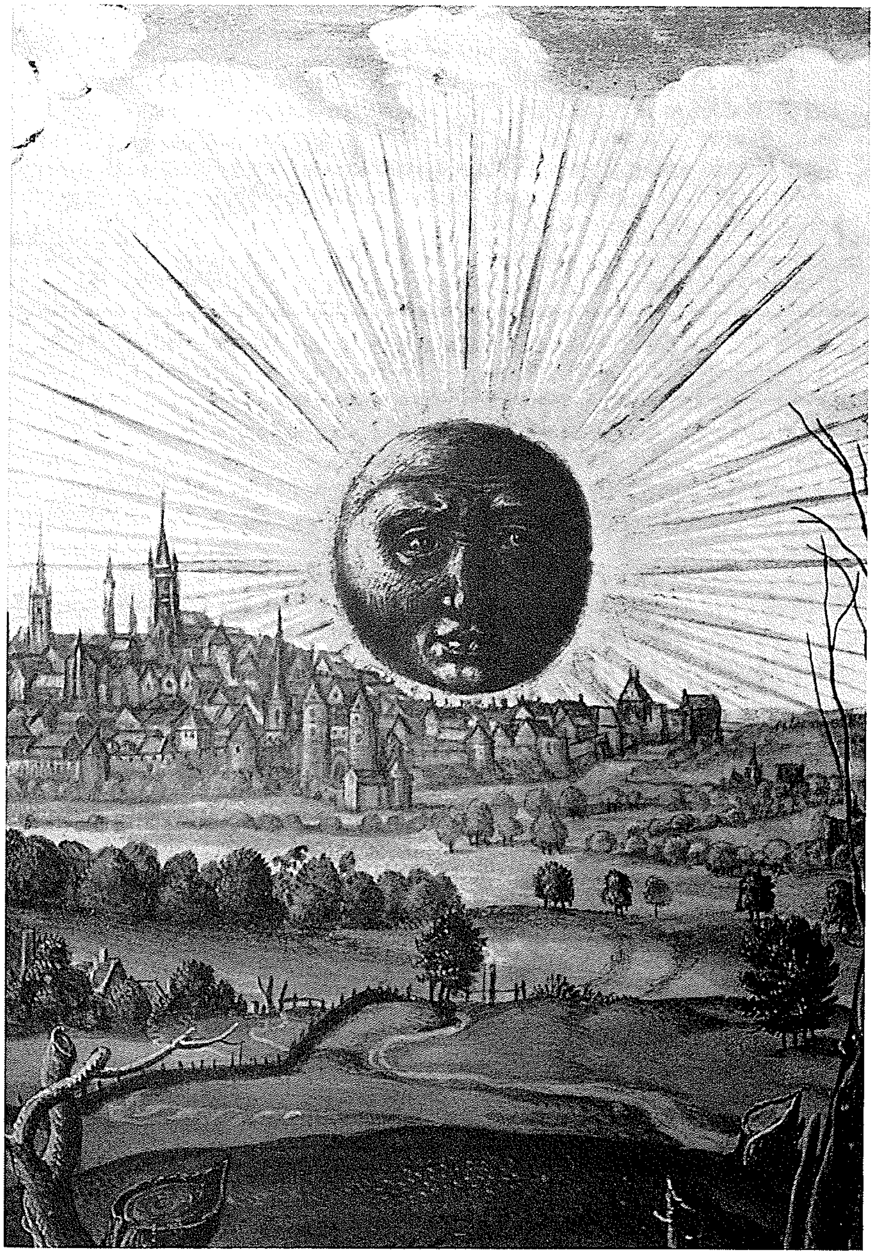


A benign sun rises over a European city in this picture from Solomon Trismosin's text, Splendor Solis *(1582). Europe was then plagued by the so-called Little Ice Age. Summers were often short and cool, causing crop failures and famines, and spurring fears of a permanent change in climate.*

Climate

Last summer, as much of the United States endured stifling heat waves and severe drought, climatologists warned that the hot weather could be a harbinger of worse to come. Because of the atmospheric "greenhouse effect," they said, Planet Earth is slowly becoming warmer. Their specific predictions vary: In a "greenhouse world," some regions may benefit, others may suffer. The outlook has changed; only a decade ago, several respected scientists feared the onset of a new Ice Age. Here, Diana Morgan assesses the recent evolution of climatology—the study of climate and its impact. She describes past efforts to determine how changes in climate have influenced human history. Today, Steven Lagerfeld's survey of the research indicates, most climatologists think that the "greenhouse effect" is here to stay. They believe that mankind can learn to live with a slight "global warming," and may be able to avert more radical shifts in temperature and rainfall.

CLIMATOLOGY

by Diana Morgan

Climate, along with the stars and the tides, is one of the oldest subjects of human speculation. What accounts for heat waves and times of drought? How does climate influence the evolution of societies and the course of history?

In China, archeologists have unearthed some of the oldest evidence of man's anxiety about climate: a set of oracle bones inscribed with a weather report for the 10 days from March 20 to 29, 1217 B.C., along with prayers for snow and rain. Three thousand years later, climatologists have the technology to chart the outlines of the world's changing climate over a timespan going back millions of years. Even without the aid of Chinese oracle bones, they can now reconstruct a portrait of the weather in some parts of the world around the year 1217 B.C. with a reasonable degree of accuracy. Scholars have recently managed to document the periodic droughts, hot and cold spells, and other climatic fluctuations that have afflicted, and sometimes aided, human societies in various regions of the Earth over the centuries.

Yet scientists and other researchers are still far from understanding *why* climate changes and far from agreeing on *how* (or whether) climate has altered human history. They still cannot reliably predict the weather 10 days from now, or the climate 10 years from now. As Reid A. Bryson of the University of Wisconsin, Madison, observes, climatologists sum things up with the quip: "Forecasting is very difficult, especially if it deals with the future."

Climatic 'Energy'

The Greeks may have been the first people to recognize climate as something distinct from weather, as a phenomenon that might change over time and distance. More than 2,000 years ago, Greek captains sailing north in the Black Sea to trade wine and oil found the air turning colder, just as the weather grew more inviting as they sailed farther south from their homeland toward Crete, Egypt, and Libya. *Klima*, a word originally denoting latitude, came also to mean the kind of weather specific to a locale.

The Greeks were also the authors of the oldest surviving theories about the effects of climate on human health and history. A fifth-century B.C. medical treatise, "On Airs, Waters, and Places," possibly authored by Hippocrates, attributed what the Greeks viewed as the "pusillanimity and cowardice" of the Asians to "the nature of the seasons [in Asia], which do not undergo any great changes either to heat or cold, or the like; for there is neither excitement of the understanding nor any strong change of the body whereby the temper might be ruffled.... It is changes of all kinds that arouse the understanding of mankind, and do not allow them to get into a torpid condition."

Greek notions about climate and its effects persisted for centuries. "In the North," wrote Thomas Jefferson in 1785, men are "cool; sober; laborious; independent.... In the South they are fiery; voluptuary; indolent; unsteady."

But no grand theory of climate's effects emerged until the early 20th century, after Darwin's concepts of natural selection and evolution had opened the way to a questioning of man's position in the natural world. No longer would man be universally regarded in the Christian world as a creature made in God's image, only modestly affected by his surroundings on Earth. Adherents of a new school of climatology marched in Darwin's wake: To these determinists, man was solely a creature of his environment, especially climate.

The "grand old man" of climatic determinism was Ellsworth Hun-

Diana Morgan, 30, formerly an editor at Science 86, *is a writer specializing in science. Born in Washington, D.C., she received a B.A. from Johns Hopkins University (1980).*

In Buddhist mythology, the winds were ruled by the White Tiger god of the West, depicted here by the 17th-century Japanese painter Sōtatsu. In many ancient faiths, priests looked chiefly to wind deities for good weather.

tington, a Yale geographer who expounded his theories in a series of semipopular books, such as *The Pulse of Asia*, between 1907 and 1945. Huntington contended that the productivity and mental ability of individuals—and, ultimately, the rise and fall of entire civilizations—were inseparable from the impact of climate.

In some of the first scientific studies of climate's physiological and psychological effects, Huntington diligently measured the impact of seasonal fluctuations of temperature and humidity on human beings: the weight gains of 1,200 tubercular patients in New York between 1893 and 1902, the efficiency of 65 young women in a North Carolina label-pasting factory, and the mathematics grades of 240 West Point cadets between 1909 and 1912.

Huntington's conclusion: A climate with an average temperature of 64 degrees Fahrenheit and relative humidity of 60 percent was most conducive to health and to physical and mental performance. Equally important were the stimulation of daily and seasonal weather fluctuations and, significantly, racial inheritance. (For example, the "Teutonic race," he wrote, enjoyed "an ineradicable" advantage in "mentality.")

Writing at a time of Anglo-Saxon hubris, when the British Empire was at its apex and the United States was a rising power, Huntington maintained that no nation "has risen to the highest grade of civilization except in regions where the climatic stimulus is great." The civilizations of Rome, Persia, and Egypt had declined, he believed, because of changing climates. He singled out northwestern Europe, the Pacific and northern Atlantic coasts of the United States, and Japan (which had recently won a startling victory over the Tsar in the Russo-Japanese war of 1904–05) as regions with the greatest natural "climatic energy" of modern times.

Not surprisingly, Huntington's ideas won broad popular acceptance among Anglo-Saxons on both sides of the North Atlantic. They also gained a following in academia, especially among scientists. But, beginning during the late 1920s, Arnold Toynbee, a noted English historian and admirer of Huntington, developed a new theory, arguing that climate and culture throughout history had been involved in a *pas de deux* of challenge and response. "The stimulus toward civilization," he wrote, "grows stronger in proportion as the environment grows more difficult," citing as one example the flowering of Hellenistic Greece in the arid heat of Attica.

