ATMOSPHERE, CLIMATE, AND CHANGE

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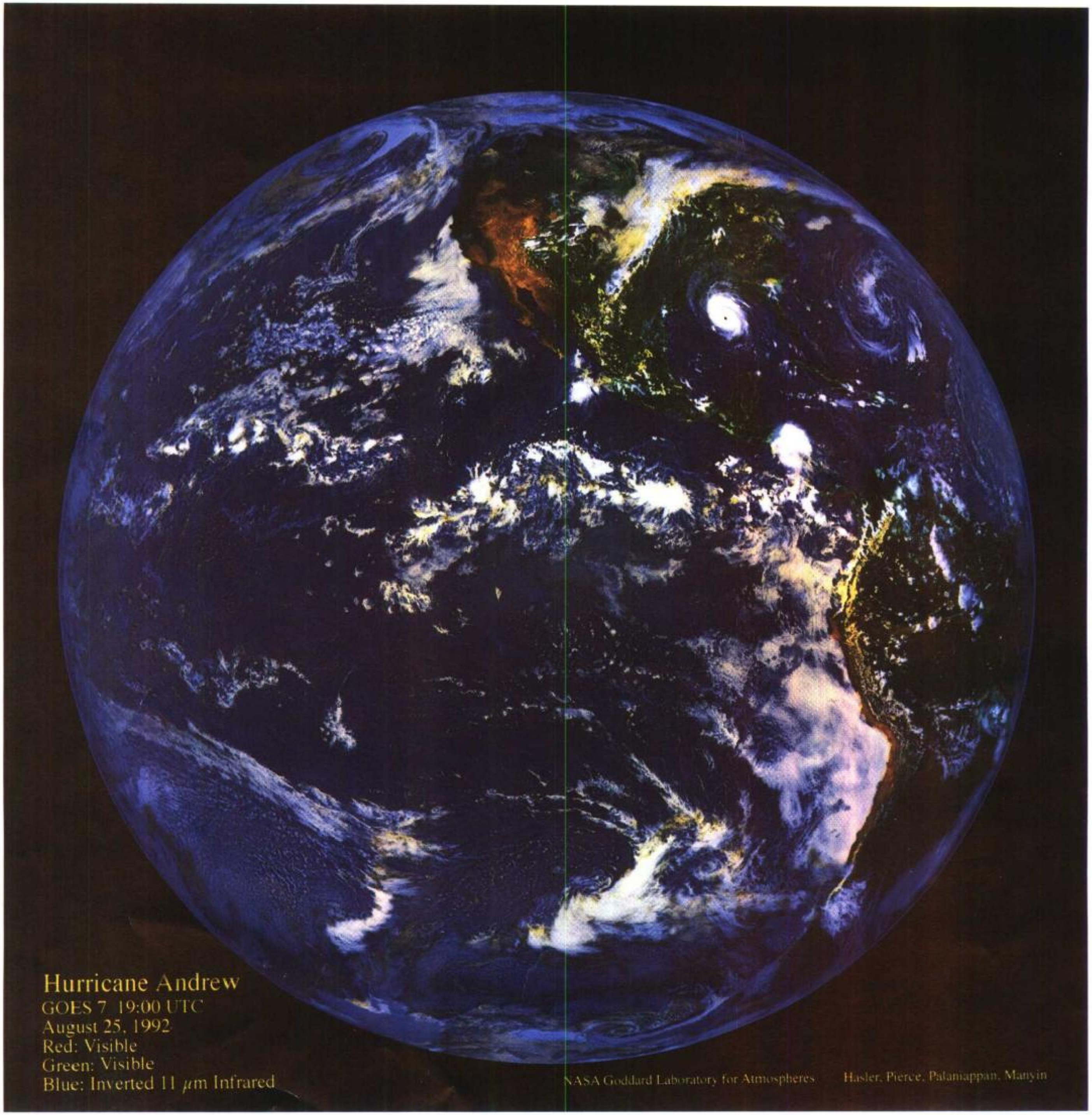


Hurricane Andrew nears the east coast of the United States in this August 25, 1992 image from the GOES satellite. It is conjectured that one of the consequences of global warming could be an increase in the frequency of hurricanes and tornadoes.

Preface

When the two of us were college students in the 1960s, almost nothing was known of the chemistry of the atmosphere and the resulting effects on the climate of our planet. It was our great good fortune to help launch these areas as fields of study and then to participate in the explosive growth of understanding as increasing numbers of outstanding scientists addressed these topics. The excitement of this work has perhaps been heightened because every living thing on Earth is affected every day by atmospheric and other planetary processes—heating by the Sun, the formation of clouds, cycles of volcanic emission and deposition—and that appreciating how these processes work is not science removed to an ivory tower but science thrusting itself into all our lives. There is perhaps no greater thrill, at least not for us, than learning how our planet goes about its business, and each day we learn more.

