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Meteorology of Air Pollution

The need to preserve our air resources challenges our understanding of the atmosphere's capacities.

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The obvious solution to our widely discussed air-pollution problem is to prevent all the pollutants from reaching the atmosphere. Ultimately we may have the technical ability and legal authority to accomplish this in an economical fashion. However, it is quite logical and reasonable to use the atmosphere for the disposal of gaseous and particulate wastes, if we know the effects of this use and keep them within acceptable limits. The layer of air (about 10 kilometers thick) which is readily available for the dilution of pollution represents an enormous reservoir, about 5 $\times$ 10^{18} cubic meters, which can be used for this purpose.

Atmospheric diffusion is ultimately accomplished by the wind movement of pollutants, but the character of the source of pollution requires that this action of the wind be taken into account in different ways.

These sources can be conveniently grouped into three classes: point sources, line sources, and area sources. In practice, the first two classes must be further divided into instantaneous and continuous sources.

The instantaneous point source is essentially a "puff" of material created or ejected in a relatively short time, as by a nuclear explosion, the sudden rupture of a chlorine tank, or the bursting of a tear-gas shell. The wind of immediate importance is, of course, that occurring at the place and time at which the pollutant is created. Since the wind is highly variable, the initial direction of movement of the puff is also variable and difficult of prediction; a soap-bubble pipe and five minutes' close observation of the initial travel of successive bubbles will convincingly demonstrate the difficulty of predicting the exact trajectory of the next bubble. In addition, dilution of a puff source is a very strong function of time after its release. At first, the small-scale fluctuations of the wind cause it to grow rather slowly and the larger-scale wind variations simply carry it along on erratic paths. But as the puff grows, larger-scale motions can get a "hold" on it to tear it apart and dilute it more rapidly. Thus, the unique feature of the instantaneous point source is its increasing dispersion rate with time, whence the necessity to consider successively larger scales of meteorological phenomena in calculating its spread.

Continuous point sources (the smoke plume from a factory chimney, the pall from a burning dump) are the most familiar, the most conspicuous, and the most studied of pollution sources. The meteorology of the continuous source must take into account the time changes of the wind at the point of emission. The behavior of a plume from a factory chimney is very much like that of water from a hose being played back and forth across a lawn. It is evident that if the hose is steady the same area will be continually exposed to the water. But if the hose (wind) moves back and forth in an arc, the water (pollution) will be distributed over a wider area, hence the concentration will be less. For a truly continuous source there are other changes of great importance—primarily the diurnal and seasonal cycles.

The isolated line source is less common and therefore of less general interest, with two important exceptions—heavily traveled highways, and the swath of chemicals emitted by crop-dusting apparatus. In both these examples, if the line of pollutant is uniform and is long enough, the dispersion of the pollution must be attained in only two dimensions, along the wind and in the vertical. If the line source is a continuous one, as might be the case of a freeway in rush hours, spreading in the downwind direction becomes ineffective (at a particular downwind location), so that only the vertical dimension is left to provide dilution. This behavior of the continuous line source has been exploited by meteorologists in field experiments with controlled tracers to permit the detailed study of vertical diffusion, uncomplicated by effects in the other two coordinates.

The area source can vary enormously in size. It may be distributed over several square kilometers, as in an industrial park, over tens or hundreds of square kilometers, as in a city, or over thousands of square kilometers, exemplified by the almost continuous strip city (the "megalopolis" or "megapolitan area") along the eastern seaboard of the United States. These area sources usually include combinations of all the single-source configurations. A large city will include many thousands of home chimneys, thousands of factories and shops, hundreds of kilometers of streets, open dumps, burning leaves, evaporating fumes from gasoline storage or from cleaning plants and paint factories, and everywhere the automobile. The weather

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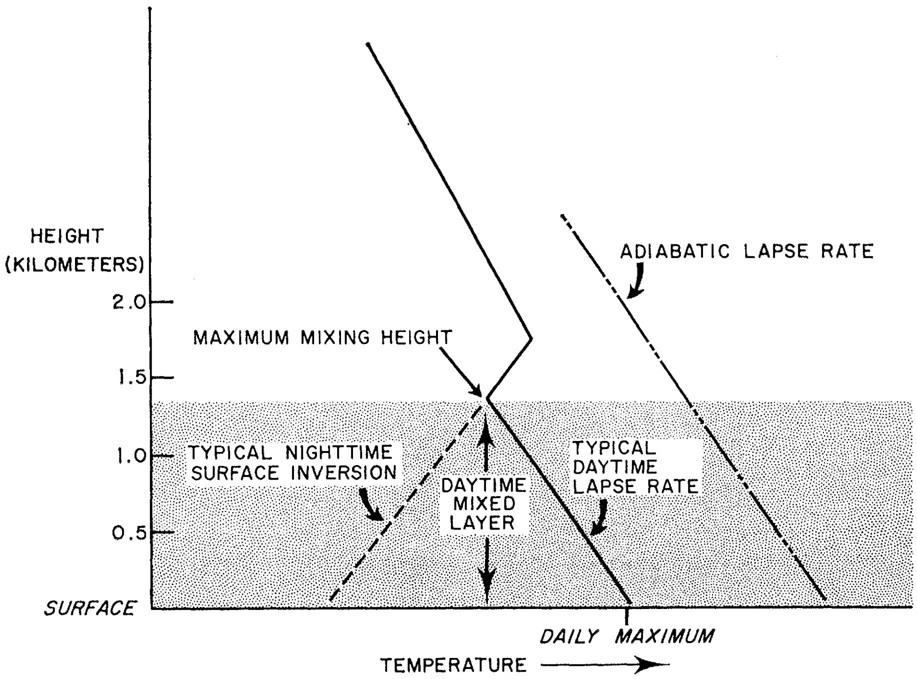


Schematic representation of the effect of vertical temperature gradient on atmospheric mixing.

problem of the city area source becomes, in the aggregate, quite different from that of a single source. Here we are concerned not with the increasing rate of wind dispersion with increasing scale, or with the behavior of wind with time at a single point, but rather with the replenishment rate of the air over the city. We must consider the total movement of a large volume of air as it "ventilates" the city. Anything that reduces this ventilation rate, whether it be the confining effect of surrounding mountains or the reduced velocities of a slow-moving anticyclone, is of concern.

In the construction of cities man has modified the weather. The volume of effluent injected into the air has reduced the solar radiation. The absorption characteristics of cement and asphalt instead of grass and trees create urban "heat islands." These effects must be considered in the meteorology of urban air pollution.

