AT

P/A.

Mr A Turnbull
PPS/PM

From: Chief Medical Officer

Date: 21 April 1989

You will know best whether the Prime Minister would find this succinct and, I believe, accurate piece on the "Greenhouse" helpful.

Donald Acheson

E D ACHESON
Department of Health
Room 109, Richmond House
79 Whitehall
01-210 5150

THE LANCET

Health in the Greenhouse

As a result of man's industrial activities, several changes are likely to occur in the global atmosphere in the coming decades. The magnitude of these changes is a function of the world population, the increasing demand for energy, and the burning of forests to free land for cultivation. The rate of change is the subject of much debate, the chief uncertainties being related to the ability of oceans to absorb carbon dioxide, the effect of increased cloud cover, and the destabilising effects of increasing moisture, melting ice caps, and ocean currents altering course.[1] Most computer models predict a global temperature increase of between 1·5 and 4·5°C by the middle of the next century, with maximum changes occurring at the Poles.[2] The impact on world ecosystems will be enormous, because world temperatures have changed by only 4°C since the last ice age. At the very least, there will be substantial shifts in biomass, food production, and the distribution of terrestrial species.[3] At the worst, global ecosystems will be unable to adapt to a rapidly changing climate, world food production will collapse, and coastal areas will be inundated by rapidly rising sea levels. Such end-of-the-world sketches are familiar, usually in relation to AIDS or nuclear war, but there is an inevitability about global warming, which stems not from human behaviour or human error but from the radiative properties of atmospheric releases and the fundamental laws of physical science.

The sun emits most of its energy between 0·2 and 4 μm, covering the ultraviolet, visible, and near infrared regions of the electromagnetic spectrum. 20% of this energy is absorbed by the atmosphere, 50% is absorbed by and warms the earth's surface, and 30% is reflected back into space.[4] Because the earth is vastly colder than the sun, the energy emitted from the surface of the planet lies in the thermal infrared region of the electromagnetic spectrum (4–50 μm). Much of this energy is trapped by the earth's atmosphere, by carbon dioxide and by water vapour, so raising the surface temperature of the earth from well below zero to about 13°C. In this context, warming of the lower atmosphere (troposphere) is not only beneficial but also essential for the maintenance of life on the planet.

The greenhouse problem has emerged because carbon dioxide concentrations have risen from a pre-industrial level of 280 ppm to 350 ppm, and because other gases of anthropogenic origin are extremely efficient absorbers of thermal infrared radiation.[5] Some of the chemicals that cause stratospheric ozone depletion—eg, chlorofluorocarbons (CFCs) 11, 12, and 113—can effect a warming more than 10 000 times greater than that produced by carbon dioxide on a molecule for molecule basis. Because their atmospheric concentrations are low, their overall greenhouse warming potential is less than that of carbon dioxide. Even so, without an international agreement to limit production, CFCs are predicted to increase the global warming effect of carbon dioxide by 50% in the year 2030.[6]

The contributions of other greenhouse gases, as a percentage of carbon dioxide warming, are methane 20%, nitrous oxide 14%, and tropospheric ozone 9%. Increasing methane levels result mainly from enteric fermentation in cattle and biological decay in wetland areas. Permafrost holds enormous quantities of methane which could be released by global warming with potentially catastrophic results.[8] Nitrous oxide and tropospheric ozone are also derived from several sources, man-made contributions being related mainly to energy production and transport. Ozone is especially interesting because its formation in the lower atmosphere is a photochemical reaction whose rate will increase as stratospheric ozone declines. Thus, CFCs compound the greenhouse effect both directly and indirectly. Moreover, increased penetration of ultraviolet light into the surface of the oceans will adversely affect plankton populations and may interfere with an important sink for carbon

1. Broecker W. Unpleasant surprises in the greenhouse. *Nature* 1987; **328:** 123–26.
2. Hansen J, Fung I, Lacis A, et al. Global climate changes as forecast by Goddard Institute for Space Studies three dimensional model. *J Geophys Res* 1988; **93:** 9341–64.
3. Emanuel W, Scheugert H, Stephenson M. Climatic change and the broad scale distribution of terrestrial ecosystem complexes. *Climatic Change* 1985; **7:** 9–43.
4. Shine K. The Greenhouse effect. In: Russell Jones R, Wigley T, eds. Ozone depletion—health and environmental consequences. Chichester: John Wiley and Sons, 1989.
5. Dickinson R, Cicerone R. Future global warming from atmospheric trace gases. *Nature* 1986; **319:** 109–15.
6. Wigley T. Future CFC concentrations under the Montreal Protocol and their greenhouse-effect implications. *Nature* 1988; **335:** 333–35.
7. Ramanathan V, Cicerone R, Singh H, Kiehl J. Trace gas trends and their potential role in climate change. *J Geophys Res* 1985; **90:** 5547–66.
8. Cicerone R. Greenhouse effect—methane linked to warming. *Nature* 1988; **334:** 198.

dioxide.[9] Finally, warming of the troposphere will be associated with a cooler stratosphere, so creating meteorological conditions ideal for the catalytic destruction of ozone. The rapidity with which ozone disappears each year in Antarctica has been attributed to increased formation of polar stratospheric clouds and the heterogeneous chemical reactions that take place on the surface of ice crystals.

Nobody knows how widespread such processes might become; nobody really knows how much more chlorine loading the atmosphere can withstand. The only certainty among atmospheric physicists is that global warming and stratospheric ozone depletion will interact to destabilise the atmosphere in unpredictable ways, and that a total phase-out of CFCs is not merely desirable but an absolute and urgent requirement for any strategy to combat climatic change. Most scientists would like to see the Montreal protocol widened to include substitutes such as HCFC 22, since its desirability as a chemical with low ozone-depleting potential is offset by its potency as a greenhouse gas. If uncontrolled, HCFC 22 will be adding 15% to the global warming effect of carbon dioxide by the year 2030.[4] Similar, if less immediate, considerations apply to HFC 134a, industry's favoured substitute for fridges and cooling systems, which could add 15 or 20% by the end of the next century if emissions are uncontrolled.[4]

Whilst research into atmospheric chemistry continues, it is important to consider what might happen at ground level. Much has been written about the effects of stratospheric ozone depletion,[10-13] but the implications for human health of global warming have received less attention. Temperature extremes will become more frequent and diseases caused by lack of sanitation will accompany widespread flooding.[14] Global warming, increased ultraviolet flux, and higher levels of tropospheric ozone will reduce crop production, with potentially devastating effects on world food supplies.[9,14] Malnutrition might then become commonplace, even among developed nations, and armed conflicts would be more likely as countries compete for a dwindling supply of natural resources. Diseases hitherto confined to the tropics may spread to higher latitudes as global temperatures increase, and vector-borne diseases will become more widespread, either because the vector can survive at higher latitudes or because the parasite requires a minimum temperature to complete its life cycle. Malarial parasites, for example, require temperatures of at least 15–18°C to complete their development within mosquitoes. Temperature increases will lengthen the breeding season, and survival rates for the *Anopheles* species, flooding will provide areas of stagnant water ideal for breeding, and malaria could again become prevalent in European countries.[14] A global analysis of all temperature-dependent diseases has yet to be undertaken, but in North America the US Environmental Protection Agency has pinpointed four vector-borne diseases, apart from malaria, that are predicted to increase in prevalence and extent—Lyme disease, Rocky Mountain spotted fever, dengue fever, and arbovirus-related encephalitis.

Such changes in disease distribution are difficult to quantify with any certainty, but the message for decision makers is clear. Action to combat global warming must not be allowed to await the results of further research. Remedial measures are needed now. Already this decade has produced six of the warmest years this century. Moreover, the lag effect as a result of the thermal inertia of oceans means that we are already committed to a further 0·5°C of warming, even if carbon dioxide is held at its present level. Any strategy to combat global warming must be conducted on a global scale and is bound to involve enormous investment in energy conservation, re-aforestation, renewable sources of energy, and changing patterns of agriculture and transportation. This approach will require a new agenda for world leaders, a new role for the United Nations Environment Programme, and a new awareness of man's fundamental reliance on the integrity of world ecosystems. The expense may be considerable, but the cost of doing nothing is incalculable.

9. Worrest R. Effects of ultraviolet-B radiation on terrestrial plants and marine organisms. In: Russell Jones R, Wigley T, eds. Ozone depletion—health and environmental consequences. Chichester: John Wiley and Sons, 1989.
10. Environmental Protection Agency. Assessing the risks of trace gases that can modify the atmosphere. Washington, D.C.: US Environmental Protection Agency, 1987.
11. Russell Jones R. Ozone depletion and cancer risk. *Lancet* 1987; ii: 443–46.
12. Mackie R, Rycroft M. Health and the ozone layer. *Br Med J* 1988; **297:** 369–70.
13. Russell Jones R. The health effects of stratospheric ozone depletion. In: Russell Jones R, Wiley T, eds. Ozone depletion—health and environmental consequences. Chichester: John Wiley and Sons, 1989.
14. Grant L. Health effect issues associated with regional and global air pollution problems. Paper presented to conference on The Changing Atmosphere—Implications for Global Security, Toronto, Canada, 1988.

Alternatives to Growth Hormone

THE availability of human growth hormone (HGH) manufactured by recombinant DNA technology has led to renewed interest in the problems of children with short stature—at least three proceedings of symposia have been published in the past two years.[1-3] Although HGH is now available in potentially unlimited quantities, exploration of alternative modes of therapy continues, not least because of the very high cost of biosynthetic HGH.

All studies of growth hormone or of alternative agents are complicated by the considerable genetic

1. Flodh H, ed. Progress in clinical research on recombinant human growth hormones. *Acta Paediatr Scand* 1987; **331** (suppl).
2. Flodh H, ed. Diagnosis and treatment of impaired growth hormone secretion. *Acta Paediatr Scand* 1987; **337** (suppl).
3. Chatelain P, Gunnarson R, eds. Growth and growth disorders. *Acta Paediatr Scand* 1988; **343** (suppl).

ANNEX A

SCIENTIFIC AMERICAN April 1989 Volume 260 Number 4

Global Climatic Change

Evidence suggests that production of carbon dioxide and methane from human activities has already begun to change the climate and that radical steps must be taken to halt any further change

by Richard A. Houghton and George M. Woodwell

The world is warming. Climatic zones are shifting. Glaciers are melting. Sea level is rising. These are not hypothetical events from a science-fiction movie; these changes and others are already taking place, and we expect them to accelerate over the next years as the amounts of carbon dioxide, methane and other trace gases accumulating in the atmosphere through human activities increase.

acceleration

The warming, rapid now, may become even more rapid as a result of the warming itself, and it will continue into the indefinite future unless we take deliberate steps to slow or stop it. Those steps are large and apparently difficult: a 50 percent reduction in the global consumption of fossil fuels, a halting of deforestation, a massive program of reforestation.

There is little choice. A rapid and continuous warming will not only be destructive to agriculture but also lead to the widespread death of forest trees, uncertainty in water supplies and the flooding of coastal areas. When the ice now covering the Arctic Ocean melts, further unpredictable changes in the global climate will ensue. There may be controversy over whether the data are adequate and whether the warming is caused by changes in the atmosphere. Yet there is an unusually powerful consensus among climatologists that the dominant influence on global climate over the next centuries will be a warming driven by the accumulation of heat-trapping gases. The consequences are threatening enough so that many scientists, citizens and even political leaders are urging immediate action to halt the warming.

RICHARD A. HOUGHTON and GEORGE M. WOODWELL have collaborated for more than 20 years on topics of environmental concern. Houghton is an ecologist and a senior scientist at the Woods Hole Research Center in Woods Hole, Mass. For the past 10 years he has been concerned with the global carbon cycle and has specialized in the response of ecosystems, particularly forests, to climatic change. Woodwell is also an ecologist and is the director of the Woods Hole Research Center. He and Houghton hope to be able, along with their Woods Hole colleagues, to advance improved models for the management of renewable resources.

The fact that heat-trapping gases have been accumulating in the atmosphere is well established. Since the middle of the 19th century the amount of atmospheric carbon dioxide has increased by about 25 percent. The increase has come about because human activities, especially the burning of coal and oil and the destruction of forests, have released greater quantities of carbon dioxide into the atmosphere than have been removed by diffusion into the oceans or by photosynthesis on land [*see illustration on page 38*].

The increase in carbon dioxide appears trifling when one considers that the total amount in the atmosphere is a little more than .03 percent by volume. But in spite of its low concentration, carbon dioxide and several other gases present in even smaller amounts have an important role in determining the temperature of the earth. In contrast to both nitrogen and oxygen, which together make up more than 99 percent of the atmosphere, these trace gases absorb infrared radiation, or radiant heat. Since in this regard they act much like the glass over a greenhouse, they are commonly referred to as greenhouse gases.

