Chapter 1
Earth's Climate as a Dynamic System

ESSENTIAL QUESTIONS

- What is a system?
- How is climate defined?
- Why is climate a unique and complex system?
- What comprises the climate system?
- How are humans affecting climate?
- How are humans affected by changes in this system?
- What are identifiable characteristics in each of the sub-systems of climate?
- Why is climate change such a substantial challenge for humanity?

Introduction

The starting point in the study of Earth's climate system is conceptualizing what is an almost ideal scientific investigation. The remarkable image in Figure 1.1, generated from a composite collection of National Aeronautics and Space Administration's (NASA) space probe perspectives, shows Earth as a giant ball surrounded by the immensity of space. Evident is the planet's essential receipt of radiant energy from the distant Sun, some of which is reflected spaceward. Seen in the sunlit portion of Earth are ocean, land and ice blanketed with a thin atmosphere abundant with clouds.

Less detailed photographs from early space probes of the 1970s dramatically changed our perception of Earth when we thought of Earth as immensely large and globally immune to the effects of human habitation. We now see Earth, in particular Earth's climate system, as finite and fragile. Earth's **climate** is defined as the state of a complex *system* consisting of five major components, the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions amongst them. A **system** is an arbitrary portion of the universe with fixed or moveable boundaries or walls, which may contain matter, energy or both. Earth's climate system evolves over time under the influence of its own internal dynamics and because of forcings such as volcanic eruptions, solar variations and our own actions as we change the composition of the atmosphere and clear the land for agriculture, urbanization and industrialization.

Figure 1.1 shows visible light reflected back to space, but not the infrared (heat) radiation emitted day and night by Earth in all directions. When the rates of radiant energy to and from Earth balance globally, then the global climate system is generally stable. When the planetary rates of incoming and outgoing radiation are unbalanced, the system shifts according to the net gain or loss of energy. Evidence is unequivocal that Earth is not currently in *global radiative equilibrium* (Chapter 4) because its climate system is gaining energy, and so climate change is taking place.

Figure 1.1
NASA's Blue Marble. When created in 2002, it was the most detailed true-color image of the Earth's surface ever produced. For further information on how this image was generated by NASA scientists, visit: http://earthobservatory.nasa.gov/Features/BlueMarble [NASA]

Climate is important because it is really about us. Earth's climate system establishes the environmental conditions and sets the boundaries of weather. Climate is dynamic. We know it changed in the past, we have proof that it is currently changing, and we expect it to change in the future. Changes occur on different scales and vary in both magnitude and direction. Superimposed on the natural cycles of climate change are those caused by human actions. As part of a complex, coupled human/natural system, we individually and collectively contribute to the changing climate on all scales, locally to globally, which often results in negative consequences on natural ecosystems and human society. These consequences are expected to grow in number and intensity, and, unfortunately, some are already committed to by our past and current actions.

We have choices. We can fatalistically accept climate change and do nothing about it or, based on scientific understandings of Earth's climate system, we can reduce, and even prevent, negative impacts through mitigation and adaptation. Although incomplete, our understandings of the climate system and the far-reaching risks associated with climate change require immediate identification and strategies for sustainable development and long-term stewardship of Earth.

Climate and Society

The Importance of Climate Studies for Human Endeavors

Climate is inherently variable, but is currently changing at rates unprecedented in recent Earth history. The warming of Earth's climate system is unmistakable and is caused in large part by our relentless burning of fossil fuels and alteration of Earth's surface. These activities now drive global climate change, linking human actions to our planet's biophysical systems, meaning climate change is the changing state of a complex, coupled human/natural system. Our ability for critical thinking and utilizing scientific studies makes us aware of our impact on climate. With this understanding come choices and actions, including mitigation and adaptation.

Mitigation refers to our actions that reduce sources of gases, which contribute to the warming of the climate system, or enhance the mechanisms that remove them from the atmosphere. Some of these gases are described in this chapter, but those that contribute to warming the climate system are collectively known as **greenhouse gases**. According to the Intergovernmental Panel on Climate Change (IPCC) (AR4-Working Group 2, discussed in Chapter 2), the preeminent worldwide organization composed primarily of climate scientists, **adaptation** is the adjustment in natural or human systems to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.[1]

Earth's climate system is synergistic, so that the many different local activities we all individually engage in connect to the larger scope of Earth's climate system. For example, our burning of fossil fuels contributes to the global-scale problem, the same as burning of fossil fuels in Australia affects us. Yet the consequences are unique to each locale. While one locale experiences drought another may endure flooding, both are effects of a changing global climate. This connection can be taken further, given how interdependent we have become in modern society, especially in an economic sense. Economies have greater dependencies among nations as evidenced by recent agreements among nations to trade food, energy and manufactured goods. The advent of the European Union and the North American Free Trade Agreement (NAFTA) are two examples of multi-nation collaboration and dependency. Should there be changing climatic conditions that endanger one or two nations, many other nations' economies are affected because of these interdependencies.

In his second term, President Obama introduced a new Climate Action Plan to the nation. His plan identifies three major goals: cutting carbon pollution in the United States, preparing the nation for the impacts of climate change, and leading international efforts to address climate change. This ambitious plan involves many parts of government, like the Environmental Protection Agency (EPA), and underscores that climate variability and change threaten human lives, property, businesses, ecosystems and governments, as well as imperiling future generations.

In evaluating the plan proposed by the President, we recognize that the climate system can be thought of as a natural resource, which can be managed and affected by our actions. For example, the Climate Action Plan calls for carbon pollution standards to be established by the EPA in working with industrial power plants. In other words, the waste products created by energy production, which are released into our atmosphere, negatively affect our climate system. The plan calls for alternative methods of energy production that

---

1 The Center for Climate and Energy Solutions (C2ES – http://c2es.org) has a slightly different definition of adaptation. C2ES states that adaptation isdefined as "actions by individuals or systems to avoid, withstand or take advantage of current and projected climate changes and impacts."

may not harm our shared natural resource.

Human Vulnerability to Climate

Climate is inherently variable. **Climate variability** can be defined as a change in the average state of the climate on all spatial and temporal scales separate from singular weather events. Precise differences between weather and climate are examined later in this chapter. Variability may be due to natural internal processes within the climate system or to variations in anthropogenic (caused by human) external forcing. In other words, climate variations occur with or without our actions. It is critical to assess precisely which human actions affect climate and those that do not. This delineation is a major theme throughout the book. To distinguish the language relating to climate, **climate change**[2] is a change in the state of the climate system, identified by changes in the average conditions and the variability of its properties, that persists for an extended period, typically decades or longer, due to natural and/or anthropogenic processes and forcings.

While our actions affect climate, the converse statement is also true—climate affects humanity. The degree to which physical, biological, and socio-economic systems are susceptible to, or are incapable of coping with, adverse impacts of a variation in climate is **climatic vulnerability**. To provide perspective on this vulnerability it's instructive to examine the past. Noted anthropologist, Brian Fagan, argues in many of his recent texts that humanity has a strong tie to climate and its variation, and that a quickly changing climate often catches societies off-guard. Using paleoclimatic evidence, he has documented the rise of modern civilizations at the conclusion of the last ice age and, more recently, the dramatic effect the "Little Ice Age" had on the peoples of Western Europe. In those instances, human strife and conflict precede entire societies breaking down. While Fagan doesn't cite climate as the prime cause of these societal endpoints, he notes that significant climate variations are a recurring stressor that contributes greatly to the undoing of many well-structured societies from all geographic regions of Earth.

In modern society we like to think that we're shielded from climate-induced societal degradation but recent storms across the U.S. caused humanitarian disasters—Hurricanes Katrina and Sandy. Neither storm could be prevented, nor totally mitigated, resulting in human casualties, ruin of property and disruption of ecosystems. Many parts of the government were unable to cope with these disasters, which are of tremendous economic cost to society. While neither of these storms can be directly attributed to climate change, nor has there been a significant increase in Atlantic hurricanes since the late 1880s, scientists have found that *sea-level rise* has led to more damage in coastal communities, as was the case with Sandy in New York and New Jersey (Figure 1.2). NOAA's Earth System Research Laboratory notes that this trend of rising sea levels will very likely continue in some places into the future.

---

2 The United Nations Framework Convention on Climate Change (UNFCCC) prefers a slightly different definition of climate change as that which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable time periods. UNFCCC ascribes climate change to <u>human actions</u> changing the atmospheric composition, and climate variability attributable to natural causes.

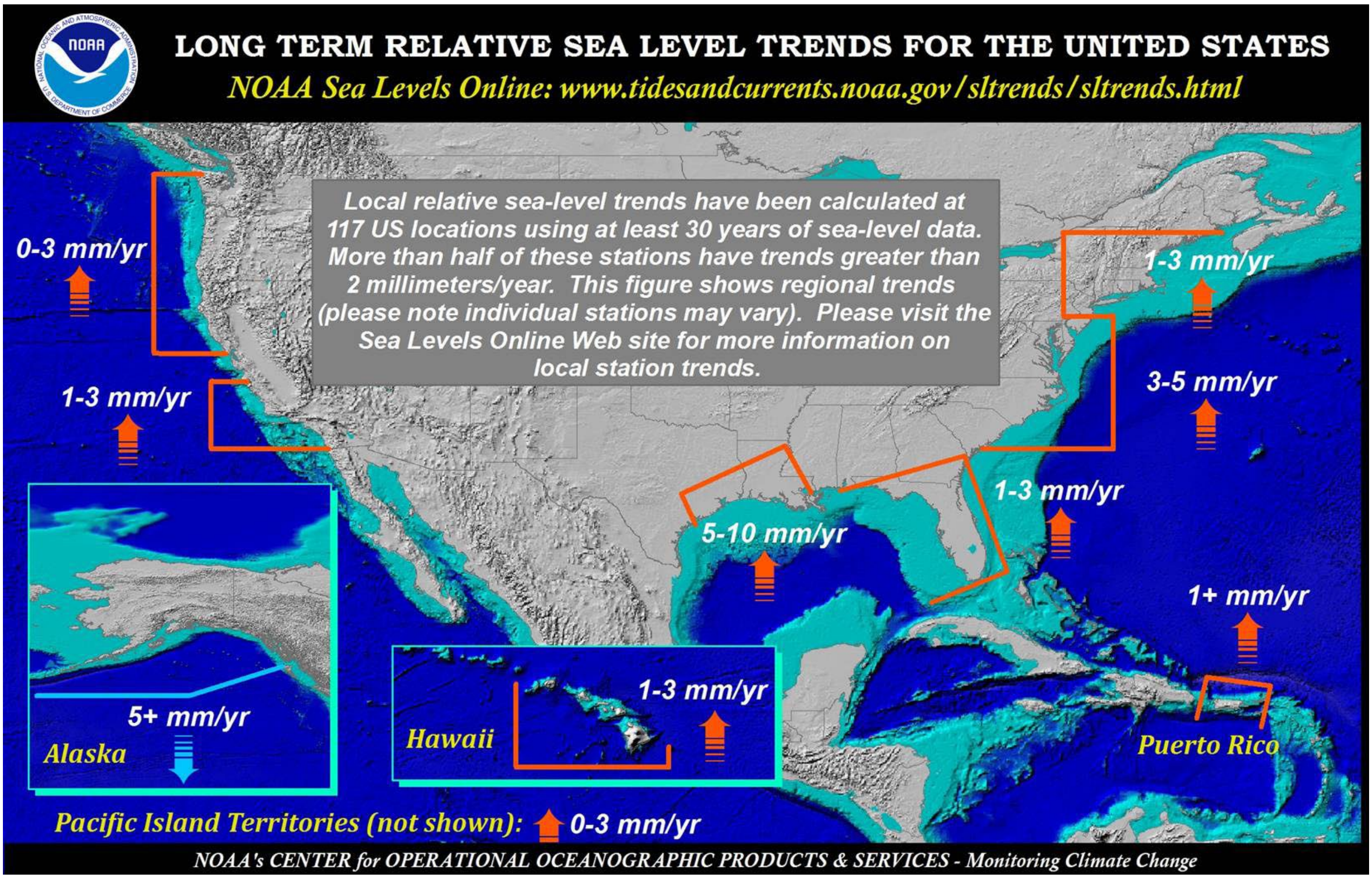
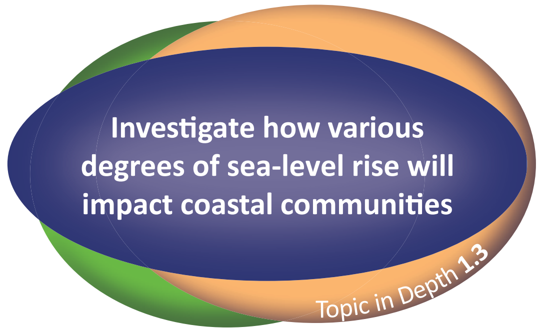


Figure 1.2.
Sea-level trends for regions of the U.S. [NOAA]

In fact, modern society is increasingly vulnerable to natural processes on Earth. Approximately half the world's population lives within 60 km (37.3 mi.) of the ocean and three-quarters of all large cities are located on the coast, which places over 3 billion people in harm's way to rising sea levels and threat of storm surge. Persons in cities have become dependent upon utilities like sewage treatment and electrical power grids. Imagine how your life would be disrupted by significant time "off the grid," without power for days or more, as were those persons affected by Katrina and Sandy.

Preparing for changes in climate is roughly analogous to fire insurance. While the possibility of a house fire is rather small, when one occurs, the results are devastating. You would have to rebuild much of your life. The aftermath isn't dissimilar to what many people experienced after Sandy and Katrina. While the possibilities of a Sandy-like storm recurring in the next few years, similar to a home fire, might be small, the results of such a hazard are overwhelming. A recent study from NOAA scientists found that sea-level rise has practically doubled the annual probability of a Sandy-level flood in the New York City region since 1950. The study also concluded that anthropogenic factors influence these extreme events. So, while there is no discernible trend in Atlantic tropical cyclone frequency, the fact that sea level has risen means coastal cities like New York have an increased risk from similar intensity storms.



Sea-level rise is not the only change taking place. The IPCC concluded in 2013 that, "it is likely that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. There are likely more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has likely increased in North America and Europe." The IPCC is described in greater detail in the next chapter.

Environmental changes related to climate present a serious threat to the security of nations, especially if their disaster-response capabilities become overwhelmed. Internationally, these changes contribute to political violence as societies compete for diminishing resources, especially fresh water. They may also hasten the demise of weak governments struggling to maintain control of an unstable populace. Destabilization abroad affects other nations, especially given how interconnected modern society has become. Many nations, including the U.S., strategize how they would respond to climate-induced problems. In 2007, the U.S. Council for Foreign Affairs drafted an agenda for action in preparation for a world changed by climate. Many of the recommendations were based on the IPCC's fourth assessment report, which was more conservative than the 2013 report. The inherent variability of climate and its effects can ravage modern society, if ill prepared, compromising many nations' security.

Many of the responses to climate change discussed later relate to concepts of sustainability. The World Commission of Environment and Development defines **sustainability** as the "capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs." In other words, if we recognize that our modern way of life endangers future generations and limits their ability to have a similar or better lifestyle, there is an ethical obligation to make changes. Additionally, we have to make sure any response to mitigate the effects of climate change should not imperil our own livelihood. Thus, we have a potential conflict. Believing that change can jeopardize the economy may promote resistance to adapting to climate change. There is some validity to concerns for the economic structures. Attempts to reconcile this balance for the climate system and the economy, as well as people's willingness to give up perceived necessities, should be considered for both the present and future generations. Ultimately, this measured approach will allow for the improvement in quality of life without degrading the environment for current and subsequent generations.

Importance of the Climate System

A Changing Climate

To validate that the current time we live in is truly undergoing significant climate change, one need only look at the observed trends of the climate system. While climate is inherently variable over long periods of time, the recent trends in observed temperatures show changes unprecedented over past decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished worldwide, sea level has risen, and the concentrations of greenhouse gases have increased (Figure 1.3A & B).

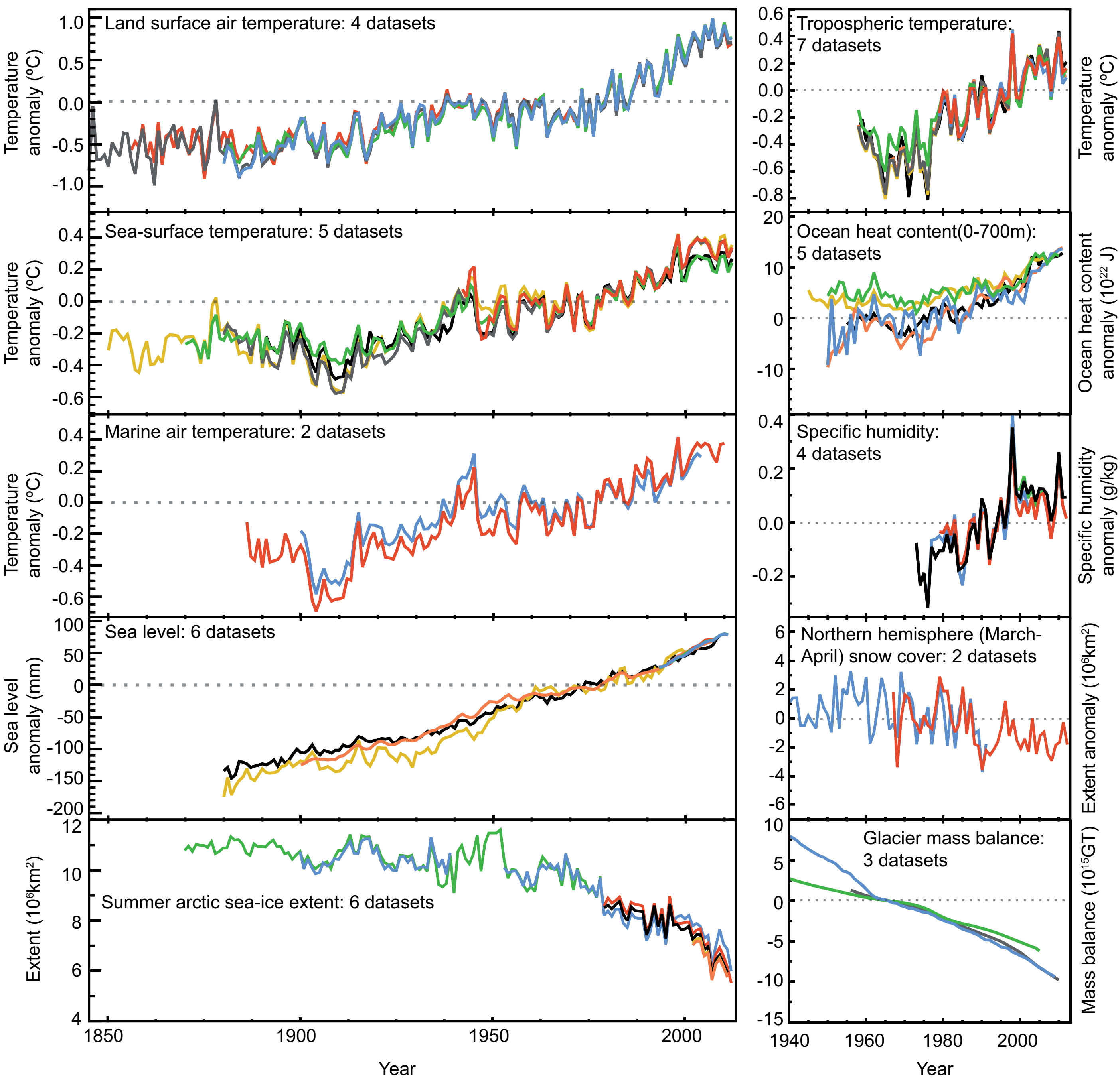


Figure 1.3A
Multiple independent indicators of a changing global climate. Each line plotted represents an independently-derived estimate of change in the climate variable. Anomaly refers to a departure from the long-term average. [Stocker et al., 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution

of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. FAQ 2.1, Figure 2.]