In studies of environmental chemistry and climate, it is quite natural for the atmosphere to take a central role, but more and more specialists in those fields find themselves entering into collaborations with oceanographers, soil scientists, hydrologists, volcanologists, plant pathologists, and hosts of other kinds of experts, because Earth's complex processes—especially atmospheric ones—very quickly override interdisciplinary boundaries. Thus, we cannot write meaningfully about the atmosphere without discussing the entire Earth system to some degree. Such an endeavor can be a wonderful intellectual exercise for authors and readers if done properly, chaotic if not. We hope we have struck the right balance in dealing with these topics. Another issue we wrestled with was whether and when to use chemical equations, cognizant of Stephen Hawking's rule that each equation included in a book would halve the sales. Our eventual decision was a compromise: although some explicit chemistry was necessary for optimum understanding, we did confine its use to Chapter 3 (and a bit in Chapter 5). Readers who wish a general picture of atmospheric change can acquire it while skimming that material, but we encourage you to spend a little time with it; the result will be a much better understanding of how the atmosphere works.

Notwithstanding our enthusiasm for learning about what we might call "the atmosphere as it functions today," it is obvious that *changes* in the atmosphere and climate have become such a media topic that concerns about the atmosphere are now a common part of our lives. Every month brings, it seems, a new potential horror story about a different threat to the planet, with the atmosphere at the forefront of many of them: acid rain, smog, the ozone hole, global warming. Thoughtful people are led to ask a few reasonable questions: Are there really so many problems? Why don't scientists understand them better? How accurately can scientists predict the future? Must people change their way of life in order to help solve these problems?

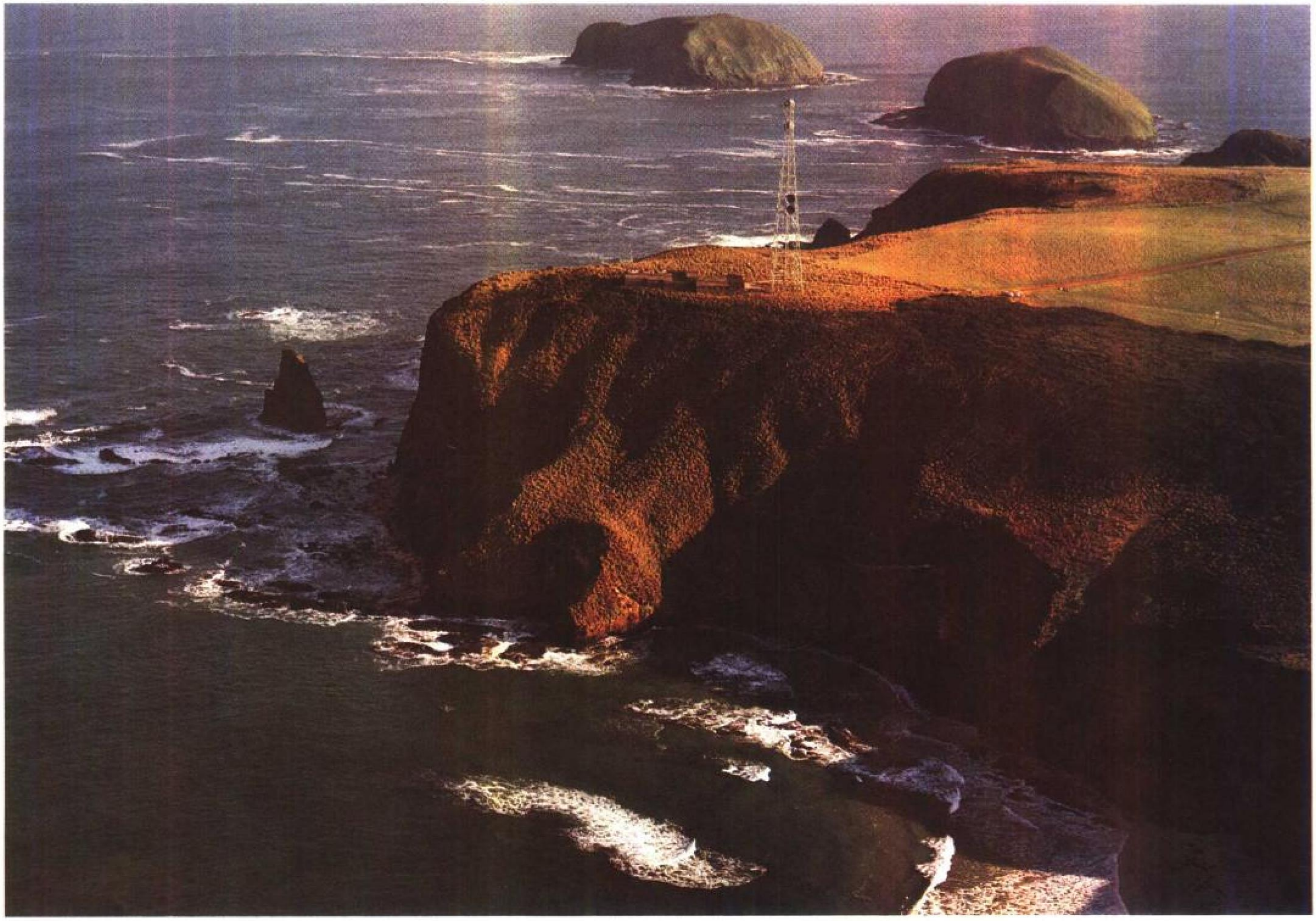
In this book, we try to answer some of these questions and to indicate why answers to some of the others still elude us. In many ways, atmospheric and climatic change are symptomatic of many topics currently under discussion in our technological society, where attempts to solve scientifically related problems often seem to be motivated more by corporate public relations or political propaganda rather than by facts or, at least by informed opinion. Practical responses to global change and steps toward the sustainable development of the planet will not be made by scientists alone. Rather, scientists must share their knowledge with society as a whole in the hope that political leaders and citizens of all kinds can work together to make rational decisions about the future of "Spaceship Earth." It is disturbing but true that many of the technological problems facing humans today have three attributes that render them very different from traditional social problems: they have developed (and can only be remedied) over a long time scale, decades to centuries or more; many of the details of their causes and consequences are likely to be uncertain at the time decisions must be made; and the results of ignoring them may be catastrophic.

