensation

deposition

precipitation

distillation

in situ measurement

remote sensing

profiling float

electromagnetic radiation

electromagnetic spectrum

geostationary satellite

polar orbiting satellite

model

Review Questions

1. What is the second largest reservoir in the hydrosphere, and where is it located?
2. Identify and describe the layer of the atmosphere that interfaces directly with the ocean.
3. What are the two most abundant gases in the atmosphere?
4. Distinguish between weathering and erosion.
5. What are two pathways for freshwater to return to the ocean?
6. What is the significance of a food web?
7. Identify the various sources of atmospheric water vapor. Which one of these is the principal source?
8. Compare the total annual amounts of precipitation and evaporation in ocean areas versus the amounts over land. What does this imply about the directions of the net horizontal flows of water between ocean and land in the atmosphere and on and under Earth's surface?
9. Remote sensing by sensors onboard Earth-orbiting satellites generally restricts the direct monitoring of ocean properties to surface waters. Explain this limitation.
10. Why is remote sensing a powerful way to measure and observe Earth's subsystems (hydrosphere, atmosphere, geosphere, and biosphere)?

Critical Thinking Questions

1. Describe how an understanding of the workings of the Earth system relates to our ability to predict how each subsystem (hydrosphere, atmosphere, geosphere, and biosphere) might respond to a large-scale disturbance, such as increased greenhouse gas emissions.
2. Provide some examples of how the atmosphere is coupled with the ocean.
3. Identify and describe some of the major interactions between the hydrosphere and geosphere.
4. Speculate on the source of the salt that is dissolved in ocean water.
5. About 99% of the water in the atmosphere occurs in the troposphere. Explain why.
6. Satellite-borne sensors that monitor the ocean are either active or passive. Describe how satellites

can be used to monitor the ocean.

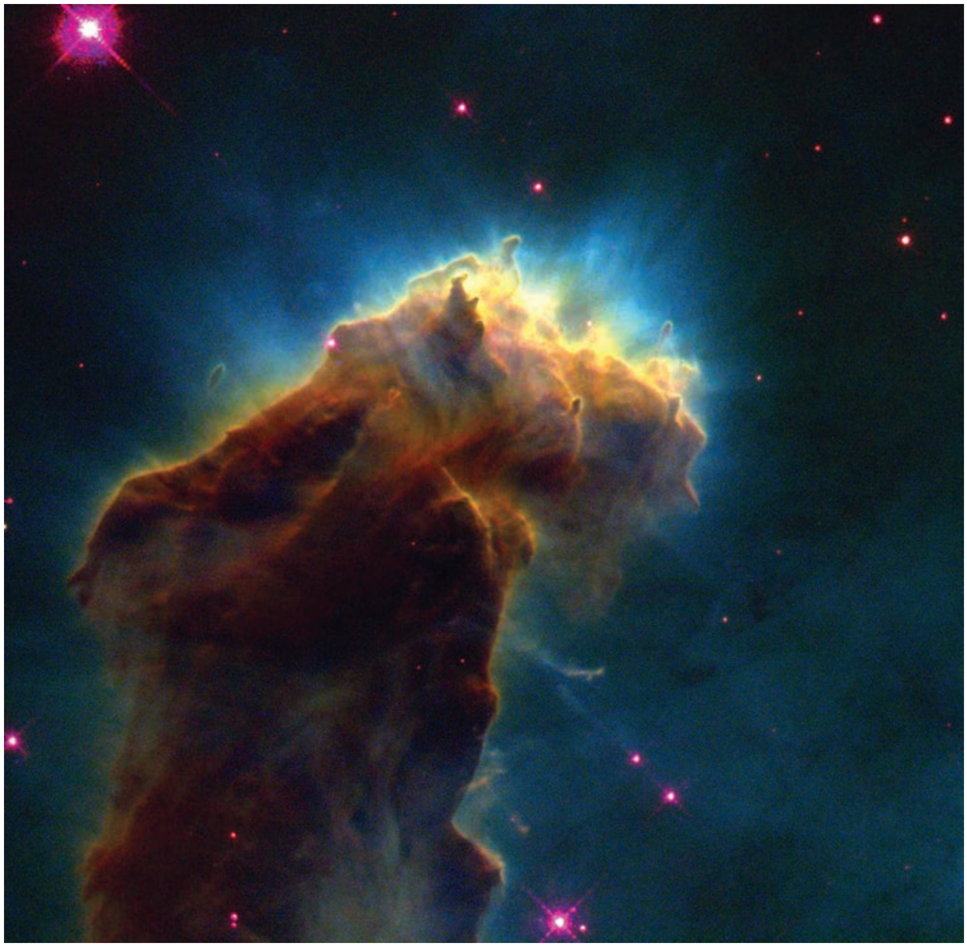
7. Explain how the ocean acts to stabilize (resist change in) Earth's climate system.
8. Give some examples of how Earth's various subsystems (hydrosphere, atmosphere, geosphere, and biosphere) interact within the Earth system.
9. How does the biosphere affect the concentration of oxygen in the atmosphere?
10. What are some examples of impacts Argo floats have had on oceanographic research?