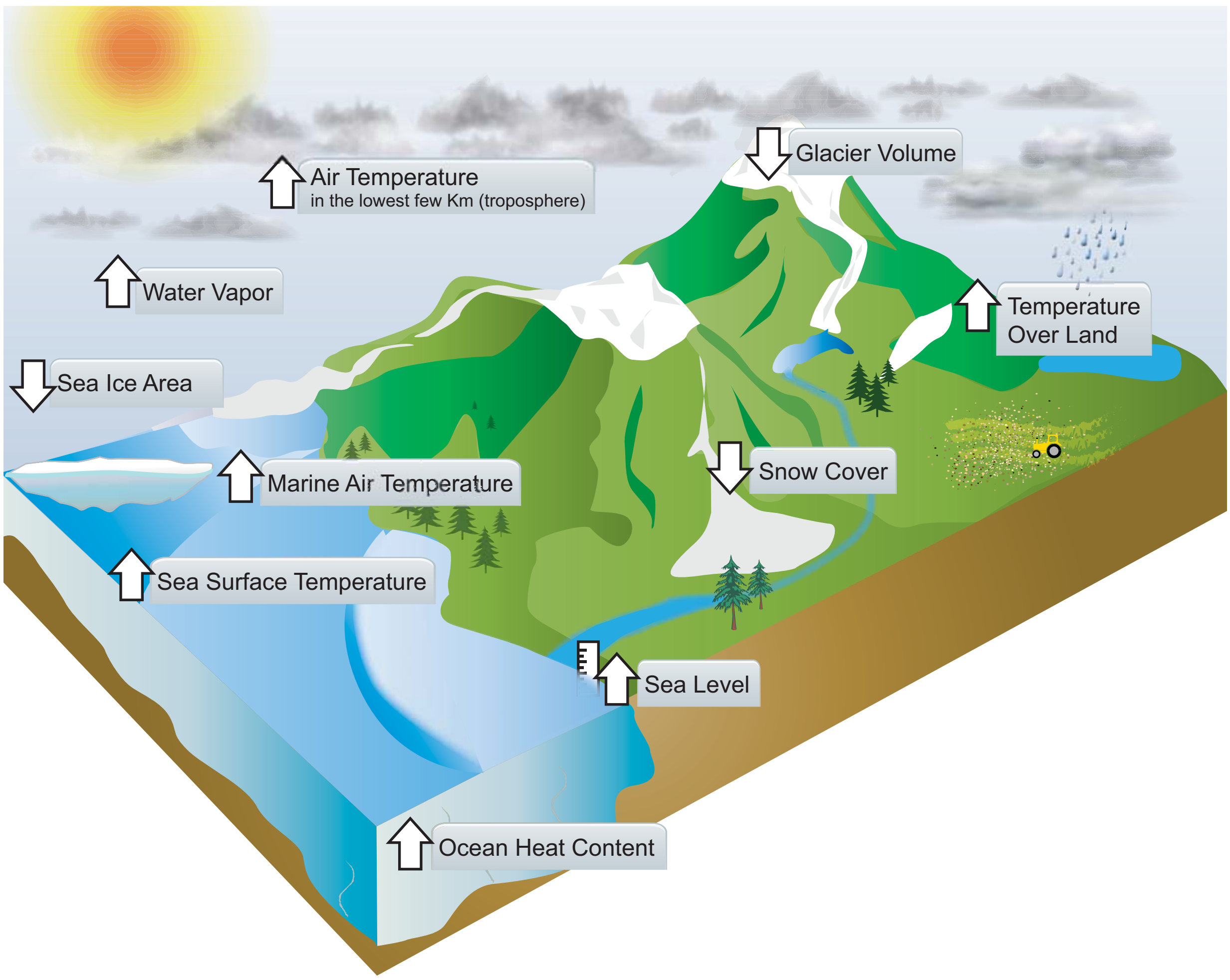


Figure 1.3B
Schematic diagram showing the trend of each climate variable as graphically depicted in Figure 1.2A. [Stocker et al., 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. FAQ 2.2, Figure 2.1.]

The IPCC notes that each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983-2012 was likely the warmest 30-year period of the last 1400 years (Figure 1.4).

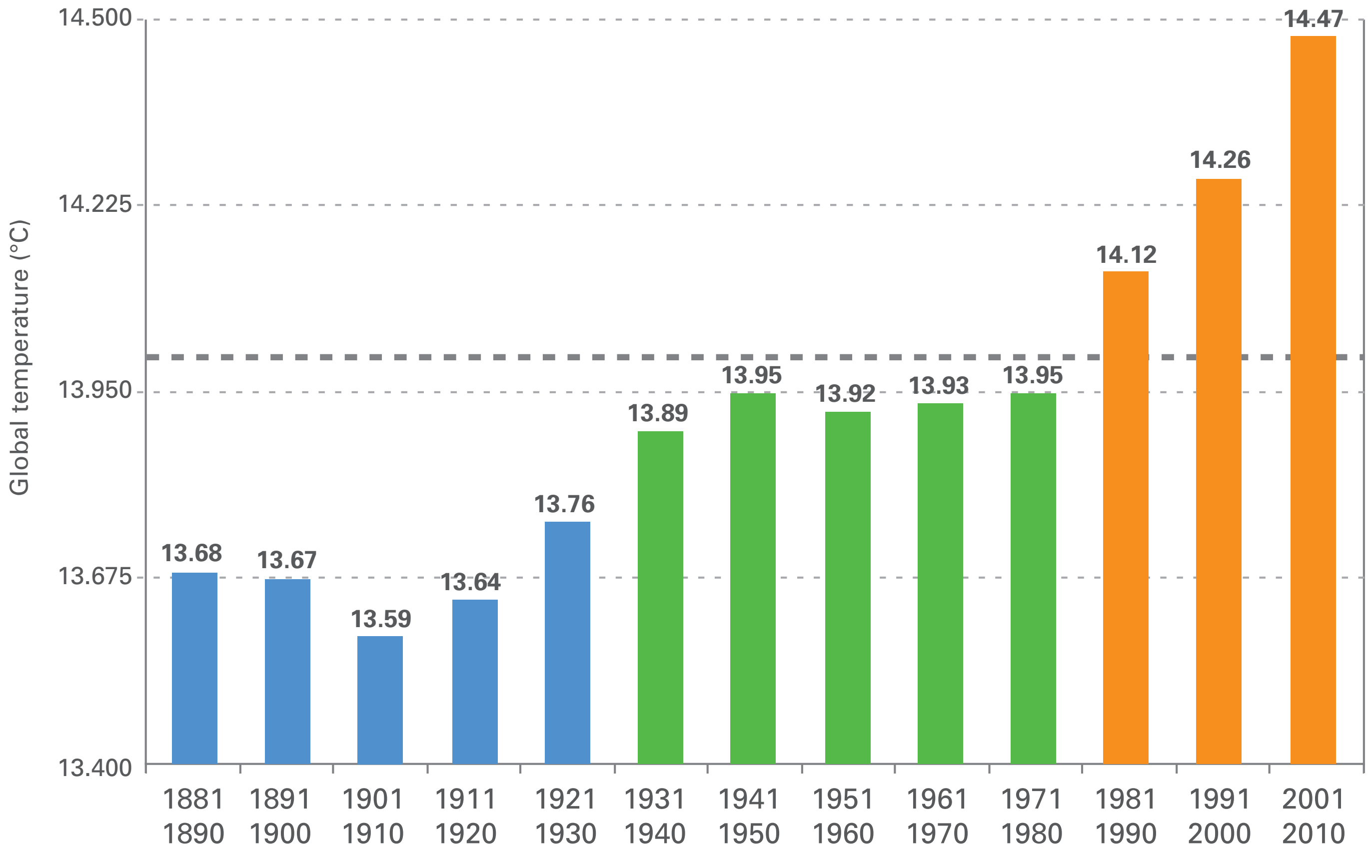
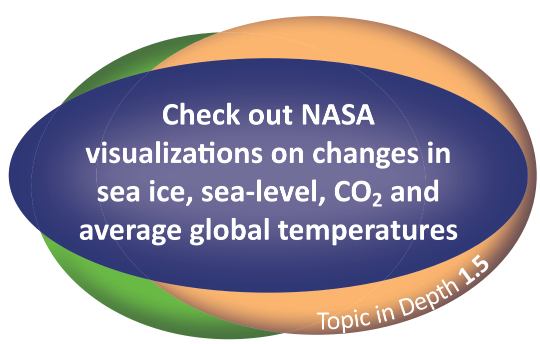


Figure 1.4
Global combined surface-air temperature, by decade, over land and sea-surface temperature (°C) obtained from the average over the three independent datasets maintained by the HadCRU, NOAA-NCDC and NASA-GISS. The horizontal grey line indicates the long term average value for 1961-1990 (14°C). [The Global Climate 2001-2010, A Decade of Climate Extremes Summary Report, WMO, Figure 1]



The global rise in average surface temperatures since the mid-twentieth century is caused by the increasing heat in the climate system. However, more energy has accumulated than can be accounted for just by temperature change at the Earth's surface. Where has the rest gone? In its 2013 report, the IPCC stated with high confidence that "ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010; it is virtually certain that the upper ocean (0−700 m; 0−2296 ft.) warmed from 1971 to 2010" (Figure 1.5). Most likely, much of this energy is stored at deeper depths of the ocean as well. Oceanographers from the World Ocean Circulation Experiment measured deep ocean properties from the past several decades and detected a consistent warming signal in the abyssal ocean (3000−6000 m; 1.9−3.7 mi.) around the globe. The IPCC is confident that the ocean will continue to warm during the 21st century, affecting ocean circulation and the atmosphere with its own circulation.

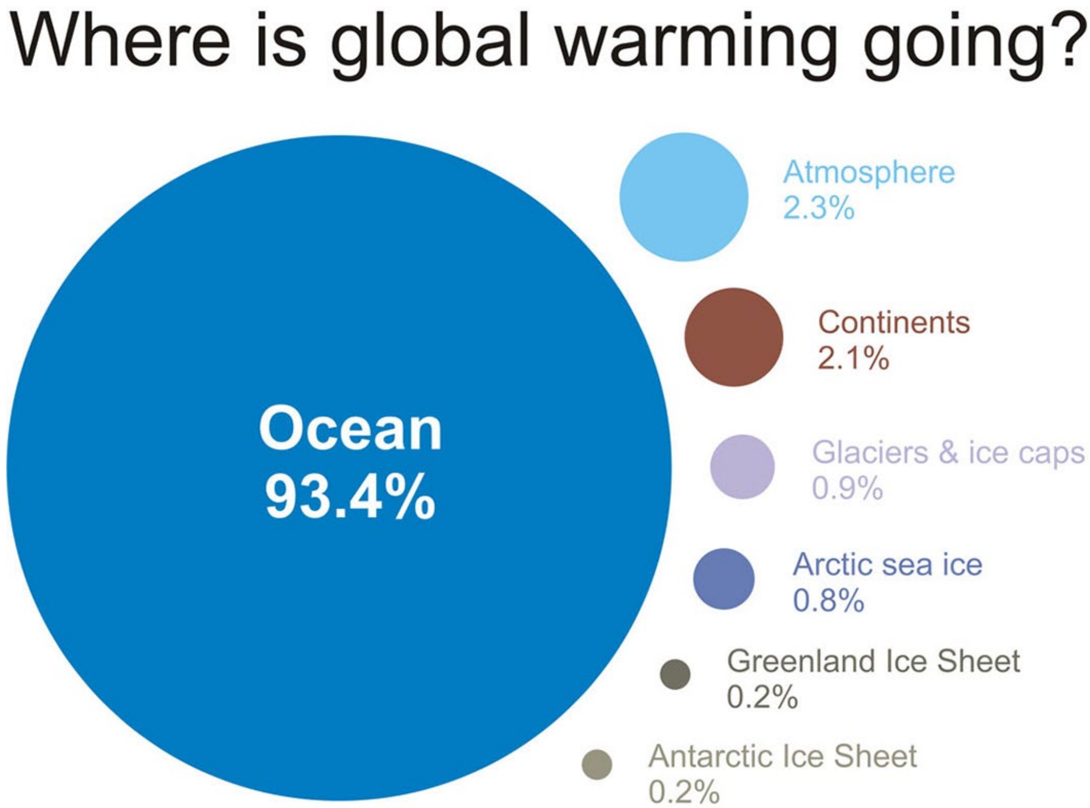


Figure 1.5
A visual depiction of energy quantity changes in different components of Earth's climate system for the period 1993 to 2003. Percentages calculated from the IPCC AR4 5.2.2.3 Report, Figure 5.4. [Skeptical Science, http://www.skepticalscience.com/graphics.php?g=12]

An important component in the climate system, the ocean is integral to our understanding of climate. Exchanges of matter and/or energy exist both within and between other sub-systems of the climate system. The ocean sequesters energy as heat, which can resurface at a later time to affect climate on a large scale. In an example discussed in Chapter 7, anomalous warming of the eastern Pacific Ocean, called El Niño, likely contributed to recent warming trends in the surface temperature record since energy is exchanged between these systems. In climate studies we monitor exchanges of energy and where they currently reside, on the land surface, in the ocean, in the atmosphere or other sub-systems. The challenges in monitoring all quantities of energy in the climate system are a matter of constructing arrays of instrumental devices to account for it.

Some effects of climate change aren't identified solely by instrumentation. Plant and animal species also react to changes in climate. These plants and animals connect to the climate system because they share our environmental spaces. Thus, it's important to identify their habitats in the context of a changing climate. In doing so, one must consider the nature of an **ecosystem** as a collection of living organisms within the non-living substances they depend on or near the surface of the Earth. Within this environment, plants and animals rely upon each other in a synergistic fashion. Changes in the climate affect ecosystems in many of ways. Warming temperatures push species to seek higher latitudes and altitudes. Rising sea levels permit saltwater to intrude into deltas and rivers, which were previously suited for freshwater species. When biologists identify changes in ecosystems, it is an ominous harbinger to other living organisms—including humans. Just as canaries were previously used in mining operations to provide early detection of noxious gases, so does significant ecosystem disturbance signal a potential change in the climate system.

Watch a video on the effect of sea-level rise on the atoll islands of the Federated States of Micronesia

Topic in Depth 1.6

Climate Variability versus Climate Change

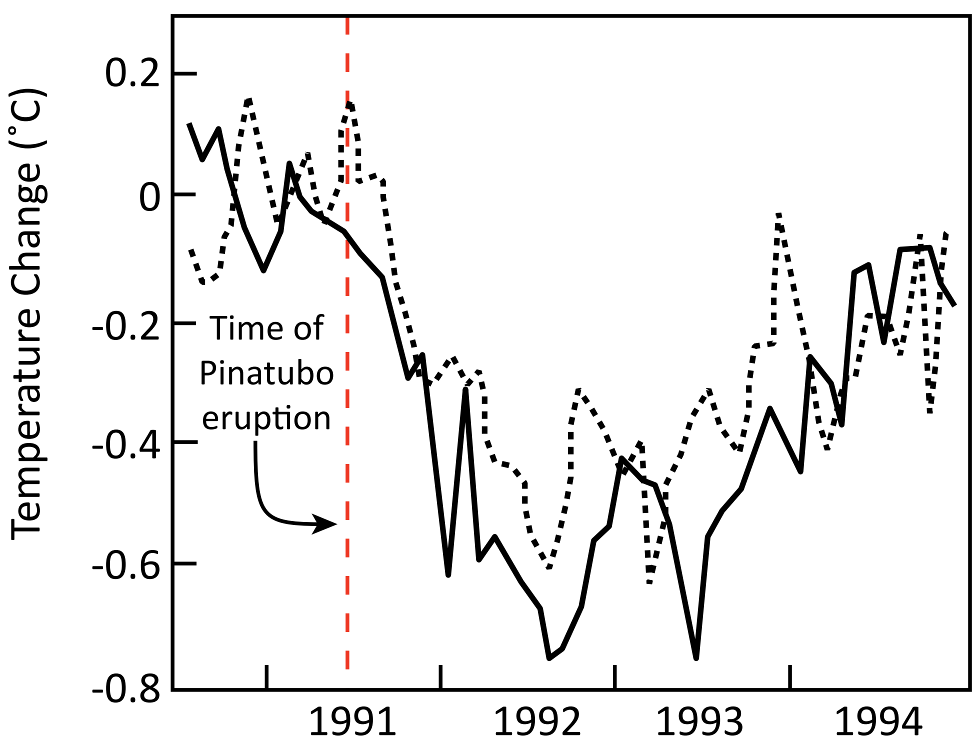
Having defined climate change and climate variability in the previous section, it is important to further elaborate on distinctions between climate change and climate variability. The variability of climate relates to relatively shorter time scales. Many mechanisms can cause the state of the climate system to be different than the calculated "normal" or average conditions, but no single explanation describes all variability. The ranges of both climate variation and climate change are a response to the interactions of a multitude of governing mechanisms, which operate both internally and externally relative to the systems and sub-systems that make up Earth's climate. There will always be climate variability at many scales: decadal, yearly and singular events.

Climate scientists distinguish between mechanisms that force climate to shift to a new state and those that cause only a temporary variance, often called finding the "signal versus noise." Much like listening to an AM radio station, the static (noise) interferes with your music (signal). Climate scientists more easily detect climate change if the "signal" isn't clouded by climate variability in the observational record.