This book owes its existence to a textbook entitled *Atmospheric Change: An Earth System Perspective*, which we prepared for science undergraduates in colleges and universities. We had intended, early in its development, to write the book so that it could serve a lay audience as well. This eventually proved to be impossible, and we have instead used the textbook as a resource from which to draw in writing the present volume.

A number of our scientific colleagues read portions of early drafts of the present material. We are especially grateful to Russell Dickerson and Alex

Pszenny, who reviewed the entire manuscript. Many of the staff at W. H. Freeman and Company have provided important, often invaluable, service. We are especially pleased to single out Jonathan Cobb, under whose overall guidance this project took form, Moira Lerner, whose fierce determination to make each concept understandable and each sentence proper has added greatly to the clarity of the presentation, Travis Amos, who labored to find just the right visual images to illustrate our ideas, and Diane Cimino Maass, who guided all the pieces into final form as project editor.

As always, we thank our wives, Susannah and Terttu, for their love and support.



The atmospheric measurements station at Cape Grim, Tasmania.

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1

Taking the Pulse of Earth

Civilization exists by geological consent, subject to change without notice.
—Will Durant

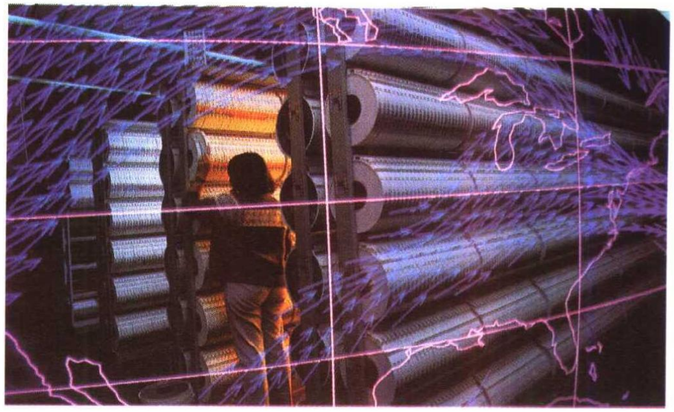
Cape Grim, at the western edge of Tasmania, was well named by the early mariners who attempted to avoid its shoals and rocks. Today, perched on a Cape Grim cliff, an atmospheric measurements station of the Commonwealth Scientific and Industrial Research Organisation of Australia receives air that has traveled over 5000 kilometers (km) of southern ocean. Since 1976, concentrations of atmospheric chemicals have been measured here at regular intervals.

