

Meteorological Aspects of Local High-Concentration Air Pollution

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1. General role and action of the atmosphere

The discharge into the atmosphere of gases and small particles from combustion and chemical processes is the beginning of a complex series of actions. These may be considered in three main stages:

- (a) general drift in the prevailing airstream with progressive spreading sideways and vertically,
- (b) chemical and physical transformation in the airborne stage,
- (c) removal from the atmosphere by various natural processes.

All these stages are important to some degree in controlling the resultant level of pollutant concentration. For the local effects, ie those within a distance of say 10 kilometres from the source, the determining factor is more often (a), though (b) and (c) cannot be generally ignored and may sometimes be decisive.

The general drift in the airstream introduces a particularly effective and direct dilution of the pollutant when, as is usual, this is emitted gradually. Then the pollutant emitted over a given time will tend to be distributed through a volume of air directly proportional to the wind speed. In this respect wind speed is one of the most important meteorological factors.

Apart from the general transporting action and initial dilution the lower atmosphere also exerts a progressive diluting action, through the vertical and sideways spreading by the turbulent and convective motions which disturb an otherwise steady flow. In the same way material released in concentrated batches is spread alongwind as well as vertically and sideways.

The intensity of the turbulent variations in the wind is greater the rougher the underlying surface, and is markedly affected by the daytime heating or nocturnal cooling of the surface, which produce characteristic changes of air temperature with height - respectively a fairly rapid fall (strong lapse) or an increase with height (inversion), the intermediate (neutral) condition being a slight decrease with height. The strong lapse and inversion profiles of temperature imply changes of density with height which are respectively unstable or stable, in that vertical mixing is respectively enhanced or suppressed. The depth of the atmosphere over which rapid vertical mixing extends (the mixing depth or layer) depends on the temperature profile and is frequently limited decisively by an overhead stable layer in which there is an inversion.

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The velocity fluctuations which produce vertical spread are so rapid that in most cases their full action is achieved in ten minutes or so - ie in so far as the concentration downwind of a continuous emission is dependent on vertical spread the concentration will have reached a fairly steady value when exposure to the effluent has continued for such a period. However, those fluctuations (in wind direction) which affect sideways spread include very much slower variations in addition, extending over hours and days. Accordingly the reduction of average concentration by crosswind spreading continues progressively as the exposure time of interest (or sampling time) is extended into tens of minutes, hours, days and so on.

## 2. Theoretical treatments of dispersion

The literature available on the theoretical treatment of the effects of atmospheric turbulence in diluting windborne material is now very extensive.<sup>(1, 2)</sup> All treatments demand idealization of the flow situation as a prerequisite for representing the dispersive action in a way that can be handled mathematically. Different degrees of sophistication are attempted in the various mathematical analyses but all the resulting dispersion formulae are necessarily of common form to the extent that the concentration downwind of a continuous emission is

- (a) directly proportional to the **rate of emission**.
- (b) inversely proportional to the product of the wind speed, the crosswind spread and the vertical spread.

The product in (b) represents the effective volume of air over which a given amount of material has been spread and neglects effects of wind speed other than that of direct dilution. In this respect the theoretical treatments do no more than formalise relations expected on simple physical grounds, and their most important potential is in correctly representing the magnitudes of the spreads in relation to measureable meteorological properties.

The fact that the theoretical treatments refer to idealised conditions of flow and terrain, which are rarely realised in situations for which air pollution is a problem, is often quoted as a criticism of their inherent value. Moreover such are the virtually random variations in the apparent dispersive behaviour of the natural atmosphere that at best the theoretical treatments offer estimates of average behaviour, from which the behaviour on individual occasions may be expected to depart to some extent. It is important to keep these reservations in mind, but there are many situations of weather and terrain and many types of practical questions for which it will be technically useful and economically worthwhile to be able to make estimates of likely pollutant concentration without embarking on difficult and prolonged measurements of actual pollutants or of tracers simulating them. In all cases it is preferable that the application of the theoretical treatments should be made by scientists with meteorological experience, who can also through that experience make as much allowance as



possible for the particular nature of the site and terrain and for the non-ideal nature of the air flow.

