Appendix 1

Copies of Analysed Texts Showing Their Semantic Elements

Explanatory notes;

1. All articles have been reproduced as they appeared in their journals of publication and include accompanying visuals in the sequence in which they appear in the articles.
2. The semantic elements identified in each texts are noted (under abbreviations for their levels) to the left of the paragraph or passage of text in which they appear. A key to the label abbreviations appears at the foot of the first page of each article.
3. Labels denoting an element appear in an extended (vertical) bracket which closes adjacent to the last line of the two elements. If an element ends, and another begins mid-paragraph then the break is denoted by " ‖ ".
4. [[...]] denotes an embedded element both in the label abbreviation and when enclosing text in the article.
5. Where a paragraph or passage of text contains more than one element, their labels will appear adjacent to one another. In such cases, the sequence of the elements, as they occur in the paragraph is to be taken from the sequence of the element labels. For example, ┌——BRG [[SPC]] [[EVN]]——┐shows that the paragraph or passage of text commences with a BRIDGING element and that BRIDGING in this case contains two embedded elements, SPECIFIC CLAIM and EVALUATION which are found in that order in the text.
6. If two instances of SPECIFIC CLAIM appear in the same paragraph or body of text, then a number after the label e.g. SPC 1, SPC 2, shows that they are considered as separate elements.
7. Each visual (photograph, table) in each article has a code and label attached to enable its identification for the purpose of the discussion of visuals in chapter five. For example, PGN1 (multiple man 1) denotes a visual from a population growth text which has been given the label "multiple man". The specific articles in which visuals appear are fully indentified in the text when the visual is referred to.

Appendix 1.1

TTL

Cold Comfort

BY LORI OLIWENSTEIN

GLM

As Earth warms, ice caps will melt and sea level will rise, right? Maybe. But there's another possibility: global warming may hasten the ice age.

PRB

OFTEN WHEN WE think of the greenhouse effect, we think of islands and coastal cities, of beaches and estuaries—and even one-sixth of Bangladesh—taken over by a rising sea. Such projections rely on a simple logic: as the planet gets warmer, the ice sheets on it should begin to melt and sea level should rise. But that logic, it now seems, is not unassailable. A number of studies over the past few years have revealed evidence for the notion that polar ice sheets may actually grow in the face of greenhouse warming—and sea level may drop, or at least not rise as fast as had been feared.

GCL

Some of the most compelling evidence comes from the geologic record of past ice ages. By measuring the proportion of oxygen isotopes in deep-sea sediments, geologists have been able to track changes in the amount of ice on Earth's surface—and thus changes in sea level—over hundreds of thousands of years. (As water evaporating from the ocean surface gets locked up in continental ice sheets, the water molecules containing the heavier isotope of oxygen tend to remain behind in the ocean.) The oxygen record shows, for instance, that the last glaciation began with a rapid ice buildup some 120,000 years ago.

BRG

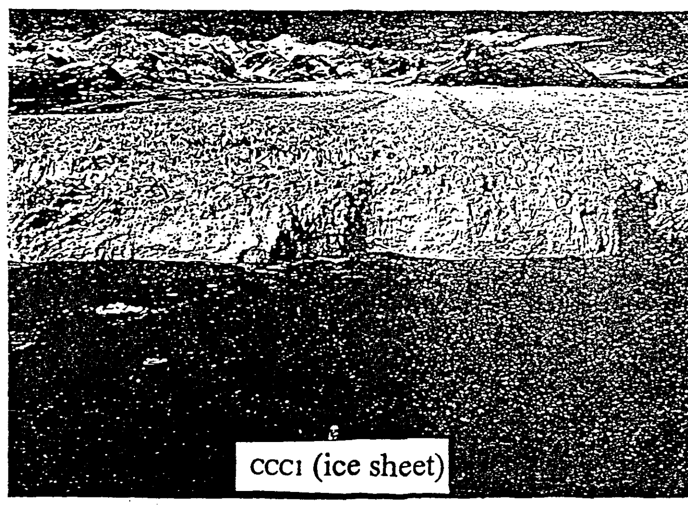
But this year the circumstances of the ice buildup were put in an interesting new light by Gifford Miller of the University of Colorado in Boulder and Anne de Vernal of the University of Quebec at Montreal.

SPC1

De Vernal, a marine micropaleontologist, has studied the fossils of tiny marine algae that she has culled from 120,000-year-old seafloor sediments in Baffin Bay, the Labrador Sea, and the northwest Atlantic. Different species of algae thrive in water of different temperatures, so the types of algae found in sediments are a measure of the sea-surface temperature at the time the algae rained down onto the seafloor. Similarly, pollen grains in coastal sediments reveal what the climate was like on the neighboring land.

SPC1

While De Vernal was looking at sediment cores, Miller, working independently, was determining the ages of glacial deposits on the eastern coast of Baffin Island. "It was the remarkable parallelism of our two totally independent data sets that got us thinking about the implications," says Miller. What they



ccc1 (ice sheet)

A. UPITIS/THE IMAGE BANK

ARE ICE SHEETS coming or going? Coastal cities would like to know.

SPC1

found was this: Ice was building up 120,000 years ago, all right, and it was building up in the Canadian Arctic—but at a time when the world in general was as warm as it is today. Indeed, the sea surface around the Arctic was warmer.

How can ice sheets grow in a warm climate? The answer is really very simple. The Arctic is so far north that even in a

SPC1

warmer climate than today's the summers still wouldn't be warm enough to melt much ice. But the warmer temperature of the sea surface would cause more water to evaporate. Winds would carry this moisture over the land, where in winter it would precipitate out as snow and, as the summers failed to melt it, become transformed into ice. At the beginning of the last ice age, moreover, Arctic summers were getting cooler, thanks to cyclical changes in Earth's orbit that reduce summer sunlight in the north.

SPC1

The net effect, say Miller and De Vernal, was that enough water was taken out of the ocean and locked up in ice sheets to cause sea level to drop by more than two feet a century. Once ice sheets formed, they helped cool the planet down by reflecting sunlight back into space. But the ice came *before* the cold. And it was the warm climate at the beginning of the glaciation that provided the precipitation needed to form the ice in the first place.

Miller and De Vernal also see evidence for this scenario—that warmth

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		

leads to ice-sheet growth—in the more recent past. The ice age that began 120,000 years ago reached its final peak around 18,000 years ago. After that the North American ice sheet began to recede. But between 9,000 and 8,000 years ago it expanded again in the Arctic—at a time when the rest of the planet was warmer than it is today.

A few thousand years later, a similar event took place in the Southern Hemisphere. Eugene Domack of Hamilton College in Clinton, New York, and his colleagues have been studying the history of the South Polar ice cap by examining sediment cores hauled up from the Antarctic continental shelf. The sediments dating from periods when the continental shelf was an open sea are rich in plankton; those dating from periods when the shelf was covered with ice consist primarily of rocks and pebbles dropped by the ice. This sediment record shows that between 7,000 and 4,000 years ago, when Earth was well into the present interglacial period and the temperature around Antarctica was about four degrees warmer than it is today, the Antarctic ice sheets were growing again.

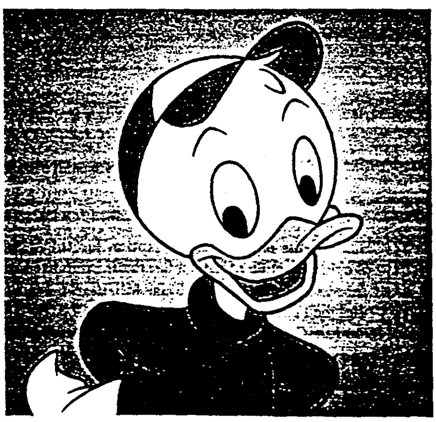
"This was surprising to us," says Domack. "But it is consistent with models that suggest you could warm the area by up to nine degrees before the excess melting would surpass the increase in precipitation and snowfall due to the warmth. And this suggests that under future global warming you would have a net negative contribution to sea level from the Antarctic, rather than a net positive one."

Indeed, that is precisely what is happening right now, according to Charles Bentley of the University of Wisconsin. While De Vernal, Miller, and Domack have been tracking the waxing and waning of ice sheets in the historical record, Bentley and Mario Giovinetto of the University of Calgary have been monitoring the condition of the Antarctic ice sheet today, balancing data on the amount of snow falling over Antarctica against the amount of ice breaking away from the edges of the ice sheet. They calculate that the Antarctic is already sopping up enough water each year to lower the ocean two-hundredths of an inch—apparently, says Bentley, because more snow is falling on the ice cap.

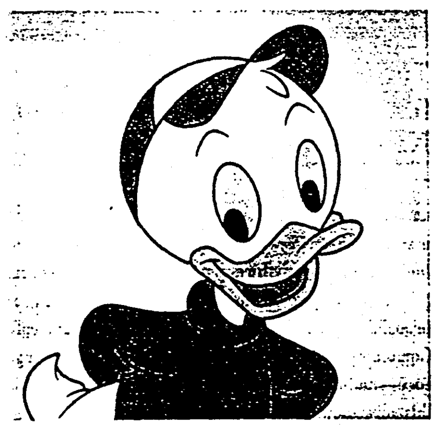
"The warmer air is, the more moisture it can hold," he explains. "In Antarctica the moisture-carrying air comes in over the continent, and before it leaves again, it drops most of that moisture. So the snowfall over the continent increases as the temperature gets warmer."

The same phenomenon may also have been observed in present-day Greenland. Satellite data compiled by Jay Zwally and his colleagues from NASA's Goddard Space Flight Center seem to suggest that the southern two-fifths of the ice sheet that covers most of Greenland is thickening at a rate of about nine inches a year. Although the Goddard workers have no data for the northern three-fifths of the ice sheet, they note that it usually receives about half as much new snow as the southern part. If that's true—and if the satellite data are accurate, which some researchers doubt—the Greenland ice sheet could be lowering sea level as much as the Antarctic ice sheet is, around two-hundredths of an inch per year.

So what is the bottom line? What is sea level doing now, and what is it likely to do as the greenhouse effect warms the planet? Measuring sea level is tricky be-



Huey.



Dewey.

cause it can only be measured in relation to the land, and the land itself moves—it slowly rebounds upward, for instance, when a glacier recedes and stops pressing it down. But long-term records from tide gauges suggest that sea level has actually risen over the past 50 years by about a tenth of an inch a year. How those measurements jibe with the data from Antarctica and Greenland, however, and what they portend for our future in the greenhouse, are far from clear.

MOST RESEARCHERS AGREE THAT the amount of carbon dioxide in the atmosphere has risen by about 25 percent since the world began to industrialize, and may well double within the next 50 years. There is also broad agreement that Earth's average temperature has risen between half a degree and one and a quarter degrees Fahrenheit over the past century. Researchers are still squabbling, however, about whether that means greenhouse warming—which most now regard as inevitable—has already begun, and about how large a temperature rise we should expect. The estimates range from three to eight degrees.

As Earth warms, sea level will tend to rise for the simple reason that water expands as it heats up. In a greenhouse world, thermal expansion alone could raise sea level by as much as one and a half inches a decade. Warmer temperatures will also melt glaciers on mountains in the temperate and tropical latitudes—indeed, the process seems to have already begun. Geologist Lonnie Thompson of Ohio State University has documented the shrinking of glaciers in the Andes, on the Tibetan plateau, and in Kirghizia, in the former Soviet Union. "The evidence is very clear that warming is taking place," Thompson told a Senate committee earlier this year. "It is clear that tropical glaciers and ice caps are currently retreating . . . and the rate of retreat seems to be increasing." The Quelccaya ice cap in Peru, for instance, has pulled back 370 feet in just eight years.

But the great unanswered question is the extent to which these two sea-level-raising effects—thermal expansion and the melting of ice at low latitudes—will be balanced by the buildup of ice at high latitudes. The most popular forecast right now is that sea level will rise two to three feet during the next century. If Miller and De Vernal are right, however, that rise could be wiped out entirely by the growth of ice sheets in the north.

It is possible they are right about history—that Arctic ice sheets started expanding during a warm period 120,000 years ago—but wrong about the future. Most of the water that would get locked up in northern ice sheets would have to come from the warming of nearby seas. But as climatologist Stephen Schneider has pointed out, the regional effects of global warming can't yet be forecast. So we can't count on the subpolar seas warming in time to prevent a sea-level rise in the next century.

In the long run, probably within a millennium, the fluctuations in Earth's orbit that control the pace of the ice age cycle will bring the present interglacial period to an end. As ice sheets creep once again over the continents, sea level will surely fall. What Miller and De Vernal are suggesting, in effect, is that global warming might preserve us from drowned coasts by hastening the next ice age along. With alternatives like that, it's hard to know which outcome to root for.

TTL — the **Parasol** EFFECT

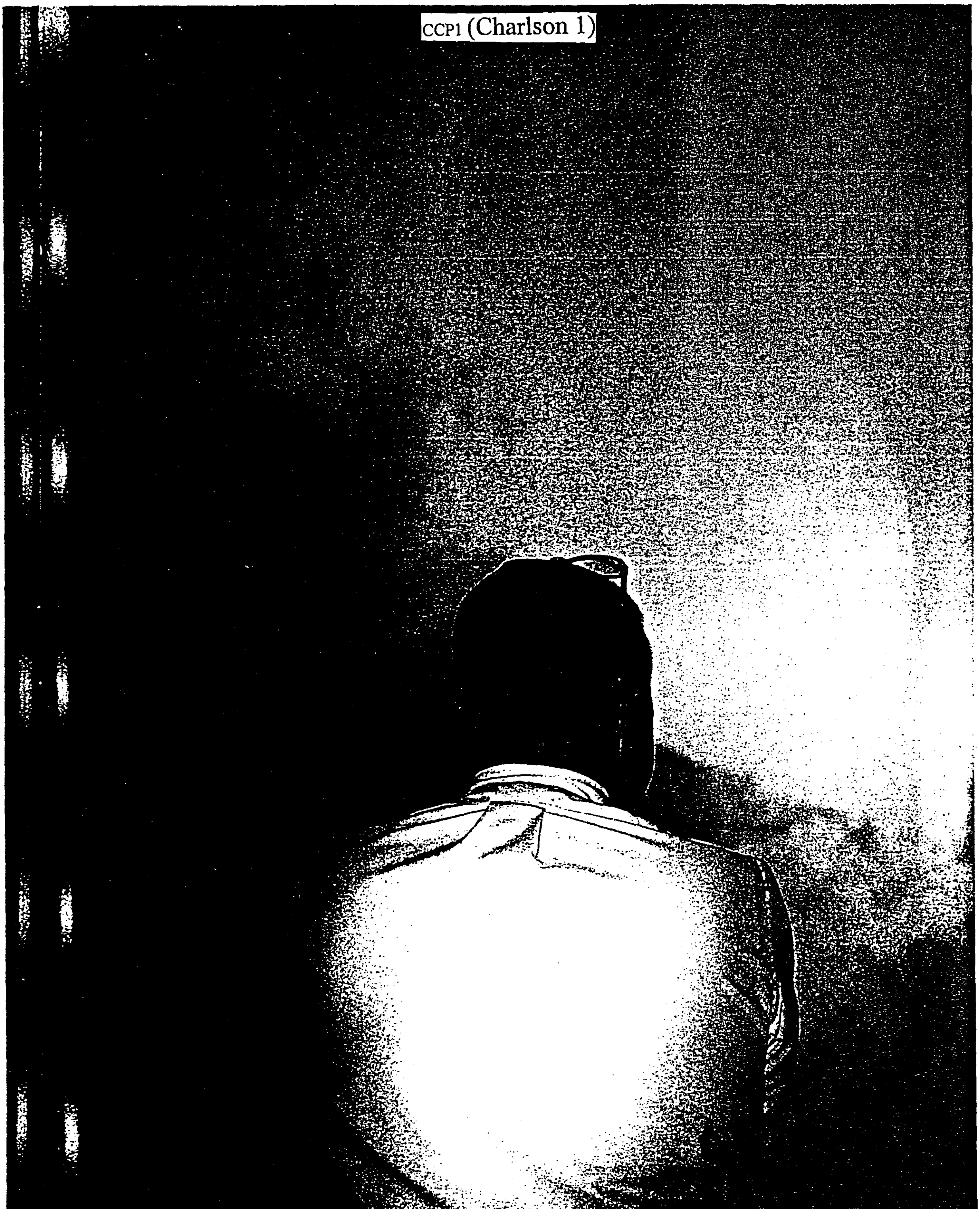
GLM — A hazy umbrella of sulfur particles is reflecting enough sunlight and heat back into space to offset global warming. You might think that's good news. Think again.

