Man and Climate: An Overview

EARL W. BARRETT

Abstract—**The possibility that human activities are affecting climate on a regional or global scale has been studied with increasing diligence during the past 20 years. Monitoring programs have been started and expanded, and mathematical models of climatic change, of ever increasing complexity, have been developed as computer capability has increased.**

Examination of all published information shows that the atmospheric carbon-dioxide content has increased by about 3 percent between 1958 and 1975 as a result of fossil-fuel combustion, that the solid-particle loading of the atmosphere has risen noticeably downwind of large urban-industrial complexes in developed countries, although volcanoes and wind still provide nearly all the dust loading on a global scale, and that waste heat from man's activities now amounts to about 0.016 percent, or 1 part in 6000, of the average input of solar energy to the planet. Human influences are felt most strongly in and downwind of cities; in such areas the mean temperatures are higher, the mean diurnal temperature range is smaller, and the annual precipitation is higher than they would be were the cities absent. The urban influence is felt for only tens or a few hundred kilometers from these source regions.

Although the global effects of human activities on climate are still undetectable against the background "noise level" of natural climatic fluctuations, some of the latest mathematical climate models (which are still rather crude) predict significant effects in the relatively near future if present rates of population growth, increase in per-capita energy use, and industrial expansion persist or rise.

Introduction

THIRTY-SIX YEARS AGO, the United States Department of Agriculture published a yearbook [1] with the title, *Climate and Man*. This volume consisted of a set of articles describing the impact of climate on human activities, with emphasis on agriculture. The purpose of the present article is the discussion of the influence of human activities on climate; it therefore seems fitting to adopt the converse of that title for this presentation.

There is little doubt that climatic fluctuations have played a major role in the social (and even the physical) evolution of man. There are strong reasons to believe that many of the folk migrations within historical times, such as the movement of the Goths southward from Scandinavia and the Huns, Turks, Mongols, etc., from central Asia came about at least in part because of incompatibilities between their agricultural or pastoral practices and a changing marginal climate. A more recent example is the so-called "little ice age," a climatic recession which prevailed during the approximate period 1300–1700 of the present era. It is most probable that this event stopped the movement of Scandinavian explorers and colonists across the Atlantic and thereby postponed the European settlement of North America.

A natural reaction to the stresses of adverse weather and climate is the desire to control these features of the environment. Until 1946, however, techniques for doing this were limited to invoking supernatural intervention. The work of Schaefer [2], which started in that year, provided the first scientific basis for intentional weather modification. Since that time, cloud modification by addition of condensation or freezing nuclei ("seeding") has been studied extensively.

In contrast to the work on purposeful modification, little attention was paid to the question of accidental, or inadvertent, modification of weather or climate (except on the local urban scale) until the mid-1950's. The development and testing of thermonuclear weapons in the period 1952–1958 then triggered a spate of publications predicting various dire climatic consequences. Most of these had little or no sound physical basis. By 1960 it was clear that no long-term or global climatic consequences would result from weapons testing at the levels of the 1950's, and that no energy that man could liberate could alter atmospheric motions on a large scale by "brute force." It was realized that human influences on climate would have to be weak forcings acting over long time spans; they would be slow and insidious unless (or until) aided by internal positive-feedback loops within the earth-atmosphere-ocean system.

Since the mid-1950's, scientific programs for studying inadvertent weather and climate modification have grown in number and scope because of the realization that the "spacecraft earth" concept is a valid one, and that all pollutants (material ones, at least) are trapped inside the system. These programs include the following: 1) the establishment of "benchmark stations" in wilderness areas for detection of long-term and global trends of climate parameters and pollutant concentrations [3]; 2) development of theoretical and numerical models to describe and predict climatic effects of pollutants; 3) workshops for sharing and disseminating ideas and information [4]-[6]; and 4) intensive one-time (or few-time) field programs to investigate specific problems [7], [8].

After a short discussion of natural climatic change, the remainder of this article will summarize the state of knowledge of man's influence on climate as of a fairly recent date (mid-1975). Due to space limitations the discussion cannot be exhaustive; readers interested in a more thorough treatment are referred to a previous paper by the author [9], of which the present paper is a condensation.

Natural Climatic Changes

Climate may be defined as the statistics of weather elements as computed for a suitably long period. The length of the period is rather arbitrary; the frequency spectra of the various elements tend to be rather smooth (except for obvious forced cycles such as diurnal and annual cycles). Thirty years is generally taken to be a standard climatological epoch. The choice of weather elements is also somewhat arbitrary, but the primary

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The author is with the National Oceanic and Atmospheric Administration, Atmospheric Physics and Chemistry Laboratory, Environmental Research Laboratories, Boulder, CO 80302.

ones are those which have direct impact on the biosphere. These include temperature, wind, precipitation, evaporation, radiation, and humidity near the ground.

It is evident that if these statistics are nonstationary, the climate will change. If the changes are small or slow, records of many epochs will be needed to detect them. In particular, detection of an anthropogenic influence through statistical analysis alone requires a long run of data of good quality *and careful attention to measures of significance.* It is most important to avoid the *post hoc ergo propter hoc* fallacy that a trend of a few years' duration or less, following some change in human activities, can be attributed to that change even when no sound physical causal relationship is evident. As an example of this error, the hemispherically cold winter of 1962–1963 was attributed by some to the resumption of nuclear weapons testing the year before; these people ignored the fact that the winter of 1941–1942 was approximately as cold. "Cycle-hunting" without a good physical hypothesis can also be misleading; the supposed periodicity may lie in a broad, flat maximum of the spectrum and thus be statistically insignificant.

While one must presume that natural climatic fluctuations result from the operations of the laws of physics and chemistry, it is practically impossible to isolate simple cause-and-effect relationships in the internal workings of the earth–atmosphere–ocean system. This is because all the processes are interconnected by multiple nonlinear positive and negative feedbacks. Also, data about conditions in the distant past are necessarily of indirect type (pollen types in peat bogs, isotope ratios in sedimentary deposits, etc.) and involve assumptions about the constancy over the ages of various factors. These assumptions cannot be proved rigorously. It is therefore necessary at the present time to treat the natural climatic fluctuations as a noisy background spectrum from which we must try to extract the man-forced responses on the basis of coherent physical relationships. Mathematical models of climate are thus essential to the improvement of this signal-to-noise ratio.

