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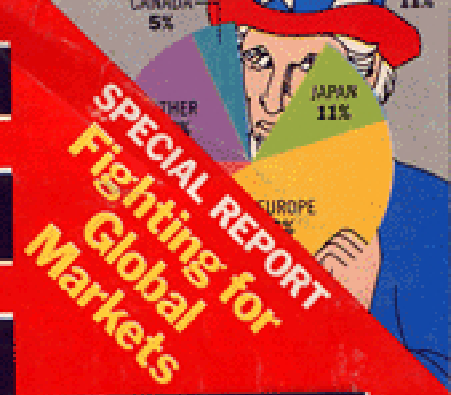
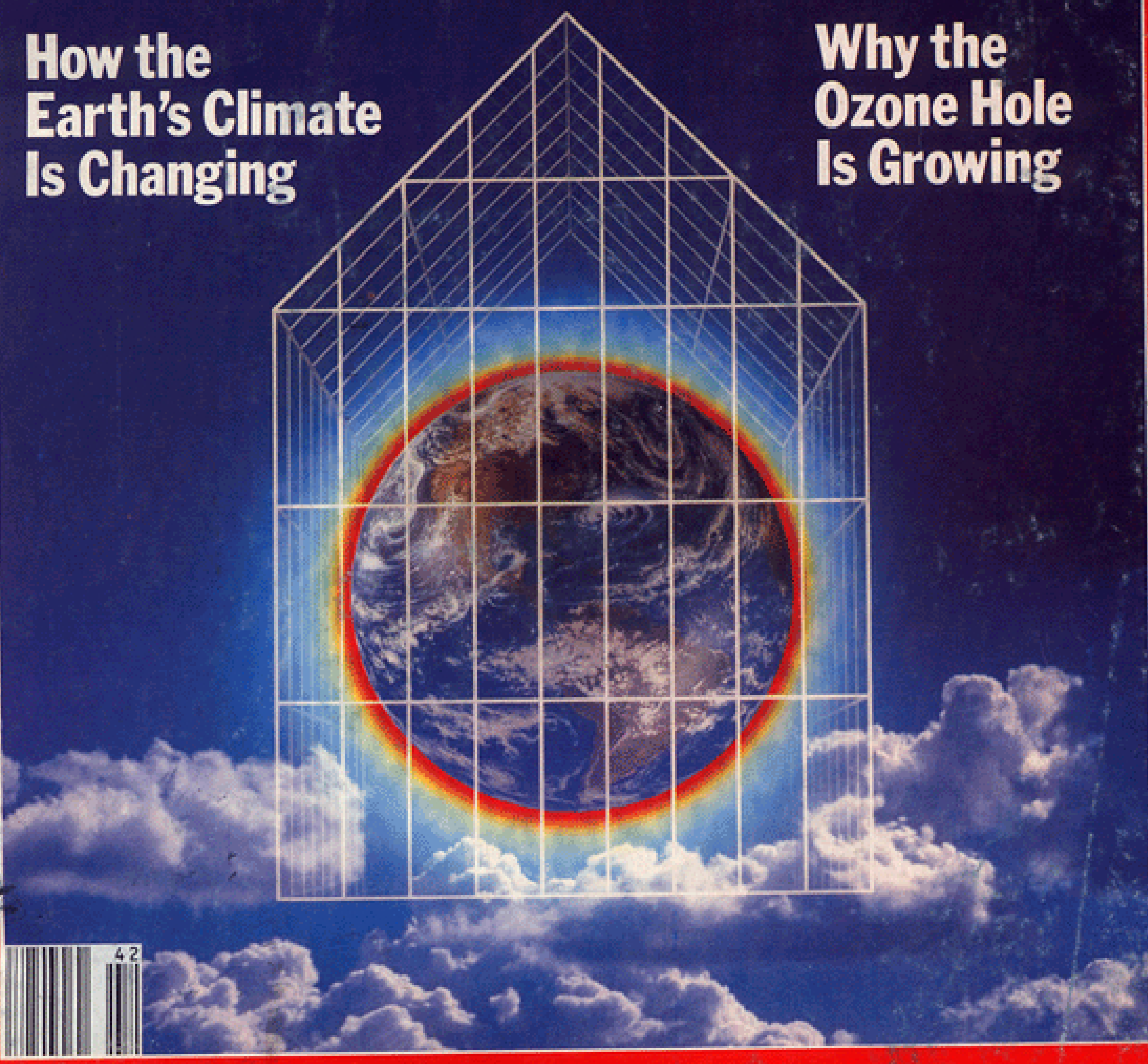