For Further Exploration

ESSAY 1.1: Where did the Water Come From?

Earth is known as the water planet because ocean waters cover 70.8% of its surface. Yet, given how the solar system likely formed, it is surprising that there is any present on Earth at all. Where did the water come from? While there are several hypotheses, the scientific community has not come to a consensus. In recent years, scientists have offered new alternatives for the origin of water on Earth.

Scientists believe the atmosphere, hydrosphere, geosphere, and biosphere co-evolved through the vast expanse of Earth history. According to astronomers, the solar system came into existence more than 4.6 billion years ago from an immense rotating cloud of cosmic dust, ice and gases, called a *nebula* (Essay 1.1 Figure 1). The temperature, density, and pressure were highest at the center of the nebula, and gradually decreased outward. With temperatures exceeding 400°C (750°F) at the nebula's center, ice and the lighter elements were vaporized, driving them toward the nebula's outer reaches. Consequently, residual dry rocky masses formed the inner planets, including Earth, suggesting that our water came from elsewhere.

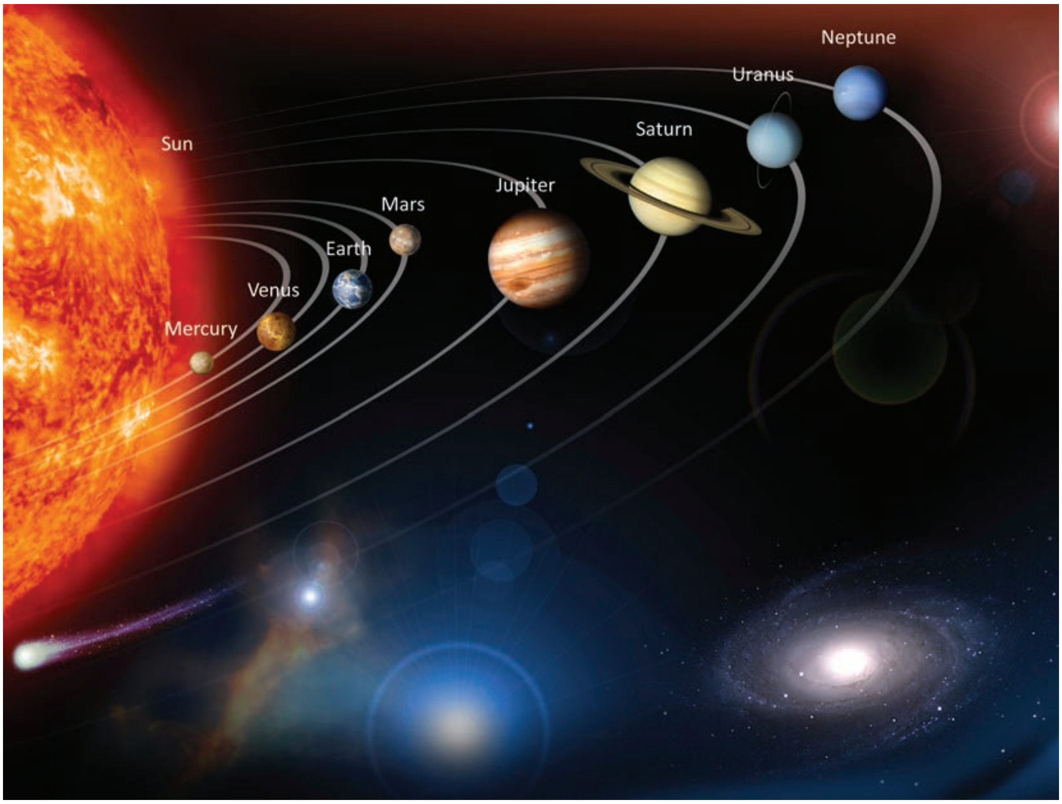


Essay 1.1 Figure 1
The leftmost "pillar" of interstellar hydrogen gas and dust in M16, the Eagle Nebula. [Courtesy of NASA/NSSDC Photo Gallery]