A complete discussion of theories relating to natural climatic change is beyond the scope of this paper. Most of them do attempt to rely on a single dominant cause-and-effect relationship and are therefore inadequate for the reason given above. "Extraterrestrial" theories include long-term variations in solar emission, variations in the orbital parameters of the earth, and variations in the density of interstellar dust along the sun's galactic orbit. "Terrestrial" theories include: continental drift; volcanic dust; natural variations in carbon-dioxide concentration; and internal oscillations due to feedbacks involving ice-cover and planetary albedo.

The main features of the long-term temperature record are long periods of warm, ice-free, stable conditions lasting for more than 200 million years separated by cold, highly variable periods of mean duration around 10 million years: the ice ages. Within the latter are higher frequency fluctuations between periods of heavy and light glaciation. Until recently the long-period variations had no convincing explanation, but the rather firm establishment of the modern continental-drift concept based on plate tectonics provides a reasonable explanation for the very slow changes. In the first place, many parts of the crust which now lie in higher latitudes were in low latitudes during

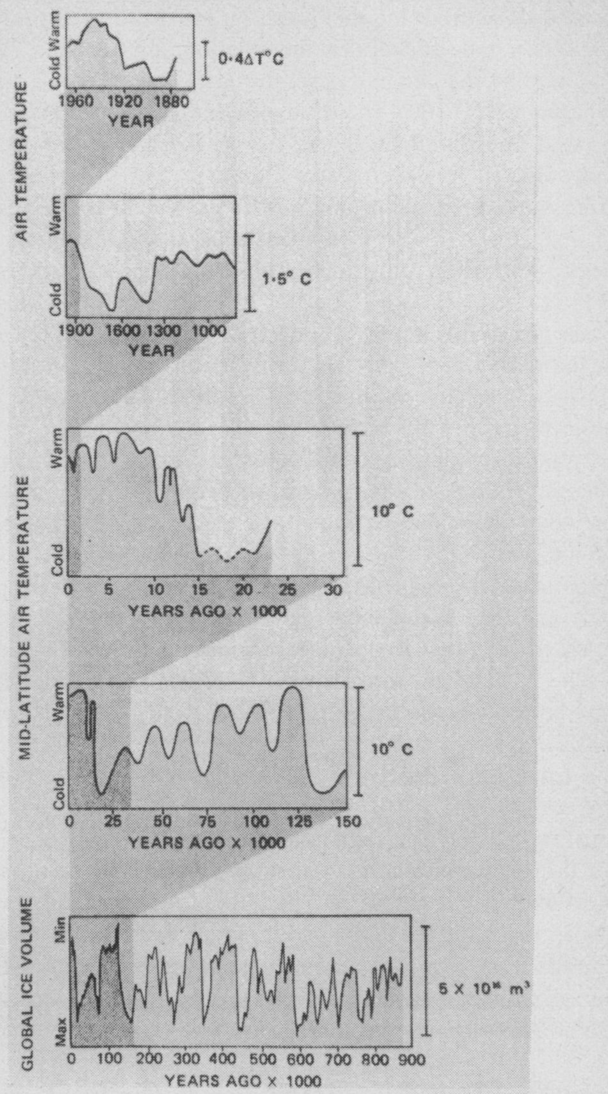

Fig. 1. Variations in temperature and ice cover during the past 9×10^5 years. Time scales run from *right to left*. Maximum ice cover is at the *bottom* of the last graph so that the curve is in phase with the temperature traces. Shading shows where each time interval fits into the next longer one. (From "The Physical Basis of Climate and Climate Modelling" [77].)

the warm periods. More importantly, when the continents are placed as they are at present, the free motion of sea water from low latitudes to one or both polar regions is restricted, thus cutting off an important source of winter heat and permitting the polar sea to freeze. This in turn cuts off the only winter source of heat to the high-latitude atmosphere. The higher frequency oscillations, of the order of 10^4–10^5 years, within the ice ages are probably due to internal feedbacks involving ocean circulations, the effect of ice cover on albedo, evaporation from the sea, cloud cover, wind circulation patterns, etc.

Fig. 1 gives a time series of northern-hemisphere mean temperatures (0-80° N latitude) as reconstructed for past 1.5×10^5 years. The time scale runs from *right to left* in each case. The top graph gives the most recent data on an expanded temperature scale; the 1880–1940 warming trend and the subsequent cooling stand out clearly. The next lower segment shows the period from 800 A.D. to the present; the shading carried down from the first graph shows the latter's position in the longer time frame. The climatic optimum around 1000 is followed by the two minima of the "little ice age" and a gradual recovery after 1700. The third segment has a much more compressed temperature scale and covers the period from 32 000 years B.P. (before the present) to the present. The emergence from the last glacial maximum, with occasional setbacks, is the main feature. It also shows that a thermal optimum about a degree warmer than the present one occurred about 7000 years B.P. The series starting at 1.5×10^5 B.P. shows that only one other glacial maximum, around 1.35×10^5 B.P., was as severe as the most recent one. On the other hand, the ice-cover data (bottom graph) show that the glacials of 4×10^5 B.P. were more severe than the most recent ones.

From these graphs it can be seen that 1) natural climatic changes within an ice age have peak-to-trough amplitudes for the hemispheric-mean temperature changes at low frequencies of the order of 10°C and 2) the frequency spectrum of the fluctuations is very broad, with tendencies toward spectral peaks at several frequencies and a high-frequency rolloff of amplitude (until the very high frequencies of annual and diurnal cycles are reached). The impact of such a change is greater than might first be thought; a change of a few degrees in the hemispheric mean implies a much greater change in high latitudes because the tropics experience the least change but comprise most of the surface area. It is against this noisy background that we must try to detect any man-induced fluctuations. Also, because we do live in an ice age with a 50-percent chance of lasting eight million years more, and because of the apparently greater susceptibility of the system to internal oscillatory instabilities during an ice age, it is necessary to be more alert to possible human influence than if the planet were now enjoying one of the 200-million-year warm spells.

Carbon Dioxide and the Terrestrial Heat Balance

Carbon dioxide exhibits an exceedingly strong and wide absorption band from 13- to 18-μm wavelength, centered on 15 μm, as well as narrower but still strong bands at 2.8 and 4.3 μm and several other weak bands. The 15-μm band is in the part of the infrared spectrum where the radiation from the earth's surface is intense. The terrestrial radiation is absorbed and reemitted by the CO_2, which thus acts as a radiative resistance to the flux of heat to space. The earth, however, must radiate to space as much power as it receives from the sun (in the long run). To do this in the presence of the CO_2 resistance, it must raise its "potential," the planetary surface temperature, to a higher value than if the CO_2 were absent. This is commonly referred to as the "greenhouse effect," although the analogy is not exact. Variations in CO_2 concentration would modulate this effect.