The atmosphere disperses pollutants because, like the sea, it is in constant motion, and this motion is always turbulent to some degree. There is as yet no fully accepted definition of turbulence, but empirically it can be described as random (three-dimensional) flow. There is as yet no complete explanation for the complexities even of controlled wind-tunnel turbulence, hence it is not surprising that the understanding of turbulent diffusion in the atmosphere has progressed largely through empirical treatments of controlled tracer experiments. It would be an injustice to the reader and to a fascinating and challenging subject to try to condense turbulent-diffusion theory to a few paragraphs. The current tendency is to deal with turbulence through statistical concepts derived from aerodynamics and fluid dynamics. This treatment, with its emphasis on the detailed properties of the turbulence, is in contrast to earlier theories which centered around a virtual-diffusivity concept based on analogy with molecular diffusion. In the practical application of computing pollution concentrations, it is more usual to employ the statistical method for distances to perhaps 150 kilometers from the source, and equations based on virtual-diffusivity ("K") theory for longer distances, particularly for calculations on a hemispheric or global scale.

Vertical Turbulent Diffusion

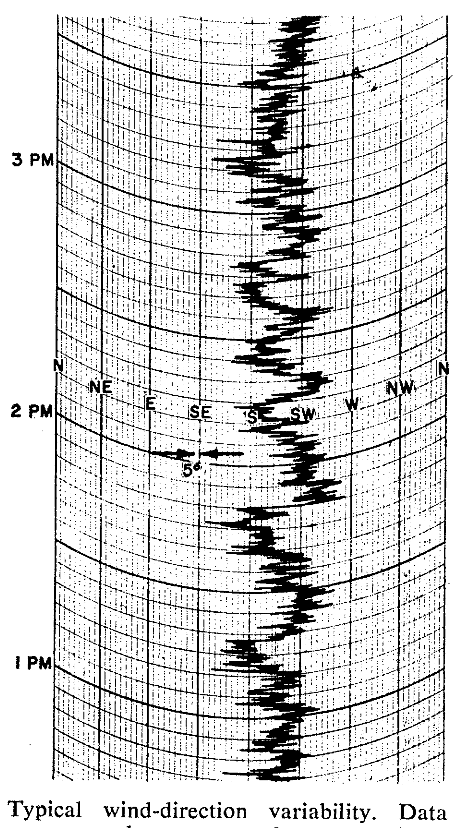
To all intents and purposes rapid atmospheric diffusion in the vertical is always bounded: on the bottom by the surface of the earth and at the top by the tropopause. The tropopause—the demarcation between the troposphere, where temperature decreases with altitude, and the stratosphere, where the temperature is relatively constant or increases with altitude—is lowest over the poles, at about 8 kilometers, and highest in the tropics, about 20 kilometers. The detection of radon products throughout the troposphere is conclusive evidence of the eventual availability of the full depth of the troposphere for vertical dispersion, since the radon source is exclusively at the earth's surface. Utilization of this total vertical dimension can take place at very different rates, depending on the thermally driven vertical wind. These rates are intimately related to the vertical temperature profile. On the average (and if we neglect the effects of the phase change of water in the air), enhanced turbulence is associated with a drop in temperature with height of 10°C per kilometer or greater. (This is the dry adiabatic rate.) If the temperature change with height is at a lesser rate, turbulence tends to be decreased, and if the temperature increases with height (an "inversion"), turbulence is very much reduced. The temperature profile, particularly over land, shows a large diurnal variation. Shortly after sunrise the heating of the land surface by the sun results in rapid warming of the air near the surface; the reduced density of this air causes it to rise rapidly. Cooler air from aloft replaces the rising air "bubble," to be warmed and rise in turn. This vigorous vertical interchange creates a "superadiabatic" lapse rate—a temperature decrease of more than 10°C per vertical kilometer—and vertical displacements are accelerated. The depth of this well-mixed layer depends on the intensity of solar radiation and the radiation characteristics of the underlying surface. Over the deserts this vigorous mixing may extend well above 3 kilometers, while over forested lake country the layer may be only one or two hundred meters thick. Obviously, this effect is highly dependent on season; in winter the lesser insolation and unfavorable radiation characteristics of snow cover greatly inhibit vertical turbulence.

In contrast, with clear or partly cloudy skies the temperature profile at night is drastically changed by the rapid radiational cooling of the ground and the subsequent cooling of the layers of air near the surface. This creates an "inversion" of the daytime temperature profile, since there is now an increase in temperature with height. In such a situation the density differences rapidly damp out vertical motions, tend to reduce vertical turbulence, and stabilize the atmosphere. The longer hours of winter darkness favor the formation and maintenance of inversions. In the polar regions, in areas relatively unaffected by storms, inversions of 20°C or more may persist for weeks. Under such extreme circumstances, vertical mixing is very slow and the surface layers of the atmosphere can almost be considered as decoupled from the air above. Such a situation may also occur in middle latitudes, but surprisingly winter is not the time of most intense and persistent surface-based inversions. The greater frequency and intensity of large-scale storm systems, with their higher wind speeds and extensive cloud cover, tend to prevent the frequent formation of this very stable situation. It is in autumn, with its combination of relatively long nights and fewer storms, that inversions are most frequent and persistent.

Two other temperature configurations, on very different scales, have important effects on vertical turbulence and the dilution of air pollution. At the smaller end of the scale, the heat capacity of urban areas and, to a lesser extent, the heat generated by fuel consumption act to modify the temperature profile. The effect is most marked at night, when the heat stored by day in the buildings and streets warms the air and prevents the formation of the surface-based temperature inversion typical of rural areas. Over cities it is rare to find inversions in the lowest 100 meters, and the city influence is still evident 200 to 300 meters above the surface. The effect is a function of city size and building density, but not enough observations are yet available to provide any precise quantitative relations. Although the effect even for the largest cities is probably insignificant above a kilometer, this locally produced vertical mixing is quite important. Pollution, instead of being confined to a narrow layer near the height of emission, perhaps only 100 meters in thickness, can be freely diluted in more than double the volume of air, the concentrations being reduced by a similar factor.

On a much larger scale the temperature profile can be changed over thousands of square kilometers by the action of large-scale weather systems. In traveling storm systems (cyclones) the increased pressure gradients and resulting high winds, together with the inflow of air into the storm, create relatively good vertical mixing conditions. On the other hand, the flat pressure patterns, slower movement, and slow outflow of surface air in high-pressure cells (anticyclones) result in much less favorable vertical mixing. This is primarily due to the gradual subsidence of the air aloft as it descends to replace (mass-continuity requirement) the outflow at the surface. During this descent the air warms adiabatically, and eventually there is created a temperature inversion aloft inhibiting the upward mixing of pollution above the inversion level. As the anticyclone matures and persists, this subsidence inversion may lower to very near the ground and persist for the duration of the particular weather pattern. This pattern is typically associated with the beautiful weather of "Indian summer," but it has also been associated with all the major air-pollution disasters (Donora, Pennsylvania, in 1948, London in 1948, 1952, and 1962, and others).