SET — Robert Charlson glances at a stand of dark pines a few hundred yards away, across the flat gray waters of Lake Washington. "This air looks pretty clean," he says. ▪ It sure does. A cold scent of fresh water is blowing off the lake behind the parking lot of the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory in Seattle. Sparrows are cheeping all

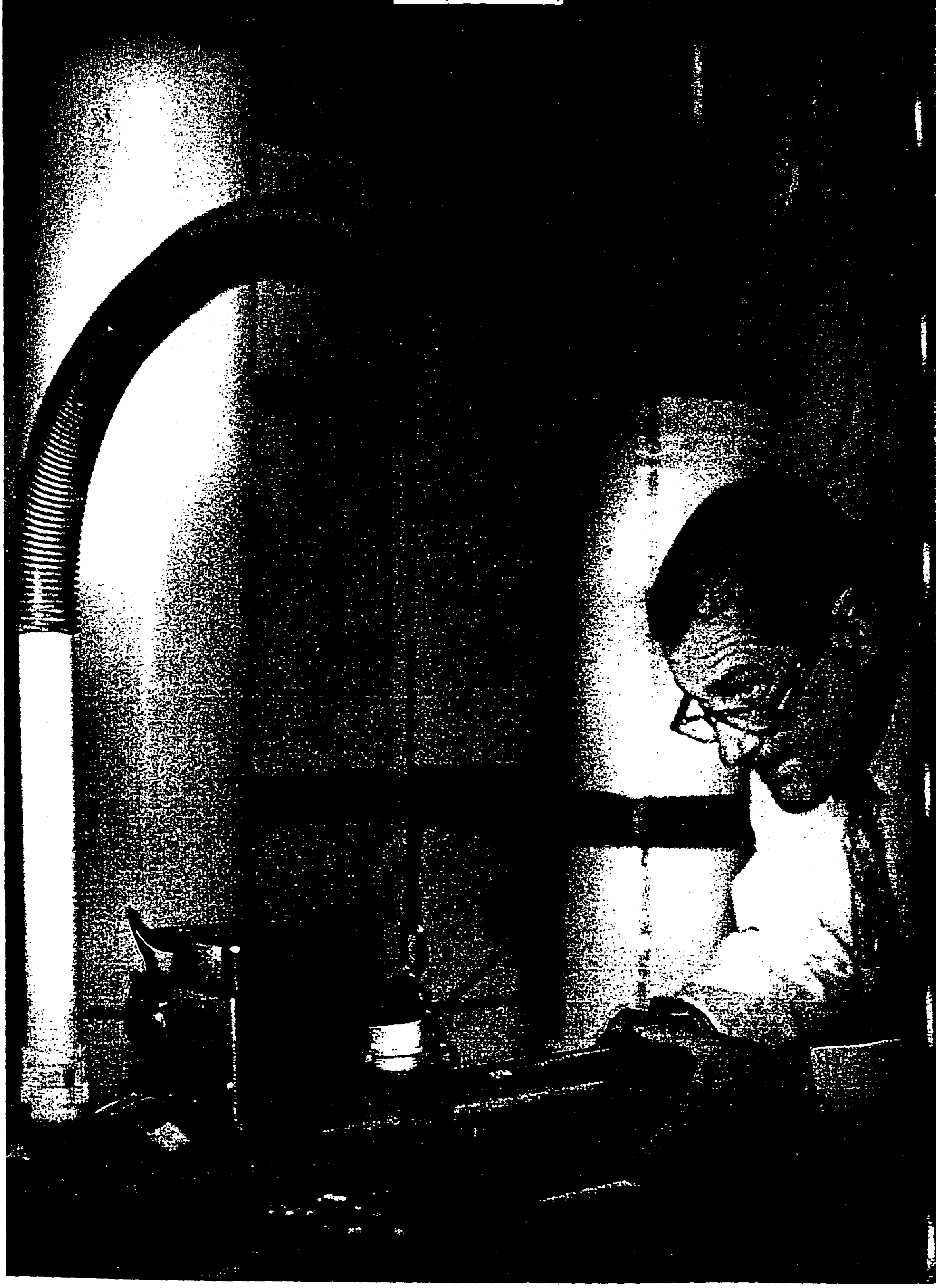
DISCOVER 44 JULY

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		


CCP1 (Charlson 1)

CCP2 (Charlson 2)



around as they flit among the red and gold leaves of trees in full autumn display. There's a constant *scritch-scritch* sound coming from the lawn, where a flock of Canada geese, each approximately the size of a well-fed third grader, is munching grass. The sensible compacts in the parking lot aren't belching exhaust, and even the smoke coming from one of NOAA's boxy white buildings looks like harmless water vapor. It's hard to imagine how the atmosphere could be any cleaner and still have any modern, car-driving, industry-dependent people in it.

"Well, let me tell you, it's not clean," Charlson says. "See the trees on the other side of the lake?" He points east. "If it were really clear, you'd be able to see every branch over there." Instead, some of the details are lost because some of the light reflected from the trees isn't reaching us. On its trip across the lake, the light is slogging through a thin haze of solid specks and liquid globules, most of which are sulfur compounds. Some of these particles are as small as viruses; some are no bigger than a handful of molecules. Belched forth from smokestacks and car exhausts, these airborne particles, or aerosols, don't absorb much light, so they don't appear dark. But light that strikes an aerosol doesn't pass through it, either—it just bounces off at a new angle. The more haze, Charlson says, the more this "optical scattering" degrades the view.

Charlson, a professor of both atmospheric sciences and chemistry at the University of Washington in Seattle, has been studying aerosols since the 1960s, when standard textbooks said optical scattering would never be measured accurately (among the first of Charlson's half-dozen patents is for a device that does just that). Like a nineteenth-century explorer painstakingly drawing hills and streams on the blank spots that were once labeled HERE THERE BE TIGERS, he has spent 30 years creating an almanac of details about what he calls "this peculiar state of material floating around in the atmosphere."

> So great is the aerosol concentration east of the Mississippi that people who grew up in that part of the country don't even know what the sky is supposed to look like.

A clear-sighted man: ROBERT CHARLSON'S NEPHELOMETER MEASURES THE AMOUNT OF LIGHT SCATTERED BY HAZE-CAUSING AEROSOLS IN A SAMPLE OF AIR SUCKED INTO ITS CHAMBER.

As a result of his work, one feature of haze is now very clear: there's much more at stake than the view. Our whole climate is in jeopardy. Just as aerosols scatter light traveling from one side of a lake to another, they also interfere with light coming in to Earth from the sun. "Some of it's being reflected back," Charlson says. "It goes right out into the blackness of space."

And sunlight, on our planet, means heat. Last year Charlson, together with six of his fellow atmospheric researchers, published the first reliable calculations of just how much heat is getting bounced away from Earth. Some regions, they found, are so blanketed by haze that they are undergoing an aerosol cooling, a cooling great enough that what might be called the parasol effect is neutralizing the better-known greenhouse effect. In other words, the explorer is back with news. Here be tigers, indeed.

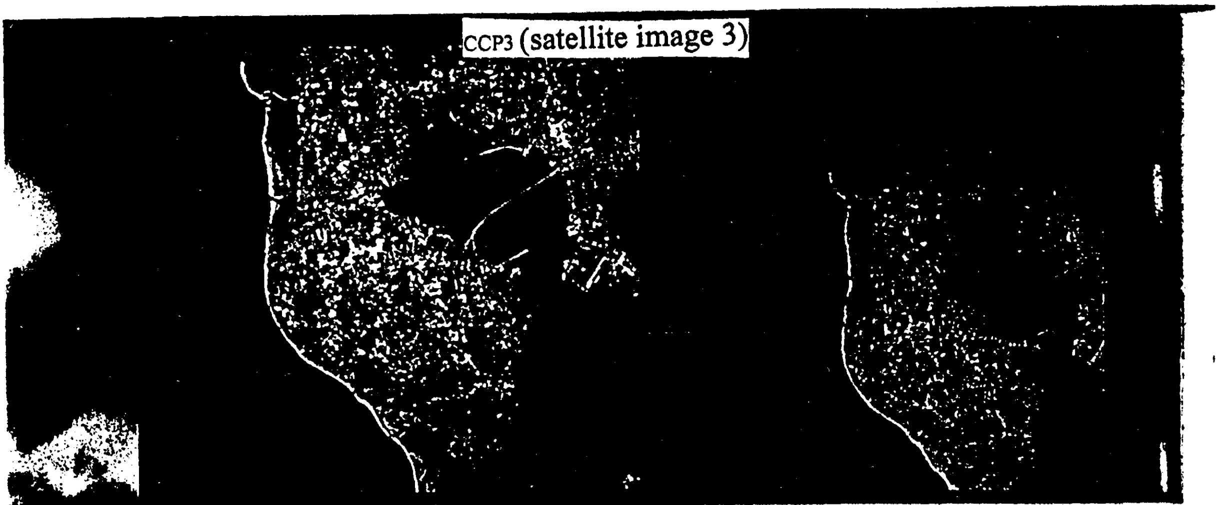
When Charlson and his colleagues made this announcement, they noted that their finding might explain why even the best models of global warming have predicted hotter temperatures than those that have actually been measured. They also pointed out that their assessment of aerosol effects may in fact be too conservative. Charlson says it includes only the direct effect of aerosols; there's even more cooling going on indirectly. Those colorless combinations of oxygen and sulfur—collectively known as sulfates—have a chemical affinity for water. They pull free-floating moisture out of the air and condense it into droplets of liquid water and acid; in fact, sulfates are the acid in acid rain. Put a bunch of these droplets together and you get a cloud. So wherever there are excess aerosols, clouds are more numerous, further shading the planet.

Moreover, the more aerosols that are in the air, the smaller will be the water droplets making up the clouds, because the available water vapor will be condensing around a larger number of particles. That also has a cooling effect. "Try putting equal amounts of table salt and rock salt on a black tablecloth and you'll see it," Charlson says. "You can see the table through the rock salt because there are fewer particles blocking your view. Everything else held constant, the cloud with more droplets will be brighter than the one with fewer droplets." And a bright cloud reflects more heat than a dull one. The physics and chemistry of cloud formation are not yet understood well enough for Charlson or any other expert to make a good estimate of the scope of this indirect cooling effect, but few in the field doubt that it's large.

This might, of course, seem like good news. At first blush, it looks like we've created a type of "good" pollution that is eliminating the effects of "bad" greenhouse-gas pollution. Perhaps we should even be congratulating ourselves for polluting our way out of a global disaster.

Indeed, says Charlson, just this type of reasoning has been used by politicians to justify going slowly on problems associated with global warming. "Since the days of the Nixon administration," he says, "there have been people suggesting that aerosol pollution might counteract global warming. Some people have actually suggested that if we learn how to pollute just right, everything will be fine."

But as Charlson points out, there are a number of subtleties to the parasol ef-



The Florida look: TAMPA BAY IS HAZY IN THE PHOTO ON THE RIGHT, TAKEN BY SHUTTLE ASTRONAUTS IN MAY 1992. TO CLEAR THE VIEW, THEY TOOK THE PICTURE ON THE LEFT WITH INFRARED FILM.

Courtesy NASA

fect suggesting that aerosols, far from preventing a greenhouse world, are more likely to send global warming veering in a new, unexpected, but no less dangerous direction. To understand why, he says, you have to take a closer look at the haze.

A certain amount of aerosol haze occurs naturally. Twenty-two million tons of sulfur are emitted every year by minuscule, single-celled marine algae, giving the sea its faintly musty smell. The occasional volcano contributes its share. But this natural background isn't the cause of modern haze. For that, industry is squarely to blame. Over the past 150 years humanity has been busy adding sulfur to the natural background, gouging the element out of the earth in the form of coal, metal ores, and oil. After being cooked from those substances by industrial processes, sulfur links up with oxygen and emerges from smokestacks as sulfur dioxide gas. Charlson estimates that, worldwide, industry puts out some 90 million tons of sulfur every year—almost 500 million pounds every single day. "It's like having lots of volcanoes erupting 24 hours a day, 365 days a year," he says. In a "multiple-step chemical reaction that has not been fully elucidated," many of the atoms of this gas recombine to form trillions of tiny sulfate particles.

These particles stay up for no more than a few days before they fall back to Earth. Only sulfates from the most powerful of volcanic eruptions ever reach the stratosphere, where powerful wind currents keep them suspended for a year or two and distribute them all over the globe. Those produced by human beings stay in the lower atmosphere—below 36,000 feet at the middle latitudes, 50,000 feet at the equator. The gentler winds of this part of the atmosphere can push aerosols only about 600 miles at most before they come back to Earth, often as acid rain.

So Seattle air, which blows in after a 6,000-mile journey over the industry-free Pacific, is far less aerosol-laden than the stuff people are breathing in, say, Steubenville, Ohio, "the epicenter of North American haze," according to Charlson. In fact, he says, so great is the aerosol concentration everywhere east of the Mississippi that people who grew up in that part of the country don't even know what the sky is supposed to look like. The sky they know is murky—visibility is perhaps 20 miles, as opposed to the 100 miles or more that your average Antarctic penguin enjoys—and often it's not even the right color.

"When you have lots of photons bouncing around in a scatter, the sky goes from blue to a whitish color," Charlson says. "From the ground anywhere in the eastern third of North America, you look up on an otherwise sunny day, and the sky directly overhead may be blue or bluish, but off at angles it'll be whitish. That white sky you see in the East is due to aerosol. That doesn't happen very often in Montana."

Hence, for many years aerosols were considered a "local" problem for industrial areas and their neighbors a few hundred miles downwind. In fact, for most of the time that Charlson pursued his research, the government agencies that paid his bills were concerned about the view rather than far-flung effects on the climate. Among the customers for his instruments was the U.S. Defense Department, which wanted to understand haze so weapons guidance systems could pierce its veil.

Indeed, Charlson himself, with his longtime collaborator Bert Bolin of Stockholm University, wrote a paper in the mid-1970s that said aerosols could not have much impact on global climate. "We had made a mistake," Charlson says now. "We didn't have the global chemical model. We were guessing as to numbers. We didn't get the geographical extent of sulfates right."

Then, in the 1980s, sulfate haze began to register as more than a technical problem for tourists and bomber pilots. Sulfate aerosols were recognized as the key culprit in the acid rain that is killing lake fish, stunting forests, and corroding buildings and equipment in Europe and North America. The acid rain problem led to more support for research into sulfates.

Out of this focus on the problem came better techniques for measuring emissions, as well as new and more accurate computer models of wind patterns and chemical mixing in the lower atmosphere and of the dispersal of particles on those winds. In early 1990 this led to a big break. Charlson was attending a meeting on sulfates in a huge nineteenth-century faux-medieval castle in Bavaria. Many other climate experts were there also, of course, including two other collaborators and old friends of Charlson's from Stockholm University, Henning Rodhe and Joakim Langner, who were showing off one of these improved computer models. The new Swedish model was the first devised to process data about industrial activity and weather, and it yielded a crucial variable in acid rain—the distribution of sulfur in the air after it leaves the pollution centers that create it.

Fortunately, Charlson recalls, "one of the talks after theirs was very boring." His mind wandered back to the Swedes' model, which—not surprisingly—predicted strikingly high concentrations of sulfates throughout the heavily industrialized Northern Hemisphere and related that finding to acid rain. But they hadn't related such levels of sulfates to one of Charlson's areas of expertise—optical scattering.

Charlson won his first patent for measuring such scattering nearly 30 years ago, with an invention dubbed the nephelometer (*nephelos* is the Greek word for cloud). [The prototype still sits on a bookshelf in his office. It's gunmetal gray, roughly the size and shape of a bazooka. Through an inlet on the bottom, a tiny pump sucks aerosol-laden air into a chamber. On one side of the cylindrical chamber, about halfway down its length, is a halogen movie-projector lamp. At one end of the chamber is an electric light detector—the technologically more sophisticated great-grandson, Charlson says, of those electric eyes that open doors and set off alarms. By determining how much light makes it through an air sample to the light detector, Charlson can accurately measure how much light is being deflected by aerosols in the sample. "It gives you the 'scattering efficiency,'" Charlson says. "You might think of it as the amount of a light beam that a particle blocks out per gram of material."

To get a complete measure of optical scattering, Charlson explains, "you make a measurement with a nephelometer; simultaneously you filter the air, get the particles out of it, and do a chemical analysis of the material. That gives you an amount of sulfate per cubic meter of air. Then you take the ratio of the scattering to the concentration of material. That's what allows you to say that given X amount of sulfate in the air, there will be Y amount of scattering."]

As he sat in the Bavarian castle, listening to the high figures for sulfates that the Swedish model yielded, Charlson realized

"More frequent occurrence of drought is a possibility," Charlson says. "Or of violent storms. Or the opposite—less frequent storms. I'd give either chance equal billing."

that he "knew how to make the optical calculations, to get the amount of scattering in meters squared per gram of material in the air." He took out a pencil and did some rough math on a scrap of paper.

"It was much bigger than I thought," he recalls. "So after the boring talk was over, at the coffee break, I grabbed Langner and Rodhe and said, 'Look at this!' That was the light bulb, right there. That was a Thursday. I was due to see them in Stockholm the next week. When I got there on Monday, a new model, with my light-scattering calculations incorporated, was sitting on a desk waiting for me."

The computer model confirmed his rough calculation. The aerosol umbrellas over the Northern Hemisphere, he saw, are keeping, on average, about a watt of solar energy per square meter from reaching Earth's surface. That may not sound like much—very roughly, Charlson says, it's perhaps a fifth of the amount of heat put out by a Christmas-tree light bulb, spread out over an average desktop. But that's enough to cool Earth substantially. It's also, on average, equal to the amount of heat *added* to the planet by man-made greenhouse gases, according to some estimates.

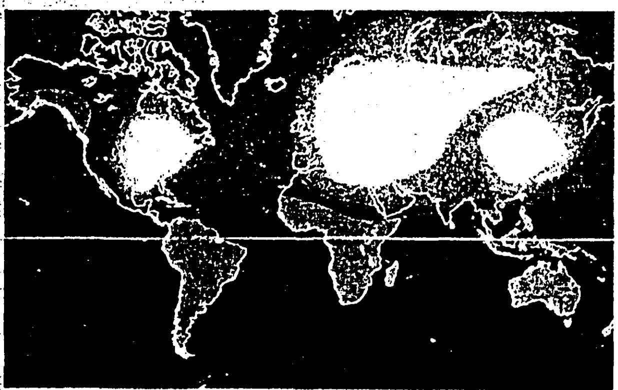
And that, says James Hansen, director of NASA's Goddard Institute for Space Studies in New York, could explain why models of global warming have predicted that Earth should be warmer than it actually is. Hansen gained some unwanted notoriety in 1989 when he charged that officials in the Bush administration made him lower his own estimates of the power of the greenhouse effect. His latest simulation of climate change over the past 150 years now takes aerosols into account as a global cooling force and incorporates Charlson's model of aerosol distribution over the Northern Hemisphere. The result, Hansen says, "is quite consistent with the amount of warming that has been observed" in the real world. "For the best estimates we can make, the aerosols are second in importance only to the greenhouse gases."

But opposite in effect. Is the aerosol umbrella, then, a mandate to do nothing about global warming? Or to do nothing about reducing sulfur emissions? In a word, Charlson says, no. To him, the notion that humanity could fine-tune a system as big and complex as the climate is laughable. "There's always this temptation to tell ourselves we can handle it, that we're bigger than it is," he says. "Personally, I find that attitude very arrogant. It assumes that we understand climate well enough to engineer it, and we don't."

Some of Charlson's findings about the parasol effect suggest that it won't help at all with some serious aspects of the global warming problem, such as rising sea levels. Sulfate aerosols may even make some warming effects worse, Charlson says. The reasons lie in the fundamental difference between greenhouse gases—which rise to the stratosphere and cover the globe—and sulfates, which travel only a few hundred miles.

