18 December 1970, Volume 170, Number 3964

SCIENCE

Man-Made Climatic Changes

Man's activities have altered the climate of urbanized areas and may affect global climate in the future.

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Climate, the totality of weather conditions over a given area, is variable. Although it is not as fickle as weather, is fluctuates globally as well as locally in irregular pulsations. In recent years some people have voiced the suspicion that human activities have altered the global climate, in addition to having demonstrated effects on local microclimates. There have also been a number of proposals advocating various schemes for deliberately changing global climate, and a number of actual small-scale experiments have been carried out. For most of the larger proposals, aside from considerations of feasibility and cost, one can raise the objection that a beneficial effect in one part of the earth could well be accompanied by deterioration elsewhere, aside from the inevitable disturbances of the delicate ecological balances.

But the question "Has man inadvertently changed the global climate, or is he about to do so?" is quite legitimate. It has been widely discussed publicly—unfortunately with more zeal than insight. Like so many technical questions fought out in the forum of popular magazines and the daily press, the debate has been characterized by misunderstandings, exaggerations, and distortions. There have been dire predictions of imminent catastrophe by heat death, by another ice age, or by acute oxygen deprivation. The events foreseen in these contradictory prophesies will obviously not all come to pass at the same time, if they come to pass at all. It seems desirable to make an attempt to sort fact from fiction and separate substantive knowledge from speculation.

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Natural Climatic Fluctuations

In order to assess man's influence, we must first take a look at nature's processes.

The earth's atmosphere has been in a state of continuous slow evolution since the formation of the planet. Because of differences in the absorptive properties of different atmospheric constituents, the energy balance near the surface has been undergoing parallel evolution. Undoubtedly the greatest event in this evolution has been the emergence of substantial amounts of oxygen, photosynthetically produced by plants (*1*). The photochemical development of ozone in the upper atmosphere, where it forms an absorbing layer for the short-wave ultraviolet radiation and creates a warm stratum, is climatically also very important, especially for the forms of organic life now in existence. But for the heat balance of the earth, carbon dioxide (CO_2) and water vapor, with major absorption bands in the infrared, are essential constituents. They absorb a substantial amount of the dark radiation emitted by the earth's surface. The condensed or sublimated parts of the atmospheric water vapor also enter prominently into the energy balance. In the form of clouds they reflect incoming short-wave radiation from the sun, and hence play a major role in determining the planetary albedo. At night, clouds also intercept outgoing radiation and radiate it back to the earth's surface (*2*).

Over the past two decades Budyko (*3*) has gradually evolved models of the global climate, using an energy balance approach. These models incorporate, among other important factors, the incoming solar radiation, the albedo, and the outgoing radiation. Admittedly they neglect, as yet, nonlinear effects which might affect surface temperatures (*4*) but it seems unlikely that, over a substantial period, the nonlinear effects of the atmosphere-ocean system will change the basic results, though they may well introduce lags and superimpose rhythms. Budyko's calculations suggest that a 1.6 percent decrease in incoming radiation or a 5 or 10 percent increase in the albedo of the earth could bring about renewed major glaciation.

The theory that changes in the incoming radiation are a principal factor governing the terrestrial climate has found its major advocate in Milankovitch (*5*). He formulated a comprehensive mathematical model of the time variations of the earth's position in space with respect to the sun. This included the periodic fluctuations of the inclination of the earth's axis, its precession, and the eccentricity of its orbit. From these elements he calculated an insolation curve back into time and the corresponding surface temperature of the earth. He tried to correlate minima with the Pleistocene glaciations. These views have found considerable support in isotope investigations, especially of the $^{18}O/^{16}O$ ratio in marine shells (*6*) deposited during the Pleistocene. Lower ^{18}O amounts correspond to lower temperatures. Budyko and others (*7*) raise some doubts that Milankovitch's theory can explain glaciations but admit that it explains some temperature fluctuations. For the last 1700 years there is also evidence that the ^{18}O content of Greenland glacier ice is inversely correlated to a solar activity index based on auroral frequencies (*8*). Again, low values of ^{18}O reflect the temperature at which the precipitation that formed the firn fell.

The fluctuations of externally received energy are influenced not only by the earth's position with respect to the sun but also by changes in energy emitted by the sun. Extraterrestrial solar radiation fluctuates with respect to spectral composition, but no major changes in total intensity have yet been measured outside the atmosphere. The occurrence of such fluctuations is indicated by a large number of statistical studies (*9*), but ironclad proof is still lacking. Such fluctuations are of either long or short duration. They have been tied to the solar activity cycle. Inasmuch as details are yet unknown, their effect on climate is at present one factor in the observed "noise" pattern.

In the specific context of this discussion, we are not concerned with the major terrestrial influences on climate, such as orogenesis, continental drift, and pole wanderings. But other, somewhat lesser, terrestrial influences are also powerful controllers of climate. They include volcanic eruptions that bring large quantities of dust and CO_2 into the air, and natural changes of albedo such as may be caused by changes in snow and ice cover, in cloudiness, or in vegetation cover (*10*). The fact that we have not yet succeeded in disentangling all the cause-and-effect relations of natural climatic changes considerably complicates the analysis of possible man-made changes.