The action of mechanical turbulence in the vertical requires rather less discussion. It is obvious that if a moving mass of air reaches an obstacle it cannot penetrate, it must go over or around the obstacle. If the obstacles are numerous (blades of grass, rows of trees, or streets of buildings) the air will be constantly rising and falling. Thus, vertical mechanical turbulence is the response to the roughness of the underlying surface and has the most effect in the first few hundred meters above the surface.

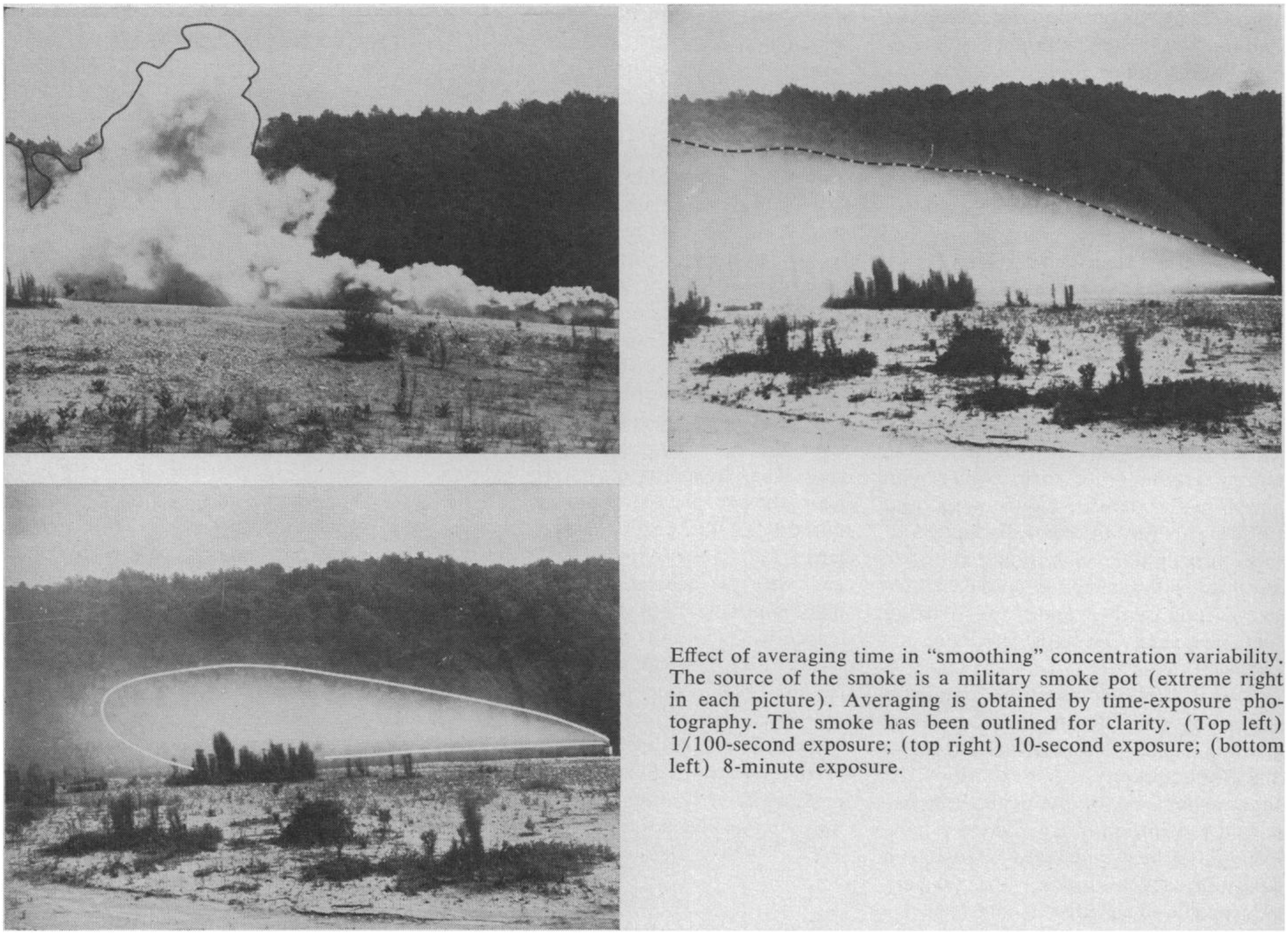


Typical wind-direction variability. Data are an analogue trace of a conventional wind vane.

Horizontal Turbulent Diffusion

The most important difference between the vertical and horizontal dimensions of diffusion is that of scale. In the vertical, rapid diffusion is limited to about 10 kilometers. But in the horizontal, the entire surface of the globe is eventually available. Even when the total depth of the troposphere is considered, the horizontal scale is larger by at least three orders of magnitude, and the difference, say during a nocturnal inversion which might restrict the vertical diffusion to a few tens of meters, is even greater since the lateral turbulence is reduced less than the vertical component. Mechanically produced horizontal turbulence is, on a percentage basis, much less important than the thermal effects; its effects are of about the same order of magnitude as the vertical mechanical effects.

The thermally produced horizontal turbulence is not so neatly related to horizontal temperature gradients as vertical turbulence is to the vertical temperature profile. The horizontal temperature differences create horizontal pressure fields, which in turn drive the horizontal winds. These are acted upon by the earth's rotation (the Coriolis effect) and by surface friction, so that there is no such thing as a truly steady-state wind near the surface of the earth. Wind speeds may vary from nearly zero near the surface at night in an anticyclone to 100 meters per second under the driving force of the intense pressure gradient of a hurricane. Perhaps the absolute extreme is reached in the thermally driven vortex of a tornado, where speeds of 200 meters per second or more (they have never been accurately measured) may occur. The importance of this variation, even though in air pollution we are concerned with much more modest ranges, is that for continuous sources the concentration is inversely proportional to the wind speed. Con-



Effect of averaging time in "smoothing" concentration variability. The source of the smoke is a military smoke pot (extreme right in each picture). Averaging is obtained by time-exposure photography. The smoke has been outlined for clarity. (Top left) 1/100-second exposure; (top right) 10-second exposure; (bottom left) 8-minute exposure.

sider a source emitting one unit of pollution per second in a wind of one meter per second. If the wind increases to two meters per second, the volume of air passing the source is doubled; hence the concentration is halved. It is not quite so simple for multiple emissions in a large area source, but the variation of wind speed is still a fundamental factor in the dilution of air pollution.