Because sulfates have such a limited range, almost all man-made aerosols are floating above the Northern Hemisphere, where 90 percent of industrial activity is still concentrated. By contrast, the Southern Hemisphere gets almost no such "protection" from man-made sulfates. Even in the relatively clean air of Seattle, Charlson says, "the amount of light scattered by haze is probably 10 to 100 times higher than it is in the Southern Hemisphere." With one hemisphere bearing the full

CCP4 (CFC map)



Veiled skies: MAN-MADE AEROSOLS ABOUND IN THE NORTHERN HEMISPHERE. THE HIGHEST CONCENTRATIONS OF AIRBORNE SULFATES (WHITE) HOVER OVER THE GREAT LAKES AND CENTRAL EUROPE.

brunt of global warming while the other is protected by an umbrella of pollution, he says, seas would still rise uniformly all over the globe, as the warmer southern waters expand. In other words, sulfates can't save the Maldives, the low-lying island nation in the Indian Ocean.

But a rise in sea levels, Charlson says, might not be the biggest effect to worry about. Much more important, he points out, could be the increased difference in temperature between the two hemispheres. That's likely to affect the large-scale weather systems on which people depend.

"More frequent occurrence of drought is a possibility," Charlson says. "Or of violent storms. Or the opposite—less frequent storms. I'd give either chance equal billing. The thing people need to understand is that a slight regional shift in any direction is a big concern. Last year in the mountains around Seattle we had more precipitation as rain and less as snow than normal. And the snowpack is our reserve of water that fills the reservoirs in late spring. So just because the balance of snow to rain changed, we had a drought here."

Charlson is a neatly trimmed man who comes to work in a tie knotted tightly at the neck. The fuzzy carelessness of most public talk about world climate seems to offend him personally. To his mind, the aerosol results are a perfect illustration of the extent to which we don't know what we're doing. "The biggest problem the public has is that it perceives that we should do research in order to solve problems—but after those problems occur. It's wrong. It can't work that way. You have to have the fundamental knowledge ahead of time so you can apply it when the problem shows up."

Charlson recalls the time in the 1960s when some researchers, extrapolating from measurements that showed some cooling in the globe's average temperatures, predicted that another ice age was already starting. "They were wrong," Charlson says. "That's the problem we've always had in this field—this kind of lurching off and making grandstand statements without a good scientific foundation. We need a decades-long intensive scientific inquiry, because in reality these things are not going to submit to quick answers."

With that in mind, Charlson is very quick to insist on what his discovery is not. He says that so much remains to be understood about aerosols—especially with regard to their indirect influence as the seeds of clouds—that any estimates about their effects could be off by an order of magnitude. "There are substantial uncertainties," he says. "Perhaps as much as a factor of 2 up or down, which would mean, statistically, that a calculation of, say, .6 watts per square meter could represent a reality of maybe .3 or maybe 1.2. We can't say yet where it would fall in that range. But the key point is that even using the lowest estimates doesn't make this effect go away. It's definitely there."

So Charlson is continuing to chip away at the aerosol mysteries with a network of colleagues, students, and former students scattered throughout the world. One graduate student, for instance, has been dispatched to Antarctica to examine sulfate deposits trapped in ancient ice. Because the same ice that collects sulfate particles also traps carbon dioxide in bubbles, it's possible to track the relationship between levels of sulfate and levels of the gas, which is more abundant when the climate is warmer. Not surprisingly, says Charlson, higher amounts of sulfate do seem to correlate well with lower levels of carbon dioxide. The main purpose of the work is to build a record of preindustrial sulfate levels and temperatures. A historical standard of comparison will give researchers a much better handle on the extent to which sulfates can drive the climate.

Charlson is also working with several colleagues at the National Oceanic and Atmospheric Administration lab who are assembling a shipborne expedition to get a more complete picture of the boundary between the sulfate-laden Northern Hemisphere and the more pristine southern half of the planet, to learn more about any possible aerosol carryover. As the research vessel goes steaming up north of Tahiti, Charlson says, "they will see the westerly winds flowing out of Asia carrying a load of sulfate pollution from China, Japan, and Korea, so they'll be getting measurements of the transition from clean Southern Hemisphere air to more polluted Northern Hemisphere air and quantifying the amounts of it and defining the optical properties of it." Meanwhile, airplanes will be taking measurements of aerosol and cloud properties, and an NOAA satellite will measure the amounts and wavelengths of light bouncing off the atmosphere and out into space over the ship.

The effort is very much needed. If it took this long for atmospheric scientists to get the drop on an effect as important as that of sulfate aerosols, Charlson says, who knows what other consequences of our monkeying with the climate are drifting through the air, waiting to be noticed? Most of what we do know about aerosols comes from observing our own haphazard release of the particles into our air. "In a kind of sinister way we're doing a giant worldwide meteorological experiment," Charlson says. "And we don't know what's going to happen."

IAN WORPOLE

Appendix 1.3

E N V I R O N M E N T   W A T C H

TTL – Son of Ozone Hole

BY CARL ZIMMER

GLM – The ozone hole over Antarctica is likely to get worse before it gets better: it seems to lead a self-reinforcing life of its own.

PRO

SPRING IS RETURNING TO the Antarctic, and with it the hole in the stratospheric ozone layer. Last year's hole was the deepest ever; this year's is expected to be as bad and possibly worse. Although 74 nations have committed themselves under the Montreal Protocol to ending the production of chlorofluorocarbons by the end of 1995, ozone-destroying chlorine from the compounds already in use will continue to accumulate in the atmosphere for another decade after that. Only then, researchers believe, will the concentration of the chemical begin to decline slowly—so slowly that it will take at least until 2060 for the chlorine concentration in the Antarctic stratosphere to return to the level it was at in the late 1970s, when the ozone hole was first noticed.

PRB

Gloomy as this scenario is, there are signs that it may not be gloomy enough. A new study suggests that the Antarctic ozone hole may be self-reinforcing: it apparently prolongs its life each year by cooling the stratosphere, and it may even strengthen itself from one year to the next, regardless of any change in the chlorine concentration. And while the Arctic has so far been spared a major ozone hole, another new study suggests it may get one soon, thanks in part to that other great unintended consequence of industrial civilization, the greenhouse effect.

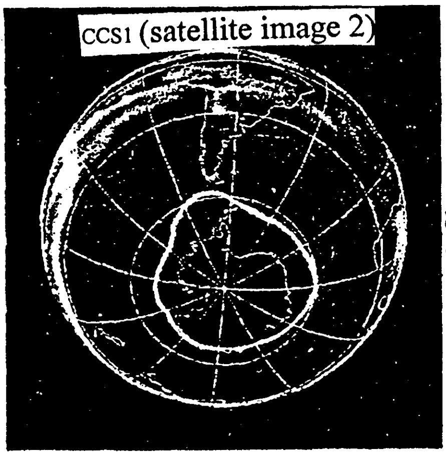
BRG

Chlorine isn't the only ingredient needed to make a hole in the ozone layer. Ice and sunlight, in that order, are essential, too. As the winter night settles over the South Pole and the atmosphere there gets progressively colder, the temperature difference between the Antarctic and the sunlit regions of the planet increases. That sharp temperature contrast produces a pressure difference that drives strong winds in the stratosphere. Below the Cape of Good Hope the winds encounter no mountains to deflect them as they circle the globe from west to east. The result is a stable wind pattern, called the polar vortex, that traps the cold air over the South Pole. The stratosphere there becomes so chilly (120 degrees below zero or colder) that water vapor condenses into clouds of ice.

BRG

On the surface of these ice crystals, chlorine undergoes a chemical transformation that makes it capable of stealing one of the three oxygen atoms in an ozone molecule—destroying ozone by converting it into ordinary molecular oxygen. The ozone-destroying reactions, though, are driven by solar energy, so they don't begin in earnest until the sun rises over the South Pole in spring. The destruction ends when the sun has warmed the stratosphere enough to break up the polar vortex.

But this warming of the stratosphere, researchers have long realized, depends on the presence of ozone itself. As the ozone layer absorbs ultraviolet sunlight—thereby protecting life on Earth from the effects of the radiation—it also heats up the air around it. Conversely, ozone destruction tends to cool the stratosphere.



PURPLE PULSING presence of the polar spring: The ozone hole.

SPC1

And that, says Jerry Mahlman, is how an ozone hole can feed on itself. Since 1980 Mahlman and his colleagues at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Lab in Princeton, New Jersey, have been perfecting a computer model of the global circulation of the atmosphere. Mahlman's model divides the atmosphere into blocks and, from a given set of initial weather conditions, calculates how air flows from one block into adjacent ones. Such models are used in weather forecasting, but Mahlman's model is different in that it also tracks the movements and chemical reactions of particular gases—including the reactions that destroy ozone.

Recently Mahlman used the model to simulate five years of ozone destruction over the Antarctic. He found that the ozone hole has a striking effect on the Antarctic stratosphere: it cools the air inside the polar vortex so much that in effect it delays the spring warming by ten days. That means ten more days of ice clouds—and ten more days of ozone destruction than there would be if this feedback loop didn't exist.

Eventually, of course, the spring warming does banish the ice clouds, break up the polar vortex, and flush the ozone-poor air from the hole, dispersing it over the rest of the planet. But Mahlman has found, alarmingly, that some of the stale, ozone-poor air remains over the South Pole until the following winter. Linger-

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		

SPC

ing in the stratosphere, it makes the air even colder that winter, which encourages ice clouds to form faster. Up to a point, the effect is cumulative; each year's leftover pool of ozone-poor air accelerates the next year's cooling. Mahlman suggests that this effect may explain why the Antarctic ozone hole is getting more robust and predictable—and deeper—from year to year.

BRG

In the real world there has yet to be a major ozone hole in the Arctic (although there have been substantial pockets of ozone depletion), and such is also the case in Mahlman's ozone world. In the Northern Hemisphere, mountain ranges such as the Rockies and the Himalayas interrupt the west-to-east motion of the winds, shunting warm air north into the Arctic. The warm intrusions tend to break up cold patches of air before stratospheric ice clouds—the prerequisite for massive ozone destruction—can form. Thus the Arctic is intrinsically less susceptible to an ozone hole than the Antarctic.

GCL [PRE]

But calculations done recently by British meteorologists indicate that the Northern Hemisphere may be living on borrowed time as far as ozone goes. The reason is the increasing level of carbon dioxide in the atmosphere. Carbon dioxide absorbs heat rising from the surface of the planet; that's the greenhouse effect. By trapping heat in the lower atmosphere, however, the greenhouse effect also cools the stratosphere. Simulating a world with twice as much atmospheric CO_2 as there is today, the British researchers discovered that the Arctic stratosphere would become cold enough in winter to form widespread ice clouds.

SPN

While the resulting ozone hole would cover a smaller area than the one in the Antarctic, it would affect far more people. And Mahlman thinks global warming could also promote ozone destruction in ways the British researchers didn't simulate. Some circulation models suggest that global warming could slow the movement of warm air in the stratosphere toward the Arctic, and thus strengthen the Arctic vortex. At that point the stratosphere-chilling feedback Mahlman has identified in the Antarctic might kick in, helping dig a deep ozone hole that would tend to deepen itself from year to year. "Anything that makes the Northern Hemisphere more Southern Hemisphere-like," Mahlman says, "pushes the system toward the edge."

New Scientist 6 May 1989 19

TTL–Methane: the hidden greenhouse gas

GLM

Methane from cows, rubbish tips and rice fields is warming the Earth. Car exhausts may help the process. But methane from the Arctic tundra could be most damaging of all

Fred Pearce

SET

IT IS hard to measure the methane in a cow's farts. But Dieter Ehhalt has de an estimate. It is hardly easy task to count how ny cattle there are in the rld. But the West German mist has tried to do that . Ehhalt's answers are, ectively, 200 grams per y and 1300 million. Together, they suggest that the rld's cattle emit into the osphere approaching 100 llion tonnes of methane h year, enough to warm the planet.

PRB [TLI]

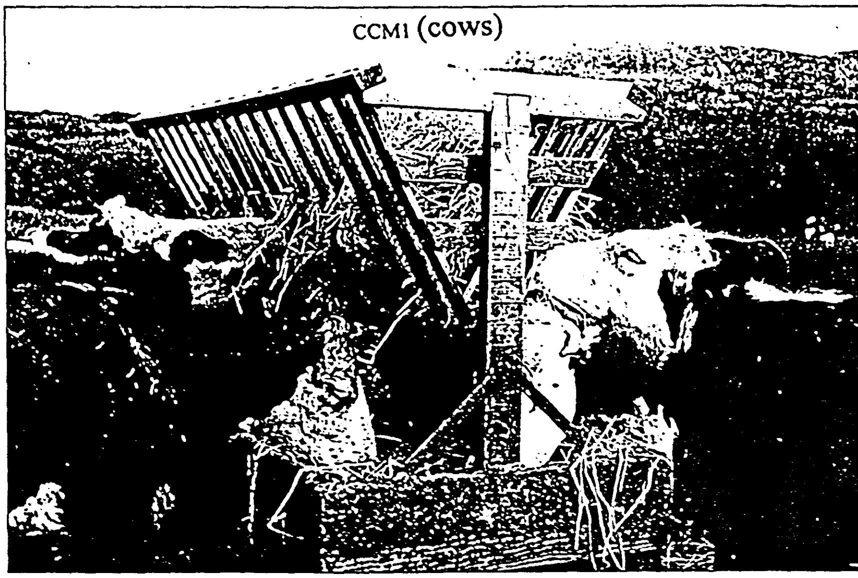
Public concern about the enhouse effect and its ential to warm the Earth's osphere has so far used on carbon dioxide, eashed into the air as we n coal and oil and chop n trees. But methane is o a greenhouse gas, second importance to carbon xide. Like carbon dioxide, traps infrared radiation that would otherwise escape into ce. Indeed, molecule for molecule, it traps 25 times as ch of the Sun's heat in the atmosphere as carbon dioxide.

Hence the concern about the methane in the farts of cattle, ose world population has doubled in the past 40 years. re is roughly one head of cattle for every four human ngs. Bacteria that break down cellulose in the guts of cattle vert between 3 and 10 per cent of the food that the cattle eat o methane.

Wherever bacteria break down organic matter in the ence of oxygen, they produce methane. When the same cess occurs in the presence of oxygen, carbon dioxide is oduced. Concentrations of methane in the air have been ng at 1 per cent per year, at least since 1950. This is four es the rate of increase of carbon dioxide. Levels are already re than double those recorded before the explosion in man activity on Earth that followed the Industrial Revolution. Carbon dioxide is not ected to double its pre-ustrial concentration until ound 2030. Within 50 ars, methane could be the me greenhouse gas, say estigators such as Ralph erone from the US's ional Center for mospheric Research in lorado.

GCL

Despite methane's growing importance, no one is sure out where the extra gas is ming from. Isotopic analy-s shows that about 20 per t of the methane in today's



Chris Jones

atmosphere was produced long ago and is now leaking from coal seams, melting permafrost, rocks beneath the oceans and from natural gas deposits (see Box 1). One recent estimate is that between 4 and 12 per cent of the gas carried in natural gas pipelines leaks into the atmosphere.

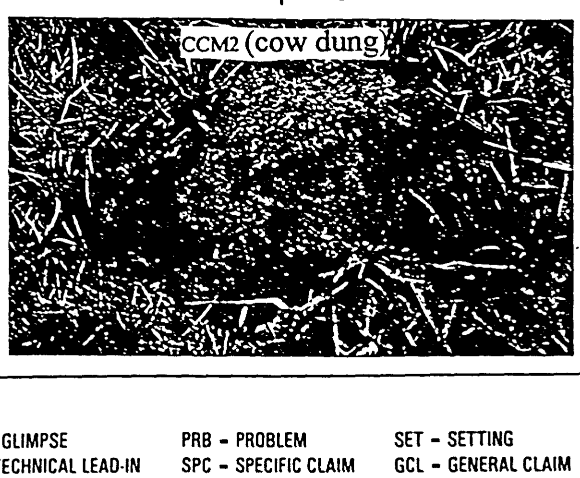
GCL [EVN]

The rest of the methane is being produced today. The list of modern sources includes cattle, the world's 5 million square kilometres of bogs and marshes, the 1·5 million square kilometres of rice paddies, the burning of forests and grasslands by farmers, putrefying waste tips and termites.

These sources give off a total of about 500 million tonnes of methane each year. But the uncertainty around estimates of each source are large, and no one knows what the trends are for any of the sources.

BRG

Methane-producing bacteria cannot tolerate oxygen. Until about 2 billion years ago, they were in their element. But once oxygen from new life forms had saturated the oceans and began to bubble into the atmosphere, the methane-loving microbes took refuge wherever oxygen could not reach: in swamps, coral, the guts of animals such as termites and, latterly, herbivorous mammals. And there they remain.



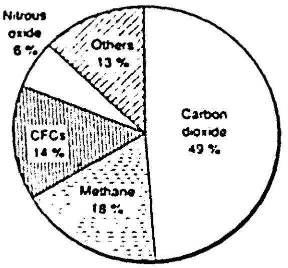
David Kirby

BRG

Isolated, as they are, these bacteria still play an important part in determining the planet's atmospheric chemistry. In February this year, scientists from around the world met in West Berlin to discuss the role of methane

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		



How greenhouse gases contribute to global warming: carbon dioxide comes largely from burning fossil fuels but also from the destruction of forests. Chlorofluorocarbons (CFCs) are synthetic chemicals that also destroy the ozone in the stratosphere. Nitrous oxide comes largely from agricultural activity. Other gases include ozone in urban smogs and halons in fire extinguishers

and other biologically produced gases in the greenhouse effect. They asked two key questions: how is human activity altering the amount of these gases in the atmosphere, and how will the changing atmosphere, including global warming, influence the processes that release those gases? Underlying those questions was the fear that some of these feedbacks could amplify the greenhouse effect, accelerating global warming. But for the moment, there is great uncertainty about the importance of various sources of methane.