SPECIAL REPORT
Fighting for Global Markets

The Heat Is On

How the Earth's Climate Is Changing

Why the Ozone Hole Is Growing



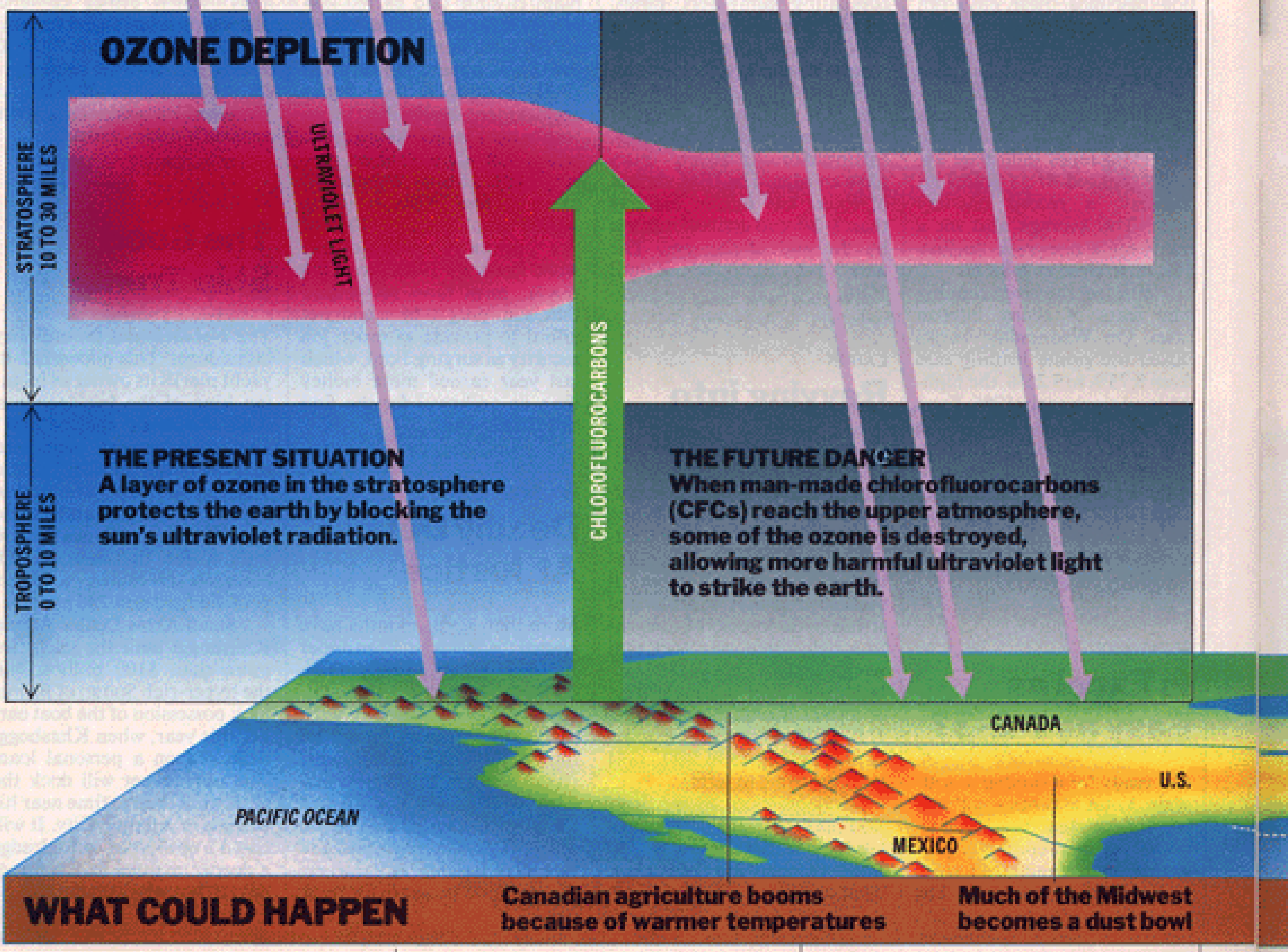
COVER STORY

The Heat Is On

Chemical wastes spewed into the air threaten the earth's climate

At this time of year, the Cabo de Hornos Hotel in Punta Arenas (pop. 100,000) is ordinarily filled with tourists who spend their days browsing in the local tax-free shops or mounting expeditions into the rugged, mountainous countryside just out of town. But the 120 mostly American scientists and technicians who converged on Chile's southernmost city for most of August and September ignored advertisements for hunting, hiking and ski tours. Instead, each day they scanned the bulletin board in the hotel lobby for the latest information on a different sort of venture.

Thirteen times during their eight-week stay, a specially outfitted DC-8 took off from the Presidente Ibañez Airport, twelve miles northeast of Punta Arenas. Often the 40-odd scientists and support crew listed for a given flight had to leave the hotel soon after midnight to prepare the plane and its research instruments. Once airborne, the DC-8 would bank south toward Antarctica, 1,000 miles away, fighting vicious winds before settling into a twelve-hour round-trip flight at altitudes of up to 40,000 ft. Along the way, the instruments continuously collected data on atmospheric gases, airborne particles and solar radiation high above the frozen continent. Meantime, parallel flights took off from Ibañez to gather additional atmospheric data at nearly twice the altitude. Manned by a lone pilot, a Lockheed ER-2, the research version of the high-altitude U-2 spy plane, made twelve sorties into the lower stratosphere, cruising at nearly 70,000 ft., or more



than 13 miles, for six hours at a time.

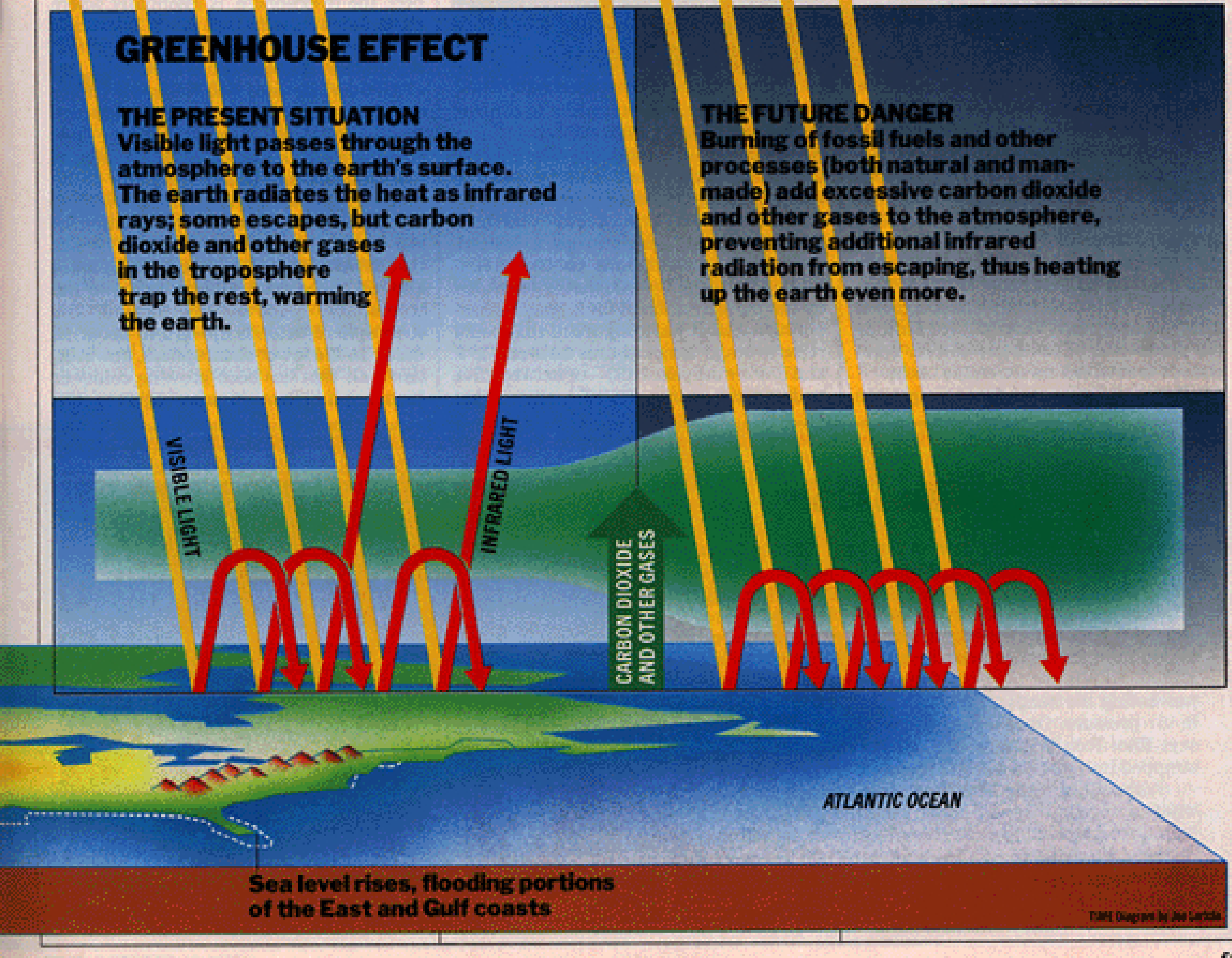
Both aircraft were part of an unprecedented, $10 million scientific mission carried out by the U.S. under the combined sponsorship of NASA, the National Oceanic and Atmospheric Administration, the National Science Foundation and the Chemical Manufacturers Association. The purpose: to find out why the layer of ozone gas in the upper atmosphere, which protects the earth's surface from lethal solar ultraviolet radiation, was badly depleted over Antarctica. The scale of the mission reflected an intensifying push to understand the detailed dynamics of potentially disastrous changes in the climate. The danger of ozone depletion is only part of the problem: scientists are also concerned about the "greenhouse effect," a long-term warming of the planet caused by chemical changes in the atmosphere.

