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Meteorological Effects of Environmental Controls

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The solution of the continuity equation in practical applications is examined, and the values needed for approximate solutions are indicated. Models are adequate for investigating what could happen, but are less satisfactory for predicting what will happen. An example is given in relation to the distribution of SO_2 over Connecticut. More knowledge is needed about atmospheric chemistry before better predictions can be expected. The effect of particulates on atmospheric opacity is reviewed.

If we modify or control an emission, how are we sure, even in the simplest case of a stable pollutant, that we know the resulting effects on air quality? Further, how do these changes of air quality react on the weather and climate? We consider here the suitability of models to provide data for criteria and standards and, by implication, as tools in the planning of control measures.

Air quality models solve the continuity equation of the concentration of a pollutant by integrating from given initial conditions subject to certain boundary conditions and a specification at some level of detail of the meteorological situation. (Some models assume a form of solution and insert numerical values of certain parameters determined by the meteorological and initial and boundary conditions.) The boundary conditions must include the source inventory. Inventory errors inevitably lead to errors in air quality computation, but we are concerned at the moment with the meteorology and will assume that we have a perfect source inventory. We may write the continuity equation as:
Local rate of change of concentration = Transport (divergence of flux) + Chemistry (local conversion rate)

In practical applications the equation is solved by finite difference methods on a two- or three-dimensional grid of points, the solution at each point representing mean conditions over the surrounding unit "box" for the finite time interval used in integration. I will concern myself mainly with discussion of the transport term. We must divide the transport term into transport by processes which in principle are known in detail and transport by processes unknown in detail. The former include gravitational settling and wash-out, and transport by the mean wind (i.e., the box-average wind). The second, the diffusive term, includes the effect of fluctuations of wind. There is no soluble set of equations for any kind of average of the fields of concentration and motion. Any formal statement in terms of averages and fluctuations contains more unknowns than equations and some "closure'" approximation is required. Eddy diffusion coefficients and the standard deviations of plume models are such "closure" devices. The requirements for solution, so far as the transport term is concerned, are (1) specification of the "box mean" wind and (2) specification of an approximate method of relating the diffusive term to observables.

The degree to which the first specification is developed within the model varies from model to model, the more advanced models

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compute the local variations induced by topography and diurnal heating.

However well the "average" terms are modeled and however accurately the source inventory is specified, the second requirement introduces error. We may estimate the magnitude of the error by a brief consideration of one of the more popular methods of specifying diffusion: that introduced by Pasquill (*1*) which relates the diffusive terms, usually by means of a dispersion σ, to wind speed, cloudiness, time of day, and season in a number of categories. Each occasion of model application must be placed in a category, and the parameter σ may jump by a factor of 2 between categories. There is immediate probability of at least a twofold error in a single computation, a single computation being a time mean over a period of about an hour. A large-scale or long-term picture of air quality, arrived at by multiple application of the model is, thus, always more reliable than estimates of local short-term concentrations (unless the systematic errors which can be introduced by topography, etc., are deliberately ignored). If long-term integrated dosage of a conserved pollutant is in question, models are a very satisfactory basis for decision. If short-term high dosage rates are the danger, models are adequate to investigate what could happen, but less satisfactory indicators of what did or will happen in specified circumstances. Note that a "conserved pollutant" was specified. Unhappily, none of the pollutants of major concern is in this sense "conserved".

We illustrate this by an example: the 24-hr mean concentration of SO_2 over the State of Connecticut on December 12, 1968. On this date, several million people in an extensive region to the northeast of New York City were subject to concentrations of SO_2 considerably above the primary short-term standard for a full 24 hr. (Likelihood of a repetition of this situation has been considerably reduced by control measures.) Two models were used in this investigation: one a continuity equation model of the State of Connecticut on a 5000-ft grid (including topography) and the other a line-source Gaussian plume model, due to the late Professor Ben Davidson, of the distant effect (at about 50 mi) of the New York City sources.* Data for verification included two-hourly means of SO_2 concentration from about 30 special fixed measuring stations and continuous sampling of SO_2 concentration from aircraft and automobiles traversing routes across the direction of the mean wind. Qualitatively, validation is very good. All the mobile records show the broad plume from New York City with superposed the narrower intense plumes from the local sources. The aircraft shows the "lid" at about 3000 ft, which was the major cause of the high concentrations, and incidentally of the good validation statistics. None of the fixed monitoring stations showing appreciable pollution is in error by more than a factor of 1.5 which, in view of the high space gradients of concentration indicated by the model and the mobile monitors, is probably a fortuitously good result. The whole picture is a very impressive demonstration of the power of air-quality modelling—wide areas, distant complex sources, topography, land-sea contrasts—all successfully handled. There is one snag, and it completely dispels any developing complacency. Agreement between model and measurement was obtained by postulating, arbitrarily, that the mass of an emitted parcel of SO_2 decreased with time by a factor e^{-kt}, with $k = 3\ hr^{-1}$ on December 12, 1968 in the area covered by the model. So we have a very good way of mapping the SO_2 concentration, but we do not know what happened to the SO_2, except, of course, that it did not turn into good clean breathable air. The question we are addressing, "Are models adequate to provide material for criteria and standards?", must be answered—"Not without knowledge of the chemistry and ultimate fate of the pollutant concerned."