Take termites. In 1982, scientists from the US, Kenya and West Germany thought that they had identified termites as an important new source of methane. They had collected American termites from beneath rocks in Colorado and in cow dung from Arizona. Back in the laboratory they found that bacteria in the guts of termites convert most of their woody food into carbon dioxide and methane.

The investigators estimated that there are 250 000 billion termites in the world, occupying two-thirds of the world's land area and eating a third of the world's vegetation. They said that the annual emission of methane from termites could amount to 150 million tonnes, almost a third of the total. And the figure could be rising fast. Termites like grasslands best, as farmers replace tropical rainforests with pasture, the termite population could be growing. However, seven yea later, new estimates have downgraded the likely metha output of termites, largely because of new guesses about th number of termites in the world. The latest estimate is emission of a mere 5 million tonnes per year, but the deba continues.

As fast as some sources of methane are dismissed as trivi others emerge. Paul Crutzen, a Dutch atmospheric chem now based at the Max Planck Institute for Chemistry in Main West Germany, takes pride in promoting heretical ne thoughts. He was the first to suggest that a nuclear holocau could trigger off a nuclear winter. And he was one of th authors of the termite study. In 1984, he proposed that was tips in rich nations could be generating prodigious quantities methane as bacteria broke down organic matter such as o food and paper packages.

Production could already be around 70 million tonnes year, said Crutzen, and "very large increases in metha production from waste dumps are expected in the comir decades from the developing world". In Britain, metha from several tips is already tapped and burnt as fuel. A rece estimate put the escape of methane from landfill sites Britain each year at 2·2 million tonnes.

After waste tips, what next? Last year, two researchers fro the University of South Florida suggested asphalt. Sunlig causes photochemical reactions on hot asphalt roads and roo which, they wrote in a letter to *Nature*, may liberate up 5 million tonnes of methane a year in the US alone.

Human activity has clearly created a number of new sourc of methane. But we have also profoundly disturbed most the natural sources. Modern cattle herds are almost certainly more prolific source of methane than the wildebeest, giraff

1: Ice captures methane in bubbles of ancient air

THE PRESENCE of methane in the atmosphere in significant quantities was first noticed in the 1940s, when spectroscopic studies showed the characteristic absorption lines of the methane molecule. But it was not until the 1960s that accurate measurements were made. Since then, continuous monitoring has shown an increase from about 1·4 parts per million at the end of the 1960s to 1·7 parts per million at the end of the 1980s. The increase is equivalent to 1 per cent a year.

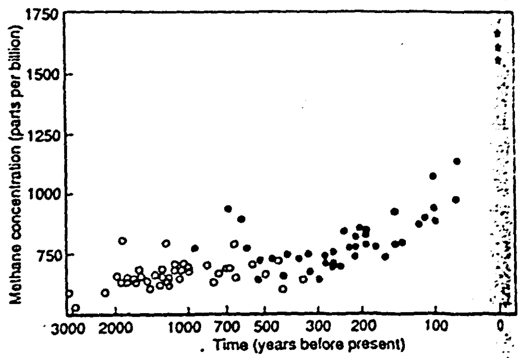
Methane is trapped in air bubbles in ice cores. Studies of bubbles from the Greenland ice cap show that the concentration of methane in the air remained steady for 10 000 years, up until about 300 years ago. This natural concentration of methane in the air was about 0·7 parts per million. Over the past 300 years, the concentration has increased almost exactly in line with the growth in the human population of the world. Most of the increase to date has come from agricultural activities.

Carbon present in the atmosphere in the form of carbon dioxide comes in three varieties. There are two stable isotopes. They are carbon-12 (the most common) and carbon-13. There is also one radioactive isotope, carbon-14, that is produced by the action of cosmic rays on atoms of nitrogen-14 in the air.

Of the two stable isotopes, the biochemistry of photosynthesis favours the uptake of the heavier atoms by plants, so that plant material contains a greater concentration of carbon-13 than does non-living material. When the plant material burns, some of the carbon in it is locked up in molecules of methane.

Measurements of the methane that is trapped in bubbles inside ice cores drilled in both Greenland and Antarctica show that the proportion of carbon-13 has increased in recent decades. The measurements imply that at least 50 million tonnes of methane is now being produced each year by burning plants.

Methane from burning plants, or from the biological activity going on in paddy fields, cow guts and termite mounds, is relatively rich in carbon-14, because it is in equilibrium with the ratio of the carbon isotopes in the atmosphere. But ancient sources of methane, such as coal mines, contain no carbon-14, since it has all decayed. The half-life of carbon-14 is a little under 6000 years. Deposits of organic material, such as peat, that are a few hundred or a few thousand years old contain a proportion of carbon-14 that reflects their age, and so does any methane they emit.



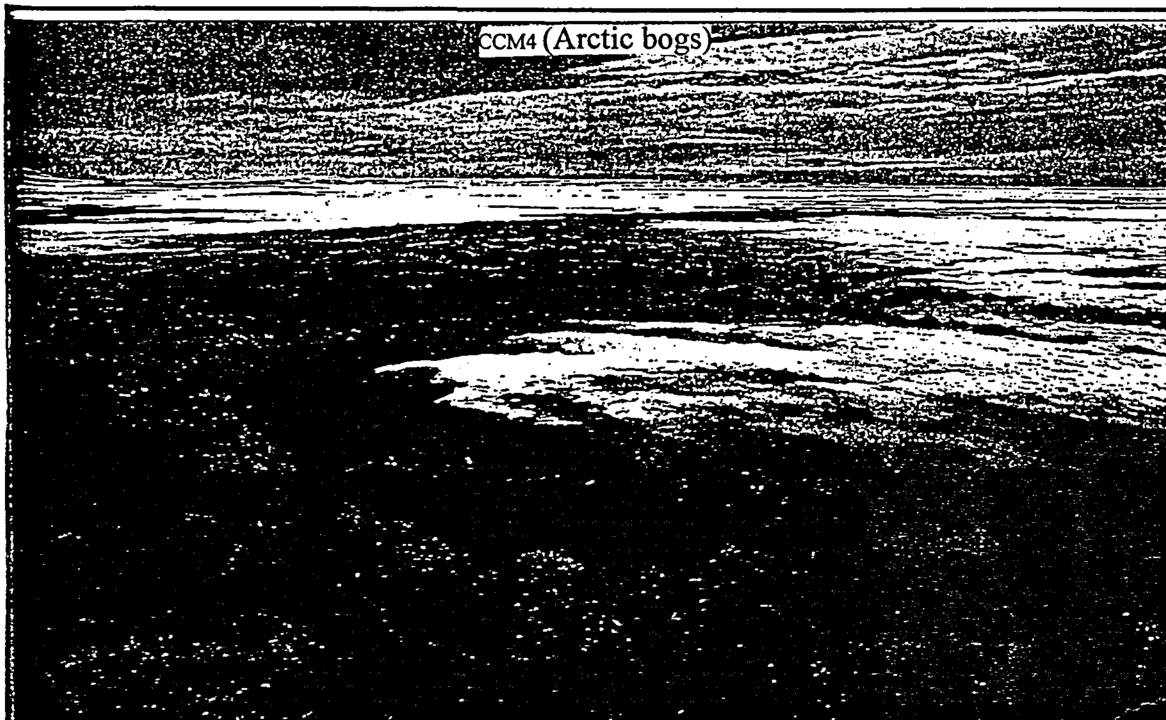
Air trapped in ice reveals the build-up of methane in the atmosphere from analysis of carbon isotopes

Measurements of the amount of carbon-14 in atmospheric methane today show tha there must be a large source of old methan getting into the air. This cannot be ex plained solely by the emissions tha researchers have already identified as coming from coal mines and oil wells.

The conclusion reached by researcher such as Ralph Cicerone, of the US Nationa Center for Atmospheric Research, is that global warming is causing the releas of old methane from some natural reservoir

The two candidates are the melting of th frozen tundra of the Arctic and methan hydrates.

John Gribbin



Bogs in arctic tundra will release methane when the permafrost melts as the world warms up

[illegible]d bison that roamed the planet before humans invented [illegible]ces. But by how much? We have probably encouraged the [illegible]read of termites. We have drained marshes and bogs round [illegible]e world, thus depriving methane-producing bacteria of their [illegible]mes. But we have effectively replaced many of these natural [illegible]tlands with our own artificial versions: rice paddies. [illegible]ddies could be extremely efficient creators of atmospheric [illegible]thane. At certain seasons and times of day, the roots of rice [illegible]nts seem to capture methane from the muddy bottoms and [illegible]nsport it through the plant's vascular system and into the [illegible], thus bypassing microorganisms in the water that would [illegible]xidise some of the methane. Up to 90 per cent of methane [illegible]m the depths of the flooded fields seems to reach the air this [illegible]y. The "green revolution" is fundamentally changing the [illegible]e paddies of the world, notably by the use of fertilisers. Field [illegible]sts in Italy found that urea and ammonium sulphate reduce [illegible]thane emissions, while other fertilisers, including rice [illegible]aw, double it. We know little about the implications of all [illegible]is for the chemistry of the atmosphere.

Researchers have recently set up instruments at two sites in [illegible]e Zhejiang province of China to monitor the methane [illegible]leased from paddy fields. It is the first such experiment in [illegible]ia and has revealed much higher emissions than observed [illegible]om European paddies. Researchers are now revising up[illegible]ards their estimates of the contribution of paddies to the [illegible]orld's methane emissions. One West German investigator, Wolfgang Seiler, told the meeting in Berlin that "rice paddies [illegible]re likely to be the most important individual source for [illegible]mospheric methane", emitting 150 million tonnes per year. [illegible]dia, with its millions of cattle and swathes of paddy fields, is [illegible]metimes called the biggest source of methane in the world. [illegible]ut, according to Bob Harriss from the University of New [illegible]ampshire, there are no measurements of methane fluxes at [illegible]l over India.

Much the same is true for the output of methane from [illegible]rning trees and grasslands. Contrary to popular belief, says [illegible]rutzen, it is not burning rainforests that produce the largest releases of gases such as methane. The annual burning of grasslands, a feature of farming from northern Australia to the Savanna regions of Africa, may release the most. This appears to be due largely to changes in the activity of microbes in the soil. But data are sparse. There have been very few experiments to measure emissions of methane from soils; moreover the problems of "scaling up" from a few square metres of ground to the whole planet are considerable.

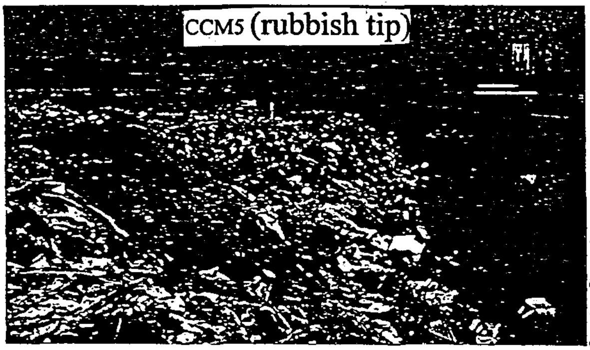
Investigators in Berlin concluded that "what little evidence we have suggests that changes in [methane] fluxes can be dramatic immediately following clearing and that subsequent fluxes can be high or low depending on subsequent land use. For most areas of the tropics we do not know the magnitude, direction or duration of these changes". The role of microbial communities in soils is very uncertain. Some communities produce methane, but most of this is reoxidised by others before it reaches the atmosphere. The balance of those communities could depend on human factors ranging from crop burning to acid rain and climatic change.

In all these areas, concluded the meeting, "much of the basic field work remains to be done". The truth, says Henning Rodhe from the University of Stockholm, is that "if we are asked by politicians how we can reduce methane emissions, we are in a bad way".

If there is one subject more uncertain than where the methane in the atmosphere comes from, it is where it goes. Each year, 50 million tonnes more methane enter the atmosphere than leave it. This is partly due to increased emissions, but also because methane is lasting longer and longer in the atmosphere. The "sinks" for methane may be altering as much as the sources.

Methane currently lasts an average of 10 years in the atmosphere. After that, it may be consumed by oxidising bacteria or by chemical processes in the atmosphere itself. Bacteria that oxidise methane turn up in marine sediments, lakes and the water table in wetlands, but probably the biggest sink on land is bacteria in soils. Typical rates of consumption

CCM5 (rubbish tip)



…lane Picture Agency

Rubbish tips ferment to produce a tappable source of methane

BRG[GCL][CNS]

reported from the dozen or so monitoring sites around the world are 1 milligram of methane per cubic metre of soil per day. The total terrestrial sink could account for up to 50 million tonnes of methane each year. [Recent studies in the US suggest that nitrogen fertilisers applied to soils may reduce the ability of soils to consume methane. So might the nitrogen in acid rain.]

Another big unknown is the oceans. There appears to be little exchange of methane between the air and the sea. But that is because methane rising from the ocean depths is apparently oxidised by marine organisms and so never reaches the air. ["This is a very important regulator," says Cicerone, "yet we don't know what the oxidisers are. What might happen if they all died? This is worrying."]

Probably 90 per cent of the destruction of methane occurs in the atmosphere, however. And this is where, by a circuitous route, another human influence arises: vehicle exhausts. There are several hundred million automobiles around the world, belching out a wide variety of pollutants from lead to chemicals that cause acid rain and smogs. So far, less atte has been given to carbon monoxide, which plays a crucia in allowing methane to accumulate in the atmosphere.

BRG

Human activities are the dominant source of ca monoxide in the atmosphere. One estimate puts our cont tion at 1500 million tonnes of the gas a year, largely vehicle exhausts. Humans have doubled the amount of ca monoxide in the air in the past century. The concentrati the air above Europe since 1950 has risen at a rate of 2 per per year. Carbon monoxide does not survive as long as gases such as carbon dioxide or methane, but its tenden react easily gives it a potent influence on other chem which do have a global range. The most important of th hydroxyl, a free radical made up of one atom of oxyge one of hydrogen that is produced when ultraviolet radi bombards ozone in the atmosphere.

PRE SPC4

Hydroxyl is present in the atmosphere only in m quantities, yet it is the atmosphere's most important oxic agent. It removes many pollutants from the air, including methane and carbon monoxide. So it is worrying to disc from research by Joel Levine at NASA's Langley Res Center that there was about a quarter less hydroxyl in lower atmosphere in 1985 than in 1950. Levine blame decline of "the key species in the photochemistry o troposphere" on the increasing concentration of methane carbon monoxide in the atmosphere. [It seems that planetary cleansing service is becoming overloaded. could have many consequences: sulphur dioxide may t further before it is oxidised and falls to the ground in acid It could also explain why methane is lasting longer in the

In an unpolluted world, there appears to have be balance between methane and carbon monoxide in the The balance was managed by hydroxyl. But vehicle exh have upset that balance. Recent estimates suggest that up per cent of the destruction of hydroxyl in the atmosp results from reactions with carbon monoxide. And that l methane lingering in the air.

2: Methane clouds the view in the ozone layer

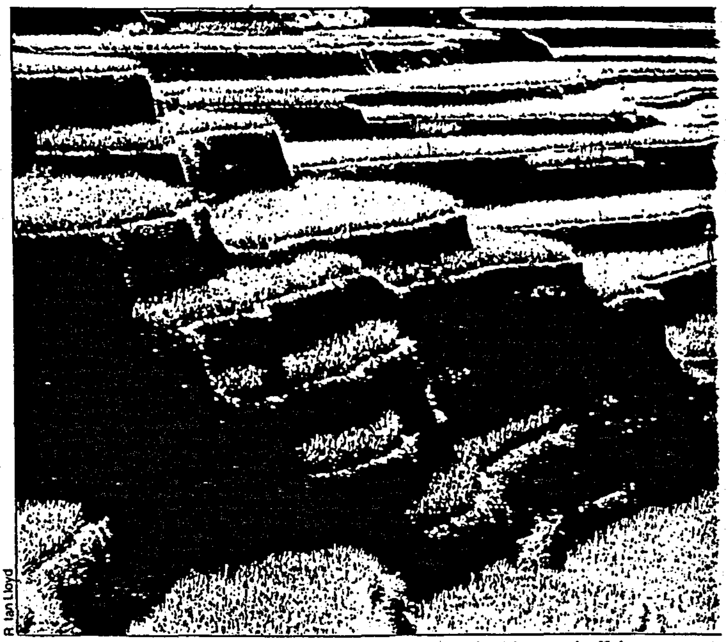
AS METHANE helps to warm the world, it may also have a surreptitious role in a second global environmental concern: the thinning ozone layer.

A final "sink" for methane is the stratosphere, where it breaks down to form water vapour. The stratosphere is generally very dry but over the polar regions unusual ice clouds known as "polar stratospheric clouds" form. Inside these clouds occurs the complex chemistry which causes the runaway destruction of the ozone layer in the stratosphere.

According to Donald Blake of the University of California at Irvine: "An increase in stratospheric water vapour . . . could contribute to further decreases in total ozone over Antarctica." The theory is that more methane means more clouds and more clouds will mean greater destruction of ozone.

Blake and his colleague, Sherry Rowland, who first identified the risks to the ozone layer from pollution, estimate that methane is largely responsible for a rise in the amount of water vapour in the stratosphere in the past 40 years of 28 per cent.

However, to confuse the picture, it seems that methane in the stratosphere also reacts with chlorine compounds that destroy ozone. No one knows which effect of methane dominates. Farting cattle are unlikely to be the main cause of the ozone hole—but they may well contribute. □



Ian Lloyd

Perfect bioreactors: take rice fields and add water buffalo

Jim Anderson of Harvard University, who specialises in analysing the chemistry of radicals in the atmosphere, believes that the destruction of hydroxyl by carbon monoxide contributes more to rising amounts of methane in the air than any increase in sources. Cars could be more damaging than cows.

The big question for the future is whether the greenhouse effect could further upset the comings and goings of methane into and out of the atmosphere. A warmer world might release more methane into the air, thus making the world warmer still.

Worries are greatest over the northern bogs and tundra of Canada, Siberia and Scandinavia. These bogs produce a lot of methane, and they are found at the latitudes likely to warm the most, by between 6 and 8 °C in the coming 50 years, according to most current climate models. And the production and emission of methane from wetland soils are very sensitive to changes in soil temperature and moisture. A warmer, wetter climate will release more methane.