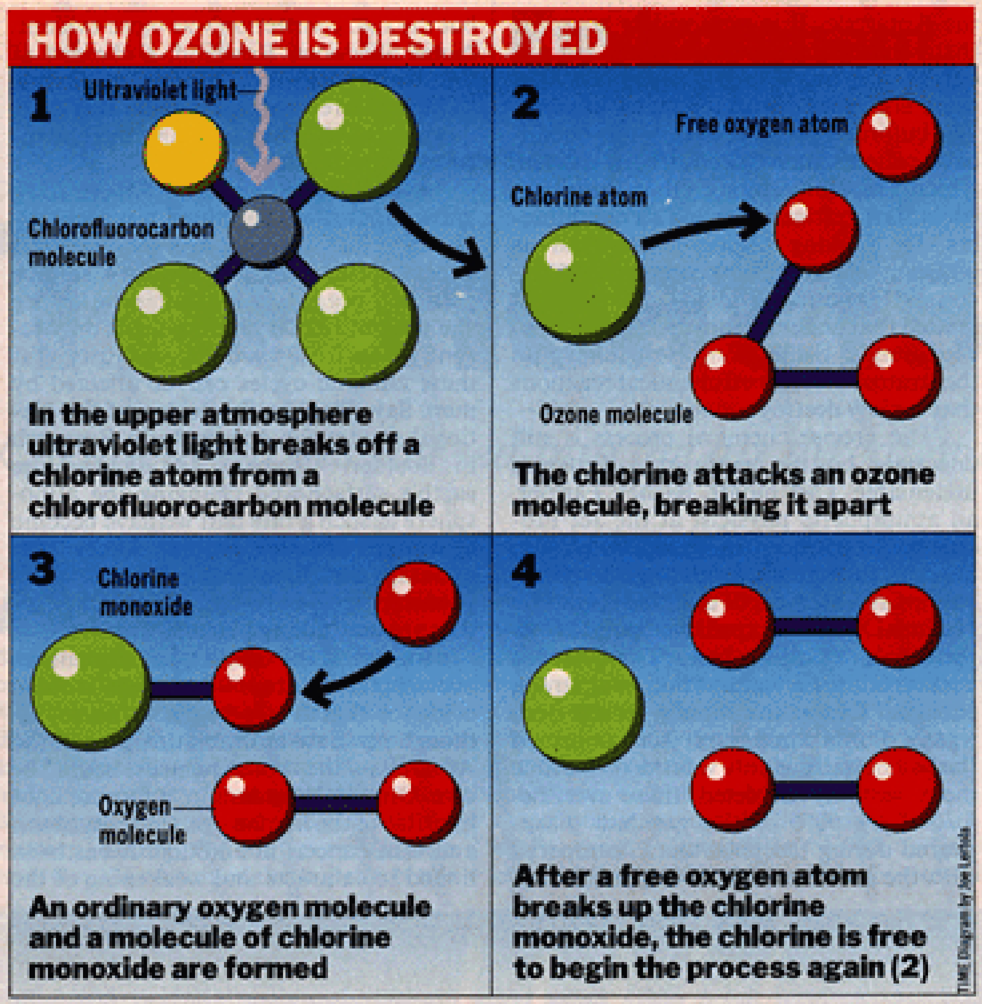
The threat to the ozone was first discovered in 1983, when scientists with the British Antarctic Survey made the startling observation that concentrations of ozone in the stratosphere were dropping at a dramatic rate over Antarctica each austral spring, only to gradually become replenished by the end of November. At first they speculated that the phenomenon might be the result of increased sunspot activity or the unusual weather systems of the Antarctic. It is now widely accepted that winds are partly responsible, but scientists are increasingly convinced that there is a more disturbing factor at work. The culprit: a group of man-made chemicals called chlorofluorocarbons (CFCs), which are used, among other things, as coolants in refrigerators and air conditioners, for making plastic foams, and as cleaning solvents for microelectronic circuitry. Mounting evidence has demonstrated that under certain conditions these compounds, rising from earth high into the stratosphere, set off chemical reactions that rapidly destroy ozone.

The precise chemical process is still uncertain, but the central role of CFCs is undeniable. Last month Barney Farmer, an atmospheric physicist at the Jet Propulsion Laboratory in Pasadena, Calif., announced that his ground-based observations as a member of the 1986 Antarctic National Ozone Expedition pointed directly to a CFC-ozone link. "The evidence isn't final," he said, "but it's strong enough." Earlier this month, results from NASA's Punta Arenas project confirmed the bad news. Not only was the ozone hole more severely depleted than ever before—fully 50% of the gas had disappeared during the polar thaw, compared with the previous high of 40%, in 1985—but the CFC connection was more evident. Notes Sherwood Rowland, a chemist at the University of California at Irvine: "The measurements are cleaner this time, more detailed. They're seeing the chemical chain more clearly."