Because water vapor also absorbs strongly in the infrared region, scientists of the early decades of this century believed that the CO_2 contribution to the greenhouse effect would be small because of the spectral overlap and the wide variability of atmospheric water-vapor concentration.

The question of whether man-made CO_2 from fossil-fuel combustion might cause a warming trend was first raised in 1938 by Callendar [10], [11]. Using a rather crude radiative-transfer model, he estimated the temperature trend to be 7×10^{-3}°C · year^{-1} for the period 1910-1930; this is equivalent to an increase of 2.4°C in the mean planetary surface temperature when the CO_2 mixing ratio doubles from 300 to 600 ppmv. He compared this trend with the climatological temperature data and showed that the global mean temperature was rising somewhat faster than the model predicted (this rising trend reversed in 1940).

Eriksson and Welander [12] produced the first CO_2 climatic model to be run on a first-generation electronic computer; it allowed for nonlinear interactions between the sea, atmosphere, and biosphere. Plass [13]-[15] devised a model containing interactions between air, sea, and ice cover which predicted a temperature increase of 3.6°C for a doubling of the CO_2 mixing ratio. He also showed that the overlap between the absorption spectra of H_2O and CO_2 was much less than had been believed previously.

In 1955, Suess [16] began to apply the radiocarbon dating technique to the study of the geochemical cycle of CO_2. Because fossil carbon is nearly free of C^{14} due to radioactive decay, the CO_2 from combustion should be poor in the heavy isotope. The carbon laid down in tree rings of recent date should therefore be deficient in C^{14} as compared with earlier wood, and the trend in the ratio of man-made to total CO_2 should be deducible from radiocarbon analyses of the wood. His results indicated that the man-made CO_2 had caused an increase of only 1 percent since 1900 (as against Callendar's forecast of 10 percent). He concluded that the sea took up 90 percent of the man-made CO_2.

Over most of the globe the sea is characterized by a shallow, warm upper mixed layer (20-100 m thick), separated from the colder main mass by the thermocline, in which the temperature falls rapidly with depth. This layer strongly suppresses any exchange of water between the upper mixed layer and the deeper strata. Only in winter in high latitudes does the surface water cool enough to eliminate the thermocline and permit new water to enter the main mass of the sea; the return of water from below to the surface layer takes place only in regions of upwelling caused by wind stress, mainly off the west coasts of continents. As a result, only about 2 percent of the ocean mass can interact quickly with the atmosphere. The mean residence time of a CO_2 molecule below the thermocline has been found (by radiocarbon dating) to be in the range of 500-3000 years, while the atmospheric residence time is of the order of 20 months to 10 years [16]-[24].

Bolin and Eriksson [25] devised a model containing one atmospheric and two marine reservoirs. The most important achievement of the model was to show that Suess's data were compatible with an uptake by the sea of only 25-40 percent of the annual CO_2 produced by combustion, rather than 90 percent.

All of the data used by Callendar, as well as that collected in the mid-1950's by a Scandinavian sampling network of 15 stations, were obtained by wet-chemical analysis of air samples collected in evacuated flasks. This imposed a severe limitation on the number of data points per unit time which could be acquired. This bottleneck was broken in 1953 by a technological development: the infrared gas analyzer. With this instrument, measurements became continuous, thereby eliminating sampling errors. The manipulatory errors associated with wet chemistry were also eliminated. For the first time, CO_2 measurements with a relative accuracy of ±1 ppmv became possible.

Computation of the effect of a CO_2 increase on global temperature is a somewhat difficult task. Prior to 1956 the models used (such as Callendar's) were very crude and considered only the transfer of energy by radiation. The real atmosphere, however, transfers energy vertically by convection and horizontally by general circulation and eddy diffusion as well as by radiative exchange.

Even as late as 1960, the models appearing in the literature considered only radiative transfer; the main improvement over the older ones was in the use of finer structure in the absorption spectra. The calculations of Plass [13], [14], [26], [27] predicted a mean temperature rise of 3.6°C for a doubling of the CO_2 mixing ratio; contemporary work by Kaplan [27], [28] arrived at a figure only half as large. Another model devised by Möller [29] gave the even lower figure of 1.5°C.

Manabe and Wetherald [30] included the effects of convection as well as radiative transfer and also allowed the water vapor in the atmosphere to increase with temperature; they treated the *relative* humidity as constant. Their prediction was for a rise of 2.36°C with "average cloudiness" when CO_2 is doubled. Other models have yielded increases of 1.2-1.9°C. Giving greater weight to the newer and more realistic models, one can conclude that the climatic effect of raising the CO_2 mixing ratio to 600 ppmv would be a 2°C rise in the global mean air temperature near the ground. This translates (assuming linearity for small changes) into 6×10^{-3} deg $(\text{ppmv})^{-1}$. The CO_2 increment since 1958 has been about 12 ppmv; the climatic effect of man-generated CO_2 should therefore be a warming of about 0.07°C. Since the observed trend after 1940 has been a net cooling (see Fig. 1), it is clear that the effect of CO_2 is buried in the noise level of other unexplained fluctuations.

Particulate Matter: Effects on the Global Heat Balance

Atmospheric aerosols of natural origin, particularly those from volcanoes, had been suggested as possible climate modifiers at a fairly early date. The aerosol problem is rather more complex than the CO_2 problem because of the physical and chemical inhomogeneities of particles and the fact that they are not well-mixed constituents of the atmosphere. Sampling, measuring, and analytical techniques are much more complicated than those used for gas analysis. The interaction of aerosols with radiation involves scattering as well as absorption; in the visible part of the spectrum scattering is dominant.

The particles generated by man are superimposed on a natural background arising from seven sources: wind-raised soil particles, sea spray, volcanoes, forest and grass fires, meteorites, and gas-to-particle conversions by oxidation of sulfur dioxide and organic vapors of biological origin. The main removal mechanism for tropospheric particles is precipitation scavenging; the mean residence time is of the order of one or two weeks. In the stratosphere sedimentation is the removal mechanism; the mean lifetime there is one to three years. In the troposphere, wind-raised dusts dominate except on rare occasions. The main source regions are the Sahara, the Middle East, Pakistan, and northwest India. The dust may extend to altitudes of 9000 m above sea level, may be blown 5000 km or more by wind, and may be dense (areal loadings of $1\ g \cdot m^{-2}$). The "blue haze" formed by oxidation of terpenes from coniferous forests is another widespread but weaker source. Sea-spray particles are ubiquitous, being found even in remote inland locations. Carbon and ash from forest fires appear intermittently, often persisting for 2000 km or more from the source. The most highly variable source, which is sometimes dominant for short periods, is vulcanism.