3. Practical systems for estimating dispersion

In any practical system for estimating the dispersion of pollutants the aim must be to combine to the best advantage three components:

- (a) the idealised theoretical treatments, reduced to a simple but flexible type of formula.
- (b) the practical experience gained from tracer studies and previous air pollution surveys.
- (c) the specialised knowledge available or obtainable on the particular configuration of the emission site and the area downwind.

In addition to the information on wind velocity - and here of course the general direction is important in defining the zone affected - the main meteorological problem is that of appropriately representing the crosswind and vertical spreads. Full use of the available theoretical treatments requires meteorological measurements which except in special and limited projects are too detailed and specialised to be envisaged. Examples are the fine detail of the temperature profile near the ground and the magnitude and scale of the turbulent fluctuations. For general and extensive practical use the estimation has to proceed in terms of routine meteorological data.

Of the available routine data the factor most directly reflecting the amount of daytime surface heating or night-time cooling (hence the "stability" in the lower atmosphere) is the amount of cloud. It is possible to define combinations of state of sky and wind speed to represent categories of stability and to assign to them "normal" values of the spreads. A system on such lines<sup>(3)</sup> has been in extensive use for some time. Rough but useful estimates of the effects of a given source on the level of pollution may thus be made given only the wind speed and direction and state of sky (with the locality, date and time otherwise determining the amount of sunshine). Such a system can be used in planning studies and also in operational studies in the absence of special meteorological data. Improvements in various aspects of the system may be expected as basic knowledge is increased and experience gained<sup>(4)</sup>. The accuracy achievable depends on how well the terrain and flow conditions conform to the ideal state and on the correctness of the meteorological data. On individual occasions the actual short-term concentration may differ one way or the other from that estimated, by a factor of several-fold.

4. Effect of elevation of sources

The significance of the usually gradual nature of pollutant emission as regards dilution has already been noted. The other very important characteristic



of the source is its elevation above the general ground level. Elevation is advantageous as long as the plume of pollution is not deflected downwards as a whole. Then a definite amount of vertical spread (and a corresponding amount of crosswind spread) must occur before the edge of the plume reaches ground level. The more intense concentration of pollution close in to the source is thereby avoided at ground level, and the maximum concentration now occurs some distance away depending on the height of the source. Thereafter the concentration at ground level decreases, always being lower than that which would have occurred had the same source been at ground level, but tending closer and closer to this value as distance increases.

For a given elevation of source the distance at which the pollution appears at ground level with maximum effect depends on the rate of vertical spreading and hence on the stability of the atmosphere. Thus the effects of an elevated source may be apparent at very short range in unstable conditions. On the other hand in stable conditions it has been known for an elevated plume to travel tens of kilometres without the ground being affected.

Wind speed has an important effect on the behaviour of an elevated plume, in addition to the diluting effect, in that it controls the amount by which a hot plume may rise above the chimney exit and so determines the effective total height of the plume. A strong wind keeps the plume low, so that a relatively small amount of vertical spread is required for the ground to be affected, and so this effect of wind speed is in opposition to its direct diluting action. It is also likely that at the greater heights reached by modern power station plumes the relative magnitudes of the vertical and crosswind spreads are also affected by wind speed, but to an extent which is not yet clear. The overall influence of wind speed may thus be rather more complex than is assumed in the usual simple model treatment of an elevated source. However, recent surveys suggest that except in a combination of light wind and unstable conditions the concentrations are on average somewhat less than those estimated from the simple model, in which the ratio of the spreads is taken to be a constant independent of wind speed and distance.

#### 5. Multiple sources

Although there may be considerable interest in the effects of a single large source of pollution there is also an obvious and perhaps over-riding interest in the combined effect of an array of various sources in an urban-residential area or an urban-industrial complex. There has accordingly been a focussing of interest recently on the methods of making estimates of concentration in such cases, from source inventories and meteorological or



climatological data. This so-called "mathematical modelling" of the effects of multiple sources is essentially a matter of summing individual contributions which in the simplest context are independent and directly additive.