The Climatic Seesaw

It was only a relatively short time ago that instrumental records of climate first became available. Although broad-scale assessments of climate can be made from natural sources, such as tree rings (*11*) or pollen associations, and, in historical times, from chronicles that list crop conditions or river freezes, this is tenuous evidence. But a considerable number of instrumental observations of temperatures and precipitation are available for the period from the early 18th century to the present, at least for the Northern Hemisphere. These observations give a reasonably objective view of climatic fluctuations for the last two and a half centuries. This is, of course, the interval in which man and his activities have multiplied rapidly. These long climatic series are mostly from western Europe (*12*), but recently a series for the eastern seaboard of the United States has been reconstructed from all available data sources. In this series Philadelphia is used as an index location, since it is centrally located with respect to all the earlier available records (*13*). Figures 1 and 2 show the annual values for temperature and precipitation for a 230-year span; there are some minor gaps where the data were inadequate. These curves are characteristic of those for other regions, too. In particular they reflect the restlessness of the atmosphere. Many analysts have simply considered the variations to be quasi-random. Here I need only say that they do not reflect any pronounced one-sided trends. However, there are definite long or short intervals in which considerable one-sided departures from a mean are notable. On corresponding curves representing data for a larger area that encompasses most of the regions bordering the Atlantic, the major segments are those for the late 18th century, which was warm; the 19th century, which was cool; and the first half of the 20th century, in which there was a notable rising trend. This trend was followed by some cooling in the past 2 decades.

In the precipitation patterns, "noise" masks all trends, but we know that during a period in the middle of the last century there was considerably more precipitation than there is now. For shorter intervals, spells of drought alternate with high precipitation. Sometimes, for small areas, these can be quite spectacular. An example is the seasonal snowfall on Mount Washington, in New Hampshire; there the snowfall increased from an average of 4.5 meters in the winters of 1933–34 to 1949–50 to an annual average of 6 meters in the period 1951–52 to 1966–67 (*14*). Yet these values should not be taken as general climatic trends for the globe, or even for the hemisphere. Even if we take indices that integrate various climatic influences, we still cannot make categorical statements. Glacier conditions are typical in this group of indices. For example, the glaciers on the west coast of Greenland have been repeatedly surveyed since 1850. In consonance with temperature trends for lower latitudes, they showed their farthest advances in the 7th decade of the 19th century and have been retreating ever since (*15*). This pattern fits the temperature curves to the 1950 turning point, but, although glaciers in some regions of the world have been advancing since then, this is by no means true of all glaciers. The question of whether these changes reflect (i) relatively short-term temperature fluctuations, or (ii) alterations in the alimenting precipitation, or (iii) a combination of these two factors remains unanswered.

Many of the shorter fluctuations are likely to be only an expression of atmospheric interaction with the oceans. Even if external or terrestrial impulses affect the energy budget and cause an initial change in atmospheric circulation, notable lag and feedback mechanisms involving the oceans produce pulsations which, in turn, affect the atmosphere (*16*). The oceans have a very large thermal inertia, and their horizontal motions and vertical exchanges are slow. Namias (*17*) has investigated many of the fluctuations of a few years' duration. He concluded, for example, that drought conditions on the eastern seaboard of the United States in the 1960's were directly affected by the prevailing wind system and by sea-surface temperatures in the vicinity but that the real dominant factor was a wind-system change in the North Pacific. Such teleconnections (relations among conditions in distant parts of the globe) complicate interpretations of local or even regional data tremendously. The worldwide effect of changes in the Pacific wind system is obvious from Namias's estimate that accelerations and decelerations cause large-scale breaks in the regime of sea-surface temperatures. These seem to occur in sequences of approximately 5 years and may cause temperature changes of 0.5°C over the whole North Pacific. Namias estimates that this can cause differences of 8×10^{18} grams in the annual amounts of water evaporated from the surface. The consequences for worldwide cloud and rain formation are evident. It is against this background that we have to weigh climatic changes allegedly wrought by man.

Carbon Dioxide

The fact that the atmospheric gases play an important role in the energy budget of the earth was recognized early. Fourier, and then Pouillet and Tyndall, first expressed the idea that these gases acted as a "greenhouse" (*18*). After the spectrally selective absorption of gases was recognized, their role as climatic controls became a subject of wide debate. The capability of CO_2 to intercept long-wave radiation emitted by the earth was put forward as a convenient explanation for climatic changes. Arrhenius (*19*) made the first quantitative estimates of the magnitude of the effect, which he mainly attributed to fluctuating volcanic activity, although he also mentioned the burning of coal as a minor source of CO_2. The possibility that man-made CO_2 could be an important factor in the earth's heat balance was not seriously considered until Callendar (*20*), in 1938, showed evidence of a gradual increase in CO_2 concentration in the earth's atmosphere. But it was Plass (*21*) who initiated the modern debate on the subject, based on his detailed study of the CO_2 absorption spectrum. The crucial question is, How much has CO_2 increased as a result of the burning of fossil fuels? It is quite difficult to ascertain even the mean amount of CO_2 in the surface layers of the atmosphere, especially near vegetation. There are large diurnal and annual variations. Various agriculturists have reported concentrations ranging from 210 to 500 parts per million. The daily amplitudes during the growing season are about 70 parts per million (*22*). Nearly all early measurements were made in environments where such fluctuations took place. This, together with the lack of precision of the measurements, means that our baseline—atmospheric CO_2 concentrations prior to the spectacular rise in fossil fuel consumption of this century—is very shaky. Only since the International Geophysical Year have there been some regularly operating measuring points in polar regions and on high mountains and reliable data from the oceans which give some firm information on the actual increase (*23*).

