CHAPTER 1

The Ocean Planet

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC5 Transfer and Storage of Heat by Water
CC9 The Global Greenhouse Effect
CC10 Modeling
CC11 Chaos
CC14 Phototrophy, Light, and Nutrients

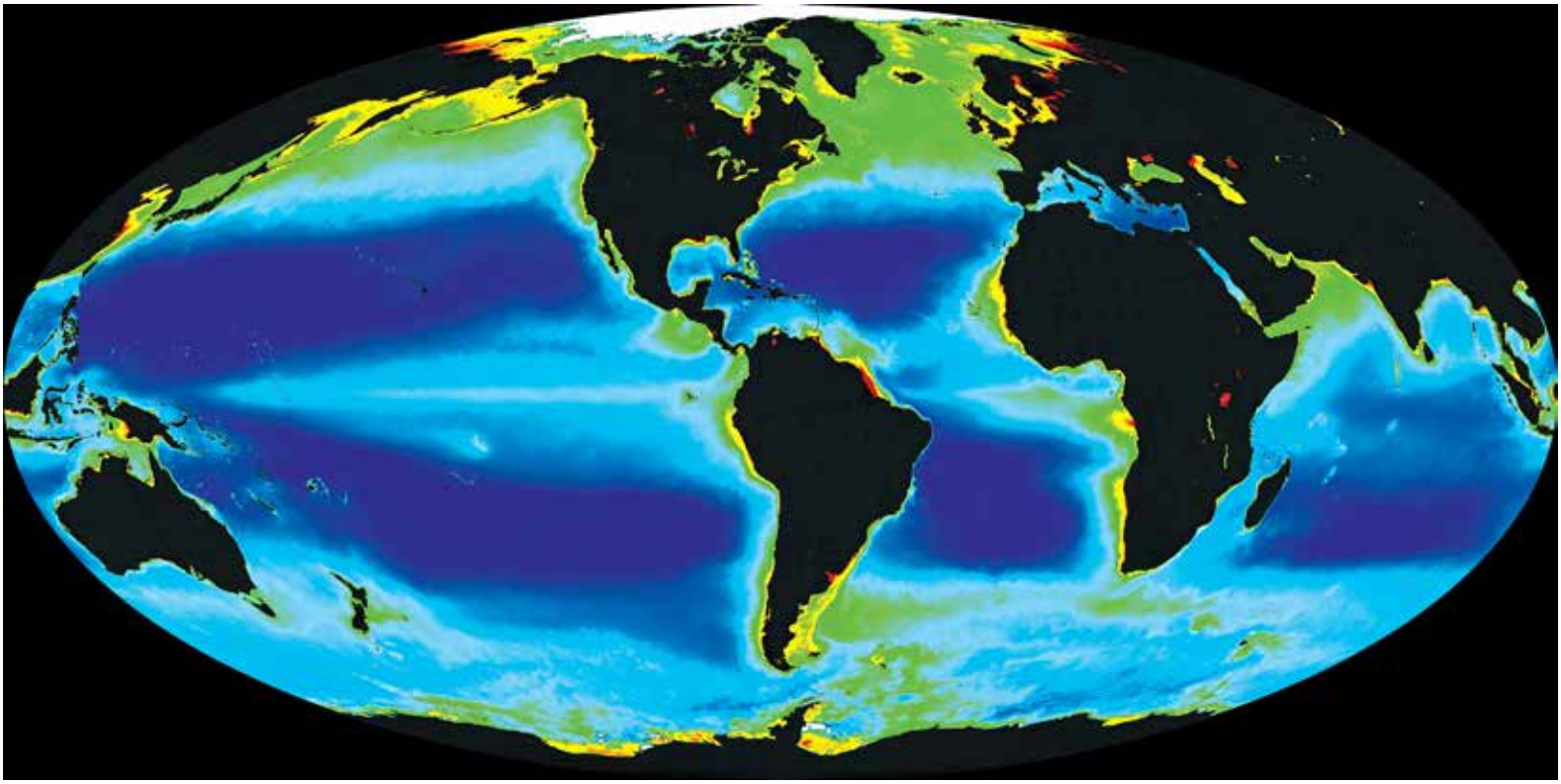


Figure 1-1. Why is this map of the world not drawn on a sphere or represented in a rectangular map shape such as we are used to? Why are the continents oddly misshapen? Why are the oceans those odd colors? Maps of the Earth are made on two-dimensional surfaces. Because they must represent the Earth's continents, which lie on a sphere, they distort the shapes and sizes of the Earth's features. This map is drawn to distort the Earth's surface features in a different way than is done in most of the maps that are familiar to us. Second, the strange colors that shade various areas of the oceans do not represent the color of the ocean surface itself, but instead represent biological productivity. The colors reveal details of the distribution of this property in the oceans.

INTRODUCTION

About half of the world's human population lives within a few tens of kilometers of the oceans. A large proportion of the remainder live within a few tens of kilometers of a river or estuary that is connected to the oceans. These facts hint at, but do not fully reveal, the importance of the oceans to human civilizations.

In this text, we will explore the fundamental physical, chemical, geological, and biological features and processes of the oceans, why the oceans are difficult to study, and review the difficulties of studying the oceans and the methods ocean scientists have used. We will discuss the range of resources that the oceans provide us, and the impacts from human use of the oceans and the exploitation of their resources. We will also examine the direct and indirect effects of climate change, not just on human civilization and natural ecosystems but also on the fundamental chemistry of the global ocean. Some of these changes pose a long-term threat of extinction for many ocean species. After reading this text, you will have a new appreciation for the intimate and intricate linkages between our lives and the oceans. More importantly, you will be better prepared to analyze, understand, and assess the growing influx of scientific and popular reports on ocean-related findings, theories, and the impact of human activities.

In recent decades, human interest in the oceans has grown in response to our rapidly deepening knowledge and understanding of the creatures that inhabit the underwater world. Scuba diving has become a popular pastime, avocation, or sport, and all forms of ocean recreation have grown explosively. New and higher-quality videos are becoming available, allowing us to experience the ocean from the comfort of our homes. Many cities now have ocean aquariums that allow the public to see ocean life up close. A large portion of the planet's population experiences the ocean at beaches, when boating or enjoying other water sports, or by sailing the oceans on cruise ships. On a more somber note, humans are also fascinated and terrified by the death and destruction caused by tsunamis, hurricanes, severe storms, ships running aground or sinking, and sharks. These interactions with the ocean lead to such questions as:

- Why do some say that we know less about the oceans than

we do about the moon or the planet Mars?

- Why are the world's active volcanoes located where they are?
- Why does the east coast of the United States have many barrier islands and tidal wetlands (marshes and mangrove swamps), whereas the west coast does not?
- What is a tsunami, and what should I do if I am ever on a beach when one is approaching?
- What is a rip current (rip tide), and how can I survive one?
- What is unique about water, and how do these unique properties affect daily life and our environment?
- What do we need to know about the oceans to understand and predict climate changes?
- Why are fisheries concentrated mostly in coastal zones, and why do some areas of the coastal ocean produce more fish than others?
- Almost all hurricanes in the Atlantic Ocean, especially large hurricanes causing severe damage, make landfall on the coast of the Caribbean, Gulf of America or the Southeast United States. Only a very few weak hurricanes make landfall in the Northeast United States and hurricanes virtually never make landfall on the Atlantic Africa or Southern European coasts. Why is this?
- Is ocean pollution from oil spills and industrial discharges as bad as many reports often portray it?
- What are the main causes of the widely reported destruction of coral reefs and damage to other ocean ecosystems?
- What is ocean acidification, and why is it important?
- What is ocean deoxygenation? What are its causes and consequences?
- There have been at least 5 mass extinctions in Earth's 4.6-billion-year history. Why do many scientists now believe that the planet may already have entered a new mass extinction of species? What long-term changes in ocean physical characteristics and chemistry are expected to contribute to this mass extinction?

Answers to some of the questions listed above may be found in a single section or chapter of this text. However, the oceans are a complex environment in which geology, physics, chemistry, and biology are all linked in intricate ways. As a result, finding answers to many of these questions requires fitting together information from several different chapters. You will be reminded numerous times of the interdisciplinary nature of ocean sciences as you study this text.

One particular theme that exemplifies the interdisciplinary nature of ocean sciences is revisited many times throughout this book. This theme concerns what may be the most important scientific questions facing contemporary human society: Is human activity permanently altering the environment in a manner that will ultimately damage or diminish civilization itself? Specifically, will the release of gases from the combustion of **fossil fuels** alter the oceans and atmosphere and cause major changes in the global climate and ecosystems?

THE OCEANS AND EARTH'S ENVIRONMENT

Only very recently have we come to realize that humans have already caused profound changes, not just in local environments but in the global ocean, atmosphere, and terrestrial environments as a whole. Too little is known about the global or regional consequences of environmental changes already caused by human activities. Even less is known about the future consequences if our civilization maintains its current exponential growth and development. The urgent need to assess the unknowns has been felt throughout the environmental science community. The oceanographic community has been particularly affected because most global environmental problems involve the oceans and ocean ecosystems, and our knowledge of the oceans is much poorer than our knowledge of the terrestrial realm. Changes in the marine environment caused by human activities are many and varied. They include many forms of pollution (**Chap. 16**) and physical changes in the coastal environment (**Chaps. 11, 13**). Many pieces of information must be obtained by different oceanographic

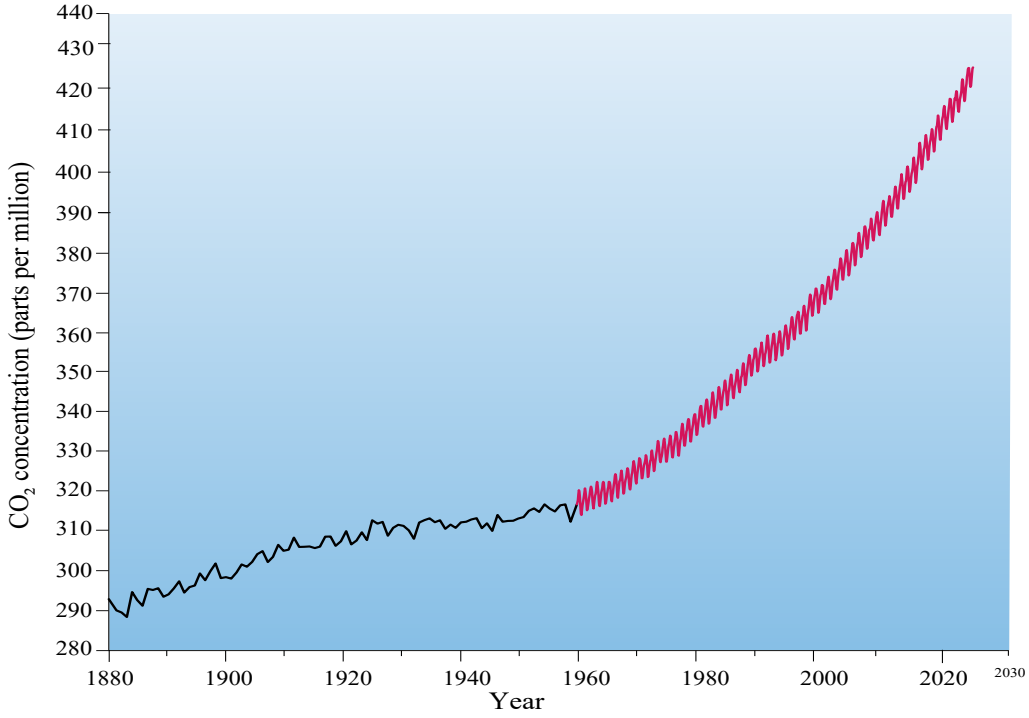


FIGURE 1-2. Change in the concentration of carbon dioxide in the atmosphere since 1880. Data for the smooth part of the curve were obtained from ice cores. Data from 1960 were obtained from direct measurements at Mauna Loa, Hawaii, and show both seasonal oscillations and a long-term upward trend. The upward trend continues. The seasonal peak in concentration exceeded 430 ppm for the first time in 2025 and the increase in concentration from May 2024 to May 2025 was 3.5 ppm.