The variation of turbulence in the lateral direction is perhaps the most important factor of all and certainly one of the most interesting. In practice this can best be represented by the changes in horizontal wind direction. We have the basic wind currents of the globe—the polar easterlies, the mid-latitude westerlies, the easterly trades of the subtropics, and so on. These are manifested in the semipermanent pressure systems with a superposition of traveling cyclones and anticyclones. Within each of these systems, which may be several thousand kilometers across, the wind is not steady but is varied by the temperature contrasts between ocean and land, mountain and plain, city and field. These create local land-sea breezes, up- and downslope flows, and even in special cases rural-to-city drifts of air. The situation is succinctly described in a parody of a verse by Swift attributed to the meteorologist L. F. Richardson: "Great whirls have little whirls, that feed on their velocity; And little whirls have lesser whirls, and so on to viscosity."

The net effect of these systems is a constantly varying wind direction. Within a few minutes, the wind may fluctuate rapidly through 90 degrees or more. Over a few hours it may shift, still with much short-period variability, through 180 degrees, and in the course of a month it will have changed through 360 degrees numerous times. Over the seasons, preferred directional patterns will be established depending upon latitude and large-scale pressure patterns. These patterns may be very stable over many years, and thus establish the wind climatology of a particular location.

The emitted pollution travels with this ever-varying wind. The high-frequency fluctuations spread out the pollutant, and the relatively steady "average" direction carries it off—for example, toward a suburb or a business district. A gradual turning of direction transports material toward new targets and gives a respite to the previous ones. Every few days the cycle is repeated, and over the years the prevailing winds can create semipermanent patterns of pollution downwind from factories or cities.

Atmospheric Transport

It is convenient to distinguish the turbulent diffusion of pollution from the bulk transport of pollution away from its source. In fact, the statistical theories of diffusion speak of a steady mean flow and the turbulent fluctuations about this mean. This separation, however, is very dependent on the time and space scale of interest. Five hours of southwest wind may become only statistical fluctuations about a mean monthly northwesterly flow, which is in turn a portion of the annual wind frequency distribution. Nevertheless, this division of wind behavior into turbulent fluctuations and mean flow is of practical value, because it permits the use of average wind statistics (the mean flow) to describe the "ventilation" of an area. Certain features of the physiography and meteorology of particular areas can seriously reduce this transport or ventilation. Two of the most effective mechanisms for this reduction are topographical barriers and semipermanent subsidence inversions.

Topographical barriers are best described by examples. The semicircular ring of hills and mountains around the Los Angeles Basin slows the flow of air in and out of the area and acts to form a catch basin for pollutants. On a much larger scale, the Great Basin of Utah and Nevada functions in the same way, particularly in winter, providing a huge bowl which can contain a stagnating air mass with very light winds of variable direction. The narrow valleys of western Pennsylvania also act to slow the flow, but in this instance air movement is constrained to follow the contours of the valley, so that the natural variability of the wind is largely ineffective and pollution repeatedly follows the same path. Again on a larger scale, the San Joachin Valley of California has much the same effect. The persistent surface fogs of the winter season attest to the reduced air transport in the surface layers of air in this area.

The semipermanent inversion is a feature of west coasts of continents throughout the world; Africa, the Iberian Peninsula, South America, and the southwestern coast of the United States all have this typical vertical-turbulence lid created by the subsidence associated with the semipermanent high-pressure areas of the eastern subtropical oceans. If, as in the case of southern California and Chile, there is also a mountain barrier, the meteorological stage is set for man and his technology to create a persistent air-pollution problem.

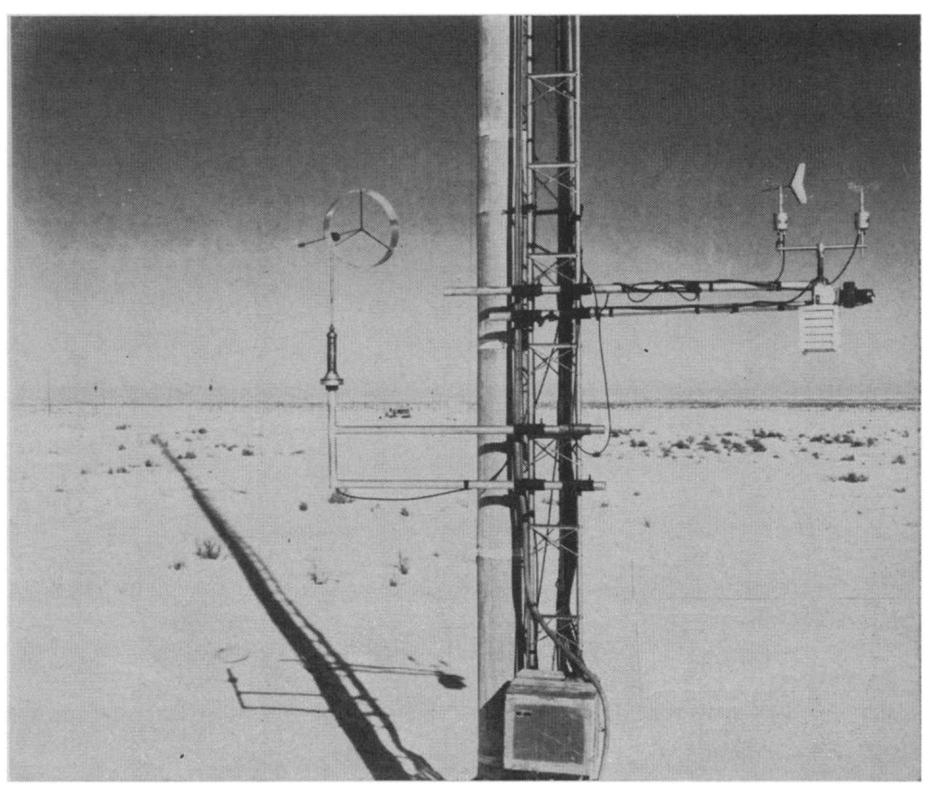
Applications of Air-Pollution Meteorology

It was a military weapons system, in this instance the use of gas in World War I, that led to the early quantitative meteorological studies on the dilution of pollutants by the atmosphere. Application to military technology has continued and has provided much valuable information for application to more general and widespread civilian problems.

The major U.S. effort in the meteorology of air pollution began with the Manhattan Engineering Project and the construction of the Hanford Works in the state of Washington. It is a credit to the acumen of this predecessor of the Atomic Energy Commission that it recognized, at a very early stage, the need to study atmospheric dilution near such plants. A group of meteorologists, under the direction of Phil E. Church of the University of Washington, set the pattern by measuring, in detail, the variations, wind speed, and direction throughout the Hanford area, and used a 125-meter instrument tower to measure vertical wind and temperature profiles. This early program was followed by similar efforts at the National Laboratories at Brookhaven, Oak Ridge, and Argonne, at the National Reactor Testing Station, and at the Nevada Test Site. Other nuclear sites have had similar meteorological studies.

