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Excerpt
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1 Earth's Climate System

1.1 Introduction

The climate system of Earth includes the surface of the globe, the oceans, and the atmosphere, together with the interactions among these across a range of time scales. Understanding and predicting the behavior of the climate system requires both observations of past behavior and objective models that project into the future. In this book, we attempt to explain and illustrate the methods used to create and use climate datasets based on the wide variety of relevant observations.

We use climate to denote the mean state and variations of the physical environment of Earth's surface and nearby atmosphere and ocean. "Mean state and variations" is not adequately well defined without further specification, but here we begin to see the nature of the problem. Hardly anyone would disagree with a statement that the monthly averages of the daily high and low temperatures at some location are climatic parameters. When we refer to a recent month as being relatively warm or cold, we are discussing recent climate events in the context of some longer time period, such as the average of the same parameters over the past 30 years. In the same sense, few who are familiar with the field would claim that yesterday's high and low temperatures are climate parameters – there is some minimum time span that implicitly separates climate from weather. The difficulty is made clearer when we try to unambiguously define a specific time that separates the two.

Similarly, we must clarify which elements of Earth's surface are part of the climate, as well as what we mean by "nearby" atmosphere and ocean. For example, most climate scientists would agree that vegetation growing on the land surface is part of the climate system and must be observed and simulated if we are to understand and predict the climate. Similarly, most would include as climate components water on the surface, in rivers and lakes, ground water within a meter or two of the surface, and snow and ice resting on the surface. The atmospheric part of the climate system certainly includes the lowest 50 or so kilometers, and the oceanic part includes at least the upper several hundred meters.

The climate system also responds to forcing from external agents, and we will discuss the most important ones. Radiation from the sun is a major influence, although we typically exclude radiation that enters the atmosphere from other sources, such as stars other than the sun. Most variations of the solid earth, such as earthquakes, are excluded as well, but large volcanic eruptions produce both particulates and gases in sufficient quantity to affect the climate and are generally thought of as forcing climate variations. We choose to include human activities as another forcing, as discussed in Section 1.4.

Analysis is the decomposition of a complex substance or topic into its component parts in order to improve understanding. While that definition certainly applies to our goals here, there is another quite specialized and idiosyncratic usage that is relevant as well. In the early days of weather forecasting, observations of conditions at a number of points were used to construct maps of, for example, the atmospheric pressure contours over a broad region. Such maps were used to locate significant weather features like storms and fronts. The process of locating and drawing lines connecting points with equal pressure values, or isobars, was referred to as analysis. The term came to be used more generally for the task of creating a complete field on a regular array of points from a sparse and irregularly distributed set of observations. This usage remains common in atmospheric and oceanic science and applications such as weather forecasting. The need for analysis in this sense is particularly critical in climate studies because individual observations are rarely complete in their original form.

So, climate analysis, for our purposes here, is the science and practice of creating and examining complete and comprehensive datasets to describe, understand, and predict the state and evolution of the climate system. The first two chapters provide an overview of the climate system as a whole and a discussion of how climate analyses are performed. Chapter 3 describes the observations and instruments used to form atmospheric climate datasets. Chapters 4 and 5 summarize the nature of climate variability and change. Chapters 6 through 10 discuss in some detail the data that describe the atmosphere, the oceans, the cryosphere and the Earth's surface. Chapter 11 illustrates how these datasets are used together with mathematical models of the climate system to improve our understanding of its behavior and to predict its future. Finally, Chapter 12 describes how the current state of the climate is monitored.

Chapter 1 continues with a very high-level overview of the climate system. We describe the components and their interactions, the external agents that drive changes in the climate, and the systematic behaviors, or cycles, that characterize the system. Since our focus is on climate datasets and the observations and techniques used to produce them, we will not spend much time on the theoretical understanding required to create predictive models – a number of excellent texts are available for that purpose.

1.2 Components of the Climate System

We defined the components of the climate system as the land surface, the upper parts of the ocean and the solid earth, including in particular water in both solid and liquid form, and most of the atmosphere (Figure 1.1).