Collecting, measuring, and analytical techniques are numerous and varied. Direct collection on plastic filters, by aspiration at the ground or on aircraft, is used when chemical analysis is required. The newest and most convenient analytical technique is scanning electron microscopy combined with X-ray emission spectroscopy [31].

When information is desired throughout a large volume of the atmosphere, direct sampling is far too slow. If one does not need the chemical composition but only the concentration and size distribution, "flow-through" optical imaging and counting instruments [32] may be used to acquire data millions of times faster than filter sampling and processing. Remote sensing techniques can be employed to increase the data acquisition rate even more; the most commonly used technique is measurement of atmospheric attenuation of sunlight (turbidity). The lidar, or laser radar [33]-[36], is also useful because it gives information on the spatial distribution of the particle concentration. Both of these procedures depend on the light-scattering properties of the aerosol; for that reason they cannot give unique determinations of particle loading or size distribution. One must make some physical assumptions to close the problem.

Another "flow-through" *in-situ* automatic measurement which gives indirectly (and nonuniquely) the aerosol concentration is measurement of the electrical conductivity of the air. Molecular ions are continually formed by cosmic rays and natural radioactivity. Being of small mass, these ions are highly mobile. When particles are present, the ions attach themselves to the particles and their mobility decreases greatly. This gives rise to lower conductivity for higher particle concentrations.

Because solar-radiation measurements, stellar brightness measurements, and conductivity measurements have been made for other reasons at many locations and for many years, a large stock of data is available for interpretation in terms of aerosol loading. Conductivity measurements using the same technique have been made on oceanographic cruises for the past 70 years; Cobb and Wells have summarized this data [37]. The downward trend in the North Atlantic and the absence of such a trend in the South Pacific suggest that a particulate plume from the United States extends into the mid-Atlantic and that it is becoming denser with time. A similar, but weaker, plume is located in the Pacific east of Japan [38], [39]. A more recent study by Cobb [40] shows that all ocean areas except the two just mentioned and one other in the Indian Ocean are showing constant conductivities. The Indian Ocean change is probably due to increase in wind-raised particles in connection with drought conditions in Africa and Asia. The North Atlantic plume has been confirmed by direct sampling from ships [41].

Aircraft sampling and optical sounding have revealed the existence of a permanent aerosol layer in the stratosphere. This layer, named unofficially for Junge, who first sampled it from an aircraft [42]-[44], is found at about a 15-km altitude in high latitudes and near 23-km altitude in the tropics. Its main constituents are solid sulfate particles and sulfuric-acid droplets. The particle loading in this layer increases greatly after strong volcanic eruptions; the base level is probably maintained by oxidation of natural (and man-produced) SO_2 and H_2S by atomic oxygen or ozone.

An estimate of human production of SO_2 in 1965 is 149 megatons (Mt) per year [45] (whenever "ton" or a multiple thereof is used in this paper, the metric ton, 10^3 kg or 2240 lb, is meant). The production of H_2S is 3 Mt yr^{-1}. Conversion to H_2SO_4 gives 237 Mt yr^{-1} for the anthropogenic source strength of this substance. Man-made solid particles amount to between 10 and 90 Mt yr^{-1}, while the natural solid-particle production is between 425 and 1100 Mt yr^{-1} [6, p. 189]. The conversions from the gases provide a human contribution of between 175 and 325 Mt yr^{-1} (the spread of the figure given above) and a natural one of 345-1100 Mt yr^{-1} of which 25-150 come from volcanoes [46]. The man-made contribution to the atmospheric aerosol is therefore somewhere between 11 and 35 percent of the total and is of the same order as the volcanic contribution. Why, then, does the volcanic aerosol dominate the picture completely in areas remote from human sources?

The answer is that the precipitation scavenging of particles produced near the ground is very efficient, giving rise to the short residence time in the troposphere [47]. Most of the volcanic aerosol is also scavenged in this way, but more energetic eruptions deliver some of their particles and gases directly to the stratosphere where the residence time is much longer.

Weickmann and Pueschel [47] also point out that at present growth rates, the human aerosol production will equal the natural by the end of the century and that this production is concentrated on only 2.5 percent of the earth's surface.

A synthesis of the data discussed above leads to the conclusion that the climatic effects of particulate pollution are not likely to be felt on a global basis unless emissions increase by an order of magnitude or more, but that they are already noticeable on the local and regional scales and will become more so if upward trends in particle emissions are not checked.

Unlike CO_2, increases in aerosols may cause either a net cooling or a net warming, depending on the optical properties of the particles and the underlying surface. It the albedo of the earth for solar radiation is lowered by the addition of aerosol, net warming will result; if it is raised by the particles, cooling will ensue. The effect on climate near the ground will depend on the altitude of the aerosol layer. If net warming is expected on the basis of the albedo, but the particles are at a high altitude, the air at that height will be warmed but cooling will take place at the ground. The vertical temperature gradient will be reduced and convection will be inhibited. If the aerosol's absorption of solar radiation is weak, cooling will occur regardless of the altitude of the particles.

A number of models has been devised in the past six years or so for predicting the climatic effect of aerosols. In the interest of conserving pages they will not be described in detail; the reader is again referred to the author's earlier paper [9].

Because of the sensitivity of the calculations to the imaginary (absorptive) part of the refractive index, which is poorly known for atmospheric aerosols, it is not surprising that the various models predict a wide range of effects, from strong cooling to weak warming. The models also vary with regard to the amount of interaction between effects of particles, CO_2, and water vapor which they allow.

A few numerical results are given below. Barrett [48] assumed no absorption by the particles and no interactions, considering only the depletion of insolation due to backscattering The model yielded an almost linear relation between percentage depletion and areal particle loading up to $0.1\ g \cdot m^{-2}$. This loading corresponds to a total aerosol burden of 51 Mt, or a little more than ten times the estimated mean volcanic dust load. The computed loss of insolation for this loading was 13 percent, resulting in a cooling of 10°C near the ground.

Rasool and Schneider [49] used a more elaborate model in which CO_2, water vapor, aerosols, and clouds were all present. They found less warming from CO_2 than did Manabe and Wetherald [30] and found that quadrupling the present mean dust load reduced the surface temperature by 3.5°C.