There are 1·5 million square kilometres of peat bogs in the world, mostly in the Hudson Bay area of Canada and in western Siberia. According to Georgy Zavarin of the Institute of Microbiology in Moscow, every year 100 square kilometres of peat bog forms in Siberia. "The direct cause is excessive free water, which raises the ground water," he says. The water may come from a mixture of deforestation, increasing rainfall and the melting of permafrost. Changes in methane and other gases released from these bogs are so sensitive to fluctuations in climate that many researchers believe that monitoring them could provide the first unambiguous signal of greenhouse warming. According to Harriss, "the Siberian lowlands are the highest priority in this area". He wants an international research effort there to investigate the mechanisms of methane production in boggy soils.

Much of the methane generated in the northern swamps is locked into permafrost. If the permafrost begins to melt, the methane will be released. Perhaps it already is. Arthur Lachenbruch, a geophysicist from Menlo Park, California, has measured the temperature of permafrost inside disused oil wells in northern Alaska. Since changes in surface temperature work their way slowly through the permafrost, this provides a record of past temperatures at the surface. It shows, says Lachenbruch, "a marked warming of the permafrost of between 2 and 4 °C at most sites during the 20th century".

Isotopic analysis confirms that some 20 per cent of the methane released into the atmosphere today is ancient. Cicerone believes that much of this may be from melting permafrost. The positive feedback "may already be happening", he suggests. A second source of ancient methane lies beneath the oceans, where methane is locked in the form of methane hydrates, lattice-like structures of methane and water. The structures depend for their stability on the low temperatures and high pressures of the ocean bottom. Methane hydrates have been found at the bottom of the Arctic Ocean and in the sediments of deep ocean troughs. If warmer waters penetrate to the bottom of the oceans, the methane may be released.

The solid hydrates form a shell up to 300 metres thick beneath which large quantities of gas may build up. If cracks form in the shell, the gas could be released in a rush. Soviet scientists observed a "plume of methane" 500 metres long when methane was released from hydrates beneath the Sea of Okhotsk on the east coast of Siberia. A Soviet science magazine suggested fancifully that the release of methane from hydrates beneath the Bermuda Trough in the Atlantic could explain the loss of ships in the Bermuda Triangle.

Gordon McDonald, a geologist at Mitre Corporation in the US, calculated at the end of last year that 10 000 billion tonnes of carbon could be tied up in these structures, more than in all the known coal reserves of the world. It could be released by global warming or a fall in sea levels, he said. □

Much of the material for this article came from a Dahlem Conference on biogenic gases and the atmosphere, held in West Berlin in February.

CCII (icecap 1)

Shackleton Range: snow that falls in Antarctica eventually becomes part of the icecap, recording the climate of the past

Charles Swithinbank

TTL – # Icy prospects for a warmer world

GLM – In the past, a warmer climate has brought thicker ice. If this happened in a greenhouse world of the future, sea levels would fall, not rise

Garry Davidson

PRB – AN ABIDING concern of climatologists faced with the prospect of global warming has been the behaviour of the great ice sheets of Greenland and the Antarctic. The world has become warmer over the past hundred years or so[1] and many scientists ascribe this to the increase in carbon dioxide and other greenhouse gases in the atmosphere. At first glance, it seems likely that a warmer world would bring smaller ice sheets and rising sea levels. But while there is evidence of ice sheets melting at the lowest latitude margins, the ice in the interiors of the sheets is growing. Researchers interested in the interplay of ice sheets and sea level are now discovering a similar pattern in the past.

TLI – By looking into the past, scientists hope to understand the effects of the threatened runaway greenhouse effect. Turning to the rocks and sediments of the Earth's most recent ice age, in the Pleistocene epoch that stretches back 1·6 million years, they are searching for an example of how the Earth behaved as it warmed then. During Pleistocene times the Earth switched from a glacial to a milder interglacial climate and back again nine times. These cycles are subdivided into cooler and warmer periods known as stadials and interstadials respectively. The timing and duration of these minor cycles closely match fluctuations in the distribution of the energy the Earth receives from the Sun, which are caused by periodic changes in the shape of the Earth's orbit and by variations in the tilt and precession of its axis, together known as Milankovitch cycles.

TLI – At least two periods in the Pleistocene epoch had very mild climates, milder than today. The first, termed the Hypsithermal interstadial, was between 7000 and 3000 years ago, when the world was, on average, about 2 °C warmer than now. The second was the most recent major interglacial, between 132 000 and 120 000 years ago, when the world basked in a climate 2 to 3 °C warmer, on average.

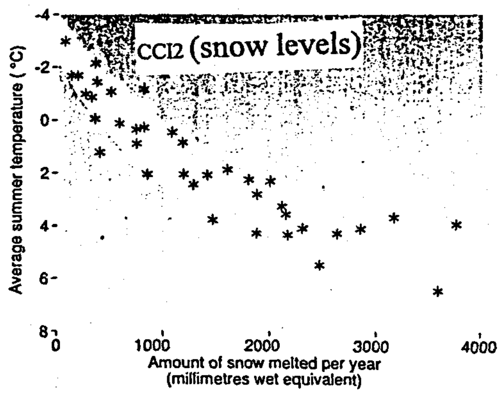
Back to the future

SPC1 – Evidence for the Hypsithermal warming comes from sediments below the Southern Ocean around Antarctica. Just the idea of Antarctica in a hotter world provokes alarming images of ice cubes disappearing in bubbling hot water; many visions of a greenhouse future have included the melting of this huge ice sheet and a consequent rise in sea level of 5 metres or so. But this simple assumption can be tested by looking at how the Antarctic ice has responded to warming in the past.

8 August 1992 23

KEY:

TTL – TITLE	GLM – GLIMPSE	PRB – PROBLEM	SET – SETTING	PRO – PROPHECY
THR – THREAT	TLI – TECHNICAL LEAD-IN	SPC – SPECIFIC CLAIM	GCL – GENERAL CLAIM	BRG – BRIDGING
EVN – EVALUATION	ONP – ONGOING PROJECT	PRE – PREDICTION	CNS – CONCERNS	SLN – SOLUTION
SGN – SUGGESTION	SUM – SUMMARY	CON – CONCLUSION	ANX – ANXIETY	SPN – SPECULATION
COL – CALL FOR COLLABORATION		REC – RECOMMENDATION		



Rising temperatures in summer quickly cause more snow to melt

Eugene Domack of Hamilton College in New York, Timothy Jull of the University of Arizona and Seizo Nakao of the Geological Survey of Japan have been looking for an answer in the sediments on the sea floor around the Antarctic. They have used cores drilled in 1987 and 1988 by the Ocean Drilling Program, together with other cores from geological expeditions in Antarctica over the past decade. The sites were carefully chosen to provide a continuous record of the sediment accumulating at places that were sensitive to the amount of ice in Antarctica over the past 10 000 years. Cores contain a wealth of information—the types of sediment found near ice-covered continents change with the climate.

Selecting the sites

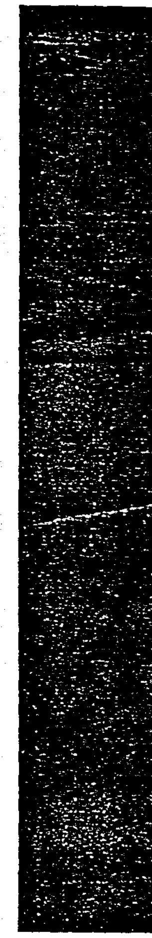
[[Antarctica's ice comes from snow and frozen sea. Snow accumulating inland becomes ice and slowly flows down towards the shores, ending in the floating ice shelves that fringe the continent. When ice volumes in the Antarctic are low, these shelves retreat towards the shoreline. But if there is a lot of ice, the shelves spread around the continent as more ice flows outward from the land. The shelves touch the sea floor close to the shore, and, because they float farther out, they begin to scrape away sediments on the sea floor at a position known as the grounding line. So, to collect a complete sediment record for a particular period of Earth history, a drill hole has to be placed beyond the grounding lines of the sheets that were active then.

Domack's team chose three submarine troughs more than 500 metres deep, lying between 30 and 130 kilometres offshore along the line of major ice rivers or glacial drainage systems. One site was near the Amery Ice Shelf, which lies in front of the Lambert Glacier, the largest stream of ice in East Antarctica.

Each site records the same 10 000-year story. For the past 4000 years mud and diatomaceous ooze have accumulated in the troughs beneath an ocean free of solid ice. The ooze is named after diatoms—the creatures whose skeletons form the bulk of this sediment. They are microscopic algae with silica shells and countless numbers of them live in the top 200 metres of the ocean when there is no covering of ice.

In the preceding 3000 years, from 4000 to 7000 years ago, silty sands and gravels were laid down. Today these sediment types are accumulating closer to Antarctica, beneath the ice shelves. The sediments are made up of debris ploughed from the Antarctic landmass by glaciers and ice sheets, which eventually break up into icebergs that melt into the ocean. There are fewer diatoms in these sediments because the combination of fresh water from the melted ice and low levels of sunlight below the shelf inhibit their growth. Before about 7500 years ago, the oceans were free of ice again at these sites, with conditions probably much like today.]]

Ice archive: Antarctica is yielding clues about our future climate



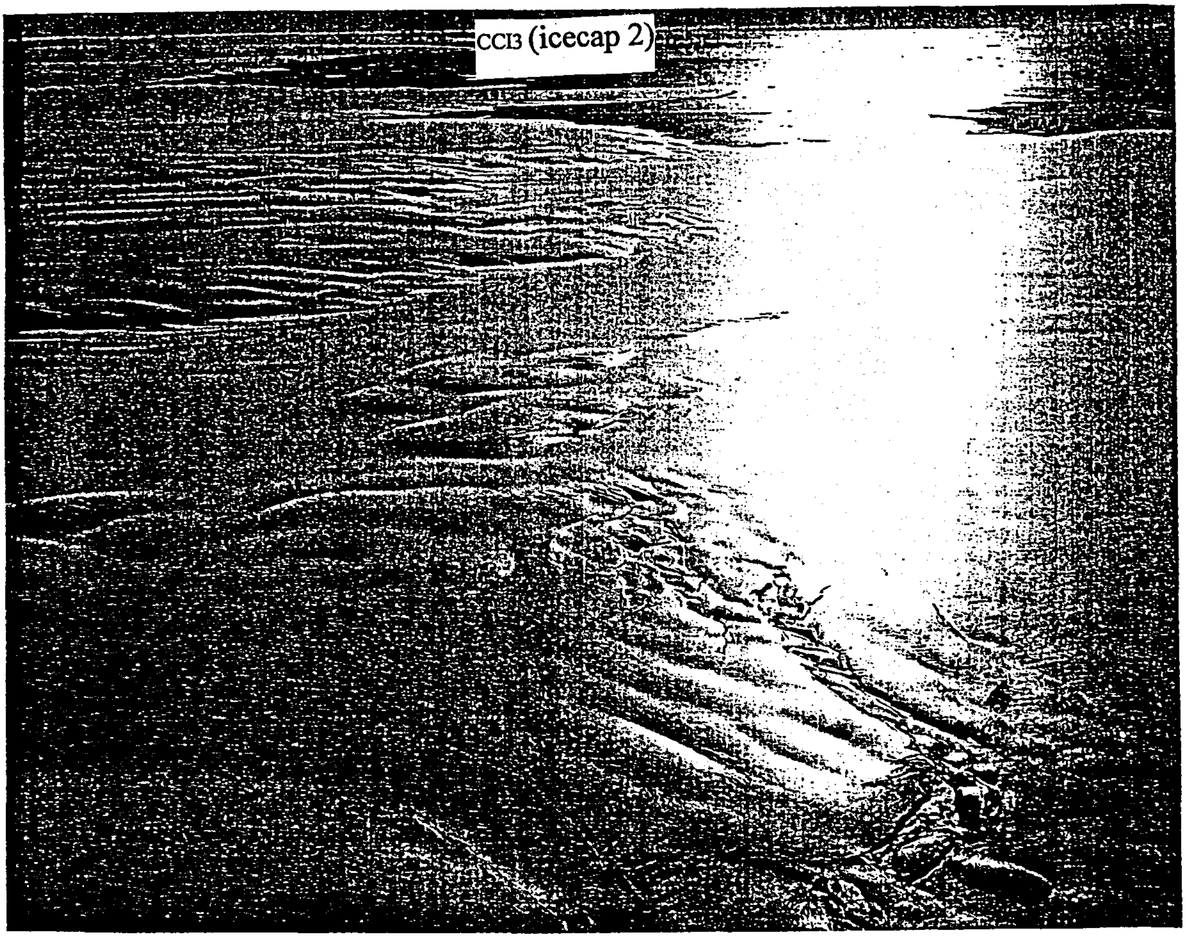
Domack matched the record of larger ice shelves between 4000 and 7000 years ago with the record of average world temperatures over the same period. To his surprise, he found that the Antarctic ice sheets grew significantly between 3000 and 7000 years ago—at the same time as a period of global warming. "At first we thought that the Antarctic ice-sheet outlets were simply lagging behind the retreat of northern hemisphere ice sheets," says Domack. (These ice sheets mainly disappeared 10 000 years ago.) "But the Lambert Glacier drill-core clearly records the end of a major Antarctic ice-expansion episode at the same time as the great ice sheets of the northern hemisphere disappeared," he notes. The team concluded that the Antarctic ice sheets were expanding at a time when the world was, on average, 2 °C warmer than today.

Other researchers are arriving at a similar picture. Gifford Miller of the University of Colorado and Anne de Vernal of the University of Quebec have examined the interglacial period that ended 120 000 years ago. They believe they have evidence that continental ice in the northern hemisphere began to grow and spread southward when the climate was at its mildest, not as a response to cooling as researchers had thought.

[To follow the growth of ice sheets worldwide, Miller and de Vernal concentrated on one of the tiniest forms of life in the oceans—foraminifera, or forams. These creatures grow shells of calcium carbonate and the proportion of two isotopes of oxygen (oxygen-16 and oxygen-18) in the carbonate varies as the ice sheets wax and wane. The link is in the sea water. When water evaporates from equatorial regions of the Earth, there is a higher level of the lighter isotope, oxygen-16, in the vapour than there was in the original sea water. Some of this water vapour is carried to the poles, where it falls as snow and eventually forms the polar ice. The ice too has a higher proportion of oxygen-16 than the sea, and the more ice that forms at any one time, the greater the imbalance between the isotope ratios of ice and sea.

In glacial periods, organisms living in these seas with a higher proportion of oxygen-18 grow shells that are also especially rich in the heavier isotope; this tell-tale sign is fossilised in sediments after they die. The shells of the forams give a record of the balance of oxygen isotopes through time, which is in turn linked to the volume of water locked away in the ice sheets.]

Miller and de Vernal have compiled a wealth of data showing that when the shells of forams began to accumulate greater amounts of oxygen-18, signalling the growth of polar ice 120 000 years ago, plants and animals characteristic of warm climates were living farther north than they are today. There are also signs that the climate zones were different: species of plankton that lived near the sea surface show that the waters were nearly as warm as they are today during summer. But they were also much warmer in the winter, although glaciation had started on the continents of the northern hemisphere.[Like Domack, Miller and de Vernal concluded that there is a relationship between climatic warming and the growth of polar ice.]



Charles Swithinbank

Similar signals come from the modern world, which has on average warmed by 0·6 °C over the past century. There have been *short-term increases in the amount of snow at the poles: snow* lines in regions such as Arctic Canada, Baffin Island and Alaska are moving to lower altitudes. The Greenland ice sheet is thickening at a rate equivalent to a fall in sea level of about 0·45 millimetres per year. Some coastal and interior sites in Antarctica have accumulated ice over the past 80 years, giving a growth rate equivalent to a fall in sea level of 0·75 millimetres per year.

Confusing signals

But today's climate is signalling the opposite effect, too—that *the melting of ice is accelerating*. For instance, glaciers in most mountain chains are melting and retreating rapidly, behaviour that began a century ago. And some ice shelves on the Antarctic Peninsula are disintegrating, fuelling fears for the long-term stability of the West Antarctic ice sheet.

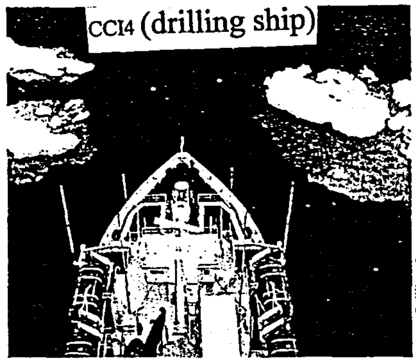
This confusing, contradictory behaviour also shows up in the geological record. Domack notes that in the Hypsithermal period, glaciers on the Antarctic Peninsula and islands immediately north of the Antarctic Circle receded at the same time that ice sheets were growing from the snouts of major ice-drainage streams. How are these conflicting signals to be understood?

The most likely explanation is that mild global warming brings a net increase in the amount of snow at the poles rather than a net melting. In a warmer world, more water evaporates from the oceans, to be transported to the poles to become snow. When this happens, the feedback processes that starve ice sheets, such as the extra melting during hotter summers, cannot be important enough to override the effect of air circulation. The key factor in the growth of ice sheets seems to be conditions that do not melt or remove snow, as exist today in the cold, dry climates of central Antarctica and northern Canada. In particular, Miller and de Vernal found that a change to warmer, wetter winters alternating with cooler, dryer summers, is ideal for retaining snow all year round.

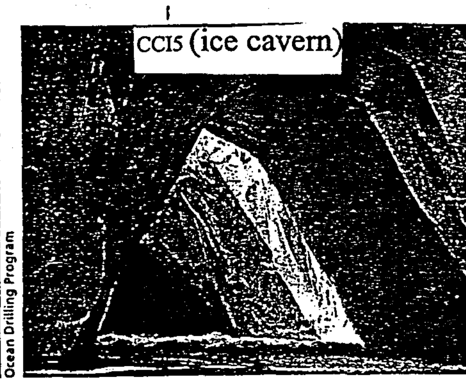
Domack and his colleagues suggested that there may be other climatic factors that affect the preservation of snow. They think that katabatic winds on ice sheets may play a part. These winds develop when air cooled on high ground becomes dense enough to flow downhill. As they descend, they remove recently fallen snow. In Antarctica, katabatic winds reach tremendous speeds, averaging 75 kilometres per hour at some places on the Antarctic plateau. But if the world was warmer and the drop in temperature with height reduced, the strength of katabatic winds would diminish and more snow would survive.