Although Huntington's empirical data on climate and individual behavior are still generally respected by specialists, his conclusions were soon rejected as racist, exaggerated, and overly deterministic. (Toynbee fell out of favor for other reasons.) Huntington's notions were also undermined by the work of scholars in several new specialties. By the 1930s, sociologists and other practitioners of the social sciences were advancing a more sophisticated picture of the evolution of human societies; they included such influences as religion and migration. At roughly the same time, the field of climatology was moving away from speculation about climate's *influence* into an era of technological inquiry and precise historical measurement of climates past.

Appealing to the Deities

In retrospect, it is surprising how late this effort began—much later than some of man's other scientific investigations (notably in astronomy and biology). Yet, climate long ruled man. It is difficult for modern American city-dwellers, cossetted by central heating in winter and air conditioning in summer, and virtually assured of supermarket groceries even when drought-stricken crops are withering in farmers' fields, to comprehend how important a predictably stable climate was to the people of earlier times. As late as the 15th century, historian Fernand Braudel writes, the world population "consisted of one vast peasantry where between 80 and 95 percent of people lived from the land and from nothing else. The rhythm, quality, and deficiency of harvests ordered all material life."

But prior to our own century, man's ability to measure the vagaries of weather and climate was limited—and slow to develop. The first known attempts were in ancient Egypt, from which archeologists have unearthed fragments of a large stone stele, carved by minions of the pharaohs during the 25th century B.C., that was used to record the levels of the annual Nile River floods. The Egyptians counted on these annual floods to irrigate the fields and nourish the croplands with nutrients from upstream. The Chinese, who began systematic observations shortly after the Egyptians, were compulsive record-keepers. They can probably claim mankind's longest continuous documentation of natural events. But, aside from crude rain gauges, weather vanes, and other simple devices, these early investigators possessed few reliable measuring instruments.

Utterly dependent upon a friendly climate for their survival, but with very little understanding of the atmospheric forces that could bring a crop-destroying drought or a decade of bountiful harvests, farmers appealed to the deities for favorable weather. The Greeks paid tribute to several gods of the winds, including Zephyrus, who ruled the western wind; medieval Catholics appealed to Saint Médard for rain. The earliest climatologists were probably priests; they studied the sky to determine the time for sowing and reaping. In ancient Sumer, they were responsible not only for predicting the onset of the seasonal rains and floods but also for inspecting the irrigation canals, which channeled precious water to the fields.

'Erratic' Boulders

Man's sinfulness was believed to be at the root of many calamities. Throughout Europe from the fifth through 15th centuries, rich harvests were celebrated by ritual feasts; times of famine were often followed by purges of heretics and unbelievers. In Germany, Catholic priests exhorted their congregations to destroy witches in the wake of hailstorms and other meteorological scourges.

By the end of the medieval era, Europeans were beginning to expand their knowledge of the physical world. But it was not until about 1590 that Galileo invented the thermometer; one of his followers, Evangelista Torricelli, created the first barometer soon thereafter. Comparative meteorology was born in 1654, when the Grand Duke of Tuscany, Ferdinand II of the de' Medici family, ordered dozens of identically calibrated thermometers from an Italian glass blower and established the world's first meteorological network across Italy.

After periods of unusually bad weather, the anxious monarchs of France (in 1775) and Prussia (in 1817), fearful of a permanent climatic change, also established nationwide networks to record daily temperatures, barometric pressure, and rainfall.* For the first time, Europeans

*As researchers now know, the climate of 18th- and early 19th-century Europe *was* in flux. But Prussia's King Frederick William III acted after the extraordinary (and disastrous) "year without summer" of 1816, when crops in some parts of the Northern Hemisphere were killed by frosts as late as mid-June. Many climatologists now suspect that the violent eruption of Indonesia's Mount Tambora in April 1815 was the likely cause. They believe that ash and gases from the volcano, high in the atmosphere, reduced the amount of sunlight reaching the Northern Hemisphere. Eruptions as massive as Mount Tambora's, which killed 10,000 islanders, are rare.

had turned to scientists rather than priests or folklorists to understand the forces of climate.

The bad seasons passed, but the weather stations remained. Toward the end of the 19th century, scientists were able to report that, while average temperatures did indeed fluctuate from year to year, they could find no evidence of long-term changes. Classicists, poring over the scattered weather observations of the ancient Greeks, concurred. Europe's climate, they believed, had not changed for at least 2,000 years.

Of course, there had been inklings that the Earth's climate had been dramatically different in the very distant geologic past. In Europe's glacier-studded Alps, country folk who lived surrounded by ice-scarred rockface and rubble at the foot of the mountains took it for granted that the glaciers had once advanced and then retreated. Until the mid-19th century, however, most geologists rejected the notion as fanciful.

Western theologians had determined from readings in the Bible that the Earth could not possibly have been as old as the existence of ancient moving glaciers would suggest. The 17th-century conclusion of John Lightfoot, vice chancellor of Cambridge University, was still taken as the last word on the subject: "Heaven and Earth and clouds full of water and Man were created by the Trinity on 26th October 4004 B.C. at nine o'clock in the morning." The so-called erratic boulders in the Alpine valleys, early 19th-century geologists said, were probably deposited by the Flood described in the Book of Genesis.

Discovering the Ice Ages

Bits of contrary evidence continued to accumulate, however, and by 1832, Reinhard Bernhardi, a professor at an obscure school of forestry in the German town of Dreissigacker, dared suggest that an enormous ice sheet had once blanketed all of northern Europe. A few years later, the Swiss-born naturalist Louis Agassiz began to popularize this view, writing dramatically of the frozen past, when the sun, which had once risen over a Europe "covered with tropical vegetation and inhabited by herds of great elephants," met only "the whistling of northern winds and the rumbling of the crevasses."

By the 1860s, thanks to Agassiz's efforts and much new evidence, few scientists still doubted the existence of a past Glacial Epoch.

The Glacial Epoch was an era, later research would show, that began almost three million years ago—one that, in fact, we may still be living in. At various times during the Glacial Epoch, the Earth was colder than it is today by as much as 36 degrees Fahrenheit, and the oceans were perhaps 500 feet below current levels. Ice sheets up to two miles thick blanketed a third of the Earth's land mass, extending as far south as the Great Lakes and Cape Cod in North America, covering Scandinavia and the British Isles in Europe, and burying much of northern Asia.

These cold periods during the Glacial Epoch were the Ice Ages.

There have been perhaps 10 of them during the last million years; scientists still are not certain. (It was probably during the last Ice Age, 15,000–35,000 years ago, that humans first crossed what is now the Bering Strait from Asia to North America.) The Ice Ages were punctuated by warmer spells known as "interglacials." It was not until about 8,000 B.C., as the Earth began to warm during one such interglacial, that homo sapiens first took up farming, probably in ancient Mesopotamia and other areas. The interglacials have been rare and relatively short, lasting 9,000 to 12,000 years. "The present 'interglacial,'" observes climatologist Reid Bryson, "has been with us for about 10,800 years."*

As late-19th-century geologists began their first crude attempts to map the movement of the ancient ice sheets, other researchers continued to dismantle the concept of an unchanging climate.

Climate's 'Morse Code'

During the 1860s, Scotland's James Croll, a self-taught physicist who was employed as a janitor at Glasgow's Andersonian College before his theories won him international acclaim, suggested that 100,000-year variations in the Earth's orbit may have drastically reduced the amount of sunlight reaching the planet during the Ice Ages.

Others speculated that the solar system had passed through one of the Milky Way's spiral arms, becoming blanketed in dust dense enough to filter out light from the sun. As the 19th century wore on, other scientists scrutinized the influence on climate of everything from the tidal effect of neighboring planets and the slow "drift" of the Earth's continents to the spewed effluvia of volcanoes, the wandering of the magnetic poles, and sunspots. Finally, during the 1920s, a Serbian mathematician named Milutin Milankovitch reworked Croll's theory of variations in the Earth's orbit, showing with a series of complicated equations how "stretch," "tilt," and "wobble" might have produced the Ice Ages. Gradually, climatologists came to accept (albeit with many qualifications) the general outlines of Milankovitch's theory.

Meanwhile, geologists and climatologists searched the glaciers and other sites for physical clues to date the waxing and waning of the Ice Ages, turning to Nature herself to chronicle the planet's tumultuous climatic history.

The concept of Nature as self-chronicler was not new. It had apparently been the brainchild of Robert Hooke, a brilliant, irascible English philosopher who counted among his accomplishments the invention of the first accurate pocket watch and a famous feud over the nature of gravity with Sir Isaac Newton. In 1686, toying with fossilized shells that,

*During the 1970s, a cluster of especially cold winters in the United States stirred widespread fears that a new Ice Age was dawning. The National Academy of Sciences warned that it could begin within 100 years; analysts at the U.S. Central Intelligence Agency prepared an assessment of American power in "a cooler and therefore hungrier world."

CLIMATE AND EVOLUTION

Climate clearly has put its imprint on the tint of our skin, the size of our noses, and other physical traits.

The study of skin color and racial differences has been a touchy matter in Western science ever since the mid-19th century, when naturalist Louis Agassiz asserted that whites had bigger brains than others, and promptly concluded that they must therefore be more intelligent. Today, scientists differ over what a "race" is. During the late 1960s, for example, anthropologist Grover S. Krantz of Washington State University distinguished between "climatic races"—groups that share traits, such as skin color, which can change over generations in response to climate—and "descent groups," which share ancient and immutable genetic traits, such as blood type. Climatic races have evolved separately from descent groups, Krantz maintained, and the two should not be considered "inherently connected."