On the other hand, calculations by Mitchell [50], [51], Atwater [52], [53], and Ensor *et al.* [54], predict either cooling or warming depending on slight shifts in the ground albedo and the particle absorption index. Russell and Grams [55] found experimentally an absorption index of 5×10^{-3} for Colorado soil particles; they concluded that for this index and the size distribution they observed (rather larger mean size than that of aerosol with long residence time), the aerosol would produce a net warming.

On the basis of the foregoing, it may be tentatively concluded that wind-raised dusts and carbon particles near the ground should produce warming, but that the stratospheric aerosol layer should cause net cooling at the ground at all times, even when it contains mineral particles from volcanoes (the layer itself will be warmed in that case).

There is evidence that the strongest volcanic eruptions which delivered substantial dust loads to the stratosphere, such as Laki and Asama (1783), Tamboro (1815), and Krakatoa (1883), were followed by temporary drops in mean mid-latitude surface temperatures of the order of 1°C and of one to three years' duration [56]. Unfortunately, the climatological data base was not really adequate in those years to permit an accurate experimental determination of the interrelationship of solar-energy depletion, dust load, and cooling. Other short-term coolings of the same magnitude and duration have occurred in the absence of volcanic activity. Since the man-made contribution to the atmospheric aerosol with a long residence time is undetectable against the fluctuations in volcanic-dust loading, and since the thermal perturbations from even the largest eruptions are of the same order as other unexplained fluctuations, it can be concluded that man-generated aerosols are not exerting a measureable influence on global climate at present.

Thermal Pollution: Global Effects

Radiation is the only means by which energy can escape from the planet. All received solar radiation as well as any energy released by man (combustion or nuclear) must be radiated to space. An exception is that stored as chemical energy in natural (peat) or man-made (plastics) organic matter with a long lifetime, but this amount is relatively small. Increased energy use therefore leads to increased infrared radiation from the earth and a higher temperature at the ground.

If feedbacks are neglected, an estimate of the climatic effect of man-released energy may be made on the basis of recent energy use and its growth rate. An upper bound to the power demand in 1970 [5], [6] was 8×10^6 megawatts (MW), or 1.57×10^{-2} W · m^{-2} averaged over the globe. The solar input, averaged over the globe and over the year, is 100 W · m^{-2}, the human contribution is 0.016 percent, or about one part in 6000, of the received solar energy. If, however, the anthropogenic part is considered to be released in urbanized areas, the power density in them rises to 12 W · m^{-2} or almost an eighth of the solar input; this is a very sizeable fraction.

The growth rate of energy use in 1970 was 5.7 percent per year for the world as a whole [5, p. 64]. Assuming constancy of this figure, the waste heat would be 0.087 percent of the solar power by the year 2000, and the global mean temperature (calculated with the Stefan-Boltzmann law) would have risen by 0.06°C. By 2050, these figures would become 1.5 percent and 1.07°C, respectively; the effect would begin to be generally perceptible. If such growth continued until 2100, the human contribution would be 25.9 percent of the solar and the rise in mean temperature from the 1970 base would be 17.1°C, more than enough to terminate the current ice age. So long as man is dependent on fossil fuels and current nuclear-power technology, however, the last pair of figures will never be attained. At the projected growth rate, fuel consumption in 2100 would have to be 1652 times as great as in 1970. The known fossil-fuel reserves in 1970 amounted to about 3×10^6 Mt, expressed as carbon. Calculating with the 1970 rate of use and applying the 5.7 percent annual growth in consumption gives the result that all fuel would be gone by the year 2032. At that time, the human contribution would be 0.85 percent of the solar power and the temperature elevation would be 0.39°C. This probably gives an upper bound to the climatic effect of thermal pollution.

If, however, a nearly inexhaustible energy source such as hydrogen fusion, or total conversion of mass to energy, should be developed, and if this were taken as a carte blanche for unlimited population growth and energy use, then a climatic disaster would ultimately ensue. In particular, the concentration of energy release in huge cities would render them uninhabitable if the projected energy use by 2100 were actually attained. It must be realized that there exists a Malthusian limit on total energy release by man which is set by the upper bound to temperature tolerance by man and his sources of food, and that this limit cannot be circumvented by any exercise of human ingenuity.

The sea would, of course, buffer the temperature rise to some extent. However, just as for CO_2, only the upper mixed layer would be actively involved; this limits very greatly the amount of buffering. Melting of polar ice would retard warming, but would raise sea levels, thereby inundating many heavily populated areas and causing severe social and economic problems.

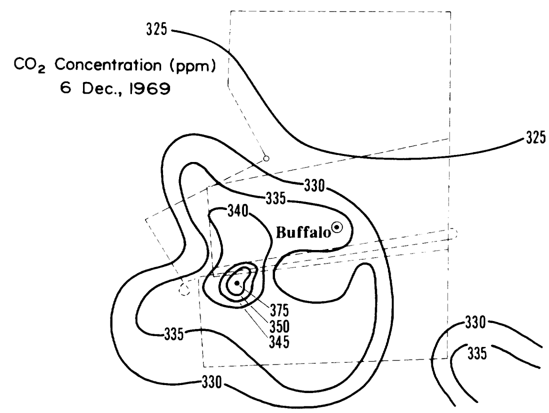

Fig. 2. Contours of carbon dioxide mixing ratio at approximately 300 m above ground level near Buffalo, NY on Dec. 6, 1969. Dashed lines show aircraft flight track. (From Barrett *et al.* [60].)

Local and Regional Effects of Urban Pollutants

Generally speaking, the primary sources of pollutants are large metropolitan areas with concentrations of heavy industry and automobile traffic. Differences between urban and rural climates were apparent to the inhabitants long before climatological networks existed. Particulate pollution in the form of smoke was an urban problem long before the industrial revolution, but was, of course, greatly exacerbated by it.

The thermal climate of urban areas has been studied for well over a century; a bibliography of publications from 1833 to 1951 has been published [57]. More recent work with more sophisticated instrumentation and aircraft has provided a three-dimensional picture of the urban "heat island." At the ground, on calm, clear nights, the inner-city temperature may be as much as 20°C warmer than adjacent rural locations which lie in shallow concavities. The heat also prevents the formation of the nocturnal temperature inversion close to the ground; an isothermal or even a lapse layer overlies the central city. Sometimes an elevated inversion is found above this urban boundary layer. The destabilization of the air over the city is also effective by day; it results in an earlier onset of cumulus clouds and rain showers over the city. The heat islands of larger cities show up clearly on the infrared radiometers of weather satellites. Radiative temperatures 3 to 4°C warmer than the surroundings are typical of east-coast United States cities [58].