Atmospheric scientists have long known that there are broad historical cycles of global warming and cooling; most experts believe that the earth's surface gradually began warming after the last ice age peaked 18,000 years ago. But only recently has it dawned on scientists that these climatic cycles can be affected by man. Says Stephen Schneider, of the National Center for Atmospheric Research in Boulder: "Humans are altering the earth's surface and changing the atmosphere at such a rate that we have become a competitor with natural forces that maintain our climate. What is new is the potential irreversibility of the changes that are now taking place."

Indeed, if the ozone layer diminishes over populated areas—and there is some evidence that it has begun to do so, although nowhere as dramatically as in the Antarctic—the consequences could be dire. Ultraviolet radiation, a form of light invisible to the human eye, causes sunburn and skin cancer; in addition, it has been linked to cataracts and weakening of the





immune system. Without ozone to screen out the ultraviolet, such ills will certainly increase. The National Academy of Sciences estimates that a 1% drop in ozone levels could cause 10,000 more cases of skin cancer a year in the U.S. alone, a 2% increase. These dangers were enough to spur representatives of 24 countries, gathered at a United Nations–sponsored conference in Montreal last month, to agree in principle to a treaty that calls for limiting the production of CFCs and similar compounds that wreak havoc on the ozone.

Potentially more damaging than ozone depletion, and far harder to control, is the greenhouse effect, caused in large part by carbon dioxide (CO_2). The effect of CO_2 in the atmosphere is comparable to the glass of a greenhouse: it lets the warming rays of the sun in but keeps excess heat from reradiating back into space. Indeed, man-made contributions to the greenhouse effect, mainly CO_2 that is generated by the burning of fossil fuels, may be hastening a global warming trend that could raise average temperatures between 2° F and 8° F by the year 2050—or between five and ten times the rate of increase that marked the end of the ice age. And that change, notes Schneider, "completely revamped the ecological face of North America."

The relationship between CO_2 emissions and global warming is more than theoretical. Two weeks ago, a Soviet-French research team announced impressive evidence that CO_2 levels and worldwide average temperatures are intimately related. By looking at cores of Antarctic ice, the researchers showed that over the past 160,000 years, ice ages have coincided with reduced CO_2 levels and warmer interglacial periods have been marked by increases in production of the gas.

Although the region-by-region effects of rapid atmospheric warming are far from clear, scientists are confident of the overall trend. In the next half-century, they fear dramatically altered weather patterns, major shifts of deserts and fertile regions, intensification of tropical storms and a rise in sea level, caused mainly by the expansion of sea water as it warms up.

The arena in which such projected climatic warming will first be played out is the atmosphere, the ocean of gases that blankets the earth. It is a remarkably thin membrane: if the earth were the size of an orange, the atmosphere would be only as thick as its peel. The bottom layer of the peel, the troposphere, is essentially where all global weather takes place; it extends from the earth's surface to a height of ten miles. Because air warmed by the earth's surface rises and colder air rushes down to replace it, the troposphere is constantly churning. A permanent air flow streams from the poles to the equator at low altitudes, and from the equator to the poles at higher levels. These swirling air masses, distorted by the rotation of the earth, generate prevailing winds that drive weather across the hemispheres and aid the spread of pollutants into the troposphere. Above this turmoil, the stratosphere extends upward to about 30 miles. In the lower stratosphere, however, rising air that has been growing colder at higher and higher altitudes begins to turn

Flying High—and Hairy

From preflight preparation to landing, piloting NASA's specially equipped ER-2 high-altitude research aircraft is not for the fainthearted. The three pilots who flew the twelve solo missions through the Antarctic ozone hole found the task grueling. An hour before zooming into the stratosphere, each had to don a bright orange pressure suit and begin breathing pure oxygen to remove nitrogen from the blood and tissues, thus preventing the bends, which can result from rapid reductions in air pressure. Once airborne, "you have to have patience," says Pilot Ron Williams, who flew the first mission. "You're strapped into a seat and can't move for seven hours."

Although the pilots had been briefed by meteorologists on what to expect, they still found conditions aloft astonishingly harsh. Accustomed to clear, broad vistas at high altitudes, the pilots—who took the ER-2 as high as 68,000 ft.—were startled to encounter layers of translucent mist composed of tiny ice

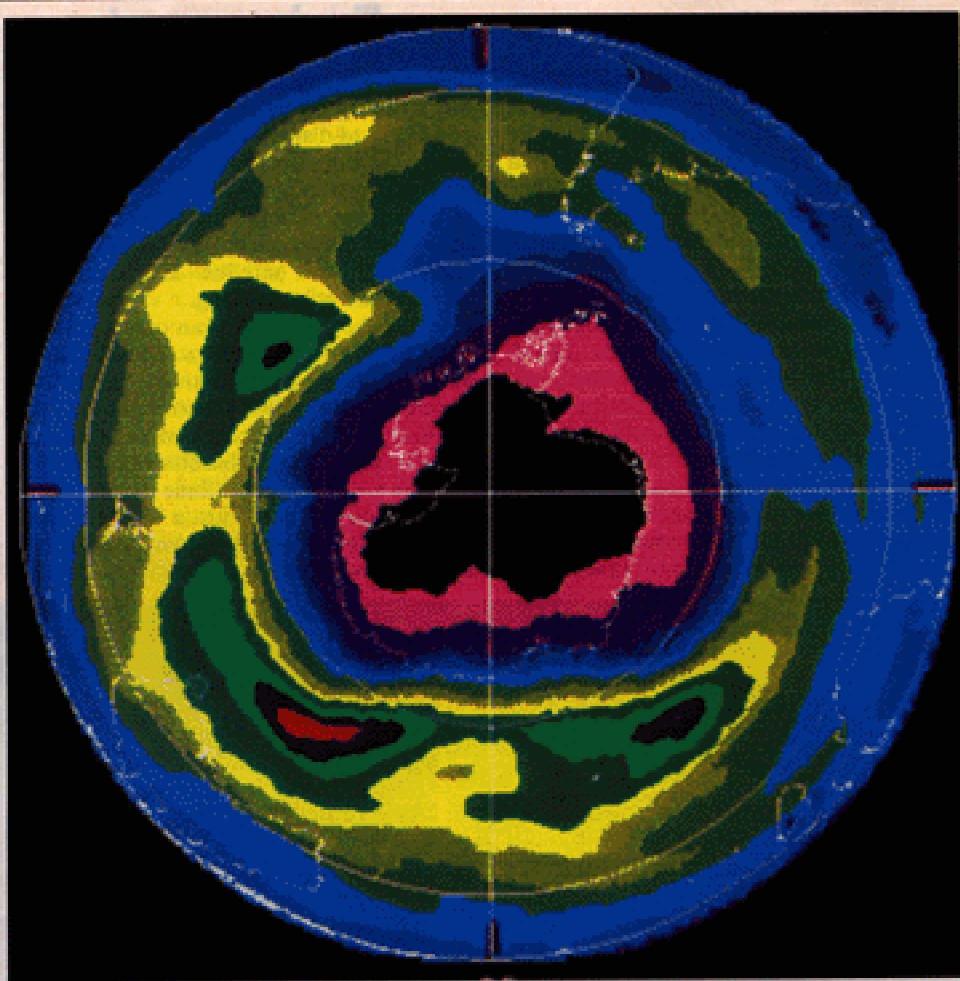
LOCKHEED—CALIFORNIA CO.