Such a study usually begins with recording the small scale (1-to-50-kilometer) variation of the dilution in order to identify diurnal and seasonal patterns and any combination of meteorological parameters that would complicate effluent releases (for example, a persistent wind direction occurring simultaneously with a persistent inversion). The various data are organized as background statistics for engineering design. A model compendium of the type was ORO-99, "A Micrometeorological Study of the Oak Ridge Area," prepared by J. Z. Holland and collaborators in 1953. It remains a useful guide.

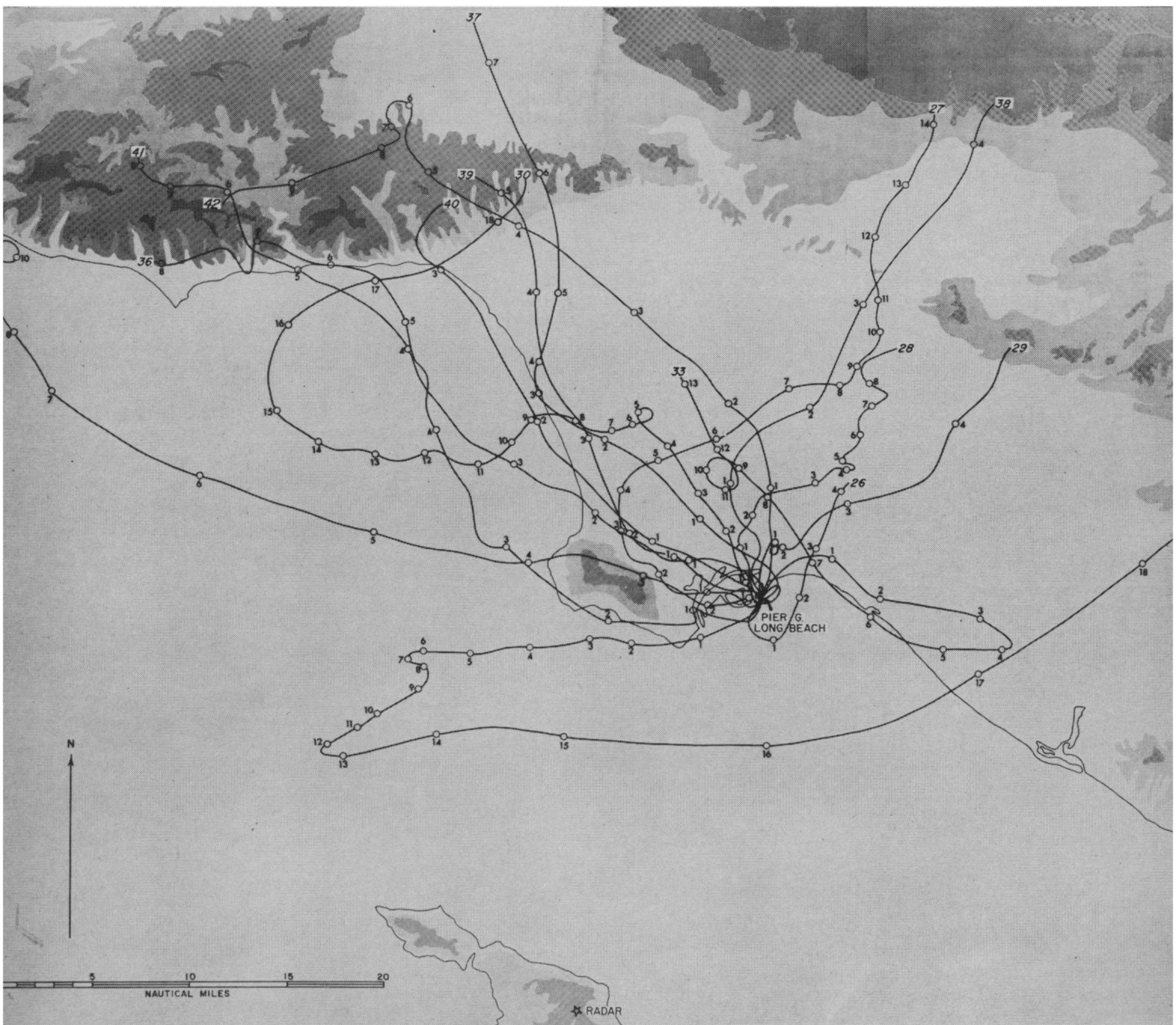
Most of the larger installations have supplemented the measurements of meteorological parameters with direct measurements of atmospheric diffusion through the analyses of concentration measurements from "sources of opportunity." Intensive measurements of argon-41 from the stack of the



Wind and turbulence instrumentation for diffusion tracer tests. The annular fin vane at left measures vertical and horizontal motions. A sensitive anemometer and vane and a temperature sensor are on the right.

Brookhaven air-cooled reactor and of iodine isotopes from the chemical processing plants at Hanford and the National Reactor Testing Station, combined with the concurrent meteorological data, have been used to determine average long-period concentration patterns around such installations and the quantitative relation between concentration and averaging time. This latter information, the "peak-to-mean" concentration ratio, is of great practical importance in evaluating biological effects of acute versus chronic exposures to pollutants, and also makes possible the extrapolation of sampling data taken over fixed, and usually short, times to a wide variety of conditions.

As understanding of the diffusion process has become more exact, meteorological information has been used more frequently in the design of experiments involving the release of radioactivity, both in order to optimize safety and to increase the efficiency of the experiment. Knowledge of the seasonal and diurnal frequency of necessary wind directions and trajectories helps in scheduling experiments so as to minimize weather delays. Knowledge of the existing meteorology during experiments is often indispensable for the correct evaluation of test results. This requirement was particularly pertinent in the determination of fallout from atmospheric nuclear detonations. Comparison of fallout from different devices, with different yields, and perhaps exploded under different conditions, required the "normalization" of the meteorology. The inten-



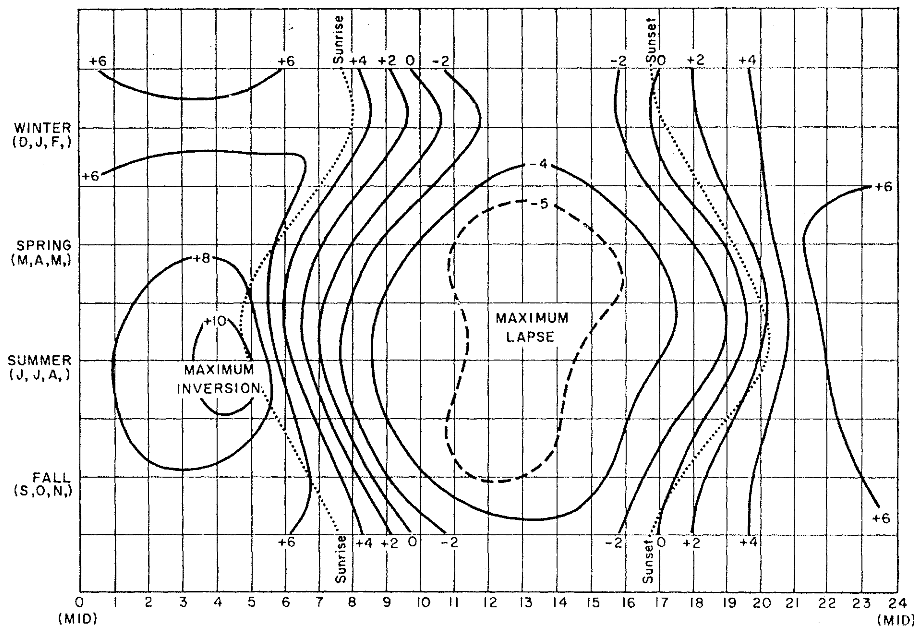
Air trajectories in the Los Angeles Basin measured by radar-balloon-transponder system. Note the variability and complexity of individual trajectories. Numbers along each trajectory are time (hours) after release. The large number at the end is the flight identification number.