As with any interactive system, determining where to begin a description is both arbitrary and significant: The order in which elements are discussed will inevitably influence how the discussion is perceived. Our arbitrary choice is to order the discussion

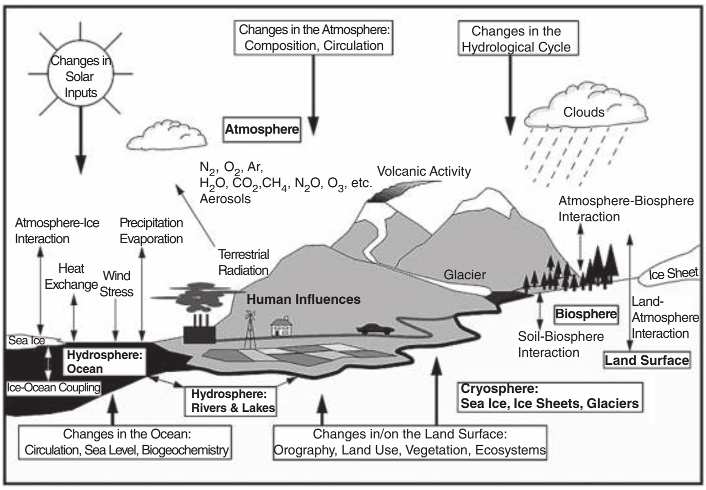

Figure 1.1 Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows).
Source: IPCC Third Assessment Report, Working Group 1, The Scientific Basis.

according to the time scale of the memory[1] of the component. In the atmosphere, this time scale is on the order of two weeks (Kalnay, 2002, p. 31). The ocean's memory is longer than that of the atmosphere, and the other climate system components generally exhibit longer time scales.

The atmosphere is the gaseous envelope extending from the surface to several hundred kilometers. Its characteristics, including temperature, density, composition, and movement, exhibit variations on a wide range of time and space scales. The troposphere and the stratosphere, which make up the lowest 50 km of the atmosphere, are of the greatest significance to our topic and will be the focus here. The troposphere extends from the surface to about 12 km and is characterized by a general decrease of temperature with height; the stratosphere begins just above the upper boundary of the troposphere, the tropopause, and extends up to roughly 50 km. The troposphere and stratosphere exhibit relatively strong coupling[2] with each other and with the surface.

Clearly not all variations of the atmosphere are part of the climate. Time and space scales can separate weather from climate quite effectively, except near the land surface as discussed in this chapter. The atmosphere is a fluid insofar as its variations in

[1] By memory we mean the time scale over which the influence of the initial state endures. For example, the state of the atmosphere at a given time is strongly influenced by its state a few hours before, less so by the state several days before, and little if any by the state a month earlier. A reasonably complete definition of memory in a system can be derived from the behavior of a trusted forecast model: It is the time scale at which predictions beginning from indistinguishable, but not identical, initial conditions diverge sufficiently to be effectively uncorrelated.

[2] Coupling is the linkage between two entities, such as components of the climate system, whose behaviors are influenced relatively strongly by each other. The components of any system are coupled to one another, which provides a useful definition of system: a collection of coupled entities.

temperature, density, and movement or flow are concerned, and its behavior can be described by a set of equations (Panofsky, 2014). Atmospheric composition changes result from interactions with the surface (vegetation, animals, and human society), the solid earth (volcanoes, dust), the ocean (evaporation), and the sun (ultraviolet radiation from the sun creating ozone in the stratosphere). All of these variations can be climate or weather, depending on the scales, and a clear demarcation is not always possible.

In this book, we will consider time scales longer than the memory of the atmosphere, about two weeks, to characterize climate; shorter time scales will be weather. The spatial scales of climate are more difficult to settle upon. In the free atmosphere, above the lowest few hundred meters, climatic scales are relatively large, but near the surface, where large changes in the nature of the surface–atmosphere interaction can occur on very short length scales, microclimates are evident. An example might be where an asphalt parking lot borders woodland; a large diurnal temperature range characterizes the parking lot while the wooded area next to it will exhibit a much smaller range. Such microclimates are found everywhere near the surface, created by terrain, vegetation, and built structures.

The ocean/sea is conventionally defined as the contiguous body of salty water that covers a bit more than 70% of the surface of Earth. For the purposes of this book, ocean will refer to any permanent body of water that is large enough to interact with the atmosphere so as to influence the large-scale climate. Thus land-locked bodies of salt or fresh water like the Caspian Sea, the Great Salt Lake, and Lake Superior are part of the ocean for our purposes. Rivers, transient water bodies, smaller permanent bodies of water, and other land surface water such as swamps will be considered as elements of the land surface.