disciplines before human impacts on the ocean can be identified, assessed, and effectively managed. Throughout this text, we refer to how oceanographic findings, principles, or studies can be applied to the practical problems of ocean management. The intent is to facilitate understanding of similar problems reported almost daily in the media.

Among contemporary environmental problems associated with human activities, three related impacts stand out as the most important and complex: global climate change due to enhancement of the **greenhouse effect** (CC9), **acidification** of the oceans (Chaps. 5, 13, 16), and **deoxygenation** of the oceans (Chaps. 12, 13, 16). Each of these problems are caused largely by the release of large quantities of carbon dioxide to the atmosphere, primarily as a result of fossil fuel burning.

A greenhouse maintains a higher internal temperature compared to the outside temperature because the windows allow more solar energy into the greenhouse than they allow to radiate out, warming the interior. The Earth's atmosphere acts in a similar way to control temperatures at the Earth's surface, with several gases, especially carbon dioxide, functioning like the glass in a greenhouse. The greenhouse effect is crucial for maintaining Earth's climate, but an increase in greenhouse gas concentrations increases its efficiency, leading to rising global temperatures. Since the Industrial Revolution, the burning of fossil fuels has steadily increased the concentration of carbon dioxide in the atmosphere, as shown in Figure 1-2. The concentrations of other greenhouse gases, such as methane and chlorofluorocarbons, are also increasing as a result of human activities. If there are no other changes to compensate for the consequent increase in greenhouse efficiency, the Earth's temperature will rise as concentrations of greenhouse gases rise.

The trend in atmospheric carbon dioxide concentration has accelerated from about 0.7 ppm per year in the 1960s to 2.6 ppm per year in the 2020s and is expected to continue increasing. The concentration is now more than 50% above the pre-industrial concentration of about 280 ppm and has been consistently above 420 ppm since 2023. The data has not shown any significant slow down of the rate of increase due to the COVID-19 pandemic or the emissions reductions of Western nations, including the United States.

Since 1950, Earth's temperature has risen 1–2 degrees Celsius and is projected to rise by an additional several degrees Celsius in the next two to three decades.

If the predicted increase in the global temperature does indeed occur, it will cause dramatic climate changes throughout the world. These changes are likely to be devastating to agriculture, the environment, and our entire civilization. In addition, if the predicted warming occurs, sea level will rise as a result of thermal expansion of the warmed ocean water and melting of ice from glaciers and polar ice sheets in Greenland and Antarctica. Some experts predict that sea level will rise a meter or more during the next several decades, inundating large areas of low-lying coastal land and entire low-lying island chains.

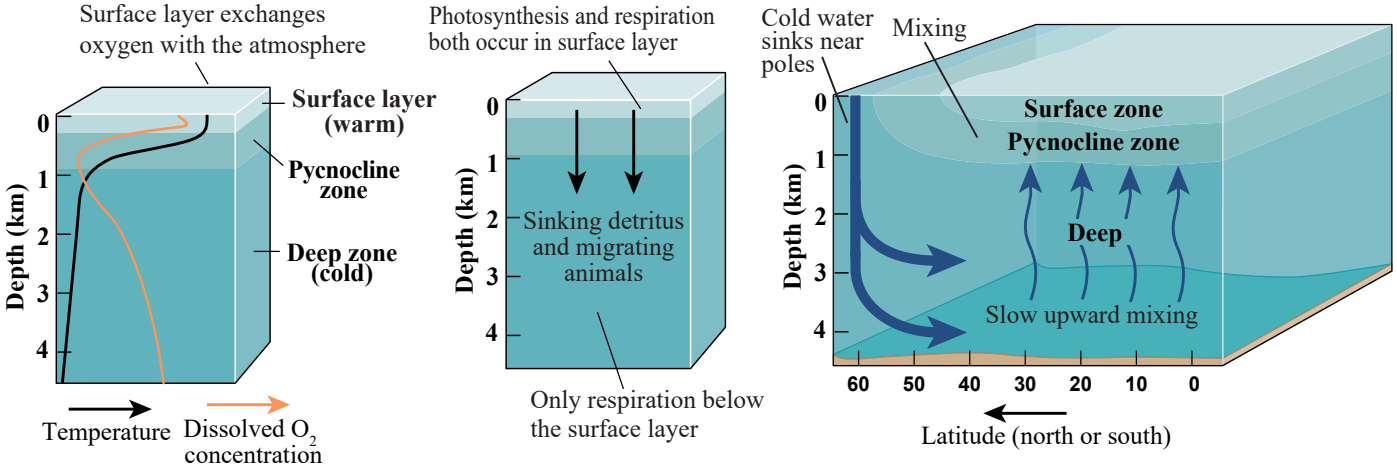
More than 30% of the carbon dioxide released by fossil fuel burning has been absorbed by the oceans. However, the added carbon dioxide reacts to form a weak acid. Consequently, although ocean waters are still weakly alkaline, with an average **pH** of approximately 8.1, the acidity of the oceans is rising. The acidity of a substance is measured by its pH, with lower pH values indicating more acidity. The oceans have been more acidic in the ancient past than they are today, but the rate at which acidification is currently taking place is believed to be many times faster than has ever occurred before. Because the rate of acidification is far too fast to allow many species to evolve and adapt, it is anticipated that ocean acidification will result in the extinction of many marine species and a drastic alteration of marine ecosystems. Species that are especially at risk include those that create hard parts (skeletons, shells, and other structural materials) of calcium carbonate. These include many of the most important groups of marine organisms, such as shellfish and, perhaps more critically, the pteropods that are the base of many marine food chains that provide food for fishes and marine mammals.

The effects of ocean acidification on marine ecosystems are already significant. For example, the acidity of coastal waters of the Pacific Northwest has risen in recent decades to a level that prevents oyster larvae from growing to maturity. This has significantly affected the large oyster industry in the region. Oysters must now be hatched and grown in remote locations such as Hawaii, where the water is less acidic, or in tanks with controlled pH water. Due to its cold water and high biological productivity, the Bering Sea off Alaska is the most acidic part of the world ocean, with pH values of 7.7 already observed there and continuing to decline. At these low pH values, there is strong evidence that the Alaska King Crab population will decline and that populations of the small animals called pteropods, a principal food source for Bering Sea fishes, including salmon, will also decline since the water is too acidic for the pteropods to make their calcium carbonate shells.

Research suggests that future ocean acidification will cause major changes in the species composition of diverse marine food chains and is likely to severely damage coral reefs before the end of the century. However, some species that rely on calcium carbonate skeletal material do appear to be capable of adapting to this predicted increase in acidity levels. If we are going to mitigate or minimize the ecosystem effects of ocean acidification, we must not only reduce the amount of carbon dioxide we release to the atmosphere but actually remove much of the **anthropogenic** carbon dioxide already in the atmosphere.

Another consequence of anthropogenic releases of carbon dioxide is expected to be widespread deoxygenation of the oceans. This threat is caused by a combination of anthropogenic releases of carbon dioxide and civilization's releases to the oceans of large amounts of nitrogen and phosphorus, primarily from agriculture and in treated sewage discharges. This threat is a little complicated as several of the physical, chemical, and biological processes that are explained in later chapters of this book are involved.

For now, it is important to understand the following points that are illustrated in Figure 1-3. The oceans are essentially separated into a warm surface layer and colder deep water, and oxygen concentration in ocean water is controlled by both physical and biological processes. The surface layer is constantly mixed and in contact with the atmosphere, allowing it to exchange gases; therefore, its oxygen concentration is primarily determined by the atmospheric oxygen concentration. The much thicker deep-water layers below the warm surface layer are colder and mix with the surface layer only slowly (Fig. 1-3a, CC1, Chaps. 5, 8). In the deep-water layer, **respiration** (including microbial decomposition of **detritus**) removes oxygen from the water and replaces it with carbon dioxide (Fig. 1-3b, Chaps. 5, 12). If water in the deep layers of the oceans was not continu-



(a) Layered structure of the oceans. Pycnocline zone is a transition zone where water temperature decreases and density increases rapidly with depth and vertical mixing is slow.

(b) Oxygen is used up by respiration in the pycnocline and deep zones. Rate of respiration is higher just below the pycnocline zone than at deeper depths.

(c) Ocean circulation carries oxygen rich surface water into deep layers. This oxygen rich water is slowly mixed back toward the surface layer while its oxygen concentration is progressively decreased by respiration.