Amid such discussions, however, a consensus exists that climate *has* influenced the evolution of the human physique.

Skin color, for example, is determined largely by the amount of melanin, a

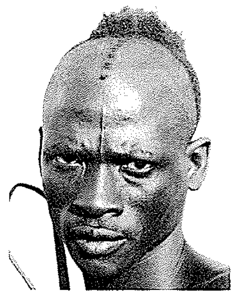
dark pigment, in the outer layer of the skin. (Carotene imparts a yellow tint.) In sunny climates close to the Equator, natural selection has favored dark, melanin-rich skin, which protects its owner by absorbing harmful ultraviolet rays before they penetrate to lower layers. But *some* ultraviolet light must penetrate the skin so that the body can produce Vitamin D. Thus, at higher latitudes, where sunlight is less intense, pale skin with little melanin is the norm.

Among dark-skinned people, moreover, there are great variations in skin color. The drawback of dark skin is that, like dark cloth, it absorbs more heat from the sun than does lighter skin. In prehistory, anthropologists explain, those who roamed the savannah "traded off" some protection from ultraviolet rays for the reduced heat retention of lighter skin. For forest-dwellers, living in less extreme heat, a darker complexion was an evolutionary advantage.

Melanin also determines eye color. The human eye appears blue when there is no melanin in the outer iris, and turns darker as melanin increases. In the iris, as in the skin, melanin absorbs light, protecting the eye from glare. Thus, dark eyes are generally favored by nature. In Europe, however, almost 50 percent of the population has blue, green, or gray irises. Such people may see further in dim light, but scientists still do not fathom the evolutionary logic of blue eyes—or blond hair, for that matter.

The eyes of the Chinese, Japanese, Eskimos, and other people of Mongoloid descent—one third of the world's population—are protected by epicanthic folds. These folds, composed of fatty tissue, probably evolved among their forebears inhabiting the Arctic in order to insulate the eye against freezing, and to provide an additional shield against glare from snow and ice.

Even the human nose adapts to climate. Inside the nose, a series of wet, mucus-lined air chambers "conditions" inhaled air before it reaches the throat and the delicate air sacs of the lungs, warming it to about 95 degrees Fahrenheit and raising its relative humidity to 95 percent. Humans in cold climates—or in hot, dry ones—thus have the greatest need to condition the air they breathe. Natural selection in such climes generally favors larger noses with more mucus lining: flattened, to protect against frostbite, in frigid environments; long and narrow in arid regions.



In a like manner, the size and shape of the human form help the body regulate internal temperature. Over thousands of years, cooler climates tend to produce larger people. The reason: Their extra mass helps them retain heat. Although large people also have more skin surface from which heat can escape, the tradeoff still works to their advantage. As the body grows larger, mass becomes greater *relative* to skin area.

The Alakaluf Indians on the frigid southern tip of South America, for example, are 25 percent taller than the Ituri Pygmies of Central Africa. Yet, the Alakalufs are more than two times heavier—and thus store much more body heat.

Variations in body *shape* complicate the picture. A tall, skinny man has more surface area—and heat loss—than does a shorter, huskier man of the same weight. Thus, cold territories closest to the North and South Poles tend to be populated by stocky folk.

In southern Africa, Pygmies, the world's shortest people, dwell very near the Nilotic tribes (e.g., the Dinka), the tallest. But the Nilotic tribes live in the dry, open savannahs, the Pygmies, in the shaded forests. The Nilotics' environment puts a premium on having more skin surface to release heat, thus their extremely tall, slender build. And, occasionally, there appear uniquely adapted humans. A notable example: the Khoikhoi women of the open African savannah, who have thin torsos suited to the hot climate, but also protruding buttocks (steatopygia) containing storehouses of fat to draw upon in times of famine.

Just as it is difficult to *prove* a correlation between past climatic change, and, say, the demise of an ancient civilization, so today's anthropologists are not certain that all their inferences about climate and human evolution are well founded. Very few of the world's peoples in all their variety now inhabit the same territories where, long ago, their ancestors presumably developed certain characteristics in response to climate. Often, notes Grover Krantz, anthropologists resort to "pulling people out of areas where their . . . traits don't fit the environment and putting them back where they do fit."

—*D.M.*

though plucked from his native shore, more resembled tropical species, Hooke mused whether Britain had once lain within a "torrid zone," its climate since altered by a series of natural calamities. It is very difficult "to raise a *chronology*" by examining the shells, he observed, "and to state the intervals of the times wherein such and such catastrophes and mutations have happened; yet 'tis not impossible."

It seemed impossible for more than a century thereafter. Before they could "raise a chronology," scientists needed field methods and technologies that would allow them to quantify past climatic change.

One such method was dendrochronology—the technique, developed during the early 19th century, of counting growth rings to determine the ages of trees. At the turn of the century, Andrew Douglass of the University of Arizona advanced the science further. He likened the annual rings to Morse code: The sequence of dots (narrow rings indicating growth-limiting conditions) and dashes (wider rings indicating years of favorable conditions) relayed a message about the climate during the tree's lifespan. Around 1910, Douglass pushed the technique forward by showing how the rings of a recently felled tree could be matched with those of an older stump or piece of fossilized wood, which could then be linked to an even older sample, ultimately allowing dendrochronologists to stretch the record back 8,200 years. Still, that took the story only to the edge of the last Ice Age.* Other methods would be needed to delve deeper into the past.

The Dust Bowl

The Earth's history is written in layers of environmental debris. If each stratum of ocean sediment, ancient soil, or Arctic ice was layered more or less chronologically, scientists reasoned, the perceptive investigator, by sifting through layered clues, would be able to discover the climate at the time each layer was formed.

In 1916, Swedish botanist Lennart von Post capitalized on this now common notion when he reported on his study of rich deposits of pollen grains dug from lakes and bogs in his native land. Soon, scientists throughout the West were digging up soil samples, analyzing everything from beetle genitalia and fossilized leaves to microscopic creatures and chemical isotopes for clues to climate changes in the past.

By examining a millimeter of soil under a high-powered microscope, investigators such as von Post could make a connection between the relative amounts of pollens and prehistoric climate, up to 100,000 years in the past. An abundance of grass and shrub pollen suggests the existence of frigid tundra and grasslands at the edges of glaciers; birch and pine pollen hints at a somewhat warmer climate; and the presence of oaks and elms signals a temperate zone. In China, the spread of bamboo

*Tree rings are wonderfully specific, however, and recent techniques allow scientists to calculate yearly variations in temperature, rainfall, and even atmospheric pressure at sea level.

is a reliable indicator of regional warming in centuries past.

By the early 20th century, most educated laymen had accepted the once unbelievable, once sacrilegious notion that the planet had experienced a climatic upheaval during the distant Ice Age. But, among scientists and laymen alike, the comforting belief that Mother Earth had remained immutable at least since the dawn of civilization died hard. Most American college textbooks remained adamant on this point until the late 1940s.

In the United States, the Dust Bowl disaster in the Great Plains during the 1930s (which was exacerbated by poor farming methods) and several abnormally hot summers during the 1940s jolted the public into a new awareness of climate. Actually, the warming trend had begun during the 1890s; it peaked during the 1940s, when the Northern Hemisphere endured its highest summer temperatures, and enjoyed its mildest winters, in perhaps 1,000 years. (The 1980s have been warmer still, with several of the hottest years on record; yet *average* annual temperatures have been less than one degree Fahrenheit above normal.)

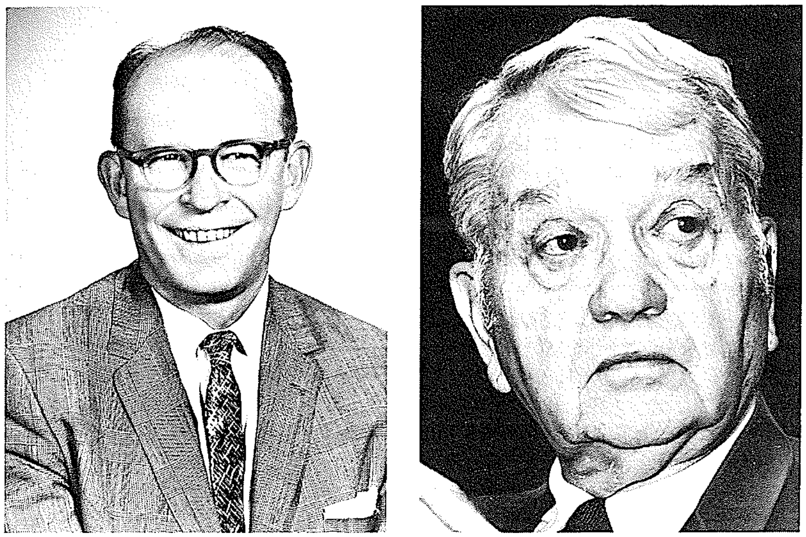
Climate and History

In America and Europe, all of this prompted the first wide discussion among scientists (if not in the press) of the "greenhouse effect": Heat that formerly would have escaped into outer space, the argument went, was being trapped close to Earth by vast amounts of carbon dioxide pumped into the atmosphere from factory smokestacks and other manmade sources. For the first time, it seemed possible that man could inadvertently alter the global climate.

Then, for reasons unknown, a worldwide cooling began during the late 1940s.