Differentiating between climate change and variability can be done by matching as many possible causes of climate change to a probable cause (forcing agent) with a specific climate fluctuation (response). For example, a one-year reduction in global average surface temperatures in 1992 was caused by the eruption of Mount Pinatubo—arguably the largest volcanic eruption of the 20th century (Figures 1.6 A and B). Natural drivers of climate change, such as solar radiation changes, volcanic eruptions, tectonic movement of continents, and our own contributions, such as burning of fossil fuels, can be separated. Scientists tease out the effects on all the complex systems and sub-systems, and how "sensitive" climate is to each of these changes. The delineation between the drivers of climate change and variability is further addressed later in this chapter and in succeeding chapters.

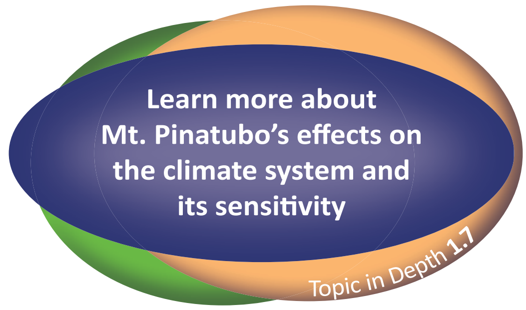
A.

Figure 1.6A
The 1991 eruption of Mount Pinatubo in the Philippines. (Photograph by Dave Harlow, courtesy of the U.S. Geological Survey)



B.

Figure 1.6B
Comparison of predicted (solid line) and observed (dashed line) global tropospheric temperatures. [Hansen, J., et al. 1996. A Pinatubo climate modeling investigation. In The Mount Pinatubo Eruption: Effects on the Atmosphere and Climate. NATO ASI Series Vol. I 42, pp. 233-272. Springer-Verlag. Heidelberg, Germany]



Much has been made of the last 10-15 years in the observed surface temperature trends by both media and climate change critics. Global average land surface temperatures have plateaued, showing no discernible trend, though temperatures remain well above the long-term average. However, this brief change in slope (trend) is almost certainly a coincidence of climate variability. The most recent 15 years are described here to make a point about the *variability* of climate as opposed to climate change. A short record of 15 years is meager relative to the more significant warming trend since the mid-twentieth century. Climate scientists rarely focus on such a short record as they are statistically insignificant, or as David Easterling and Michael Wehner point out in a recent study, "fitting trends to such short periods is not very meaningful in the context of long-term climate change" (Figure 1.7)

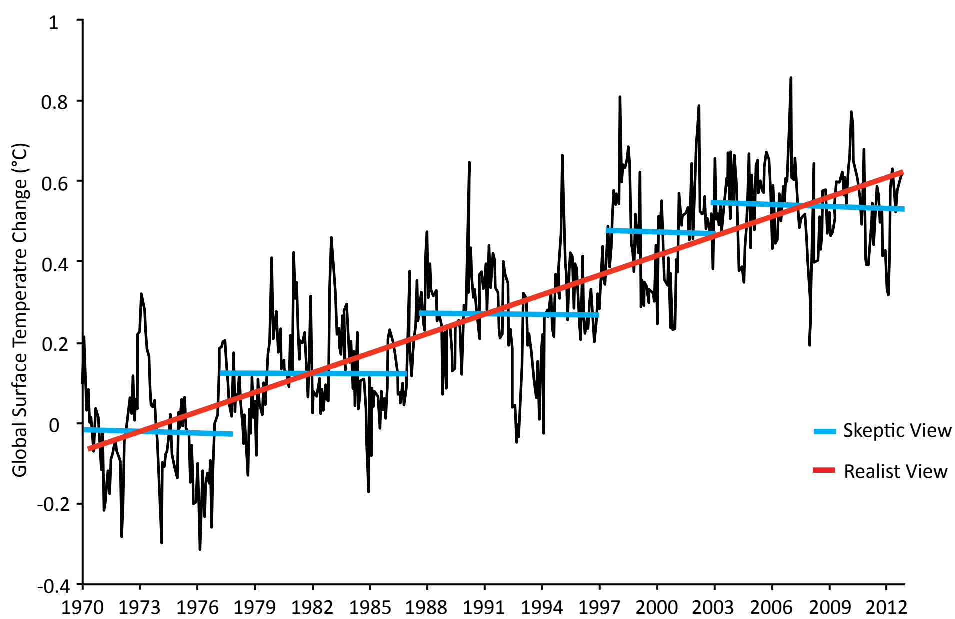


Figure 1.7
The black line represents the global surface temperatures with the long-term trend shown as the red line. The blue lines show how shorter time periods can be parsed out of the same temperature data (black line) to select cooler time periods even though the long-term trend (red line) is shown to be increasing. [Adapted from Skeptical Science, http://www.skepticalscience.com/graphics.php?g=47]

Assessing Credible Climate Information

In 1792, the *Old Farmer's Almanac* was first published and has become the oldest continuously published periodical in North America. It's famous for its weather and climate forecasts, preparing farmers for inclement weather. A few centuries ago, there were few other sources of information about changing weather or climate conditions. The *Almanac* was, and is still, a popular source of cataloged Earth system information (moon phases, tides, etc.), but times have clearly changed since the 18th century. Technological advances have allowed us to observe much more of the climate system and our knowledge of the atmosphere and ocean has grown with it. Given these advances, why do so many people still claim that the *Old Farmer's Almanac*, which avoids a full disclosure of its scientific forecasting methods, is a source for credible predictive information? The *Almanac* itself asserts that their predictive skill is upwards of 80%, yet offers no verifiable confirmation of their results. When their claims are objectively tested, they never approach that value. This is the first rule in evaluating credible information about climate and statements of climate events: credible sources verify their projections.

As an example of those who validate their climatic projections, Peitao Peng and other climate scientists at NOAA's Climate Prediction Center (CPC) verified 15 years' worth of climate outlooks in a published scientific journal. During climate events like El Niño, it was found that forecasters are more skilled in predicting temperature trends in the U.S. Without this oceanic anomaly, predictive skills diminish. While challenges remain in making credible projections, shortcomings are revealed by authenticating the results. Through this process of examination, we reveal new insights, we learn new information, we modify our analytical process, and ultimately we improve our forecasts. Without this process of critical analysis, we are ignorant of what we really know and cannot improve it.

Verifying that whoever is making climate statements has had their work evaluated by others certified in climate sciences also adds credibility. This evaluation by objective, professional reviewers is called the **peer review process**. Reputable journals that publish studies of climate abide by peer evaluation to maintain a high level of quality and credibility. Investigations that do not meet the scientific standards are either returned for further work or refused outright. In this manner, lower quality works related to climate are never widely disseminated, nor are they given acceptance by the discipline. The reason an overwhelming majority of climate scientists attribute recent climate change to human influence is because most of the work asserting these statements has been peer reviewed and published in reputable scientific journals. Their data, analysis and conclusions have been vetted by experienced individuals working in the discipline. Thus, a journal that employs this peer review process can be trusted more than a publication such as a newspaper or an online blog.

There has been a concerted effort to cast doubt on climate studies, and even science as a whole. This issue is addressed more fully in the final chapter of this text, but is raised here because of the importance of assessing credible versus non-credible analysis of climate. Most who deny the changing climate do not want to deal with the restraints that would change the status quo. The challenges associated with climate change are vast and require large scale cooperation among nations as well as changes in our individual lives. One way to lessen anxieties is to trust that the scientific process will provide us important insights and solutions. Yet it is not faith-based, as there is evidence it works; the scientific process has existed for centuries, solved numerous environmental problems, enhanced our lives and led us to the conveniences of our modern way of life. It can serve a similar purpose in dealing with our current challenges related to climate change.

Interest in climate science doesn't require understanding the specific codes for computer models or the methods for examining climate data, but climate information is important to make informed decisions about interests and livelihoods. With further investigation and critical analysis to evaluate the credibility of published research or a media report, anyone can become better informed and understand the implications of climate change locally and nationally. There are uncertainties in all scientific endeavors, but that does not justify complacency or inaction. Everyone has a role in addressing the global issues of the climate system.

Current Climate Paradigm

In the 1980s, the former head of the NASA Goddard Institute for Space Studies, James Hansen, first reported on the danger of climate change to the U.S. government. Yet we have been slow to recognize the significance as a society. Our society is presented with a major environmental challenge that affects over 7 billion people, including us. Given the vast nature of the problem, some might believe it's "too big" to change. But that's not true.

Consider a similar, albeit smaller, global environmental problem: the depletion of the ozone layer. This protective layer, described in greater detail later this chapter, allows for life to thrive on the planet by blocking harmful types of solar radiation. Yet with our own actions through the invention and use of commercial refrigerants, propellants and solvents, we began to destroy it, thus creating a threat to our own existence. Scientists recognized the environmental challenge and alerted government officials and policy makers worldwide. Eventually, governments cooperated via the United Nations and numerous treaties were ratified by 197 nation-states. It was one of the most widely ratified treaties in U.N. history. Former Secretary-General, Kofi Annan said that these treaties were perhaps the single best international agreements to date. The treaties phased out the production of numerous gases believed to be responsible for ozone depletion. They represented an immensely effective example of international cooperation and policy implementation to solve an environmental problem affecting humanity.

If we were able to address this predicament through mutual cooperation, why can't we address the climate change obstacle that affects us today? We address these questions in forthcoming chapters by presenting what we know about climate, how it shapes our lives and livelihoods, and how many aspects of climate are connected through all facets of the Earth's systems and our own actions. We will also define actions that are necessary to reduce our effects on climate, as well as place ourselves in a less vulnerable situation.

In order for us to understand this complex climate system and solve the related environmental predicament facing humanity, we examine its various domains, sub-systems and interactions. **Climatology** is the scientific discipline that investigates Earth's climate system, focusing on how it functions, what drives its changes, and how it varies in both space and time. Both an empirical and theoretical science, climatology infrequently requires laboratories, such as chemistry or biology do. Empirical studies require observations of climatic elements to build an understanding of climatic processes. Theoretical investigations are typically based on mathematical models using physical laws that simulate various states of climate. Used in association with climatology, **climate science** is a more comprehensive term, generally focusing more on the physical processes on Earth that can affect or force climate to change.

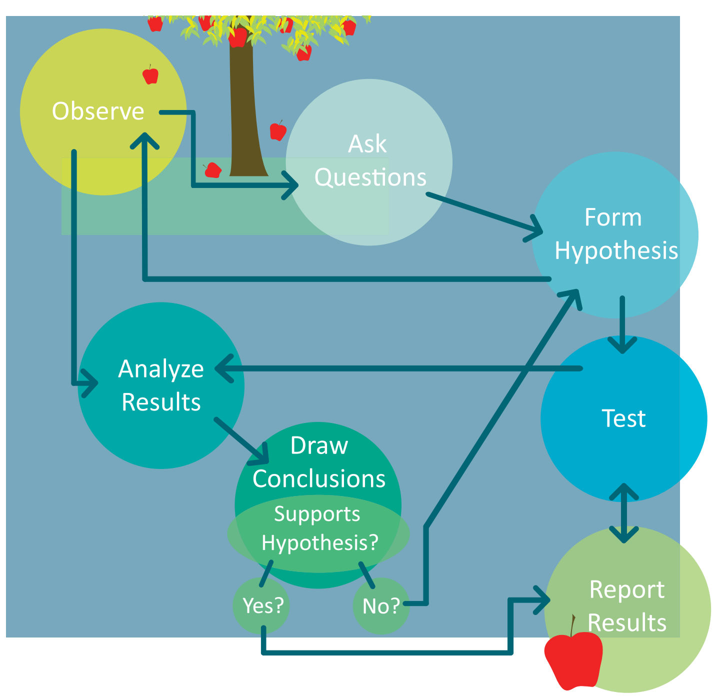


Figure 1.8
Steps of the scientific method.

Whether one is referring to climatology or climate science, the scientific method is the template for investigations. The **scientific method** is defined as a process entailing systematic observation, measurement and experimentation, and the formation, testing and modification of hypotheses (Figure 1.8). Therefore in climatology, climate scientists propose a hypothesis (or supposition) as an explanation for climate events and variations, collect observations of climate and design experiments to assess those hypotheses. Ultimately, predictions can be made from tested hypotheses, and the process must be repeated for verification. Repeating the process with the same and different methods while achieving the same results validates them. The climate system is inherently chaotic with many interlaced sub-systems on multiple spatial (space) and temporal (time) scales. The scientific method allows us to investigate this web of interconnections to identify the reasons for climate variability and change.

Modes by Which Climate Is Defined

While their origins are the same and are frequently used to refer to similar phenomena, weather and climate are neither the same nor equal. The scale of each differentiates between weather and climate, both temporally and spatially. Where a small movement of wind over the short distance of a few city blocks (place), or a rapid rise in temperature in a few hours (time) is considered a weather event, wind or temperature patterns over thousands of miles or months to years are climate events. The continuous interactions of the atmospheric conditions with the other portions of Earth's systems make climate more encompassing and enduring than weather. Climate then, in a broad, top-down perspective, causes weather.

This difference in scale presents us with a challenge because the components of the atmosphere continuously flow within the entire climate system. The atmosphere is a continuum, with energy and mass exchanged within it, between the other systems, and with space. Investigating these systems through the scientific method requires many observations of various elements to understand them thoroughly. However, in order to observe and understand climatic phenomena, part of the observational process is akin to weather observation. We change our perspective of scale to determine whether our observations relate to weather or climate, though they are not mutually exclusive. What this means is that if the climate is in a particular state, there may be a common weather event that occurs quite frequently. For example, if there is a long term drought occurring in Australia, one can expect many rain-free days in the weather pattern. However, if it does rain, the drought has not ended. This rain shower is a small-scale weather event while the continuing drought is a climate event.

A rain shower during a drought underscores that the atmosphere is greater than just the air that surrounds you on any given day. Your locale is miniscule to the grand scale of the climate system. Small scale events (rain shower) may occur within larger ones (drought) but they are intimately connected and determined by the state of the climate system. Observational tools (discussed in Chapter 2) are also small in scale and finite. To understand the differences between a long-term continental scale climate event and a smaller scale weather event, similar observational tools are used. Think of observations as pieces in a jigsaw puzzle. A collection of weather "puzzle pieces" may start to look like an image when placed together, but the puzzle isn't complete and we don't know how this cluster yet fits into the entirety. Perhaps this small cluster of pieces is only one of many similar clusters in the entire puzzle. A single observation only gives you one puzzle piece. To further understand what the entire puzzle (state of the climate system) looks like, many more pieces (observations) over a longer period of time are necessary. A small collection of observations may describe the weather phenomena of the day, but contribute little understanding of the climate for longer periods.

Hence, when we collect a group of observations taken over some particular time interval, it is an assemblage of *weather* variables. The past record of daily temperature recordings for one or more locations for a 30-year period would be considered a climate database even though it consists of past weather measurements. Climatologist Kenneth Hubbard endorses these statements in a published journal by noting that "it wouldn't be incorrect to call the values from the most recent days either weather or climate since they are short in temporal scale." Remember, these atmospheric elements are separated by a perspective of scale. Values from the more distant past are climate variables, despite the fact they were initially collected as an observation of weather. The takeaway point here is that observational data can have both weather and climate applications.

Climate System

A system was defined at the very beginning of this chapter, but due to the complexity of climate, we must further detail the elements within a system and their relationship to climate. Components of a system interact in a logical manner according to the laws of physics and chemistry. An example of a system borrowed from computer sciences is the *operating system* (OS) on a mobile phone. An OS consists of a series of identifiable sub-systems that interact so the phone functions properly. Your phone's OS needs a battery for power to run, a network to connect to, hardware, a screen for the user to interact, and applications ("apps") to perform tasks. The input you provide needs to be exchanged between the various sub-systems. Examples of input you provide external to the system are instructions to the OS to perform certain functions like "call grandma" or play a game. In a properly functioning mobile operating system, all of the functions operate in regular and predictable ways. The amount of energy required for it to function can be quantified and budgeted. Based upon the known capabilities of the OS, computer programmers can study a device's OS to determine how they might construct a new app for the phone.

Climatologists monitor and observe the climate system and its sub-systems, to pose hypotheses about how it will operate in the future, based upon the input/output of energy. Based upon these projections, the potential implications for human life can be identified. The situation with climate, however, isn't completely straight-forward. Systems are described as **open** or **closed systems**.

Both closed and open systems exchange *energy* with their environment, however, only an open system can exchange *mass*. Earth's climate system is considered a closed system because there is practically no exchange of mass between Earth and space. While meteors enter the atmosphere from space and approximately three kilograms of hydrogen and 50 grams of helium are lost per second at the top of the atmosphere, these mass quantities are exceedingly negligible, leaving an essentially closed system.

Climate sub-systems are open as both mass and energy are exchanged between them. As mass, liquid water moves from the ocean into the atmosphere via evaporation, becoming water vapor. Transfer of matter or energy across a system boundary will cause fluctuations inside the system, leading to a change in the physical state of the system. When enough water evaporates from the ocean into the atmosphere, along with the latent heat it is transporting, the fluctuations might be involved in tropical disturbances or cyclones.

Atmosphere

The open sub-systems of Earth's climate are identified as the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. These sub-systems can affect the larger climate system to shift or vary from time to time or place to place, at many different scales (Figure 1.9). Within these sub-systems, biogeochemical cycles (global carbon cycle, global water cycle, etc.) allow us to chronicle the exchange of mass and energy both within and between these systems. An examination of each sub-system follows next.