FIGURE 1-3. Oxygen concentration in ocean water is controlled by both physical and biological processes. The oceans consist of two main layers, a warm surface layer and a cold deep layer, with a transition zone, called the pycnocline zone, between them. (a) Surface layer water is well mixed and in contact with the atmosphere, and its oxygen concentration is primarily controlled by gas exchange with the atmosphere. (b) Photosynthesis by marine life in this layer converts carbon dioxide to organic matter and releases oxygen, but this is offset by respiration, which converts oxygen to carbon dioxide. Respiration also occurs in the deep layer, fueled by animals that migrate vertically or live in the deep and decomposition of organic material (detritus), but there is no photosynthesis and no contact with the atmosphere, so respiration continuously consumes oxygen in this deep layer, and, therefore the longer the water remains in the deep layers, the less oxygen it contains. (c) The deep layer water is continuously replenished by sinking of cold water in some near-polar regions and then circulates through the oceans while being slowly mixed upward, eventually into the surface layer again. The pycnocline provides a barrier that inhibits mixing, so the upward mixing process is slow..

ously replaced by oxygenated surface waters, the deep layers would lose all oxygen and would become void of all life, except for certain microbial species (**Chaps. 12, 13**). However, surface layer oxygen-rich water does sink at certain locations in high latitudes where it is cooled and becomes dense enough to sink. This water moves slowly through the deep oceans, continuously losing oxygen and gaining carbon dioxide due to respiration, then eventually mixes back into the surface layers to be re-oxygenated (**Fig. 1-3c**, **Chap. 8**). This circulation results in a vertical profile of dissolved oxygen concentration with high oxygen concentrations in the surface layer and in the deepest water layers with an oxygen minimum at depths in or just below the pycnocline zone (**Fig. 1-3**, **Chap. 8**). The concentration of dissolved oxygen at this oxygen minimum depth varies from location to location but, in some areas, is too low for animal life to survive. Areas that exhibit such low oxygen concentrations are referred to as Oxygen Minimum Zones (OMZ). OMZs are usually found at depths of between about 200 and 1000 m (**Fig. 1-3**, **Chap. 8**), and at least some such oxygen-deficient areas are currently expanding.

For many centuries, the balance between the supply of oxygen-rich water to the deep layers and the rate of respiration by organisms in the deep layer of the ocean has maintained enough dissolved oxygen for the organisms that live there. However, that has not always been true in several episodes of Earth's past when the deep ocean layers were devoid of oxygen. No animals or any other marine life, except for some species of microbes, can exist in water devoid of oxygen.

There are two ways that the deep oceans can lose all their oxygen and become **anoxic**. This can occur if the rate at which water circulates through the deep oceans is reduced, allowing a longer time for respiration to consume the oxygen, or if the rate at which respiration takes place in the deep oceans increases, or a combination of these. Respiration of living organisms in the deep layers of the oceans is fueled by the decomposition of organic matter (food) just as it is elsewhere. However, since no light penetrates down to the deep layer to support **phototrophy**, most of the food supply in the deep layers comes from the surface layer, as falling detritus or vertically migrating organisms (**Fig. 1-3b**). This food supply is limited, which limits the total respiration and, therefore, oxygen loss as water flows through the deep oceans. If the supply of food from the surface layer to the deep ocean water is increased, the additional food supports more deep-layer marine life, which means more respiration, and the oxygen concentrations in deep water decline.

The Earth has experienced at least 5 known mass extinctions of species, including the one that occurred when the dinosaurs became extinct (**Fig. 1-4**). While deoxygenation of the oceans is thought not to have been the sole cause of these extinctions, both acidification and deoxygenation did occur during most of these extinctions and are thought to have contributed to the extinction.

Now, we can consider why scientists believe that deoxygenation of the oceans is a major long-term threat. First, less oxygen can dissolve in seawater at higher temperatures, so climate warming will reduce oxygen concentrations in the surface layers of the oceans that are in contact with the atmosphere. Second, warming of the oceans is likely to enhance the temperature differences between deep ocean layers and surface layers, which will inhibit vertical mixing of the two. Warming of ocean surface waters is also expected to reduce the rate at which cold surface waters near the poles sink into the depths. Each of these effects will lengthen the time that deep ocean water spends out of contact with the atmosphere before returning to the surface layers to exchange

gases and re-equilibrate with the atmosphere. Third, warmer ocean water is expected to increase the rate of production of food by phototrophy in the ocean's surface layer, which will increase the supply of detritus to the deep layer, accelerating oxygen consumption. Current research indicates that each of these three changes have already begun to occur. Moreover, **photosynthetic** food production in most of the oceans is limited by the low concentrations of nutrients, especially nitrogen and phosphorus. Humans release large amounts of these nutrients, especially in agricultural runoff and treated sewage wastes. This is expected to enhance the rate of photosynthesis and production of organic matter, which will increase the production of detritus and the amount of detritus transported below the surface layer. Decomposition of this detritus is expected to increase, which would increase the rate of oxygen loss in the deep ocean layers.

Our understanding does not yet allow us to assess the future of ocean acidification and deoxygenation in the global ocean with any certainty. However, we do have observations of the ecological damage that they can cause in limited regions. For example, as mentioned earlier, acidification of the coastal waters off the west coast of North America has already been observed to have exceeded the ability of oysters to reproduce successfully (**Chaps. 5, 16**). Also, there are numerous coastal and estuarine areas, including the Chesapeake Bay and the coastal waters west of the Mississippi Delta, that experience low or totally depleted oxygen in their deeper water layers (below a shallow pycnocline), either periodically or permanently, due primarily to excess anthropogenic nutrients. These areas have been called "dead zones" because living organisms that are unable to move out of these areas as they develop die due to a lack of oxygen (**Chaps. 13,16**). Also, water from an OMZ in the North Pacific Ocean has periodically encroached on the Oregon continental shelf, causing a periodic "dead zone" to appear.

The oceans and atmosphere act together as a complex system that regulates our climate and the concentrations of carbon dioxide and other gases in both the oceans and atmosphere. An essential role of the oceans is to capture, store, and redistribute the sun's heat energy to the atmosphere (**CC5**), so the oceans are integral to weather and climate. Within the ocean-atmosphere system, numerous complicated changes and feedbacks occur as a result of increases in atmospheric concentrations of carbon dioxide and other gases. Some changes add to the predicted global warming, whereas others reduce or even negate it. This is also true for ocean acidification and deoxygenation. However, our current understanding of the ocean-atmosphere system is poor, especially those segments of the system that are associated with ocean processes. To predict Earth's future with less uncertainty so that we can take appropriate actions, we must improve our understanding of the oceans.

In addition to studying contemporary ocean processes, oceanographers study the oceans to uncover important information about past changes in the world's climate. Such historical information, found primarily in ocean seafloor **sediment** and sedimentary rocks, can reveal how the Earth's climate has changed over tens of millions of years and help us assess how it might change in the future, either as a result of natural changes or as a result of the enhanced greenhouse effect.

Climate change, ocean acidification, and deoxygenation are complex processes involving many concepts referenced in the preceding paragraphs. You might ask why they are summarized in this introductory chapter. The reason is simple. Each chapter contains information needed to fully understand how these processes work. If climate change, acidification, and deoxygenation continue unchecked, the ultimate likely consequences include global mass species extinction, a far greater threat than the damage that may be caused by any other environmental issue. Keep this in mind as you learn about the oceans, and you will realize that what you are learning is not just science but information about things that are vital to your life and the lives of all other humans and living creatures. We will return to the subjects of ocean acidification and deoxygenation in **Chapter 16**, when we discuss human impacts on the oceans. By then, you will have learned about the fundamental physical, chemical, and biological processes operating in the oceans and will be able to much better understand how acidification and deoxygenation are developing and that they represent a major long-term threat to both ocean ecosystems and human civilization.

Many important decisions must be made by current and future generations about human use and the protection of our environment. It is important for all of us to participate in these decisions with an understanding of the complexity of the ocean-atmosphere system and the uncertainties inherent in all scientific studies and predictions of such complex environmental systems (**CC10, CC11**). We must also recognize that science cannot provide definitive answers to even the most intensively studied environmental problems, as all environmental systems include non-linear relationships, making them chaotic. This means that predictions based on even the best science and modeling will always have high uncertainty.

OCEANS AND THE ORIGINS OF LIFE

To investigate the origins of life, a number of laboratory studies have attempted to reproduce the conditions thought to exist in the early oceans and atmosphere, including high ultraviolet radiation levels and frequent lightning discharges. Under these conditions, a wide range of organic compounds are created from mixtures of carbon dioxide, methane, ammonia, hydrogen, and water. The organic compounds formed in these experiments included amino acids, which are considered the most important building blocks of the complex molecules needed for life to exist. However, we do not understand how or know where these building blocks were assembled into the much more complex molecules that were needed to form the first living matter. Several hypotheses have been proposed. The chemical reactions necessary to construct complex molecules may have taken place on the surface of solid particles, deep within the Earth, or at hydrothermal vents (**Chap. 15**). Another possible explanation for the origin of these complex compounds is that they first reached the Earth in meteorites.

All life as we know it depends on the transport of chemical elements and compounds within cells and between cells and the surrounding environment. In all known living organisms, from **archaea** to mammals, these chemical substances are transported dissolved in water. Therefore, water is essential to all life on Earth. As a result, it is not surprising that life appears to have been nurtured and developed in the oceans for most of the billions of years of Earth's history. **Figure 1-4** shows the 4.6 billion years of Earth's history compared with a year with significant dates including the formation of the oceans, the first primitive animals, evolution of humans, and the 5 well-known mass extinc-