Although researchers' concerns over the greenhouse effect faded, they began to recognize that the Earth's climate could no longer be viewed as stable and predictable. As a byproduct of the World War II boom in technology, moreover, new and highly sensitive dating techniques and field methods were created, bringing the science of climatology into a rambunctious adolescence. Suddenly, there seemed to be no aspect of learning that climate did not touch, as historians, historical geographers, economists, botanists, sedimentologists, dendrochronologists, glaciologists, archeologists, and medical scientists, as well as meteorologists and other researchers, flocked to the study of climate and developed their own sub-themes.

One of the most important new technological developments was radiocarbon dating, a technique developed in 1947 by Willard Libby, a University of Chicago chemist, later a Nobel laureate. It allowed scientists to determine the age of fossilized plants and animals up to 40,000 years old. At about the same time, Harold Urey, also an American Nobel laureate in chemistry, introduced another far-reaching technique: isotope



Two chemists whose discoveries have greatly aided the work of climatologists: Willard Libby (1908-1980), the inventor of radiocarbon dating, and Harold Urey (1893-1981), the creator of isotope analysis.

analysis of ocean sediments and ice cores.* Suddenly scientists could peer into the very distant past—up to 570 million years ago—when ancient deep-sea creatures began absorbing oxygen from the oceans to form protective shells.

A 20-foot "core"—a cylinder of compacted mud and ooze from the ocean floor—can provide a sampling of sediments built up over millions of years, allowing geologists, using Urey's method, to chart not only the progressive deep freezes of the Ice Ages but also the temperature fluctuations of the interglacial warm spells. In 1950, when Urey shaved a sliver from the 150 million-year-old fossil of a squid-like creature, he was able to determine that the creature had been born in early summer and died four years later in early spring.

When the technique was later applied to the comparatively spongelike material of the Greenland and Antarctic ice sheets, scientists were able to trace the waxing and waning of the interglacial periods with remarkable precision. They were suddenly much closer to an under-

*On average, 99.8 percent of the oxygen in water is ordinary oxygen, but .2 percent is composed of isotope atoms weighted with two extra neutrons. In warm weather, when ocean water evaporates quickly, the relative amount of the isotope O^{18} increases as the lighter O^{16} is drawn up into the clouds. Urey reasoned that past ocean temperatures could be measured by determining the ratio of the two isotopes in ancient sea fossils: The more O^{18} in the fossil, the warmer the weather had been. Urey's method did ***not*** allow scientists to date samples; that had to be done by other means, chiefly by counting the layers of sediment or ice.

standing of past climatic change—and, possibly, by extension, climate present and future.

Just as scientists after World War II were mapping broad climate variations across millions of years, a new breed of "documentary" climatologist began the painstaking task of reconstructing climate over a shorter timespan.

A leader of the "documentary" school was Emmanuel Le Roy Ladurie, an unconventional French historian. Ladurie was determined to develop a new historiography of the past 1,000 years, with special emphasis on Western Europe during the 16th, 17th, and 18th centuries. His chief method was to assess written records of vineyard harvest dates in 18th-century France. The principle behind this "phenological" method, as Ladurie described it in 1971, was simple. The date at which the grapes ripened reflected the temperatures "to which the plant [was] exposed between the formation of the buds and the completion of fruiting.... These dates are thus valuable climatic indicators."

Other "documentary" climatologists, before and since, have dusted off epistolary accounts of winter storms or counted the number of prayers said for rain. They have looked for clues to climatic change in the accounts of Venetian diplomats, the ships' logs of sea captains, and in reports on the frequency of the canals freezing over in the Netherlands. They have made two periods of relatively drastic climatic change the focus of especially obsessive examination.

The Medieval Warm Epoch (circa A.D. 1000 to A.D. 1400) brought the world the highest temperatures in perhaps 5,000 years. During this brief spell, the Vikings, unconfined by sea ice, invaded Europe's Atlantic coast, traded with the Italians and Arabs, colonized now inhospitable Greenland, and possibly voyaged to North America. Plagues of locusts descended on Continental Europe. In Britain, farmers cultivated flourishing vineyards and began working lands in the north of Scotland, only to abandon them forever a few centuries later.

The Little Ice Age

The Earth began to cool again around A.D. 1200, gradually dropping about two to four degrees Fahrenheit below today's levels, and the period from 1400 to 1850 has been christened, with considerable exaggeration, the Little Ice Age. Those four centuries saw the modest advance of glaciers in the Alps and elsewhere, the occasional wintertime freezing of the Thames River, and periods of widespread famine, as Europe's summers became shorter, cooler, and wetter. Massive ice floes hampered ocean travel in the northern Atlantic: In 1492, Pope Alexander VI cited "the extensive freezing of the waters" in lamenting that no Catholic priest had visited Greenland for 80 years.

The Europeans of that era scribbled as busily as do their chroniclers today; diaries, monastic and manorial chronicles, and tax reports have all

HEAT, COLD, AND THE HUMAN BODY

Although most climatologists are reluctant to draw broad conclusions about climate's effects on human societies, the study of its impact on *individuals* has flourished since World War II. "Human health, energy, and comfort are affected more by climate than by any other element of the physical environment," observes Howard Critchfield of Western Washington University.

"Bioclimatology" attracts researchers from a variety of specialties, with markedly different interests—industrial psychologists, physicians, space scientists. They have linked climate to everything from homicide to human fertility to mental acuity.

At the extremes of hot and cold, climate's effects are relatively easy to measure—and to avoid. In the United States, heat stroke and hypothermia together claim only about 325 lives each year. Yet W. Moulton Avery, of the Center for Environmental Physiology, contends that it "would be front page news" if federal researchers had actually collected data on the thousands of heat-*related* deaths (e.g., from stroke) among elderly Americans last summer.

Climate exerts its influence in subtler ways. According to one study, for example, "excessive aggressiveness" begins to manifest itself between 82.4 and 86 degrees Fahrenheit, when the relative humidity is 100 percent. The Federal Bureau of Investigation (FBI) lists climate as one of a dozen factors that influence crime rates.

Some researchers have tried to link climate-induced physiological changes to physical and intellectual performance. As temperatures rise above 86 degrees, they note, the body cools itself by increasing blood flow to the skin and reducing the flow to the brain and muscles. One result: a loss of energy and ability to concentrate. When the thermometer drops below 68 degrees, the body conserves warmth by restricting blood flow to the skin. Yet, some groups, such as Eskimos, may have developed different tolerances through evolution; individuals undergo short-term adaptations to harsh climates.

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Most studies suggest that comfort and mental vigor are not entirely synonymous. Andris Auliciems of the University of Toronto found that English schoolchildren performed best on a variety of tests at temperatures of 58.5 to 62.9 degrees. Some bioclimatologists have put the optimum temperature as high as 82 degrees; others dismiss such correlations as worthless.

Science does confirm much folk wisdom. Winter in the temperate zones of the world means more flu, partly because the cold depresses the body's immune system, but mostly because it drives people indoors, where microbes spread easily. Other sicknesses plague the tropics because certain disease-bearing organisms flourish in heat and humidity.

Climate has other, unexpected, effects. Wolf H. Weihe, a Swiss biologist, reports that the fertility rate of women in Bombay, India, drops by more than 50 percent during the monsoon season. In the United States, he says, statistics indicate that fertility is lowest during the winter—except, for some reason, in Kansas, where it jumps when the temperature drops to 18 degrees below zero.

become fodder for countless late-20th-century doctoral theses packed with the minutiae of a lost age. It is difficult to find a season in Europe during the past 1,000 years for which there is not an account of someone's impression of the weather.

Until the last decade or so, however, the "documentary" climatologists, for all their obsession with detail, were regarded with indifference by most "hard" scientists, who dismissed their attempts to stitch together definitive analyses from stacks of crumbling church records and other sources. However, since the 1960s, when Britain's Hubert H. Lamb, originally trained as a meteorologist, came to the fore of documentary climatology and began urging his colleagues to employ greater rigor, the discipline has gradually won more acceptance from scientists.

Recently, other scholars, such as historian David Hackett Fischer of Brandeis University, have criticized some of the "documentary" climatologists (and most mainstream historians) for giving short shrift to the effects of climatic change on human affairs. Ladurie came in for especially harsh criticism. To Ladurie, rigorous documentation and strictly factual chronology were everything, and "climate merely in its human or ecological aspects" next to nothing. "In the long term," the Frenchman concluded in 1971, "the human consequences of climate seem to be slight, perhaps negligible."

Sinning Against Nature?

Not so fast, said Fischer. In 1980, he proposed a history of the "conjunctions" of climate and culture. During the first conjunctive period, up until about 10,000 years ago, he wrote, "variations in climate determined the possibility for human culture to exist at all." Later, climate influenced the survival of complex civilizations. During the third epoch, from about A.D. 1000 to the present, man has been able to adjust, albeit painfully at times, to changes in climate.

These modern historians, along with a few climatologists and popular writers, have avoided the determinism of Ellsworth Huntington; but they have not shied away from large generalizations. Even Fischer, an exacting historian, has pointed out that during the climatic upheaval of the sixth and fifth centuries B.C., which seems to have brought droughts to large parts of the world, many of the "world's great ethical and religious systems were created." He suggests that the teachings of Confucius in China, Buddha in India, Zoroaster in Iran, and the Jewish prophet Deutero-Isaiah were all responses to the same problem of creating stable values in a world of disquieting social and climatic change.

No less single-minded, other researchers have debated the reasons for the disappearance of the advanced Indus society in northwestern India 5000 years ago, pitting the impact of Indo-European invasions against flooding in the Indus Valley and, dubiously, to a long period of drought. Analysts have variously tied the global distribution of political stability to temperature, and correlated the size of standing armies with the degree of north or south latitude. In 1970, a popular author, Robert Claiborne, went so far as to suggest that a climate shift in A.D. 1200, which led to the failure of the German herring fishing fleets, paved the way for the rise of Adolf Hitler seven centuries later.