Because the total amount of greenhouse gases is small, their concentrations are easily changed. An increase in the concentration of any one of them increases the atmosphere's capacity to retain heat and raises the temperature at which the atmosphere comes into equilibrium with the energy it receives from the sun. In recent years investigators have recognized that the atmospheric burden of greenhouse gases other than carbon dioxide, such as methane (CH_4), nitrous oxide (N_2O) and the chlorofluorocarbons (CFC's), is also growing at an increasing rate. By the mid-1980's, in fact, these gases had reached levels at which their combined effect approached that of carbon dioxide.

In this article we emphasize the role of carbon dioxide and methane because they are the principal contributors to the current warming, because their concentrations are strongly influenced by biological processes and because slowing or stopping the global warming will require control of carbon dioxide emissions in particular.

Global warming due to the accumulation of heat-trapping gases, particularly carbon dioxide, was predicted at the turn of the century by Svante Arrhenius in Sweden and Thomas C. Chamberlin in the U.S. Systematic research on the atmospheric accumulasequences of a known virus. The discoveries suggest that the virus, or one related to it, could play a role in the disease. If it does, workers might have a target at which to aim new therapeutic strategies.

One report comes from E. Premkumar Reddy, Hilary Koprowski and their colleagues at the Wistar Institute of Anatomy and Biology in Philadelphia and Magnhild Sandberg-Wollheim of the University of Lund in Sweden. They reported in 1985 that some MS patients have antibodies that react with HTLV-I (human *T*-lymphotropic virus type I)—a meager clue. Early this year they presented in *Science* direct evidence of a virus: by means of a powerful technique that amplifies known DNA sequences they detected HTLV-I-like sequences in blood samples taken from a series of six Swedish MS patients. Only one out of 20 healthy people had the sequences. Koprowski says that "the association [between virus sequences and MS] is very strong." He believes the viral sequences in MS patients might be from HTLV-I itself or from a related virus.

The other report is the work of Steven J. Greenberg of the National Cancer Institute and Bernard J. Poiesz and Garth D. Ehrlich of the State University of New York Health Science Center at Syracuse. They say they will publish their results soon in *Proceedings of the National Academy of Sciences.* These workers also amplified DNA to search for several fragments of HTLV-I-like DNA. Greenberg's group found one of the fragments in blood from six out of 21 MS patients but not in blood from 35 healthy people. (Two other fragments they searched for could not be found either in the patients or in healthy people; a third fragment was found in every sample tested.) Thomas A. Waldmann, one of the investigators at the NIC, says the results lead him and his colleagues to believe "a novel human retrovirus related to but distinct from HTLV-I might be present in some cases of MS."

Circumstantial evidence also seems to strengthen the case: HTLV-I is known to cause at least one other degenerative disease of the nervous system and one form of leukemia. Other viruses of the same general type, the retroviruses, cause slow-acting diseases in animals as well as AIDS in human beings.

Neither group contends that a virus is the single cause of MS. Dale E. McFarlin of the National Institute of Neurological and Communicative Diseases and Stroke agrees: he observes that MS is commonest in northern regions where HTLV-I is rare. He concl[illegible] it is unlikely that HTLV-I alone causes MS. One theory is that the sequences might represent a viral accomplice that is activated when another agent triggers an immune reaction; the immune reaction might then turn against the patient.

There are other sources of doubt. McFarlin points out that the DNA-amplification technique is so sensitive that the most careful workers could easily contaminate samples and thereby produce invalid results. Furthermore, a disease called tropical spastic paraparesis caused by HTLV-I is hard to distinguish from the type of MS studied by Greenberg's team.

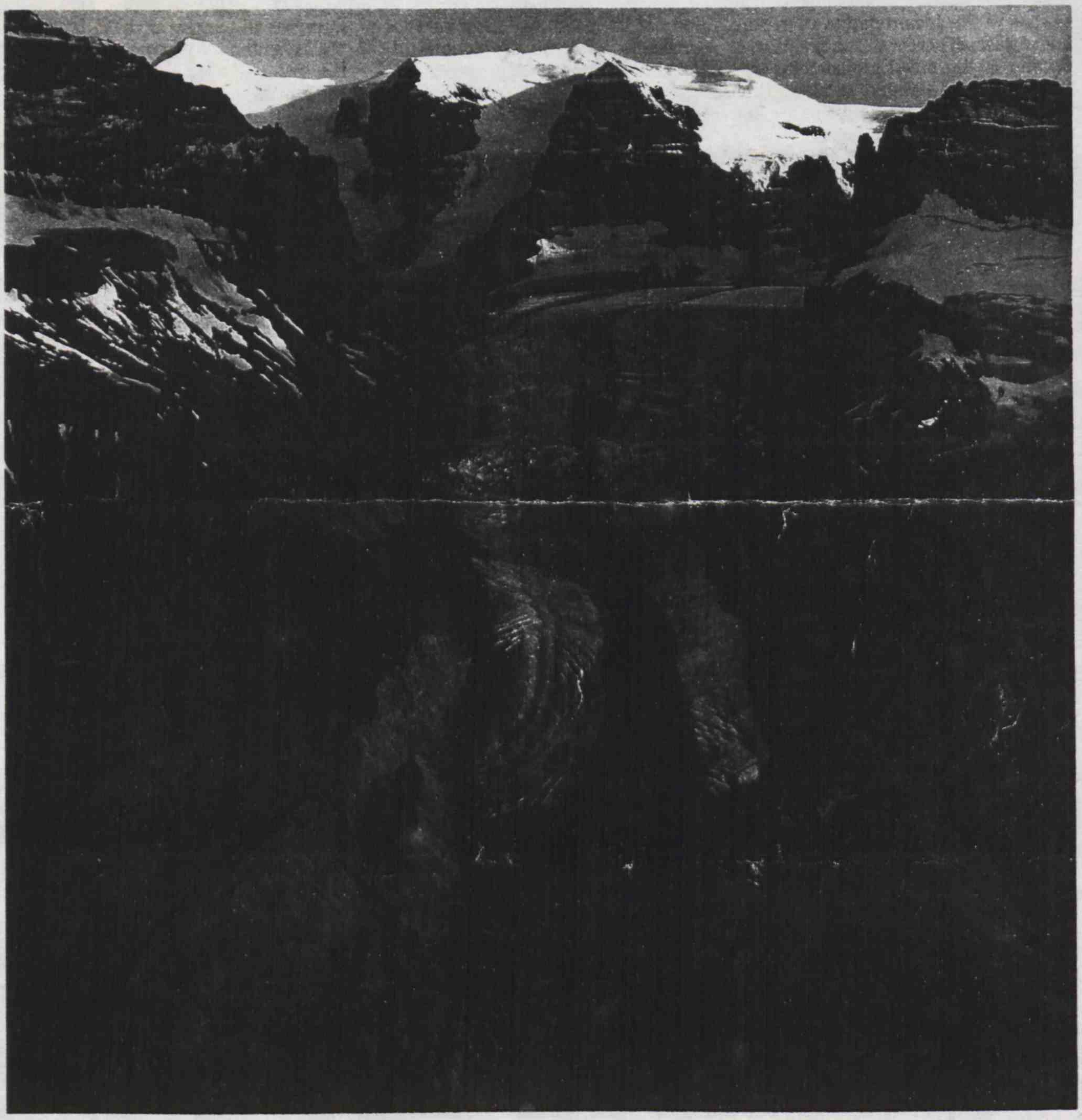
The knowledge that 20 different viruses have been implicated in MS over the years (three of them by Koprowski) further tempers the excitement, as does the fact that retroviral fragments are common in human DNA. Byron H. Waksman of the National Multiple Sclerosis Society points out that normal human genetic material contains genetic fragments from at least five families of retroviruses.

Nevertheless, these new findings mean the pursuit has once again been joined; this time the quarry, and perhaps hope for MS patients, may prove less elusive. —*T.M.B.*

tion of carbon dioxide began only in 1958. Since then Charles D. Keeling of the Scripps Institution of Oceanography has provided a continuous record of the carbon dioxide level at various stations, the best-known of which is at Mauna Loa in the Hawaiian Islands [*see illustration on page 39*].

Information on the earth's temperature has been more difficult to accumulate. Strong evidence for global warming became available by late 1988. The most direct evidence lies in temperature records from around the world. James E. Hansen of the National Aeronautics and Space Administration's Goddard Institute of Space Studies and his colleagues have analyzed temperature records going back to 1860. Their analyses suggest that the average global temperature has increased by from .5 to .7 degree Celsius since that year. The greatest increase has taken place in the past decade; this recent warming is both statistically significant and consistent with their experience based on theory and on models of the global climatic system.

Thomas M. L. Wigley and his colleagues, working independently at the University of East Anglia in England, have also shown the increase in average global temperature. The rise has



HOLE-IN-THE-WALL GLACIER in Wrangell-St. Elias National Park, Alaska, is shown in an aerial view. The exposed ground at the foot of the glacier exhibits striations and moraines, the piles of debris left by a moving glacier; the ground has not had time to grow vegetation. All these are signs of recent glacial retreat. Similar behavior of a number of glaciers around the world (*see illustration on page 41*), the increasing depth to permafrost and other data suggest that warming has continued since the last glacial period. Its cause, however, extending back long before the current buildup of greenhouse gases, remains a puzzle.

not been observed in all regions: a recent analysis of climate records by Kirby Hanson and his colleagues at the National Oceanic and Atmospheric Administration shows no trend in temperature for the contiguous U.S. Such regional variation is not unexpected; the contiguous U.S. covers only 1.5 percent of the globe's surface.

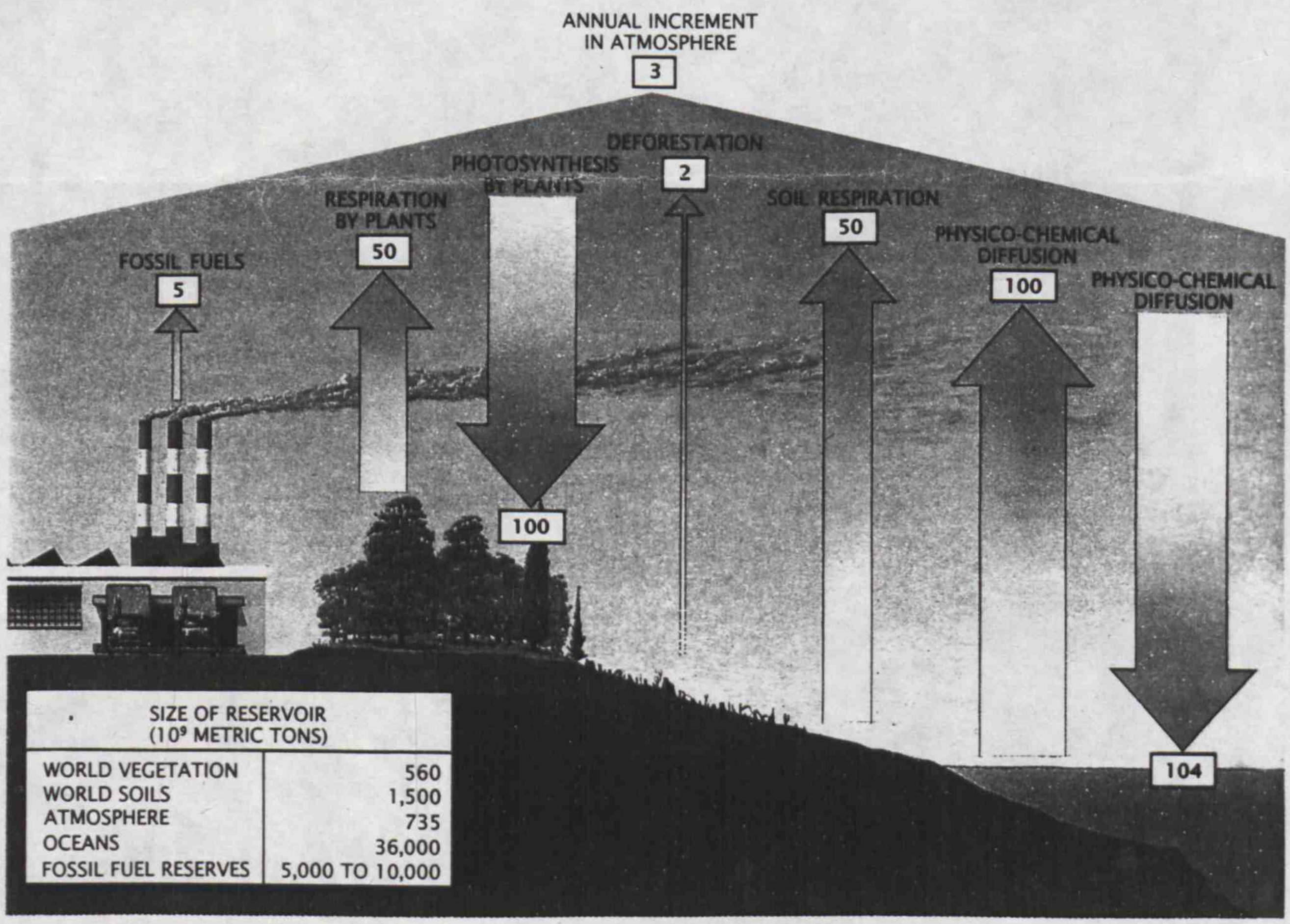
The observed rise in global temperature has not been steady and is clearly not simply a response to the accumulation of greenhouse gases. There was, for example, a decline in the mean global temperature between 1940 and 1965 in spite of the continued increase of heat-trapping gases in the atmosphere. Nevertheless, Phil D. Jones, one of Wigley's collaborators, has just recently reported that the global temperature has risen about .5 degree C since the beginning of the century and that the six warmest years on record were 1988, 1987, 1983, 1981, 1980 and 1986 in that order.