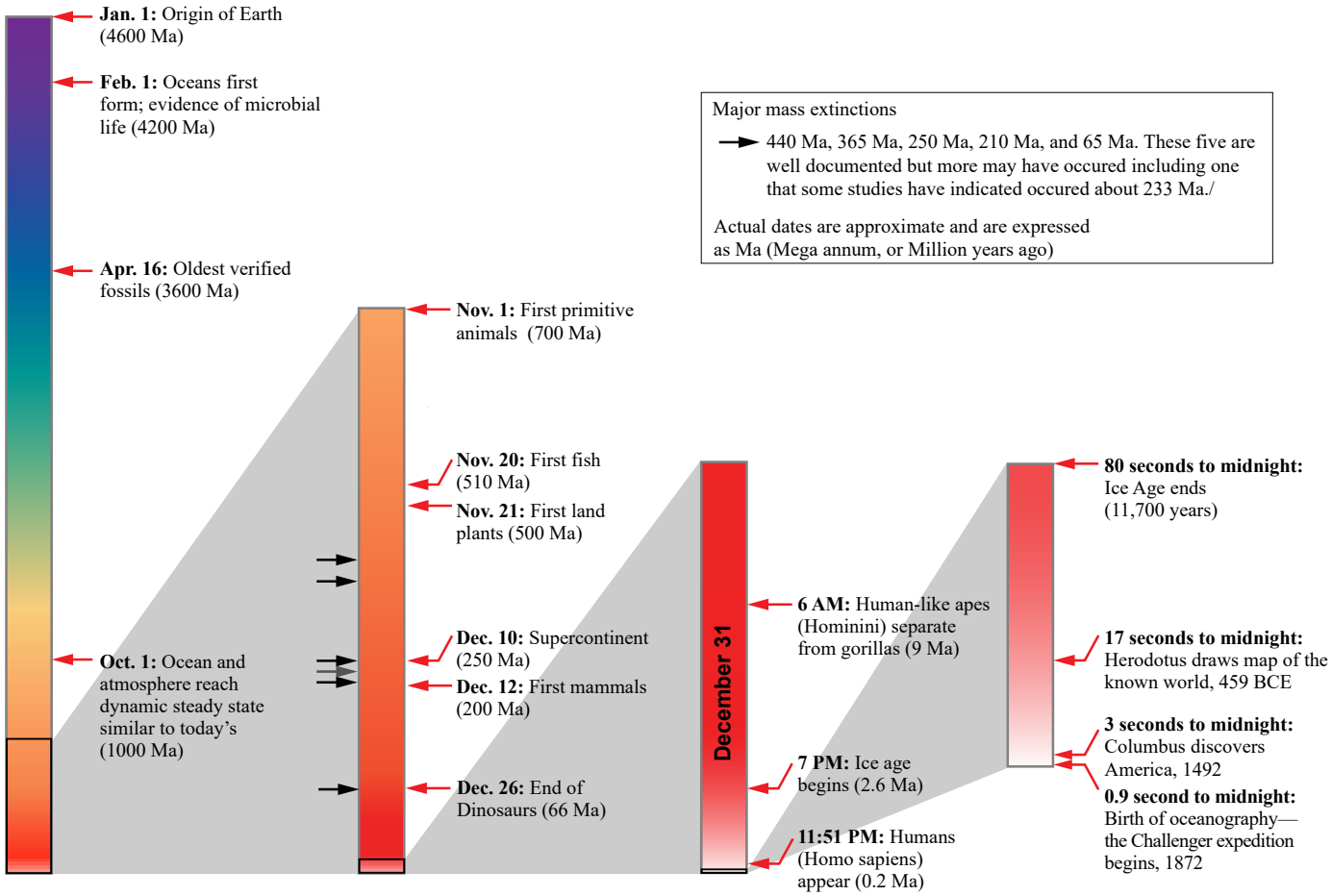


FIGURE 1-4 The history of the Earth, shown as if it were 1 year. The Earth formed about 4.6 billion years ago. Animals have existed on the Earth for only an extremely brief period of its history. If the age of the Earth were only 1 year, animals would have existed for only 2 months, our species Homo sapiens for about 9 minutes, and the science of oceanography for less than a single second. Most actual dates on the figure are expressed as Ma (Mega annum, or Million years ago) and are approximate.

tions.

Evidence from the fossil record indicates that life has existed on the Earth for a very long time. Although there is evidence that life began much earlier, the first life forms for which we have direct evidence were bacteria-like microorganisms that existed about 3600 million years ago (Ma), approximately 1 billion years after the Earth was formed (Fig. 1-4). When the oceans were first formed about 4200 Ma, the atmosphere consisted mostly of nitrogen, with smaller amounts of carbon dioxide and methane. Because there was no free oxygen in the atmosphere or oceans, it is thought that some of the earliest life forms were similar to the **chemosynthetic** microbes that are currently found in many isolated environments such as hydrothermal vents and deep within the Earth's **crust** (CC14, Chap. 15). These environments contain no free oxygen and are often characterized by conditions of extreme temperature and pressure, similar to the conditions that are thought to have existed in the oceans and within Earth's crust when the oceans were first formed.

If the first organisms did utilize chemical energy to support their energy needs, then at some unknown time, the first species of microorganisms that utilized the sun's light energy developed. These organisms were **phototrophic** (CC14). Early phototrophic microorganisms probably used hydrogen sulfide as their source of hydrogen, which is needed for building chemical compounds. Later, photosynthetic microorganisms, likely cyanobacteria, developed the ability to split water molecules, using the hydrogen to build their chemical compounds, releasing oxygen in the process. Over a period of time, between about 2000 and 1000 Ma, these photosynthetic organisms changed the composition of the Earth's atmosphere. Oxygen concentrations steadily increased until they reached approximately the 20% present in the current atmosphere (Fig. 1-4). This change was fundamental to the development of the majority of living species now on the Earth. As the free oxygen accumulated in the atmosphere, it reacted with sulfides and other chemical compounds in the oceans that supported the life cycles of chemosynthetic species. As a result, chemosynthetic species largely disappeared or became restricted to extreme environments, such as those where they are found today. Furthermore, the free oxygen permitted the development of the animal kingdom. All species of animals depend on respiration using oxygen obtained from their environment.

The oceans and atmosphere reached a **steady state** (maintaining approximately the same chemical compositions that they have today) approximately 1000 Ma, and this relative stability permitted the development of more complex life forms. The first primitive higher animals were marine **invertebrates**, perhaps similar to sponges and **jellies** (**jellyfish**), that developed about 700 Ma, followed by the first fishes about 500 Ma (Fig. 1-4). The first plants appeared on land about 500 Ma, and the first mammals only about 220 Ma. Humans are latecomers. Hominids (human-like species) have existed for only about 4 million years—less than one-tenth of 1% of the history of the Earth. In the 1-year

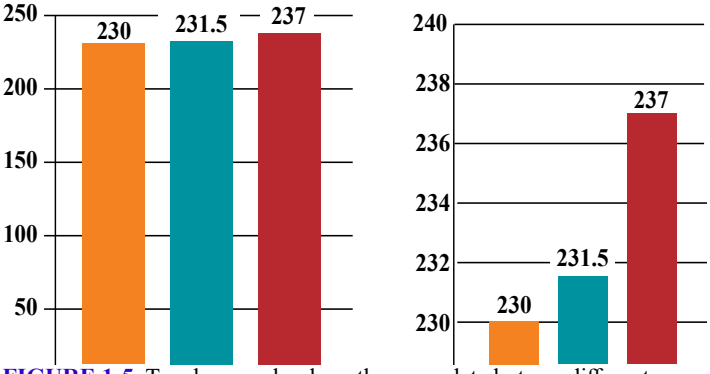


FIGURE 1-5. Two bar graphs show the same data but use different y-axis ranges. They give very different impressions about the differences among the three values. In part (b), the true nature of the differences can be found only by carefully examining the scale on which the data is plotted.

model, this is less than 9 minutes (**Fig. 1-4**).

Although the specific environment in which life first developed is not known, the oceans clearly played a major role in nurturing the development of life on the Earth.

HOW TO STUDY OCEAN DATA

Before we begin to explore the intricacies of the relationships among humans, the oceans, and the environment, it is important to review some of the basic tools used to describe the Earth and its oceans. These include various forms of maps, graphical representations of data that vary geographically or with time, graphs that can show the relationship between two variables, and standard scientific notation for numbers and units of measurement.

As is true for other sciences, describing what we know about the oceans and ocean processes requires the use of graphs and similar diagrams, and sometimes mathematics. For ocean sciences, we must also be able to represent data in a geographic context, which requires the use of maps or **charts**. Graphs, diagrams, and maps make it easy to understand certain features of even complex data sets without using mathematics (a goal we have set for this text). However, these visual representations can be properly interpreted only if we understand how a particular graph or map presents, and often distorts, the data. To make it possible for you to properly study and understand the rest of this text, the remainder of this chapter discusses some of the characteristics of graphs and maps that are used extensively in this text. Even if you are familiar with scientific diagrams, you are strongly urged to review this material.

Graphs

Graphs are probably the most widely used way to present data in science and elsewhere. They provide a means of visualizing relationships between two or more variables or properties, but they can be extremely misleading unless they are read properly. To understand a graph, you must not only look at the general shape of the line or curve connecting points or the apparent difference in sizes of bars in a bar graph, for example, but you must also carefully examine the axes. Two simple examples in **Figure 1-5** illustrate why.

In **Figure 1-5**, three simple values that could be, for example, the prices of an item at different stores or the depths of the thermocline at three locations in the ocean are plotted in a simple bar graph. The same data are plotted in both parts of the figure. Why do the plots look so different? In **Figure 1-5a**, the y-axis (vertical axis) extends from 0 to 250. In **Figure 1-5b**, the data are "expanded" by showing only 228 to 240 on the y-axis. Items 1, 2, and 3 have nearly the same values, but one plot seems to show that item 3 has a much higher value than items 1 and 2. Have you ever seen this technique used in advertisements or news reports to present data differences in a misleading way?

can be found only by carefully examining the scale on which the data is plotted.

The second example is a simple nonlinear (**CC10**) relationship between two variables ($x^2 = y$). These variables could be, for example, light intensity and depth, or primary production rate and nutrient concentrations (although the relationships between these pairs of parameters are actually more complicated). Notice that the first plot (**Fig. 1-6a**) shows that y increases more rapidly as x increases, which is exactly what we would expect from the equation. However, the same data in **Figure 1-6b** appear to show the exact opposite (y increases more slowly as x increases). The reason for this difference is that the y-values are plotted as the log of the value, not the value itself. Log plots are commonly used for scientific data but may be confusing unless you examine the axes carefully. One of the reasons why log plots are used is illustrated in **Figure 1-6c**. This figure is a plot of the same data as in **Figure 1-6a** and **Figure 1-6b**, but it plots the log value for both variables. The plot is a straight line, revealing a feature of this nonlinear relationship that is often important to scientists.

Contour Plots and Profiles

Contour plots are used to display the two-dimensional spatial distribution of a variable, such as atmospheric pressure on

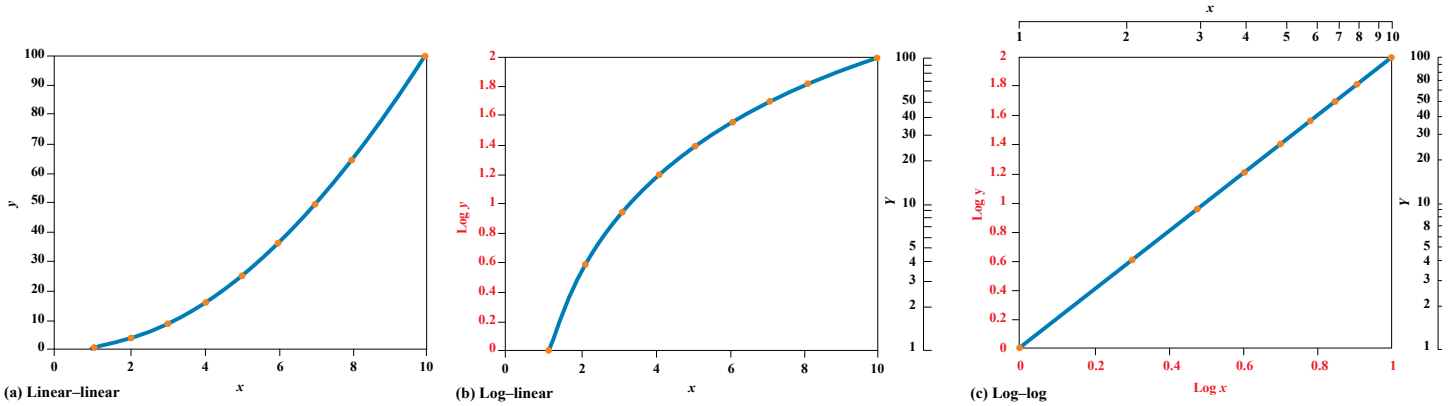


FIGURE 1-6 A simple nonlinear relationship is plotted in three different ways to show how logarithmic scales can change the apparent nature of the relationship between the two variables: (a) a linear–linear plot, (b) a log–linear plot, (c) a log–log plot. Notice that in parts (b) and (c), the scale on the log axis can be expressed as the log of the number (left side) or the number on a log scale (right side). This shows how important it is to analyze every part of a figure to distinguish the details.

weather maps. The variable plotted can be any parameter, such as pressure, temperature, soil moisture, vegetation type, or concentration of a substance.