Halfway around the world from Cape Grim is Mauna Loa, a volcanic peak on Hawaii's largest island. Upon its western slope sits an atmospheric measurements station operated jointly by the Scripps Institution of Oceanography in La Jolla, California, and the U.S. National Oceanic and Atmospheric Administration. On most days, the wind is from the west, bringing air that has crossed half the Pacific Ocean on its passage from China. Carbon dioxide and other gases have been monitored at Mauna Loa since 1958.

Cars, buses, and motorized cycles jockey for space on the crowded streets of a university suburb of Mainz, Germany. Above them, students of the Max Planck Institute for Chemistry assemble on a rooftop to examine the readings of instruments measuring sulfur and nitrogen oxides, ozone, and other urban air pollutants, as well as wind speed, wind direction, and rainfall.

Working in offices at the University of East Anglia in Norwich, England, researchers organize and analyze temperature measurements from hundreds of locations around the world, deriving average hemispheric and global temperatures to determine whether the planet is cooling or warming.

At Cape Grim, evidence accumulates that the concentration of small atmospheric particles is increasing. At Mauna Loa, atmospheric carbon dioxide concentrations show not only an annual cycle corresponding to plant photosynthesis and respiration, but an underlying upward trend related to the global use of fossil fuels. At Mainz, urban ozone is showing an increase. In Norwich, analyses of historic temperature measurements show Earth to be about half a degree centigrade warmer than a century ago. As the pace of investigation has intensified over the past few decades, scientists have become increasingly aware that such phenomena are not independent attributes of continent, ocean, and sky, but the vital signs of an interconnected system. We are all familiar with how physicians approach the human system: they measure pulse rate, cholesterol level, and motor function as clues to the state of the system and to the rates of change of its properties. In just such a way, today's geoscientists monitor what the British scientist James Lovelock has termed "the physiology of Planet Earth."



A climate forecast for the North American continent, as produced by the meteorological center at Reading, England. Massive amounts of atmospheric information are needed to produce the computer calculations that generate the forecast.

The Earth System Perspective

Systems of all types share a few common characteristics, the most basic of which is that each is a group of interacting, interrelated, or interdependent elements forming a collective entity. Another characteristic of systems is that they are dynamic, reacting constantly to driving forces and perturbations from within and from without. A consequence of this dynamism is that the longevity of a system is not assured: some systems remain virtually unchanged for long periods, others alternate rapidly between growth and decline, some sicken and die. Our view of Earth as a dynamic, interdependent system is supported in part by solid evidence that the planet has seen all these stages except the last, and perhaps even that stage can be predicted.

Developing scientific approaches to imperfectly understood systems has been the central focus of ecosystem ecologists, who attempt to understand ecosystems (the living organisms that make up an ecologic community together with the physical environments that they occupy) by evaluating how each element functions as a part of the greater whole. They also attempt to understand how entire ecosystems evolve and age, as perhaps happens in all cases but certainly occurs if external conditions change.

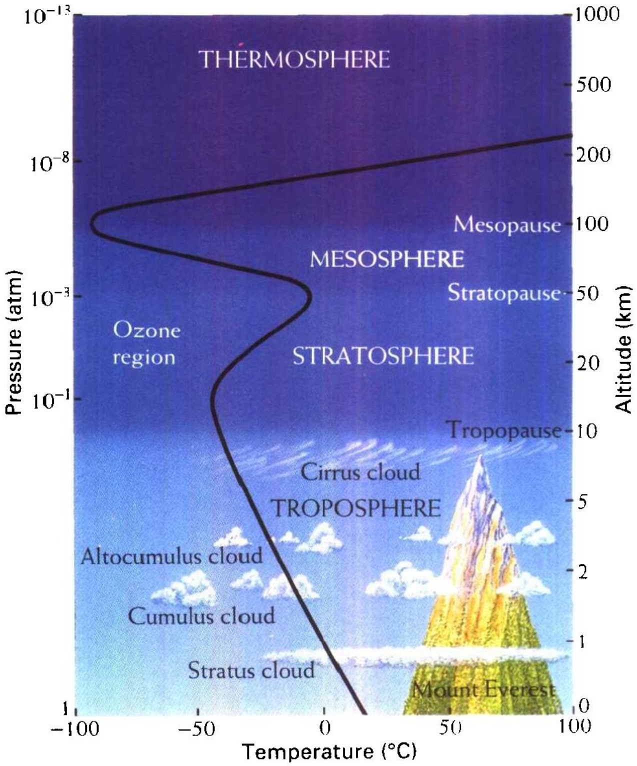
If Earth, then, is properly labeled a system, it should be possible to describe its processes in the same terms that ecosystem scientists use, and indeed we can do so. Its energy sources (that is, its driving forces) are solar radiation and, to a substantially smaller degree, the heat lost gradually from Earth's hot inner core. Earth's primary digestive system, if we may so term it, is its plant life, which transforms a fraction of the energy that is supplied into useful forms such as leaves and seeds. And, just as ecosystem elements such as birds or elephants adjust their immediate physical states by eating food or seeking shelter, elements of the planetary system such as oceans, deserts, and tectonic plates adjust their physical states by such processes as the evaporation and condensation of water and the exchange of minerals.