sive system developed for the Nevada Test Site of measuring and forecasting wind and temperature profiles was designed to provide not only operational data for safety purposes but also the documentation needed to evaluate the scientific experiments.

On a much larger scale, knowledge of global circulation patterns, long-range diffusion, and atmospheric removal processes, part of it gained by using the radioactive debris of previous tests as wide-ranging meteorological tracers, has permitted accurate forecasts of the time and space distribution of global fallout to be expected in various parts of the world.

Still another use of air-pollution meteorology is in the analysis of an accident, particularly in the determination of the amount of material released. In the two major reactor accidents that have occurred, one at Windscale, England, in 1957 and the other at the National Reactor Testing Station in 1961, perhaps the best estimates of the amount of radioactivity released to the air were obtained by calculating the diffusion equations backward, from the observed concentrations through the existing meteorological conditions to the source strength. These results were particularly interesting because they required spatial and temporal integration of observed concentrations, extrapolation of weather information from only a few points, and the use of reasonable models of diffusion.

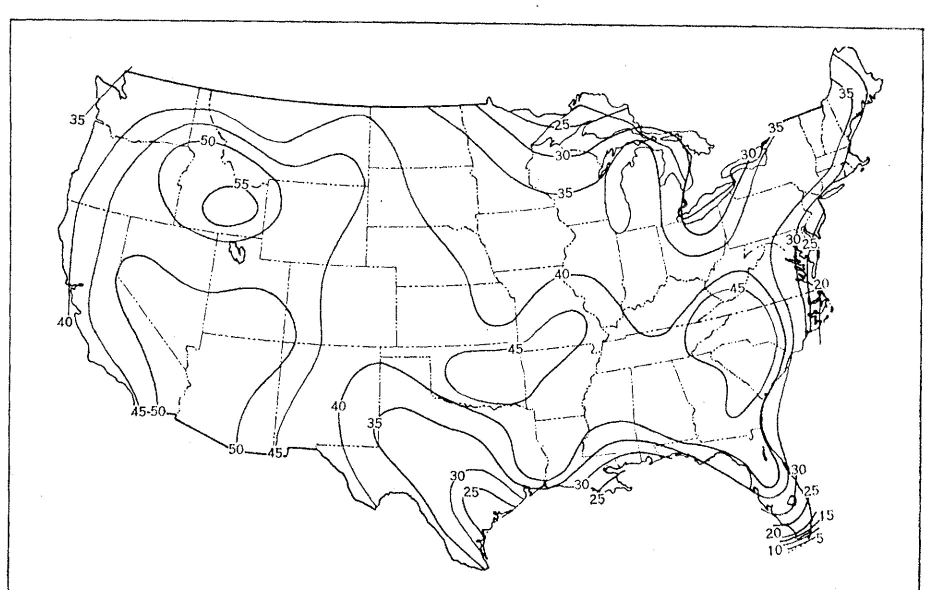
There is a very strong motivation to deduce generalized information, as well as empirical results, from these essentially "free" sources of opportunity, and very useful results have been obtained. Useful as such analyses have been, they cannot, however, entirely substitute for well-designed experiments where the atmospheric conditions can be selected with care, the source is controlled, and the sampling procedures are commensurate with the experimental goals. Thus, most of the advances in understanding diffusion have been due to careful field experiments with gaseous or aerosol tracers, concurrent with elaborate measurements of atmospheric turbulence, wind, and temperature gradient. The technology that has developed around these tracers, which range from natural spores to Kleenex lint and soap bubbles, is an interesting one. One of the more recent developments is the use of alpha-particle excitation of the filter samples of a fluorescing particulate to



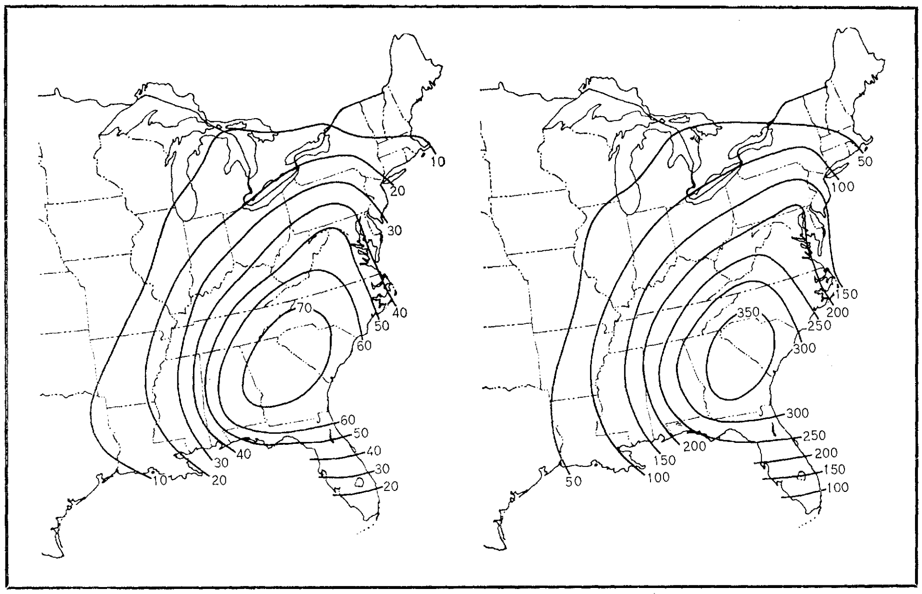
Diurnal and seasonal variation in temperature profile (between 1.2 and 120 meters) at the National Reactor Testing Station. Isopleths are temperature differences (degrees Fahrenheit). Abscissa is time of day.

permit automated analysis of the sample concentration. Free balloons have traditionally been used as meteorological tracers. This technique has been given new impetus by the use of new materials and low-cost electronics to provide a nearly-constant-volume balloon and a lightweight radar beacon system, the position of which can be continuously measured by radar to ranges of more than 100 kilometers.