Contour plots show how variables are distributed across flat surfaces. In some cases, the variable being plotted represents a measurement in the third dimension—perpendicular to the surface—such as depth or height. The most common examples are **topographic** maps that depict the height of the land surface above sea level and **bathymetric** maps that depict the depth of the ocean below sea level. Sea level is used as the surface on which the third dimension variable, the height or depth, is plotted. Contours of pressure are usually called **isobars**, temperature contours are **isotherms**, density contours are isopycnals, and depth contours are called isobaths. The prefix "iso" means "equal" or "the same," so these lines connect locations with the same value of the variable, with each line representing a different value. Often, but not always, the values contoured are spaced at equal intervals of the variable, such as 50 m, 100 m, 150 m, and 200 m above sea level for a topographic map.

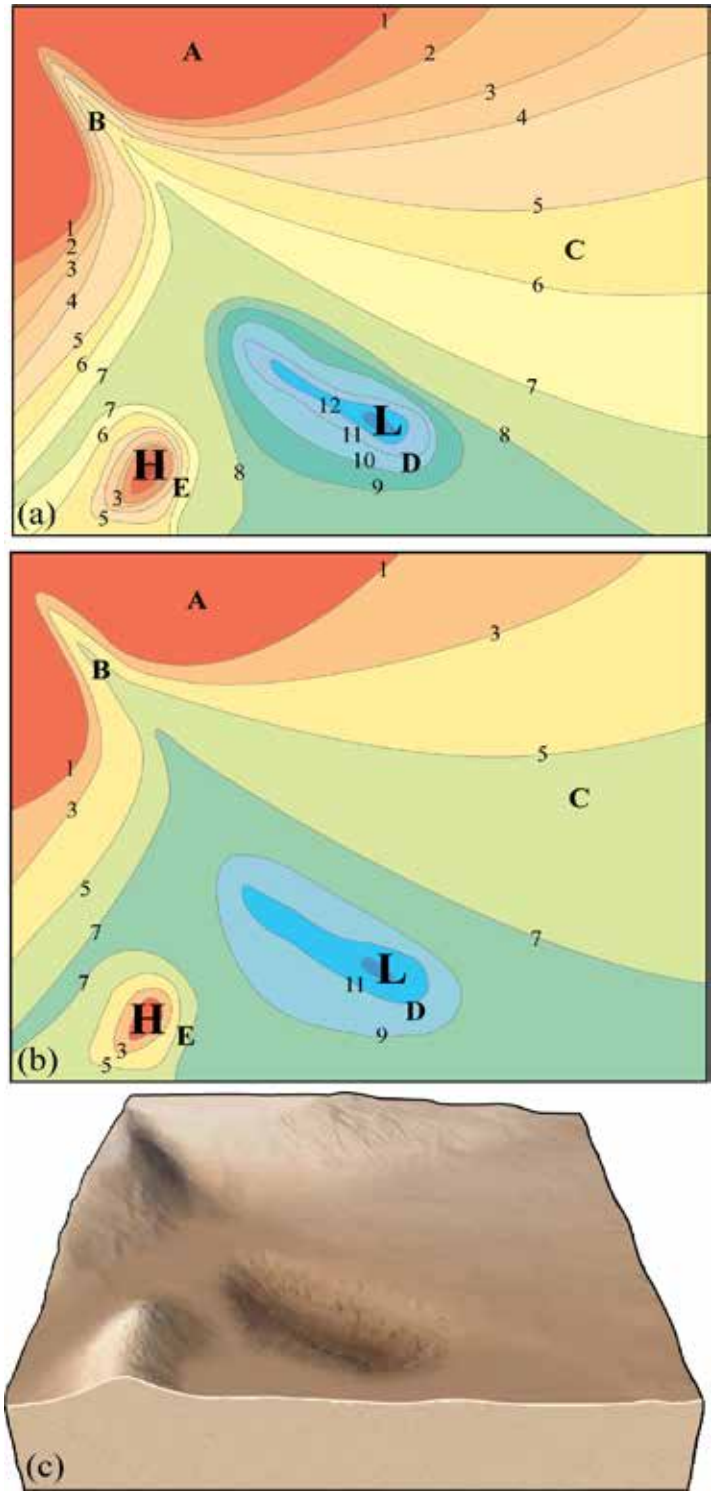


FIGURE 1-7 Contour plots. These plots reveal areas of higher and lower values of the plotted parameter, identified as H and L. They also indicate the strength of the gradient, which is stronger where adjacent contours are closer to each other. (a) In this example, which is a topographic map of the seafloor, there is a flat plateau at point A, a steep-sided valley at point B, an area of gentle slope at point C, a depression at point D, and a hill or mountain at point E, which has a very steep slope, especially on its right side. (b) Here, the same data are plotted with a greater interval between contours. Unless you examine it carefully, this plot can give the appearance that gradients are not as steep as they appear in part (a). (c) A three-dimensional representation of the topography plotted in parts (a) and (b).

One very important rule of contouring is that contours cannot cross or merge with each other. This is because each contour line always follows its own value. If the plotted parameter is elevated or depressed (forming hills or depressions) in two or more areas, contours around any two such features do not connect with each other. Instead, they form closed loops unless they are at the edge of the plot (**Fig. 1-7**). Contour lines show the distribution and magnitude of highs and lows of the plotted parameter. In any particular contour plot, high and low features (hills and valleys in a topographic map) that have more contours surrounding them are of greater magnitude than those with fewer surrounding contours. For example, higher hills are shown with more contour lines between sea level and the summit than lower hills. Contours also reveal the strength of gradients at different points on the plotted surface. Where the contours are closely bunched together, the value of the parameter changes quickly with distance across the surface, and the gradient is relatively strong (steep terrain on a topographic map). Conversely, where the contours are further apart, the gradient is relatively weak. The term relatively is important because the number of contours and the intervals between the contours can be different in different plots; even plots of the same data, which can be seen by comparing **Figure 1-7a** and **Figure 1-7b**.

When you study contour maps, make sure you look at the values on each of the contour lines to determine the value assigned to each contour. This will enable you to see which features are highs and lows and to assess the relative magnitude of gradients at different points on the plot accurately. Many contour plots are now produced by computers, and in some of these, contour lines are not used. Instead, the entire plot is filled with color that varies according to the value of the parameter plotted. Usually, the order of colors in the spectrum of visible light is used. Red represents the highest value, grading progressively through orange, yellow, green, and blue to violet, which represents the lowest value (**Fig. 1-7**). These plots are essentially contour plots that have an infinitely large number of contour lines and in which the range of values between each pair of adjacent contours is represented by a slightly different shade of color. **Figure 3-3**, **Figure 7-12**, and **Figure 8-24** are additional examples of this convention. This color convention, from red to violet, is now universally accepted and makes it easy to visually identify the areas of high and low values. Consequently, with a few exceptions made for specific reasons, we have used this convention to color-code the regions between contours in all of the contour plots in this text.

Cross-sectional profiles show the distributions of properties

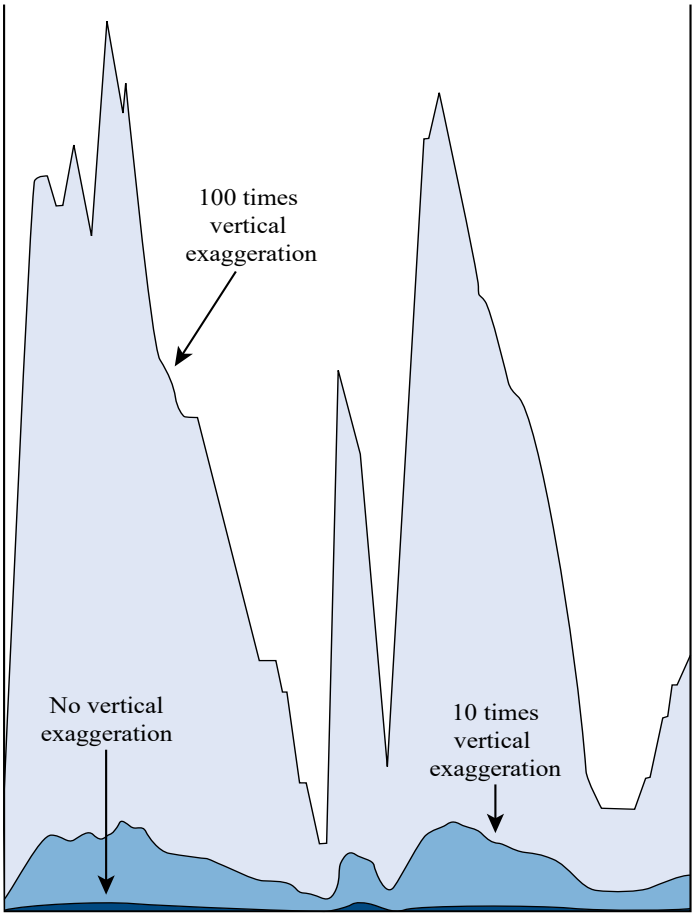


FIGURE 1-8 Cross-sectional vertical profiles used to depict ocean or atmospheric data are almost always vertically exaggerated. The effect of vertical exaggeration is shown in this figure. If the dark blue area below the lowest line in this graph were a plot of seafloor depth or land surface elevation, we would conclude that the topography was relatively flat. However, when vertically exaggerated 10 times (the mid blue plot area), it appears to be much more rough. When exaggerated 100 times (the light blue plot area), the topography looks like extremely rugged mountain chains with very steep slopes. Cross-sectional profiles in this book are plotted with vertical exaggerations greater than 100 times. This distortion cannot be avoided and must be considered when interpreting the data these cross sections depict.

on slices (cross sections) through, for example, the Earth or an ocean. Oceanographers commonly use cross-sectional profiles with contour plots to show the distribution of properties with depth and distance across the vertical slice. Because the oceans and the Earth's crust are extremely thin in comparison with the widths of the oceans and continents, these profiles almost always have a large vertical exaggeration. For example, the maximum depth of the oceans is approximately 11 km, whereas their widths are several thousand kilometers. If we were to draw a vertical profile across an ocean with no vertical exaggeration on a page in this book and use an ocean depth of 11 km scaled to a height of 11 cm on the vertical axis, then the profile would have a width of 1000 cm (more than 50 page widths) for each 1000 km of ocean width plotted. Because this is obviously not possible, the scale on which distance across the ocean is plotted is reduced. This decreases the width of the plot but also introduces vertical exaggeration, which distorts the data.