Heat budgets of some cities have been estimated. In the case of Budapest, Hungary, with a continental climate, the man-released energy is 11.7 kcal · cm^{-2} · yr^{-1} as against a solar input of 87.0 in the same units, or 13.4 percent of the latter [59]. For Sheffield, England, with a cloudier maritime climate, the human contribution is about 30 percent. The magnitude of these figures shows the need for concern over urban thermal climates if present exponential growth rates of energy use continue.

Gaseous and particulate pollution are also concentrated near cities. Fig. 2 shows contours of CO_2 mixing ratio (ppmv) at about 300 m above the ground near Buffalo, New York, on a winter day. Excesses of 17 percent over the rural level of 320 ppmv are found in the industrial areas [60]. The distribution of Aitken nuclei (total small particles) over and near the city,

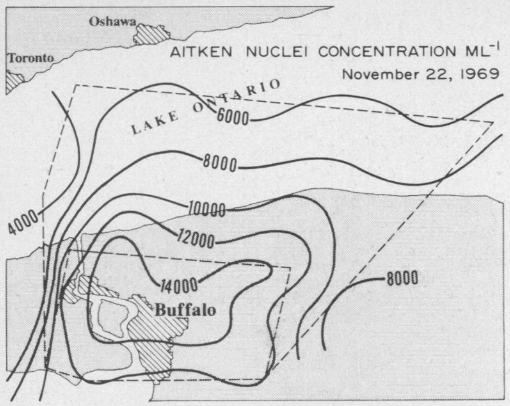

Fig. 3. Contours of Aitken nucleus counts total (small particles) in number per milliliter of air measured at approximately 300 m above ground level near Buffalo, NY on Nov. 22, 1969. Dashed lines show aircraft flight track. (From Barrett *et al.* [60].)

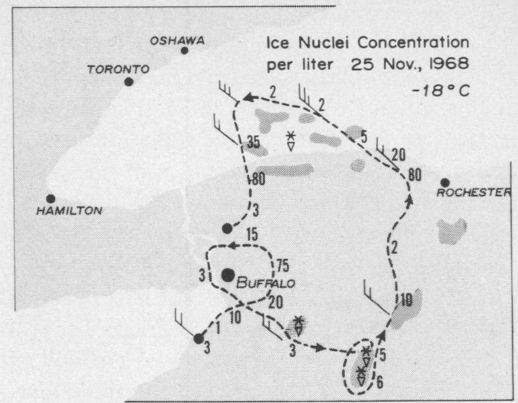

Fig. 4. Winds and ice-nucleus counts (number per liter active at -18°C) near Buffalo, NY at approximately 300 m above ground level. Dashed curve is aircraft flight track. Heavy stippled areas are snow showers observed by radar; conventional symbols are snow showers reported by ground observers. Positions of showers correlate well with plumes of elevated ice-nucleus counts emanating from Buffalo, Toronto, and Oshawa. (From Barrett *et al.* [60].)

shown in Fig. 3, again demonstrates the city's role as a source.

These urban and regional blankets of particles reduce the insolation received at the ground; the effect on temperature is, as already discussed, still uncertain. Since the layers are close to the ground, they could produce warming if carbon or other good absorbers are major constituents; cooling is likely if they are mainly sulfate or sulfuric acid. There is some evidence [61], [62] that thick urban aerosol layers contribute to the greenhouse effect; nocturnal minimum temperatures correlate positively with turbidity, and measured downward infrared fluxes increase by some four percent in very turbid episodes. It is uncertain whether the aerosols alone are responsible or whether the effect is due to concomitant elevations of CO_2 concentration.

Aerosols can also act as modifiers of clouds. The hygroscopic sulfates and other soluble or wettable species act as cloud condensation nuclei (CCN) on which all cloud droplets must form; they may also serve as ice nuclei (IN) which induce supercooled cloud drops to freeze and grow faster as ice crystals (water out of contact with solid bodies never freezes at 0°C). One would expect to find differences in the statistics of clouds and precipitation in the vicinity of urban particle sources. The well-known London "pea-soup" fogs come immediately to mind in this connection. Remarkable decreases in fog density and frequency in London and other British cities took place after the Clean Air Act of 1956 went into effect. Kew Observatory experienced 50 percent more hours of sunshine in winter during the period 1958-1967 as compared with the mean for the climatological epoch 1931-1960 [63]-[65].

Until recently, the effect on precipitation was uncertain. A few suggestions that cities received more rainfall than their environs appeared in the earlier literature, but no clear-cut evidence was presented. The physical problem is complicated by the fact that CCN and IN can enhance or reduce precipitation depending on the temperatures and vertical extent of the clouds; this is one reason why the outcome of intentional cloud seeding experiments is so variable. (For a more complete discussion of this point, see [9, p. 66].) The work of the METROMEX program [8] at St. Louis, Missouri, from 1971 to 1975 has shed some light on the matter. This program made use of a surface precipitation-measuring network of 228 stations, 13 pilot-balloon tracking stations, several whole-sky cameras, atmospheric-electric measuring equipment, radar, lidar, and as many as seven instrumented aircraft. The final report of the project is not yet available, but preliminary reports [8] show that rainfall, lightning frequency, and hail attain maxima 15-25-km downwind from the city. Chemical tracers were used to verify the entry of the urban aerosols into convective clouds; these experiments showed that heated and polluted plumes did rise from the city and enter the clouds. Increases in CCN counts inside the clouds of 50-90 percent were measured; clouds affected by these nuclei differed in their drop-size distributions from upwind clouds in just the way predicted by a cloud microphysical model.

Another example of a direct connection between urban-industrial pollution and precipitation is given in Fig. 4 [66], in which winds and ice-nucleus counts observed along the flight track of a NOAA DC-6 research aircraft near Buffalo are displayed. Dark stippled areas are snow showers as seen by radar; conventional symbols are locations of snow showers observed from the aircraft. It can be seen that the precipitation correlates very well with the elevated IN counts, that the latter are found in plumes downwind of the industrial areas of Buffalo, Toronto, and Oshawa, and that no snow is falling elsewhere. For a more thorough review of urban climatic influences, the reader is referred to an article by Landsberg [67].