Harsh and lonely work: NASA's high-altitude ER-2 research plane warmer. The reason, in a word: ozone.

Ozone (O_3) is a form of oxygen that rarely occurs naturally in the cool reaches of the troposphere. It is created when ordinary oxygen molecules (O_2) are bombarded with solar ultraviolet rays, usually in the stratosphere. This radiation shatters the oxygen molecules, and some of the free oxygen atoms recombine with O_2 to form O_3. The configuration gives it a property that two-atom oxygen does not have: it can efficiently absorb ultraviolet light. In doing so, ozone protects oxygen at lower altitudes from being broken up and keeps most of these harmful rays from penetrating to the earth's surface. The energy of the absorbed radiation heats up the ozone, creating warm layers high in the stratosphere that act as a cap on the turbulent troposphere below.

Ozone molecules are constantly being made. But they can be destroyed by any of a number of chemical processes, most of them natural. For example, the stratosphere receives regular injections of nitrogen-bearing compounds, such as nitrous oxide. Produced by microbes and fossil-fuel combustion, the gas rides the rising air currents to the top of the troposphere. Forced higher still by the tremendous upward push of tropical storms, it finally enters and percolates slowly into the stratosphere.

Like most gaseous chemicals, manmade or natural, that reach the stratosphere, nitrous oxide tends to stay there. Indeed, a recent National Academy of Sciences report likened the upper atmosphere "to a city whose garbage is picked up every few years instead of daily." As long as five years after it leaves the ground, N_2O may finally reach altitudes of 15 miles and above, where it is broken apart by the same ultraviolet radiation that creates ozone. The resulting fragments—called radicals—attack and destroy more ozone molecules. Another ozone killer is methane, a carbon-hydrogen compound produced by microbes in swamps, rice paddies and the intestines of sheep, cattle and termites.



Worse than ever: satellite image recorded Oct. 5 showing ozone hole over Antarctica

For millenniums, the process of ozone production and destruction has been more or less in equilibrium. Then in 1928 a group of chemists at General Motors invented a nontoxic, inert gas (meaning that it does not easily react with other substances) that was first used as a coolant in refrigerators. By the 1960s, manufacturers were using similar compounds, generically called chlorofluorocarbons, as propellants in aerosol sprays. As industrial chemicals, they were ideal. "The propellants had to be inert," says Chemist Ralph Cicerone, of the National Center for Atmospheric Research. "You didn't want the spray in a can labeled 'blue paint' to come out red. Since then the growth of CFCs has been fabulous, and they've been pretty useful." Indeed, CFCs turned out to be a family of miracle chemicals: produced at a rate of hundreds of thousands of tons yearly, they seemed almost too good to be true.

They were. In 1972 Rowland heard a report that trace amounts of CFCs had been found in the atmosphere in both the northern and southern hemispheres. What were

particles. "I went into clouds at 61,000 ft., and I didn't come out the whole time," says Williams of the first flight. Another surprise: temperatures did not warm when the plane soared into the stratosphere. Instead, they plummeted to −130°F, low enough to cause worries about a fuel freeze-up.

At 60,000 ft., winds as high as 150 knots buffeted the aircraft. Even so, the real difficulty came from 40-knot gusts that tossed the plane around during landings. With special scientific instruments installed in pods on its long, droopy wings, the ER-2 is "like a big albatross—it's heavy-winged," says Operations Manager James Cherbonneaux of NASA's Ames Research Center. While watching a particularly hairy approach to the runway at Punta Arenas, he recalls, "I chewed a little bit of my heart out."

Conditions aboard the DC-8 were considerably better. The plane, which carried up to 41 scientists, flew no higher than 42,000 ft. on its 13 missions, and those on board were free to move about. But heavy clouds obscured views of Antarctica most of the time, and the flights were a tedious eleven hours long. Observes Atmospheric Scientist Ed Browell, of NASA's Langley Research Center in Virginia: "I sort of likened what we were doing to taking off from the East Coast, flying to the West Coast to do our work, then flying back East to land."

Williams suits up for takeoff

To break the monotony, scientists took aboard a variety of stuffed animals, including a seal, cat and penguin, and warmed up snacks of pizza, empanadas, popcorn and hamburgers in the microwave oven. Cabin temperature was kept cool to avoid overheating the high-tech instrumentation. Says Atmospheric Physicist Geoffrey Toon, of the Jet Propulsion Laboratory in Pasadena, Calif.: "If you tried to sleep during your off hours, usually you froze."

they doing there? The answer, as Rowland and his colleague, Mario Molina, soon found, was that there was nowhere else for them to go but into the atmosphere. CFCs in aerosol cans are sprayed directly into the air, they escape from refrigerator coils, and they evaporate quickly from liquid cleaners and slowly from plastic foams.

In the troposphere, CFCs are immune to destruction. But in the stratosphere, they break apart easily under the glare of ultraviolet light. The result: free chlorine atoms, which attack ozone to form chlorine monoxide (ClO) and O_2. The ClO then combines with a free oxygen atom to form O_2 and a chlorine atom. The chain then repeats itself. "For every chlorine atom you release," says Rowland, "100,000 molecules of ozone are removed from the atmosphere."