The information thus developed facilitates one of the most important uses of air-pollution meteorology, the planning of the location of pollution sources in relation to sensitive areas (people, animals, and vegetation). Proper site selection makes possible the use of the average features of the weather to minimize the effects of air pollution. Preplanning can be applied to problems of all sizes—choice of location for a rendering plant, selection of a site for a nuclear or coal-fired power plant, urban industrial zoning. The meteorology involved can be as simple as determining the direction of the most prevalent wind or so complex



Frequency of low-level (surface to 150 meters) inversions in the fall season. Isopleths are average percentage of hours of inversion per day.



Frequency of large-scale slow dilution (stagnating anticyclones). Isopleths at left are average number of occurrences of stagnation "cases"—4 days or more—in the period 1936–1960. Isopleths at right are average number of days of stagnation in the same period.

as to require three-dimensional wind statistics, temperature profiles to several kilometers, and data about air trajectories for tens of kilometers from the site. The most efficient solutions must take into account not just meteorology alone, but the entire process, including the economics.

Meteorology and Urban Air Pollution

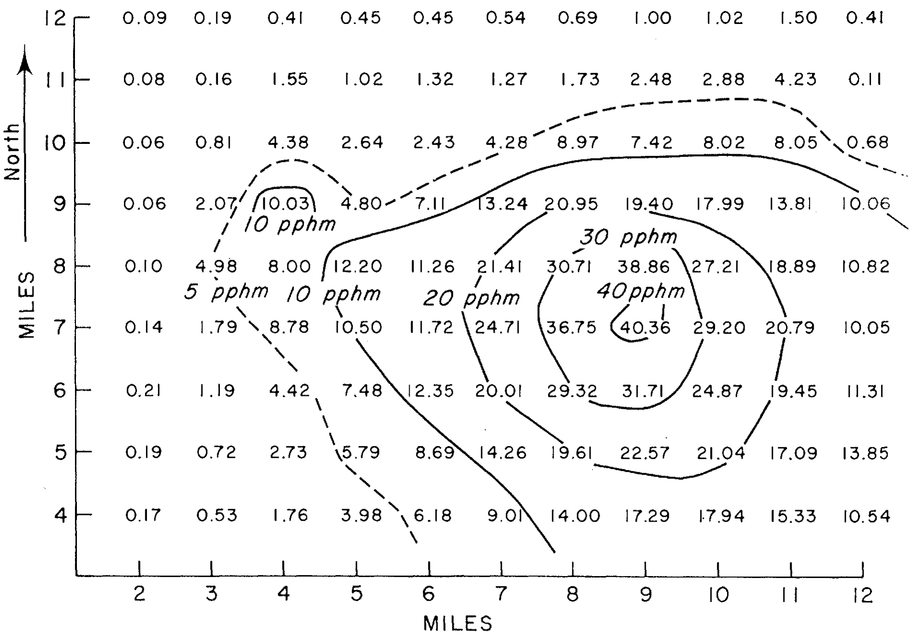
In the applications previously discussed, the pollution source is usually discrete, readily identifiable, and, with sufficient effort, amenable to individual study and analysis. In fact, most diffusion theory and experiment have been directed to such sources. These problems are important and will remain so. Air pollution meteorology is being increasingly applied, however, to the growing problem of urban air pollution, and here the number and variety of pollution sources prohibit individual study. Indeed, one of the major sources, the automobile, does not even stay put. Another complication and one of the most interesting features of this entire problem is that, while in the short term the meteorology of diffusion shows great variation and pollution emissions stay relatively constant, over periods of several years it is the meteorology that becomes stable and the pollution sources that vary.

To deal with these factors, two different approaches have been used. For the short term—and to answer such questions as: What is the statistical distribution of pollutant concentrations? Do different pollutants behave differently in the atmosphere? What are the effects of pollution on weather?—the meteorologist has inverted the problem; instead of calculating the field of concentration from a known source (source-oriented approach), he examines the measured field of concentration and the concurrent weather, and through standard statistical techniques relates the two (receptor-oriented approach). This technique has produced interesting results concerning the atmospheric "half-life" of pollutants, the seasonal variability of pollution, the role of sunlight in the production of photochemical smog, the reduction of solar radiation in cities, to mention only a few examples.

In fact, one of the most recent applications of meteorology completely ignores the source. Several years ago the Weather Bureau, on the basis of a statistical evaluation of the concurrent relation of high air-pollution values and large-scale meteorology, found that persistent high values of air pollution were associated with large areas of light wind, at the surface and aloft (slow horizontal ventilation), and sufficient atmospheric stability to inhibit vertical motion. These conditions are most often associated with a slowly moving or stagnant anticyclone; hence the designation of this condition as a "stagnation" model. In 1963, after several years of successful testing, the Weather Bureau began issuing "Air Pollution Potential Forecasts" for the United States when meteorological conditions satisfy the stagnation model and are expected to persist for at least 36 hours. These are area forecasts and are currently limited to situations where at least 90,000 square kilometers are affected. This limitation is necessary because of the significant role played by very local meteorological variations such as sea breezes or mountain-valley winds and local pollution emissions, neither of which can be adequately predicted from the large-scale meteorology. In particular the designation "Pollution Potential" is required. If a stagnation area occurs in the Great Plains (as has happened) the air pollution levels should be very different from those in a similar weather pattern over the industrialized Atlantic States (and they have been). These forecasts, by making advance preparation possible, provide unique opportunities for examining high pollution levels through medical studies, special sampling programs, and so on. Eventually they may contribute to the reduction of pollution levels through control of emissions during these unfavorable periods.

Other applications require a "source-oriented" viewpoint for answers to the questions: What is the origin of this particular pollutant? What are the effects of new pollution controls? Given a specific growth rate, what are the likely future concentrations of pollution? In this approach the sources within a city might be grouped into, for example, industrial, domestic, transportation; then subdivided according to constituents—sulfur dioxide, carbon monoxide, and so on; and further divided by allocation to specific geographical areas. One of the most promising developments of recent years has been the success of mathematical models of urban diffusion, which can accept such source information and calculate the field of urban pollution concentration. The initial field test of such a model was carried out in Nashville, Tennessee, in conjunction with an intensive program of pollution measurements and medical surveys conducted by the Public Health Service and Vanderbilt University. City-wide concentrations of sulfur dioxide were computed for periods as short as 2 hours, and these values were summed to obtain average daily levels. The model, which incorporated an SO_2 "half-life" and treated all the sources within a 2.5-square-kilometer source area as if they were centered in the middle of this area, was not very sophisticated meteorologically, although it did, by virtue of the two-hour time step, allow for diurnal variability. Crude as this first attempt at prediction was, it gave results that were very similar to the observed values and that in fact had a smaller variability than the sampling values with which the computations were compared. Source inventories are under way which will permit testing and refinement of the model in other locations. At the same time additional measurements of the diffusion within cities and studies of the best way to measure city ventilation rates will enable the meteorological portion of this and other models to be more sophisticated and more realistic. This work was, as one would expect, performed on a high-speed computer. As in so many other scientific problems, the required calculations (about 10^6 for the 24-hour average concentration field) became feasible only with such assistance.