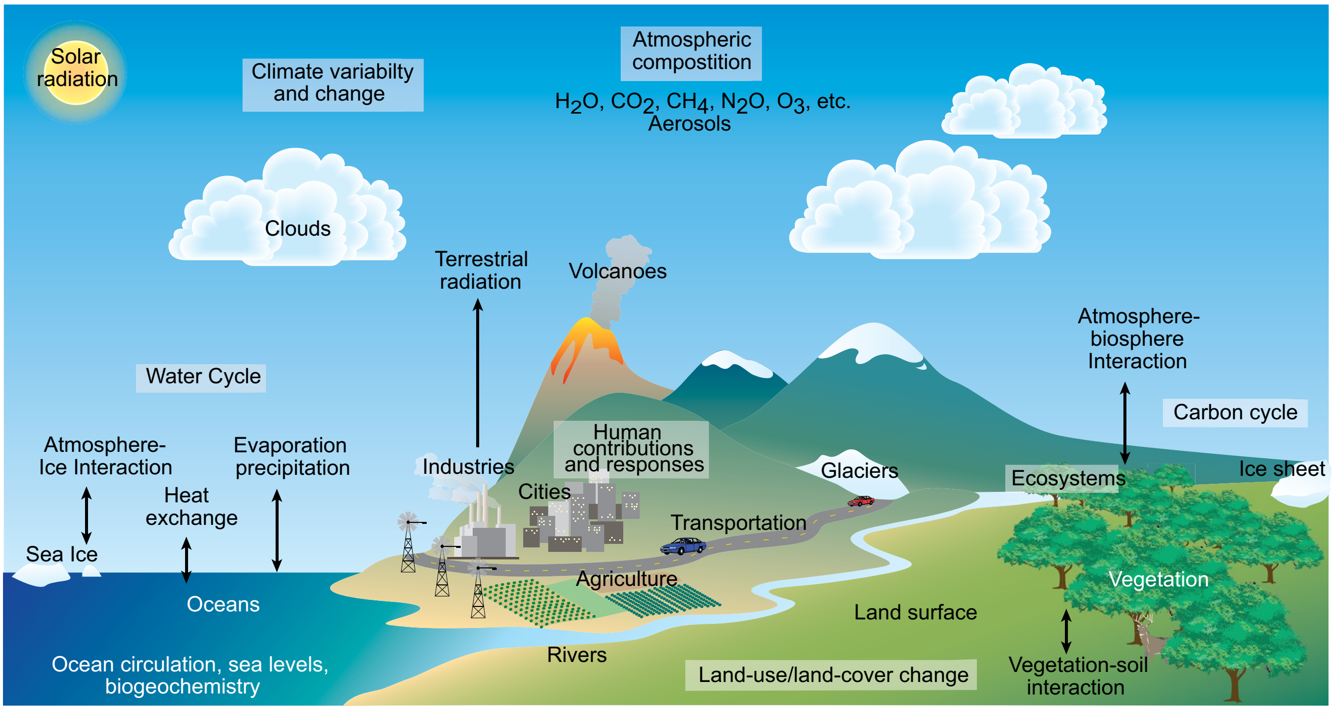


Figure 1.9
Major natural and anthropogenic processes and influences in the climate system. [NOAA, Geophysical Fluid Dynamics Laboratory (GFDL)]

The atmosphere, the most obvious component of the climate system, yet only a thin cloak over the planet, is often misinterpreted as the only part of Earth's climate system. It is a free-flowing, well-mixed (below 80 km) envelope of gases at the interface of Earth and space. No one can imagine life on the planet without the gases of nitrogen (N_2), oxygen (O_2) and water vapor (H_2O). Yet ozone (O_3) and carbon dioxide (CO_2) are other prominent gases present in the atmosphere (in a lesser quantity) which are critical to life. These gases (and others) allow for the explanation of how this fluid envelope surrounding the planet flows and moves. The gases in the atmosphere aren't evenly mixed or concentrated. For example, atmospheric density decreases with increasing altitude above Earth's surface so that about half of the atmosphere's mass is concentrated below roughly 5.5 km (3.4 mi.) and 99% of its mass occurs below an altitude of 32 km (20 mi.).

By volume, the two largest dry-air (exclusive of water vapor) gases in the lower atmosphere are nitrogen (78.09%) and oxygen (20.95%), accounting for 99.04%. Other significant gases, by volume, are argon (0.93%), carbon dioxide (0.039%) and methane at 0.00018% (Figure 1.10). Since these latter gases have much smaller concentrations, they are referred to as **trace gases**. Trace gases may seem unimportant due to their lesser amounts but, as discussed in Chapter 4, some of them remain immensely important to Earth's climate system.

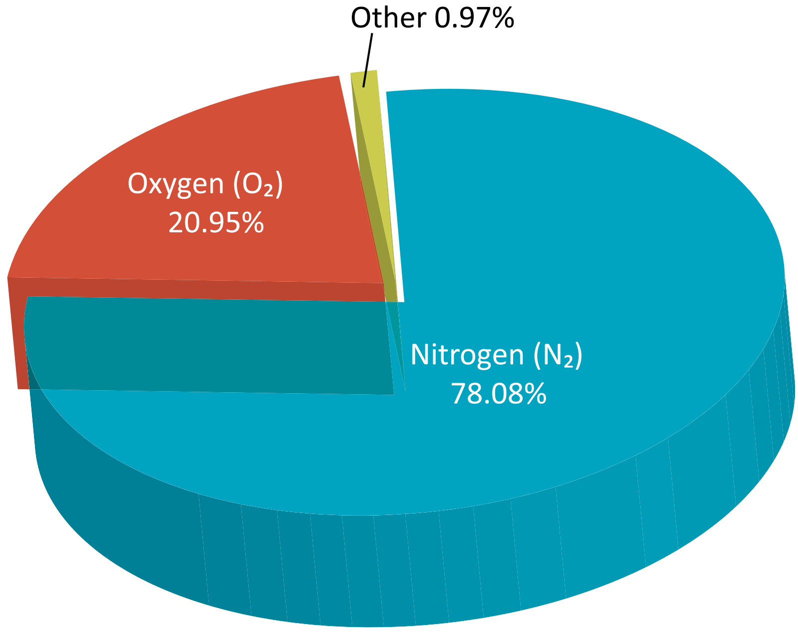


Figure 1.10
Concentration of gases by volume in the atmosphere. Trace gas concentrations, labeled “Other”, include Argon (0.93%), Carbon Dioxide (0.039%), Neon (0.00182%), Helium (0.00052%), Methane (0.00018%), Krypton (0.00011%), and Hydrogen (0.000055%). Numbers do not add up to exactly 100% due to roundoff and minor uncertainties. [Data courtesy of NASA]

Water vapor, another atmospheric component, varies significantly near the surface of Earth, between 0.1 - 4%. In a weather forecast, water vapor concentration information is useful when dealing with humidity or precipitation, but in the climate system the abundance or lack of water vapor plays a role in defining regions like rainforests and deserts.

This particular mixture of gases, especially water vapor’s inherent variability, is characteristic of the **troposphere**, the lowest layer of the atmosphere which interacts with other sub-systems of climate. The exchange of mass and energy between the sub-systems manifest in the troposphere as turbulent motion. Because the weight of overlying atmosphere compresses gases below, 75% of the atmosphere’s mass is in the troposphere, making it the densest part of the atmosphere.

A common way to examine the atmosphere is by its temperature profile in the vertical (Figure 1.11). In doing so, it is found that the atmosphere can be segregated into four “layers” based upon the average change in temperature with height.

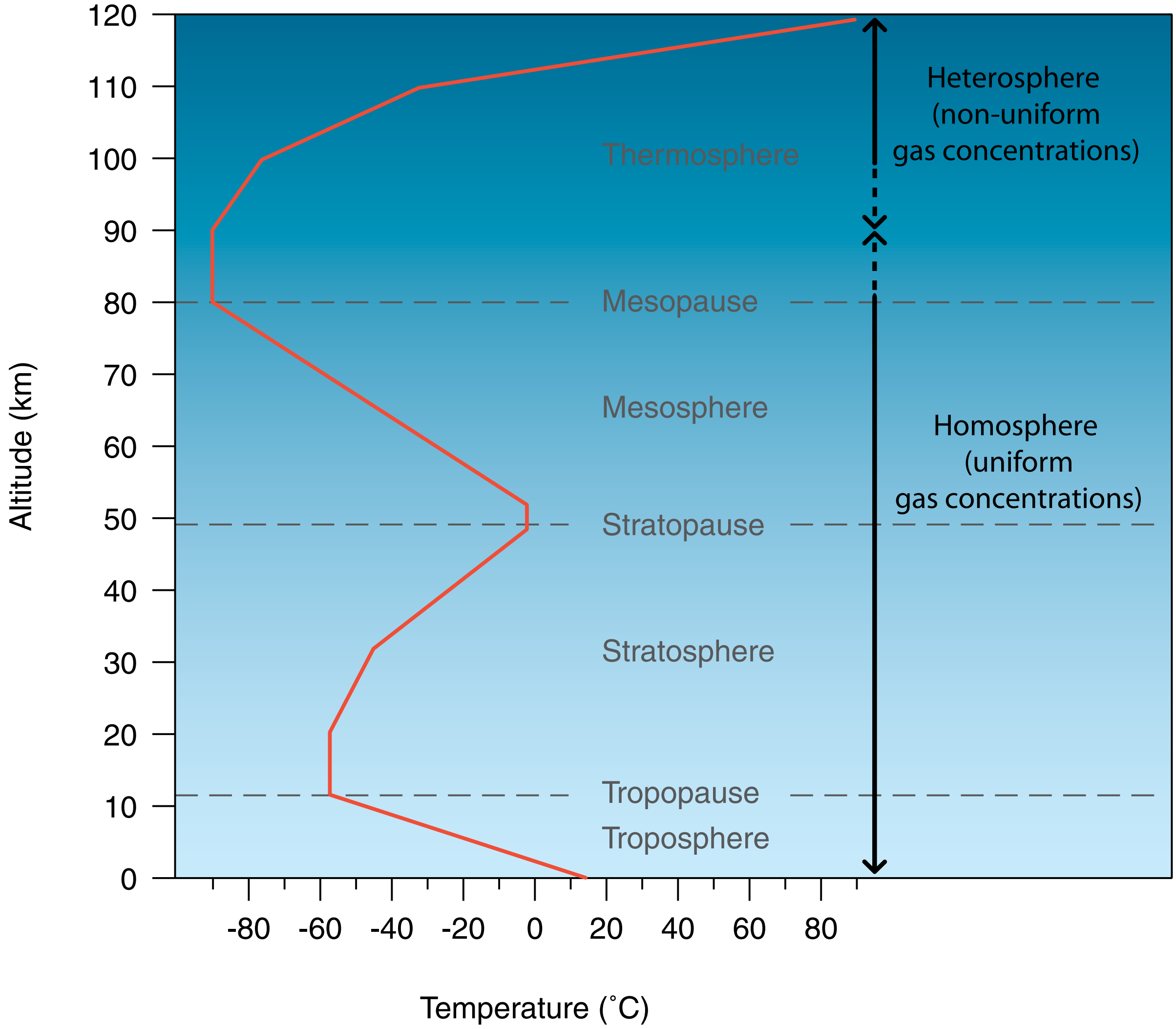


Figure 1.11
Variation in average temperature with altitude within the atmosphere. The delineation between the homosphere and heterosphere is another way to define the vertical extent of the atmosphere.

Temperature changes with increase in altitude are called **lapse rates**. The average lapse rate in the troposphere is a decrease of about 6.5 °C for every 1 km in the troposphere (also known as the *environmental lapse rate)*. This temperature drop results from the increasing distance from the relatively warm surface, which absorbs solar radiation, and mixing by air motions (Figure 1.12).

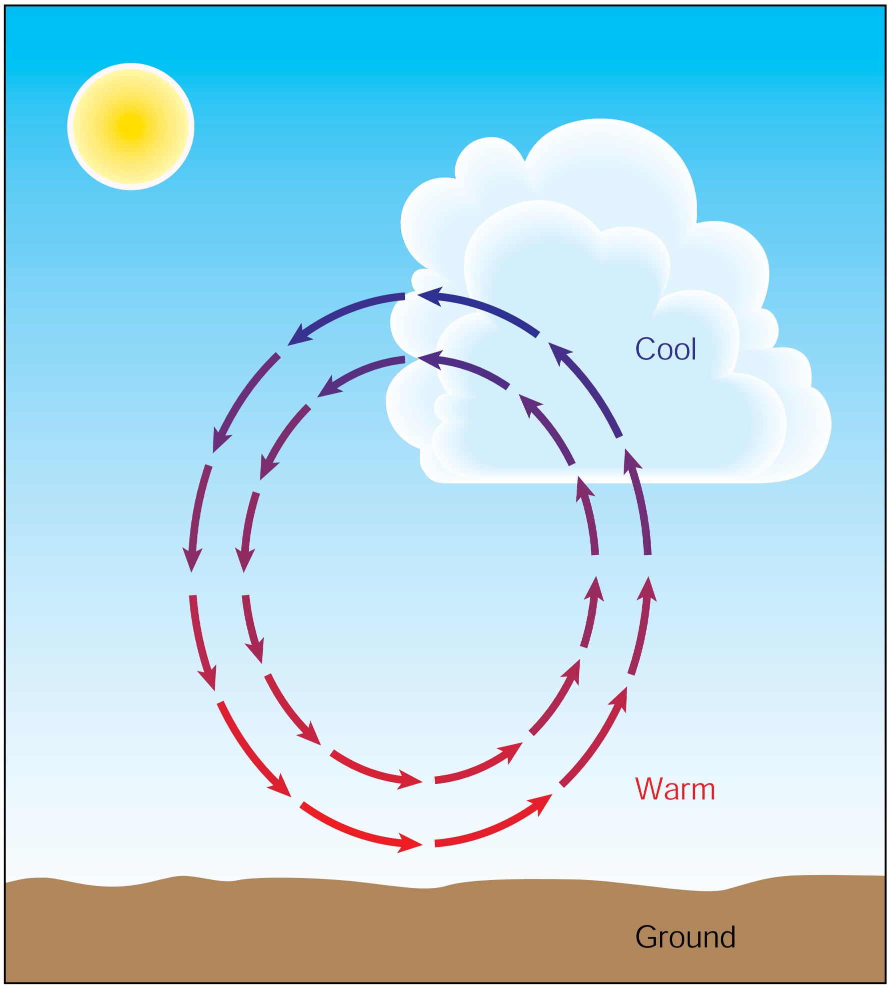


Figure 1.12
Turbulent motions transport heat from Earth's surface into the troposphere.

There are portions of the troposphere which have slightly varying density values but overall it is well-mixed. The height at which the lapse rate decreases to zero, causing a "pause" in temperature changes, defines the upper boundary of the troposphere called the *tropopause.* This *isothermal* ("one temperature") layer means that there is no change in temperature with distance—the lapse rate is zero. But this transition also affects the buoyancy of rising air at this altitude. Parcels of air, like a hot-air balloon, may rise to this level. Most rising parcels cannot maintain their upward motion since the temperature contrast that helped to produce lift due to different air densities inside and outside of the parcels ends because of the change in lapse rate. These issues of stability are discussed later in the text.

The intensity of UV radiation arriving from the Sun near the boundary of the atmosphere to space is approximately 350 million times stronger than at the Earth's surface. Yet, there is a relatively great concentration of a certain gas—**ozone** (O_3), at 20-30 km (12-19 mi.) in altitude which significantly alters the thermal profile. A variant of oxygen, ozone is a triatomic molecule, consisting of *three* oxygen atoms rather than two in the most common form of oxygen. While limited in its concentration in the atmosphere, consisting of only 0.6 ppm (parts per million) overall, its concentration reaches a maximum of nearly 10 ppm at this altitudinal range (Figure 1.13). The presence of ozone plays an important role to life. Ultraviolet radiation is especially detrimental to humans because it can cause direct and indirect DNA damage, leading to various forms of cancer.

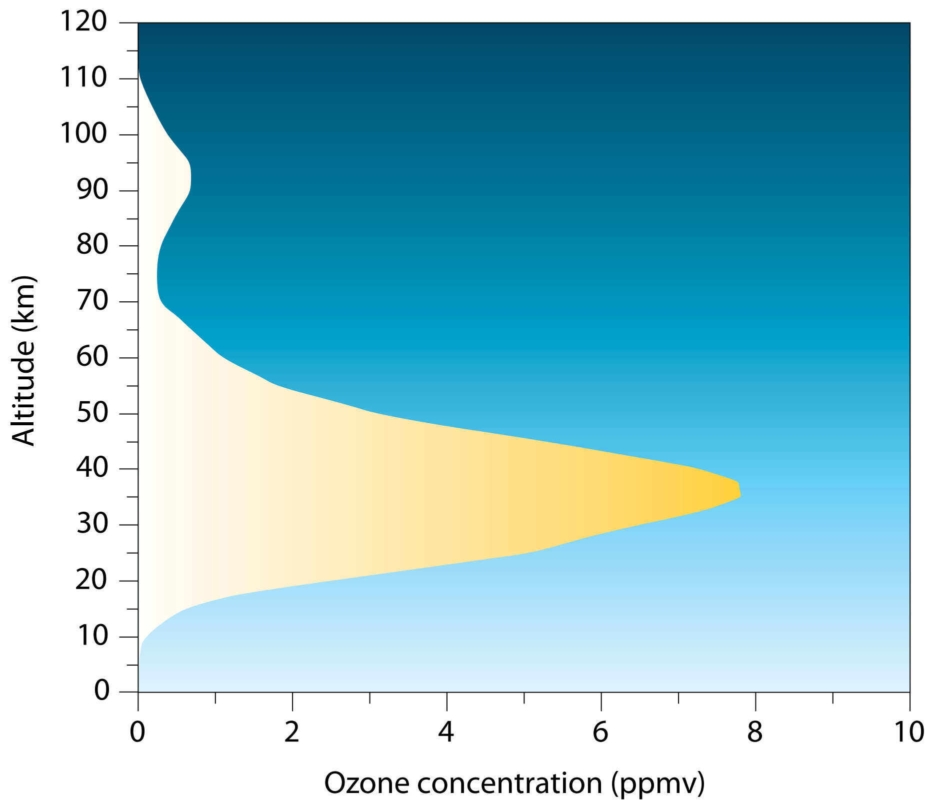


Figure 1.13
Ozone (O3) concentrations peak in the stratosphere. [Source: U.S. Standard Atmosphere, 1976]

Read more about the EPA's ozone reduction strategies
Topic in Depth 1.8

Ultraviolet (UV) radiation helps to form and dissociate (break apart) ozone molecules (Figure 1.14). Both of these processes are *exothermic reactions*, which means they release energy to their surroundings in the form of heat. By consequence, these reactions warm all the gases in the region above the tropopause where ozone is concentrated. That region of the atmosphere is called the **stratosphere**. The isothermal characteristics above the tropopause continue upward for several kilometers into the stratosphere before a major change occurs. That change is a marked increase in temperature with height, an *inversion (*opposite of the average lapse rate of the troposphere).