If a .5-degree temperature change seems insubstantial, one should remember that in 1816, the "year without a summer," the mean global temperature drop was also less than one degree. It was nonetheless sufficient to cause frosts in June in New England and widespread crop failures [see "The Year without a Summer," by Henry Stommel and Elizabeth Stommel; SCIENTIFIC AMERICAN, June, 1979]. The heat and drought that have afflicted North America and other regions of the earth in recent years are consistent with the predictions of a global warming trend.

There are other indications of an accelerated warming. According to Arthur H. Lachenbruch and B. Vaughn Marshall of the U.S. Geological Survey, the depth to permafrost in the Alaskan and Canadian Arctic has increased in recent decades. The average temperature of Canadian lakes has increased; the annual maximum extent of sea ice surrounding the Antarctic continent and in the Arctic seas appears to be declining; in glaciers throughout Europe and elsewhere have receded.

These observations are consistent with predictions made by climatologists on the basis of theory aided by general circulation models. Several such global models exist and, although analyses based on them do not agree in detail, the general predictions are consistent with theory and experience. Climatologists expect that the greatest warming will occur at higher latitudes in winter. In these latitudes the warming, according to the models, will probably be at least twice the global average. In addition it is expected that the upper atmosphere will cool as the lower atmosphere warms and that there will be less precipitation and less moisture in the soil at lower latitudes. All these trends have been reported in recent years.

Data such as those are always open to further analyses, interpretation and augmentation. They invariably appear to suffer from inadequacies of



SIZE OF RESERVOIR (10^9 METRIC TONS)	
WORLD VEGETATION	560
WORLD SOILS	1,500
ATMOSPHERE	735
OCEANS	36,000
FOSSIL FUEL RESERVES	5,000 TO 10,000

ANNUAL CARBON FLUXES are shown in units of one billion (10^9) metric tons. Photosynthesis on land removes about 100 billion tons of carbon from the atmosphere annually in the form of carbon dioxide. Plant and soil respiration each return about 50 billion tons. Fossil-fuel burning and deforestation release into the atmosphere respectively about five and two billion tons. Physicochemical processes at the sea surface release about 100 billion tons into the atmosphere and absorb about 104. The net atmospheric gain is about three billion tons annually. The table lists the world's major carbon reservoirs.

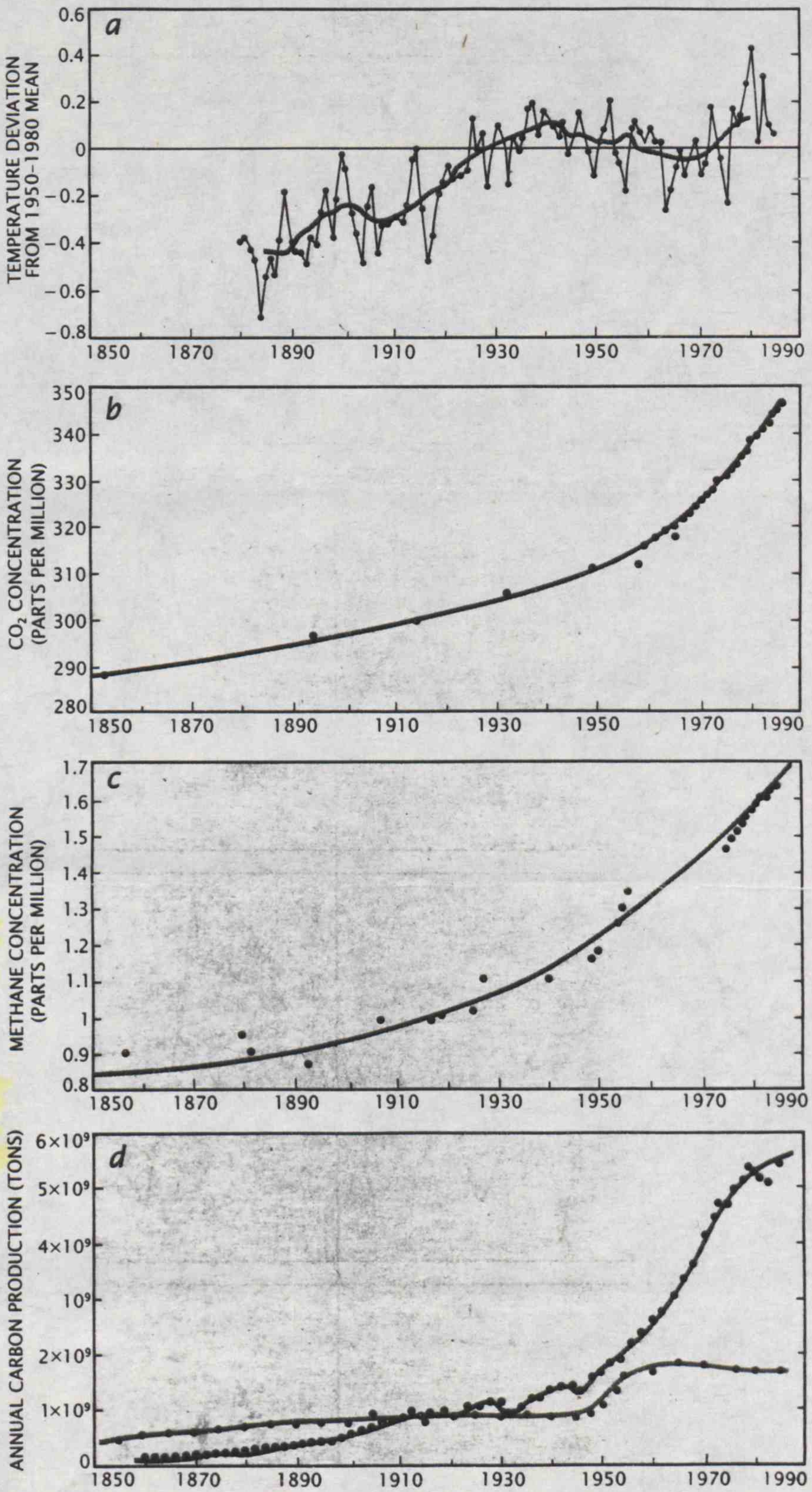
measurement and uncertainties about whether the period over which the measurements were taken was long enough to be significant. Investigators are currently improving the data and the analyses, but the fact remains that the observations described above, taken together with the rising concentration of greenhouse gases, constitute strong evidence that the process anticipated nearly a century ago by Arrhenius is under way.

One can learn much about potential future changes in climate by examining past climatic change. A mere 15,000 years ago glaciers covered much of North America and northern Europe. Were changes in the composition of the atmosphere involved in the great climate swings that brought glacial and interglacial periods? The answer is not completely clear, but one of the most important advances in recent years has been the ability to determine atmospheric composition in previous eras from tiny samples of air trapped in glacial ice. In particular, determination of the atmospheric composition during periods of glacial expansion and retreat has been made possible by data obtained from an ice core drilled by a joint French-Soviet team at the Antarctic Vostok station.

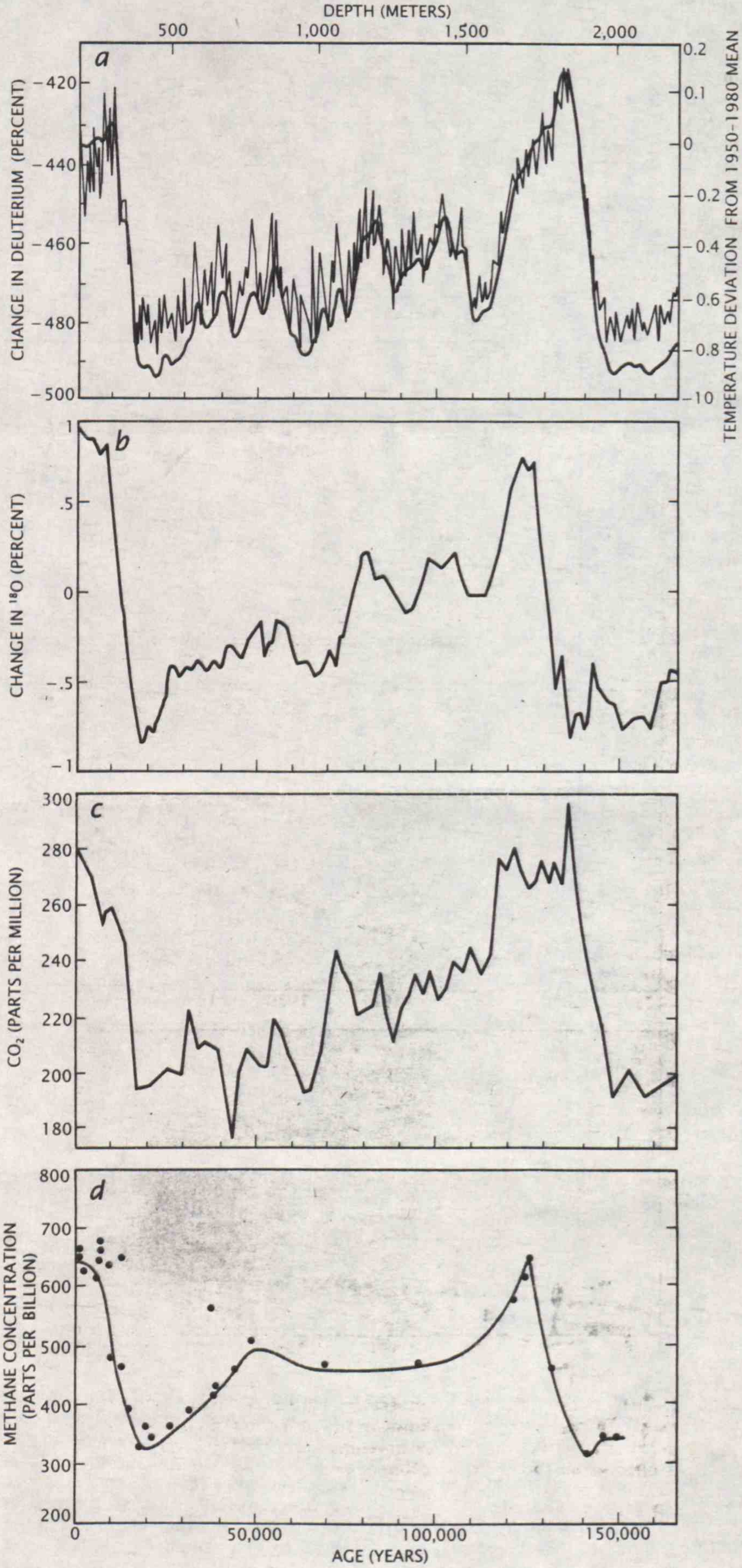
The Vostok core, as it is called, was 2,000 meters in length, long enough to sample ice dating through the past 160,000 years [*see illustration on next page*]. The data show fluctuations in temperature of up to 10 degrees; such fluctuations are derived from changes in the isotopic ratios in the core. It is well established, for example, that the ratio of the two common isotopes of oxygen, ^{18}O and ^{16}O, in cores of marine sediments reflects past temperature changes.

The Vostok data also show how the abundances of atmospheric gases have fluctuated with temperature over the past 160,000 years: the higher the temperature, the greater the concentration of carbon dioxide and vice versa. To be sure, the correlation of carbon dioxide with temperature does not establish whether changes in atmospheric composition caused the warming and cooling trends or were caused by them. Although the carbon dioxide content follows temperature very closely during periods of deglaciation, it apparently lags behind temperature during periods of cooling.