Overall, the evidence seems conclusive that past ice sheets grew when the average temperature was higher. So what might the future hold in terms of the rise or fall of sea level in response to global warming? Unfortunately this is a complex area in

Avoiding caverns in the ice that float around Antarctica, the ship of the Ocean Drilling Program has provided cores from sediments around the ice shelves going back 10 000 years



Ocean Drilling Program



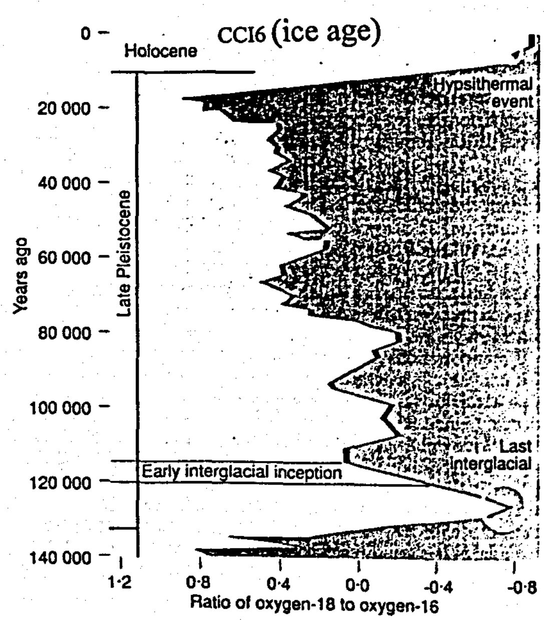
B&C Alexander

which detailed information is lacking. Geologists and polar scientists are urgently addressing the range of factors that contribute to the sea level we measure.

First, there is the inevitable and immediate rise in sea level that comes from the thermal expansion of warmer oceans, giving a rise of about 10 centimetres for every extra 2 °C. Secondly, sea level is affected by the amount of water stored on land as ground water and in lakes and rivers. Thirdly, the influence of gravity is important: ice sheets exert a gravitational pull on nearby water, so the sea level around an ice sheet is higher than that farther away. Fourthly, there is the effect of the weight of icecaps on the rock beneath. A continent covered with ice sinks beneath the extra weight, and the land at its periphery bulges. The net effect is a rise in sea level as the ice builds up.

Moreover, sea level is both relative and subjective. The effects of gravity and loading, for example, are not uniform around the Earth, so perception of a rise or fall in sea level will depend on the observer's location.

To place these competing effects in perspective, Kurt Lambeck of the Australian Research School of Earth Sciences, Canberra, has been studying the variation in sea level over the past 20 000 years using models that incorporate the rebound of continents



Oxygen isotopes in foram shells reveal how ice sheets changed

after ice has melted, observations of coastal landforms, and records from tide gauges. Lambeck and Masao Nakada of Kumamoto University, Japan, have found that sea rose quickly between 12 000 and 6000 years ago in response to the disappearance of global ice sheets. Then the rate slowed appreciably. Lambeck and Nakada calculate that the current rate of rise is about 1·2 millimetres per year, although some estimates are double this. They believe that the melting of mountain glaciers and floating ice sheets accounts for about half of this.

Falling sea levels

The slowdown 6000 years ago may support Domack's observation that ice sheets were growing in the Hypsithermal, but there are also other explanations. One is that glaciers in the northern hemisphere melted later than was previously thought. This area needs more research. But more importantly, Lambeck's calculations show that although ice and snow are now accumulating at the poles, this is not taking in water fast enough to overcome the processes that are raising the sea level.

Looking back further, sea levels fell while temperatures were mild as the Earth slid into its last great glaciation, which began 120 000 years ago. Miller and de Vernal saw clear signs of ice sheet growth in the steady enrichment of oxygen-18 in fossils, at the same time as average sea levels fell by about 70 metres. This led them to forecast that modern ice sheets will grow and sea level could fall by up to 7 millimetres per year, in the longer term, if greenhouse gases continue to accumulate in the atmosphere. This is in accord with predictions made by Mark Meier of the Institute of Arctic and Alpine Research in Colorado, who calculates that the world is not likely to see an increase in the size of floating ice sheets before 2050, because glaciers respond only slowly to changes in the mass of ice feeding them.

So the future of the ice at least looks less bleak than some early estimates of the impact of global warming have suggested. The ice sheets look likely to grow, not melt, in the next few decades, and the seas should eventually fall, not rise. If anything, the early stages of global warming seem to be pushing the world towards a climate closer to the one in which the last glacial period began. But two qualifications arise.

First, studying mild climates of the past may not produce accurate models of the effects of very rapid warming. The hotter intervals of the past 150 000 years developed because of slow processes such as changes in the Earth's orbit and axis and not from a leap in carbon dioxide levels that is virtually instantaneous in geological terms. Secondly, the temperature in these warm intervals was on average less than 3 °C warmer than today. If temperatures increase by more than 5 °C, as some models predict, the balance of polar ice would tip towards melting, and a rapid and inexorable rise in sea level would follow. □

Garry Davidson *is a postdoctoral fellow in the geology department at the University of Tasmania, Australia.*

M- Predicting how the Earth will respond to global warming is a tricky business. But the latest research into sulphur-producing algae, ancient ice cores, and sea sediments from the North Atlantic region could help climatologists to make more accurate forecasts. Over the next three weeks, *New Scientist* will look at the evidence and the uncertainties

L-

Can algae cool the planet?

Nolan Fell and Peter Liss

SET — EACH spring and summer, microscopic algae become visible: huge "blooms" form in the oceans and foam banks appear along the east coast of England and the coast of the Netherlands. The growth of algal blooms is often linked to the pollution of coastal areas by nitrates and phosphates. Sometimes algae themselves, like the "red tide" that swept south from the Baltic in 1989, are toxic. But recent evidence suggests that some algae play a vital and subtle role in regulating the Earth's climate.

PRB — Algae produce a sulphur compound which seems not only to be a key link in the global sulphur cycle, but which also influences the formation of clouds, and therefore the Earth's temperature. Understanding how these algae affect cloud formation in the remote oceans could be crucial to predicting how the Earth will respond to global warming.

TLI — Climatologists know that clouds are important regulators of radiation. Clouds reflect incoming short-wave radiation from the Sun and absorb and re-emit long-wave radiation from the Earth's surface. The freezing of water vapour or the melting of ice within clouds is part of the basic energy balance of the atmosphere. But no one knows how global warming will affect the distribution of cloud. Clouds are fiendishly tricky to study, and even the most complex computer models of the Earth's climate can only treat them very crudely.

SPC1 EVN BRG — Last year, Catherine Senior and John Mitchell of the Hadley Centre for Climate Prediction and Research, which operates under the Met Office, came the closest yet to an accurate description of how clouds influence and are influenced by climate change. Their model shows in detail how clouds would respond to global warming by acting as a negative feedback mechanism, reducing the rate at which the Earth warms up. But even this model is greatly simplified and, like all other "general circulation" models, it cannot encompass the potential influence on cloud formation of microscopic marine algae. There is growing evidence that these algae are important to this process.

The link between algae and climate involves dimethyl sulphide, or DMS, the gas that gives sea air its bracing smell. It forms from the enzymatic breakdown of a salt, dimethylsulphoniopropionate (DMSP). Marine algae produce DMSP to keep their osmotic balance with sea water, without which water would leave the cells of the algae, killing them. The processes by which DMSP is released into the sea are not well understood, but most researchers think it occurs when algae die, or are grazed by zooplankton. In the sea, DMSP breaks down to form DMS. A fraction of this DMS, perhaps a tenth, then enters the atmosphere. The rest is either consumed by bacteria or broken down by sunlight to form dimethylsulphoxide. — BRG

> Microscopic marine algae produce an essential ingredient that keeps levels of sulphur constant in the environment, and helps clouds to form. Could this same ingredient be used to control global warming?

CCA1 (ocean algae)

SPC2 — In the early 1970s James Lovelock, the British chemist who originated the Gaia hypothesis, suggested that DMS might provide a way of returning sulphur washed from the land to the sea (see Box 1). Sulphur is a vital biochemical element, and Lovelock was looking for an explanation of how sulphur levels on land are maintained. In 1987 Robert Charlson of the University of Washington, his colleague Stephen Warren, and Meinrat Andreae of Florida State University, put forward with Lovelock a theory which suggested that the influence of DMS goes far beyond its role in the sulphur cycle. DMS, and therefore algae, they argued, play a vital role in regulating the Earth's climate. DMS reacts in the atmosphere to form three types of compound: sulphur dioxide, sulphates and methane sulphonic acid. Water vapour can condense around particles containing the last two to form clouds. Charlson's idea was that in remote open regions of the oceans —which together make up around half of the Earth's surface— most of the clouds form as a result of this process.

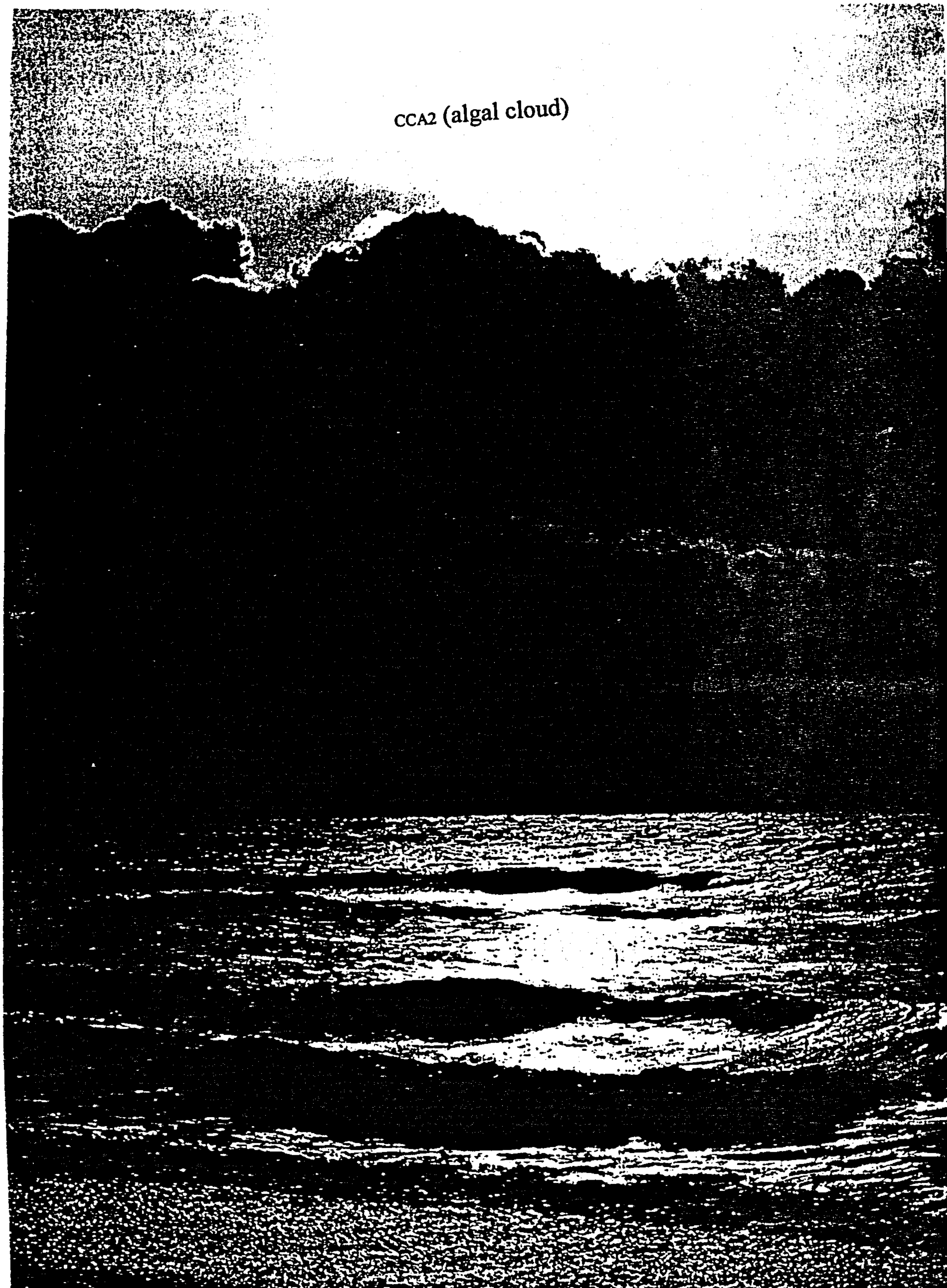
BRG — Charlson's ideas about DMS sparked off a flurry of research, as scientists realised that to test these ideas they needed to understand in much more detail how sulphur travels between the atmosphere, the geosphere, the biosphere and the hydrosphere. They already knew the basic cycle: the ultimate source of all sulphur on the Earth's surface is volcanic emissions, and sulphur tied up in microorganisms and sea salt is returned to the geosphere through sedimentation. DMS was known to be part of this cycle, but its precise role has only recently been established.

Algae transfer between 20 and 50 million tonnes of sulphur

R. Ould/Robert Harding

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		



CCA2 (algal cloud)

CCA3 (cloud formation model)

1: Sulphur and the Gaia hypothesis

THE interconnection and interdependence of all life is the theme of James Lovelock's Gaia hypothesis, which sees the Earth as a "superorganism". "The entire range of living matter on Earth, from whales to viruses, and from oaks to algae, could be regarded as constituting a single living entity, capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with powers far beyond those of its constituent parts."

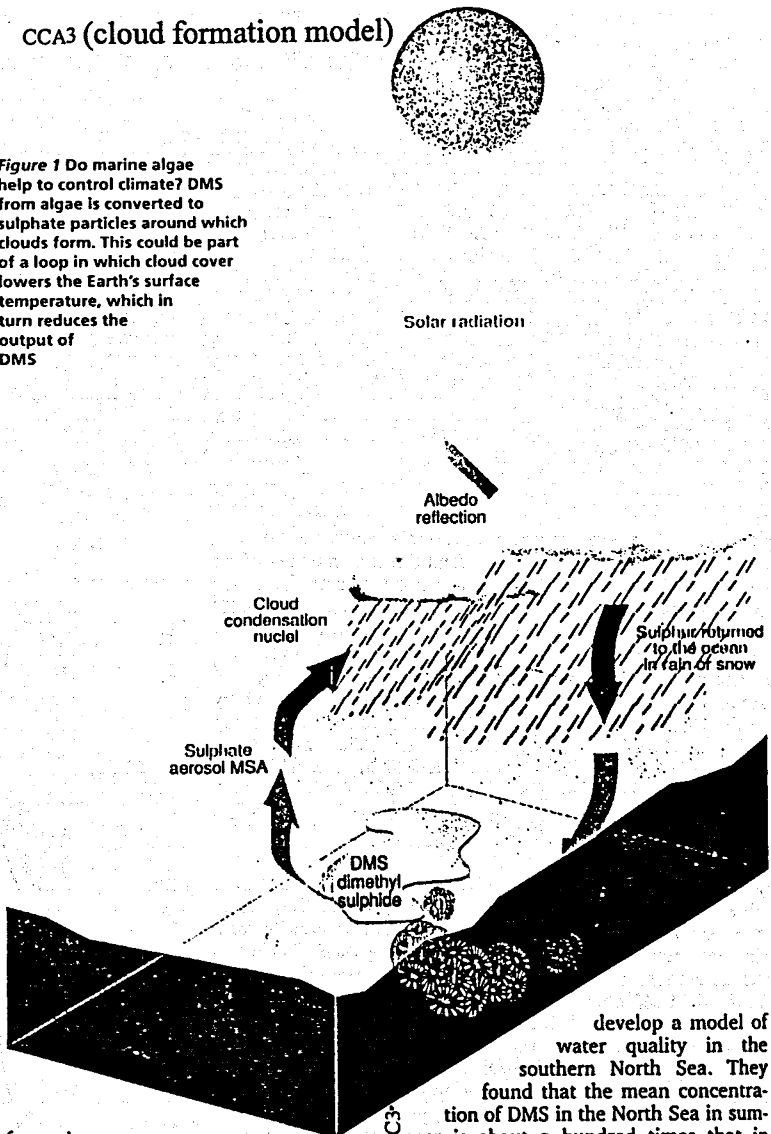
Lovelock was struck by the differences between the atmospheres of the living Earth and the dead Venus. Life preserves an atmosphere in dynamic equilibrium, one in which oxygen and methane coexist. Without life Earth would be like Venus, dominated by CO_2 and residing in its lowest energy state.

The influence of life on its surroundings, its ability to produce oxygen and absorb carbon, led Lovelock to consider that "if the atmosphere is...a device for conveying raw materials to and from the biosphere, it would be reasonable to assume the presence of carrier compounds for elements essential in all biological systems, for example...sulphur". After a voyage across the southern oceans in 1971, Lovelock was the first to suggest that the carrier compound in which sulphur is returned to land is dimethyl sulphide (DMS).

Without the return of sulphur to the land, terrestrial life would have major problems. Without algae, antelopes and elephants would not exist. But algae do not produce DMS for impala. The return of sulphur to land increases the productivity of biota and the rate at which rocks weather. Both processes ultimately provide the algae with a greater flow of nutrients. Lovelock cites this type of symbiotic relationship as support for the Gaia hypothesis.

DMS also had an important influence on the Earth's radiation "budget". The Gaia hypothesis would suggest that it acts as a global thermostat, but this idea is still controversial. Lovelock has suggested that Gaia's preferred temperature and ours may not be the same. The interglacial phases, such as the one which has existed for the last ten thousand years, may be Gaian "fevers", and the ice ages Gaia's more stable state. The data from the Vostok ice core (Figure 2) does not necessarily contradict this idea and if it is correct, algal-induced cloud cover may help to keep the Earth comfortably cool.