Nonurban Aerosols as Nuclei

Although urban-industrial areas are the main sources of particulate pollution, some agricultural practices involving burning of extensive areas of vegetation produce enough nuclei to have at least a local effect on clouds and precipitation. The best example is the preparation of sugar cane for harvesting by burning off the leaves of the standing plants. Warner [68] found that this smoke was a good source of CCN; he then examined 60 years of data from stations upwind and downwind of the sugar-growing district in Australia and found significantly lower rainfall at the downwind stations during the harvest season. The difference disappeared at other times of the year. This is the expected result of introducing excess CCN; the clouds of that region (20° S latitude) are warm and produce rain mainly by the coalescence process. An excess of CCN leads to formation of clouds with smaller and more nearly monodisperse droplets whose coalescence efficiency is very low; such clouds are colloidally stable.

More recently, Pueschel and Langer [69] showed that the ash from cane-field burning in Hawaii is a source of IN. They observed more than a tenfold increase in IN counts downwind from a cane field after the fire was started. Laboratory tests showed that the ash rather than the smoke was the source of the nuclei; the authors suggested that the copper and zinc compounds present in the ash are the active substances.

Although these nuclei sources may be important locally, their global contribution is overshadowed by those from naturally occurring forest and grass fires and those started accidentally by man.

Mathematical Modeling of Climatic Change

It has been shown in the preceding sections that, up to now, man's impact on the global climate has been too weak to stand out from the noise level of unexplained natural fluctuations. If one must rely only on statistical treatment of data, then long series are necessary to permit extraction of a weak effect. On the other hand, if the planetary climate exhibits instabilities as a result of feedbacks, it is possible that a weak effect might undergo rapid amplification after a latency period. It is therefore desirable and necessary to have mathematical models, based on physical relationships, to supplement the statistical methods.

Because changes with time are the essence of climatic modeling, climate models are almost always prognostic; they solve initial-value problems. They are classified according to the number of spatial dimensions which they treat. Zero-dimensional models have occasionally been used to forecast global-mean temperature changes; they are energy-budget equations of the form: power in from sun minus power radiated or scattered to space equals time derivative of stored energy. One-dimensional models provide vertical distributions of global means. Two-dimensional models are concerned with either areal distributions of ground-level parameters or with vertical profiles of zonal-mean quantities; they ignore variations with longitude and are axisymmetric. The latter type requires the energy-balance (thermodynamic) equation, the mass-balance (continuity) equation, and the north-south momentum equation for quantities averaged around each latitude circle. They obviously cannot cope with the uneven distribution of land and water which is so instrumental in determining the real climate.

Three-dimensional models are, of course, the only ones capable of describing and predicting climates of specific geographic regions. They involve the full set of physical relationships (conservation of mass, energy, and momentum) and specification of boundary conditions over the globe. The couplings between the ocean and the atmosphere must be incorporated. These models are, in general, of the same type as those used for short-term weather prediction, but require more care in design because effects of such things as air-sea interaction and radiative energy transfer, which are not so important for short-range forecasts, are critical for climatic predictions.

The demands on the computer increase strongly as the number of dimensions and the fineness of temporal and spatial resolution are increased. This is an important reason for the existence of zero- and one-dimensional models. When computing, continuous fields must be represented by values at discrete grid points. Space and time derivatives are replaced by their finite-difference analogs. The memory capacity of the computer and the time limit for a computation set the lower bounds for grid-point spacing. If too coarse a grid is used, on the other hand, the cumulative errors arising from the finite-difference approximations will completely dominate the model output. A compromise must be made; the data must be carefully smoothed in space and time so that a coarse grid may be used, and the small-scale and high-frequency phenomena thus filtered out must be reintroduced in parameterized form as diffusion-like transport processes affecting the larger scales.

The reader interested in a more complete discussion of climate modeling is referred to an article by Smagorinsky [70].

Progress in climate models has been tied closely to advances in computer technology. Mintz and co-workers [71], [72] devised three-dimensional models in 1965 based on the smoothed fluid-mechnical and thermodynamic equations. These were used to study the consequences of such things as changes in the Arctic Sea ice pack. Because of computer limitations, these models used only two grid levels in the vertical. These workers noted that a computer would need one order of magnitude more memory and two to three orders of magnitude increase in speed to permit the resolution to be raised to a really acceptable degree of fineness.

Sellers [73] developed a model which deals with all three dimensions, but uses explicitly only the energy-balance equation averaged over a month. Vertical profiles of temperature, wind, and humidity are parameterized on the basis of their ground-level values, the surface pressure, and the north-south temperature gradient. Radiative effects of CO_2, ozone, water vapor, and aerosols are taken into account. A virtue of the model is the high ratio of model time to real time; one year of model time corresponds to 18 of running time on a CDC-6400 computer. In spite of the heavy parameterization, the model did react in a fairly realistic way to simulated changes in CO_2 and solar energy input. A most interesting feature was the existence of a bistable (two-valued) solution for the global-mean temperature at the present value of the solar constant; different temperatures were obtained when this input was approached from above and from below. Schneider and Gal-Chen [74] modified the model by relaxing some of its artificial constraints and studied the effects of varying the initial conditions (rather than the forcing). For some combinations of parameters they also obtained bistable solutions for the temperature.

Manabe and Holloway [75] developed a three-dimensional general-circulation model in which the atmosphere and the sea are coupled, but in which the state of the sea is updated much less frequently than that of the atmosphere. The price paid for this physically more realistic approach is a slow-running program; one model year for the atmosphere required 1200 h of computer time (on a Univac 1108). Washington [76] used a general-circulation model to simulate effects of thermal pollution. When the heating was increased 0.4 $W \cdot m^{-2}$ (about 100 times the present-day release by man) the mean temperature in the polar regions increased by about 8°C.

Although these efforts at climate modeling do show what appear to be realistic responses to changes in forcing or initial conditions, one cannot be certain that they are not simply reflecting their designers' choices of the parameterizations which are always necessary to make the computations feasible. The models which contain the most physics and the least human judgment are likely to give the most realistic results. On the other hand, it seems likely that the ultimate physical limits to computer capacity and speed will be too low to accommodate a model based entirely on fundamental physics and having adequate space-time resolution and running speed. Meanwhile, close interaction between the monitoring networks, the computer designers, and the modelers will undoubtedly improve very long-range forecasts to some extent.