The best present estimate places the increase in atmospheric CO_2 since 1860 at 10 to 15 percent. This is hardly a spectacular change, but the rate of increase has been rising, and various bold extrapolations have been made into the 21st century. Much depends on the sinks for CO_2 which at present are not completely known. At present concentrations, atmospheric O_2 and CO_2 stay in approximate equilibrium, through the photosynthetic process in plants. It is estimated that 150×10^9 tons of CO_2 per year are used in photosynthesis (*24*). A corresponding amount is returned to the atmosphere by decay, unless the total volume of plant material increases (*25*). This volume is one of the unknowns in the estimates of CO_2 balance. Perhaps satellite sensors can give some bulk information on that point in the future. The oceans are a major sink for CO_2. The equilibrium with the bicarbonates dissolved in seawater determines the amount of CO_2 in the atmosphere. In the exchange between atmosphere and ocean, the temperature of the surface water enters as a factor. More CO_2 is absorbed at lower surface-water temperatures than at higher temperatures. I have already pointed out the fact that surface-water temperatures fluctuate over long or short intervals; most of these ups and downs are governed by the wind conditions. The interchange of the cold deep water and the warm surface water through downward mixing and upwelling, in itself an exceedingly irregular process, controls, therefore, much of the CO_2 exchange (*26*). Also, the recently suggested role of an enzyme in the ocean that facilitates absorption of CO_2 has yet to be explored. Hence it is quite difficult to make long-range estimates of how much atmospheric CO_2 will disappear in the oceanic sink. Most extrapolators assume essentially a constant rate of removal. Even the remaining question of how much the earth's temperature will change with a sharp increase in the CO_2 content of the atmosphere cannot be unambiguously answered. The answer depends on other variables, such as atmospheric humidity and cloudiness. But the calculations have been made on the basis of various assumptions. The model most widely used is that of Manabe and Wetherald (*27*). They calculate, for example, that, with the present value for average cloudiness, an increase of atmospheric CO_2 from 300 to 600 parts per million would lead to an increase of 2°C in the mean temperature of the earth at the surface. At the same time the lower stratosphere would cool by 15°C. At the present rate of accumulation of CO_2 in the atmosphere, this doubling of the CO_2 would take about 400 years. The envisaged 2°C rise can hardly be called cataclysmic. There have been such worldwide changes within historical times. Any change attributable to the rise in CO_2 in the last

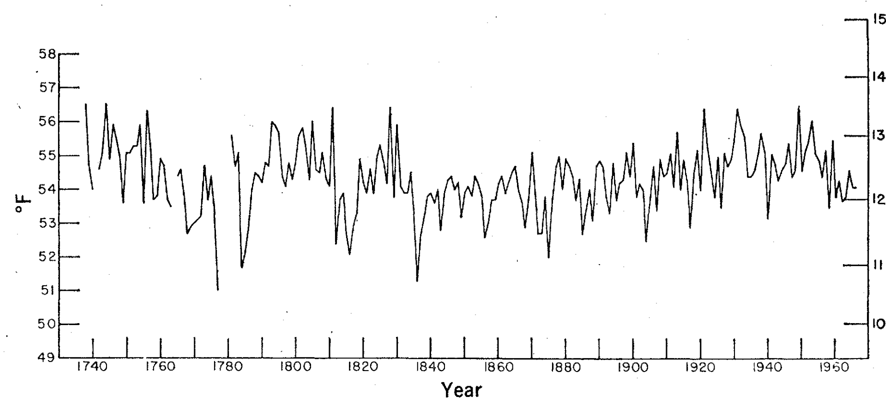

Fig. 1. Annual temperatures for the eastern seaboard of the United States for the period 1738 to 1967—a representative, reconstructed synthetic series centered on Philadelphia.

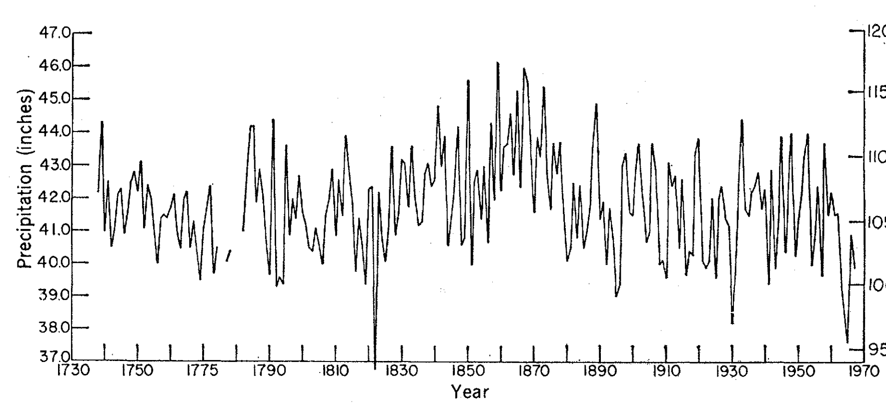

Fig. 2. Annual precipitation totals for the eastern seaboard of the United States for the period 1738 to 1967—a representative, reconstructed synthetic series centered on Philadelphia.

century has certainly been submerged in the climatic "noise." Besides, our estimates of CO_2 production by natural causes, such as volcanic exhalations and organic decay, are very inaccurate; hence the ratio of these natural effects to anthropogenic effects remains to be established.

Dust

The influence on climate of suspended dust in the atmosphere was first recognized in relation to volcanic eruptions. Observations of solar radiation at the earth's surface following the spectacular eruption of Krakatoa in 1883 showed measurable attenuation. The particles stayed in the atmosphere for 5 years (*28*). There was also some suspicion that summers in the Northern Hemisphere were cooler after the eruption. The inadequacy and unevenness of the observations make this conclusion somewhat doubtful. The main exponent of the hypothesis that volcanic dust is a major controller of terrestrial climate was W. J. Humphreys (*29*). In recent years the injection into the atmosphere of a large amount of dust by an eruption of Mount Agung has renewed interest in the subject, not only because of the spectacular sunsets but also because there appears to have been a cooling trend since (*30*). The Mount Agung eruption was followed, in the 1960's, by at least three others from which volcanic constituents reached stratospheric levels: those of Mount Taal, in 1965; Mount Mayon, in 1968; and Fernandina, in 1968. Not only did small dust particles reach the stratosphere but it seems likely that gaseous constituents reaching these levels caused the formation of ammonium sulfate particles through chemical and photochemical reactions (*31*). The elimination of small particulates from the stratosphere is relatively slow, and some backscattering of solar radiation is likely to occur.