Ecosystems often respond quickly and dramatically to changes in energy sources, as the Earth system does to fluctuations in solar radiation. Hence, we are here concerned with possible changes in solar radiation, with the responses of the receptors of that radiation, such as ice caps and maple trees, and with the factors that influence those receptors. Ideally, we hope to study and predict those changes on all time and space scales that have a bearing on the system's behavior. In practice, of course, the facets of the Earth system that are easiest for us to study are those that operate on the time and space scales most like our own. The most obvious such system element is climate.

What exactly is meant by the term "climate"? The usual definition is that climate is the average condition of the weather over several decades, as exemplified by such characteristics as temperature, wind velocity, and precipitation. Climate is influenced by many factors: the heights of mountain ranges, the slowly changing locations of the continents and oceans, the ocean currents, clouds in the atmosphere, the extent of polar ice caps, the density of vegetation, and so on.

Temperature, air motions, and climate are influenced by five different Earth system regimes with widely varying impacts and time scales. The atmosphere is one of the five; the others are the biosphere, the hydrosphere, the cryosphere, and the pedosphere. The atmosphere, by far the most rapidly varying, responds quickly to external forces, such as daytime heating and nighttime cooling. It is the regime to which we as human beings are most directly exposed. A key property of the atmosphere, one that determines many others, is its pressure, which is highest at Earth's surface and decreases rapidly with increasing altitude by about a factor of 2 for each 5 kilometers (km). Another crucial atmospheric property is the temperature; unlike the pressure variation, the temperature variation with height is quite complex. Atmospheric scientists use the altitudes at which temperature changes abruptly to distinguish different regions for study and reference, as shown in the diagram below. Beginning at Earth's surface, these regions are called the troposphere, the stratosphere, the mesosphere, and the thermosphere, and their boundaries the tropopause, the stratopause, and the mesopause, respectively. In this book, we will restrict our discussions to the troposphere and stratosphere, which are the most important regions for climate and life on Earth. Both regions are strongly affected by anthropogenic, or man-made, and natural emissions at the surface. In addition, the stratosphere is affected by volcanic explosions, aircraft emissions, and solar eruptions.

Closely linked to the atmosphere is the biosphere, the aggregate of plant and animal life on Earth. Seasonal changes in vegetation affect the albedo (the degree of absorption of solar radiation) of a geographical region, as well as its water budget. As part of the biosphere ourselves, we have wrought changes on it such as deforestation, agri-



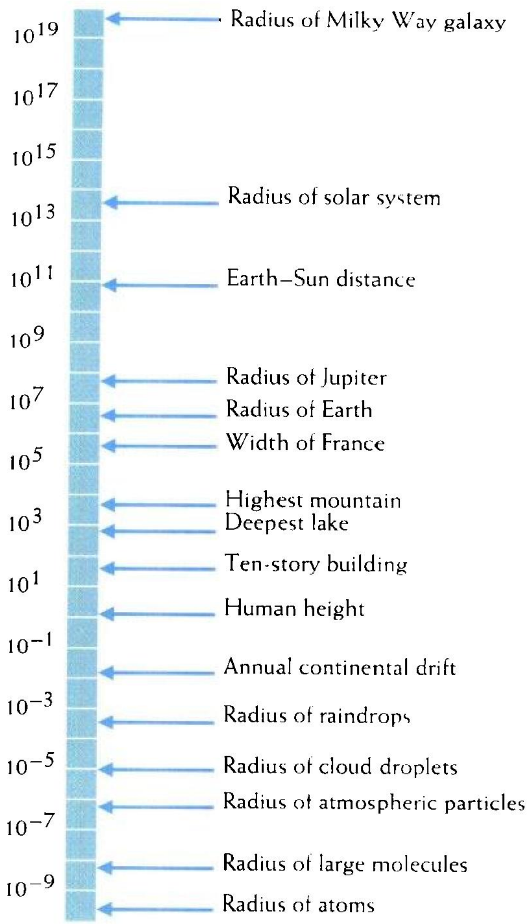
The variation of atmospheric pressure and temperature with altitude above Earth's surface. The regions of the atmosphere are noted, and the Himalayas are drawn in for perspective.

culture, and urbanization that can also have profound effects on climate locally, regionally, and globally.