Figure 1-8 shows the effects of 10 and 100 times vertical exaggerations of a topographic profile. Most profiles used in ocean sciences have exaggerations greater than 100 times. Vertically exaggerated profiles make the gradients of topographic features appear much greater than they really are. Two points are important to remember as you examine vertically exaggerated profiles in this textbook. First, the seafloor topography is much smoother, and the slopes are much shallower than depicted in the profiles. Second, ocean water masses are arranged in a series of layers that are very thin in comparison with their geographic extent, and this is not adequately conveyed by the vertically exaggerated cross-sectional profiles.

Maps and Charts

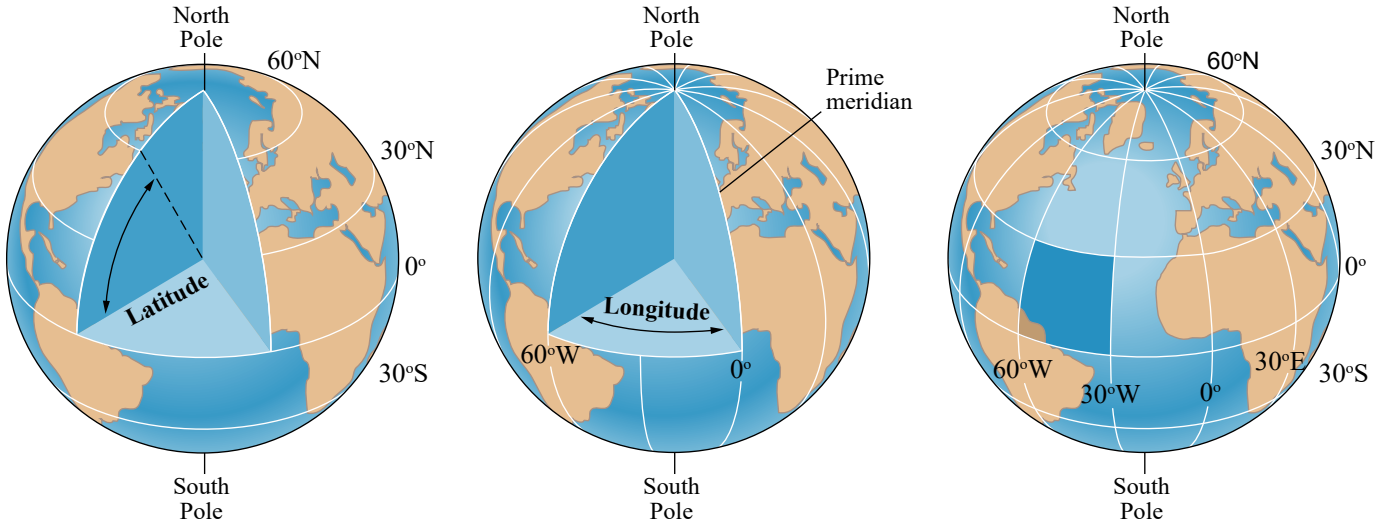
The Earth is spherical, and the ideal way to represent its geographic features would be to depict them on the surface of a globe. Although virtual-reality computer displays make such representation possible, it is impractical for most purposes. Consequently, geographic features of the Earth's surface are almost always represented on two-dimensional maps or charts. To represent the spherical surface of the Earth on a two-dimensional map, a projection must be used. A projection is a set of rules for drawing maps of Earth's features on a 2-dimensional screen or a piece of paper. All projections distort geographic information, each in a different way. The projection that most people are familiar with is the Mercator projection, which was designed to be used for navigation. However, several different projections are used in this textbook, and you may see other projections elsewhere.

To draw accurate maps of the Earth, we must relate each location on the Earth's surface to a particular location on the flat map's surface. Therefore, we must be able to identify each point on the Earth's surface by its own unique "address." **Latitude** and **longitude** are used for this purpose.

In a city, the starting "address" is usually a specific point downtown, and the street numbers and house numbers on each street increase with distance from that point. On the Earth's surface, there is no center from which to start. However, two points, the North and South Poles, are fixed (or almost so), and the equator can be easily defined as the circle around the Earth equidistant from the two poles. This is the basis for latitude. The equator is at latitude 0°, the North Pole is 90°N, and the South Pole is 90°S. Every location on the Earth, other than at the poles or on the equator, has a latitude between either 0° and 90°N or 0° and 90°S. Why do we use degrees (°)? **Figure 1-9a** shows that if we draw a circle around the Earth parallel to the equator, the angle between a line from any point on this circle to the Earth's center (dashed line) and a line from the Earth's center to the equator is always the same. If the circle is at the equator, this angle is 0°; if it is at the pole, the circle becomes a point, and this angle is 90°. If the circle is not at the equator or one of the poles, this angle is between 0° and 90° and is either south or north of the equator.

Latitude can be measured without modern instruments. Polaris, the Pole Star or North Star, is located exactly over the North Pole, so at 90°N, it is directly overhead. At lower latitudes, Polaris appears lower in the sky until, at the equator, it is on the horizon (at an angle of 90° to a vertical line). In the Northern Hemisphere, we can determine latitude by measuring the angle of the Pole Star to the horizon. In the Southern Hemisphere, no star is directly overhead at the South Pole, but other nearby stars can be used and a correction made to determine latitude. Star angles can be measured accurately with very simple equipment, and the best ancient navigators were able to measure these angles with reasonable accuracy without instruments.

Latitude is a partial address of a location on the Earth. It specifies only the hemisphere, northern or southern, in which the



(a) Latitude **(b)** Longitude **(c)** Latitude and longitude

FIGURE 1-9. Latitude and longitude are measured as angles between lines drawn from the center of the Earth to the surface. (a) Latitude is measured as the angle between a line from the Earth's center to the equator and a line from the Earth's center to the measurement point. (b) Longitude is measured as the angle between a line from the Earth's center to the measurement point and a line from the Earth's center to the prime (or Greenwich) meridian, which is a line drawn from the North Pole to the South Pole passing through Greenwich, England. (c) Lines of latitude are always the same distance apart, whereas the distance between two lines of longitude varies with latitude.

location lies and that the location is somewhere on a circle (line of latitude) drawn around the Earth at a specific distance from the pole (equivalent to "somewhere on 32nd Street"). The other part of the address is the longitude. **Figure 1-9b** shows that the relative locations of two points on a line of latitude can be defined by measurement of the angle between lines drawn from the Earth's center to each of the locations. This angle is longitude, but it has no obvious starting location. Consequently, a somewhat arbitrarily chosen starting location, the line of longitude (north-south line running between the North and South Poles) through Greenwich, England, has been agreed upon as 0° longitude and is known as the "prime meridian."

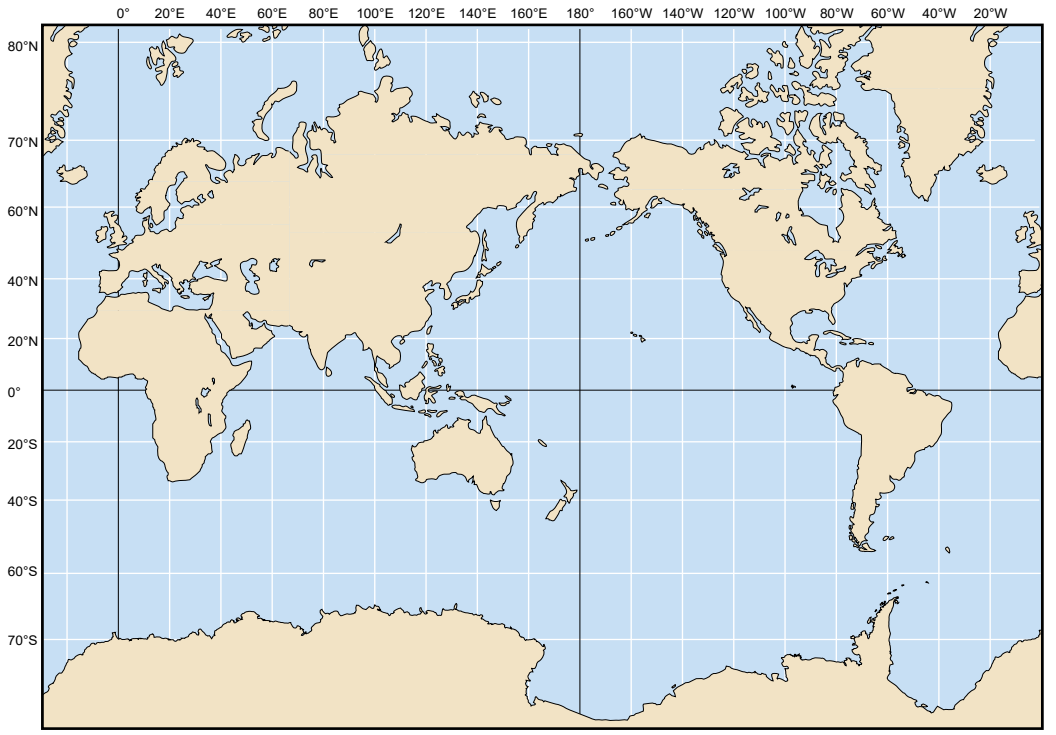
Longitude is measured in degrees east or west of the prime meridian (**Fig. 1-9b**). Locations on the side of the Earth exactly opposite the prime meridian can be designated as either 180°E or 180°W. All other locations are between 0° and 180°E or between 0° and 180°W. Longitude is not as easy to measure as latitude because there is no fixed reference starting point, and no star remains overhead at any longitude as the Earth spins. The only way to measure longitude is to accurately fix the time difference between noon, when the sun is directly overhead, at the measurement location and noon at Greenwich. The Earth rotates through 360° in 24 hours, so a 1-hour time difference indicates a 15° difference in longitude. To determine longitude, the exact time (not just the time relative to the sun) must be known both at Greenwich and at the measurement location. Before radio was invented, the only way to determine the time difference was to set the time on an accurate clock at Greenwich and then carry this clock to the measurement location. Consequently, longitude could not be measured accurately until the invention of the **chronometer** in the 1760s.

Latitude and longitude lines provide a grid system that specifies any location on the Earth with its own address and enables us to draw maps. Before we look at these maps, notice that 1° of latitude is always the same length (distance) wherever we are on the Earth, but the distance between lines of longitude is at a maximum at the equator and decreases to zero at the poles (**Fig. 1-9c**).