As yet man cannot compete in dust production with the major volcanic eruptions, but he is making a good try. However, most of his solid products that get into the atmosphere stay near the ground, where they are fairly rapidly eliminated by fallout and washout. Yet there is some evidence that there has been some increase in the atmospheric content of particles less than 10^{-4} centimeter in diameter (*32*). The question is simply, What is the effect of the man-made aerosol? There is general agreement that it depletes the direct solar radiation and increases radiation from the sky. Measurements of the former clearly show a gradual increase in turbidity (*33*), and the same increase in turbidity has been documented by observations from the top of Mauna Loa, which is above the level of local contamination (*34*). From these observations the conclusion has been drawn that the attentuation of direct solar radiation is, in part at least, caused by backscattering of incoming solar radiation to space. This is equivalent to an increase in the earth's albedo and hence is being interpreted as a cause of heat loss and lowered temperatures (*35*). But things are never that categorical and simple in the atmosphere. The optical effects of an aerosol depend on its size distribution, its height in the atmosphere, and its absorptivity. These properties have been studied in detail by a number of authors (*36*). It is quite clear that most man-made particulates stay close to the ground. Temperature inversions attend to that. And there is no evidence that they penetrate the stratosphere in any large quantities, especially since the ban, by most of the nuclear powers, of nuclear testing in the atmosphere. The optical analyses show, first of all, that the backscatter of the particles is outweighed at least 9 to 1 by forward scattering. Besides, there is a notable absorption of radiation by the aerosol. This absorption applies not only to the incoming but also to the outgoing terrestrial radiation. The effectiveness of this interception depends greatly on the overlapping effect of the water vapor of the atmosphere. Yet the net effect of the man-made particulates seems to be that they lead to heating of the atmospheric layer in which they abound. This is usually the stratum hugging the ground. All evidence points to temperature rises in this layer, the opposite of the popular interpretations of the dust effect. The aerosol and its fallout have other, perhaps much more far-reaching, effects, which I discuss below. Suffice it to say, here, that man-made dust has not yet had an effect on global climate beyond the "noise" level. Its effect is puny as compared with that of volcanic eruptions, whose dust reaches the high stratosphere, where its optical effect, also, can be appreciable. No documented case has been made for the view that dust storms from deserts or blowing soil have had more than local or regional effects.

Dust that has settled may have a more important effect than dust in suspension. Dust fallen on snow and ice surfaces radically changes the albedo and can lead to melting (*37*). Davitaya (*38*) has shown that the glaciers of the high Caucasus have an increased dust content which parallels the development of industry in eastern Europe. Up until 1920 the dust content of the glacier was about 10 milligrams per liter. In the 1950's this content increased more than 20-fold, to 235 milligrams per liter. So long as the dust stays near the surface, it should have an appreciable effect on the heat balance of the glacier. There is fairly good evidence, based on tracers such as lead, that dusts from human activities have penetrated the polar regions. Conceivably they might change the albedo of the ice, cause melting, and thus pave the way for a rather radical climatic change—and for a notable rise in sea level. There has been some speculation along this line (*39*), but, while these dusts have affected microclimates, there is no evidence of their having had, so far, any measurable influence on the earth's climate. The possibility of deliberately causing changes in albedo by spreading dust on the arctic sea ice has figured prominently in discussions of artificial modification of climate. This seems technologically feasible (*40*). The consequences for the mosaic of climates in the lower latitudes have not yet been assessed. Present computer models of world climate and the general circulation are far too crude to permit assessment in the detail necessary for ecological judgments.

All of the foregoing discussion applies to the large-scale problems of global climate. On that scale the natural influences definitely have the upper hand. Although monitoring and vigilance is indicated, the evidence for man's effects on global climate is flimsy at best. This does not apply to the local scale, as we shall presently see.

Extraurban Effects

For nearly two centuries it has been said that man has affected the rural climates simply by changing vast areas from forest to agricultural lands. In fact, Thomas Jefferson suggested repetitive climatic surveys to measure the effects of this change in land use in the virgin area of the United States (*41*). Geiger has succinctly stated that man is the greatest destroyer of natural microclimates (*42*). The changeover from forest to field locally changes the heat balance. This leads to greater temperature extremes at the soil surface and to altered heat flux into and out of the soil. Cultivation may even accentuate this. Perhaps most drastically changed is the low-level wind speed profile because of the radical alteration in aerodynamic roughness. This change leads to increased evaporation and, occasionally, to wind erosion. One might note here that man has reversed to some extent the detrimental climatic effects of deforestation in agricultural sectors, by planting hedges and shelter belts of trees. Special tactics have been developed to reduce evaporation, collect snow, and ameliorate temperature ranges by suitable arrangements of sheltering trees and shrubs (*43*).

The classical case of a local man-made climatic change is the conversion of a forest stand to pasture, followed by overgrazing and soil erosion, so that ultimately nothing will grow again. The extremes of temperature to which the exposed surface is subjected are very often detrimental to seedlings, so that they do not become established. Geiger pointed this out years ago. But not all grazing lands follow the cycle outlined above. Sometimes it is a change in the macroclimate that tilts the balance one way or another (*44*).

Since ancient times man has compensated for vagaries of the natural climates by means of various systems of irrigation. Irrigation not only offsets temporary deficiencies in rainfall but, again, affects the heat balance. It decreases the diurnal temperature ranges, raises relative humidities, and creates the so-called "oasis effect." Thornthwaite, only a decade and a half ago, categorically stated that man is incapable of deliberately causing any significant change in the climatic patterns of the earth. Changes in microclimate seemed to him so local and trivial that special instrumentation was needed to detect them. However, "Through changes in the water balance and sometimes inadvertently, he exercises his greatest influence on climate" (*45*).