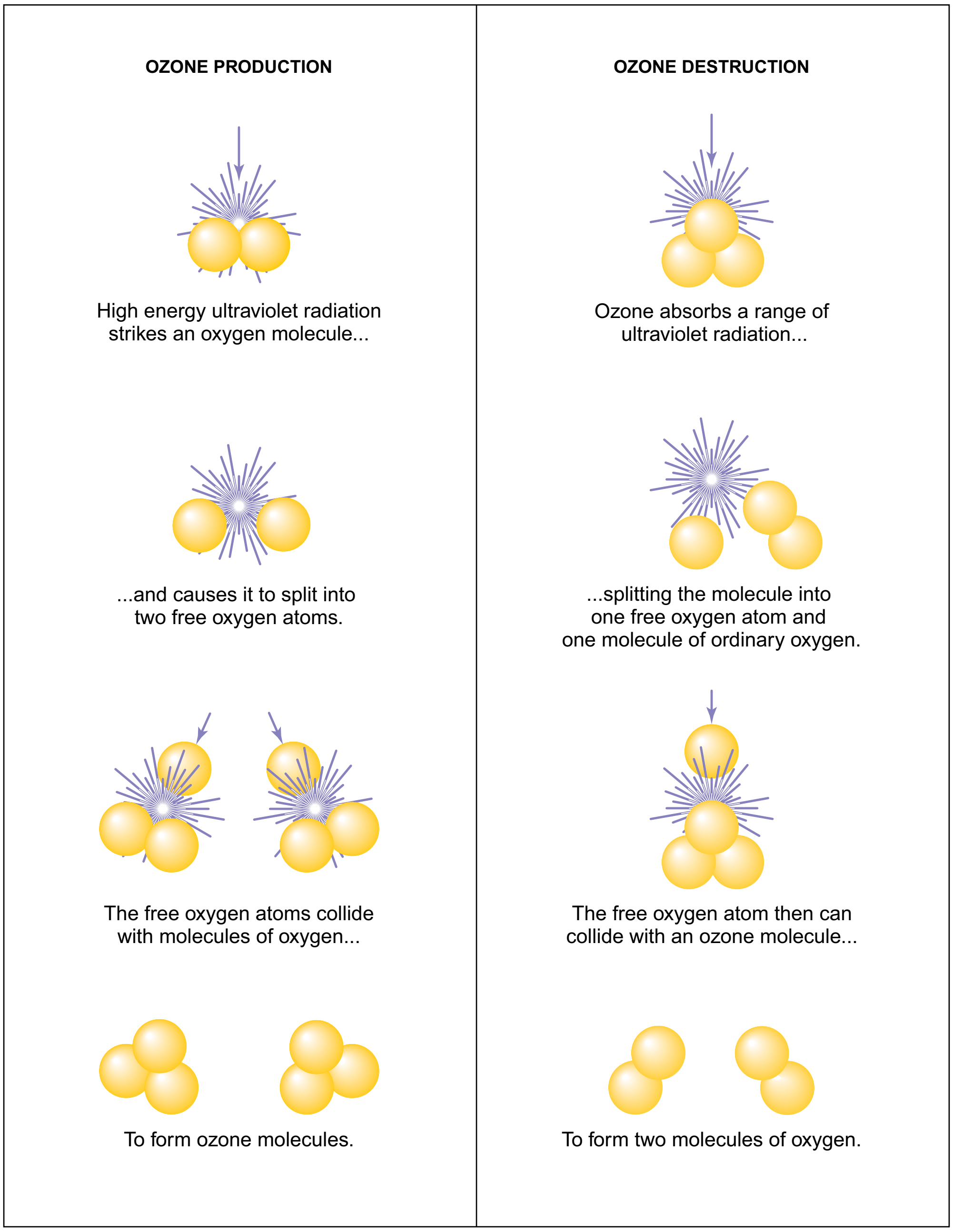
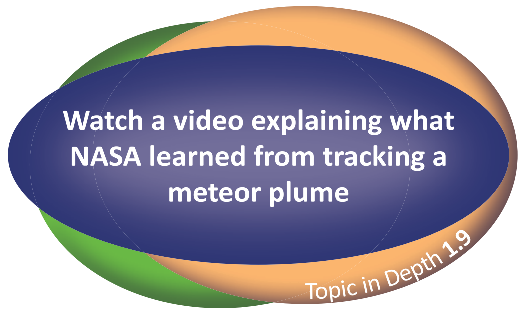


Figure 1.14
Within the stratosphere, two sets of competing chemical reactions continually generate and destroy ozone (O_3). [Adapted from "Ozone: What is it and why do we care about it?" NASA Facts, NASA Goddard Space Flight Center, Greenbelt, MD, 1993.]

The isothermal and inversion layers inhibit large scale vertical air motions, resulting in a region which is more stable. You may have first-hand experience of this if you have traveled on commercial airline flights. The ascent upwards through the troposphere can be bumpy. After ascending beyond the troposphere into the lower portions of the more stable stratosphere, the flight typically becomes smoother. At an average height of about 50 km (31 mi.) the temperature reaches a maximum of about -15 °C (5 °F) before dropping with further increase in altitude. This maximum temperature marks the top of the stratosphere, the *stratopause*.

On an ascent upwards from the stratosphere, maximum warming from the formation and dissociation of ozone lessens due to the lessening concentration of ozone. This next layer where temperatures decrease with height is called the **mesosphere**. In fact, the drop in temperature is so pronounced that at the top of this layer, the *mesopause*, it is typically the coldest part of Earth's atmosphere with temperatures approaching −143 °C (−226 °F). These values vary by geographic location and time of year. Despite the incredibly cold temperatures, millions of meteors enter this layer of the atmosphere only to vaporize as a result of compression forces surrounding them as they rapidly move downward through an increasingly dense atmosphere.



Above the mesosphere is the **thermosphere** where the average temperature again increases with altitude. Temperature becomes a challenging quantity to measure in this layer as will be discussed in Chapter 4. Gases in the thermosphere absorb highly energetic solar radiation. These gases are highly agitated by the solar activity here since these altitudes are at the gradation of the atmosphere to interstellar space. The energetic, but rarified molecules at this level behave as if heated to 2000 °C (3,630 °F). Despite the difficulty in temperature measurement, this high-energy solar radiation causes atmospheric particles to become electrically charged, or ionized. Ionization is the process by which an atom or a molecule acquires a positive or negative charge by gaining or losing electrons. The ionization of these gases can cause unique interference with radio wave propagation and represents the inner layer of Earth's magnetosphere. This region of the atmosphere, because of the ionization, is called the ionosphere.

At altitudes approaching 80-100 km (50-62 mi.), Earth's atmosphere incorporates lighter gases, like hydrogen (H_2) and helium (He), and begins to stratify by the molecular weight of those gases. We then have a well-mixed layer of gases in the lower atmosphere, called the homosphere, and a segregated layer, where the stratification by molecular weights begins, called the heterosphere. The delineation between the homosphere (mixed gases) and heterosphere (stratification) is another way to survey the atmosphere, different than the previously described thermal profiles.

A discussion of these layers and gases in the atmosphere is critical to understanding how they may be changing over time in a climate system that interacts with its sub-systems in a synergistic fashion. The atmosphere is perhaps the most dynamic component of the climate system. It constantly circulates in response to different rates of heating and cooling, yet generally is limited to within one thermal layer, the troposphere. Warming in one layer may lead to cooling in another. One reason this is possible is because the thermal layers do not easily mix, despite the internal circulation within one. Studies have shown that with significant warming in the troposphere, primarily by heat-trapping greenhouse gases, less energy is available to be translated outwardly into the stratosphere. Thus, the climate changes we experience at the surface in the troposphere have opposite effects in the stratosphere. While measuring temperature in the stratosphere is a bit more difficult, evidence we have for the past few decades corroborates this connection. Aside from temperature declines caused by exchanges of volcanic products emanating from the lithosphere, there has been a steady decline in stratospheric temperatures as the troposphere warms (Figure 1.15).

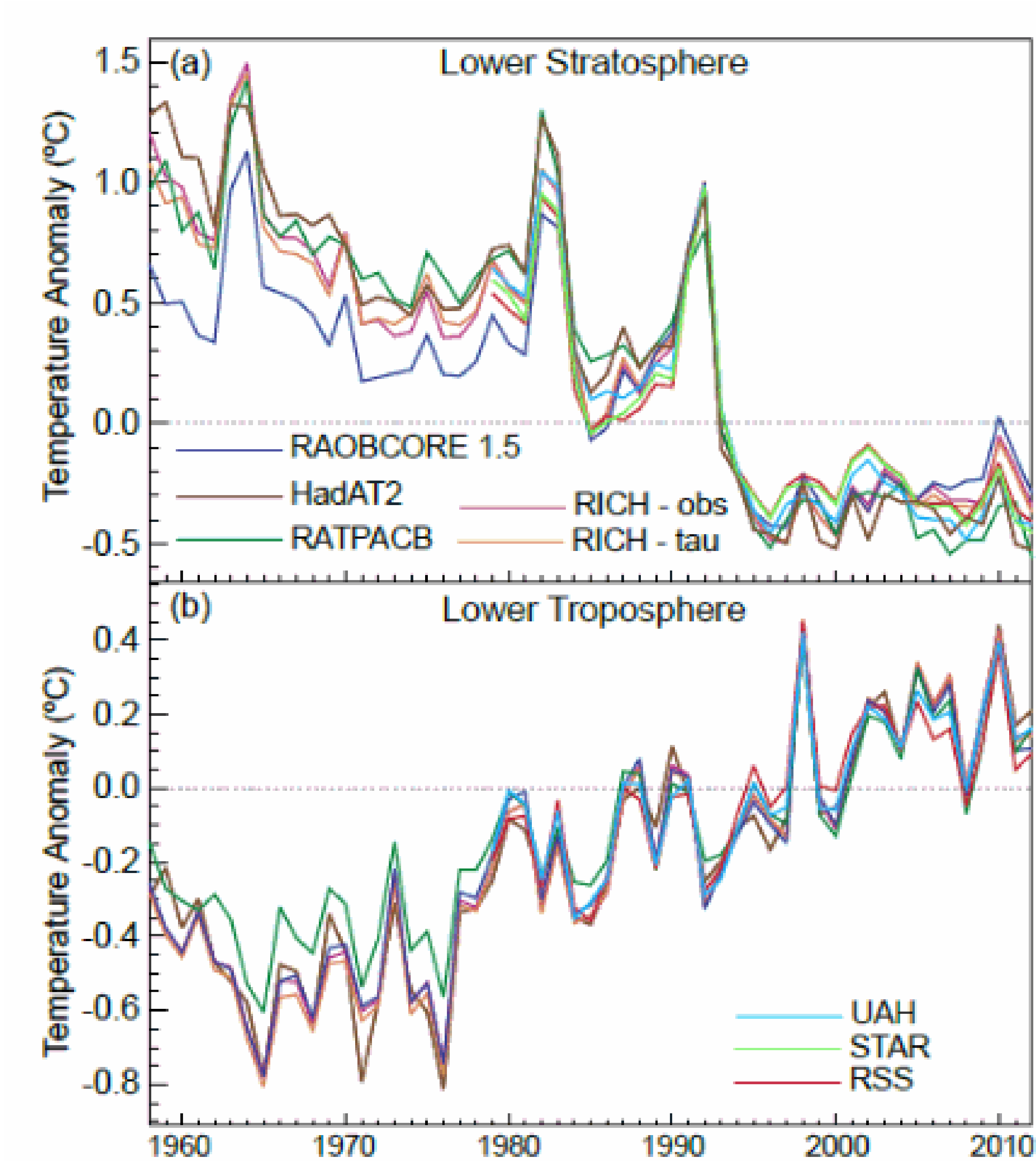


Figure 1.15
Global annual average lower stratospheric (top) and lower tropospheric (bottom) temperature anomalies relative to a 1981–2010 climatology from different datasets. Note that the y-axis scale differs between the two panels. [Stocker et al., 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Figure 2.24]

Hydrosphere

Water covers more than two-thirds of the surface of the planet in the form of Earth's ocean, which plays a dominant role in the climate system. Water is unique because it is the only naturally occurring substance that can exist in Earth's climate system in all three phases (solid, liquid, and vapor). These physical states of water and their corresponding changes between states have major implications for the climate system. Change from one state to another matters because there is an inherent energy gain/loss with each transformation. An elaboration on this connection between state of water and energy will occur in Chapter 5. Since water occurs in all three phases, the ocean isn't the only reservoir of water for consideration in describing Earth's climate system.

The **hydrosphere** in Earth's climate system includes all water, in all forms on, under and over Earth's surface (Table 1.1). Salt water in the ocean represents over 96.5% of all water in the hydrosphere, but other forms, including ice and water vapor, must be considered as integral players affecting climate. Of the remaining roughly 3.5%, *freshwater* accounts for approximately 3.4% of that total. Freshwater can be categorized in two realms. Ice, including glaciers, ice caps and permanent snow/ice in polar and alpine regions, represents most of the freshwater in the hydrosphere, about 68%. Some sea ice might be included because when seawater freezes, the ice contains relatively little salt because most of the impurities are excluded as ice crystals form. Some salt is trapped between crystals, but that gradually migrates downward to the seawater below, leaving "freshened" sea ice. Ice has a significant influence on climate, despite its rather small segment of the hydrosphere. The remaining realm of freshwater is accounted for by groundwater, lakes, rivers, streams, soils and atmospheric water in vapor, liquid and solid forms. Hence, despite water's preponderance on the planet, only a very small portion is fresh, or usable and easily accessible for societal endeavors.

Table 1.1
Distribution of water in the global hydrosphere.

Reservoir	Volume (1000 km^3)	% of Total Water	% of Fresh Water
Oceans, seas and bays	1,338,000	96.5	–
Ice caps, glaciers and permanent snow	24,064	1.74	68.7
Groundwater	23,400	1.7	–
Fresh	*10,530*	*0.76*	*30.1*
Saline	*12,870*	*0.94*	*–*
Soil Moisture	16.5	0.001	0.05
Ground ice and permafrost	300	0.022	0.86
Lakes	176.4	0.013	–
Fresh	*91.0*	*0.007*	*0.26*
Saline	*85.4*	*0.006*	*–*
Atmosphere	12.9	0.001	0.04
Swamp water	11.47	0.0008	0.03
Rivers	2.12	0.0002	0.006
Biological water	1.12	0.0001	0.003
TOTAL	**1,385,984**	**100.0**	**100.0**

[Adapted from NASA, http://earthobservatory.nasa.gov/Features/Water/page1.php] Original source: Gleick, P. H., 1996: Water resources. In *Encyclopedia of Climate and Weather,* ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp.817-823.

Notice that moisture in the atmosphere, actually winds up being a very tiny portion of the total water in the climate system. Only one thousandth of 1% of the water in the hydrosphere exists as water *vapor* in the atmosphere. While we focus on this small portion in weather considerations, the climate system mandates that we give greater attention to these other larger reservoirs of water in the hydrosphere and the changing phase of water's various states, as energy is released and absorbed during these phase changes.

The hydrosphere, similar to the atmosphere, is dynamic. Like the atmosphere, movements can be generated by gravity and the second law of thermodynamics, as there are gradients in water just as there are in the atmosphere. Water moves in response to changes in heating and salinity (quantity of dissolved salt content) in Earth's climate system.

The average salinity of the Earth's oceans is about 35 grams of salt per kilogram of sea water or 35 ppt (parts per thousand), while freshwater salinity is usually less than 0.5 ppt. Ocean salinity is affected by changes in the hydrosphere as freshwater enters or exits this reservoir in the form of rainfall, snowfall, via evaporation, river runoff, or ice formation. It's also important to note that evaporation into the atmosphere, followed by movements of vapor, condensation and precipitation is the mechanism by which water is distilled (purified) and made potable again.

Gradients of temperature and salinity cause the ocean to respond and change. Also, at the ocean surface winds of the overlying lower atmosphere cause frictional drag on the surface of ocean water and begin moving it in large quantities. Just as if you blow air across the rim of your coffee cup, the liquid inside will flow and mix in response. Movements of large quantities of surface ocean water ultimately take the form of entire ocean currents, which are sometimes basin-wide in scale. This frictional drag by the atmosphere is limited in vertical scope. Surficial currents of the ocean typically only influence a depth of approximately 100 m (300 ft.). Effects of this influence include upwelling and downwelling, which are introduced later. Since neither the atmospheric wind flow nor solar radiation can directly reach to greater depths of the ocean, movements of *deep* ocean water may take a few months to years, up to a thousand years or more, to cross an ocean basin. We also have challenges in monitoring these deeper layers of Earth's climatic sub-system, as is outlined in Chapter 2.

Cryosphere

As mentioned in the discussion of the hydrosphere, there are significant energy exchanges as water changes phases. Just as essential, there are important controls on energy exchange between the hydrosphere and the atmosphere while water is in its *solid* state. We therefore need an entire sub-system of the hydrosphere to define these solid-state interactions. The **cryosphere** is that portion of the hydrosphere in solid form that includes glaciers, snow cover, ice on bodies of water (sea, lake and river), ice caps/sheets, ice layers within ocean sediments, and permafrost (Figure 1.16). Ice in various geographic locations can influence not only energy exchanges but moisture flows into and out of the atmosphere.

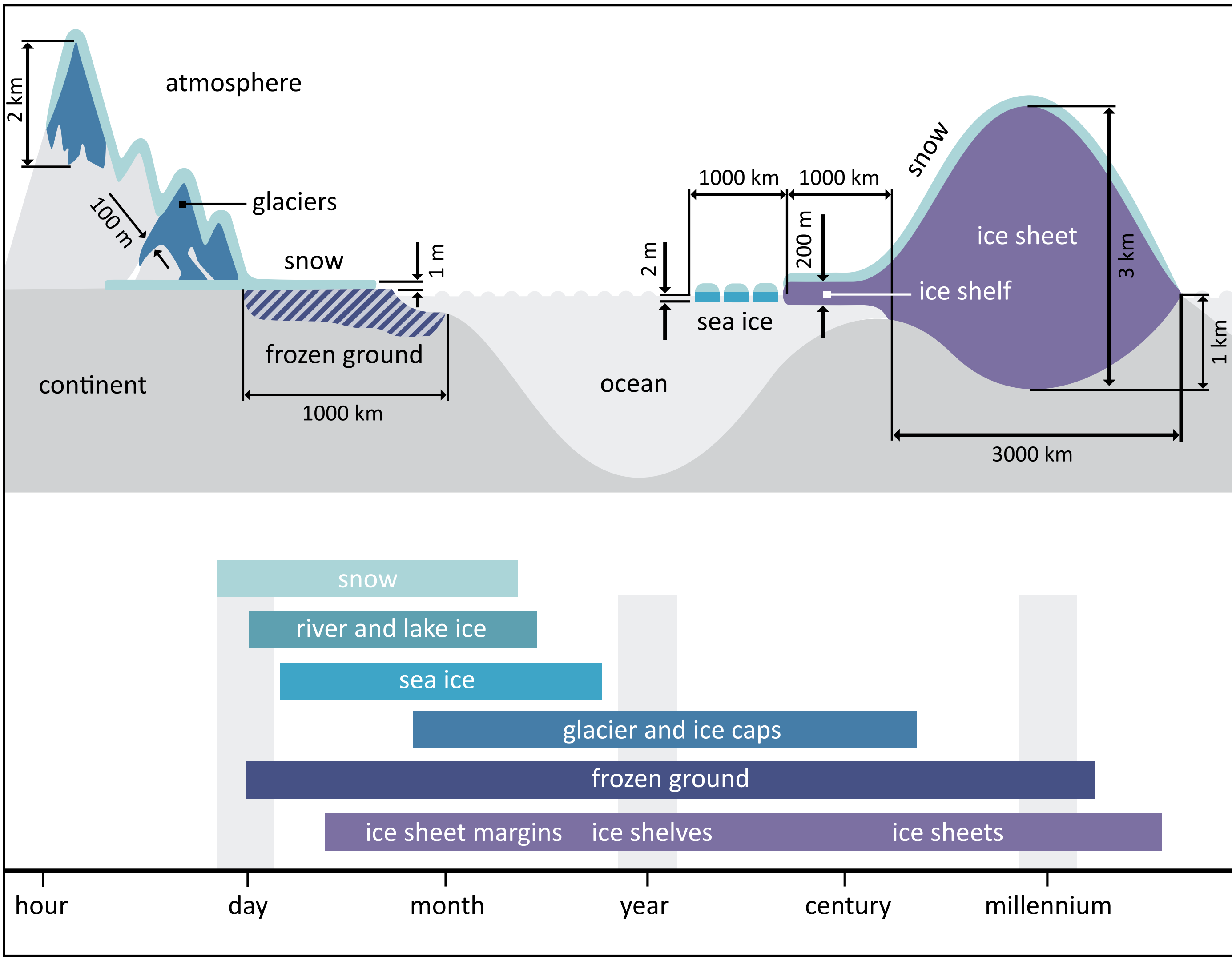


Figure 1.16
Components of the cryosphere and their time scales. [NASA/IPCC]

As one might expect, most of the world's ice volume is found at polar locations. Since there is a large continent positioned at the South Pole versus the ocean surface of the North Pole, a greater proportion of the world's ice is deposited in Antarctica. The East Antarctic ice sheet (EAIS) is the largest ice sheet on Earth (Figure 1.17).