By far the largest component of the ocean is the conventionally defined World Ocean. While both water and air are fluids and can be simulated using mathematical models, they differ in profound and significant ways. As a liquid, water exhibits defined upper and lateral surfaces, while the gaseous atmosphere does not. Water is also very nearly incompressible, and so the vertical structure and dynamics of the ocean are very different from those of the atmosphere.

In the climate context, it is important that the ocean represents the lower boundary for much of the atmosphere, and that humans rarely reside on or in the ocean for long periods. The surface of the ocean is also more uniform than the land surface. These facts make it convenient for our purposes to ignore most small-scale phenomena in the ocean unless they impact the atmosphere on climatic time and space scales.

Both observation and modeling of the oceans are less advanced and complete than for the atmosphere. This is particularly true for the deep ocean, below the thermocline. The thermocline is the lower boundary of the upper ocean layer that interacts more significantly with the atmosphere, and below which water temperatures vary more slowly with depth. The deep ocean is thought to be extremely important for climatic variation and change on multi-decadal and longer time scales but has been very poorly observed until quite recently.

The cryosphere consists of the persistent ice and snow on Earth's surface. It includes both sea ice and ice and snow on land. Highly transient ice and snow, such as drifting icebergs or short-lived snow cover on land, are not included in the cryosphere, but the seasonal changes in sea ice and snow cover generally are.

The cryosphere, like the ocean, is a part of Earth's surface that is treated in its own category because of its important role in interacting with other components of the climate system and because of its relative homogeneity – otherwise it would be simply included with all other aspects of the land surface. The qualities that distinguish the cryosphere from other land surface elements are temperature, always freezing or below, and albedo. The albedo is the fraction of incoming solar radiation that is reflected from a surface, and snow and ice are characterized by very high values, ranging from 0.5 to as high as 0.9. Few other land surfaces have albedos above 0.4, and so the cryosphere is a very unusual and important element of the climate system due to the role of ice–albedo feedback (to be discussed in the next section).

The cryosphere is made up of a number of different elements, including sea ice, land-based glaciers and ice sheets, and seasonal snow cover. Sea ice can be either transient on a seasonal time scale or persistent, lasting through the warm season but changing on longer time scales. The albedo of sea ice is related to its age – persistent sea ice is typically less reflective – and to the amount of surface melting and fractures, both of which reduce reflectivity. A fresh snow cover greatly increases sea ice albedo. Sea ice is less dense than seawater and therefore floats and moves with both ocean currents and near-surface winds.

Glaciers and ice caps are permanent ice on land, differentiated mainly by size and the nature of movement. Glaciers originate at high altitudes, relative to their surroundings, and flow[3] through valleys to lower altitudes. They terminate at the point where melting and other ablation processes balance the flow. Ice caps or ice sheets are different mainly in that they are thick enough, and extensive enough, that they are not contained within a basin at high altitude. In either case, the climatic significance is the same: They are cold and have a relatively high albedo. Just as with sea ice, albedo tends to decrease with the age of the ice, which, particularly in the case of glaciers, is closely correlated with the distance from the source region. Snow cover increases the albedo of surface-based ice just as it does for sea ice.

Snow that lasts through the winter and melts during the summer is seasonal snow cover. This snow has a strong impact on seasonal climate: The albedo in visible light[4] of freshly fallen snow is the highest of any substantial natural land type, and so a fresh snow cover immediately reduces the amount of solar heating in a region. The albedo of snow depends on its age and thickness. Other characteristics of snow affect the climate in various ways: by insulating the ground below, cooling the air immediately above, and by increasing the thermal inertia of the land surface and delaying the onset of the warm season.

[3] Ice, while solid, is plastic and both deforms and flows over relatively long time periods. Large masses of ice will tend to take on the shape of the underlying and surrounding terrain just as water does, but over much longer time spans.

[4] Albedo can differ for different wavelengths of light. For the most part, the albedo in the visible spectrum is of greatest importance for climate because it controls the heating due to solar forcing.