What happens when vast areas come under irrigation? This has taken place over 62×10^3 square kilometers of Oklahoma, Kansas, Colorado, and Nebraska since the 1930's. Some meteorologists have maintained that about a 10 percent increase in rainfall occurs in the area during early summer, allegedly attributable to moisture reevaporated from the irrigated lands (*46*). Synoptic meteorologists have generally made a good case for the importation, through precipitation, of moisture from marine sources, especially the Gulf of Mexico. Yet ^3H determinations have shown, at least for the Mississippi valley area, that two-thirds of the precipitated water derives from locally evaporated surface waters. Anyone who has ever analyzed trends in rainfall records will be very cautious about accepting apparent changes as real until many decades have passed. For monthly rainfall totals, 40 to 50 years may be needed to establish trends because of the large natural variations (*47*).

This century has seen, also, the construction of very large reservoirs. Very soon after these fill they have measurable influences on the immediate shore vicinity. These are the typical lake effects. They include reduction in temperature extremes, an increase in humidity, and small-scale circulations of the land- and lake-breeze type, if the reservoir is large enough. Rarely do we have long records as a basis for comparing conditions before and after establishment of the reservoir. Recently, Zych and Dubaniewicz (*48*) published such a study for the 30-year-old reservoir of the Nysa Klodzka river in Poland, about 30 square kilometers in area. At the town of Otmuchow, about 1 kilometer below the newly created lake, a 50-year temperature normal was available (for the years 1881 to 1930). In the absence of a regional trend there has been an increase in the annual temperature of 0.7°C at the town near the reservoir. It is now warmer below the dam than above it, whereas, before, the higher stations were warmer because of the temperature inversions that used to form before the water surface exerted its moderating influence. It is estimated that precipitation has decreased, because of the stabilizing effect of the large body of cool water. Here, as elsewhere, the influence of a large reservoir does not extend more than 1 to 3 kilometers from the shore. Another form of deliberate man-controlled interference with microclimate, with potentially large local benefits, is suppression of evaporation by monomolecular films. Where wind speeds are low, this has been a highly effective technique for conserving water. The reduction of evaporation has led to higher water surface temperature, and this may be beneficial for some crops, such as rice (*49*).

The reduction of fog at airports by seeding of the water droplets also belongs in this category of man-controlled local changes. In the case of supercooled droplets, injection of suitable freezing nuclei into the fog will cause freezing of some drops, which grow at the expense of the remaining droplets and fall out, thus gradually dissipating the fog. For warm fogs, substances promoting the growth or coalescence of droplets are used. In many cases dispersal of fog or an increase in visual range sufficient to permit flight operations can be achieved (*50*). Gratifying though this achievement is for air traffic, it barely qualifies as even a microclimatic change because of the small area and brief time scale involved. Similarly, the changes produced by artificial heating in orchards and vineyards to combat frosts hardly qualify as microclimatic changes.

Finally, a brief note on general weather modification is in order. Most of the past effort in this field has been devoted to attempts to augment rainfall and suppress hail. The results have been equivocal and variously appraised (*51*). The technique, in all cases, has been cloud seeding by various agents. This produces undoubted physical results in the cloud, but the procedures are too crude to permit prediction of the outcome. Thus, precipitation at the ground has been both increased and decreased (*52*). The most reliable results of attempts to induce rainfall have been achieved through seeding clouds forming in up-slope motions of winds across mountains and cap clouds (*53*). Elsewhere targeting of precipitation is difficult, and the effects of seeding downwind from the target area are not well known. No analysis has ever satisfactorily shown whether cloud seeding has actually caused a net increase in precipitation or only a redistribution. In any case, if persistently practiced, cloud seeding could bring about local climatic changes. But an ecological question arises: If we can do it, should we? This point remains controversial.

Attempts to suppress hail by means of cloud seeding are also still in their infancy. Here the seeding is supposed to achieve the production of many small ice particles in the cloud, to prevent any of them from growing to a size large enough to be damaging when they reach the ground. The seeding agent is introduced into the hail-producing zone of cumulonimbus—for example, by ground-fired projectiles. Some successes have been claimed, but much has yet to be learned before one would ac-

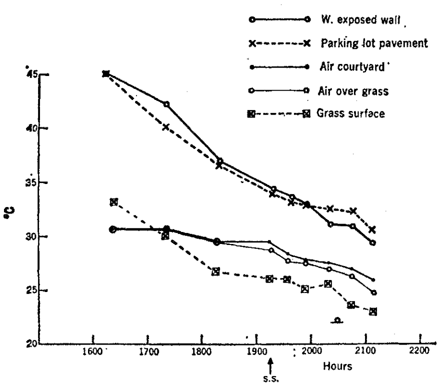

Fig. 3. A typical example of microclimatic heat island formation in incipient urbanization. The top two curves show radiative temperatures of wall and parking lot pavement on a clear summer evening (6 August 1968). The two middle curves show air temperatures (at elevation of 2 meters) in the paved courtyard and over an adjacent grass surface; from sunset (*s.s.*) onward, the courtyard is warmer than the air over the grass. The bottom (dashed) curve gives the radiative temperature of grass. The symbol at 2030 hours indicates the start of dew formation.

claim seeding as a dependable technology for eliminating this climatic hazard (*54*).

Hurricane modification has also been attempted. The objective is reduction of damage caused by wind and storm surges. Seeding of the outer-wall clouds around the eye of the storm is designed to accomplish this. The single controlled experiment that has been performed, albeit successfully in the predicted sense, provides too tenuous a basis for appraising the potential of this technique (*55*). Here again we have to raise the warning flag because of the possibility of simultaneous change in the pattern of rainfall accompanying the storm. In many regions tropical storm rain is essential for water supply and agriculture. If storms are diverted or dissipated as a result of modification, the economic losses resulting from altered rainfall patterns may outweigh the advantages gained by wind reduction (*56*). As yet such climatic modifications are only glimpses on the horizon.