Figure 1 Do marine algae help to control climate? DMS from algae is converted to sulphate particles around which clouds form. This could be part of a loop in which cloud cover lowers the Earth's surface temperature, which in turn reduces the output of DMS



from the oceans to the atmosphere every year. Human activity accounts for not much more—about 80 million tonnes. Algal volumes in the temperate oceans reach a peak in spring and summer, and one important source of DMS is the alga *Phaeocystis poucheti*, which also forms banks of foam along Britain's east coast and the coast of the Netherlands.

Peter Liss's team at the University of East Anglia made the conclusive link between algae and DMS emission after measuring concentrations of DMS (see Box 2) in the surface waters of the North Sea for 9 months, as part of the Natural Environment Research Council's North Sea Community Project. This was a multidisciplinary project whose main aim was to develop a model of water quality in the southern North Sea. They found that the mean concentration of DMS in the North Sea in summer is about a hundred times that in winter. Such a seasonal variation matched the growth patterns of the algae. The team is now looking at the factors which control the rate of DMS production, while together with another group at Plymouth Marine Laboratory, led by Andrew Watson, they are investigating how DMS is transferred from the sea to the atmosphere.

Concentrations of DMS in different regions of the oceans also vary. Generally, the nutrient-rich waters of the continental shelves have more algae, and by implication more DMS, than the relatively barren open ocean. However, things are not always quite this simple, because different species of algae produce DMS in different quantities. For example, Coccolithophores, which form huge blooms covering areas of

2: Tracking down DMS

ESTIMATING the flux of dimethyl sulphide (DMS) accurately is extremely difficult. The usual method is to measure DMS concentrations in sea and air samples taken from a boat. But as the oceans cover 70 per cent of the earth's surface and the DMS flux varies greatly over space and time, techniques that show the fraction of biogenic sulphur in any given sample are extremely important.

Atmospheric sulphur dioxide has many sources, but DMS is the only major source of methane sulphonic acid (MSA), so this can be used as a marker for oceanic sulphur. However, the ratio between MSA and sulphate is quite variable, so the technique does not always provide a very clear picture.

An alternative method, developed by Nicola McArdle at the University of East Anglia, uses the ratio between the two stable sulphur isotopes, sulphur-32 and sulphur-34, to estimate the algal contribution of sulphur to an atmospheric sample. Biogenic and anthropogenic sulphur have different isotopic "signatures". DMS-derived sulphur has a higher proportion of sulphur-34 than does sulphur released from the burning of fossil fuels.

This is because bacteria that lived in the swampy anaerobic environment of a carboniferous forest absorbed sulphur across a membrane and ultimately provided coal and oil with its sulphur content. The bacteria absorb sulphur-32 more easily, as it is lighter.

The ratio between sulphur-32 and sulphur-34 in any sample can be used to estimate the percentage of sulphur derived from algae that derived from fossil fuels. Using this technique, McArdle showed that atmospheric aerosols collected off the west coast of Ireland in spring and summer have around 25 per cent of their sulphur acidity from DMS and 75 per cent from fossil fuel combustion.

up to 500 000 square kilometres in the relatively nutrient-poor open oceans, produce about a hundred times as much DMS as some other algae—such as diatoms, which thrive on the continental shelves, among other places, but produce very little DMS.

While Liss's team was establishing the importance of DMS as part of the sulphur cycle, evidence was also growing that DMS has another, perhaps more profound influence on the global system. Charlson's original idea was that waters heated by greenhouse warming could encourage algal production, leading to more DMS and hence more cloud. This would lead to more solar energy being reflected, which would in turn lower the Earth's temperature. Could algae act as a global "thermostat", compensating for any forced change in climate?

Global thermostat

The work of two Australian scientists helped to inspire Charlson to develop his "thermostat" theory. Keith Bigg and Greg Ayers of the Commonwealth Science and Industrial Research Organisation in Australia were indirectly measuring DMS concentrations in remote parts of the oceans near Antarctica. Large amounts of DMS entering the atmosphere never reach land at all, but are redeposited in the oceans by rainfall. Once in the atmosphere, DMS reacts rapidly with reactive hydroxyl or nitrate radicals, which are produced by interaction between sunlight and water vapour, ozone and nitrogen oxides. Two things then happen. If it loses a hydrogen atom DMS will ultimately form sulphur dioxide and sulphate aerosols. If it gains a hydroxyl group, it forms methane sulphonic acid (MSA).

Sulphur dioxide and sulphate have many different sources, but there is no other significant way in which MSA is produced. Bigg and Ayers used MSA as a marker in the atmosphere to measure concentrations of DMS. Their measurements at Samoa, Cape Grim in Tasmania and Mawson on the edge of Antarctica showed a strong link between levels of sunlight and the concentration of atmospheric particles. Data from Cape Grim also showed a relationship between the number of atmospheric particles and the amount of MSA. There is no industrial activity in these areas, so they assumed that the seasonal variation they saw is due to the natural variability in DMS production. Because such particles form the nuclei of cloud droplets, the implication of the finding was that DMS influences cloud formation.

One assumption behind Charlson's theory is that increased temperatures will lead to increased DMS production. The idea is appealing, particularly to those who believe pumping ever-increasing quantities of greenhouse gases such as carbon dioxide into the atmosphere is nothing to worry about. But more recent evidence that DMS would act in this way is not convincing.

CCA4 (climate record)

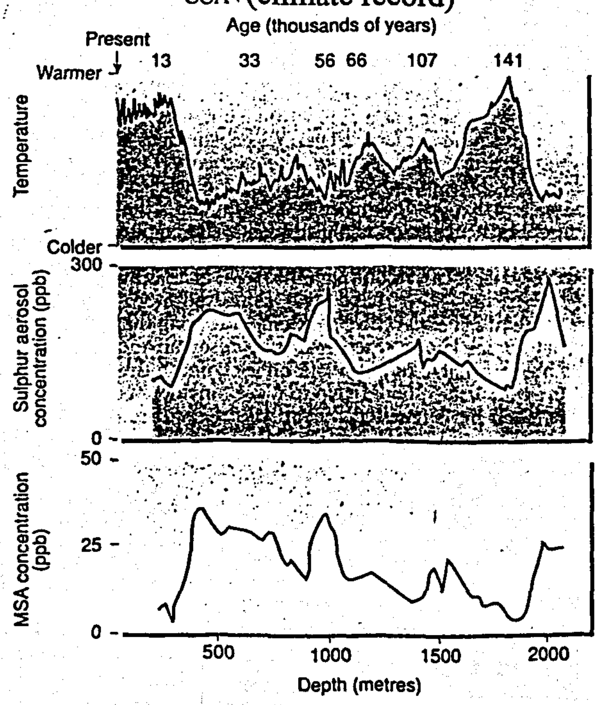
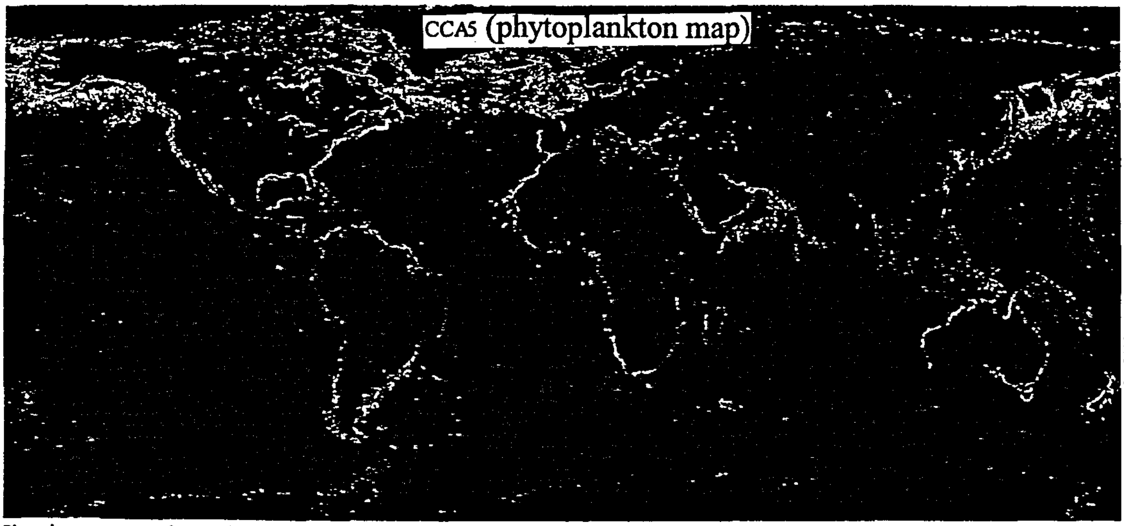


Figure 2 **The climate record of the Vostok ice core shows that when temperatures fell, the concentration of DMS-derived sulphate increased, which does not match the theory that in the past algae acted as a damper on climate**

Ice cores from the Arctic and the Antarctic provide a record of the atmosphere's chemical make-up going back thousands of years. In 1991 Michel Legrand from the Laboratory of Environmental Glaciology and Geophysics near Grenoble in France and colleagues from Russia and the US used the Vostok ice core in Antarctica to reconstruct the atmospheric concentration of MSA over the past 160 000 years, covering a whole glacial-interglacial cycle. Their results suggest that concentrations of sulphate aerosols derived from DMS and MSA are lower during warm interglacial phases and higher during ice ages (Figure 2). This



Dr Gene Feldman, NASA GSFC/SPL

Blooming oceans: understanding the effect of phytoplankton on CO_2 production is essential, but reducing CO_2 emissions is even more so

SPC5

is the opposite of what would be expected if the DMS-derived aerosols were acting as a damper on climatic change.

Scientists have put forward various explanations as to why the experiment does not seem to fit the theory. One is that the ecology of the southern oceans during a glacial may favour algal species that produce more DMS. Another is that changes in atmospheric circulation could influence the amount of aerosol material deposited on the Antarctic land mass. Also, more of the earth's water is frozen during an ice age, increasing the salinity of the oceans—so perhaps algae produced more DMSP as a response to salt stress. One problem with using the Vostok core is that no one knows whether it is representative of the whole Earth's atmosphere or not. Work on ice cores in Greenland (see next week's issue) should help to dispel any doubts.

Charlson has suggested that to counteract dramatic global warming—caused, for example, by a doubling of the atmospheric CO_2 level from its pre-industrial concentration of 280 parts per million—would require a corresponding doubling in the numbers of cloud condensation nuclei. So even if algae do not act as a natural "thermostat", could they still be used as part of a future management strategy for global warming?

CONT

Iron management

SPC6[EVN]

The late John Martin of Moss Landing Marine Laboratories in California explored this possibility. He was a chief proponent of the theory that algal growth is limited in many areas not by a lack of conventional nutrients such as nitrogen and phosphorus, but by iron. Iron reaches the remote oceans via dust, blown off land masses which may explain why remoter waters rich in nitrogen and phosphorus, such as the Antarctic seas, are not more biologically active. Martin's laboratory experiments at Moss Landing, carried out over the past five years, show that when iron is added to water samples taken from nutrient-rich regions, biological activity increases by about ten times.

These findings led Martin to suggest that it may be possible to counteract global warming by adding iron to parts of the oceans which are rich in nutrients, but low in biological activity. The initial proposal was that greater algal productivity would "fix" more of the excess carbon entering the atmosphere, in the same way that planting trees does on land. Data from the Vostok ice core supports this idea, as it shows that an increase in iron is linked with a decrease in CO_2 levels in the atmosphere over the last glacial-interglacial cycle.

In October, Kenneth Johnson of Moss Landing, with Liss and Watson, will try out iron fertilisation in the ocean for the first time in experiments devised by Martin before his death earlier this year. A patch of the Pacific near the Galapagos Islands, perhaps a square kilometre in area, will be fertilised with iron and the water marked. The researchers will then look for changes in the volume and distribution of algal species, and will monitor the emission and absorption of gases such as CO_2 and DMS.

If such an experiment were applied on a large scale to control global warming, the whole marine ecosystem would be fundamentally altered. But no one knows how. Would increased iron concentrations, or warmer temperatures, favour the production of diatoms, Coccolithophores or *phaeocystis*? Diatoms fix carbon, but produce little DMS. Coccolithophores produce DMS, but release CO_2, so whether an increase in either group would counteract global warming is doubtful. Phaeocystis absorbs carbon and produces DMS. Because of uncertainties like these, Johnson doubts whether iron fertilisation will ever become part of a plan for managing global warming. "I think the chances of using this method to control the CO_2 in the atmosphere are very remote," he says. He expects to see a shift from small to large diatoms, on the basis of which computer models show a reduction of no more than 2 gigatonnes in CO_2. This is small even compared with the 5 gigatonnes now released per year as a result of human activities, only about half of which is absorbed by the biosphere, and even smaller when compared with the predicted output of 15 gigatonnes within 50 years.

"The reason we are carrying out these experiments is to try to understand marine ecosystems better," Johnson says. "At the moment we don't even understand what regulates primary productivity in the oceans, and the more knowledge you have the better you can manage a system when pollution occurs." He is in no doubt as to where the emphasis should lie; "To control greenhouse warming we need to reduce CO_2 production."

CON

Meanwhile, Liss's team will monitor the impact of iron fertilisation on DMS emissions. They hope that such studies will help them to predict what might happen to the climate if the marine ecosystem is affected by global warming. Until the dynamics of algae are well understood, any attempt to predict their effect on climate will, it seems, remain elusive. □

Nolan Fell *is a freelance environmental journalist and* **Peter Liss** *is Professor of Environmental Sciences at the University of East Anglia.*

NEW SCIENTIST

TTL

DRYING OUT

PRB

WHEN global warming takes hold, who will suffer most? Conventional wisdom has it that the high latitudes and polar regions are the most vulnerable. The tropics are supposed to remain more or less unscathed. But this reassuring picture is fading in the face of accumulating evidence that global warming could, after all, wreak havoc in the tropics. Within a century, temperature increases may disrupt climate in a band that circles the globe and stretches from southern Europe in the north to South Africa in the south, putting 350 million people at risk of famine.

PRE

Double trouble

Despite international efforts to limit emissions of carbon dioxide (This Week, 18 March), the amount of CO_2 in the atmosphere is expected to effectively double by the middle of next century. The full effects on the global climate will come later, and even if the amount of CO_2 in the atmosphere stabilises at double today's levels the International Panel on Climatic Change (IPCC) estimates that by end of the 21st century the global temperature will have increased by between 1·5 °C and 4·5 °C. And if no replacements for fossil fuel are found, the temperatures could continue to escalate.

PRE

Until recently, most climate researchers were predicting that the tropics would escape virtually all the effects of this warming. This comforting view was based on a mass of evidence from prehistoric periods, which suggested that in the past temperatures in the tropics have remained stable while the rest of the world became warmer or cooler. Some of the most persuasive of this evidence came from the last ice age, which peaked some 20 000 years ago, when the world as a whole cooled by 4 or 5 °C. As tiny changes in the Earth's orbit around the Sun reduced the amount of solar radiation that arrived, vast ice sheets crept across much of North America and northern Europe.

SPC

But according to an assessment published in 1981 by the Climate Mapping Project (CLIMAP), temperatures in the tropical ocean hardly changed during this time. The CLIMAP researchers studied the remains of microscopic shelled organisms known as foraminifera and diatoms which lay buried at the bottom of tropical oceans. They found that roughly the same species were present during the ice age as thrive there today, and from this they deduced that the ocean temperatures, too, were the same.

GCL

The more limited evidence available from around 3 million years ago—the last time the Earth was a few degrees warmer than today—led to similar conclusions. For several decades researchers have sifted through the few foram and diatom shells that have survived from this period, and like the CLIMAP scientists they deduced ocean temperatures from the distributions of the different foram species. They also examined the ratios of different isotopes of oxygen in the creatures' shells, as this is a sensitive measure of the temperature of the water they lived in.

EVN

Although the data are sparse, and the conclusions tentative, it seemed that temperatures in the equatorial regions were much the same as they are today, while the high latitudes were up to 10 °C hotter then than now.

KEY:

TTL - TITLE	GLM - GLIMPSE	PRB - PROBLEM	SET - SETTING	PRO - PROPHECY
THR - THREAT	TLI - TECHNICAL LEAD-IN	SPC - SPECIFIC CLAIM	GCL - GENERAL CLAIM	BRG - BRIDGING
EVN - EVALUATION	ONP - ONGOING PROJECT	PRE - PREDICTION	CNS - CONCERNS	SLN - SOLUTION
SGN - SUGGESTION	SUM - SUMMARY	CON - CONCLUSION	ANX - ANXIETY	SPN - SPECULATION
COL - CALL FOR COLLABORATION		REC - RECOMMENDATION		

SPC2 [EVN]

Another question is what caused global temperatures to be so warm then. Could it be that CO_2 was responsible? In the 1980s, Bob Berner from Yale University developed a method for modelling past levels of CO_2 in the atmosphere. His method used the knowledge that the process of creating new ocean floor releases CO_2 to the atmosphere, and that weathering of the land reduces atmospheric CO_2 levels. Three million years ago, the ocean floor was being created faster than it is today, and less of the Earth's surface was covered by land, so Berner deduced that there must have been more CO_2 in the atmosphere then than now. [Most scientists put two and two together and concluded that the CO_2 was the cause of the warmer temperatures—just as it is expected to be in the future.]

BRG

There was even an explanation for why tropical temperatures should have remained stable. V. Ramanathan and colleagues at the National Center for Atmospheric Research in Boulder, Colorado, reasoned that the extra water vapour that would be released by any warming of the tropical seas could have two competing effects on climate. Clouds cool the Earth by reflecting sunlight back out to space; the thicker they are, the more sunlight they reflect. But water in clouds, or water vapour free in the atmosphere, can cause warming by absorbing radiation from the Earth and trapping it, just like other greenhouse gases such as CO_2. For thin clouds the greenhouse effect tends to dominate, but at a certain cloud thickness the reflecting, cooling effect takes over.