The summation may be carried out in two ways:

- (a) by a mathematical integration - which is possible for certain simplified forms of the dispersion formulae - leading to a convenient formula representing the overall effect in terms of the total output over a specified area.
- (b) by a numerical summation on a computer - the effects at any point being first evaluated separately for all sources or convenient combinations of small sources.

It should be emphasised however that both methods depend ultimately on the validity of the dispersion formulae, and on the quality of the data on source inventory, wind speed and direction, and spread.

Both methods have been tried, though recently the emphasis has been on the second. <sup>(6)</sup> Very extensive arithmetic is required but this can be carried out very quickly on modern high speed computers. It is debatable however whether the realism of the final answers is always likely to be enough to justify the great elaboration advocated in the numerical models. There is some indication that a combination of both methods may be advantageous in <sup>(7)</sup> eliminating much of the numerical labour without seriously reducing the validity of the results. The advantage may be particularly significant when use is made of the principle that other things being equal the concentration at a given position will be dominated by the sources in a relatively small area immediately upwind.

It is to be expected on theoretical grounds and is evident from practical surveys that in a multiple source situation concentrations vary widely from position to position in the area, and from time to time. Nevertheless, the concentration averaged over a long time and over the whole of the multiple source area may be predictable with some accuracy (within a factor of two say). On the other hand the concentration estimated for a particular position, even when averaged over some hours, may be very much more in error. <sup>(8)</sup> Thus although much of the point of method b. lies in the prospect of correctly representing variability of the concentration in space and time this seems unlikely in respect of individual positions and periods. It is possible however that the application of the method to a large number of periods may provide a realistic estimate of the range of variation at a given position. <sup>(9)</sup>

## 6. Complexities of weather and terrain

It has already been emphasised that ideal conditions of flat uniform terrain and straightforward airflow are necessarily assumed in any simple generalisations about the local distribution of air pollution. In



practice there are many departures from this ideal, the more important being as follows:

- (a) The effect of buildings. In a collective sense these affect the general level of turbulence in the airflow, and some useful allowance for this may be estimated when the dispersion has proceeded sideways and vertically well beyond the sizes of individual buildings. The principle difficulty arises from the immediate local effect on a nearby source of the aerodynamic disturbance by an individual building. Only very crude generalisations can at present be offered, and the best hope for accumulation of necessary experience seems to lie in wind tunnel work. <sup>(10)</sup>
- (b) Topographical effects. Irregular terrain introduces important modification of the general drift of pollutants. Apart from the physical deflection and channeling of the airflow there occur downslope (drainage) winds from cooling at night and upslope winds from heating during the day. Dispersion tends to be affected adversely mainly by the vertical confinement of the air in valleys in stable conditions and the direct prevention of cross-stream spreading by valley sides. Useful attempts have been made to allow for such effects in the adaptation of the methods applicable to flat terrain.
- (c) Light winds and calms. These are the conditions which, especially in association with slow or restricted vertical mixing or with topographical confinement of the airflow, lead to the disastrous air pollution incidents. The slow drifting and dispersive action of the atmosphere is then not readily and reliably estimated by the usual procedures. Such extensions as are made of these procedures must be regarded with caution and even more reliance than usual placed on actual experience of particular sites in stagnant air situations.

## 7. Warning, forecasting, climatology

The ultimate basis for the preparation of warnings or forecasts of the incidence of important levels of air pollution is in the known relations between the concentration field, the source distribution and the meteorological conditions. In principle therefore a warning procedure may be designed in terms of continuous measurements of a significant meteorological parameter - such as the level of turbulence or the detailed form of the vertical profile of temperature - from which these relations may be evaluated. In the practice of warnings and forecasting, as in that of planning and operational studies



of air pollution, the meteorological requirements must generally be reduced to those normally satisfied in the regular programme of a national weather service. This means also that the parameters of the source-dispersion relation must be in terms of wind speed, broad vertical profile of temperature as available from routine upper air data, and state of sky.