General Urban Effects

By far the most pronounced and locally far-reaching effects of man's activities on microclimate have been in cities. In fact, many of these effects might well be classified as mesoclimatic. Some of them were recognized during the last century in the incipient metropolitan areas. Currently the sharply accelerated trend toward urbanization has led to an accentuation of the effects. The problem first simply intrigued meteorologists, but in recent years some of its aspects have become alarming. Consequently the literature in this field has grown rapidly and includes several reviews summarizing the facts (*57*).

We are on the verge of having a satisfactory quantitative physical model of the effect of cities on the climate. It combines two major features introduced by the process of urbanization. They concern the heat and water balance and the turbulence conditions. To take changes in turbulence first, the major contributory change is an increase in surface roughness. This affects the wind field and, in particular, causes a major adjustment in the vertical wind profile so that wind speeds near the surface are reduced. The structural features of cities also increase the number of small-scale eddies and thus affect the turbulence spectrum.

The change in the heat balance is considerably more radical. Here, when we change a rural area to an urban one, we convert an essentially spongy surface of low heat conductivity into an impermeable layer with high capacity for absorbing and conducting heat. Also, the albedo is usually lowered. These radical changes in surface that accompany the change from rural to urban conditions lead to rapid runoff of precipitation and consequently to a reduction in local evaporation. This is, of course, equivalent to a heat gain —one which is amplified by radiative heat gain resulting from the lowering of the albedo. This heat is effectively stored in the stone, concrete, asphalt, and deeper compacted soil layers of the city. In vegetated rural areas usually more incoming radiation is reflected and less is stored than in the city. Therefore structural features alone favor a strongly positive heat balance for the city. To this, local heat production is added. The end result is what has been called the urban heat island, which leads to increased convection over the city and to a city-induced wind field that dominates when weather patterns favor weak general air flow.

Most of the features of the near-the-surface climatic conditions implied by this model have, over the years, been documented by comparisons of measurements made within the confines of cities and in their rural surroundings, mostly at airports. Such comparisons

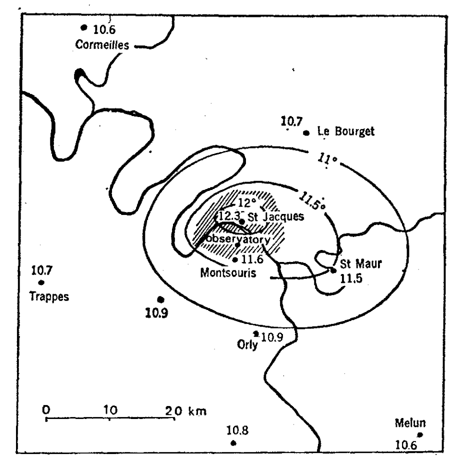

Fig. 4. The urban heat island of Paris, shown by mean annual isotherms in degrees Celsius. The region is characterized by minimal orographic complexity. [After Dettwiller (*61*)].

gave reasonably quantitative data on the urban effect, but some doubts remained. These stemmed from the fact that many cities were located in special topographic settings which favored the establishment of a city—such as a river valley, a natural harbor, or an orographic trough. They would by nature have a microclimate different from that of the surroundings. Similarly, airport sites were often chosen for microclimatic features favorable for aviation. Some of the uncertainties can be removed by observing atmospheric changes as a town grows. An experiment along this line was initiated 3 years ago in the new town of Columbia, Maryland. The results so far support earlier findings and have refined them (*58*).

Perhaps of most interest is the fact that a single block of buildings will start the process of heat island formation. This is demonstrated by air and infrared surface temperature measurements. An example is given in Fig. 3. The observations represented by the curves of Fig. 3 were made in a paved court enclosed by low-level structures which were surrounded by grass and vegetated surfaces. On clear, relatively calm evenings the heat island develops in the court, fed by heat stored in the daytime under the asphalted parking space of the court and the building walls. This slows down the radiative cooling process, relative to cooling from a grass surface, and keeps the air that is in contact with the surface warmer than that over the grass (*59*).

The heat island expands and intensifies as a city grows, and stronger and stronger winds are needed to overcome it (*60*). And although it is most pronounced on calm, clear nights, the effect is still evident in the long-term mean values. Figure 4 shows the isotherms in the Paris region, which is topographically relatively simple and without appreciable differences in elevation. A pronounced metropolitan heat island of about 1.6°C in the mean value can be seen. This is typical of major cities. In the early hours of calm, clear nights the city may be 6° to 8°C warmer than its surroundings. The Paris example is noteworthy because it has been demonstrated that the rise in temperature is not confined to the air but also affects the soil. It has been observed in a deep cave under the city, where temperatures have been measured for two centuries (*61*). Curiously enough, the cave temperature was once considered so invariant that the cave in question was proposed as one of the fixed points for thermometer scales. This artificially introduced trend in temperatures also plays havoc with the long-term temperature records from cities. They become suspect as guides for gaging the slow, natural climatic fluctuations.

Part of the rise in temperature must be attributed to heat rejection from human and animal metabolism, combustion processes, and air-conditioning units. Energy production of various types certainly accounts for a large part of it. In the urbanized areas the rejected energy has already become a measurable fraction of the energy received from the sun at the surface of the earth. Projection of this energy rejection into the next decades leads to values we should ponder. One estimate indicates that in the year 2000 the Boston-to-Washington megalopolis will have 56 million people living within an area of 30,000 square kilometers. The heat rejection will be about 65 calories per square centimeter per day. In winter this is about 50 percent, and in summer 15 percent, of the heat received by solar radiation on a horizontal surface (*62*). The eminent French geophysicist J. Coulomb has discussed the implications of doubling the energy consumption in France every 10 years; this would lead to unbearable temperatures (*63*). It is one of a large number of reasons for achieving, as rapidly as possible, a steady state in population and in power needs.