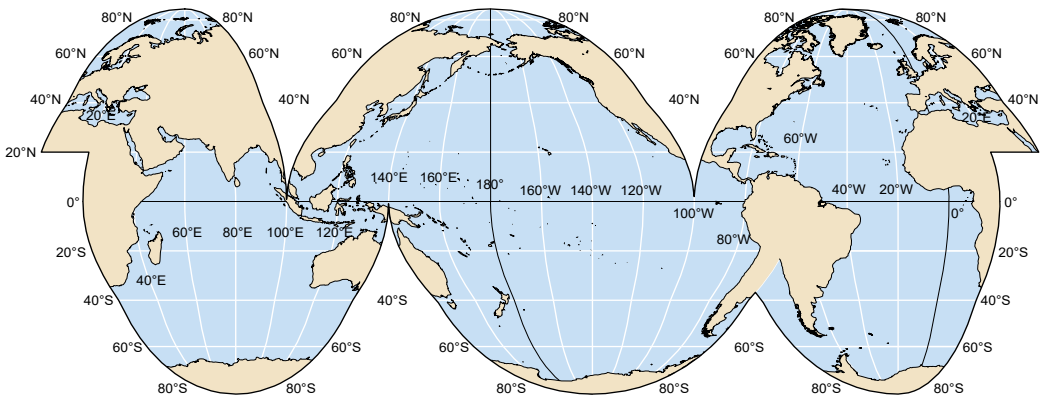
Figure 1-10a is a familiar map of the world. This representation of the Earth's features is a Mercator projection, which is used for most maps. In the Mercator projection, the lines of latitude and longitude are drawn as a rectangular grid. This grid distorts relative distances and areas on the Earth's surface. The reason is that, on the Earth, the distance between two lines of longitude varies with latitude as shown in **Figure 1-10c**, but the Mercator projection shows this distance as the same at all latitudes. Furthermore, the Mercator projection shows the distance between lines of latitude to be greater at high latitudes than near the equator, even though on the Earth's surface, they are the same.

Why, then, has the Mercator projection been used for so long? The answer is that it preserves one characteristic that is important to travelers: on this projection, the angle between any two points and a north-south line can be used as a constant compass heading to travel between the points. However, the constant-compass-heading path is not the shortest distance between the two points. The shortest distance is a great-circle route. A great circle is any circle around the full circumference of the Earth. For navigation, this great circle passes through both the starting and end point of the journey. The Mercator projection suggests that the "direct" route between San Francisco and Tokyo is almost directly east to west. However, the normal flight path for this route is almost a great-circle route that passes very close to Alaska and the Aleutian Islands. You can see the great-circle route and why it is the shortest distance by stretching a piece of string between these two cities on a globe. Over short distances, the compass-direction route and the great-circle route are not substantially different in terms of distance, and the simplicity of using a single, unchanging compass heading makes navigation easy. Ships and planes now use computers to navigate over great-circle routes that require them to fly or sail on a continuously changing compass heading.

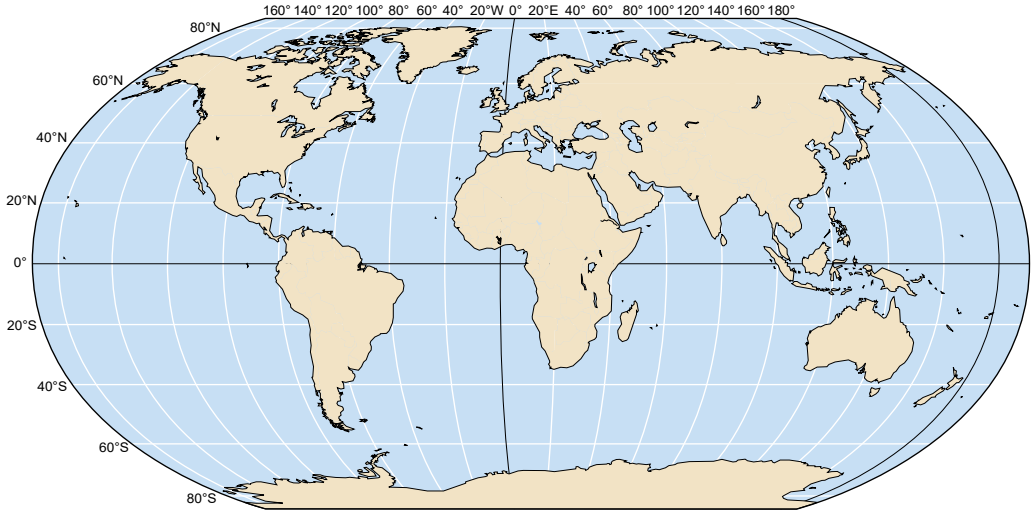
Although the Mercator projection is very widely used, other projections preserve different characteristics of the real spherical world. The following four characteristics are desirable to preserve in a map projection:



(a) Mercator projection



(b) Goode's Interrupted projection



(c) Robinson projection

FIGURE 1-10 Typical map projections. (a) Mercator projection. Higher latitudes near 90°N and 90°S are not shown because the shape and area distortions introduced by this projection increase rapidly with latitude near the poles. (b) Goode's interrupted projection preserves relative areas and shows each of the oceans without interruption. However, it distorts the shapes of the continents. (c) Robinson projection. This projection preserves none of the four desirable characteristics perfectly, but it is a good approximation for many purposes.

TABLE 1.1 Characteristics of Selected Map Projections

Projection	Preserves Relative Distances	Preserves Directions	Preserves Relative Areas	Preserves Shape	Areas Most Distorted	Common Uses
Mercator	Poor	Excellent	Poor	Fair	Mid to high latitudes	Navigation charts, world maps, maps of limited areas
Miller's cylindrical	Good	Good	Excellent	Poor	High latitudes	World maps
Robinson	Good	Fair	Good	Fair	High latitudes, 4 "corners"	World maps
Mollweide	Good	Fair	Good	Poor	High latitudes, 4 "corners"	World maps
Goode's interrupted	Good	Poor	Very good	Poor in most areas	Relative positions of continents	World maps, global oceans
Conic	Good	Excellent	Very good	Excellent	Distortion equally distributed	Maps of the U.S., individual continents
Polar azimuthal	Fair	Excellent	Good/poor	Good	Outer edges	Maps of polar regions

- Relative distances. Measured distance between any two points on the map can be calculated by multiplying by a single scale factor. Most projections do not preserve this characteristic.
- Direction. Compass directions derived from the straight lines between points on the map could be used for navigation. The Mercator projection preserves this characteristic.
- Area. Two areas of the same size on the Earth would be equal in area on the map. The Mercator projection is one of many projections that do not preserve this characteristic.
- Shape. The general shape of the oceans and land masses on a map would be similar to the shapes of these features on the globe. Most projections do not preserve this characteristic.

Because no projection (only a globe) preserves all four of these characteristics, different projections are used for different purposes. In this textbook, for example, Goode's interrupted projection (**Fig. 1-10b**) is used often because it preserves relative areas correctly and shows each of the three major oceans uninterrupted by the edge of the map. Other projections, such as the Robinson projection (**Fig. 1-10c**), are also used in this textbook. The projection used for each map is identified in each figure. **Table 1-1** lists the relative ability of each of these projections to satisfy the four desirable map characteristics described here.

Always consider the characteristics of a projection when you examine a map. For example, compare the sizes of Greenland and South America in **Figure 1-10a** and **Figure 1-10b**. The Mercator projection exaggerates the relative size of Greenland, which Goode's interrupted projection preserves. Generations have grown up thinking that Greenland is much bigger than it is, thanks to the Mercator projection.

Scientific Notation and Units

Some of the numbers mentioned in this chapter are extremely large. For example, the history of the Earth presented in **Figure 1-4** spans nearly 5 billion (5,000,000,000) years. On that figure, the abbreviation MYA was used to represent millions of years ago. In ocean sciences, such large numbers are common, as are very small numbers. For example, the concentration of lead in seawater is about 0.000,000,000,5 gram per kilogram of water. In order to avoid using long strings of zeros, scientists use a type of shorthand for numbers like these. For example, the age of the universe is $1.4 \cdot 10^{10}$ years, and the concentration of lead in seawater is $5 \cdot 10^{-10}$ grams per kilogram.

These numbers might look odd, but they are really quite simple. The numbers are written using powers of 10. The • symbol can be stated as "times" or "multiplied by" and is always followed by 10, so together they make "times ten" or "multiplied by ten". The superscript number that always follows the 10, represents the number of orders of magnitude (factors of 10) by which the digit before the •10 must be multiplied. Thus, $5 \cdot 10^9$ is 5 multiplied by ten, nine times ($5 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$) which is usually shortened to 5 times ten to the 9th. A quicker way to use this notation is to take the number before the •10 and add nine zeros. The number is said to be raised by 9 orders of magnitude (powers of 10). Similarly, $5 \cdot 10^{-10}$ is 5 times ten to the power of negative 10 (the number is multiplied by 0.000,000,000,1, which gives 0.000,000,000,5. Notice that the negative sign in the superscript part of the scientific notation denotes the number of powers of 10 by which the number is reduced. When a number has more than one nonzero digit, such as 5,230,000,000, the scientific notation becomes $5.23 \cdot 10^9$. The scientific notation places one nonzero digit to the left of the decimal so, in this example (5.23) the simple way to use the notation is to move the decimal point 9 times, adding zeros only after the decimal point has passed the numbers to the right of the decimal point in the scientific notation (23 in our example). Notice that this shorthand system makes it easy to compare two very large or two very small numbers. In our example, it is easy to see that $5 \cdot 10^9$ and $5.23 \cdot 10^9$ are not very different without having to count all the zeros. Similarly $5 \cdot 10^9$ is clearly much larger than $5.23 \cdot 10^7$. This text makes extensive use of scientific notation. Appendix 1 provides a simple conversion table if you need it.

Like other scientists, oceanographers use a variety of scientific units to identify such parameters as length, speed, and time. To avoid problems with unit conversions, such as miles to kilometers, and to make the comparison of data easier, scientists have developed an International System of Units (SI) that is steadily progressing toward being used universally, although some other units are still widely used. There are only seven SI base units:

- Length: meter, symbol m
- Mass: kilogram, symbol kg
- Time: second, symbol s
- Electric current: ampere, symbol A
- Thermodynamic temperature: kelvin, symbol K
- Amount of a substance: mole, symbol mol
- Luminous intensity: candela, symbol cd

All other units are "derived" units. For example, volume is measured in cubic meters (m^3), and speed is measured in meters per second (m/s or $m \cdot s^{-1}$). SI units are used in much of this text. However, as is still common in science, they are not used exclusively because some of them remain unfamiliar even to many members of the scientific community. Appendix 1 includes more information about SI units and a table of all scientific unit abbreviations used in this text.