And just as Ellsworth Huntington advanced a theory of climate with an explicitly ideological message earlier in the 20th century, so have others in more recent times. For example, Jayantanuja Bandyopadhyaya, an Indian political scientist, argues, much as Huntington did, that climatic handicaps account for the underdevelopment of the Third World. Western scholars, he claims, have suppressed the study of warm weather's negative impact on man, emphasizing racial superiority as the cause of the West's economic pre-eminence. But Bandyopadhyaya argues that the "neo-imperialist" West has a moral obligation to level the climatic playing field. His proposal: The United States and Western Europe should invest in research on "global climatic engineering" to find ways to artificially cool down the tropics.

Eccentric as Bandyopadhyaya's position may be, some climatologists warn that ideology subtly influences all scholarly research on climate and culture. "Even among the modern scientific community," observe British researchers M. J. Ingram, G. Farmer, and T. M. L. Wigley, "ideas about climate are inevitably influenced to some extent by current ideologies." They see the rising worldwide alarm about threats to the environment since the 1970s as the chief impetus to the growing debate over the relationship between changing climate and man's culture.

Just as 16th-century Germans viewed hailstorms as punishment by God for individual sins, many scientists (and laymen) today see man on the verge of self-destruction as a result of sins against Nature—the rapacious exploitation of natural resources, pollution, the development of harmful technologies. According to Ingram and his colleagues, the personal views of climatologists "undeniably condition differing interpretations of the often ambiguous evidence."

Even without such sentiments, serious scientists trying to penetrate the mysteries of climate past and present confront a frustrating task. Climate, it turns out, is the result of a vast array of thousands of interacting variables. Climatologists now often find themselves in the uncomfortable position of knowing more about climate every day, and seeming to understand less.

COPING WITH CHANGE

by Steven Lagerfeld

Ever since Rachel Carson's *Silent Spring* (1962), Americans have been repeatedly alerted to tangible threats—dirty water, polluted air, toxic waste dumps, pesticides—to what is now called "the environment." In recent years, environmentalists, federal officials, and scientists have shifted their attention to "invisible" threats, from airborne asbestos particles in schools to cancer-causing radon gas in the basements of suburban homes. And this autumn, after several summers of drought and record-breaking heat waves, American headline writers rediscovered two unseen phenomena miles above the surface of the Earth: the depletion of the protective ozone layer in the atmosphere and the rise of the "greenhouse effect."

The thinning of the Earth's ozone shield, which screens out harmful ultraviolet light, has been discussed, off and on, since the 1970s. [See box, p. 124.] The hot 1988 summer and some strong rhetoric have focused far more attention recently on the greenhouse effect, which appears to be gradually making the planet grow warmer.

At an international conference on "The Changing Atmosphere" sponsored by the Canadian government in Toronto last June, some 300 reputable scientists and government officials warned that "Humanity is conducting an uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war." A "greenhouse doomsday scenario" by author Jeremy Rifkin conjures up images of the Netherlands disappearing under the waves like a latter-day Atlantis, Bangladesh swept by floods claiming millions of lives, and the Mississippi River transformed into a "vast earthen plain"—while Manhattan's West Side Drive is lined with palm trees.

Exaggerations aside, there is a growing consensus among climatologists and other researchers that both the greenhouse effect and ozone depletion are not simply alarmist fantasies.

Last June, James E. Hansen, a senior physicist at the National Aeronautics and Space Administration (NASA), found himself on the network television news when, noting that the mean global temperature has increased by one degree Fahrenheit during the last century, he told a congressional committee that "the greenhouse effect has been detected and is changing our climate now." On Capitol Hill, Senators Timothy E. Wirth (D.-Colo.) and Robert T. Stafford (R.-Vt.) have each introduced legislation calling for improved energy conservation, more research, and tighter environmental regulation to combat the greenhouse effect.

Scientists are not totally certain that the greenhouse effect is the sole cause of the warming. The hot summers of the recent past could well be, at least in part, the result of natural climatic fluctuations. "Climate is a complicated thing," notes Roger Revelle of the University of California, "and the changes seen so far may be due to some other cause we don't yet understand." Indeed, even the rising temperatures of the past century were punctuated by an unexplained cool period between 1945 and 1975, when some scientists began to worry about the eventual onset of a new Ice Age.

Hubert H. Lamb, a leading British climatologist, is also wary. While the greenhouse effect is real, Lamb believes, the long-term global warming may also have natural causes. Even scientists, he cautions, follow "fashions." A particular theory "catches on and gains a wide following, and while that situation reigns, most [researchers] aim their efforts at following the logic of the theory and its applications, and tend to be oblivious to things that do not quite fit."

Bubbles in the Ice

Nevertheless, *most* scientists now agree that the greenhouse effect will warm the Earth during the decades ahead. Sometime between the year 2025 and 2050, average global temperatures could be as little as three degrees Fahrenheit above current levels, or as much as nine degrees higher—unless nature intervenes and suddenly cools the planet. Some of this change we may be able to avert; some of it we will have to adapt to.

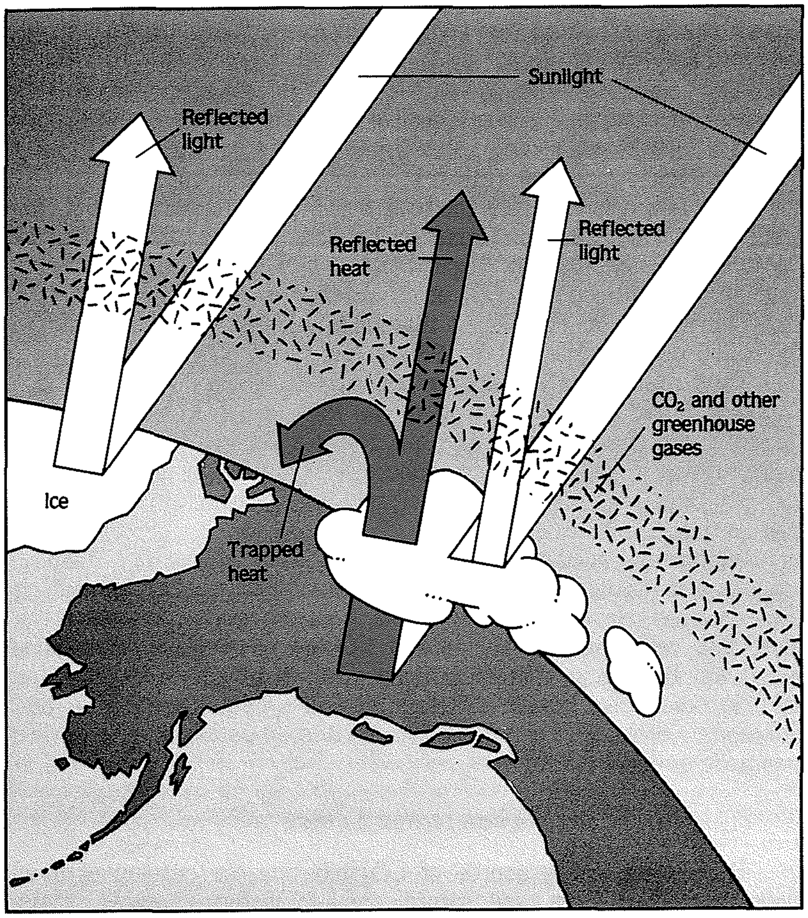
The greenhouse effect is a natural phenomenon. The Earth's atmosphere, consisting chiefly of nitrogen and oxygen, but including many other gases, is almost transparent to sunlight. The Earth's surface reflects some of the sunshine, but much of it is absorbed, only to be emitted later as infrared radiation. That is where the greenhouse effect comes in. While most sunlight easily passes through the atmosphere on its way to the planet's surface, some of the outbound radiating infrared is trapped by gases in the lower atmosphere before it can escape into space. These "greenhouse gases," chiefly water vapor and carbon dioxide (CO_2), then warm up, heating the Earth's atmosphere.

The greenhouse gases occur naturally; by regulating temperature, precipitation, and soil moisture, they make life on Earth possible. A paucity of CO_2 leaves Mars frigid and dry, while an overabundance of it makes Venus a furnace.

Carbon dioxide is also the raw material of photosynthesis in plants. Trees, shrubs, grasses, and other plants return some of the CO_2 they absorb to the atmosphere through respiration, but they store vast quantities (in the form of carbohydrates) in their cells. Only after the plants die and decay or are burned is that carbon transformed into CO_2. The

Steven Lagerfeld, 33, is senior editor of the Wilson Quarterly.

THE GREENHOUSE EFFECT



The Earth's atmosphere functions much like a giant greenhouse, admitting sunlight from outer space, but preventing heat from escaping. About 50 percent of all incoming sunlight penetrates to the Earth's surface. As this simplified diagram suggests, clouds reflect (and absorb) much sunlight; so do haze and dust in the air. The Earth's surface, especially where it is covered by snow and ice, also reflects some light. The remaining sunlight is absorbed by the land and oceans. As the Earth warms, it emits heat in the form of invisible infrared radiation. About 15 percent of this heat ultimately escapes from the atmosphere. The rest is "trapped" by a layer of clouds, water vapor, carbon dioxide, and various other "greenhouse gases" that extends from ground level up to 10 miles above the planet's surface—thus providing the warmth that supports, but at higher levels could disrupt, life on Earth.

emitted carbon is continuously reabsorbed by the Earth's "sinks"—the oceans and the "biomass" (all plant and animal matter). But carbon dioxide has been building up in the atmosphere faster than it can be reabsorbed by these "sinks."