Conclusions

Careful measurements made during the past two decades have shown that the atmospheric carbon-dioxide mixing ratio has been rising at an average rate of about a quarter percent per year from a base figure of 313 ppmv in 1958. Various models of the geochemical CO_2 cycle predict a concentration between 350 and 415 ppmv by the end of the century. Thermodynamic and hydrodynamic models indicate that the CO_2 increase from 1958 to 1973 should have caused a rise of about 0.07°C in global mean temperature. This is too small to be detected in the actual climatological data. By the end of the century the upward trend should increase the temperature by 0.3°C; this trend *might* be detectable by careful analysis unless it is offset by other effects, such as those of aerosols.

Upward trends in man-made aerosols in the vicinity of cities are easily observed by direct sampling and by turbidity measurements. Plumes of particles from the heavily industrialized east coast of the United States and from Japan have been traced several thousand kilometers downwind over the oceans. In western Europe the plumes from industrial cities often merge to produce a regional pall which depletes the solar radiation by as much as 68 percent. The mean residence time for man-made particles is, however, only a week or two; precipitation scavenging removes them rather efficiently. Natural aerosols formed in the stratosphere by gas-to-particle conversions, or injected there by volcanoes, have a much longer residence time of the order of a year or two.

Models of the thermal effect of aerosols disagree as to the magnitude and even the sign of the effect. Sulfate or sulfuric-acid aerosols (the normal stratospheric layer) should cause surface cooling, while wind-raised soil particles and man-made carbon particles would cause warming if they were confined near the ground. The probable overall effect is a slight cooling which acts in opposition to the warming by CO_2.

Particles also act to modify clouds by virtue of their nucleating properties; the effect is again felt only on a local scale near large metropolitan areas, mainly within 30 km or so of the center. The observed effect is an increase in amount and frequency of shower-type precipitation. Under stable conditions, the cloud condensation nuclei cause increases in fog duration and density. No global influence on precipitation by man-made aerosols is yet detectable.

Heat from combustion and nuclear reactors is currently about $0.016 \text{ W} \cdot \text{m}^{-2}$ when averaged over the globe, or about one part in 6000 of the mean solar power input to the planet. It is however, strongly concentrated in urban areas where the flux density is of order $12 \text{ W} \cdot \text{m}^{-2}$. The resulting "heat islands" act to increase convection, which in turn helps to carry the particulate matter into the clouds.

It may be concluded that, up to the present, we, the human population, have not had any detectable influence on the global climate. The climatic impact has been felt mainly in and around the large metropolitan areas of the developed nations; these areas have higher mean temperatures, a smaller diurnal temperature range, and higher precipitation than rural environments. Calculations also indicate that, unless feedback mechanisms exist which can result in runaway instabilities, all known fossil-fuel reserves will be exhausted before the climatic alterations become at all serious. If, however, vast new sources of energy from hydrogen fusion or some other process of total conversion of mass to energy become available, and if this is taken as a mandate for uncontrolled population growth and industrial expansion, thermal pollution will bring on climatic and ecological disaster.

Another caveat is in order. Since man's energy needs are at present less than one percent of the solar input, it would seem that conversion of solar radiation to usable energy would circumvent both the fossil-fuel exhaustion problem and the thermal-pollution problem at one stroke. While this is correct (ignoring any economic constraints for the purpose of this discussion), it must be realized that collecting any sizeable fraction of the solar input from, say, the subtropical desert regions and ultimately releasing it as heat in higher latitudes would necessarily cause modification of storm tracks and precipitation patterns.

The question of possible instabilities due to positive-feedback loops is one which must be answered by mathematical climate models (or the planet itself!). Such modeling is a child of the computer age and will always place the utmost demands on computer technology. The most sophisticated models developed to date do not exhibit runaway instability in response to small perturbations, although some give multiple-valued outputs for the same initial conditions but different rates of change of these initial conditions. On the other hand, the climatic record of the past million years does show those natural oscillations; this means that easily triggered instabilities cannot be ruled out. It is for this reason that careful monitoring at benchmark stations and research in climate modeling must be continued and in fact expanded. These complementary activities constitute an early-warning defense system to provide an alert in case the forecasts of man-induced climate modification summarized in this paper should turn out to be overly conservative.

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Letters to the Editor

Geophysical Tests for Relativistic Synchronization Procedures in Rotating Frames of Reference

JEFFREY M. COHEN AND HARRY E. MOSES

In 1905 Einstein [1] proposed a synchronization procedure for synchronizing clocks in an inertial frame. The procedure has been extended to synchronizing noninertial clocks which lie on a curve [2]. The procedure is not, in general, unique in noninertial frames, i.e., the readings which the clocks have depend on the curve along which they are synchronized.

A particularly simple noninertial frame is a rotating frame of reference for which the line element is [2]

$$ds^2 = -\gamma^{-2} c^2 (dt - r^2 c^{-2} \omega \gamma^2 \sin^2 \theta \, d\phi)^2 + dr^2 + r^2 \, d\theta^2 r^2 \gamma^2 \sin^2 \theta \, d\phi^2 \tag{1}$$

where

$$\gamma^{-2} = 1 - r^2 \omega^2 c^{-2} \sin^2 \theta$$

and ω is the angular velocity of rotation (gravity is neglected but the spatial metric given by the last three terms of (1) is curved because of the presence of γ^2). From this line element it is possible to obtain the difference in time by going around a closed path of synchronized clocks. By integrating the time-like part of the line element (1) around a closed loop, one obtains [2] (for $r\omega c^{-1}$ small)

$$\Delta t = \pm 2 \omega c^{-2} S \tag{2}$$

where S is the projected area of the contour on a plane perpendicular to the axis of rotation. The sign is positive or negative depending on whether the curve is traversed in or opposite to the direction of rotation.

It does not seem to be generally realized that synchronization effects due to the rotation of the earth and satellites about the earth are large and measureable and therefore can be used as a basis for tests of the synchronization procedure.

Example 1: Let us place many clocks about the earth's equator and synchronize around the equator. At the starting point of the synchronization process assume that there are two clocks. In going about the earth in a clockwise direction as observed from the North Pole, we synchronize the second clock with the first, the third with the second, etc., in the prescribed order. When one returns to the starting point, one synchronizes the previously unsynchronized clock with the preceding one. The difference in time between the two clocks at the starting point is from (1) or (2)

$$\Delta t = 2\pi r^2 \omega c^{-2} = 0.2 \, \mu s \tag{3}$$

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J. M. Cohen is with the Physics Department, University of Pennsylvania, Philadelphia, PA 19104.

H. E. Moses is with the Center for Atmospheric Research, University of Lowell, Lowell, MA 01854.