Before leaving models, I should mention another pollutant of universal concern: par-

* The Symposium presentation was illustrated by printout from these models but the necessary degree of detail—there are 7000 "boxes"—cannot economically be reproduced on small scale.

ticulate matter. For specific particulates of known physical and chemical properties—beryllium and asbestos plant emissions are examples of obvious concern—models, carefully applied, show very good validation statistics. It is a different story with the general particulate content of the atmosphere, as monitored by filter sampling. I have never seen a good validation in the modelling of this particulate matter. It is not the fault of meteorology or mathematics. The definition of particulates covers a wide range of sizes, shapes, and materials. The source inventories of manmade particles are not good; there is a complex and largely unknown air chemistry which almost certainly includes particle formation; and there is a little-explored natural background.

From the point of view of the major concern of this symposium, namely, whether we can foresee (and have foreseen) the effects of control measures, the answer must be not until we know more about atmospheric chemistry than we do now. This is particularly true of one simple control measure. Models suggest, and experience confirms, that if due regard is paid to such complications as the lee-waves of hills and fumigation at the breakdown of inversions, local high concentrations of pollutant can be mitigated by building high smoke stacks. The local nuisance is abated, but the regional or global spread of the pollutant is facilitated. If the pollutant is subject to chemical transformation in the atmosphere, the question which should be asked in these circumstances is which is worse for mankind in general; high local concentrations of the unmodified pollutant or very low but widespread concentrations of the modified pollutant? The answer may be, in the long run, that neither is tolerable. In that case, we must find another method of control.

I turn now to the more specific items in this section of the discussion. The first concerns modification of the radiative properties of the atmosphere by emissions and how this modification might be influenced by control measures. The tie to control measures relieves us of the necessity to consider the radiative effect of the emission of CO_2. We have increased the concentration of this major atmospheric radiator by 10% in the present century. The increase continues, and so long as we burn fossil fuel it will continue. In spite of some false alarms, it is safe to say that there have been no detected effects of this increase; which is not to say that there have been no effects. The second large radiative effect is that of particles in the atmosphere. It is certainly detected locally and is affected by control measures. Particulate pollution of city atmospheres leads to considerable attenuation of sunlight, optical paths of 0.1 to 0.2 being not uncommon. Measurement suggests that a high proportion (up to 50%) of this attenuation might be absorption, which is not readily explicable. In London, England the implementation of a clean air act demonstrably increased the solar energy reaching the ground in the winter months by 10% over an area of approximately 100 km_2—power in absolute terms of order 1 GW. In terms of temperature changes, there are compensating effects concerned with the long-wave terrestrial radiation, and detailed calculation of radiative transfer in city atmospheres suggest that the net temperature changes resulting from control measures will be small. We should remember that in some respects an increase of direct solar radiation, particularly in the erythemal ultraviolet, may not be an unmixed blessing.

On the global scale, we have to be concerned with the ubiquitous particles of hydrated sulfuric acid which seems to form the end-product of natural and pollutant emissions of H_2S and SO_2. Current analyses of the atmospheric sulfur balance suggest that one-third to one-half of these particles may be manmade, and studies of solar radiation over the oceans and in remote areas suggest that this corresponds to a manmade optical path of about 0.02. If only one-tenth of this is scattered back to space—which is a very cautious estimate—we are concerned with an average power rejection to space of 0.7 W/m^2

or 3.5×10^{14} W for the whole globe. As with CO_2, climatological effects have not been detected, (though there have been probably false alarms), which is not to say that climatological effects have not occurred.

Particles might affect the radiative properties of the atmosphere in an indirect way by changing the nature of clouds. For the same total water content, clouds of continental origin contain more, and smaller, droplets than those of oceanic origin and as a result have a higher albedo for solar radiation. Modification of the man-made particulate load of the atmosphere would modify this effect.

Finally, it has been suggested that this type of cloud modification might result in a modification of precipitation patterns. This (and the radiative effects of particles) are currently being studied in the St. Louis regional program. We must remember that the heat and moisture emission from a city, much less amenable to change by control than is the particulate emission, is at least equally likely to cause modification of precipitation patterns.

REFERENCE

1. Pasquill, F. The estimation of windborne material. Meteorol. Mag. 90: 33 (1961).