Although there is tight statistical coupling between carbon dioxide and temperature throughout the record, the temperature changes are from five



CORRELATION among the global temperature change, level of heat-trapping gases and carbon dioxide emissions is shown in the first three graphs for the past 140 years. In graph *a* both the annual mean temperature (*spiky curve*) and the five-year running mean (*smooth curve*) are plotted. Graphs *b* and *c* show the atmospheric carbon dioxide and methane content respectively. Pre-1958 data come from analyses of air trapped in bubbles of glacial ice from various sites around the world. The annual production of carbon from fossil-fuel burning (*black*) and from change in land use (*color*) is shown in *d;* the last data were obtained from historical sources.



to 14 times greater than would be expected on the basis of the radiative properties of carbon dioxide alone. This relation suggests that quite aside from changes in greenhouse gases, certain positive feedbacks are amplifying the response. Such feedbacks might involve ice on land and sea, clouds or water vapor, which also absorb radiant heat.

Other data from the same Vostok core sample show that methane also closely follows temperature and carbon dioxide. The methane concentration nearly doubled, for example, between the peak of the penultimate glacial period and the following interglacial period. Within the present interglacial period it has more than doubled in just the past 300 years and is rising rapidly. Although the concentration of atmospheric methane is more than two orders of magnitude lower than that of carbon dioxide, it cannot be ignored: the radiative properties of methane make it 20 times more effective molecule for molecule than carbon dioxide in absorbing radiant heat. On the basis of Hansen's radiative-convective model, which includes chemical feedbacks, methane appears to have been about 25 percent as important as carbon dioxide in the warming that took place during the most recent glacial retreat 8,000 to 10,000 years ago.

How can a global rise in temperature be expected to cause greater releases of carbon dioxide and methane into the atmosphere? In the process of photosynthe-

VOSTOK ICE-CORE DATA reveal a correlation between certain gas concentrations and temperature over the past 160,000 years. The ice core, 2,200 meters long, contains bubbles of air with carbon dioxide and methane that were trapped at different depths (*top scale*) and hence at different times (*bottom scale*). Several independent methods have established that the deuterium concentration in ice is a good measure of past temperature; both temperature and deuterium level are plotted in *a*. More traditional is the use of the oxygen isotope ^{18}O to track temperature; curve *b* is almost identical with *a*. The remarkable agreement with the shape of the Vostok-station carbon dioxide curve *c* argues that carbon dioxide can also serve as a global thermometer. Data on Antarctic methane compiled in 1985 and 1986 from several stations (*d*) strengthens the conclusion that levels of greenhouse gases are positively correlated with temperature and may actually influence it.

sis terrestrial plants remove about 100 billion tons of carbon from the atmosphere per year, or about 14 percent of the total atmospheric carbon content. An approximately equal amount of carbon is returned to the atmosphere through the processes of plant respiration and decay of organic matter. Because the fluxes are a substantial fraction of the carbon dioxide already in the atmosphere at any time, a change of a few percent in either the photosynthetic or the respiratory flux would soon significantly alter the atmospheric carbon dioxide content. Will global warming produce such an imbalance?

The answer is unclear and probably will remain so until after the climate has changed considerably more than it has already. Nevertheless, the general picture is probably as follows. The rate of photosynthesis is affected by many factors, particularly the availability of light, water and nutrients. It is not, however, very sensitive to temperature change. The rates of plant respiration and decay, on the other hand, do strongly depend on the temperature. A one-degree temperature change in either direction often alters rates of plant respiration by from 10 to 30 percent.

These observations suggest that a global warming will speed the decay of organic matter without appreciably changing the rate of photosynthesis. That will increase the release of carbon dioxide into the atmosphere. A warming will also result in more methane, because methane is produced by respiration in regions where oxygen is not freely available, such as swamps, bogs and moist soils. In recent years there has been a rise in the concentration of atmospheric methane of more than 1 percent per year. The increase is both rapid and significant because, as noted above, methane is 20 times as effective as carbon dioxide in trapping heat. The wet soils where methane is produced as a result of anaerobic decay probably represent the world's major source of methane. The global warming that has already occurred has undoubtedly stimulated anaerobic decay and the production of methane as well as carbon dioxide.

It is possible to estimate the size of the resulting increase in carbon production at least crudely. A significant fraction (from 20 to 30 percent) of global respiration on land takes place in the forest and tundra of the middle and high latitudes, where the warming is expected to be greatest. If we assume that the mean global warming to date has been .5 degree C, and that in the middle and high latitudes the rise has been one degree, then plant respiration in these latitudes and the decay of organic matter in soils has increased significantly. If the increase in respiration is between 5 and 20 percent over 20 to 30 percent of the total area respiring, then total global respiration will increase between 1 and 6 percent above normal. Once again assuming that the annual flux of carbon into the atmosphere is 100 billion tons and that the rate of photosynthesis remains unchanged, the warming that has already taken place has meant an injection of between one and six billion tons of carbon per year. Over the past century from 20 to 30 billion tons of carbon may have been released in this manner.

That estimate is probably high, because the average warming may have been less than assumed and because photosynthetic response will tend to reduce the release of carbon dioxide. Yet the estimate is probably not high by as much as a factor of two, and it serves to emphasize the importance of biotic feedback mechanisms.

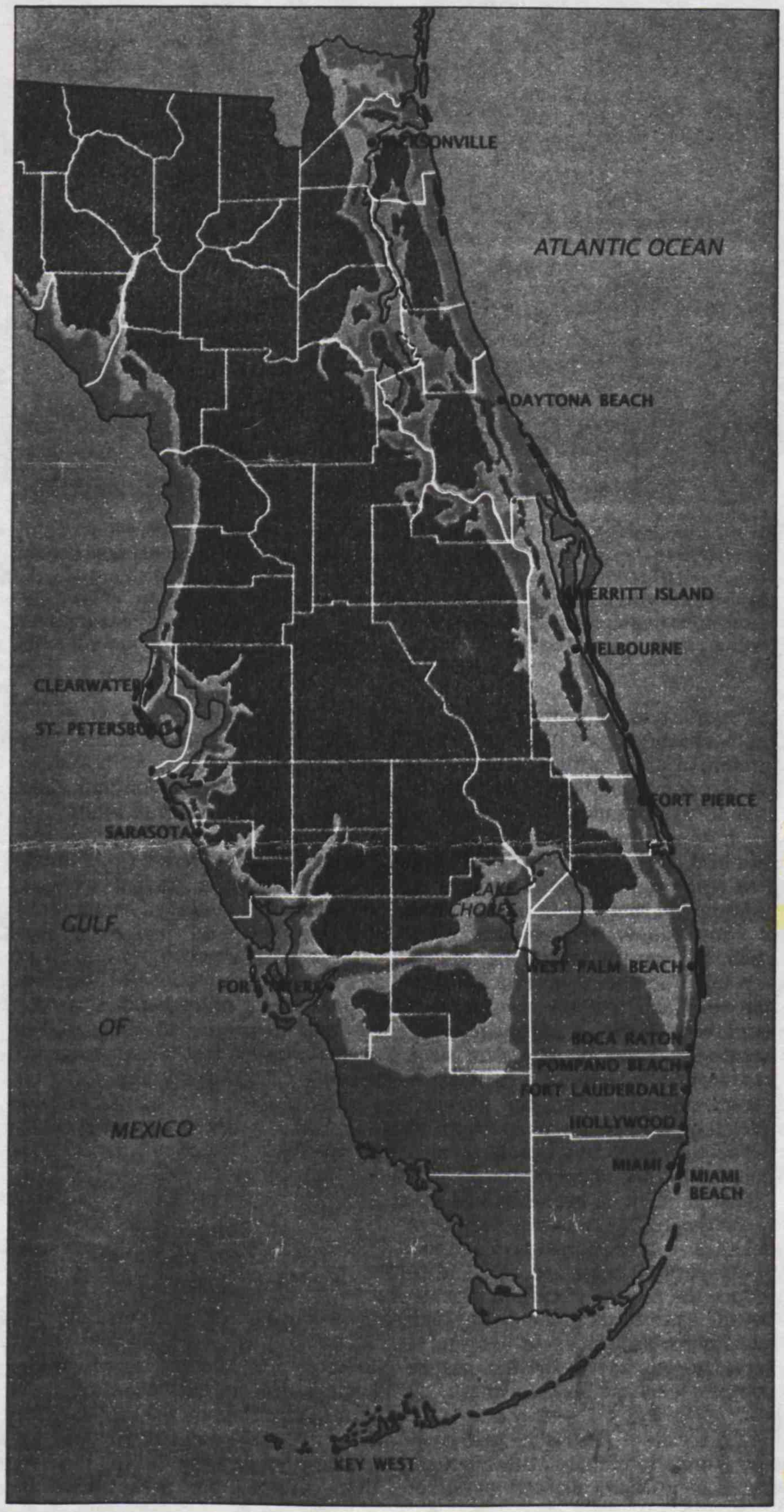
How does the value just computed compare with amounts of carbon released by other known processes? The release from the burning of fossil fuels is approximately 5.6 billion tons per year; deforestation adds an amount estimated at between .4 and 2.5 billion tons per year. The total carbon injected into the atmosphere from these two sources added to a temperature-enhanced respiration is not known, but it appears to be more than six billion tons annually and may approach 10 billion.

The release of carbon due to changes in the respiratory rate could fluctuate appreciably; a gradual warming, such as that experienced over most of this century, would change the respiratory rate slowly enough so that year-to-year changes would be inconspicuous. On the other hand, a sudden warming or cooling over a period of several years might result in an observable change in the carbon dioxide content of the atmosphere. In the past 15 years the annual rate of accumulation of atmospheric carbon dioxide has been about 1.5 parts per million, equivalent to a global accumulation of about three billion tons of carbon.

According to data recorded on Mauna Loa and at the South Pole by Keeling, however, over the past 18 months the accumulation rate has risen to about 2.4 parts per million, equivalent to about five billion tons of carbon. Keeling expects that the surge will prove transitory, as a lesser surge in 1973 and 1974 did. Nevertheless, the implication we assign to the observations at the moment is that the surge is a result of the high temperatures that have marked the 1980's, delayed by the time necessary to warm the soil. Whether this interpretation is correct remains to be seen.

Any climatic change can also be ex-

RHÔNE GLACIER in Switzerland is shown in a lithograph after an 1848 watercolor by Henri Hogard (*top*). Four sets of moraines are clearly visible. The outermost set has been dated to 1602, the second to 1818, the third to 1826 and the fourth to 1848; the pattern indicates that the glacier had been retreating up the valley for at least 250 years. A photograph from 1970 (*bottom*) shows that the glacier has retreated still farther up the valley. The retreat is additional evidence for recent global warming.



"GLOBAL WARMING FLOODS FLORIDA" could be a tabloid headline if the polar ice caps began to melt. Florida is shown here as it might look if sea level rose 4.6 meters above (*bluish green*) or 7.6 meters above (*light green*) the present level (*blue*). In either case Miami and Lake Okeechobee are submerged. A rise of four to five meters might be expected if the West Antarctic Ice Sheet broke up under global warming.

pected to affect the ability of the terrestrial biota, in particular forests and soils, to retain carbon. At warming rates that are lower than the rates at which forests develop, forests may actually expand, and with them the capacity to store carbon. But if the warming rate exceeds the rates at which forests migrate into more climatically favorable regions, widespread mortality of trees and other plants is likely to follow. The net result of such destruction of forests is difficult to predict, but it will probably mean a further release of carbon dioxide through the decay of plants, animals and organic matter in soils.

The amount of carbon dioxide that could be injected into the atmosphere would depend heavily on the rate of climatic change in the forested zones of the middle and high latitudes. Although it is impossible to make any accurate calculation, an upper limit is given by the amount of carbon in these forested latitudes: approximately 750 billion metric tons, or about the same amount of carbon as there is in the atmosphere currently.

Is it possible that a global warming could stimulate the growth of forests? In this case the spread of forests to high latitudes and tundra regions would result in a greater uptake of carbon dioxide from the atmosphere and a greater accumulation of carbon dioxide in the soil. Such a transition is unlikely. Forests require centuries to develop, especially where soils are thin and nutrients are in short supply. They also require climatic stability and sources of seeds. The climatic transitions currently under way, unless they are checked, are rapid by any measure and can be expected to continue into the indefinite future. They do not offer the conditions under which forests are able to develop on new land and remain for long periods.

Might the warming at least stimulate existing forests to store additional carbon in plants and soil? Perhaps. The boreal forest and other coniferous forests may indeed be sufficiently resilient to respond to warming with increased photosynthesis and growth. Whether the carbon taken up by photosynthesis will be stored or simply released through increased respiration remains an open question.