An immediate consequence of the heat island of cities is increased convection over cities, especially in the daytime. That has been beautifully demonstrated by the lift given to constant-

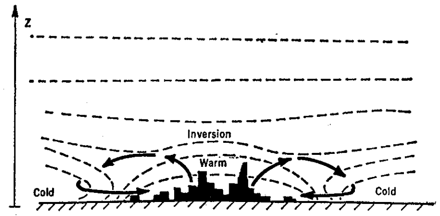

Fig. 5. Idealized scheme of nocturnal atmospheric circulation above a city in clear, calm weather. The diagram shows the urban heat island and the radiative ground inversions in the rural areas, a situation that causes a "country breeze" with an upper return current. (Dashed lines) Isotherms; (arrows) wind; *Z*, vertical coordinate.

volume balloons launched across cities (*64*). The updraft leads, together with the large amount of water vapor released by combustion processes and steam power, to increased cloudiness over cities. It is also a potent factor in the increased rainfall reported from cities, discussed below in conjunction with air pollution problems. Even at night the heating from below will counteract the radiative cooling and produce a positive temperature lapse rate, while at the same time inversions form over the undisturbed countryside. This, together with the surface temperature gradient, creates a pressure field which will set a concentric country breeze into motion (*65*). A schematic circulation system of this type is shown in Fig. 5.

The rapid runoff of rainfall caused by the imperviousness of the surfaces of roads and roofs, as well as by the drainage system, is another major effect of cities. In minor rainfalls this has probably only the limited consequence of reducing the evaporation from the built-up area and thus eliminating much of the heat loss by the vaporization that is common in rural areas. But let there be a major rainstorm and the rapid runoff will immediately lead to a rapid rise of the draining streams and rivers. That can cause flooding and, with the unwise land use of flood plains in urban areas, lead to major damage. The flood height is linearly related to the amount of impervious area. For the 1- to 10-year recurrence intervals, flood heights will be increased by 75 percent for an area that has become 50 percent impervious, a value not at all uncommon in the usual urban setting. Observations in Hempstead, Long Island, have shown, for example, that, for a storm rainfall of 50 millimeters, direct runoff has increased from 3 millimeters in the interval from 1937 to 1943 to 7 millimeters in the interval from 1964 to 1966. This covers the time when the area changed from open fields to an urban community (*66*).

It is very difficult to document the decrease of wind speed over cities. Long records obtained with unchanged anemometer exposures at representative heights are scarce. Reasonable interpretations of available records suggest a decrease of about 25 percent from the rural equivalents. This is not unreasonable in the light of measurable increases in aerodynamic roughness. These are around 10 to 30 centimeters for meadows and cultivated fields and around 100 centimeters for woodland. There are several estimates for urban areas. I will give here a value calculated from the unique wind measurements on the Eiffel tower at a height of 316 meters, and from other wind records in the Paris region (*67*). These data yield values around 500 centimeters. They also suggest a decrease in wind at the top of the Eiffel tower from the interval 1890–1909 to the interval 1951–1960 of 0.4 meter per second, or 5 percent of the mean wind speed. In view of the height of this anemometer, this is quite a notable adjustment of the wind profile to the increase in terrain roughness.

Air Pollution Effects

Most spectacular among the effects of the city upon the atmospheric environment are those caused by air pollution. The catalogue of pollutants put into the air by man is long and has been commented upon in so many contexts that reference to the literature will have to suffice (*68*). Nor shall I dwell here on the special interactions of pollutants with the atmosphere in climatically and topographically specialized instances, such as the much investigated case of Los Angeles (*69*). I shall concentrate, instead, on the rather universal effects of pollutants on local climates.

Among these is the attenuation of solar radiation by suspended particulates. Although this affects the whole spectrum, it is most pronounced in the short wavelengths. The total direct radiation over most major cities is weakened by about 15 percent, sometimes more in winter and less in summer. The ultraviolet is reduced by 30 percent, on an average, and in winter often no radiation of wavelengths below 390 nanometers is received. The extinction takes place in a very shallow layer, as simultaneous measurements taken at the surface and from a tall steeple have shown (*70*).

Horizontally, the particulate haze interferes with visibility in cities. When shallow temperature inversions are present, the accumulation of aerosols can cause 80- or 90-percent reduction of the visual range as compared with the range for the general uncontaminated environment. The haze effect is accentuated by the formation of water droplets around hygroscopic nuclei, even below the saturation point. This is the more noteworthy because relative humidities near the surface are generally lower in cities than in the countryside. This is attributable partially to the higher temperatures and partially to the reduced evaporation. Nonetheless, fog occurs from two to five times as often in the city as in the surroundings. Fortunately, this seems to be a reversible process. Recent clean-up campaigns have shown that, through the use of smokeless fuels, considerable lessening of the concentration of particulates, and hence of fog and of the attenuation of light, can be achieved. In London, for example, with the change in heating practices, winter sunshine has increased by 70 percent in the last decade, and the winter visibilities have improved by a factor of 3 since the improvements were introduced (*71*).

I have alluded above to the increase in cloudiness over cities. It is likely that the enormous number of condensation nuclei produced by human activities in and around cities contributes to this phenomenon. Every set of measurements made has confirmed early assessments that these constituents are more numerous by one or two orders of magnitude in urbanized regions than in the country (*72*). Every domestic or industrial combustion process, principally motor vehicle exhaust, contributes to this part of the particulate. Independent evidence suggests that there is more rainfall over cities than over the surrounding countryside. But the evidence that pollutants are involved is tenuous. There is little doubt that the convection induced by the heat island can induce or intensify showers. This has been demonstrated for London, where apparently thundershowers yield 30 percent more rain than in the surrounding area (*73*). Orographic conditions would lead one to expect more showers in hilly terrain. This is not the case. Although this buoyancy effect is certainly at work, it does not stand alone: in some towns there are observations of precipitation increases from supercooled winter stratus clouds over urban areas. Some well-documented isolated cases of snow over highly industrialized towns suggest a cloud-seeding effect by some pollutants that may act as freezing nuclei (*74*). Also the rather startling variation of urban precipitation in accordance with the pattern of the human work week argues for at least a residual effect of nucleating agents produced in cities. The week is such an arbitrary subdivision of time that artificial forces must be at work. Observations over various intervals and in various regions indicate increased precipitation for the days from Monday through Friday as compared with values for Saturday and Sunday. These increases usually parallel the increase in industrialization, and, again, there is evidence for a more pronounced effect in the cool season (*75*).