Only in relatively recent times have scientists gained the ability to measure the gases that are responsible for the greenhouse effect.

In 1980, by examining air bubbles trapped in the glacial ice of Greenland and Antarctica, researchers discovered that CO_2 concentration in the atmosphere before the Industrial Revolution (circa 1750) was about 280 parts per million (ppm). In 1958, as part of the International Geophysical Year, scientists began the first systematic readings of current levels of atmospheric CO_2 at an observatory atop Mauna Loa, an 11,000-foot peak in Hawaii. At that time, the level had increased to about 315 ppm. By the end of 1986, it had risen to 345 ppm.

Thus, the Earth's atmosphere now contains about 25 percent more CO_2 than it did at the beginning of the Industrial Revolution, and 10 percent more than it did a mere quarter of a century ago. Today, the concentration of CO_2 in the atmosphere is increasing by about 0.4 percent per year. That is fast enough to produce a doubling of the preindustrial level within 35 to 60 years.

Why is this buildup occurring? During the 19th century, loggers, farmers, and ranchers cleared vast tracts of virgin forest throughout the United States, New Zealand, Australia, South Africa, and Eastern Europe, thus releasing vast amounts of CO_2 into the atmosphere. Since World War II, logging (of teak, mahogany, and other tropical woods) and land clearance have largely shifted to Africa, South America, and Asia. This source probably accounts for about 10 to 20 percent of the world's manmade emissions of CO_2.

Winners and Losers

The largest single source of CO_2 today is the burning of fossil fuels—coal, petroleum, and natural gas—in factories, power plants, home furnaces, and automobile engines. Between 1950 and 1979, worldwide fossil fuel use quadrupled. Higher oil prices and greater fuel efficiency in industry and autos have since slowed the rate of increase. But, this change has been accompanied by a shift to coal, which produces far more CO_2 than either oil or natural gas.

Carbon dioxide is not the only greenhouse gas. Methane (CH_4) and nitrous oxide (N_2O) are naturally occurring substances that also have "greenhouse" properties, as do the manmade chlorofluorocarbons that have been implicated in the destruction of the ozone layer. As a result of rapid population growth, increasing affluence, and industrial expansion, they have been increasing even more rapidly than CO_2.

Nitrous oxide rises into the atmosphere from automobile exhausts, factory smokestacks, and the decomposition of the chemical fertilizers

Amid last summer's heat waves, "Washingtoon" cartoonist Mark Alan Stamaty poked fun at attitudes toward the "greenhouse effect."

that the world's farmers are using in ever-increasing amounts.

As for methane, cows are among the chief culprits. Beef and dairy cattle (along with other ruminant animals) release the gas from their digestive tracts. The global cattle population has surged during the past century, partly to satisfy the appetites of affluent Americans and Europeans for steaks and hamburgers. Methane is also produced by bacteria in the world's swamps (thus, the term "swamp gas") and the rice paddies of Asia, which have been expanded dramatically since World War II to feed growing populations. Termites, especially numerous in the savannahs and forests of Africa, where they feed on grass and felled trees, emit the gas from their digestive tracts.

Together, the buildup of nitrous oxide, methane, and other "trace gases" makes a major contribution to the greenhouse effect. "These are the little guys," observed Stephen Schneider, of the U.S. National Center for Atmospheric Research. "But they nickel and dime you to the point where they add up to 50 percent of the problem."

The ill effects of an eroded ozone layer are fairly narrow and easy to predict—an increase in the incidence of skin cancer, crop damage. But the consequences of a strong greenhouse effect are less certain. Climatologists use computerized "general circulation models" to predict how and where the world's climate will change in a greenhouse atmosphere.* The models have serious limitations: Scientists do not yet know

*The federal government now spends about $195 million annually on climate-related research under the nine-year-old National Climate Program. A variety of federal agencies are involved, including the departments of Agriculture, Energy, and Commerce, and the National Science Foundation. The leading U.S. researchers in the field are concentrated at about 10 universities, from the University of Alaska, Fairbanks, to Florida State University, Tallahassee.

exactly how temperature, winds, precipitation, and other elements of climate interact and alter one another.

Even so, climatologists seem to agree on the *outlines* of change in a "greenhouse world." They believe that the tropics will warm slightly, but land surfaces in the high latitudes in both hemispheres, especially the Northern Hemisphere, will heat up considerably more. A warmer atmosphere would hold more water, resulting in greater rainfall overall—although some regions would be drier.

But there is very little agreement among the five or six major climate modeling teams in the United States and Western Europe on how *specific* regions might be affected, especially by changes in rainfall. One thing is clear: around the world, there would be winners and losers.

A Boon to Farmers?

For example, some scientists predict that the midlatitudes of the Northern Hemisphere continents (the Great Plains in the United States, Central Europe, parts of the Soviet Union) are likely to become hotter and much more drought-prone than they are today. Others disagree. They add that the Sahara and other dry regions could get *more* rainfall. Changes in the circulation of monsoons might augment the annual rains in India, Pakistan, and Bangladesh, helping to avert the periodic droughts and famines that have cost thousands of lives in these populous lands. On the other hand, the sometimes catastrophic annual monsoon floods in Bangladesh could become more dangerous.

One much-publicized doomsday vision raises the specter of huge chunks of the Antarctic ice sheet breaking off and melting to engulf the world's coastal cities. That is highly unlikely. Scientists now know that Antarctica was largely unaffected by rapid global warmings in the distant past. But some increase in sea levels is quite possible, due to "thermal expansion" of water molecules as the oceans' waters warm. Already about five inches higher than they were a century ago, the oceans could rise by an additional five to 15 inches within the next four decades, according to the Environmental Protection Agency. Bangladesh and other low-lying countries could lose valuable coastal croplands and suffer much greater damage from storms and hurricanes. Throughout the world, beaches, marshes, and coastal farmland would be endangered. Just a one-foot rise in sea level would wash away most recreational beaches in the United States and destroy large portions of the coastal wetlands where many birds and fish breed.

In many places on Earth, even minor changes in temperature, rainfall, and water levels of streams and rivers could wipe out innumerable small plant and animal species that have adapted to very narrow local ecological "niches." A lower water level in one river, or increased flooding in another, might wipe out isolated species of birds or fish.

The rising level of CO_2 in the atmosphere could have one important positive result. Biologists have long known that bigger doses of CO_2 speed up plant photosynthesis and reduce water consumption. (Indeed, some agronomists maintain that increases in CO_2 in the air helped western U.S. wheat farmers achieve their remarkable tripling of crop yields between 1920 and 1980.) Thus, in a "greenhouse world" of the future, there might be some overall increase in farm productivity. But the most important result might be the expansion of farming in areas of the world, notably Africa's Sahel region, where lack of rainfall now limits crop production—assuming, of course, that other unforeseen climatic changes do not cancel the benefits.

These predictions are based just on the *warming* due to the greenhouse effect. Other features of the global climate may also be affected—for better or worse. The amount of sunshine reaching field crops may vary because of changing cloudiness. Winds and humidity may also shift. As always, the complex interaction of such fluctuations makes it difficult to predict exactly how the world's overall climate may be transformed. As physicist S. Fred Singer and others have noted, for example, heavier cloud cover might *cool* the globe, counteracting some of the greenhouse "warming" effect.

Most scientists agree that a worldwide temperature increase of at least three degrees Fahrenheit during the next few decades seems inevitable. But they also agree that human beings can do much to slow the rate of increase, to prevent even more severe temperature increases, and to adapt to the climatic changes that we cannot stop.

Hanging Together

Many scientists and politicians favor international efforts to restrain emissions of CO_2. (No one is quite sure what to do about the methane emitted by cows and some of the other greenhouse gases.) But effective agreements will be hard to produce. Today's global efforts to control ozone depletion, a threat with much clearer causes and effects, reveal some of the pitfalls.

In September 1987, after two years of difficult negotiations under the aegis of the United Nations Environmental Program (UNEP), representatives of 24 nations and the European Economic Community, meeting in Montreal, signed an agreement to cut production and consumption of certain chlorofluorocarbons by 50 percent by 1998. But, despite all the cheering that greeted the agreement, it was really only, as David D. Doniger of the Natural Resources Defense Council recently put it, "a major half-step forward."

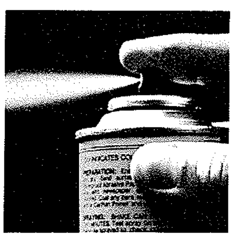
The pact's many compromises foreshadow the difficulties that will hamper any international effort to deal with the greenhouse effect. Only the industrialized nations are required to reduce production and consumption of chlorofluorocarbons; the world's poorer nations are permitted to increase output until 1999; and the Soviet Union is allowed a two-

THE EARTH'S ERODED SHIELD

Ordinary Americans probably first heard about the ozone layer some 20 years ago. During the late 1960s and early '70s, scientists and environmentalists warned that emissions from the supersonic transport (SST) favored by President Richard M. Nixon would gradually destroy ozone in the upper atmosphere. Such fears, along with high cost estimates, led Congress to kill the SST in 1971.

Three years later, in *Science*, chemists Mario Molina and F. Sherwood Rowland discussed another possible threat: chlorofluorocarbons, manmade chemicals then used chiefly as propellants in aerosol cans. In the upper atmosphere, they suggested, chlorofluorocarbons decompose, liberating chlorine molecules that then destroy ozone. Official reaction was swift. In 1977, the United States joined several other nations in banning the use of chlorofluorocarbons in aerosols—"the first time," note Stephen H. Schneider and Starley L. Thompson, "a substance suspected of causing global harm had been regulated before the effects had been demonstrated."