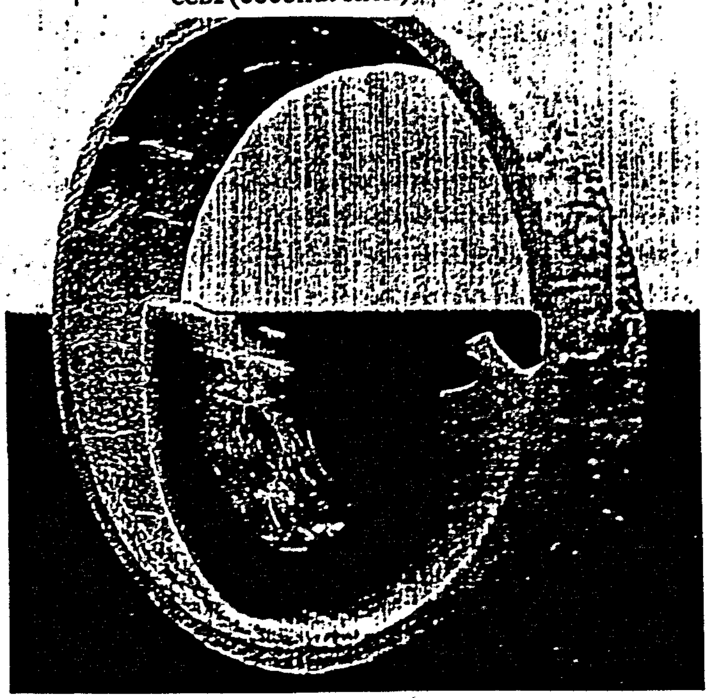
Cirrus clouds up to 16 kilometres above the tropical ocean tend to be thin, so they mainly act to warm the Earth. Ramanathan reasoned that if the tropical seas warmed, the extra heat energy would allow warm, moist air to rise higher into the atmosphere. This extra convection would cause the high-altitude cirrus clouds to thicken to the point where the reflection mode would begin to overtake the greenhouse mode, producing a net cooling rather than warming. In effect, this mechanism would act as a thermostat, preventing any large temperature swings. Because convection is much stronger in the tropics than anywhere else, this thermostat effect should be restricted mainly to tropical latitudes.

EVN

Tropical turmoil

Ramanathan's ideas have recently started to fall from favour as evidence has come in showing that warm sea surface temperatures do not tend to coincide with thick high-level clouds.

CCD2 (coconut-shell)



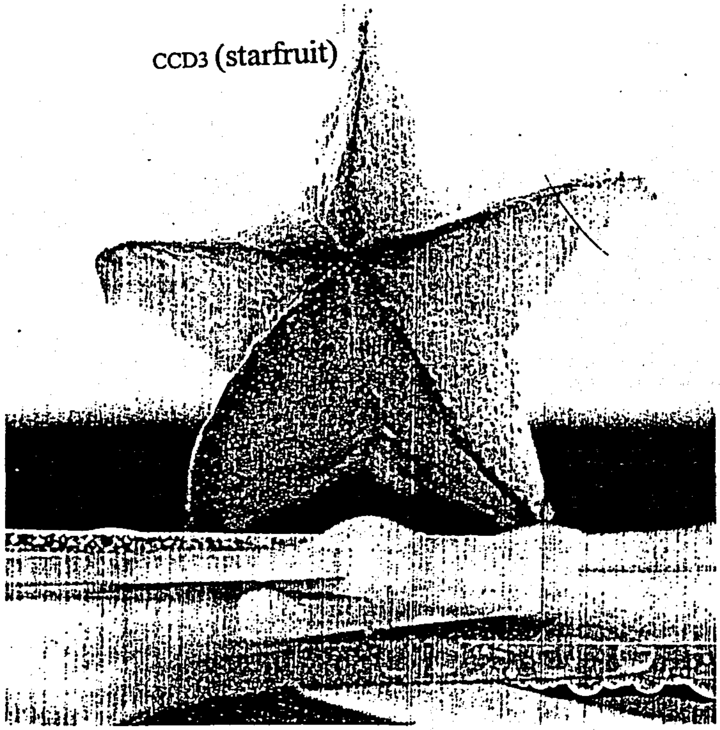
GLM

Everyone thought that the tropics would escape the dire consequences of global warming. Why have they changed their minds?

***David Rind* explains**

THE TROPICS

CCD3 (starfruit)



EVN

But at the time, everything seemed to point to stable tropical climates. This picture was perhaps all the more persuasive because it fitted well with our day-to-day perspective. Temperatures in the tropics vary little from season to season and from one day to the next. At higher latitudes, wild temperature swings are common.

But while observational studies were coming up with reassurance for the tropics, computer models were telling a different story. In particular, the computer number-crunchers suggested that as the climate started to warm, the oceans would release more water vapour into all levels of the atmosphere. Rather than acting to thicken clouds and so reflect sunlight, this additional vapour would spread itself widely and act predominantly as a greenhouse gas. This would further accentuate the warming at all latitudes, including the tropics. When the level of carbon dioxide in the model atmosphere was doubled, numerical models of the climate showed a significant tropical warming—anything from 1 °C to 4 °C. Because these models were built on rather shaky foundations—no one could be sure of the precise mechanisms associated with water vapour transport and cloud generation, for example—many researchers assumed that they must be wrong. Those scientists already convinced by the observational data that the tropics would not warm, suspected that the models were flawed and were coming up with the wrong answer.

SPC3 [EVN]

Now the balance is swinging the other way as observations of the surface air temperature come in. Data from NASA's Goddard Institute for Space Studies (GISS) in New York and the British Meteorological Office show that tropical temperatures are on the increase. The 1980s were the warmest decade on record, and this was primarily because temperatures rose in the tropics. Globally, the years 1981 to 1990 were close to 0·5 °C warmer than a century earlier, and 0·3 °C warmer than the 1951 to 1980 average. The tropical ocean temperatures were between 0·25 and 0·75 °C warmer compared with 1951 to 1980. Since 1976, the eastern tropical Pacific has been more than 0·5 °C warmer than in the previous decades. No one knows whether this change is due to global greenhouse warming, but whatever the cause, it is certain that tropical climates are not quite as unchanging as we had thought.

Ice in Hawaii

GCL

Meanwhile, the CLIMAP results are being challenged by more recent attempts to deduce conditions during the ice age. Observations at a wide range of tropical locations have revealed that glaciers crept down the mountains by some 900 metres. There is evidence of glaciation at Mauna Kea in Hawaii, for instance, where today the freezing level is hundreds of metres above the top of the mountain. Vegetation zones also crept lower as species accustomed to warmer climates migrated to lower altitudes. Evidence of past glaciation and changes in the vegetation imply that the land in the tropics chilled by 5 °C at an altitude of 3 kilometres during the last ice age.

SPC4

Last year Tom Guilderson and Rick Fairbanks of Lamont-Doherty Earth Observatory in New York State returned to the question of sea surface temperatures during the ice age. In corals, the ratios of strontium to calcium and ratios of the isotopes of oxygen are both sensitive indicators of the temperature of the sea in which the organisms lived. So Guilderson and Fairbanks sifted through coral remains from the tropical Atlantic until they found samples from the right period, then measured these ratios. Their results suggest much greater cooling than CLIMAP, more in line with the land figures.

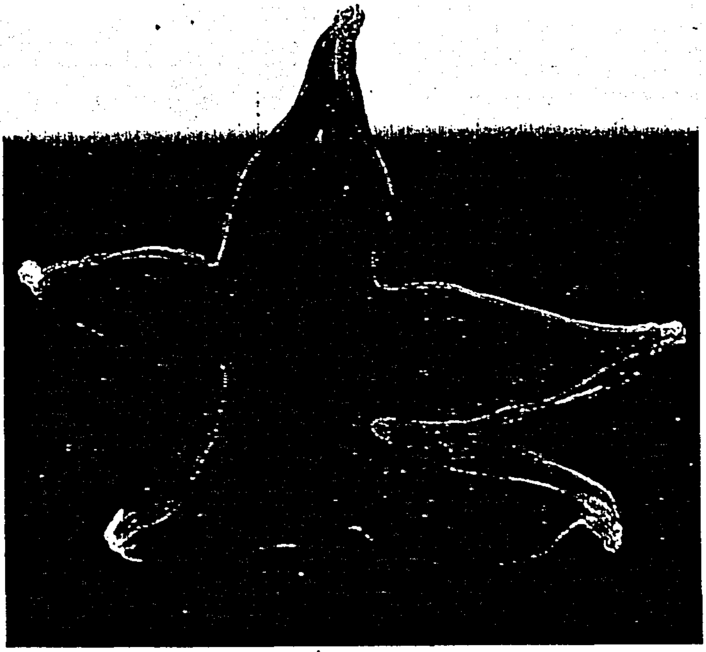
SPC5

Around the same time, Martin Stute and his colleagues, also at Lamont-Doherty Earth Observatory, looked at the amounts of the noble gases neon, argon, krypton and xenon dissolved in groundwater in the southwestern US and eastern Brazil—water that started to filter down from the surface during the last ice age. Because these gases become less soluble as the temperature rises, the quantity dissolved in the water reflects the temperature of the water as it disappeared underground. Stute and colleagues found large concentrations of noble gases, corresponding to substantial cooling of around 5 °C and

'Tropical temperatures are on the increase. It's certain that these climates are not quite as unchanging as we had thought'

CCD4 (capsicum)

SPC5 providing further evidence that the ice age affected the tropics as well as higher latitudes.



On top of these new doubts about the fate of the tropics during the ice age, questions are being raised about the stability of tropical temperature during the warmer spells too. Leaving aside suspicions about reliability of data from millions of years back, one key question is whether the climate's behaviour during past periods of warming is relevant to the future CO_2-warmed world. For one thing, it seems that CO_2 levels some 3 million years ago may not have been as high as was thought.

SPC6 Greg Rau of the University of California at Santa Cruz and Maureen Raymo of the Massachusetts Institute of Technology have used measurements of carbon isotope ratios to deduce how much CO_2 there was in the ancient atmosphere. Rau had already shown that the ratio of heavy to light isotopes of carbon in organic matter floating in the ocean seems to depend on the level of CO_2 dissolved in the water, which in turn reflects the atmospheric CO_2 level. From the carbon isotope ratios in organic matter buried in ocean sediments, the researchers concluded that the CO_2 concentration in the atmosphere 3 million years ago was probably not much higher than it is now.

SPC7 But what led to higher global temperatures in the past if not greenhouse warming caused by CO_2? A more vigorous ocean circulation than today may have been the culprit. In 1991 Mark Chandler and I published the results of modelling studies that showed how vigorous poleward ocean currents could lead to a climate that is much warmer than today's at high latitudes but unchanged at the tropics. As the oceans transported more heat to high latitudes the polar icecaps and regions of floating sea ice would melt slightly. This would reduce the amount of sunlight that the white ice reflects back to space, allowing more energy in to warm the Earth. In other words, these stronger currents would not only redistribute the warmth, they would also make the planet as a whole warmer.

'The consequences of a temperature rise in the tropics could be devastating—frequent drought, severe storms and hurricanes'

SPC8 In 1992, Raymo reported chemical signs from sediments on the North Atlantic ocean floor which support the idea that poleward currents were unusually active 3 million years ago.

SPC9 The year before, I took part in several studies analysing data on water vapour from the atmosphere gathered by the SAGE II (Stratospheric Aerosol and Gas Experiment) satellite. These found that there is more water vapour in the atmosphere over the tropical western Pacific Ocean than over the cooler tropical eastern Pacific, and that there is generally more in summer than in winter. In other words, in warmer conditions, water vapour increases in the atmosphere at all levels, exactly as computer models predicted.

SPC10 But this extra water vapour does not seem to make clouds thicker. In fact, there is even evidence that it might have the opposite effect. A study using satellite observations from the International Satellite Cloud Climatology Project, published in 1993 by George Tselioudis and colleagues from the GISS, shows that everywhere except the polar regions, low-level clouds actually become thinner as the temperature increases. One possible reason is that the extra water vapour might increase the size of the water droplets in the clouds, and thus make them more likely to precipitate as rain. Low-level clouds are usually very thick, so they act to cool the climate by reflecting solar radiation back to space. If they become thinner and less reflective as the climate warms, more sunlight will get in, and low latitudes will warm even more.

EVN [CNS] It is results such as these that are leading many researchers to abandon the idea that the tropics are not affected by global climate change. Instead they are coming to the conclusion that the computer models may have been right all along about tropical warming. In fact, the models may have underestimated it. [The consequences of a rise in temperature in the tropics could be devastating. As land and air temperatures increase, the atmosphere can hold more moisture. In tropical regions, an increase of 4 °C in air temperature means that around 30 per cent more moisture can be evaporated from the ground. The oceans warm more slowly, because their heat capacity is much greater, so the increase in evaporation from the warming ocean is much less. Computer models show that a 4 °C rise in global air temperature would lead to a 12 per cent increase in evaporation. The oceans provide the water for most of the planet's rain, so this leads to a similar increase in global precipitation. However, a 12 per cent increase in rainfall would not be enough to make good the attempt by the land to lose 30 per cent more of its water by evaporation, so the land would dry out, especially at low and subtropical latitudes. In 1990, I took part in several studies that modelled climate change during the next century. These concluded that a 2 °C increase in global temperature would bring frequent severe droughts to tropical and subtropical locations where such droughts now occur only 5 per cent of the time. A 4 °C warming would bring frequent droughts to middle latitudes as well, and arid climates would extend about 35° north and south of the equator.

EVN

Food shortages

Even though increased CO_2 levels can fertilise crops, the net effect of increased CO_2 and increased temperature would cause a 10 per cent decline in the production of wheat, maize, soya beans and rice in developing countries, according to a study published last year in *Nature* by Cynthia Rosenzweig from the GISS and Martin Parry from Oxford University. Estimates for the numbers of people who in 2060 will be affected by famine due to climate change range from 50 million to as many as 350 million. This is in addition to a baseline population at risk of hunger, which will already have been swelled by population growth to some 640 million.

PRE

Significant tropical warming would also bring increased hazards from severe storms and hurricanes, which feed on the energy unleashed as water vapour from warm oceans condenses into rain. A multitude of factors influence hurricane development, including temperature, wind and moisture, which make it impossible to predict how climate change will affect the pattern of hurricanes. But since tropical storms appear to form only at temperatures above 26 °C, it seems likely that warmer seas will fuel more of them and that they will be more intense.

Another unknown is the effect of global warming on El Niño, the erratic reversal of the warm currents in the Pacific Ocean. El Niño events can cause climate chaos round the world, and are unpredictable at the best of times (see "El Niño goes critical", *New Scientist*, 4 February). This year El Niño appeared for a record fifth year running, and the suspicion is creeping in that climate is already changing. Neither day-to-day experience, nor the prehistoric climate record, nor even our best climate models can tell us what the outcome will be.

PRE

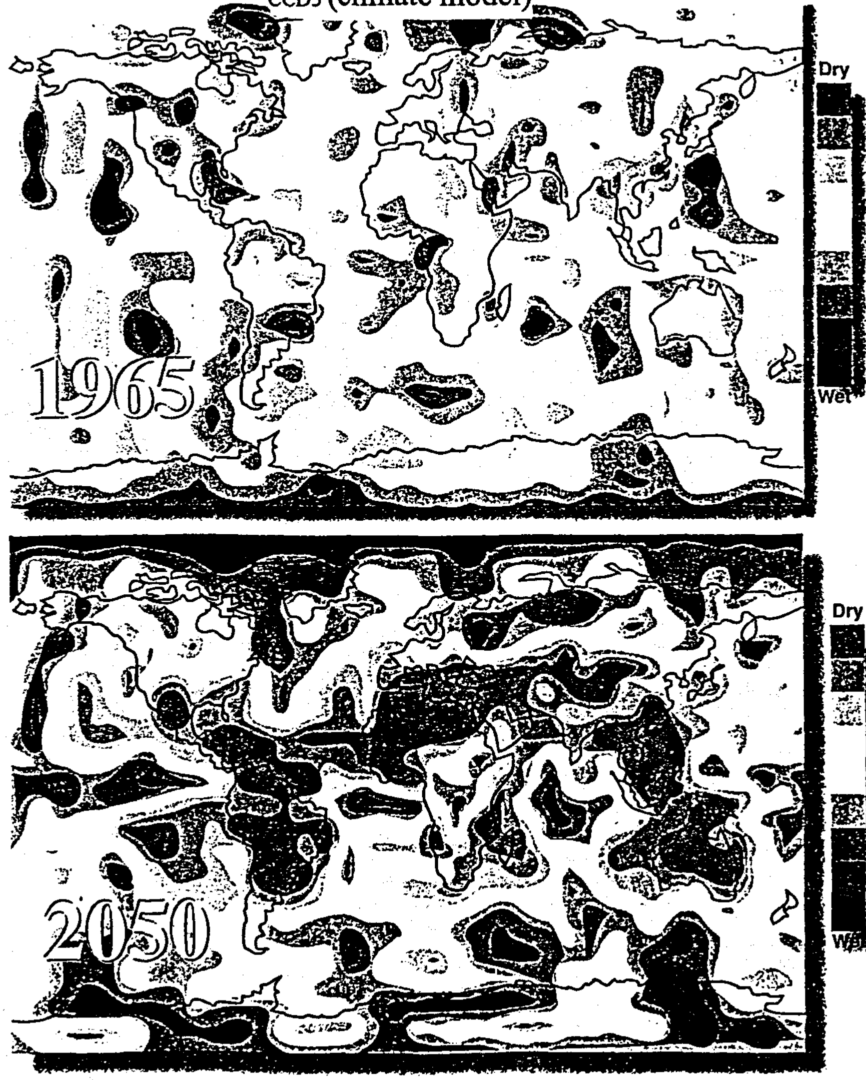
So it is vital that we keep track of tropical temperatures and watch how they change. Surface temperatures are being monitored around the world, and satellites can now provide a global picture of temperature change at different levels in the atmosphere. The planet is likely to be slow to warm, but once warmed is likely to be difficult to cool. It would be wise to bear this in mind when deciding how we should curb our emissions of greenhouse gases.

COL

By the time the alarm bells are clearly heard, it may well be too late for rescue. □

ANX

CCD5 (climate model)



Climate chaos: model predictions for the increases in drought and flood conditions due to greenhouse gas emissions, for 1965 and 2050. By 2050, with a temperature rise of 4 °C, severe droughts (red) would become frequent in the tropics and middle latitudes

David Rind is a climate research scientist at NASA's Goddard Institute for Space Studies in New York.