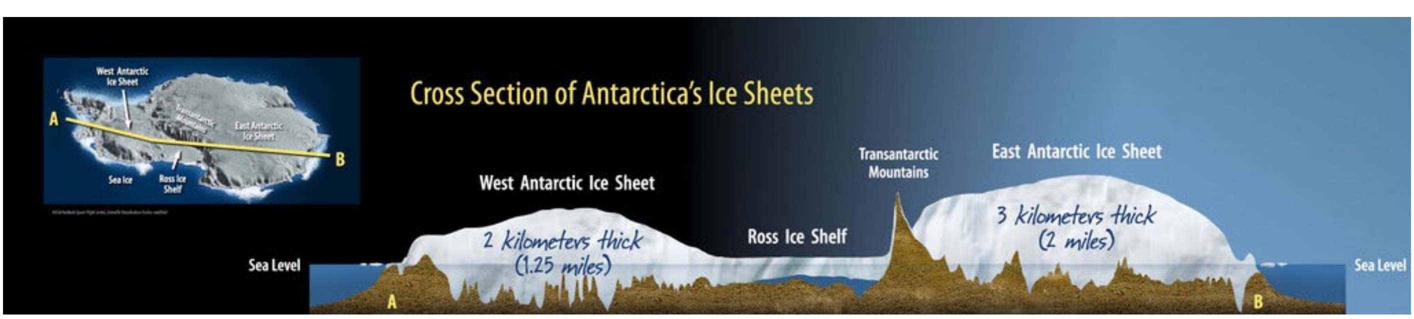
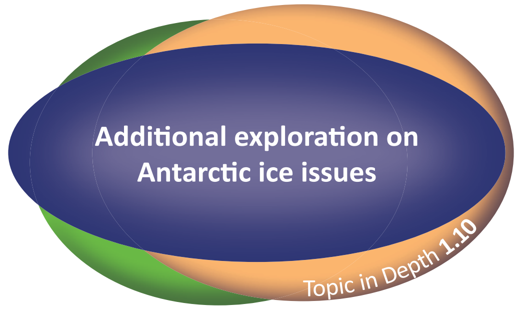
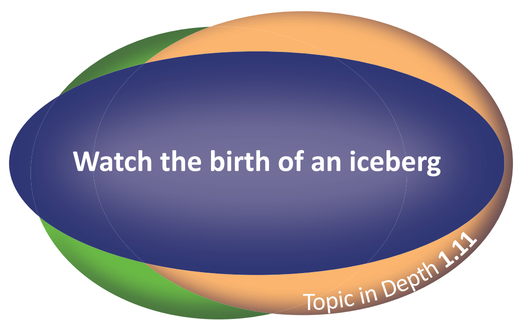


Figure 1.17
Geographic reference and cross section of Antarctica's Ice Sheets. [The Ohio State University, http://beyond-penguins.ehe.osu.edu/issue/learning-from-the-polar-past/a-dinosaur-cast-in-stone]

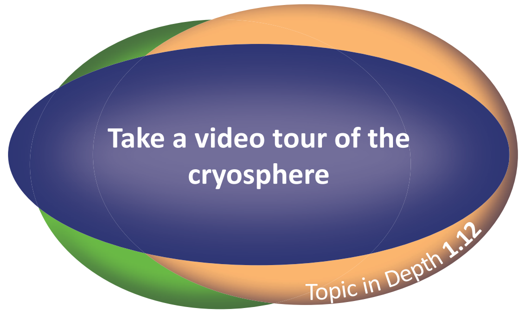


Recent evidence finds that it is particularly vulnerable to climate changes. It was originally thought that such large volumes of ice (EAIS is 3-4 km (9.8−13 ft.) thick) in very cold geographic realms weren't subject to air temperature changes on the global scale. Evidence is mounting that, due to feedbacks (Chapter 8) and oceanic interactions, increased melting (actual ice loss) of this massive ice sheet may occur more rapidly than thawing (rising temperature of ice that is still frozen). As a whole the Antarctic shows very slow growth of ice, which would seem to contradict the record-low ice extent noted recently in the Arctic. However, climate scientist Jinlun Zhang and others assert that changes in the prevailing winds around the Antarctic are counter-balancing the rising global temperatures. It is clear that there are many mechanisms affecting changes within and external to the cryosphere.



As further evidence of the dramatic changes in the hydrosphere and cryosphere, the 2013 IPCC report noted that the human influence in warming the climate system has been detected by noting reductions in snow and ice, in global mean sea-level rise and in changes in some climate extremes. Continued trends into the 21st century include further shrinkage of the Arctic sea ice cover while glacial volumes will decrease further.

If the context of ice is referenced to its *areal* (surface area) extent, Northern Hemisphere winter snow and ice extent comprises the greatest area. On average, 23% of the Northern Hemisphere is covered by snow and ice in the winter months. It is important to monitor the snow cover extent each season on many continents because the snow/ice feedbacks (Chapter 8) with the atmosphere play a substantial role in affecting not only the local but seasonal climate anomalies that occur in a given year. Annual cycles of snow and ice extent are monitored to serve as a potential signal in climate change trends. The National Snow and Ice Data Center (NSIDC) supports cryospheric research by monitoring snow extent, ice, glaciers and frozen ground. Not only do they measure the extent and volumes of ice in many places, but they describe physical properties such as surface reflectance (albedo), ability to transfer heat (thermal diffusivity), and ability to change state (latent heat).



Lithosphere

The atmosphere, hydrosphere and cryosphere are all underlain by the lithosphere, which includes the crust of our planet. The crust may not seem relevant to the climate system until you investigate the interconnections. Those connections play a significant role in affecting Earth's climate system. Earth is mostly rigid with elastic properties at certain depths and the deep core of the planet accounts for much of the planet's mass. The crust, like the rind on an orange, is the outermost brittle layer of the planet on which we reside. The depth of this crust is not uniform. It has varying thicknesses, from 8 km to 70 km (5 – 45 mi.). Thinner portions of the crust are typically found under ocean basins and, conversely, those thicker portions are found under continents with high elevation mountain ranges.

This crust houses mineral resources and fossil fuels that humans utilize in modern society. Many of these hydrocarbon resources (coal, oil and natural gas) underpin the foundations of our modern industrial economy. Chapter 12 is dedicated to discussing the roles each have in relation to greenhouse gas emissions. We can thus define the **lithosphere** as that relatively cool, crusty, outer layer encompassing Earth's surface to the deeper, hotter portions where rocks become more elastic and melt (called the upper mantle) (Figure 1.18).

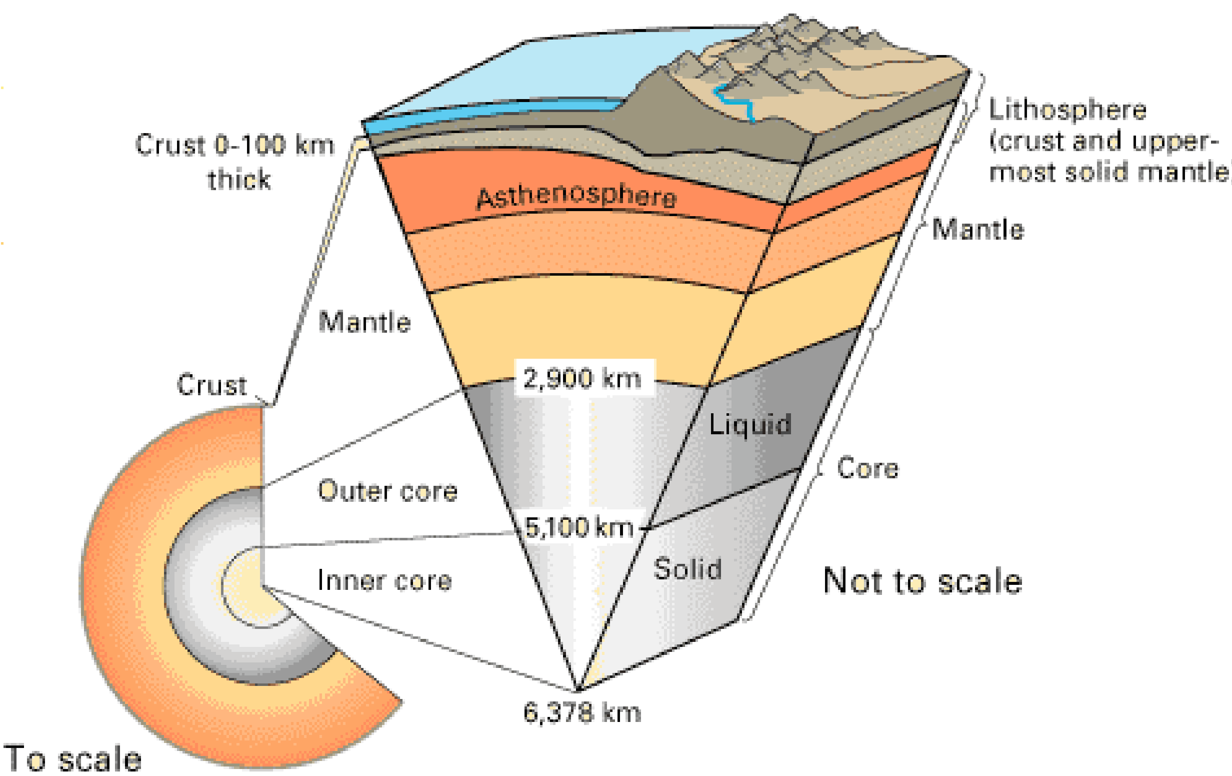


Figure 1.18
Internal structure of the Earth. [U.S. Geological Society (USGS)]

As are the atmosphere and hydrosphere, the lithosphere is also dynamic. Surficial and sub-surface mechanisms alter the shape and structure of the lithosphere. Many of these ongoing processes affect climate on both short term (volcanoes) and long term (plate tectonics) periods.

Plate tectonics is a relatively modern unifying concept in the geosciences. It is based upon the premise that there is a difference in temperatures between the outer crust and deeper depths (beyond 100 km). Cooler rocks and minerals will respond differently to stress. The outer edge of the lithosphere remains relatively inflexible for extremely long periods of time. It may begin to show signs of stress by deforming and cracking, sometimes jarringly (as in an earthquake). By contrast, layers of rock below the lithosphere, called the **asthenosphere**, bend more like a fluid and adjust to stress through plastic-like deformations. Large breaks in the lithosphere can be identified as boundaries of major tectonic plates (Figure 1.19).

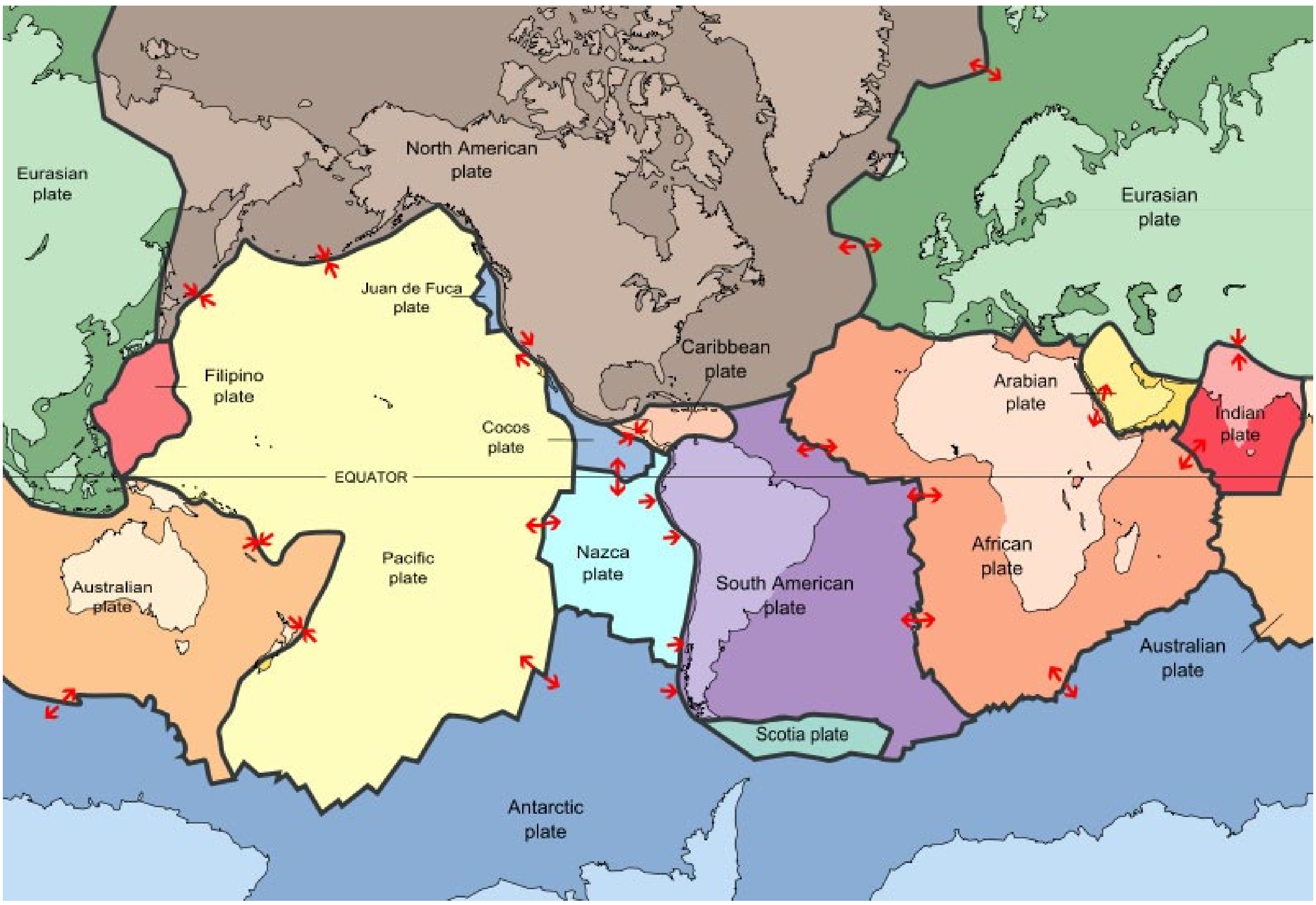


Figure 1.19
The layer of the Earth upon which humans live is broken into semi-rigid slabs called tectonic plates that are moving relative to one another. [USGS]

Continents and ocean basins are imbedded in these massive plates. Over geologic time, movement of these plates can reorient the continents, build mountains, open up new oceans or close old ones, and put new land masses in different latitudes, all of which alter radiative absorption, wind, ocean currents and climate. Additionally, the break-points between or along plate boundaries are often the location of active volcanoes, which expel gases, dust and ash far into the atmosphere. Volcanic debris ejected into the atmosphere alters circulation patterns and radiation input amounts for a year or two, or more in some occurrences.

Volcanic activity is not exclusive to plate boundaries. Volcanoes may occur over hot spots deep below the asthenosphere. A hot spot is a semi-permanent source of magma (super-heated rock in mostly liquid form) caused by rising plumes of hot material originating from below. A hot spot may be active for millennia or beyond, and may shift its location. Expulsion of magma accumulates at the surface and cools, creating new land masses. The chain of Hawaiian Islands is an excellent example of active and inactive volcanoes overlying a hot spot (Figure 1.20).

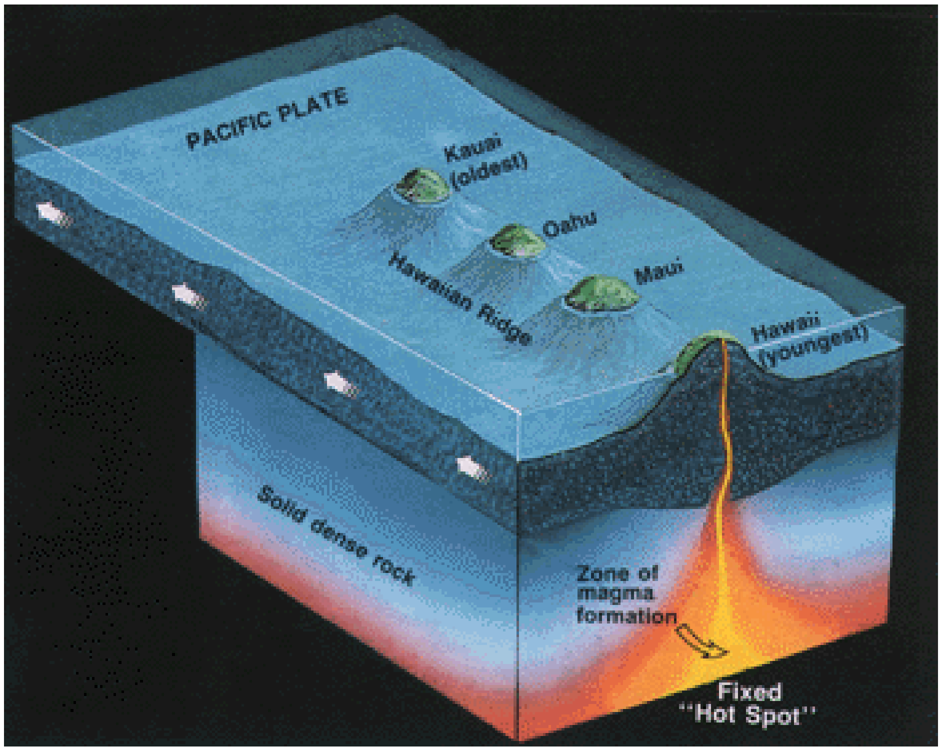


Figure 1.20
Drawing representing the movement of the Pacific Plate over a fixed Hawaiian "Hot Spot", illustrating the formation of the Hawaiian Islands. [USGS]

Over time, movement of plates directs the lithosphere over a stationary hot spot and the hotspot may itself move. In unique locations, a hot spot may coincide with tectonic plate boundaries. One of these hot spots produced the infamous eruption of Eyjafjallajökul, Iceland in 2010, which led to aviation hazards across most of the European continent affecting air travel for weeks (Figure 1.21). Billions of dollars in the aviation business were lost due to this lithosphere-atmosphere connection in the climate system.