The land surface component of climate includes everything that contacts the atmosphere and is not included in the ocean and the cryosphere. The land surface is by far the most heterogeneous major component of the climate system, and it is the most difficult to observe and model. It is characterized by abrupt boundaries with sharp gradients in climatically important properties. The most crucial characteristics of the surface with respect to climate are albedo, heat capacity, which is the ability of the surface to absorb heat from the atmosphere or sunlight, and roughness, an abstract parameter that summarizes the degree to which a surface area affects the wind flow over it. These parameters are significant for the ocean and cryosphere as well as the land surface but, as will be discussed in the next section, must be discussed and handled very differently.

The land surface is a mosaic of different elements that have varying roles in the climate. In observations and modeling of the land surface, every resolved element, or pixel,[5] is described by a set of typical values for the climatically significant parameters. Since much of the land surface is covered by vegetation, 10–20 or more vegetation types are often used, in addition to types that describe buildings and other built environments. Unvegetated land, wetlands, and other surface types are also included. Of course, even the most casual inspection of the land surface shows that it is not composed of uniform elements at any spatial scale, and so observing, modeling, and understanding the role of the land surface in the climate system require developing methods for estimating the average impact of relatively large areas with great internal diversity.

1.3 Interactions among Components

Interaction, or coupling, occurs throughout the climate system, both directly and through intermediating processes. Many of the interactions among the components of the climate system occur at the interfaces: atmosphere–ocean, atmosphere–cryosphere, and atmosphere–land surface are particularly important, but every interface plays a role. These interactions are mechanical and thermal in nature, with one component causing change in the movement or temperature of the other; usually each component affects its partner. A particularly important type of interaction is known as feedback, in which a change in some characteristic of the climate leads to a change in another, and the second change leads to a further change in the first characteristic. Feedback can be negative, in which case the initial change leads to subsequent changes in the opposite direction, tending to reduce the first change. On the other hand, a positive feedback leads to a situation in which the first change begins a chain that leads to a further increase. An example of the latter is the ice–albedo feedback in high latitudes, in which an increase/decrease in snow and ice cover causes an albedo change that leads to cooler/warmer conditions and a further increase/decrease in snow and ice cover. A positive feedback tends to amplify a small perturbation, while a negative feedback dampens it.

[5] Pixel is short for picture element and refers to the smallest resolved area in an image. The term originated in the early days of computerized image processing.

Other important interactions are less direct. For example, each of the surface components emits radiation whose intensity and spectrum are related to its temperature and physical characteristics. Some of this radiation is absorbed within the atmosphere above the surface, at locations that depend both on the properties of the atmosphere – temperature, water vapor content, clouds, and other constituents – and the characteristics of the emitted radiation. The atmosphere in turn radiates to the surface, where its effects depend upon the surface properties. This radiative interaction is one of the two principal indirect interactions of climate system components.

Other indirect interactions occur through the movements and phase changes of water. Water in the form of gas, water vapor, is a significant component of the atmosphere and, when in liquid or solid form, constitutes clouds and precipitation. The oceans are essentially all water, and the cryosphere is the solid form of water, or ice. Water vapor and clouds strongly affect radiation within the atmosphere in various ways, and heat is absorbed or released when water changes phase.[6] Movement of water in any form from one climate system component to another is an important aspect of climate variability and change, and it must be observed and understood if we are to understand the workings of the system as a whole.

The roles of radiation and water in climate system interactions are both central and complex, and good observations are vital. Obtaining these observations is difficult, because many of the needed values are nearly impossible to measure directly and must be deduced from observations of related phenomena. For example, direct measurements of clouds are not possible except in limited situations, and so cloud properties must be estimated from observations of atmospheric radiation by satellites. Models are used to complement observations to understand hydrological and radiative processes, but they also suffer from significant limitations.

One additional important agent that plays a role in the climate system is the biosphere. For the most part, we will incorporate observations of the biosphere into our discussion of vegetation on the land surface and the impact of phytoplankton on optical properties such as color in the ocean. Larger animals will not be discussed, with the exception of humanity, which has a number of significant impacts on the climate by changing the characteristics of the land surface and the atmosphere. In that sense, humanity is a part of the climate system and interactions involving humans should be included, but in this book we will take the perspective that humanity is one of the forcing agents for climate, as discussed in the next section.