In this text, we use simple SI units to express concentrations of chemicals dissolved in water, for example, grams per kilogram ($g \cdot kg^{-1}$) or milligrams per kilogram ($mg \cdot kg^{-1}$). However, you may see on the web or in other publications concentrations expressed in **molality** or **molarity**. Molality is simply the concentration of the dissolved substance in grams of dissolved substance per kilogram ($g \cdot kg^{-1}$) divided by the molecular weight of the dissolved substance. Molarity is calculated in the same way but uses the concentration of dissolved substance per liter and is expressed in grams of dissolved substances per liter ($g \cdot l^{-1}$). Dividing the mass of a substance by its molecular weight gives you the amount of substance in "moles," a unit that is related to the number of molecules of the substance present. So 1 mole of a substance has exactly the same number of molecules as 1 mole of any other substance. Chemists use molality or molarity because it can simplify some calculations.

For example, seawater contains about 19.8 $g \cdot kg^{-1}$ of chlorine, present as the chloride ion (Cl^-)ion, and about 10.78 $g \cdot kg^{-1}$ of sodium as the sodium ion (Na^+). This looks like it is a lot more chloride ion than sodium ion but, if we convert these to molality (by dividing each number by the molecular weight of the ion, which is about 35 for the chloride ion and 23 for the sodium ion, we find that chloride concentration in seawater is 0.55 molal and sodium is 0.47 molal, much closer. In fact, if seawater contained only dissolved sodium chloride, these molarity numbers would be the same, so we know that 0.08 moles (0.55 molal minus 0.47 molal) of other positive ions, such as potassium (K^+) and calcium (Ca^{2+}), must be present in seawater. In this example, molality (or molarity) is an expression of the number of atoms of sodium or chlorine. If we wanted to make sodium chloride from chlorine and sodium, we would need to add 1 mole of each to get 1 mole of sodium chloride, which is simpler to calculate than adding 35.5 g of chlorine and 22.99 g of sodium as we would have to do otherwise. With more complex molecules than sodium chloride, this simplification becomes even more valuable.

CHAPTER SUMMARY

Introduction.

The oceans influence our daily lives in many different ways. Understanding how they affect us requires an interdisciplinary approach that includes knowledge of the geology, physics, chemistry, and biology of the oceans and how these aspects interact.

Most of the world's population lives near the oceans or a river that connects to the oceans. The oceans provide many resources, especially food and transportation corridors, but they are also susceptible to pollution, habitat damage, and other impacts of human activities. Recreational uses of the oceans and awareness of the unique nature of marine ecosystems and species have grown explosively in the past several decades.

The Oceans and Earth's Environment

Humans have altered Earth's environment in a number of ways. The most important of these has almost certainly been the use of fossil fuels that has raised the atmospheric concentration of carbon dioxide from about 280 ppm prior to the industrial revolution (ca. 1750) to nearly 430 ppm in 2025. The rate at which this concentration has risen has accelerated and is now about 2.6 ppm per year. The rise in atmospheric carbon dioxide, climate change, ocean acidification, and ocean deoxygenation, which together are the most serious long-term threats to Earth's environment resulting from human activities. Each of these threatens to disrupt global ecosystems, and, when combined, they pose the risk of a mass extinction of species. Climate change also threatens to adversely impact humans directly in a number of ways, including increasing the severity and probably the rate of occurrence of extreme weather events, rising sea level, and increased coastal erosion. Climate is controlled by the atmosphere and oceans working together in complex ways, which will be explored in this text. Understanding these complex interactions is the key to understanding the oceans and the future of climate change, acidification, and deoxygenation.

Oceans and the Origins of Life.

Many organic compounds probably were formed in the early oceans, but it is not known how these simple compounds were combined into more complex molecules that formed the basis for the creation of the first life form. However, it is thought that early life was found predominantly in the oceans. The first life for which we have evidence was bacteria-like, existed about 4.2 billion years ago, and must have been chemosynthetic, as there was no oxygen in the early atmosphere. Eventually, microorganisms developed that used photosynthesis, which splits water into hydrogen (which is utilized by the organism in its metabolism) and oxygen (which is released). Between about 1 and 2 billion years ago, photosynthetic organisms added oxygen to the atmosphere until it reached its current concentration of about 20%. Chemosynthetic organisms either died out or were restricted to limited oxygen-free environments, and species developed that depended on respiration using oxygen from their environment. Today, all species of animals and most other species respire and need oxygen in their environment. The first primitive higher animals, invertebrates such as sponges, appeared about 700 million years ago. Fishes developed about 510 million years ago. The first land plants and mammals developed about 500 and 200 million years ago, respectively.

How to Study Ocean Data.

Maps and charts are used extensively to display ocean science

data. Each graph, map, or chart may represent data in a different way using different distortions of the real world. Graphs may have axes that do not start at zero or are nonlinear. The choice of axis can substantially change how the same set of data is perceived at first glance.

Contour plots are used extensively to represent the distribution of properties on a two-dimensional surface, such as the Earth's surface. If the intervals between contours on the contour plot are all the same, the relative distance between two contours is a measure of the gradient of the plotted property. However, on some maps, the contour interval changes from one area of the plot to another (usually to avoid crowding of contours), so the values of each contour must be examined to interpret gradients on the plot properly. Most contour plots in this text are color-shaded between the contours. Red always represents the highest value of the parameter plotted, grading through the spectrum to blue as the lowest value.

Maps and charts are used to represent horizontal distributions. Profiles are vertical cross sections through the Earth or the oceans and generally display contours to show the vertical distribution of properties. Most profile plots in this text are greatly vertically exaggerated. This exaggeration is necessary because the depth of the oceans, and the thickness of the Earth's crust, are extremely small compared to the width of the oceans or land masses.

The Earth is spherical, and a system of latitude and longitude has been developed to identify specific locations on this sphere. Latitude is referenced to the equator, a circle around the Earth halfway between the poles, which is designated as 0° latitude. Other latitudes are expressed by the angle between a line from the Earth's center to the location in question and a line from the Earth's center to the equator. There are 90° of latitude; the North Pole is at 90°N and the South Pole at 90°S. Longitude is referenced to the prime meridian, a line designated as 0° that is drawn through the North and South Poles and that passes through Greenwich, England. Locations on the continuation of that same circle connecting the poles on the side of the Earth away from Greenwich are designated as both longitude 180°W and 180°E. Other longitudes lie between 0° and either 180°W or 180°E, and they are determined by the angle and direction between a line drawn between the Earth's center and the prime meridian and a line between the Earth's center and the specific location. One degree of latitude is the same distance regardless of its location on Earth. The distance represented by 1° of longitude varies from a maximum at the equator to zero at the poles.

Maps and charts must represent the spherical surface of the Earth or oceans in only two dimensions. No two-dimensional projection can correctly maintain relative distances, compass directions, relative areas, and the proper shape of features on a sphere. Therefore, all maps and charts distort one or more of these characteristics. The Mercator projection, which is the most widely used projection in atlases, depicts the distance between degrees of longitude as the same regardless of latitude. Thus, this projection preserves the relative directions between locations, but it distorts all three of the other relationships. The distortion is not important in regional maps of low latitudes, but it becomes greater at high latitudes and for global maps. Ocean scientists and this text use a variety of other projections for specific purposes. For example, Goode's interrupted projection is often used because it generally preserves relative areas and distances, and it can be drawn to represent all the major oceans without having to split them at the edge of the map.

To represent very large or very small numbers, scientists use scientific notation based on powers of 10. A standard system of scientific units (SI) is now in place and is becoming more widely used, but it is not yet universal. Both scientific notation and SI units are used extensively in this text.

KEY TERMS

You should recognize and understand the meaning of all terms that are in boldface type in the text. All those terms are defined in the Glossary. The following are some less familiar key scientific terms that are used in this chapter and that are essential to know and be able to use in classroom discussions or exam answers.

acidification
bathymetric
chronometer
chemosynthetic
contour
crust
deoxygenation
detritus
fossil
greenhouse effect
invertebrates
isobar
isopycnal
isotherm
longitude
latitude
photosynthetic
pycnocline
respiration
steady state
stratification
topographic

STUDY QUESTIONS

1. What causes the greenhouse effect?
2. Why weren't the first living organisms capable of photosynthesis?
3. What are the essential things to look at the first time you study a graph?
4. What information can we get from studying a contour plot?
5. What is vertical exaggeration in a profile?
6. Are lines of longitude parallel to each other?
7. What are the four characteristics we would like a map projection to preserve?
8. On a Mercator projection map of the world, which countries or areas appear larger than they really are compared to other areas on the map?

CRITICAL THINKING QUESTIONS

1. We are concerned that the Earth's climate may change because of the increase in atmospheric carbon dioxide concentration that has resulted from human activities over the past century or more. It has been suggested that, since trees absorb carbon dioxide and release oxygen, we can solve the problem by replanting forests and planting many more trees in our urban areas. If we were to plant trees wherever they would grow on the entire planet, would this be enough to reverse the trend of increasing carbon dioxide concentration in the atmosphere? Explain the reasons for your answer. If you are not able to answer this question, what information would you need to do so?
2. A number of developing nations, especially those in Africa and South America, have suggested that world maps used in all textbooks and atlases should use a projection other than the Mercator projection. What do you think is their reason for this suggestion?

CRITICAL CONCEPTS REMINDERS

CC5 Transfer and Storage of Heat by Water: The heat proper-

ties of water are a critical element in maintaining a climate on Earth that is suitable for life as we know it.

CC9 The Global Greenhouse Effect: Perhaps the greatest environmental challenge faced by humans is the prospect that major climate change may be an inevitable result of our burning of fossil fuels. The burning of fossil fuels releases carbon dioxide and other gases into the atmosphere, where they accumulate and act like the glass of a greenhouse retaining more of the sun's heat.

CC10 Modeling: Complex environmental systems, including the oceans and atmosphere, can best be studied by using conceptual and mathematical models.

CC11 Chaos: The nonlinear nature of many environmental interactions makes complex environmental systems behave in sometimes unpredictable ways. It also makes it possible for these changes to occur in rapid, unpredictable jumps from one set of conditions to a completely different set of conditions.

CC14 Phototrophy, Light, and Nutrients: Chemosynthesis and phototrophy (which included photosynthesis) are the processes by which simple chemical compounds are made into the organic compounds of living organisms. The oxygen in Earth's atmosphere is present entirely as a result of photosynthesis.

REFERENCES

Figure 1-1 – NASA Ocean Color, 2025: Level 3 & 4 browser. Accessed 21 May 2025, https://oceandata.sci.gsfc.nasa.gov/l3/.

Figure 1-2 – Data from NOAA Global Monitoring Laboratory, 2025: Trends in CO_2, CH_4, N_2O, SF_6. Accessed 21 May 2025, https://gml.noaa.gov/ccgg/trends/data.html.