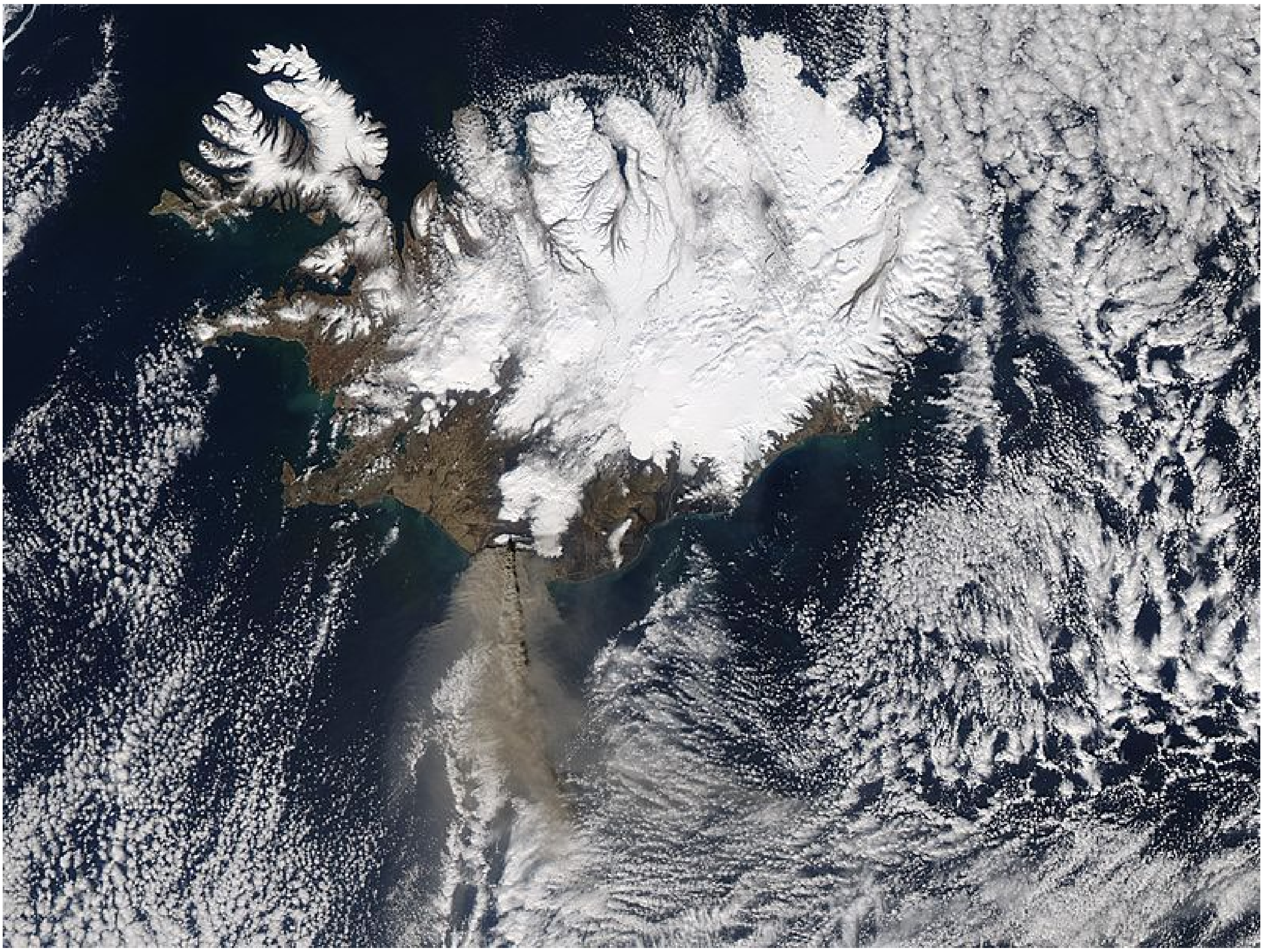


Figure 1.21
Ash plume from Eyjafjallajokull Volcano, Iceland April 17, 2010. [NASA]

An important interface between the lithosphere and all other sub-systems in climate is the **pedosphere**. The pedosphere is the portion of the lithosphere which, through various geochemical processes, forms the world's soils. The pedosphere includes all the organisms in the soils and water and air therein. Weathering and erosion occur at this interface and it is through these actions that chemical and physical breakdown of minerals occurs. Aggregates of one or more minerals, rocks are disintegrated into solution as part of these processes. Water is of primary concern in this environment since it hastens chemical reactions, especially those that affect rocks. Moreover, because of its freeze-thaw cycle, water can exert significant pressures to stress and crack rocks. This enables liquids and solutions to permeate to greater depths of this layer of the lithosphere.

Much of the water permeating this layer coalesces to form vast quantities of groundwater flow (Chapter 5). Plant roots and soil microbes add CO_2 gas to the soil, while other gases escape to the atmosphere as a byproduct of decomposition and other means. Greenhouse gas release is a critical issue based upon what we have discussed previously in this chapter. Consider that there are parts of the Arctic that have slower decomposition processes in the pedosphere due to the ground being frozen continuously from a few to several thousands of years (permafrost). If the region warms during a climate change, these processes in the pedosphere are accelerated and more of the fixed CO_2 and methane (including methane hydrates frozen in the subsurface) are released into the atmosphere.

Biosphere

As mentioned previously, an *ecosystem* is a communal system of plants, animals and microbes within their physical environment. Organisms in ecosystems are dependent upon each other as a source of food and habitat, as well as the elements and other chemical substances within their surrounding environment (water, oxygen, etc.). Geography defines the local boundaries of these systems. The entire collection of Earth's ecosystems worldwide is the **biosphere**. This larger categorical assemblage integrates all living beings and their relationships with the lithosphere, hydrosphere, cryosphere and atmosphere.

Every part of Earth's climate system supports life of some kind. Certain organisms live in extreme environments at temperatures and pressures once considered impossible to support life. Microbes have been found in the upper stratosphere and in the depths of the Mariana Trench (the deepest place in Earth's ocean). Microbes can live at great depths under Earth's terrestrial surface, as they have been directly extracted from cores drilled more than 5 km (3 mi) into the lithosphere. It is estimated that, in total biomass, the microbial life in "uninhabitable zones" may exceed all animal and plant life on the surface. Thus, the biosphere spatially pervades the atmosphere, lithosphere (including the pedosphere), hydrosphere and cryosphere.

Within these realms of the biosphere are producers (plants), consumers (animals) and decomposers (bacteria/fungi). Producers (also called autotrophs for "self-nourishing") form the base of most ecosystems, taking energy from the physical environment, usually solar radiation, and using it to create energy-rich molecules such as carbohydrates. Consumers (heterotrophs) depend on autotrophs for their energy and materials they need to survive. After the demise of any living creature, decomposers, usually bacteria and fungi, break down the remains, cycling nutrients back to the environment. In many cases, autotrophs often draw in these nutrients, which decomposers have broken down, so there are natural cycles among organisms in the biosphere, as there are in other spheres of Earth's climate system (Figure 1.22).

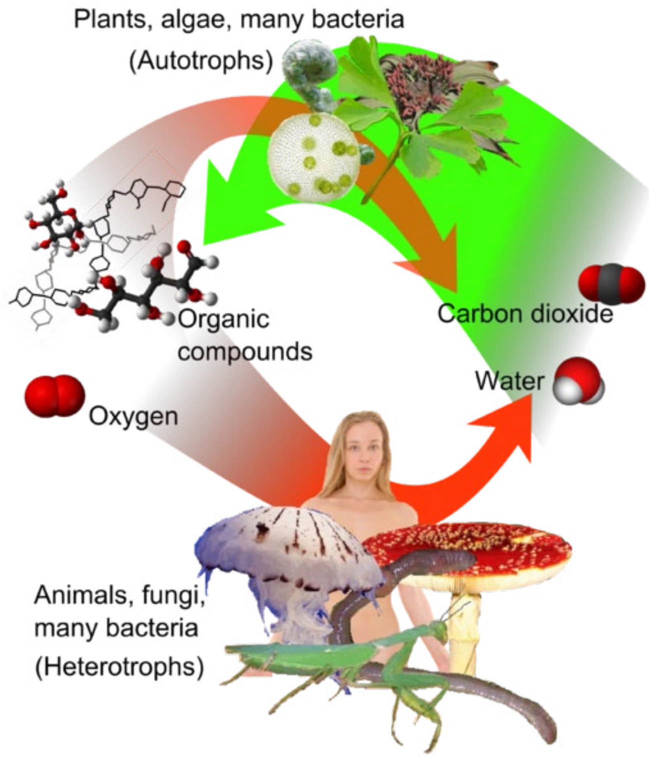


Figure 1.22
Cycle between autotrophs and heterotrophs. Autotrophs can use carbon dioxide (CO_2) and water to form oxygen and complex organic compounds, mainly through the process of photosynthesis. All organisms can use such compounds to again form CO_2 and water through cellular respiration. [Mikael Häggström, http://en.wikipedia.org/wiki/File:Auto-and_heterotrophs.png#filelinks]

As mentioned earlier, nitrogen is the most abundant gas in the atmosphere. While not critical for respiration, nitrogen, like oxygen, is necessary for life on Earth. It is required for photosynthesis and essential for many ecosystem functions (e.g., decomposition). Like carbon, discussed next, there is a fixed amount of nitrogen in the climate system, yet it cycles through many climatic sub-systems. When nitrogen becomes scarce in an ecosystem, growth factors are limited. Additionally, humans have a role in altering the global nitrogen cycle, just as they do in the carbon cycle, which has a direct impact on many aspects of the biosphere, as discussed in greater detail in Chapter 11.

The relationship between producers and consumers in which plants and animals consume or produce energy for other plants and animals is called a *food chain.* Correspondingly, a **food web** consists of all the food chains in a single ecosystem. Each living entity in an ecosystem is part of multiple food chains, each of which is one possible path that energy and nutrients may take as they move through the ecosystem. When taken together, these interconnected and overlapping food chains in an ecosystem define a food web. Humans are an intricate member of the global food web as a dominant heterotroph. Our survival is dependent upon a thriving and diverse set of ecosystems that enable energy and nutrients to be passed throughout the food web. Even more critical, climate is a chief control on ecosystems, delineating many of the boundaries and species composition of ecosystems on Earth.

Climatologist Wladimir Köppen recognized the climatic influence on ecosystems, focusing on plants and their geographic regimes based upon empirical observations of temperature and precipitation in the early 20^{th} century. This relationship between climate and vegetation is the central aspect of his widely used climate classification system (Figure 1.23). Köppen utilized simple expressions of climatic character with average annual and monthly calculations of temperatures and precipitation, and the seasonality of precipitation, creating a system of defined boundaries for local climate conditions. While being immensely popular for most of the 20^{th} century, there are now many more avenues by which we can monitor and classify climate types and communicate its variances across space and time. Thus, the reliance upon vegetation distribution alone to define climatic boundaries has become outmoded, especially in light of denser and more reliable networks of climate observation systems (Chapter 2).

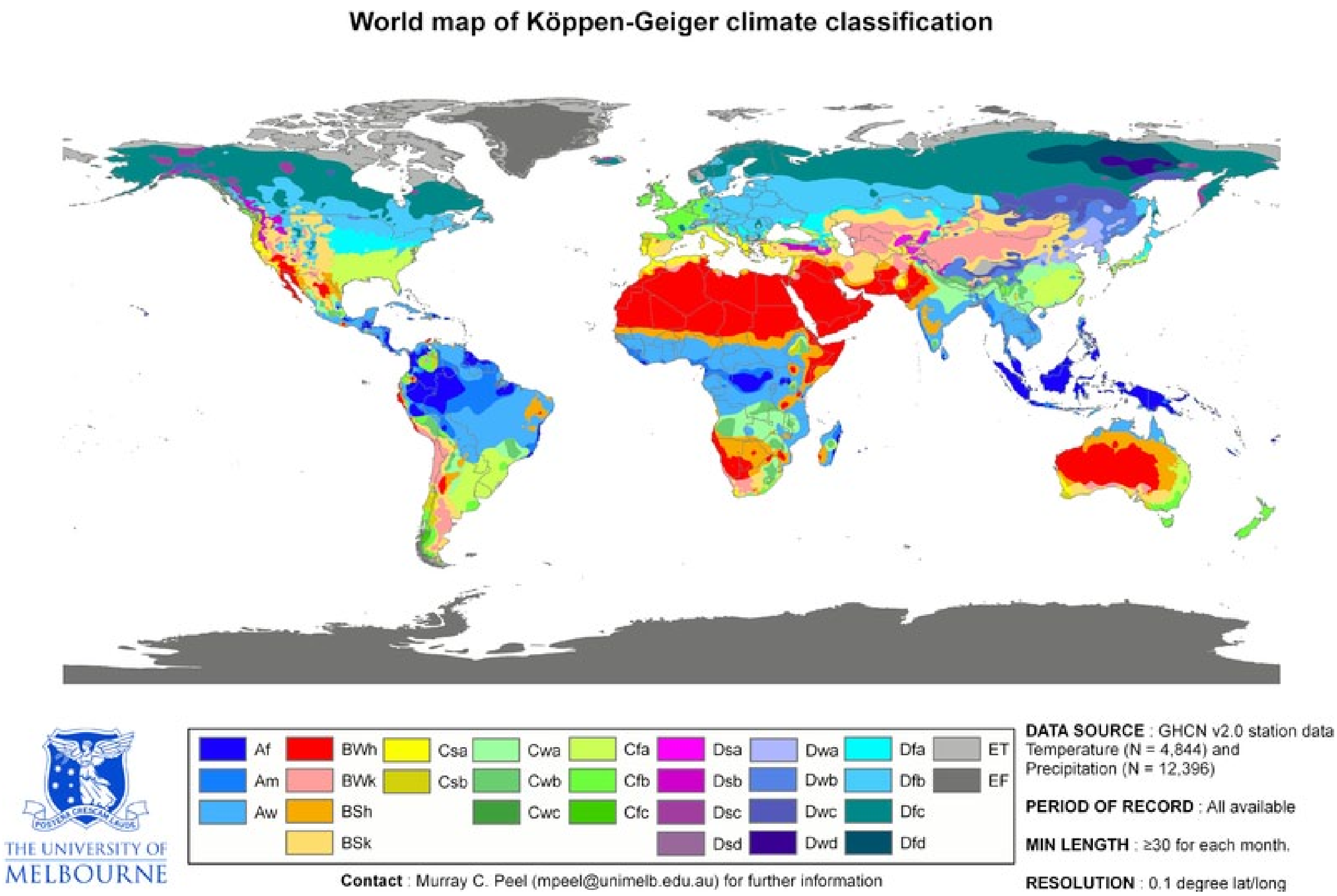


Figure 1.23
World map of Köppen-Geiger climate classification. [Peel MC, Finlayson BL & McMahon TA (2007), Updated world map of the Köppen-Geiger climate classification, Hydrology and Earth System Sciences, 11, 1633-1644.]

Carbon Cycle

We defined climate as the state of a system comprising many “spheres” on Earth. These systems, cycles and sub-systems are all dynamic and interact within and between each other. Some systems may be more or less dominant in regards to their effect on climate, climate variability and change. Senior atmospheric scientist, Michael Glantz notes in his treatise on “climate affairs,” that as with the human body, all components are important to the maintenance and viability of the body and each component of the climate system has a key role to play. Often the atmosphere dominates our attention with climate studies, similar to “focusing on the heart as part of the human body, as opposed to the whole body in order to identify its functions and influences on other parts of the system.” Yet, these other systems, including the hydrosphere, cryosphere, lithosphere and biosphere, all contribute to the state of climate and, ultimately, define how climate varies and changes through time. Moreover, there are various substances that, as they cycle through the spheres, have a significant contribution to climate system. One critical substance is carbon.

Carbon, in its pure form, is a basic element of the chemical periodic table that can have varying structural forms (allotropes), making it commonly recognized as graphite or diamond. A building block of life on Earth and present in all discovered life forms, carbon is the backbone of all the compounds in our bodies. By mass, it is the second most abundant element in the human body. It can be found in large quantities as coal, peat and oil. As an inorganic compound, it can be found dissolved in the ocean, limestone rocks and CO_2 gas in the atmosphere.

Since carbon is found in living entities (bio), non-living entities like rocks (geo) and makes up a myriad of compounds (chemical), it is part of a *biogeochemical* cycle called the **carbon cycle** (Figure 1.24). Carbon is either physically or chemically transformed within or between the biosphere, lithosphere, hydrosphere, cryosphere and atmosphere, existing in many different forms in this process.