1.4 Forcing Agents

We have discussed the components and interactions that figure in the climate system, but no system can be fully appreciated without an understanding of the external influences that affect it. In the case of the climate, these are the agents that cause variability

[6] A change in phase, or state, is a change from any of the solid, liquid, or gaseous states to any of the others.

and change but which are not themselves affected significantly by the direct response of the climate. We will consider three main forcing agents of the climate system: radiation from the sun, the geology of Earth, and humanity.[7]

The sun provides nearly all of the energy that drives the climate system on Earth. Nuclear fusion within the sun releases a very large amount of energy that supports a solar surface temperature of nearly 6000K.[8] Like any object, the sun emits thermal radiation with a spectral profile and intensity determined by its surface temperature. This radiation is strong enough that at the average distance of Earth's orbit the solar constant, a measure of the solar radiation at all wavelengths, is about 1361 W/m^2. Two things affect the amount of solar energy available to the climate system: fluctuations in total solar irradiance (TSI)[9], resulting from changes in the sun itself, and changes in the amount of radiation that impinges on Earth at a given point due to changes in its orbit and orientation over time.

Changes in TSI affect the entire planet in a consistent way, increasing or decreasing the amount of energy available at the top of Earth's atmosphere. Variations in TSI could not be measured very accurately until the advent of observations using instruments on Earth-orbiting satellites; since 1978 observations from a number of different satellite instruments have found that the systematic variation associated with the 11-year sunspot cycle is about 0.1%, which is associated with a change in global mean temperature of about 0.2K from solar maximum to solar minimum (Camp and Tung, 2007). Cycles in TSI with much longer periods have been hypothesized based on proxies for TSI, but strong evidence for climatic impacts of such cycles has not been found. Over very long time scales on the order of billions of years, solar evolution has led to an increase in intensity that is expected to continue, but these time scales are far too long to concern us here.

Since Earth is roughly spherical, the amount of solar energy that falls on a given area changes with latitude, being greatest in the tropics when the sun is nearly vertically overhead and least in the polar zones where the sun is near the horizon. Since Earth is tilted with respect to the plane of its orbit around the sun, the amount of sunlight hitting any latitude changes with the season, and because the orbit is not a perfect circle, the intensity of sunlight changes through the year as well. The impact of the tilt is substantially greater than the effect of the elongation (ellipticity) of the orbit in any given year, and while both have substantial impacts on the climate, those impacts manifest themselves as the annual cycle; climate variability and change take place relative to that annual cycle.

Over longer time spans, Earth's spin axis precesses, changing the tilt relative to the timing of the orbit, and the ellipticity of the orbit fluctuates as well, changing the timing

[7] The activities of humans clearly affect the climate on small scales and large, and so treating humanity as a forcing agent is easily justified. We recognize that, conversely, changes in the climate affect humanity, and so it would be possible to consider humans as a climate system component. In this book, however, we choose to limit our discussion to the impacts of humans as a forcing.

[8] K stands for Kelvin, the standard unit of temperature measurement above absolute zero. The other temperature unit we will use is C, or degrees Celsius; 0° on the Celsius scale corresponds to about 273K.

[9] Total solar irradiance is the total amount of radiation emitted from the sun across all wavelengths.

of perihelion, when the Earth is closest to the sun. These Milankovitch Cycles,[10] while small, lead to changes in the seasonal timing and distribution of solar insolation that are thought to determine the timing of glacial/interglacial cycles over the past million years or so.

The geology of Earth is an important influence on the climate system. The distribution of the continents determines the locations of oceans and seas, and mountain ranges and other features of the land surface influence atmospheric circulation and associated weather; all of these contribute to the characteristics of the climate. These features of Earth's geology do not themselves vary on time scales relevant to this book except on spatial scales smaller than we will consider. On much longer time scales, continental drift changes the position of landmasses in ways that modify oceanic and atmospheric circulations and is thought to be one of the factors in the transition between ice-free and glaciated conditions.

While most geological events and changes do not lead to climate variability on time and space scales of interest here, there is one that does. Volcanic eruptions can produce extremely large volumes of climatically relevant gases and small particles that can each have significant climatic effects. Volcanoes emit a wide range of gases, among them carbon dioxide, water vapor, and sulfur dioxide. Carbon dioxide and water vapor act as greenhouse gases,[11] being largely transparent to solar radiation in the visible spectrum and opaque to terrestrial outgoing radiation in the infrared. Individual volcanic eruptions are not thought to produce enough greenhouse gasses to impact the climate, but eras with extremely active volcanism may do so.