In 1974 Rowland and Molina announced their conclusion: CFCs were weakening the ozone layer enough to cause a marked increase in skin cancers, perhaps enough to perturb the planet's climate by rejuggling the stratosphere's temperature profile. In 1978 the U.S. banned their use in spray cans. "People assumed the problem had been solved," recalls Rowland. But the Europeans continued to use CFCs in aerosol cans; other uses of CFCs began to increase worldwide. Says Rowland: "All along, critics complained that ozone depletion was not based on real atmospheric measurements—until, that is, the ozone hole appeared. Now we're not talking about ozone losses in 2050. We're talking about losses last year."

For several years NASA's scientists failed to accept data on the Antarctic ozone hole that was before their eyes. The reason: computers prescreening data from monitoring satellites had been programmed to dismiss as suspicious presumably wild data showing a 30% or greater drop in ozone levels. After British scientists reported the deficit in 1985, NASA went back to its computer records, finally recognizing that the satellite data had been showing the hole all along.

Still, the existence of an ozone hole did not necessarily mean CFCs were to blame, and a number of alternative explanations were proposed. Among them, says Dan Albritton, director of the Federal Government's Aeronomy Laboratory in Boulder, was the notion that the "hole did not signify an ozone loss at all, just a breakdown in the distribution system." An interruption in the movement of air from the tropics, where most ozone is created, to the poles could easily result in less ozone reaching the Antarctic. Another theory: perhaps the sunspot activity that peaked around 1980 created more ozone-destroying nitrogen radicals than usual, which would be activated each spring by sunlight.

But while most scientists agree that atmospheric chemistry and dynamics are major causes, the increased scrutiny of the Antarctic atmosphere following the discovery of the hole has seriously undercut the sunspot theory. Data from Punta Arenas, says Robert Watson, a NASA scientist involved in that study, made the verdict all but final. Nitrogen and ozone levels were down, but concentrations of chlorine monoxide were 100 times as great as equivalent levels at temperate latitudes. Says Watson: "We can forget the solar theories. We can no longer debate that chlorine monoxide exists and that its abundance is high enough to destroy ozone, *if* our understanding of the catalytic cycle is correct. We need to go back to the lab and resolve the uncertainty."

That is not all. Scientists are still not completely sure why the hole remains centered on the Antarctic or why the depletion is so severe. It may have to do with the peculiar nature of Antarctic weather. In winter the stratosphere over the region is actually sealed off from the rest of the world by the strong winds that swirl around it, forming an all but impenetrable vortex. Says Cicerone: "Looking down at the South Pole is like watching fluid draining in a sink. It's like an isolated reactor tank. All kinds of mischief can occur."

One likely source of mischief making: clouds of ice particles in the polar stratosphere. Explains Rowland: "Mostly, you don't get clouds in the stratosphere because most of the water has been frozen out earlier. But if the temperature gets low enough, you start freezing out the rest." Indeed, ice may prove to be a central cause of the ozone hole, since it provides surfaces for a kind of chemistry only recently associated with reactions in the atmosphere. In a gaseous state, molecules bounce around and eventually some hit one another. But adding a surface for the molecules to collect on speeds up the reactions considerably.

It is not yet clear whether ozone depletion in the Antarctic is an isolated phenomenon or whether it is an ominous warning signal of more slowly progressing ozone destruction worldwide. Data indicate that the decline over the past eight years is 4% to 5%. Scientists estimate that

Factory in Saskatchewan: industrial emissions increase airborne CO_2

Termite mound in Australia: a prolific producer of methane gas

Abandoned refrigerator: coolants are made up of ozone-attacking CFCs

natural destruction of the ozone could account for 2% of that figure. The Antarctic hole could explain an additional 1%. The remaining 1% to 2% could simply be the result of normal fluctuations. As Albritton's research team reported, "A depletion of this magnitude would be very difficult to identify against the background of poorly understood natural variation."

The same can be said for the greenhouse effect: it is too soon to tell whether unusual global warming has indeed begun. Unlike ozone depletion, the greenhouse effect is a natural phenomenon with positive consequences. Without it, points out Climate Modeler Jeff Kiehl, of the National Center for Atmospheric Research, "the earth would be uninhabitable. It is what keeps us from being an ice-frozen planet like Mars." Indeed, if gases like CO_2 did not trap the sun's energy, the earth's mean temperature would be 0° F, rather than the current 59°.

Still, as far back as the late 1890s, Swedish Chemist Svante Arrhenius had begun to fret that the massive burning of coal during the Industrial Revolution, which pumped unprecedented amounts of CO_2 into the atmosphere, might be too much of a good thing. Arrhenius made the startling prediction that a doubling of atmospheric CO_2 would eventually lead to a 9° F warming of the globe. Conversely, he suggested, glacial periods might be caused by diminished levels of the gas. His contemporaries scoffed. Arrhenius, however, was exactly right. In his time, the CO_2 concentration was about 280 to 290 parts per million—just right for a moderately warm, interglacial period. But today the count stands at some 340 p.p.m. By 2050, if the present rate of burning fossil fuels continues, that concentration will double, trapping progressively more infrared radiation in the atmosphere.

Clearing the Amazon: deforestation adds to the greenhouse effect

Fast-food leftovers: deteriorating plastic foam containers give off CFCs

Sichuan paddies: underwater bacteria generate heat-absorbing gases

The consequences could be daunting. Says National Center for Atmospheric Research's Francis Bretherton: "Suppose it's August in New York City. The temperature is 95°; the humidity is 95%. The heat wave started on July 4 and will continue through Labor Day." While warmer temperatures might boost the fish catch in Alaska and lumber harvests in the Pacific Northwest, he says, the Great Plains could become a dust bowl; people would move north in search of food and jobs, and Canada might rival the Soviet Union as the world's most powerful nation. Bretherton admits that his scenario is speculative. But, he says, "the climate changes underlying it are consistent with what we believe may happen."

Such changes may already be under way. Climatologists have noted an increase in mean global temperature of about 1° F since the turn of the century—within the range predicted if the greenhouse effect is on the rise. But, warns Roger Revelle, of the University of California at San Diego, "climate is a complicated thing, and the changes seen so far may be due to some other cause we don't yet understand." The absence of a clear-cut signal, however, does not disprove the theory. Scientists expect any excess greenhouse warming to be masked for quite some time by the enormous heat-absorbing capacity of the world's oceans, which have more than 40 times the absorptive capacity of the entire atmosphere.