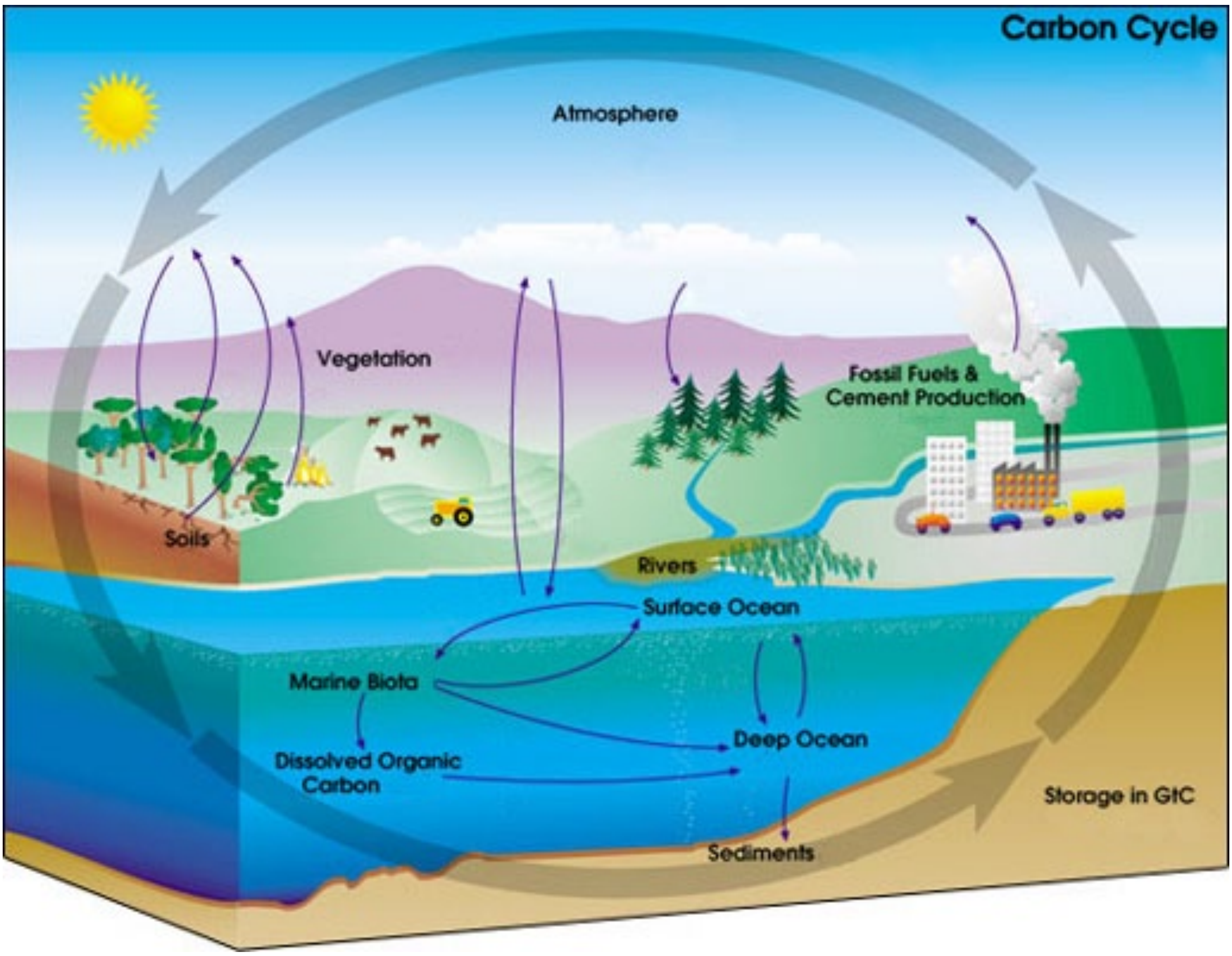


Figure 1.24
The carbon cycle. [NASA]

Associated with these transformations are transfers of energy. Biogeochemical cycles conform to the law of **conservation of matter**, which states that matter can be neither created nor destroyed, but can change in chemical or physical form. For example, when marine organisms die, their remains (shells, etc.) can precipitate down through the deep ocean. These organic carbonaceous materials reach the sea floor, accumulate, are compacted by their own weight and the weight of other sediments, and gradually transform into solid rock. Shifting tectonic plates and uplift may eventually allow for these rocks to be exposed, weathered and dissolved by slightly acidic rainwater. As part of the hydrosphere, carbon compounds can be carried back to the ocean and precipitate or be taken up by organisms and then settle to form new rock materials. Further discussion of the ocean as a carbon sink is done in Chapter 7.

There were periods in the geologic past (300-360 million years ago) whereby a vast quantity of organic carbon was produced, metamorphosed and preserved. Specifically, the *carboniferous period* defines the time frame and literally means “coal-bearing,” since it is derived from the Latin words of carbo (coal) and ferre (to carry). During this time, trillions of metric tons of organic sediments accumulated on the ocean bottom and in continental swamps from dead plants and animals. Because sea-level was so low during this period, swamps acted as reservoirs for organic materials, allowing for greater exposure of low-lying land surfaces, especially in North America and Europe. In swampy ground, heat and pressure from accumulating organic debris concentrated carbon, converting the remains of dense swamp forests into thick layers of coal. That is why we can identify so many coal beds in these continents today.

Another reason for such a buildup of carbon reservoirs was a newly evolving bark fiber on trees, called lignin, which other organisms could not break down. This thicker bark accumulated in vast quantities. Layer after layer of organic sediment accumulated, compressed and ultimately transformed into coal, oil or natural gas. Today, when we burn coal, oil and natural gas, collectively called **fossil fuels**, by such simple actions as driving our cars (utilizing the internal combustion engine), we are pulling energy, which had been locked in vegetation through photosynthesis, from the carboniferous period. During combustion, carbon is again released, adding carbon, stored for eons, as carbon dioxide (CO_2) to our present atmosphere. The reader is encouraged to visit the interactive carbon simulator found in the 'Web Resources' section at the conclusion of this chapter.

Carboniferous period coal beds provided much of the fuel during the Industrial Revolution and are still relied on today. In the past two centuries, our use of these carbon reserves with their stored energy has seriously altered the global carbon cycle. Although carbon dioxide levels have varied naturally over the past several thousand years, our recent contributions over the last several hundred years far exceed natural fluctuations (Figure 1.25).

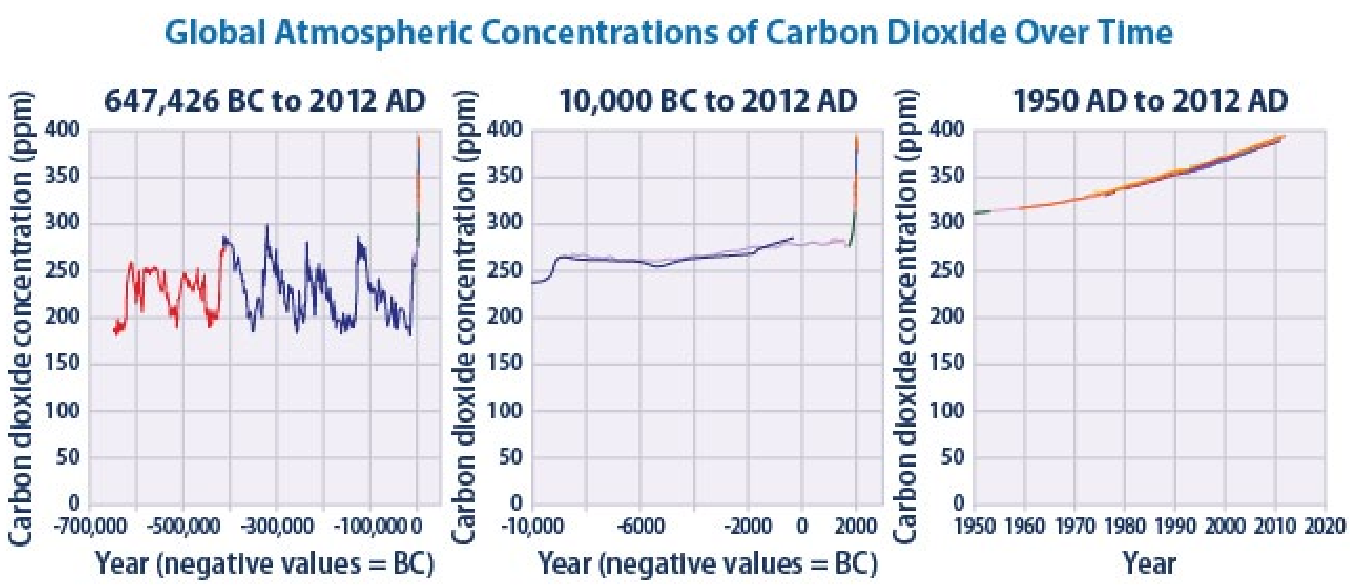


Figure 1.25
Concentrations of carbon dioxide in the atmosphere from hundreds of thousands of years ago through 2012. The data are derived from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source. [EPA]

Biological oceanographer, Paul Falkowski noted in a recent study that "our knowledge of the carbon cycle within the ocean, terrestrial ecosystems, and the atmosphere is sufficiently extensive to permit us to conclude that, although natural processes can potentially slow the rate of increase in atmospheric CO_2, there is no natural 'savior' waiting to assimilate all the human produced CO_2 in the coming century." Through our actions, we've freed trillions of metric tons of carbon into the atmosphere from hundreds of millions of years ago and there is no current, cost-effective way to return this carbon to the land or ocean, leaving only natural processes that will take millions of years. Thus, we are left with fewer choices of what to do about the predicament we are in regarding the continuing energy demands in modern society and the important role fossil fuels play, despite its atmospheric CO_2 injection, in providing this energy.

Chapter 1 Big Ideas:
AMS Climate Paradigm A Changing Climate in a Changing World.

Climate, traditionally defined as the average of weather and the extremes at a particular location over a period of time, has expanded to describe the state of the climate system as a whole. The state of Earth's *climate system*, composed of the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere results from internal and external influences, mutual interactions and feedbacks. Climate is fundamentally the journey of the Sun's energy received on Earth as it is deflected, stored, transformed, put to work, and eventually emitted back to space. Earth's climate system establishes the environmental conditions and sets the boundaries of weather that determine where life, including people, can exist.

Climate is variable and changing, yet is currently shifting at rates unparalleled in recent Earth history. Human activities have become significant drivers of global change, connecting human systems to our planet's biogeophysical processes. This bond positions climate change as part of a complex, coupled human/natural system. Unlike most other life on this planet, our self-awareness informs us, through scientific studies, of our influence on climate. Knowing this, allows us to make choices and take actions related to mitigation and adaptation.

Rapid climate change heightens the vulnerabilities of societies and ecosystems, impacting biological systems, water resources, food production, energy demand, human health, and national security. These vulnerabilities are global to local in scale, calling for increased understanding and surveillance of the climate system and its sensitivity to imposed changes. Scientific research on key climate processes, expanded monitoring, and improved modeling capabilities increase our ability to project the future state of the climate. Climate change is not an isolated problem, but occurs with concurrent environmental change and societal developments that affect our vulnerability and strategies for responding. Although incomplete, our current understanding of the climate system and the far-reaching risks associated with the negative impacts of climate change require dialog between scientists and the broader community for the immediate preparation and implementation of adaptation and mitigation strategies aimed at sustainable development and long-term stewardship of Earth.

For Further Exploration: Climate Literacy

Authored by Chad M. Kauffman

The 2013 IPCC report clearly states that the human influence on the climate system is unequivocally real. The primary evidence for our effect on climate is the consistently increasing levels of greenhouse gases from our energy dependence in burning fossil fuels, such as gasoline, coal and natural gas that power our modern world. The connection between the exhaust gases (e.g., CO_2) and their radiative connection to warming the planet is better understood in light of scientists' increased knowledge of the climate system. Observations collected since the last IPCC report further validate the connection between our fossil fuel burning, greenhouse gases and warming. The increased quality of data and quantity of observations makes it an undeniable connection. Also, our alteration of Earth's surface is instrumental in bringing about climate change.

Yet, no one should feel forlorn by these accounts from climate scientists. They're statements of facts regarding the modern life we lead in much of the industrialized world. There's no single person to blame in the present or the past, as humans have collectively been altering the planet for centuries. In fact, some anthropologists argue that our role in changing the land surface dates back millennia, and especially in the past century, generations of humans had a role in contributing to the current levels of greenhouse gases. Not only do we contribute more today, but we may have reached the precipice of climatic change that affects us in such dramatic ways that it may not be reversible. There are actions that can help lessen this "climate crisis" as climatologist David Archer calls our current state of affairs.

The IPCC reports should instill a sense of resolute determination to learn as much as possible regarding the intricate workings of climate and how we can affect change. In essence what is being described is the process of becoming literate about climate. *Climate literacy* is the ability of a person to have a basic understanding of the climate system, including the sub-systems that define it and the natural- and human-caused factors that change climate. Climate literate individuals understand how observations and records, as well as computer modeling, contribute to the scientific knowledge about the climate system (Chapter 2). They are aware of the fundamental relationship between the climate system and human life and the many ways in which climate has always played a role in human health. They have the ability to assess the validity of scientific arguments about Earth's climate and to use that information to support their decisions.

Climate literacy is an outcome of the recognition of the climate change threat. The U.S. Global Change Research Program (USGCRP) was established to build a knowledge base that describes human responses to climate and global change through integrated federal programs of research, education, communication and decision support. As part of a congressional mandate, at frequent multi-year intervals USGCRP publishes the National Climate Assessment (NCA), an important resource for understanding and communicating climate change science and impacts in the United States. Education is a critical element of this assessment so people know what these assessments mean for them and how their actions affect the climate system. Full comprehension of interconnected climate concepts requires a systems-thinking approach, bringing together interconnections among climate's sub-systems.

Key Terms:

Climate
System
Mitigation
Greenhouse Gases
Adaptation
Climate Variability
Climate Change
Climatic Vulnerability
Sustainability
Ecosystem
Peer Review Process
Climatology
Scientific Method
Open System
Closed System
Trace Gases
Troposphere
Lapse Rate
Ozone
Stratosphere
Mesosphere
Thermosphere
Hydrosphere
Cryosphere
Lithosphere
Asthenosphere
Pedosphere
Biosphere
Food Web
Carbon Cycle
Conservation of matter
Fossil Fuels

Review Questions:

1. Why is climate considered the state of a system?
2. What are the components of the Earth Climate System?
3. How is climate change both local and global?
4. What are the three goals of the Climate Action Plan?
5. How is the climate like a natural resource?
6. What is climate variability?
7. Why must we study the past climate to understand current and future climate changes?
8. What did the IPCC note in its conclusions in 2013 regarding climate change?
9. What is sustainability?
10. What is one of the main reasons for resistance to climate change adaptation?
11. Where is a majority of the surplus global energy being stored?
12. Why is it important to use sources that verify their projections?
13. What is the purpose of a peer review?
14. When was the danger of climate change first reported to the U.S. Congress?
15. How does climatology follow the scientific method?
16. What are the key differences between climate and weather?
17. Why is ozone important to human life?
18. Why is water so special in Earth's climate system?
19. Where is most of the world's ice found?
20. How are we utilizing fuels today that were deposited on Earth millions of years ago?

Critical Thinking Questions:

1. Elaborate on ways in which humans play a role in Earth's climate system.
2. Why is climate change such an imperative concern in today's modern society?
3. Explain why climate can't truly be defined as simply "average weather."
4. What are the distinctions between climate change and climate variability?
5. Identify reasons why the current change in climate is unique in Earth history.
6. Why is it necessary for climate studies to follow the scientific method and peer review processes for investigations?
7. How do the definitions of open and closed systems relate to both the climate system and its sub-systems?
8. What are some ways in which the atmosphere supports human life on Earth?
9. Why can the cryosphere be thought of as a component of the hydrosphere, yet important enough to discuss on its own?
10. Describe how the hydrosphere would interact with the pedosphere.
11. What is our role as humans in the biosphere?
12. Why does the carbon cycle pose a challenging problem in relation to recent climate change?

Web Resources

President's Climate Action Plan
– http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf

U.S. Global Change Research Program: Climate Literacy
– http://library.globalchange.gov/climate-literacy-the-essential-principles-of-climate-sciences-hi-resolution-booklet

National Snow and Ice Data Center
– http://nsidc.org

Polar Ice trends
– http://www.climatecentral.org/news/winds-of-change-why-antarctic-sea-ice-is-growing-16507

Weather and Climate Change
– http://www.climate.gov/news-features/features/global-warming-or-just-weather

Methane and Frozen Ground
– http://nsidc.org/cryosphere/frozenground/methane.html

Carbon Simulator [Annenberg Learner]
– http://www.learner.org/courses/envsci/interactives/carbon/carbon.html

Scientific Literature: Chapter 1

Brown, R.D. and W. Mote, 2009: The Response of Northern Hemisphere Snow Cover to a Changing Climate. *J. Climate*, **22,** 2124-2145.

Busby, J.W., 2007: Climate Change and National Security: An Agenda for Action. Council on Foreign Relations, CSR NO. 32, 40 pp.

Dessler, A.E., Z. Zhang, and P. Yang, 2008: Water-vapor climate feedback inferred from climate fluctuations, 2003–2008. *Geophys. Res. Lett.*, **35,** 1219-1223.

Easterling, D.R. and M.F. Wehner, 2009: Is the climate warming or cooling? *Geophys. Res. Lett.*, **36,** L08706.

Fagan, B., 2004: *The Long Summer: How Climate Changed Civilization*. 1st ed. Basic Books, 304 pp.

Falkowski, P., R. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Högberg, S. Linder, F. T. MacKenzie, B. Moore, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, and W. Steffen, 2000: The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System, *Science,* **290,** 291–296.

Glantz, M.H., 2003: *Climate Affairs: A Primer*. Island Press, 292 pp.

Hubbard, K.G., 2007: Agricultural Climatology. *J. Serv. Climatol.*, **1,** 1-9.

Miles, B., W.J., C.R. Stokes, A. Vieli, and N.J. Cox, 2013: Rapid, climate-driven changes in outlet glaciers on the Pacific coast of East Antarctica, *Nature*, **500,** 563-566.

Mote, T. L., 2008: On the Role of Snow Cover in Depressing Air Temperature*, J. Appl. Meteorol. Clim.*, **47,** 2008-2022.

National Research Council, 2003: *Understanding Climate Change Feedbacks.* The National Academies Press, 166 pp.

Peng, P., A. Kumar, M. S. Halpert, and M. Barnston, 2012: An Analysis of CPC's Operational 0.5-Month Lead Seasonal Outlooks. *Wea. Forecasting*, **27,** 898–917.

Peterson, T.C., P.A. Scott, and S. Herring, Eds., 2012: Explaining Extreme Events of 2011 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, **93,** 1041-1067.

Peterson, T. C., M. P. Hoerling, P. A. Stott, and S. Herring, Eds., 2013: Explaining Extreme Events of 2012 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, **94,** S1–S74.

Ramaswamy, V., M. D. Schwarzkopf, W. J. Randel, B. D. Santer, B. J. Soden, and G. L. Stenchikov, 2006:

Anthropogenic and Natural Influences in the Evolution of Lower Stratospheric Cooling. *Science*, **311,** 1138-1141.

Robock, A., 2003: Introduction: Mount Pinatubo as a Test of Climate Feedback Mechanisms. Volcanism and the Earth's Atmosphere *Geophys. Monogr.,* **139,** 1-8.

Trenberth, K.E. and J.T. Fasullo, 2010: Tracking Earth's Energy, *Science*, **328,** 316-317.

Zhang, J. 2013: Modeling the impact of wind intensification on Antarctic sea ice volume, *J. Climate*, doi:10.1175/JCLI-D-12-00139.1, in press.

End Notes