There is also the possibility that the tundra, the treeless plain found in arctic and subarctic regions, will respond to a warming in surprising ways, including an increase in the production of carbon and its storage in peat. The nature of the response will largely hinge on the availability of water. A wetter tundra might store additional carbon in soils; a drier tundra might release it through the decay of organic matter in long-frozen soil or soil that is normally frozen for most of the year. W. Dwight Billings of Duke University believes global warming will speed the decay of peat in tundra soils and precipitate that ultimate breakdown of the tundra known as thermal karst erosion, which allows flowing water to erode the tundra in great acre-size chunks. Not only is the tundra devastated but also substantial amounts of carbon dioxide and methane that were stored in the peat as carbon are released into the atmosphere.

The evidence indicates that under rapid planetary warming respiration rates will increase more than photosynthesis rates. The changes will lead to the release of additional carbon dioxide and methane into the atmosphere. The magnitude of the release will hinge strongly on the rate of warming: the faster the warming, the larger the release. Such behavior is consistent with (but not proved by) the data from the Vostok core.

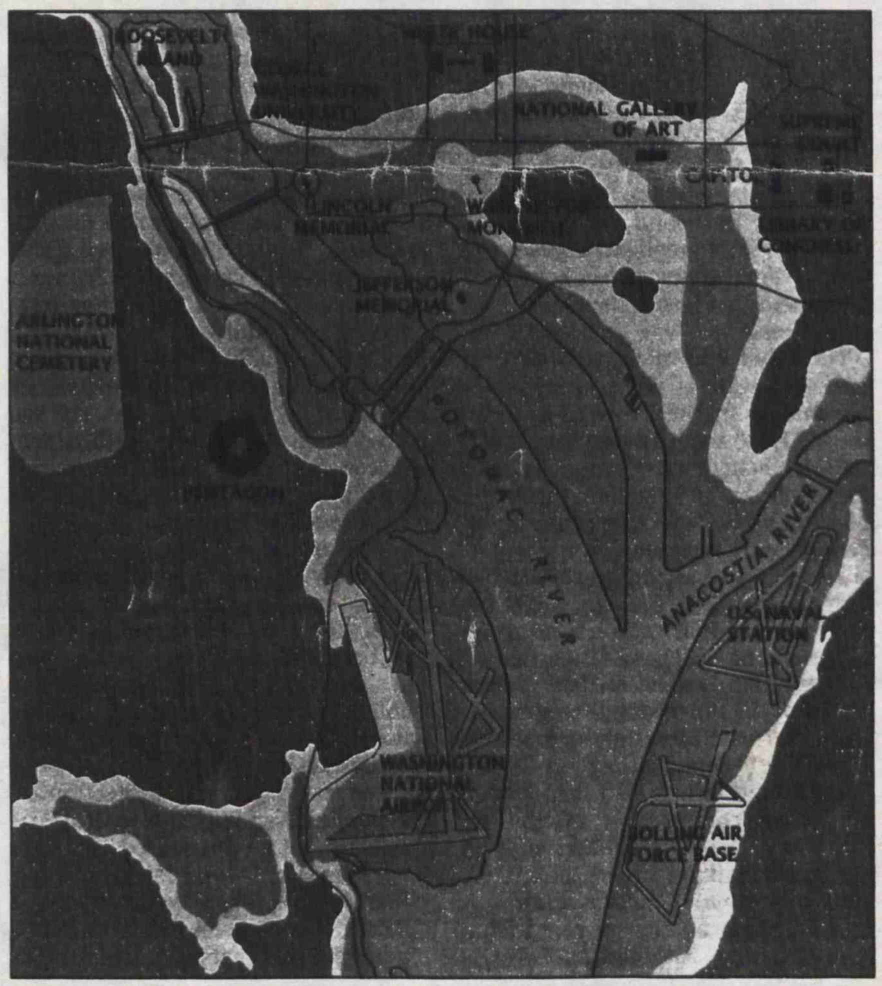
What will be the consequences of a continued global warming? In 1985 a group of meteorologists meeting under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) demonstrated that without the respiratory feedback mechanisms addressed above, the combined effect of the greenhouse gases would warm the earth by an average of from 1.5 to 4.5 degrees C before the middle of the next century. The conclusion was recently confirmed in a review written by more than 50 scientists who met in Villach, Austria, in 1987 and was published by the WMO and the UNEP.

Seldom has there been such a strong consensus among scientists on a major environmental issue. The warming, unless consciously checked by human effort, will be rapid and will be felt differentially over the earth. Winter temperatures in the middle and high latitudes can be expected to rise by more than twice the world average. If the mean global temperature were to rise by from two to three degrees C by the year 2030, the winter temperature increase in Minneapolis might approach from four to six degrees C, or about one degree per decade. Summer temperatures would also rise, but less severely. A one-degree change in temperature is equivalent to a change in latitude of from 100 to 150 kilometers. The prairie-forest border, which is now south and west of Minneapolis, might be expected to migrate north at a rate of between 100 and 150 kilometers per decade, or between 400 and 600 kilometers by the year 2030.

Such changes are likely to be difficult for most of the world's peoples. First, the changes will be continuous. Unless the warming stops, efforts to adapt to climatic changes are likely to be responses to conditions that no longer exist. Second, the changes in climate will be irreversible for any time of interest to us or our children. There is no way to cool the earth or to lower sea level; we cannot return quickly to an atmosphere with lower concentrations of greenhouse gases. The best we can do is to reduce current emissions. If that step is taken immediately, a further warming of more than one degree can be expected as the full effects of the heat-trapping gases already present are felt.

Finally, the effects are open-ended. Although most modeling to date simulates a doubling of the atmospheric carbon dioxide content, there is simply no reason to assume that the concentrations will stop at twice the current levels. Estimated reserves of recoverable fossil fuels in themselves are enough to increase the atmospheric concentration of carbon dioxide by a factor of from five to 10.

Can anything be done to slow the climatic change that is now under way? The immediate need is to stabilize the greenhouse-gas content of the atmosphere. Regardless of its source, over the past decade carbon has been accumulating in the atmosphere at a rate of about three billion tons annually. (The remainder is being absorbed by the oceans or stored in forests and soils.) If current fluxes were reduced by three billion tons annually, the atmospheric carbon dioxide level would be stabilized for a few years. The stabilization would not



WASHINGTON, D.C., is depicted here under the same conditions as in the preceding illustration. Washington National Airport and the Lincoln Memorial are inundated. The 7.6-meter contour reaches almost to the Capitol steps and to the White House.

be permanent, however. The rate of accumulation in the oceans is determined by how fast they can absorb carbon dioxide from the atmosphere; this in turn depends on the difference in carbon dioxide concentration between the atmosphere and the ocean. As the flux of excess carbon is reduced, the difference is also reduced and the ocean becomes less capable of absorbing excess carbon; carbon dioxide emissions would have to be reduced still further to prevent additional atmospheric accumulation.

The largest source of carbon dioxide emissions is the combustion of fossil fuels, which releases about 5.6 billion tons of carbon into the atmosphere annually. Industrial nations contribute about 75 percent of these emissions; steps toward stabilizing the composition must begin in the industrialized world. A recent study carried out under the auspices of the World Resources Institute and led by José Goldemberg, president of the University of São Paulo in Brazil, suggests that the consumption of energy from fossil fuels in the developed nations could be halved by a program of conservation and improved efficiency alone.

Although developing nations produce less carbon dioxide, their contributions are growing; if economic development follows conventional patterns, their potential contributions are very large. The second step toward the stabilization of greenhouse gases will require innovations in economic development that lessen dependence on fossil fuels.

The other known major source of carbon dioxide is deforestation, predominantly in the Tropics. By 1980 about 11,000 square kilometers of forest were being cleared annually, with the result that in 1980 between .4 and 2.5 billion tons of carbon (as carbon dioxide) were released into the atmosphere. The rate of deforestation has increased over the past decade. If the present release of carbon is near the upper end of the above range, halting deforestation would reduce carbon emissions by the three billion tons per year needed immediately to stabilize atmospheric composition.

Reforestation will also help to stabilize the composition of the atmosphere. The reforestation of from one to two million square kilometers (about the area of Alaska) will result in the annual storage of one billion tons of carbon. Although this area is large and productive land in the Tropics is at a premium, there may be as much as 8.5 million square kilometers of once forested land available for reforestation. Of this land, about 3.5 million square kilometers could be returned to forest if permanent agriculture were to replace shifting cultivation. Another five million square kilometers of deforested land are currently unused, and there reforestation could in principle be implemented immediately. Forests established to store carbon would, of course, have to be maintained: neither harvested nor destroyed by toxic effects or change in climate.

Each of the measures to stabilize the atmospheric carbon dioxide level would have salutary effects locally, regionally and nationally, quite apart from its effects on climatic change. An improvement in energy-use efficiency, a step that might have been taken long ago with benefits to all, would bring economic and material advantages to both individuals and nations. An improvement in efficiency would lessen reliance on fossil fuels; this in turn would reduce sulfur and nitrogen oxide emissions, acid deposition and the release of other toxins. Halting deforestation would help to maintain the genetic diversity of the planet, reduce erosion, stabilize local and regional climates, cleanse water and air and preserve opportunities for future generations.

No one remedy by itself is likely to stabilize the levels of carbon dioxide and methane in the atmosphere. If the accumulation of carbon dioxide in the atmosphere persists, the carbon burden will have shifted from three billion tons annually to five billion tons and will be that much more difficult to address. The measures that are required can begin at home, although it is clear the world must join in the effort if it is to be effective. There are precedents for international action on similar issues. The Limited Test Ban Treaty of 1962 was an agreement among certain nations to avoid atmospheric tests of nuclear weapons. It has been effective. Nations that did not sign it (France and the People's Republic of China) have yielded to international pressure and now conduct weapons tests underground. The Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol, the latter negotiated in 1987, have moved the world far toward the elimination of chlorofluorocarbons.

There is no reason to assume that similar progress cannot be made with carbon-based fuels and deforestation. With that end in view a series of steps has already been undertaken: 50 specialists in international diplomacy and law met recently under the auspices of the Woods Hole Research Center to outline approaches that might work. The greatest problem is gaining the active and effective support of the developing nations, which are poised for a massive increase in fossil-fuel consumption. Development need not, however, follow historical paths. To cite one example, the low-latitude countries stand to gain immeasurably as techniques for exploiting solar energy are perfected. Solar-powered electrolysis of water can produce hydrogen, which in turn can run automobiles and other machinery. There are few places in North America where domestic hot water cannot now be produced by solar energy at little or no cost throughout most of the year. Nor is it to the advantage of nations to allow their forests to be destroyed.

Conferences are under way in the developing nations to explore alternatives to the present course. The first was held in New Delhi in February; the second is planned for São Paulo in September under the leadership of Goldemberg. The conferences will explore the possible responses of developing nations to a world in which conventional energy sources are limited. There are extraordinary opportunities for industrial innovations, particularly in energy efficiency and solar power. But developing countries cannot be expected to shoulder the entire burden; the developed nations, which are responsible for most of the problem, must do their share.

These issues will persist throughout the next century and dominate major technical, scientific and political considerations into the indefinite future.

FURTHER READING

GLOBAL DEFORESTATION: CONTRIBUTION TO ATMOSPHERIC CARBON DIOXIDE. G. M. Woodwell, J. E. Hobbie, R. A. Houghton, J. M. Melillo, B. Moore, B. J. Peterson and G. R. Shaver in *Science*, Vol. 222, No. 4628, pages 1081-1086; December 9, 1983.

THE FLUX OF CARBON FROM TERRESTRIAL ECOSYSTEMS TO THE ATMOSPHERE IN 1980 DUE TO CHANGES IN LAND USE: GEOGRAPHIC DISTRIBUTION OF THE GLOBAL FLUX. R. A. Houghton, R. D. Boone, J. R. Fruci, J. E. Hobbie, J. M. Melillo, C. A. Palm, B. J. Peterson, G. R. Shaver, G. M. Woodwell, B. Moore, D. L. Skole and N. Myers in *Tellus*, Vol. 39B, Nos. 1-2, pages 122-139; February-April, 1987.

GLOBAL TRENDS OF MEASURED SURFACE AIR TEMPERATURE. James Hansen and Sergej Lebedeff in *Journal of Geophysical Research*, Vol. 92, No. D11, pages 13345-13372; November 20, 1987.

Dominic Morris

PM should be aware of these recent results.

[signature]

NEWS ROUNDUP

Greenhouse effect 'accelerating fast'

Research published today gives the strongest evidence that global warming (the greenhouse effect), which threatens a catastrophic change in the world's climate, is accelerating. A report giving the most comprehensive measurements of world temperature from 1982-1988 shows that the Earth's temperature is rising by 0.1 degree Celsius a year, or one degree a decade, twice the rate indicated by less detailed measurements.