The hydrosphere, comprising all liquid waters of Earth, influences temperature and circulation on time scales of seasons to centuries. The oceans are crucial to climate because they absorb the bulk of the solar radiation that falls upon Earth; the absorbed energy vaporizes water, which ascends into the atmosphere and later condenses into clouds, releasing the absorbed energy as heat. Ocean currents transfer that heat from the tropical regions, where the sun is most intense, to the polar regions.

The cryosphere is not defined by its material content but by a physical characteristic: it is the portion of Earth's surface with average temperatures below the freezing point of water. The bulk of the cryosphere is located at or near the poles, but on several continents cryospheric regions are also found atop high mountain ranges. Snow and ice are much better reflectors of solar radiation than uncovered land and sea, and they cause a substantial decrease in surface heating. Cryospheric changes occur seasonally, but major variations in the cryosphere have time scales ranging from centuries to millennia.

The slowest-acting region is the pedosphere, the solid portion of Earth's surface. The pedosphere rides on continental structures that evolve over time periods of millions of years as a consequence of tectonic plate motions. Continents covered with glaciers reflect much more solar radiation than the oceans do, so those past geological periods in which the continents were located primarily at high latitudes rather than near the equator have been periods during which the planet's climate tended to be much cooler than average.



Spatial scales in Earth system science. The ordinate is logarithmic, so each step up from the bottom represents a distance (in meters) 10 times that of the segment just below it.

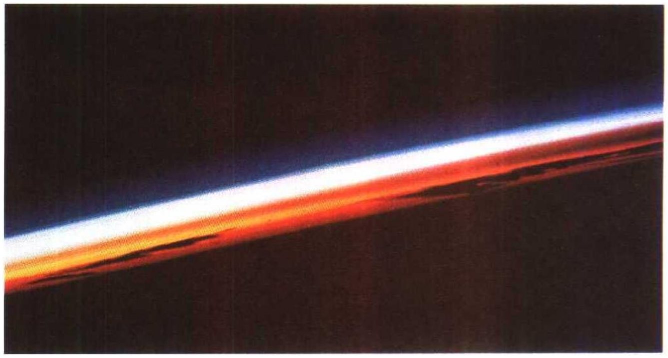
Scales of Space and Time

The components of the Earth system include atoms and continents, and their rates of change encompass eons and femtoseconds. Both spatial and temporal scales in Earth system science thus present an enormous range—in the extreme a difference of more than 20 orders of magnitude. It may not be possible for human beings whose own experiences span very limited fractions of these ranges to intuitively relate to the extremes, but even the attempt to do so will be rewarded with improved perspective.

First, consider information relating to size. The smallest spatial scales, of the order of a tenth of a billionth of a meter, are those of atoms and molecules; this is the sort of distance on which chemical reactions occur and which applies to the basic processes that change the atmosphere and climate. Larger than atoms and molecules, but still measuring small fractions of a millimeter, are the components of the atmosphere's solid and liquid water phases—particles, cloud droplets, and raindrops. The typical annual movement involved in continental drift is a hundred times greater, a centimeter or two per year; thus the procession of the continents has about the same dimension as that of a large snowflake. Lengths expressed in meters (m) are typical of human beings and their structures: a basketball player stands 2 m high, the minarets of the Taj Mahal rise 40 m above the ground. Much larger lengths, several hundreds to thousands of meters, describe major physiographic features—deep lakes, ocean depths, and tall mountains (Mt. Everest is 8872 m above sea level). The dimensions of countries, continents, and planet Earth itself are of the order of 100 to 10,000 km. The distance from Earth to the Sun is 150 million km and the radius of the solar system is a thousand times larger still. Beyond that extend the far reaches of our own galaxy, the Milky Way, and the universe itself. These realms might seem remote from our experience of atmosphere and climate. But, traveling distances so great they must be measured in light-years, galactic cosmic rays are responsible for the production of both natural radioactivity and nitric oxide in Earth's upper atmosphere.