Although most studies indicate that the increase in precipitation in urban areas is around 10 percent—that is, close to the limit of what could still be in the realm of sampling errors—some analyses have shown considerably larger increases in isolated cases. These instances have not yet been lifted out of the umbra of scientific controversy (*76*). But we should note here that some industrial activities and internal combustion engines produce nuclei that can have nucleating effects, at least on supercooled cloud particles. In the State of Washington in some regions that have become industrialized there is evidence of a 30-percent increase in precipitation in areas near the pulp mills over an interval of four decades (*77*). There are also incontrovertible observations of cloud banks forming for tens of kilometers in the plumes of power plants and industrial stacks. This is not necessarily associated with increased precipitation but raises the question of how far downwind man's activities have caused atmospheric modifications.

In the absence of systematic three-dimensional observations, we have to rely on surface data. A recent study by Band (*78*) throws some light on the conditions. He found that, for a heat island 3°C warmer than its surroundings, a small but measurable temperature effect was still notable 3 kilometers to leeward of the town. Similarly, a substantial increase in the number of condensation nuclei was noted 3 kilometers downwind from a small town. In the case of a major traffic artery, an increased concentration of nuclei was measurable to 10 kilometers downwind. For a major city, radiation measurements have suggested that the smoke pall affects an area 50 times that of the built-up region. These values, which are probably conservative, definitely indicate that man's urbanized complexes are beginning to modify the mesoclimate.

As yet it is very difficult to demonstrate that any far-reaching climatic effects are the results of man's activities. If man-made effects on this scale already exist or are likely to exist in the future, they will probably be a result of the vast numbers of anthropogenic condensation and freezing nuclei. Among the latter are effective nucleating agents resulting from lead particles in automobile exhaust. These particles have become ubiquitous, and if they combine with iodine or bromine they are apt to act as freezing nuclei. Schaefer and others have pointed out that this could have effects on precipitation far downwind (*79*). These inadvertent results would lead either to local increases in precipitation or to a redistribution of natural precipitation patterns. They are, however, among the reversible man-made influences. As soon as lead is no longer used as a gasoline additive—which, hopefully, will be soon—the supply of these nucleating agents will stop and the influence, whatever its importance, should vanish promptly because of the relatively short lifetime of these nuclei.

Perhaps more serious, and much more difficult to combat, is the oversupply of condensation nuclei. Gunn and Phillips pointed out years ago that, if too many hygroscopic particles compete for the available moisture, cloud droplets will be small and the coalescence processes will become inhibited (*80*). This could lead to decreases in precipitation, a view that has recently been confirmed (*81*).

There remains one final area of concern: pollution caused by jet aircraft. These aircraft often leave persistent condensation trails. According to one school of thought, these artificial clouds might increase the earth's albedo and thus cause cooling. Although on satellite pictures one can occasionally see cloud tracks that might have originated from these vapor trails, they seem to be sufficiently confined, with respect to space and time, to constitute a very minute fraction of the earth's cloud cover. The other view of the effect of these vapor trails, which change into cirriform clouds, is that ice crystals falling from them may nucleate other cloud systems below them and cause precipitation. Any actual evidence of such events is lacking. And then we have the vivid speculations concerning weather modifications by the prospective supersonic transport planes. For some time military planes have operated at the altitudes projected for the supersonic transports. The ozone layer has not been destroyed, and no exceptional cloud formations have been reported. The water vapor added by any probable commercial fleet would be less than 10^{-9} of the atmospheric water vapor; thus, no direct influence on the earth's heat budget can be expected. At any rate, it seems that the sonic boom is a much more direct and immediate effect of the supersonic transport than any possible impact it may have on climate (*82*).

There is little need to comment on the multitude of schemes that have been proposed to "ameliorate" the earth's climate. Most of them are either technologically or economically unfeasible. All of them would have side effects that the originators did not consider. The new trend toward thinking in ecological terms would lead us to require that much more thoroughgoing analyses of the implications of these schemes be made than have been made so far before any steps are taken toward their implementation (*83*).

Summary

Natural climatic fluctuations, even those of recent years, cover a considerable range. They can be characterized as a "noise" spectrum which masks possible global effects of man-caused increases of atmospheric CO_2 and particulates. Local modifications, either deliberate or inadvertent, measurably affect the microclimate. Some artificial alterations of the microclimate are beneficial in agriculture. Among the unplanned effects, those produced by urbanization on local temperature and on wind field are quite pronounced. The influences on rainfall are still somewhat controversial, but effects may extend considerably beyond the confines of metropolitan areas. They are the result of water vapor released by human activity and of the influence of condensation and freezing nuclei produced in overabundance by motor vehicles and other combustion processes. Therefore it appears that on the local scale man-made influences on climate are substantial but that on the global scale natural forces still prevail. Obviously this should not lead to complacency. The potential for anthropogenic changes of climate on a larger and even a global scale is real. At this stage activation of an adequate worldwide monitoring system to permit early assessment of these changes is urgent. This statement applies particularly to the surveillance of atmospheric composition and radiation balance at sites remote from concentrations of population, which is now entirely inadequate. In my opinion, man-made aerosols, because of their optical properties and possible influences on cloud and precipitation processes, constitute a more acute problem than CO_2. Many of their effects are promptly reversible; hence, one should strive for elimination at the source. Over longer intervals, energy added to the atmosphere by heat rejection and CO_2 absorption remain matters of concern.

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84. The work discussed here has been supported in part by NSF grants GA-1104 and GA-13353.