Scientists have hypothesized that the Earth's water was delivered by Oort cloud comets located inside of Neptune's orbit, Jupiter-family comets originating in the Kuiper belt outside of Neptune's orbit, or asteroid-like small bodies near Jupiter. Other scientists point to water being indigenous to Earth, meaning water that originated in or is innate to the Earth's system. An examination of water's isotopic structure, namely the ratio of *deuterium* (an isotope and heavier form of hydrogen) to hydrogen (the D/H ratio), is key to determining where it originated. The nucleus of a hydrogen atom consists of a single proton, but deuterium, an isotope of hydrogen, has both a proton and a neutron in its nucleus. Deuterium is very rare on Earth. Scientists attempt to determine the origin of Earth's water by matching the D/H ratio of Earth's ocean to other objects in space.

Comet Hypothesis

Most of the vaporized and dispersed water in the original nebula forming the solar system condensed within comets beyond Jupiter and Saturn (Essay 1.1 Figure 2). Composed of approximately equal amounts of meteoritic dust and ice, a *comet* is a relatively small mass that moves in a highly elliptical orbit around the Sun. As Jupiter's gravitational attraction strengthened, it may have drawn ice-rich comets from the outer to the inner reaches of the solar system. This would have put them on a collision course with Earth during the latter stages of its formation, producing a veneer of water on the surface. The comet hypothesis has come into question with a series of discoveries that the ice in comets is chemically distinct from that on Earth. Spectral analyses of three Oort cloud comets (e.g. Halley's comet) that approached Earth from the mid-1980s to first decade of the 21st century revealed that their water contains twice as much deuterium as water on Earth.



Essay 1.1 Figure 2
A highly stylized collage of images showing our solar system and areas beyond. The eight major planets are labeled for reference. [Courtesy of NASA/JPL]

The comet hypothesis was reexamined when scientists discovered that the Kuiper belt comet Hartley 2 had a D/H ratio very close to the value of Earth's water. This finding was unexpected, since scientists thought Kuiper belt-type comets should have an even higher D/H ratio than Oort cloud comets. However, recent analysis of the Kuiper belt comet 67P/Churyumov-Gerasimenko, by the European Space Agency's Rosetta spacecraft landing on the comet, revealed the highest D/H ratio found in the solar system. With the ratio being more than three times larger than Earth's water value; it is very unlikely that Kuiper belt comets were responsible for delivering Earth's water. These findings support models that asteroids delivered Earth's water and/or the water may be indigenous to Earth.

Asteroid Related Hypothesis

In contrast to a comet, the ice of an *asteroid*, a large rocky body a few kilometers across, contains less deuterium, however asteroids are only 10% ice by mass. Some scientists have proposed that asteroids delivered Earth's water, coming from just inside Jupiter's orbit. At that point in time, the asteroid belt consisted of rocks ranging in size from dust to small planets, which were scattered inward, including toward Earth. However, such material would have also struck Mars and greatly increased its mass beyond what it is today. Also, on Earth, the ratio of chemicals, such as certain noble gases, is not comparable to that of asteroids.

A more recent hypothesis centered on Jupiter. While the inner planets were forming, a swirl of dust and gases pulled the already formed Jupiter through the asteroid belt and into the inner solar system. Saturn followed Jupiter. The gravitational interaction between the two planets caused Jupiter to stop its inward motion towards the Sun close to where Mars is located today. At this point, Jupiter reversed direction and headed back to its current position in the solar system. When this happened, ice-rich bodies from the outer solar system were forced into new orbits, some of which headed toward Earth and delivered water.

Hypothesis of Water being Indigenous to Earth

Alternatively, water may be indigenous to Earth. Scientists recently proposed that the planet's water came directly from the nebula originally forming the solar system. Since the hydrogen isotope ratio of ocean water may have changed over geological time, the ratio measured in the present-day ocean may not reflect past ratios. Researchers traveled to Baffin Island in far northern Canada to try to measure the D/H ratio in water trapped in basalts formed when lava from the mantle hardened early in Earth's history. The researchers found that water contained in glassy inclusions inside the basalts has a much lighter D/H ratio than the ocean currently does, suggesting a shift in the D/H ratio of Earth's water over time and presenting an argument against the asteroid theory, as the water contained in the glassy inclusions does not match the D/H ratio of water contained in asteroids. The scientists point to water in the nebula as having the lighter D/H ratio now found trapped within the basalts. Though the super-hot temperatures in the nebula would have normally vaporized water, the researchers proposed that the water could have *adsorbed* (accumulates, forming a thin layer) to dust particles that coalesced to form Earth.