The only general system known to be in current and continuous operation is based on forecasting the expected occurrence and continuation of large areas of stagnant air, within which a build-up of pollution would be possible. Extension of this purely qualitative "air pollution potential" forecasting is in hand in terms of a simple "box" model in which the pollutant is assumed uniformly distributed over the "mixing depth". The product of this "mixing depth" and the wind speed constitutes an effective dilution factor to be applied to the amount of pollutant released upwind of any position. An approximation to the "mixing depth" is available from the routine upper air data by applying the same procedure as the weather forecaster uses for estimating the likely vertical extent of convection.

A further possible step in the development of pollution forecasting would be to use forecasts of wind speed and cloud cover, to derive a forecast "stability category" which could be used in more detailed calculations of concentration. It would be important in any such further elaboration to keep in mind the very rough quality of the final answers.

The climatological statistics on wind speed, wind direction and cloud amount prepared from routine observations are immediately useable in any requirement for the estimation of long-term average concentration or of the frequency of incidence of specified levels of pollutant concentration. The procedure does of course need to be used with caution, not only because of the inevitably crude representation of the dispersive action of the atmosphere, but also because there may be correlations in the occurrence of the basic meteorological elements (eg cloud cover and wind direction) which are not evident from separate statistics of these properties.

There is now the possibility of deriving a more specialised climatology for such features as the mixing depth and stability categories, but so far such analyses have been on a very limited scale.

#### 8. Transformation and natural removal of pollutants

The pollutants of major interest are neither chemically inert nor permanently retainable in the atmosphere and their dispersion after release is accompanied by a complex chain of chemical reactions and physical removal processes.

One of the most important transformations is the solution and oxidation of sulphur dioxide to give sulphuric acid and sulphates. The solution may



occur at free water surfaces, on wet ground and other solid surfaces, on vegetation, and in drops of fog, cloud and rain. The process is of immediate practical importance as regards corrosion of materials. If the oxidation is in the presence of ammonia, hygroscopic ammonium sulphate results and in aerosol form this has an important effect on visibility. Transport to ground in rain or direct uptake at wet surfaces (including vegetation even in a nominally dry state) progressively depletes the atmosphere of the sulphur dioxide or secondary products. The relative amounts of sulphur dioxide deposited and remaining airborne depend on many factors - the initial elevation of the source, the dispersive conditions, the intensity of rain and the nature and wetness of the underlying surfaces. The complexity of the processes is reflected in the variability of the effective life-time of sulphur dioxide in the atmosphere - estimates range from an hour to several days<sup>(12,13,14)</sup> - and the significance of this to the concentration and effect of sulphur dioxide locally requires continuing study.

The other chain of processes which attracts great interest is that which leads to the "photochemical smog" so well known in Los Angeles. Photochemical dissociation of nitrogen peroxide, which appears to be enhanced in the presence of certain hydrocarbons (including those in car exhausts) produces ozone which in turn reacts with the hydrocarbons to form compounds with irritant properties. For these processes the favourable meteorological conditions are those of limited transport and dispersion in the presence of abundant sunshine, a combination occurring most effectively in anticyclonic conditions in relatively low latitudes, especially when there is topographical impidence to the large-scale air flow, as in the Los Angeles basin.

#### 9. Proposals for action

Features which are considered to be in special need of further consideration are:

1. The provision of improved low-level temperature soundings or of other measurements capable of prescribing the general 'mixing depth', and the extension of the climatology of 'mixing depth' and 'stability categories'.



2. Standardisation of the practical systems for estimating and forecasting the levels of air pollution from emission data and meteorological data, embodying improvements provided by recent researches but avoiding complexities which are not warranted by the expected quality of the final answers.
3. Improvement of the understanding and representation of the chemical transformation and natural removal of air pollutants.



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