Meanwhile, however, chlorofluorocarbons grew into a $750 million industry in the United States alone. They were used increasingly as refrigerants, as propellants in making styrofoam, and as industrial solvents. Another class of chemicals with similar effects, the halons, were used in fire extinguishers. And it was discovered that methane and other trace gases also destroy ozone.



Why worry about the ozone layer? About 21 percent of the Earth's atmosphere is composed of oxygen, mostly in the two-atom molecule, O_2, but a tiny fraction exists as ozone, O_3. When it envelops major cities, ozone is considered a pollutant; in the frigid stratosphere (six to 30 miles above the Earth), it screens out the most harmful portions of the sun's ultraviolet rays. When it is absorbed by DNA, ultraviolet light can inhibit the human immune system and cause skin cancer and cataracts; it also appears to retard plant growth and reduce crop yields.

After chlorofluorocarbons in aerosol cans were banned in 1977, public concern about the ozone layer dissipated. Then, in 1985, a team of scientists led by Joseph Farman of the British Antarctic Survey discovered a massive "hole" in the ozone layer—a 40 percent drop since 1979 in the atmospheric concentration of ozone over the frozen continent. Since then, new studies have documented a less drastic, but worldwide erosion of the ozone layer.

"We have strong evidence that change in the ozone is wholly or in large part due to manmade chlorine," declared Robert Watson of the National Aeronautics and Space Administration last March. There are other possibilities: It could be that the past decade's cyclical decline in solar activity (indicated by sunspots), which has curtailed the production of fresh ozone in the stratosphere, is partly responsible. But the ozone loss is greater than can be explained by temporarily reduced solar activity. Day by day, the evidence is growing that Watson is correct; man is the villain.

thirds increase before it must begin cutting back.

Evaluating the agreement recently, the U.S. Office of Technology Assessment estimated that it might cut chlorofluorocarbon emissions by 45 percent at best—but could also permit an *increase* of 20 percent. In part because chlorofluorocarbons remain in the atmosphere for about 100 years, even a 45 percent reduction of emissions, Doniger observes, "will only reduce the *acceleration* of [ozone] depletion."

Meanwhile, the scientific studies on which the 1987 pact was based have become outdated. Just a day after the U.S. Senate approved the agreement, a new study indicated that the planet's ozone shield has eroded by 1.7 to 3 percent since 1970—even more rapidly than had been predicted. Last September, the U.S. Environmental Protection Agency called for a worldwide ban on production of chlorofluorocarbons.

Dealing with the greenhouse effect is going to pose a considerably greater political and financial challenge. The causes are much more numerous, and many are not under man's control; the costs of various proposed remedies could be much higher; and the benefits (relief from unfavorable shifts in climate) will very likely be unequally distributed among the world's regions.

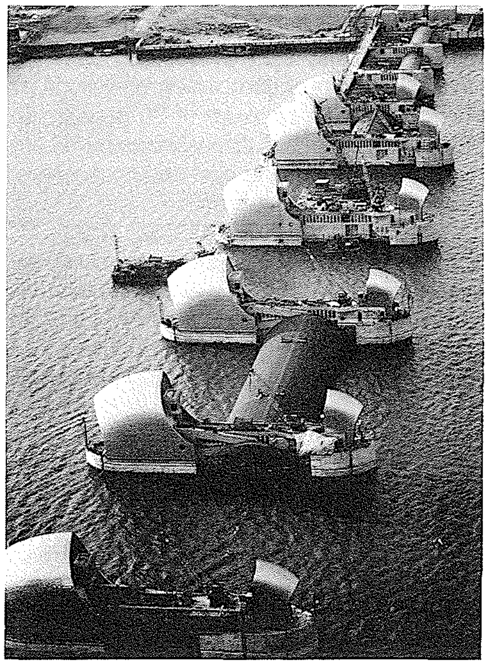
Nuclear Power Revisited

The United States and the Soviet Union now produce nearly half of the world's CO_2. Yet, much of the increase in CO_2 emissions during the decades ahead will be produced by industrializing Third World nations, such as South Korea and Brazil. "How do you get rapidly developing, hand-to-mouth nations to give up their first taste of economic security in the name of some vague and distant scare scenario?" *The New Republic* asked recently. "Environmentalism is a luxury they can't afford." Mainland China, for example, with its immense population and relative poverty, is not likely to slow the exploitation of its vast coal reserves unless scientists can point with near certainty to dire consequences for China's farmers. They cannot. In fact, China now plans to virtually double its burning of coal by the year 2000.

Similarly, as steel, autos, and other energy-intensive industries continue to shift production to the Third World, these poorer nations are not likely to take kindly to the suggestion that they cut back on the use of coal and oil—unless the West somehow finds a way to compensate them for the sacrifice of economic opportunity.*

Neither is the West eager to reduce its standard of living to combat a vaguely perceived global threat. Coal use in the United States and

*A creative experiment by Conservation International, a private organization, suggests one way this might be done: so-called debt-for-nature swaps. Using private contributions, the Washington-based group bought up (at a discount) $650,000 worth of Bolivia's international debt, then turned it over to the Bolivians. In return, the Bolivian government pledged to limit development of four million acres of Amazon lands, thus preserving a valuable CO_2 "sink." Yet, it remains to be seen whether the leaders of Bolivia and other Third World nations will be able to exert strict control over the development of such remote areas.



Adapting to climate: London's $765 million Thames Barrier, a pivoting dam, was completed in 1982. The slight rise in sea levels caused by the planet's warming during the 20th century, along with certain geological anomalies, have left the city vulnerable to flooding from once-a-century North Sea "storm surges."

Western Europe is likely to grow well into the next century. The chief "alternative" energy sources—wind and solar power, biomass conversion—are a long way from being practical (or economical) enough to make a difference. Synthetic fuels, the great energy panacea of the 1970s, are even "dirtier" than coal. The only major energy source that does not create CO_2 is nuclear power, but it faces vehement political opposition in the United States and much of Western Europe. Attitudes toward the atom may be changing. Senator Timothy Wirth's pending "greenhouse" bill includes $500 million for research into "safe" forms of nuclear power. America, said the Colorado Democrat, must get over its case of "nuclear measles."*

Stronger efforts to conserve energy would help reduce CO_2 emissions somewhat. According to the World Resources Institute, the latest electrical appliances, light bulbs, and building designs are twice as energy-efficient as older versions. Greater fuel economy in automobiles is also possible. The average new car in the United States now gets 25

*Since the Three Mile Island reactor accident in 1979, American utility companies have ordered no new nuclear power plants, and have canceled earlier plans for 65 reactors. Even so, 46 new nuclear reactors have gone into operation since Three Mile Island, serving such major cities as Houston, Phoenix, Pittsburgh, and Chicago. Today, 109 reactors across the United States supply 18 percent of the nation's electricity. Nuclear power generates 70 percent of all electricity in France, 50 percent in Sweden, and 44 percent in Taiwan.

miles per gallon, up from only 13 in 1973, but still only half of what some existing cars achieve. Even so, as S. Fred Singer notes, more conservation "can only nibble" at the CO_2 problem.

A few scientists are beginning to think about exotic schemes to combat climatic change. They range from covering the world's oceans with white styrofoam chips to reflect vast amounts of sunlight back into space, to launching huge solar power stations into orbit around the planet, to lobbing frozen "bullets" of manmade ozone into the atmosphere. As Princeton physicist Thomas H. Stix concedes, however, such ventures remain "mighty speculative."

A simpler way to slow the buildup of CO_2 is simply to plant more trees. A vast forest of fast-growing sycamores or poplars—covering approximately 1.2 million square miles, roughly twice the area of Alaska—might contain enough trees to absorb all of the excess CO_2 that man is producing today (about three billion tons annually). But even such a dramatic effort would only postpone the day of reckoning. When trees reach maturity, after about 40 years, they stop absorbing CO_2.

Living in the Greenhouse

Cutting down and replanting such vast forests would present new problems. Burn the wood as fuel, and you liberate the carbon within it (creating CO_2); sell it as lumber and you threaten the lumber industry and the woodlands that it controls.

Whatever mankind does, it now seems inevitable to most scientists that the greenhouse effect will change the world's climate somewhat—more heat waves and droughts in some areas, heavier rains and milder temperatures in others. In some locales, the shifts may be extreme. But, overall, a three-degree increase in temperatures is well within man's ability to cope. We have, after all, barely noticed the one-degree warming during the past century. And, during the so-called Little Ice Age of 1400–1850, when average annual temperatures dropped by about two degrees below today's levels, the far less sophisticated societies of Europe suffered only scattered disruptions. "If we have 20 or 50 years to plan," observes Paul Portney, a researcher at Resources for the Future, "we can take steps to mitigate the adverse effects."

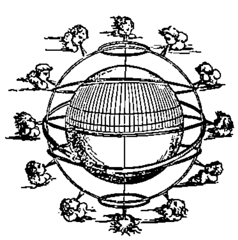
Levees can be erected to contain rising seas and rivers; if need be, people and industries can gradually move, as they always have, to follow the weather.

Surprisingly, the world's farmers may find it relatively easy to deal with change. They have always been pawns of the weather, and so have learned to respond quickly to year-to-year changes in temperature and rainfall. In the past, agricultural scientists and farmers have overcome severe local handicaps caused by climate. Since the 1920s, for example, plant breeders have helped American farmers expand the range of hard red winter wheat from Kansas and Oklahoma, south to Texas and as far north as the Canadian prairies. This kind of wheat now grows as well in Sidney, Montana, as it does in Sidney, Nebraska, although the Montana town's growing season is 10 days shorter, rainfall is 20 percent less, and annual temperatures are more than seven degrees cooler. Unlike traditional spring wheat, winter wheat is planted in autumn, quickly establishes a root system, and then lies dormant under the winter snows. It begins to grow again as the soil warms in spring, normally flowers and sets seed after the spring frosts, and is harvested before the extreme heat and drought of summer.