These recent results will cause scientists to reevaluate the various hypotheses on the origin of Earth's water. This will be a continued area of research as new discoveries are made both on Earth's surface and about other objects in the solar system.

ESSAY 1.2: The Challenges of Studying the Ocean Environment

Although humans have been studying the science of the natural environment for all of recorded history, there was almost nothing known about the oceans until about 250 years ago. By that time, almost all of the Earth's land had been visited and studied by geologist and biologists. Why did it take so long to even begin to study the oceans systematically? Why did it take so long to learn more? For example, scientists did not know of the existence of the immense mountain chains that pass through all the oceans until the mid-20th century, by which time people were already looking beyond Earth and launching satellites and humans into space. The reasons for the slowness of ocean study lie in the hostility of the oceans to oceanographers and to their instruments. In many ways, the ocean depths are more difficult to explore than the surface of the Moon or Mars.

A principal focus of oceanographers in developing techniques and instruments to study the oceans has always been, and still is, to overcome the many problems unique to studying the oceans. The most important of these problems are the following:

- Visiting the ocean depths is difficult because humans cannot breathe in water.
- Water absorbs light and other electromagnetic radiation, such as radar and radio waves, severely limiting their use for remote sensing in the oceans.
- The oceans are extremely deep.
- Pressure in the ocean depths is extremely high.
- Seawater is corrosive.
- The sea surface is dynamic.

“Seeing” through Ocean Water

Compared to the atmosphere, water is a much more efficient absorber of electromagnetic radiation, including radio and radar waves as well as ultraviolet, infrared, and visible light. In all but the shallowest areas, the sea floor cannot be seen by the naked eye or with any type of optical telescope. Even in the clearest ocean water, there is at best a distorted image of the seafloor, and only where the maximum depth is a few tens of meters. Because the sea floor cannot be seen, mapping the ocean floor was more difficult than mapping the surface of the Moon. Only in the 1920s did oceanographers discover that sound waves could be used as “eyes” to see the sea floor. Oceanographers also discovered that the magnetic and gravity fields of the sea floor could be sensed through the depths of ocean water. Even so, the ability to study the deep ocean is limited by its lack of transparency to electromagnetic radiation. For example, radar and other instruments carried on satellites can produce extraordinarily detailed maps of Earth’s land surface in a matter of days, but cannot map the sea floor directly because most electromagnetic radiation cannot penetrate the depths of the oceans. Fortunately, satellite sensors can map the sea floor topography indirectly by making very precise measurements of sea surface height. Satellite instruments can also be used to produce excellent maps of ocean surface features, including wave patterns, sea-surface temperatures, sea surface salinities, and the abundance of plant life in the near-surface waters. Nevertheless, maps of the sea floor are still less detailed and complete than our maps of Venus, a planet completely shrouded in clouds.

Inaccessibility

The average depth of the oceans is about 3688 m (12,100 ft.), and the greatest depth is 10,994 m (36,070 ft.). These depths are farther below sea level than the average and greatest elevations of the land are above sea level. The average land elevation is 840 m (2756 ft.) and the maximum elevation, at Mount Everest, is 8848 m (29,029 ft.). Most of the ocean floor is as remote from sea level as the highest mountain peaks are. Put another way, most commercial airplanes fly roughly as high above the land as the deepest parts of the ocean are below the sea surface.

To take a sample of the deep-ocean waters or sediment, oceanographers must lower instruments or samplers, usually on a wire, and then haul them back up to the ship. Because the oceans are so deep, this process is extremely time-consuming. Many hours can be spent on a single sample of mud or bottom water at one place on the ocean floor. In contrast, a scientist studying the land can collect many samples of rock, soil, plants, and animals much more efficiently.

In addition to performing the time-consuming process of lowering and retrieving instruments, research vessels, most of which have cruising speeds of about 20 km per hr (12 mph), consume large amounts of time and fuel going to and returning from sampling locations far from land. Because research vessels operating in the open ocean can cost tens of thousands of dollars a day to operate, the large amount of time needed to sample the deep oceans means that few samples can be collected during any oceanographic cruise and that each sample is very expensive to obtain.

Pressure

The pressure of the atmosphere at sea level is about 1.03 kg per cm^2, or 1 atmosphere (atm). On a journey to space, a space capsule is subject to a 1-atm pressure change because the atmospheric pressure in outer space is effectively zero. Therefore, manned spacecraft must have hulls that can withstand a 1-atm pressure difference. Because most electronic equipment can operate without any problem in the near total vacuum of space, unmanned satellites need no protection against pressure differences. In contrast, on a journey into the ocean, the pressure increases by 1.03 kg per cm^2 (1 atm) for each 10 m of depth. Hence, the pressure at 100 m depth is 11 times as high as the pressure at the ocean surface (1 atm of air pressure plus 10 atm of water pressure).