The difference has profound implications for climatic change, according to Dr Phillip Williamson, project manager for an important British study into the greenhouse effect, at the Plymouth Marine Laboratory of the Natural Environment Research Council. He said the new findings made the problems of global warming more critical than many scientists realized. The new information, published in today's issue of *Nature*, was obtained from a continual scan of the oceans by satellite-based instruments.

Times 21/4

Dominic Morris: A kind of reverse Greenhouse Effect. Massive local temperature fluctuation but a global mean fall of less than 1°C

The Year without a Summer

In 1816 in New England it snowed in June, and then killing frosts continued through August. The cause was the explosion of a volcano in Indonesia. The economic and social consequences are instructive

by Henry Stommel and Elizabeth Stommel

In New England, Canada and western Europe the summer of 1816 was extraordinarily cold. A meteorological record for New Haven that had been kept by the presidents of Yale College since 1779 records June, 1816, as the coldest June in that city, with a mean temperature that would ordinarily be expected for a point some 200 miles north of the city of Quebec. The Lancashire plain in England had its coldest July, and the summer as a whole ranks as the coldest on record in the Swiss city of Geneva for the entire period from 1753 to 1960. In New England the loss of most of the staple crop of Indian corn and the great reduction of the hay crop caused so much hardship on isolated subsistence farms that the year became enshrined in folklore as "Eighteen Hundred and Froze to Death." The calamity of 1816 is an interesting case history of the far-reaching and subtle effects a catastrophe can have on human affairs.

The chain of events began in 1815 with an immense volcanic eruption in the Dutch East Indies (now Indonesia), when Mount Tambora on the island of Sumbawa threw an immense amount of fine dust into the atmosphere. Sir Thomas Stamford Raffles, who commanded a British military force in the islands, described the eruption in his *History of Java*: "Almost every one is acquainted with the intermitting convulsions of Etna and Vesuvius, as they appear in the descriptions of the poet and the authentic accounts of the naturalist, but the most extraordinary of them can bear no comparison, in point of duration and force, with that of Tomboro. This eruption extended perceptible evidences of its existence . . . to a circumference of a thousand statute miles from its centre, by tremulous motions and the report of explosions; while within the range of its more immediate activity, embracing a space of three hundred miles around it, it produced the most astonishing effects, and excited the most alarming apprehensions. On Java, at a distance of three hundred miles, it seemed to be awfully present. The sky was overcast at noonday with clouds of ashes; the sun was enveloped in an atmosphere, whose 'palpable' density he was unable to penetrate; showers of ashes covered the houses, the streets, and the fields to a depth of several inches; and amid the darkness explosions were heard at intervals, like the report of artillery or the noise of distant thunder. So fully did the resemblance of the noises to the report of cannon impress the minds of some officers, that from an apprehension of pirates on the coast vessels were dispatched to afford relief."

This eruption, which was considerably larger than the better-known one of Krakatoa in 1883, reduced the height of Mount Tambora by some 4,200 feet and ejected some 25 cubic miles of debris. Ash was encountered by ships at sea as large islands of floating pumice as much as four years after the event. Climatologists rank the eruption as the greatest producer of atmospheric dust between 1600 and the present. The dust circled the earth in the high stratosphere for several years, reflecting sunlight back into space and thereby reducing the amount of it reaching the ground.

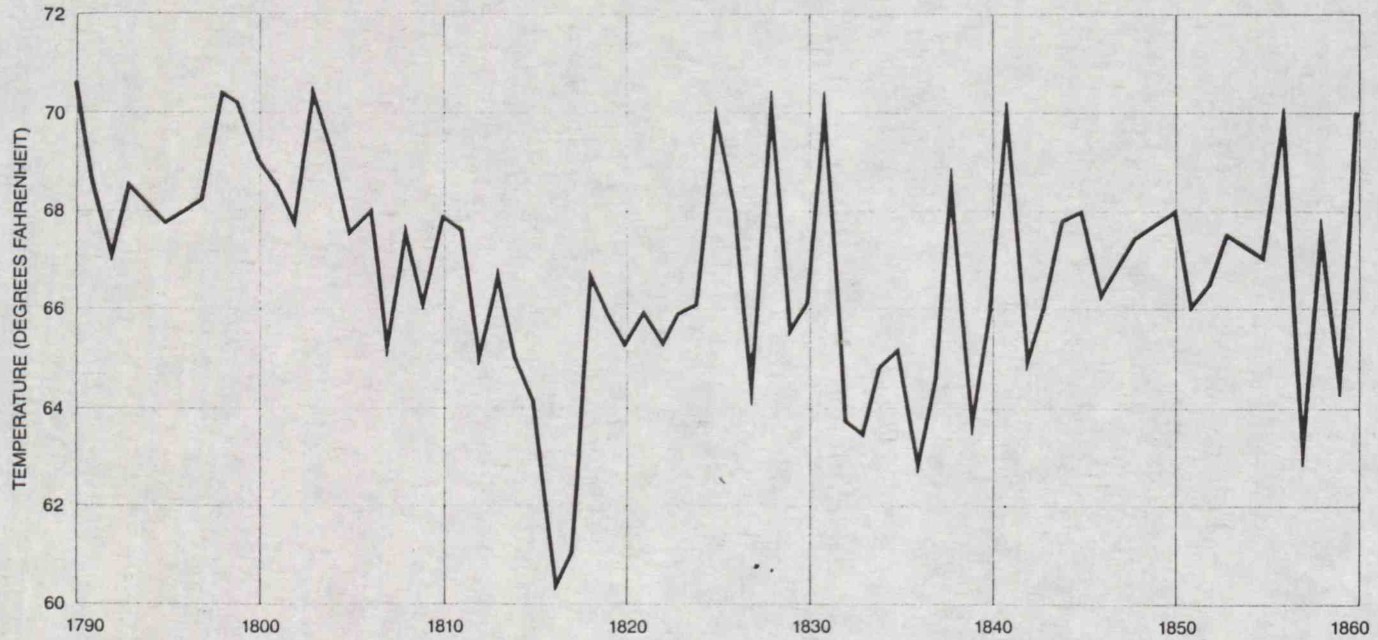
The idea that dust in the upper air can result in lower temperatures at ground level is quite old. Benjamin Franklin invoked it to explain the cold winter of 1783–84. Today the idea can be confirmed more conclusively through long records of temperature from many parts of the world, which can be compared with the fairly complete record of the volcanic eruptions that have been observed during the past two centuries.

As the dust in the upper atmosphere circled the earth after the eruption of Tambora, it gradually shadowed the higher latitudes. The first two months of 1816 were not exceptionally cold in New England, but by May observers had begun to comment on the lateness of the spring. June began auspiciously, and crops that had survived the unwonted frosts of mid-May started to progress. The first of three unseasonable cold waves moved eastward into New England early on June 6. The cold and wind lasted until June 11, leaving from three to six inches of snow on the ground in northern New England. A second killing frost struck the same areas on July 9 and a third and fourth on August 21 and 30, just as the harvest of twice-ravaged crops was about to begin. The repeated summer frosts destroyed all but the hardiest grains and vegetables.

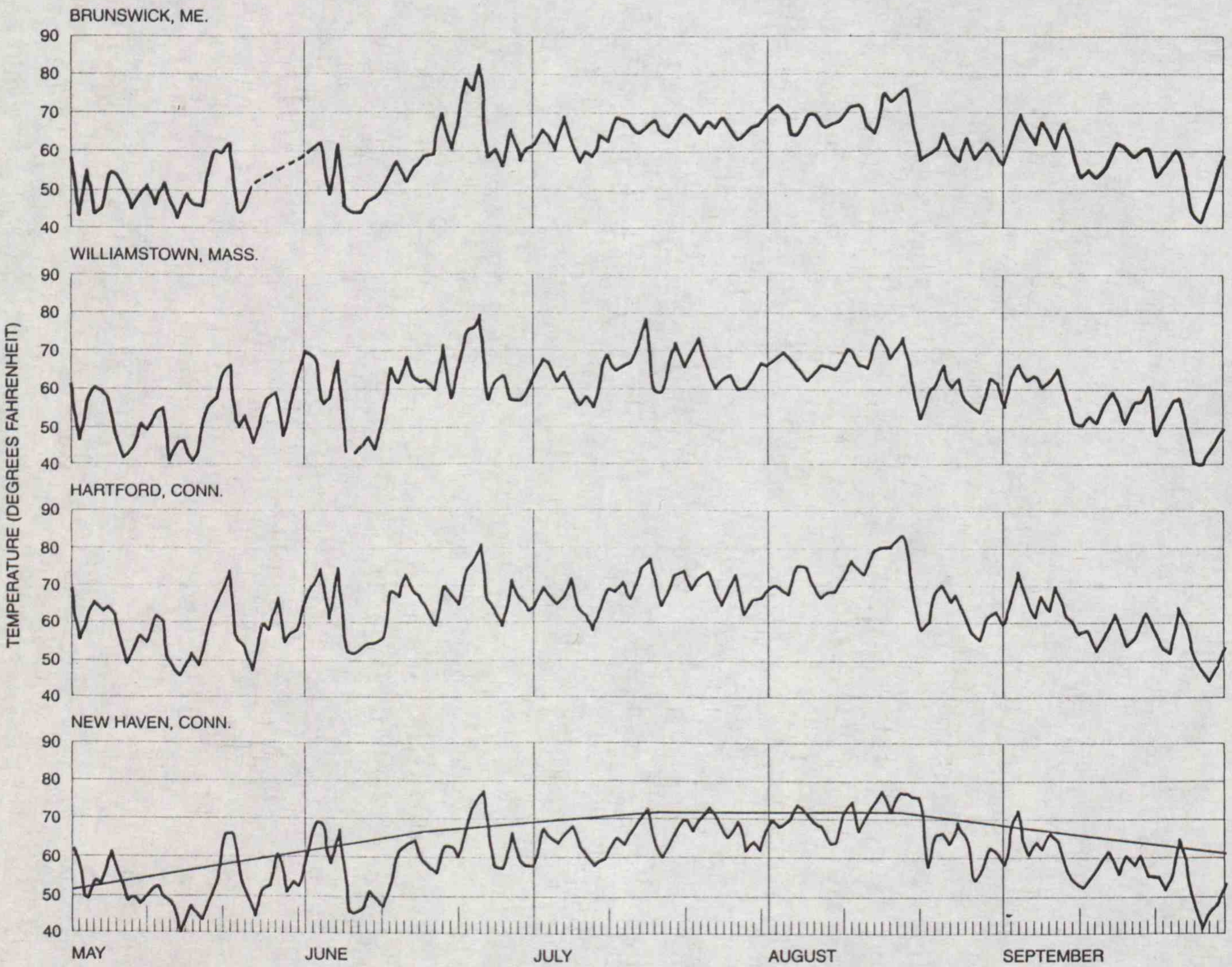
The temperatures are recorded in a number of meteorological journals kept at the time, including the one maintained by the presidents of Yale College and another kept by William Plumer, who in 1816 was governor of New Hampshire. Many personal accounts also record the unusual weather. For example, Hiram Harwood, a farmer at Bennington in the southwest corner of Vermont, remarked in his diary on the frosts of mid-May, which had hindered vegetation to the point of making it about two weeks late. When he awoke early on June 6, after a night of heavy rain and sharp northeast winds, he saw that the mountains on every side were crowned with snow. On the morning of June 7 he found his fields stiff with frost. The leaves of the trees were now blackened. On June 8 the fierce weather continued, with sweeping blasts from the north all morning and with intermittent snow squalls.