"Right now," declares University of Chicago Atmospheric Scientist V. Ramanathan, "we've committed ourselves to a climatic warming of between one and three degrees Celsius [1.8° F to 5.4° F], but we haven't seen the effect." This extra heat, now trapped in the oceans, he says, should be released over the next 30 to 50 years—unless, of course, an event like a big volcanic eruption counteracts it. Notes Ramanathan: "By the time we know our theory is correct, it will be too late to stop the heating that has already occurred." Schneider sees no need to wait. Says he: "The greenhouse effect is the least controversial theory in atmospheric science."

Maybe. But climate is governed by an array of forces that interact in dizzyingly complex ways. The atmosphere and oceans are only two major pieces of the puzzle. Also involved: changes in the earth's movements as it orbits the sun, polar ice caps, and the presence or absence of vegetable and animal life. "The feedbacks are enormously complicated," says Michael MacCracken, of the Lawrence Livermore National Laboratory in California. "It's like a Rube Goldberg machine in the sense of the number of things that interact in order to tip the world into fire or ice."

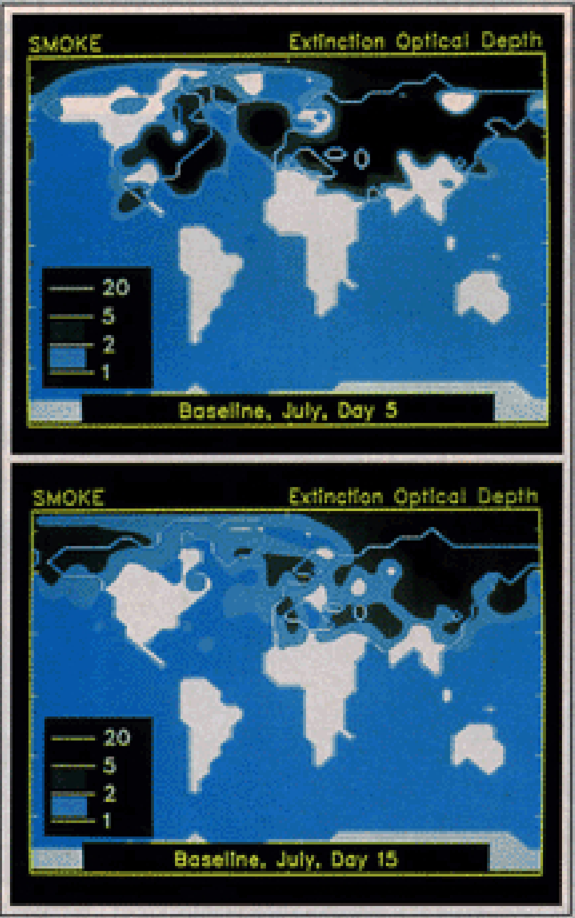
One of the most fundamental elements of the Rube Goldberg machine is the three astronomical cycles first described by Serbian Scientist Milutin Milankovitch in the 1920s. The swings, which involve long-term variations in the wobbling of the earth's axis, its tilt and the shape of its orbit around the sun, occur every 22,000, 41,000 and 100,000 years, respectively. Together they determine how much solar energy the earth receives and probably cause the earth's periodic major ice ages every 100,000 years or so, as well as shorter-term cold spells.

Cloudy Crystal Balls

Climatologists regularly issue confident warnings about impending atmospheric disasters. The secret of their wizardry: sophisticated computer models, which are no more than mathematical representations of the world's climate and the conditions that scientists think may contribute to a specific phenomenon like, say, ozone depletion. Unfortunately, when all the variables are fed into the computer, the predictions can fail miserably to match reality.

Take the Antarctic ozone hole, for example. Before it was discovered, climate modelers trying to simulate ozone loss in the atmosphere had not yet factored in the presence of ice clouds in the Antarctic stratosphere. Thus their models failed to predict the existence of the ozone hole. After the hole was finally stumbled upon two years ago, Susan Solomon, a chemist at the National Oceanic and Atmospheric Administration in Boulder, and Rolando Garcia, of the National Center for Atmospheric Research, plugged more numbers into NCAR's computer model to account for the Antarctic ice clouds. Bang! The hole appeared.

Does that mean, as one critic put it, that models projecting climatic change are "just the opinion of their authors about how the world works"? Not necessarily. That the model eventually proved accurate, if only in hindsight, was a tribute to the powers of computer climate models—and a demonstration of their shortcomings. The models attempt to reduce the earth's climate to a set of grids and numbers, then manipulate the numbers based on the physical laws of motion and thermodynamics. The sheer number of calculations involved is mind-boggling. A three-dimensional model, for example, requires more than 500 billion computations to simulate the world's climate over one year.



"Nuclear autumn": a modeling of the aftermath

Not surprisingly, the earliest models in the 1960s were hopelessly simplistic. The earth's surface was often reduced to one continent with one ocean, fixed cloud cover and no seasons. But as computing power grew, so did the complexity of climate modeling. Continents were added. So were mountain ranges, deeper oceans and surface reflectivity.

Even so, climate modelers admit, building a completely realistic mock earth is an impossibly tall order. "You divide the world into a bunch of little boxes," explains Michael MacCracken, an atmospheric scientist at Lawrence Livermore National Laboratory. The size of the geographic box—the degree of detail called for—limits the model. Smaller grids dramatically increase the number-crunching power required. "The state of the art would be to get down to small areas so we can say what's going to happen in Omaha," says Livermore's Stanley Grotch. "The models just aren't that good yet."

Why, then, do scientists trust them? How do they assess their accuracy? "You compare them with reality," explains Princeton Climatologist Syukuro Manabe. "How well do they reproduce the movement of the jet stream, the geographical and seasonal distribution of rainfall and temperature? You can also reproduce climate changes from the past. Eighteen thousand years ago, there was a massive continental ice sheet. Given the conditions that we know existed, can we reproduce accurately the distribution of sea-surface temperatures then? The answer is, We can do this very well. It gives you some confidence." Large-scale phenomena can be modeled more easily than those affecting small areas. So when it comes to the global warming produced by the greenhouse effect, for example, the outlines are predictable but the specifics are not. Says Manabe: "All we can say is that maybe the mid-continental U.S. becomes dryer."