Ordering these spatial domains by the widely varying scales that measure them, as shown in the figure on the facing page, reveals a key relationship: the scale of the physiographic features of Earth is very large, whereas the scale of the processes that drive the Earth system is very small. The creation of drops of acid from nonacidic reactants, the weathering of rocks, the eruption of volcanoes, and the formation and dispersal of clouds are all products of vast numbers of individual physical and chemical processes, each acting on a tiny scale. We cannot hope to understand the large, obvious features and dynamics of Earth unless we appreciate the minute but vital processes that bring them about.

Although many of these spatial scales are outside our common experience, it is nonetheless possible for us to observe them, using an electron microscope for the very small sizes, for example, and a telescope for the very large. More daunting conceptually are time scales beyond our direct experience. The fact that these extreme time scales are veiled from us by blinding speed or snail-like lethargy obscures our perception of many important changes in atmosphere and climate. For example, intuition encourages us to think of the chemical composition of the air and the seas as being among those few constant properties of a changing world. It is now clear, however, that atmosphere and oceans must be regarded, like Earth itself, as having evolved through a number of different stages over a long period of time. This evolution is the result of variations in chemical cycling among the atmosphere, the solid surface, and the oceans, of the movement of continents and of continental modification caused by volcanic eruptions, of changes in the intensity of solar radiation, and of the interplay of the atmosphere with flora and fauna. Therefore, it is necessary to understand how these factors have evolved since the beginning of the planet. Furthermore, intermittent impacts of meteorites are thought to have led to major perturbations in the chemical composition of the atmosphere and, as a result, in Earth's climate, with major consequences for the evolution of life on Earth.



Compared with the diameter of Earth, the atmosphere, seen here in a photograph taken from the Space Shuttle Atlantis *in August 1992, appears thin and fragile. The blue light is scattered solar radiation, while the grayish-red band is a residue of the Mt. Pinatubo volcanic eruption of June 1991.*

Is it possible to know how the properties of the atmosphere—which German astronaut Ulf Merbold described as "a fragile seam of dark blue light"—have changed over the eons of existence and through the agency of gases, particles, and droplets? Can we tell what the consequences of those changes might be for the Earth system? As we might expect, it is possible to answer these questions with some assurance for the current century and with progressively less certainty for earlier times. In the opposite direction of time's arrow, we can be reasonably sure of the answer for the immediate future and much less certain for the far future.

Scientists trace the existence of all matter and energy back to the Big Bang, a rapid expansion of primordial matter into space some 15 to 20 billion years ago. As the matter cooled, random motions coalesced the denser portions into stars, galaxies, and planetary systems. At least, astronomers *suspect* the existence of many planetary systems throughout the Milky Way and the universe, but we know for certain of only one—our own.

Radioactive dating of isotopes in meteorites and moon rocks, together with observations of star formation elsewhere in the Milky Way, make it apparent that the Sun, Earth, and the rest of the solar system were created by the gravitational collapse of a huge nebula of dust and gas between 4.5 and 4.7 thousand million years ago (that is, 4.5 to 4.7 gigayears before the present, abbreviated as Gyr BP). The oldest rock grains on Earth have been radioactively dated at about 4.2 Gyr BP, and the dates of different rock sections and the sediments in which they were identified serve to define for geologists the epochs in Earth history. Some of the events that distinguish the geological divisions in time appear in the figure on the facing page. The time scale is not linear because the more abundant evidence of Earth's recent history has allowed scientists to develop a much more detailed description for the recent past than is possible for the more distant past with its sparser data base.