Farmers can shift to improved, drought-resistant plant varieties or to entirely new crops. They can employ new water-conserving tillage techniques, and irrigate more acres only at critical stages of plant growth rather than fewer acres all the time, as they do now. In short, farmers in the United States and elsewhere ought to have little trouble feeding the world in a moderately warmer climate.

This relatively optimistic view reflects the assessments of many specialists who have studied the ways in which farmers and agronomists have responded to normal weather fluctuations—drought, extremely cold winters, heavy rainfall. Scientists are by no means unanimous in rejecting more sombre scenarios. That mankind has managed to adapt to climate as it has changed in the past, however, seems to justify a fair degree of confidence in our ability to cope with a moderate warming of the globe during our lifetime.

But even the optimists warn that if the peoples of the world do not begin to restrain their output of CO_2 and other greenhouse gases, global temperatures could *eventually* climb by nine degrees, and by much more in some places. That, they say, would take us far beyond the bounds of any climatic change that mankind has experienced in its short history, and possibly beyond our ability to cope.



CLIMATE

Why did dinosaurs suddenly disappear, along with dozens of plants and other animal species, in what appears to have been a mass extinction some 65 million years ago?

That question has long fascinated schoolchildren and scientists alike. In the popular imagination, the answer always seemed obvious: A colder climate did in the dinosaurs. To scientists, as Stephen H. Schneider and Randi Londer report in **The Coevolution of Climate and Life** (Sierra Club, 1984), the answer is not nearly so clear.

Some researchers have suggested that dinosaurs were sterilized when the Earth suddenly warmed due to an early "greenhouse effect." Others have proposed that they were destroyed by a supernova exploding in outer space.

Recently, physicist Luis Alvarez and his son Walter, a geologist, have found evidence that the planet was struck by a huge asteroid at about the time of the dinosaurs' extinction. If so, it may have thrown up a massive cloud of dust, shrouding the Earth against sunlight and leading to a catastrophic cooling. On the other hand, the Earth may have *warmed*—or it may have gone dark, or it may have temporarily lost part of its protective ozone layer. The Alvarezes are not sure. Many scientists are intrigued by the asteroid theory; but others reject out of hand the whole notion of such a catastrophic extinction.

Such are the difficulties of the climatologist; and Schneider, himself a climatologist, and science writer Londer are by far the best guides to the work of these scientists. Their book becomes, in effect, an intriguing essay on how much is still unknown.

Planet Earth, now about 4.6 billion years old, appears to have been a hot, dry, generally inhospitable place during most of its history. During the seven relatively brief Glacial Epochs, each, on average, a mere 50 million years long, Planet Earth has been, in general, *cold* and inhospitable.

If those 4.6 billion years were compressed into 46 years, then the dinosaurs vanished just over six months ago, humanity emerged about seven days ago, and the Industrial Age is about two minutes old. The last Ice Age began about a week ago. From this perspective, as Britain's Sir Crispin Tickell notes in **Climatic Change and World Affairs** (Univ. Press of America, 1986), "we live in a tiny, damp, curved space at a pleasantly warm moment."

In modern times, at least, scientists have concentrated most of their efforts on simply trying to calculate what past climates were like—with mixed success. And readers in search of cosmic speculations about the influence of climate on evolution and human existence are likely to be disappointed.

As Ronald Pearson, a University of Liverpool zoologist, shows in **Climate and Evolution** (Academic Press, 1978), most researchers fasten on discrete cases, such as documenting the adaptation of *Cepaea nemoralis* (a species of snail) to different environments by changing its coloration.

Generally, it seems, every bit of new evidence about, say, the extinction of the woolly mammoth toward the end of the Quaternary Succession (the period beginning 2.5 million years ago and ending 10,000 years ago) spawns a new theory without necessarily eliminating several competing older ones.

Nevertheless, the discussion is often fascinating. The woolly mammoth was just one of scores of species of "megafauna"—sabre-toothed tigers, giant baboons and pigs, the 20-foot tall North American sloth, and beavers as large as bears—that perished in a surprisingly short period of time beginning about 60,000 years ago. Deepening the mystery is the fact that the oversized mammals survived a whole series of Ice Ages, only to die off as the world's climate was again warming and stabilizing.

In conference papers, learned articles, and books such as **Pleistocene Extinctions: The Search for a Cause** (Yale, 1967), edited by P. S. Martin and H. E. Wright, Jr., scientists have offered several new explanations.

For his part, paleontologist John Guilday suggested that the Earth's post-Ice Age warming expanded southern deserts and northern forests, squeezing many animal species into diminishing grasslands. The smaller mammals, requiring less food, were better suited to survival in the new environment; only those megafauna that experienced evolutionary "dwarfing" (e.g., the bison) were able to survive.

But there were objections to this theory. For example, it was known that many of the later extinct species had been able to extend their range *beyond* the retreating grasslands.

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Other theories were proposed. Diseases bred among animal species isolated by glaciers during the Ice Age may have been unleashed as the planet warmed; a sudden warming could have turned vast areas of the world into deadly bogs that entrapped large mammals; or perhaps "racial senility" rendered entire species unable to adapt to climatic change. Finally, during the late 1960s, some scientists, pointing to fossil evidence that prehistoric man had slaughtered thousands of animals at a time in mass hunts, argued that humans were largely responsible for the relatively swift extinctions.

Today, as Windsor Chorlton notes in his popular account, **Ice Ages** (Time-Life Books, 1983), the "hunter" theory has few proponents. Scientists now generally agree that man may have speeded the demise of the megafauna, but that a changing climate and a variety of other factors (e.g., changing sea levels) appear to have been the chief causes. *How* climate may have helped kill the megafauna, however, remains a matter of intense debate.

The same caution and strict attention to case studies that characterize current research on climate's influence on evolution carry over to most serious investigations of its impact on human history.

The classic work on climatology is Hubert H. Lamb's two-volume **Climate Present, Past and Future** (Methuen, 1977). In his more recent **Weather, Climate and Human Affairs** (Routledge, 1988), Lamb chides historians for ignoring the effects of climate, and allows himself some passing observations about the subtlety of climate's influence. He notes, for example, that architecture seems to be affected by changes in climate. The abnormally dry weather of the 1930s and '40s encouraged the building of flat-roofed houses in England—a fashion, Lamb adds, that the present owners of these leaky-roofed dwellings no doubt regret.

As Theodore K. Rabb writes in **Climate and History: Studies in Interdisciplinary History** (Princeton, 1981), however, historians have not yet developed techniques to gauge climate's effects on human history with any accuracy—except, perhaps, in a few localized cases where climate changed rapidly.

Climate and History: Studies in Past Climates and their Impact on Man (Cambridge, 1985), edited by T. M. L. Wigley, M. J. Ingram, and G. Farmer, provides a scholarly overview of work in the field. Essays include "Climate and Popular Unrest in Late Medieval Castile," "The Economics of Extinction in Norse Greenland," and "The Historical Climatology of Africa."

Historian Emmanuel Le Roy Ladurie's **Times of Feast, Times of Famine: A**

History of Climate Since the Year 1000 (Doubleday, 1971), despite its grand title, is chiefly of interest to scholars exploring methodologies for reconstructing past climates.

The Last Great Subsistence Crisis in the Western World (Johns Hopkins, 1977), by John D. Post, is one historian's ambitious attempt to trace the effects of a single climatic drama: the eruption in 1815 of Indonesia's Mount Tambora, whose ash and gases shut off sunlight and cooled the Northern Hemisphere. The result: crop failures and bread riots throughout Europe. Among the other consequences, according to Post, were a surge of emigration to the New World—and an outbreak of anti-Semitism in southern Germany. Ultimately, he says, "it is not difficult to believe that [climate-induced] economic crisis and social unrest fused with political conservatism to foreclose the emerging liberal ideas of 1815."

Scholars seem to agree that studies of such isolated episodes and their effects are relatively easy work. The greater hazards of more wide-ranging, speculative history are illustrated by the search of climatologists Reid A. Bryson and Thomas J. Murray for past **Climates of Hunger** (Univ. of Wis., 1977). Apparently caught up in a mid-1970s anxiety about the slow onset of a new Ice Age, to which they attributed severe droughts in the Sahel region of Africa, the authors consulted history for precedents. They argued that Mycenae and several other ancient societies had perished because of droughts—produced chiefly by global cooling, exacerbated by the practices of farmers and herders.

They warned of a possible repetition in the future: "Our conclusion is that the net effect of man's burning of fossil fuels, his slash-and-burn agriculture, and his other activities that produce both carbon dioxide and dust, is to *reduce* temperatures" (emphasis added).

Today, of course, most scientists take a contrary view. Their findings and recommendations pour forth in such publications as **Developing Policies for Responding to Climatic Change** (World Meteorological Organization, 1988); **A Matter of Degrees: The Potential for Controlling the Greenhouse Effect** (World Resources Institute, 1987), by Irving M. Mintzer; and **Present State of Knowledge of the Upper Atmosphere 1988: An Assessment Report** (National Aeronautics and Space Administration, 1988). For the layman, the proceedings of various congressional hearings, such as **The National Climate Program Act and Global Climate Change** (Government Printing Office, 1988), provide some of the most accessible guides to current research and prognostications.

The study of climate is still in its youth. It lacks a grand theory. Without much fanfare, scores of scientists and other researchers, in America and abroad, are trying to devise more rigorous approaches to the investigation of the globe's changing climate and its impact on man.