The use of mathematical models for computer solution appears to promise much in the quantitive determination of pollution concentrations. As we learn more about the meteorology of cities and the distribution of pollutant emissions, it may be possible to predict expected concentrations routinely and to take into account the changes in the patterns that would occur if the emissions were changed. The auto-exhaust pollution from the Sunday-driver pattern could be differentiated from that of the weekday rush-hour regardless of the variation in the atmospheric dilution. On a larger scale, it is expected that computer-produced "Air Pollution Potential Forecasts" will replace the present techniques, which require both manual data analysis and personal judgment, and will extend both the time period and detail of these forecasts.



Computer calculations of sulfur dioxide concentrations for Nashville, Tennessee. Solutions of a multiple-source meteorological diffusion model compare favorably with measured values. Abscissa and ordinate are city dimensions (miles); isopleths are concentration values in parts per hundred million (pphm).

Future Problems

Much remains to be learned about how the atmosphere acts to dilute materials and eventually to rid itself of them. The problem is particularly acute within cities, since there now exists no adequate model to describe, in quantitative terms, the movement of air through such a complex structure as an entire city, and since most industrial pollution originates within the city itself. In the near future a major effort will be required to determine the cumulative effect on air purity of the complex of cities that are expanding and combining to create the megalopolis. Here the problem requires consideration of weather patterns over several days and hundreds of kilometers, if we are to determine the extent to which pollution from "foreign" sources 100 to 500 kilometers upwind adds to the locally emitted pollution. On this scale, chemical interactions of pollutants and their "half-lives," the effects of sunlight and humidity, the effects of depletion of pollutants due to deposition, and so on, must be known. None of these problems appears to defy practical solution, but a program of research, probably culminating in extensive, long-range tracer experiments, will be required.

In the longer, and larger, view perhaps the most important future problem is to achieve better understanding of the geochemistry of atmospheric pollutants. It has been pointed out that there are probably no undisturbed atmospheric conditions left in any of the mechanized areas of the world. The possible "greenhouse" effect of carbon dioxide is not known precisely, yet extrapolation of present measurements indicates a global increase in this constituent of about 40 percent by the turn of the century. Sulfur is emitted to the atmosphere in ever-increasing amounts, but we know neither its fate nor its rate of addition with any precision. We cannot be certain whether massive additions of air pollutants could affect our climate and, if they can, in what fashion. A careful, long-term program of measurement, probably of global extent, of the most important pollutants, additional research to increase our understanding of the self-cleansing mechanisms of the atmosphere, and more knowledge about the relation between air pollution and climate are required if we are to safeguard the air reservoir in which we live and breathe.

Bibliographical Notes

In lieu of internal references, I have listed selected material for the interested reader. The first four items cover turbulence theory and its modification for atmospheric application; the next two deal with practical meteorological relations to pollution; the last three, primarily with urban pollution.

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Imprinting in Birds

Research has borne out the concept of imprinting as a type of learning different from association learning.

Eckhard H. Hess

Thirty years ago Konrad Lorenz, the Austrian zoologist, formulated the concept of imprinting as a result of his observations of the primary socialization process in newly hatched birds (*1*). At the time, studying species such as greylag geese and partridges, where the young are able to locomote on their own soon after hatching, he thought the process to be peculiar to birds. Basically, Lorenz found imprinting to be an emotional bond of the young to the parent, formed very rapidly soon after hatching. This specific attachment to the parent was dependent on the parent's being the first moving object experienced by the young; when Lorenz himself took these young animals while they were still a few hours old and had them follow him before seeing their own mother, they would thereafter regard him as their parent, ignoring their biological mother.

Although little experimental work on imprinting has been done by the Lorenz group since these initial observations, there has been a steady increase in imprinting research in laboratories in Europe, and even more in the United States. The first paper by Ramsey and myself (*2*), published in 1954, was the beginning of mounting series of studies by numerous investigators; the bulk of this work is covered by an excellent review article by Moltz (*3*). Rather than duplicate his efforts, I discuss here the work which has been going on in our University of Chicago and Maryland laboratories since publication of my last article of this type, which appeared 5 years ago (*4*). Since that time, a great deal of observation and laboratory research on imprinting has been carried on with precocial bird species—that is, species in which the young are hatched at a relatively advanced developmental stage so that they are able to move about readily at an early age. While several experimenters in the area of imprinting seem to regard it as the same as simple association learning, our own research has led us to a different conclusion. Association learning is a widespread behavioral phenomenon and has come to dominate much psychological research. A great deal has been found out about association learning—for example, that practice makes perfect, old habits can be replaced by new ones, and so on. Thus, it is natural that some experimenters have approached the problem of imprinting with the assumption that it is a form of association learning. But all of our experiments have led us to discard this assumption, for the more we have studied imprinting, the more firmly we have become convinced that the imprinting phenomenon is considerably different from ordinary association learning.

Before considering our more recent research, I will review briefly some of the earlier experimental findings which led us to this conclusion. Knowledge of these findings is necessary to an understanding of the implications of our newer investigations.

Early Findings

One of the most important of these earlier findings is that there is a "critical period" in the life of the bird during which the imprinting experience is most effective in determining the character of its adult social behavior (*2*). The critical period for imprinting in chicks and ducklings lasts, at the most, from the time of hatching up to 32 or 36 hours of age, and the peak of sensitivity to the imprinting experience occurs at 13 to 16 hours of age in both species. We did not, of course, originate the idea of a critical period in imprinting, for Lorenz had already stated in 1935 that imprinting could occur only during a specific life period in the animal. Such limited "critical periods," during which the animal is extremely susceptible to the effects of certain kinds of experiences, have never been found in cases of association learning. This is apparently one reason why some researchers have resisted the idea of critical periods in imprinting. Nevertheless, my associates and I have found that the "critical period" is a basic characteristic of imprinting, for we have never failed to find its existence and importance. What is more, if experimentation on imprinting is carried out with animals who are beyond the critical age period, then only association learning, and not true imprinting, is possible. This fact has not been fully recognized by experimenters who believe that imprinting and association learning are the same processes.

Another basic difference which my associates and I have found between imprinting and association learning concerns the manner in which learning behavior is affected by drugs (*5, 6*). We found that administration of meprobamate or carisoprodol to chicks and ducklings learning a color discrimination problem involving food reward does not depress their ability to learn the problem. In fact, they may

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