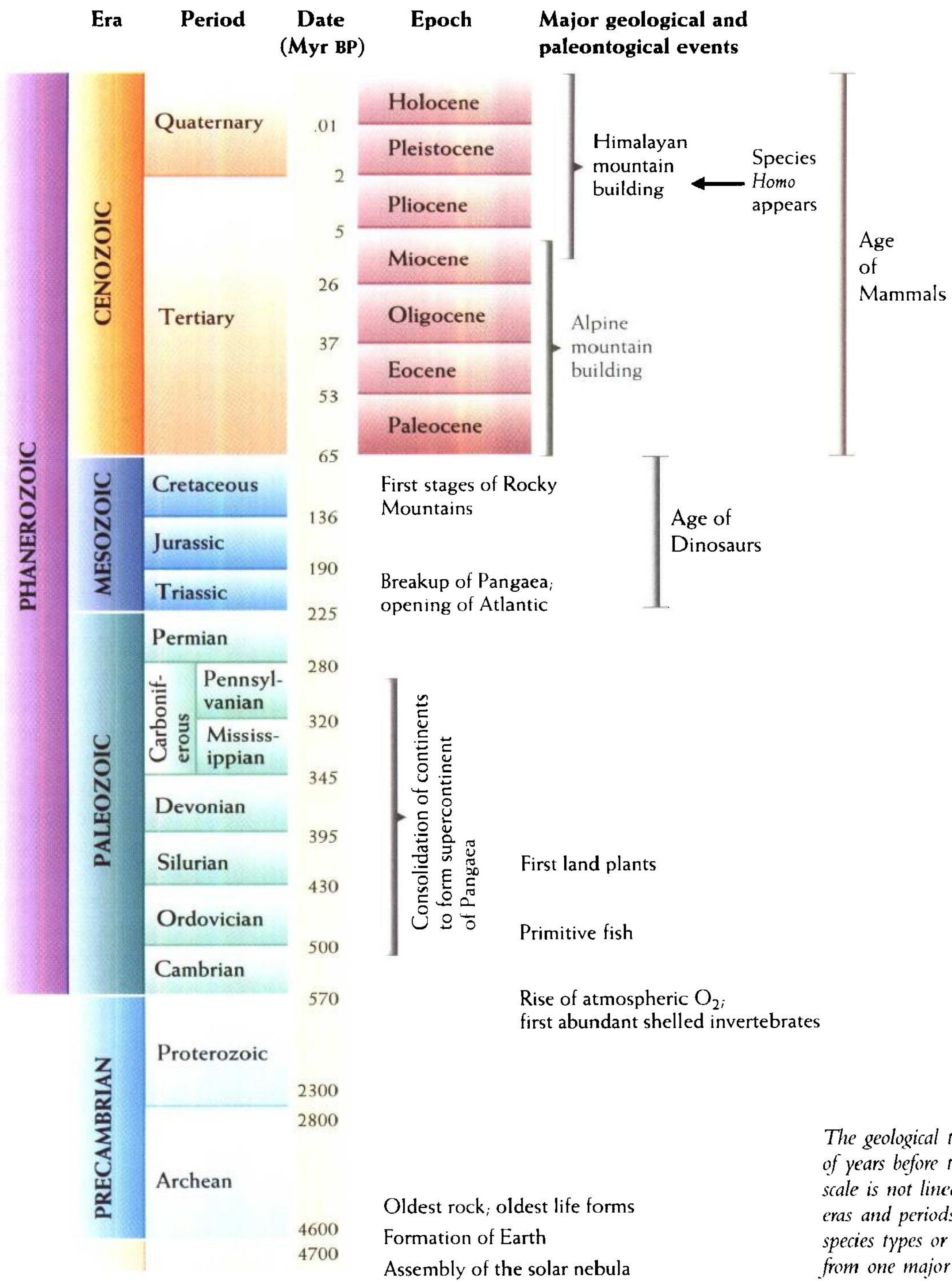
A few major geological and paleontological events are crucial to the study of the relationships among Earth's solid surface, its oceans, its atmosphere, and its plant and animal life. Perhaps the most significant points in the time scale are the formation of Earth; the appearance of the earliest known life, at about 3.8 Gyr BP; the Proterozoic–Cambrian transition, when the increasing concentrations of atmospheric oxygen permitted a great explosion of diverse life forms; the Permian–Triassic transition, when the continents as we know them first took form; the Cretaceous–Tertiary transition, when the great extinctions of dinosaurs and other life forms occurred; and the Holocene era, the 10,000 years that encompass the recorded history of humanity. We will refer again and again to events on the geological time scale.

The stability of climate over several millennia has permitted land to be cleared, developed, and cultivated so as to produce the abundance of food needed by a growing population, such as in these fields surrounding a village in the Yorkshire Dales of England.

Stability, Metastability, and Instability

Why *did* the dinosaurs die out? Did climate undergo a drastic change? Why is Earth's average temperature warm enough to keep water liquid? Could that situation change, and how rapidly might such a change occur? Evidence that major changes have occurred in the past suggests that the Earth system may not be indefinitely stable. Rather, it may oscillate among several different states of climate, with attendant impacts on dinosaurs, plants, marine microorganisms, and all other life forms—including human beings.

Although assessing the stability of complicated systems can be a demanding task, the concepts of stability and instability are fairly straightforward, especially when described by analogy with a mechanical system. Consider such a system at equilibrium. The sum of its forces is zero and is characterized by the gravitational potential of a resting object. Now consider what happens to the system if a small perturbing force is applied. A ball placed in a deep depression (position 3 in the figure on page 8) and



The geological time scale, expressed in millions of years before the present (Myr BP); the vertical scale is not linear. The boundaries between the eras and periods are defined by changes in fossil species types or abundances or by transitions from one major rock type to another.