In the deepest part of the ocean, at about 11,000 m, the pressure is a truly astounding 1101 times as high as atmospheric pressure, or over 1100 kg per cm^2 (15,600 lb per $in.^2$). Therefore, manned submersibles designed to dive to the greatest depths would need hulls capable of withstanding a greater than 1100-atm pressure difference. Most submersibles are not designed to dive that deep, but shallow dives to 1000 m require hulls that can withstand a greater than 100-atm pressure difference. Submarines and submersibles must have hulls of thick metal and viewing ports of thick, durable glass or plastic. Deep-diving manned submersibles must be massive, even when made of strong, light materials, such as titanium. In addition, submersible hulls must withstand the metal-fatiguing stresses of repetitive pressurization and depressurization. These requirements make deep-diving submersibles extremely expensive.

Conductivity, Corrosion, and Fouling

Seawater poses a problem for instrument packages because most of them rely on electrical components. Such components will not work if immersed unprotected in seawater, because seawater conducts electricity and causes short-circuiting. Oceanographic instruments must be placed inside watertight containers called "housings" that can withstand oceanic pressures while the interiors of the housings normally remain at atmospheric pressure.

Seawater is extremely corrosive, as divers and other water sports enthusiasts quickly discover when they forget to wash their equipment with freshwater. Therefore, all wires, cables, sampling devices, and instrument housings must be protected. Iron and most steels corrode quickly in seawater, so special marine-grade steel or other materials must be used to minimize corrosion. These materials were not available to early oceanographers, who used more expensive and heavier materials, such as brass and bronze. Steel is still the best material available for the wires that lower and raise most instrument packages or samples. Even so, the most corrosion-resistant steel wires must be further protected by a coating of grease or plastic. Most measurements of trace metals and organic compounds dissolved in seawater were useless until recently because of contaminants from the corroding wire, the metal sampler parts, and the grease.

In addition to corrosion problems, a variety of marine organisms foul instruments that are left in the ocean to record data for days to months, as is necessary for some studies. Some marine organisms, such as barnacles, quickly adhere to and colonize the surface of any solid material. Instruments that rely on freely moving parts or a clean surface-to-seawater contact can quickly be rendered inoperable by such biological fouling.

Wave Motion

Perhaps the most obvious difficulty faced by oceanographers is the dynamic ocean surface; research vessels therefore cannot provide a stable platform on which to work. The perils of working on a rolling and pitching vessel are many. First and foremost, oceanographers must battle seasickness, as well as mental and physical fatigue and disorientation caused by working long hours at odd times of day. (Many shipboard research activities are continuous 24 hrs a day.) All oceanographers treasure the rare days of calm seas. Besides the personal hardships, dangers and difficulties are associated with the deployment and retrieval of often extremely heavy instrument packages over the side of a research vessel. The sight of heavy equipment swinging wildly on a wire from a crane over the deck of a ship when seas are rough is frightening. Hanging over the side of a ship in a storm to clamp instruments that must be attached at certain intervals to a heaving wire is an experience few people would relish.

Less obvious than seasickness and the perils of equipment deployment and retrieval, are the problems with using scientific instruments and performing scientific experiments in shipboard laboratories. Most scientific instruments are delicate but the lurching, pounding, and vibrating to which such equipment is subjected at sea quickly expose any structural weaknesses. Equipment often is specially designed or modified to operate reliably at sea. In addition, all equipment must be clamped or tied down in bad weather.

Logistics

A profusion of other, lesser problems are associated with studying the oceans. For example, on a research vessel hundreds of miles away from port, broken equipment cannot be taken to a repair shop, a technician cannot be called in, and spare parts cannot be picked up at a store. Oceanographers and research vessel crews become skilled at using any available materials to fix equipment. Nevertheless, even the greatest ingenuity sometimes fails and research efforts must be postponed until the next cruise to the appropriate location, which may be several years later. Such postponements can also be caused by bad weather, although most ocean research cruises are planned to allow some leeway for bad-weather days.

Web Resources

NOAA National Ocean Service - http://oceanservice.noaa.gov/

NOAA National Marine Fisheries Service - http://www.nmfs.noaa.gov/

NOAA National Weather Service Pacific Tsunami Warning Center - http://ptwc.weather.gov/

International Tsunami Information Center - http://itic.ioc-unesco.org/index.php

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