The summer made enough of an impression on the mind of Chauncey Jerome, who in 1816 was a 26-year-old apprentice clockmaker in Plymouth, Conn., so that when 44 years later he came to write his *History of the American Clock Business for the Past Sixty Years*, he said: "I well remember the 7th of June, while on my way to work, about a mile from home, dressed throughout with thick woolen clothes and an overcoat on, my hands got so cold that I was obliged to lay down my tools and put on a pair of mittens which I had in my pocket. It snowed about an hour that day. On the 10th of June, my wife

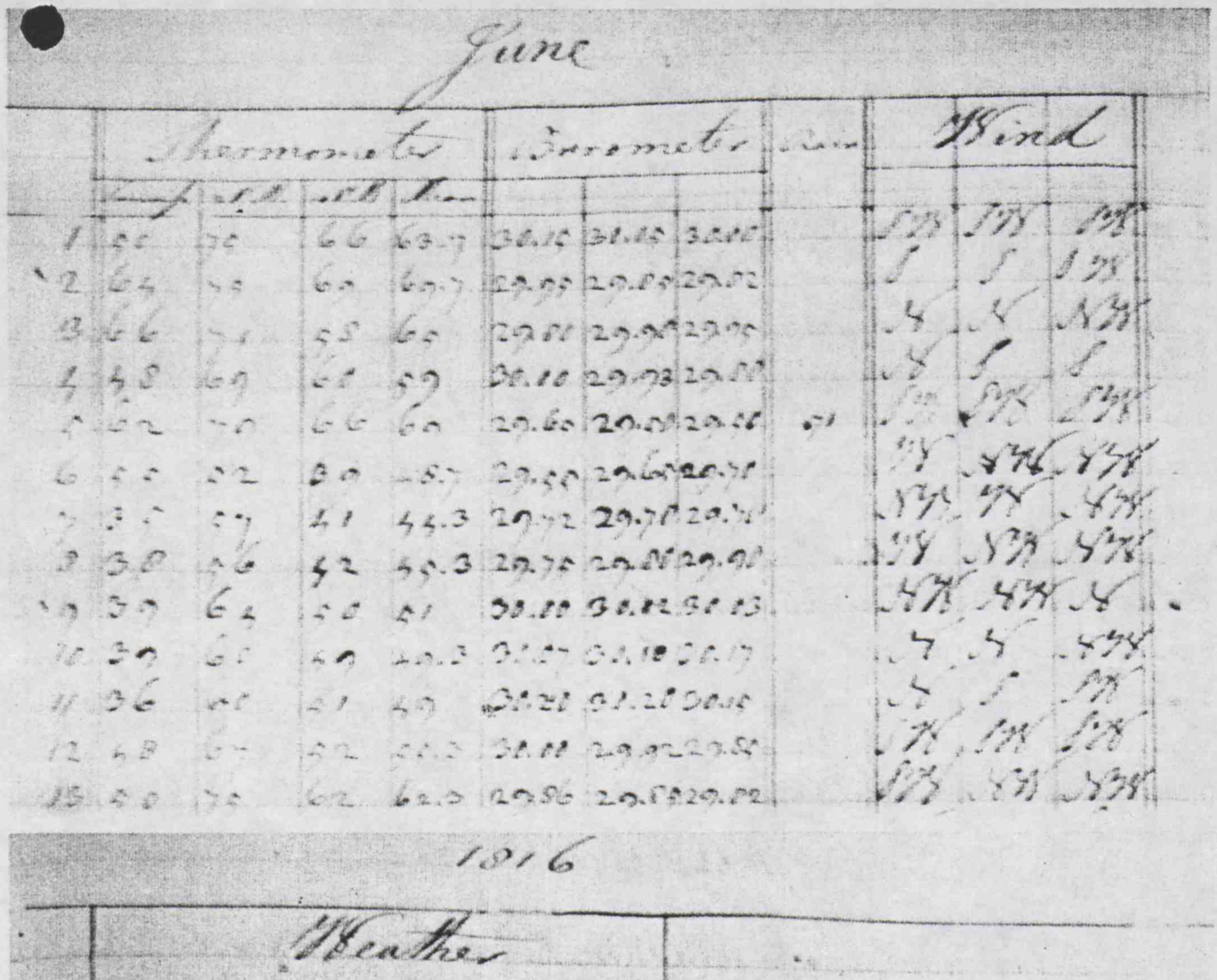
Article is June 1979



TEMPERATURE RECORDS for New Haven, Conn., convey the mean temperature in June over a period of 70 years, beginning in 1790. The low of slightly more than 60 degrees Fahrenheit in 1816 was the result of temperatures that ranged from 35 degrees at sunrise on June 7 to 88 degrees at 2:00 P.M. on June 24, according to a journal kept for many years by the presidents of Yale College.



ABNORMAL COLD in New England during the late spring, the summer and the early fall of 1816 is reflected in these charts of the average daily temperature in four towns from May through September. The black curve for New Haven indicates the normal average.



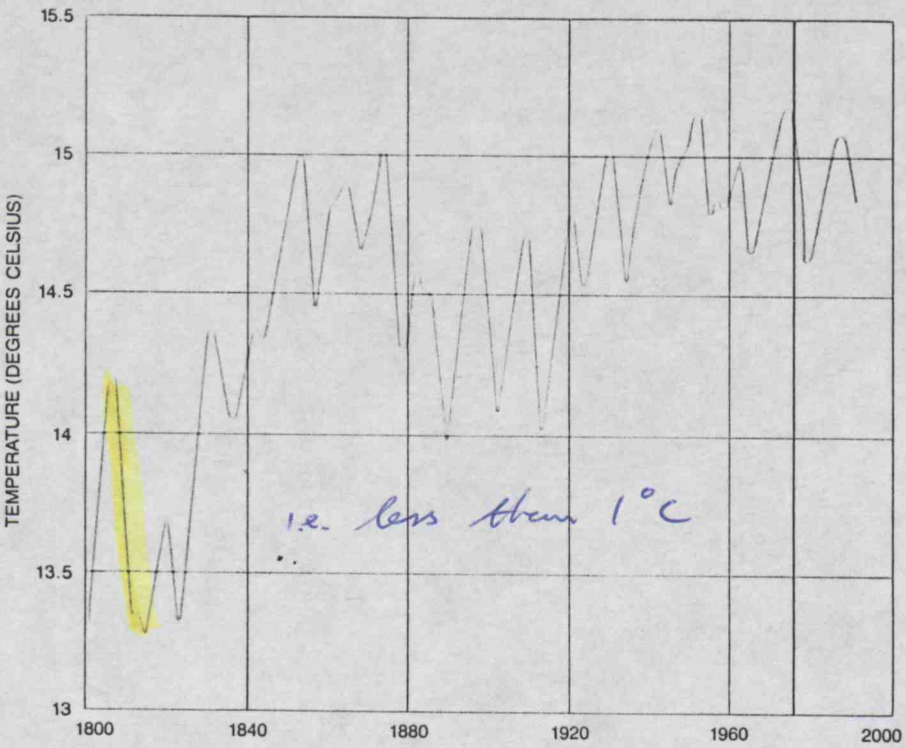
June

	Thermometer				Barometer			Rain	Wind		
	[illegible]	[illegible]	[illegible]	Mean							
1	50	70	66	63.7	30.15	30.05	30.00		SW	SW	SW
2	64	[illegible]	60	60.7	29.95	29.85	29.82		S	S	SW
3	66	[illegible]	55	65	29.80	29.90	29.95		N	N	NW
4	48	69	60	59	30.10	29.93	29.80		N	S	S
5	62	70	66	60	29.60	29.50	29.56	.51	SW	SW	SW
6	55	52	50	[illegible]	29.50	29.60	29.70		NW	NW	NW
7	35	57	41	44.3	29.72	29.70	29.80		NW	NW	NW
8	38	56	42	45.3	29.75	29.85	29.90		NW	NW	NW
9	39	64	50	51	30.00	30.02	30.13		NW	NW	N
10	39	60	49	49.3	30.07	30.10	30.17		N	N	NW
11	36	60	51	49	30.20	30.20	30.15		N	S	SW
12	48	[illegible]	52	[illegible]	30.00	29.92	29.85		SW	SW	SW
13	50	70	62	62.3	29.86	29.85	29.82		SW	SW	SW

1816

	Weather	
1	Clear — clear — clear	
2	Clear — clear — clear	
3	Br. clouds — hazy — clear	
4	Clear — br. clouds — br. clouds	
5	Br. clouds — clear — rain	
6	Br. clouds — br. clouds — clear	Gale on the [illegible] coast of U.S.
7	Clear clear — clear	Frost
8	Clear — clear — clear	Frost — Snow in Vermont
9	Clear — clear — clear	
10	Clear — clear — clear	
11	Clear — clear — clear	Frost
12	Br. clouds — clear — clear	
13	Br. clouds — cloudy — cloudy	Snow in Maine

METEOROLOGICAL JOURNAL for New Haven kept at Yale College for many years reflects the unusually cold weather that began on June 6, 1816, and continued through June 11. One sees here the upper part of two pages that face each other in the journal; the left-hand page is at the top. The series of journals was begun in the 18th century by Ezra Stiles when he was president of Yale and was continued by or under the direction of his successors. The president in 1816 was Timothy Dwight, but he was near the end of his life and was succeeded in 1817 by Jeremiah Day. Whether entries for June, 1816, are in hand of Dwight, Day or some other person at Yale is not known.



GLOBAL MEAN TEMPERATURES were worked out by Stephen H. Schneider and Clifford Mass of the National Center for Atmospheric Research in Boulder, Colo., using a mathematical model of the global radiation balance calculated on the basis of the number of sunspots and the density of volcanic dust in the atmosphere. The curve shown here does not take into account the putative warming effect of the carbon dioxide that has been put into the atmosphere by the combustion of fossil fuels. Schneider and Mass found that the density of dust is a more important factor than the number of sunspots in contributing to fluctuations of temperature.

brought in some clothes that had been spread on the ground the night before, which were frozen stiff as in winter. On the 4th of July I saw several men pitching quoits in the middle of the day with thick overcoats on, and the sun shining bright at the time."

Newspapers carried long descriptions of the extraordinary weather. Early in June the *North Star* of Danville, Vt., reported: "Some mention was made not long since of the unusual backwardness of the spring, and the remarkable instability of the weather. Although the summer months have commenced, the weather is no more steady nor the prospects more promising. Wednesday last [June 5] was perhaps as warm and sultry a day as we have had since September—At night heat lightning was observed, but on Thursday morning the change of weather was so great that a fire was not only comfortable, but actually necessary. The wind during the whole day was as piercing and cold as it usually is the first of November and April. Snow and hail began to fall about ten o'clock, A.M., and the storm continued till evening, accompanied with a brisk wind, which rendered the habiliments of winter necessary for the comfort of those exposed to it." Noting that the wintry weather continued through the week, the newspaper said: "Probably no one living in the country ever witnessed such weather, especially of so long continuance."

In the wake of the storm good growing weather returned. From Connecticut to Quebec farmers with reserves of seed plowed their blackened fields and replanted their corn and beans and other tender crops.

The second cold wave, which was less severe, came early in July. Still, it was severe enough for ice to form in Maine on July 5, and on July 9 corn was again killed by frost except in well-sheltered places. Summer weather returned on July 12, and conditions remained warm and pleasant until August 20. Then New England was hit by a series of unusually early frosts. In *Historic Storms of New England* Sidney Perley wrote: "On the night of the twenty-first, there was a frost, which at Keene and at Chester, N.H., killed a large part of the corn, potatoes, beans and vines, and also injured many crops in Maine. It was felt as far south as Boston and Middlesex county in eastern Massachusetts, and in the western portion of the state as far as Stockbridge, where it injured vegetation. The mountains in Vermont were now covered with snow, and the atmosphere on the plains was unusually cold. In Keene, N.H., the oldest persons then living said that they never saw such a severe frost in August. It put an end to the hopes of many farmers of ripening their corn, especially in the low lands, and they immediately cut the whole stalks up for fodder, but being in the milk it heated in the shocks and spoiled. By the twenty-ninth of the month the frost had reached as far south as Berkshire county, Mass., where it killed the Indian corn in many of the fields in the low lands. The farmers there saved much of it by cutting it up at the roots and placing it in an upright position, where it ripened upon the juices of the stalks. If frost had kept off two weeks longer, there would have been a very good crop of corn in Massachusetts."

The cold was still more severe in Canada. The small lakes to the north of Baie Saint Paul on the St. Lawrence River were still covered with ice in the middle of July. In Canada even wheat, which along with other grains except corn had done well in the U.S., perished. The Halifax *Weekly Chronicle* noted that "great distress prevails in many parishes throughout Quebec Province from a scarcity of food. Bread and milk is the common food of the poorer classes at this season of the year; but many of them have no bread."

It is difficult to piece together a coherent picture of the effects of the unusual weather from ephemeral accounts in the newspapers of the time. Later accounts, such as county histories in which farmers are said to have slaughtered their flocks and even to have hanged themselves because of the privations brought on by the cold summer, appear to have been to at least some extent embellished. Fortunately there are more reliable sources on the social import of the cold year: a special study instituted by the Philadelphia Society for the Promotion of Agriculture, the record of wholesale prices for agricultural products and studies of patterns of emigration from the afflicted states to new lands opening in the West.

In response to widespread interest in the effects of the cold summer the Philadelphia Society for the Promotion of Agriculture resolved on October 30 of that year to "collect facts relating to Agriculture and Horticulture, and of all circumstances connected therewith, which have occurred through the extraordinary season of 1816; and particularly the effects of Frost on vegetation." Copies of the resolution were circulated widely. Replies soon began to arrive.