A major drawback of computer models is that the various data do not necessarily behave as a system. Coaxing ocean currents to interact with the atmosphere is no small matter. For starters, oceans heat and cool far more slowly than the atmosphere. "We've had a hard time coupling the two systems," admits Manabe. "Even though the atmospheric model and ocean model work individually, when you put them together, you get crazy things happening. It's taken us 20 years to get them together, and we're still struggling."

Offsetting the obvious weaknesses of climate models, says Warren Washington, who developed the model now used at NCAR, is one significant advantage. "They are experimental tools that allow us to test our hypotheses," he says. "We can ask such questions as 'What happens when a big volcano like El Chichón goes off?' and 'How much will the earth warm up by 2030 if we continue to dump CO_2 into the atmosphere?' "

Models can also describe the effects of climatic phenomena that have never been seen. In 1983 a group of scientists that included Cornell's Carl Sagan calculated what would happen if the U.S. and the Soviet Union fought a nuclear war. Their conclusion: the dust and smoke from burning cities would blot out enough sunlight to plunge the land into a "nuclear winter" that would devastate crops and lead to widespread starvation.

The problem with their model was that it ignored such key factors as winds, oceans and seasons. When NCAR's Stephen Schneider and Starley Thompson ran the numbers through their agency's three-dimensional computer model, they found that the winter would be more like a "nuclear autumn." Schneider says the less dramatic conclusion does not change the fact that "nuclear autumn is not going to be a nice picnic out there on the rocks watching the leaves change color." Despite the limitations and omissions of climate models, he argues, scientists cannot afford to ignore their predictions. They are, he concedes, a "dirty crystal ball. The question is, How long do you wait to clean the glass before you act on what you see inside?"

—By David Bjerklie.

Reported by J. Madeleine Nash/Chicago

But Milankovitch cycles only scratch the surface of climatic change. Volcanoes, for example, send up veils of dust that reflect sunlight and act to cool the planet. Deserts, with their near white sands, also reflect sunlight, as do the polar ice caps. Tropical rain forests, however, have the opposite effect: their dark green foliage, like the dark blue of the ocean, absorbs solar radiation; both tend to warm the planet.

Clouds, which shade about half the earth's surface at any given time, are another important climatic factor. Says James Coakley of the National Center for Atmospheric Research: "If you heat up the atmosphere and pump more water in, clouds will change. But how? We don't know." Water vapor, for example, is yet another greenhouse gas, but the white-gray surfaces of clouds reflect solar energy. Which effect predominates? Answer: it depends on the cloud. The bright, low-level stratocumulus clouds reflect 60% of incoming solar rays. But long, thin monsoon clouds let solar heat in while preventing infrared radiation from escaping.

Vision of heat and desolation: new concerns that the now fertile U.S. Midwest could become a dust bowl within 60 years

Another contributor to climatic change is the biosphere—scientific jargon for the realm of all living things on earth. And it is the biosphere that threatens to tip the balance. To be sure, many of its effects are natural and as such have long been part of the climatic equilibrium. Termites, for example, produce enormous amounts of gas as they digest woody vegetation: a single termite mound can emit five liters of methane a minute. The methane escapes into the atmosphere, where it can not only destroy ozone but also act as a greenhouse gas in its own right. "Termites," says Environmental Chemist Patrick Zimmerman, of the National Center for Atmospheric Research, "could be responsible for as much as 50% of the total atmospheric methane budget."

Actually, the biosphere becomes a problem only when humans get involved. In Brazil the Amazon rain forest, which once covered 3 million sq. mi., has been slashed by an estimated 10% to 15% as the region has been developed for mining and agriculture; an additional 20% has been seriously disturbed. When the downed trees are burned or rot, CO_2 and other greenhouse gases are released. The same kind of deforestation in Africa, Indonesia and the Philippines, say experts, may already be helping to make the world warmer.

To make matters worse, a host of other gases are now known to add to the greenhouse effect. In 1975, Ramanathan was amazed to discover that Freon, a widely used CFC, was an infrared absorber. "It had a very large impact," he says. "Since then, tracking down the role of other trace gases has become a cottage industry. There are dozens of them, and they are rivaling the effects of increasing CO_2." In fact, by the year 2030 the earth will already face the equivalent of a doubling of CO_2, thanks to these other rapidly increasing gases, including methane, nitrous oxide and all the CFCs. "These are the little guys," says Schneider. "But they nickel and dime you to the point where they add up to 50% of the problem."

Is there any way to slow either the greenhouse effect or the depletion of the world's ozone? The Montreal accord, agreed to last month after nearly five years of on-and-off negotiations, is a good start on ozone. It calls on most signatory countries to reduce production and consumption of CFCs by 50% by 1999. Developing nations, however, will be allowed to increase their use of the chemicals for a decade so they can catch up in basic technologies like refrigeration. The net effect, insist the treaty's advocates, will be a 35% reduction in total CFCs by the turn of the century.

Some experts do not believe the projected cutback is good enough. Says Rowland: "The Montreal agreement simply isn't sufficient to protect the ozone. We should have signed a treaty that reduced CFC production by 95%—not 50%." Nonetheless, the Environmental Protection Agency has calculated that without the accord, a staggering 131 million additional cases of skin cancer would occur among people born before 2075.

Any similar attempt to ease the greenhouse effect by imposing limits on CO_2 and other emissions is unlikely. John Topping, president of the Washington-based Climate Research Institute, argues that adjustments in agricultural production, like limiting the use of nitrogen-based fertilizers, would have only a slight effect. A more important step would be to protect the tropical rain forests, a move that would certainly be resisted by developers. Obviously, the most far-reaching step would be to cut back on the use of fossil fuels, a measure that would be hard to accomplish in industrialized countries without a wholesale turn to energy conservation or alternative forms of power. In developing countries, such reductions might be technologically feasible but would be all but impossible to carry out politically and economically.

Until now, the earth's climate has been a remarkably stable, self-correcting machine, letting in just the right amount and type of solar energy and providing just the right balance of temperature and moisture to sustain life. Alternating cycles of cold and warmth, as well as greater and lesser concentrations of different gases, have forced some species into extinction. The same changes have helped others evolve. The irony is that just as we have begun to decipher the climatic rhythms that have gone on for hundreds of millions of years, we may have begun to change them irrevocably. And as the unforeseen discovery of the ozone hole demonstrates, still more unexpected changes may be on the way. —*By Michael D. Lemonick.* ***Reported by J. Madeleine Nash/Boulder, with other bureaus***