Sulfur dioxide has the reverse radiative effect: in the atmosphere, it reacts with water vapor to form sulfuric acid that condenses to sulfate aerosols in the stratosphere. These sulfate aerosols have a high albedo and tend to reflect a significant amount of solar radiation. Since the stratosphere has limited vertical interchange with the troposphere, once there the aerosols tend to have relatively long residence times, leading to a climatically significant reduction in solar heating and a decrease in the global mean surface temperature. The same eruptions that produce sulfate aerosols tend to generate particulate aerosols that also produce cooling, but these have shorter residence times.

The climatic effects of volcanoes depend both on the eruption size and on the number of eruptions in a given time period. There is general agreement that the effect of individual large eruptions on global mean surface temperature is detectable. Some recent studies have suggested that a series of large eruptions over a relatively short time led to a much longer lasting planetary-scale cooling (Miller et al., 2012).

There is no doubt that humans have had detectable impacts on the climate. Changes in the land surface on small spatial scales, such as pavement or changing vegetation, have obvious effects. Since humans do similar things everywhere they live, these effects

[10] After Milutin Milankovitch, a Serbian astrophysicist who calculated the impact of these factors on the amount of solar energy reaching Earth at various latitudes and seasons.

[11] The reference is from a purported analogy to greenhouses, in which visible solar radiation enters generally unimpeded while the infrared radiation of the warm surfaces within the structure is mostly retained. In actuality, greenhouses are warmer because they are enclosed and warm air cannot convect away, but the term has become entrenched.

may aggregate to detectable levels. The variety of ways in which humanity and civilization affect the climate system is large, although the impacts on the global scale remain relatively subtle.

Two of mankind's earliest activities, agriculture and animal husbandry, appear to have had measureable climatic impact. Agriculture always leads to a significant change in vegetation on the surface by replacing indigenous plant life with a less diverse population. The albedo of a cultivated area is nearly always different from its uncultivated state, and the exchanges of water and heat over such surfaces are generally quite different as well. Many of the activities associated with agriculture, such as plowing and harvesting, are also accompanied by aerosol production. All of these factors can have impacts on local climate, changing the microclimates dramatically. When extended to large amounts of land, as in deforestation of entire regions, global scale impacts have been suggested, although not yet clearly demonstrated in data.

Animal husbandry is another of humanity's ubiquitous activities and might impact climate in at least two ways. Many of the animals that humans raise for food are responsible for methane emissions, and because methane is a strong greenhouse gas, a warming effect might occur. Another evident impact of husbandry is through its impact on vegetation: forests are replaced by pastureland to facilitate raising animals. This changes both the albedo and the local fluxes of water and heat, and if extended over large enough areas it can have climatic impacts. A mechanism related to these effects may have led to desertification and drought in western Africa (Charney et al., 1977).

The use of chlorofluorocarbon (CFC) gases as solvents, refrigerants, and fire suppressants expanded rapidly from the mid-twentieth century due primarily to their very low toxicity and generally low reactivity. Their use in air conditioning systems, fire extinguishers, and as aerosol propellants led to significant and growing releases into the atmosphere. CFCs do not interact strongly with other atmospheric constituents and do not condense at atmospheric temperatures and pressures, and therefore they have a long residence time. Their presence in the free atmosphere was first demonstrated in the early 1970s, and shortly thereafter the possibility was raised that significant amounts of CFCs would be found in the stratosphere, where the presence of energetic solar ultraviolet radiation could allow them to play a more active role. It was found fairly soon afterward that CFCs were indeed catalyzing the destruction of stratospheric ozone, leading to significant decreases in ozone, particularly over Antarctica during the Southern Hemisphere winter, and to increases in ultraviolet radiation at the surface with potential associated increases in health effects. CFCs are also a strong greenhouse gas, but the Montreal Protocol, an international treaty that led to large reductions in the use of long-lived CFCs to reduce impacts on health, has limited the impact of CFCs on climate.

Carbon dioxide, or CO_2, is released by the burning of vegetation and is also a principal product of the combustion of fossil fuels. Carbon dioxide is another greenhouse gas, transparent to visible radiation from the sun but opaque to infrared radiation from Earth's surface, and so changes in its atmospheric concentration can impact global climate. While biomass burning, the term applied to combustion of vegetation, releases substantial amounts of CO_2, the climatic effects are partially balanced by the fact that