One of the first was from Samuel Latham Mitchill, a physician who was also professor of natural history at Columbia College in New York. "There will not be half a crop of maize on Long Island, and in the southern district of this state," he wrote. "Further northward there will be less. The buckwheat is so scanty, that a few days ago I paid four dollars for a half barrel of the meal, for the use of my family. The winter

Note: In 1979, Global warming was "putative".

crop of wheat and rye was abundant.... An entomologist complained to me, a few weeks ago, that it has been a most unfortunate season for the collection of insects. That kind of game, he said, was so rare, that he had added but little to his museum. There have been at New York fewer fleas and musquitoes than ordinary."

Another reply came from General David Humphreys, a hero of the American Revolution who in 1816 was president of the Connecticut Society of Agriculture. He wrote: "The principal injury done by early and late frosts, fell on our most important crop, Indian corn. Of this, there is not more than half the usual quantity; and, in many places in this neighbourhood, not more than a quarter part sufficiently hard and ripe for being manufactured into meal. That which is unripe, mouldy or soft, when given as feed to hogs and cattle, has little tending to fatten them.... Grasses, for pasturage and hay, have been diminished by the drought about 50 per cent. The hay is estimated to be nearly 25 per cent better than it is in wet seasons; containing considerably more nutriment, and having been well cured.

"All kinds of grain were a longer time than usual in filling and ripening: which is considered one reason, why those which came to maturity are more than commonly full and heavy. Wheat and rye never yielded more abundantly....

"Roots and vegetables, in gardens that were well tended by having the earth frequently moved round the plants, early in the morning, while the dew was on the ground, have generally been more flourishing and productive than in ordinary seasons. Some attentive horticulturists observed that more dew fell than usual."

a Table of thermometrical observation made at Monticello from Jan. 1. 1810 to Dec. 31. 1816

	1810.			1811.			1812.			1813.			1814.			1815.			1816.			mean of each month
	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	
Jan.	5½	38	66	20	39	68	5½	34	53	13.	35	59	16½	36	55	8½	35	60	16.	36	51	36
Feb.	12	43	73		*		21	40	75	19	38	65	14	42	65	16	36	57	15½	41	62	40
Mar.	20	41	61	28	44	78	31½	46	70	28	48	71	13½	43	73	31	54	80	25	48	75	46
Apr.	42	55	81	36	58	86	31	56	86	40	59	80	35	59	82	41	60	82	30	49	71	56½
May	43	64	88	46	62	79	39	60	86	46	62	81	47	65	91	37	58	77	43	60	79	61½
June	53	70	87	58	73	89	58	74	92½	54	75	93	57	69	87	54	71	88	51	70	86	72
July	60	75	88	60	76	89½	57	75	91	61	75	94½	60	74	89	63	77	89	51	71	86	75
Aug.	55	71	90	59	75	85	61	71	87	62	74	92	56	75	88	58	72	84	51	73	90	73
Sep.	50	70	81	50	67	81	47	68	75	54	69	83	52	70	89	45	61	82	54	63	90½	67
Octob.	32	57	82	35	62	85	39	55	80	32	53	70	37	58	83	38½	59	76	37	57	73	57
Nov.	27	44	69	32	45	62	18	43	76	20	48	71	23	47	71	20	46	70	24	46	71	45½
Dec.	14	32	62	20	38	49	13	35	63	18	37	53	18	38	59	12	36	57	23	43	69	37
Mean of each year		55			58			55			56			56⅓			55½			54½		55½

It is a common opinion that the climates of the several states of our union have undergone a sensible change since the dates of their first settlements; that the degrees both of cold & heat are moderated. the same opinion prevails as to Europe: & facts gleaned from history give reason to believe that, since the time of Augustus Caesar, the climate of Italy, for example, has changed regularly at the rate of 1° of Fahrenheit's thermometer for every century. may we not hope that the methods invented in latter times for measuring with accuracy the degrees of heat and cold, and the observations which have been & will be made and preserved, will at length ascertain this curious fact in physical history?

WEATHER RECORD kept by Thomas Jefferson at his home in Virginia shows that the summer of 1816 was somewhat colder than normal there, although the principal effects of the volcanic dust on temperature were felt farther north. Jefferson began this set of observations on the weather the year after he left the presidency. In the table he transposed, presumably through inadvertence, either the maximum and minimum readings or the column headings.

The soaring prices are a matter of record. Newspapers regularly published the wholesale prices of most agricultural products, including wheat and flour, which serve as an index of food prices as a whole. The newspaper accounts all reported a large and sudden rise in the price of flour owing to the reports from Europe of widespread crop failures.

Surpluses of American wheat and rye could have met the foreign demand without inflation had it not been for the failure of much of the corn crop from Pennsylvania northward. As it was, the price of wheat rose in 1817 to $2.45 per bushel, far higher than it had been before or would be for long afterward. In the period 1800–1811 the wholesale price of wheat was about $1.30, and for most of the 30 years after 1817 it stayed around $1.05.

In *Historic Storms of New England* Perley recorded a number of observations about the effect of the cold summer on prices. "There was great destitution among the people the next winter and spring," he wrote. "The farmers in some instances were reduced to the last extremity, and many cattle died. The poorer men could not buy corn at the exorbitant prices for which it was sold. In the autumn, stock was sold at extremely low prices on account of lack of hay and corn, a pair of four-year-old cattle being bought for thirty-nine dollars in Chester, New Hampshire....

"The next spring hay was sold in New Hampshire in a few instances as high as one hundred and eighty dollars per ton, its general price, however, being thirty dollars. The market price of corn was two dollars per bushel; wheat, two dollars and a half; rye, two dollars; oats, ninety-two cents; beans, three dollars; butter, twenty-five cents per pound; and cheese, fifteen cents. In Maine, potatoes were seventy-five cents per bushel, the price in the spring of 1816 having been forty cents, which was the usual price."

The geographer Joseph B. Hoyt extracted weekly price reports from New

MEMENTO OF COLD SUMMER is seen on this tombstone, which still stands on what was evidently Reuben Whitten's farm in Ashland, N.H. The reference to the "40 bushils of wheat" that he raised appears to reflect the fact that the wheat crop, particularly winter wheat, was comparatively good in 1816, whereas the corn crop, which was the staple of most farms in New England, was severely curtailed.

York newspapers of the period for wheat, corn, pork and beef. The prices of pork and beef usually went through a yearly cycle with the highest point (pork at $24 per barrel, for example) in late fall, when farmers were holding and feeding their stock, and the lowest point (pork at $20 per barrel) in late spring. The summer of 1816 completely reversed the cycle. Farmers, concerned about the poor prospects for hay, sold off their stock early enough to depress the summer and fall pork prices to $17 per barrel. The price of beef followed a similar pattern.

Exports of wheat to Canada, Britain and Europe substantially inflated the domestic price. The New York *Weekly Museum* for January 4, 1817, made mention of the subject: "Within a few weeks, it is said, more than 100,000 barrels of flour have been shipped from New York, Philadelphia and Baltimore for England; in consequence the price of flour here is now $14.00 a barrel."

The summer of 1816 marked the point at which many New England farmers who had been thinking of moving west finally decided to go. The movement had been under way for some time, and the cold weather of 1816 with its severe consequences for agriculture was certainly not the only motivating factor, but it did serve as an extra prod. Emigration was particularly heavy from Vermont and Maine. The Vermont historian L. D. Stilwell examined many accounts of individual migrations to the west from Vermont and found that in 1816–17 the number of people leaving was almost twice the number who had left in other years of the decade. At the other end of the migration the *Messenger* of Zanesville, Ohio, noted on October 31, 1816, that "the number of Emigrants from the eastward the present season, far exceeds what has ever before been witnessed."

The harsh summer of 1816 had even severer consequences for parts of Europe than it did for the U.S. The bad weather followed closely on the disruptions of the Napoleonic Wars, which had ended in 1815 with the exile of Napoleon to St. Helena. In many places the poor crops of 1816 caused grave shortages of food and conditions approximating famine. Although several countries were affected, we shall limit our discussion to Switzerland and France.

Since the Middle Ages, Zurich had been a center for the grain market. High prices chronicle the periods of scarcity: 1692, 1770–71 and 1816–17. Local publications record 1816 as being unusually cold, dry and unpleasant. Attempts to replant summer wheat were frustrated by a lack of seed in the state granaries. Swine had to be slaughtered for want of fodder. By the end of the year the shortage of food was severe, particularly in the cities. Parish registers record a number of deaths that show a clear association with famine. The churches designated January 26, 1817, a day for the special gathering of funds to alleviate distress. All kinds of things were eaten: sorrel, moss and cat flesh. Instructions were issued to help people identify poisonous plants.

The situation in France was equally grave. Torn by military campaigns and the defeat at Waterloo in 1815 and stripped of the feudal protection that had been one of the positive aspects of the vanished aristocracy, the French peasantry had no reserves with which to buffer the bad season of 1816. The country was in a political ferment as Louis XVIII and Talleyrand struggled to maintain the constitutional monarchy against the followers of Napoleon. The political ferment brought about a decline in industrial activity, which in combination with the meager harvest of 1816 and the high cost of food (already in short supply because of the invasions of 1815) set the stage for riots and insurrection.

In Poitiers rioting broke out because of a tax of three francs per bushel imposed on wheat. Grain carts on their way to market in towns along the Loire valley had to be protected by soldiers and gendarmes, who found themselves fighting as many as 2,000 hungry and enraged citizens. Where the harvest had been good farmers were afraid to take their produce to market because so many robbers were abroad.

In August the government suspended import duties on grain. By November it was seeking supplies for importation. According to a recent study by J. P. Housel of the mean monthly prices of wheat in France from 1801 to 1912 the highest point was reached during the first half of 1817. It was then approximately twice as high as the long-term average, a pattern similar to the one that prevailed in the U.S. The political and economic difficulties continued in Europe until the harvest of 1817 brought significant relief.

One suggested consequence of the unusual weather of 1816 is intriguing and plausible, although it cannot be proved. It is the suggestion (made by J. D. Post of Northeastern University) that the anomalous weather of 1816 was responsible for the world's first pandemic of cholera, which reached the U.S. in 1832.

Medical histories indicate that before the time of this great outbreak cholera had been confined to the region of the Hindu pilgrimage on the Ganges, with sporadic incursions into China. The failed harvests of 1816 and the ensuing famine in India weakened enough people to give rise to a local epidemic in Bengal. From there the disease was spread by British military operations to the Afghans and the Nepalese. On reaching the shores of the Caspian Sea it moved slowly westward by two routes: one up the Volga to the Baltic ports and the other through the Moslem hajj (the pilgrimage to Mecca) to the Middle East. In a time before railroads and airplanes the progress of the disease was leisurely, somewhat like the movement of plant diseases today.

When the first worldwide attack of cholera struck New York in the summer of 1832, dispersing well-to-do city folk throughout the nearby countryside, neither they nor their sometimes reluctant rural hosts connected the pandemic with the weather of 1816. News dispatches of the pandemic had come in from Europe and the Near East carrying vivid accounts of the dreadful impact of the disease in Moscow, Pest, Sevastopol, Paris and elsewhere. Then came the dismaying news from Montreal that the scourge had crossed the Atlantic. By July 20 the toll of dead in New York was as high as 100 per day. The devastation was mainly among what the authorities of the time would have called the lower orders of society. The disproportionate mortality of that stratum was so clearly a matter of sanitation and water supply that it led the city to undertake the construction of the Croton Aqueduct, which still supplies the city with much of its water.

The train of events from 1816 to 1832 is tenuous. The weather certainly caused the famine in Bengal, and the famine made conditions ripe for the outbreak of cholera there, whence it spread to the West. Even in the absence of the famine in Bengal, however, European adventures in imperialism would inevitably have loosed cholera on the world eventually.

The cold summer of 1816 did not escape the notice of contemporary scientists. Some of them blamed it on sunspots. Ernst Chladni, a well-known amateur acoustician, attributed the cold to an outbreak of Arctic ice in the North Atlantic. He put forward his theory in *Annalen der Physik*, attempting to substantiate it by reporting sightings of icebergs that had been made from ships in the North Atlantic. Another view was that a significant amount of heat came from the interior of the earth by resistive electric heating and that the introduction of the lightning rods invented by Franklin had upset the natural flow, thereby bringing on the cold weather. As far as we have been able to determine no one at the time attributed the strange weather to the massive eruption of Mount Tambora the year before, in spite of the fact that Franklin's speculations on the meteorological effects of atmospheric dust were more than 30 years old and that news reports of the bad weather appeared in many newspapers side by side with reports of large floating islands of volcanic ash in the Pacific.