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An Air Quality Management System for an Industrialized Region

K.H. Müller

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ABSTRACT

The air pollution control strategy for an industrialized region can be based upon a set of

- air quality prediction tables, calculated by a correlation of historical meteorology and air quality data. They give a forecast of short-range pollution level which can be used as a warning system,
- transmission tables, established either by a mathematical or physical simulation of the dispersion process.

When unfavourable pollution levels are predicted a reduction strategy has to be applied, which consists in (1) picking out all single emitters contributing to the pollution levels at the control points, (2) calculating reduction coefficients for the emitters which prevent the imminent pollution excess, and (3) selecting the most economic reduction from amongst the reducible source combinations.

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1. Air Modelling

Urban areas need today an air quality management. Planners and decision makers have to anticipate and evaluate the consequences of alternative arrangements and modes of operation of air polluting sources. The only acceptable way to do this is based upon mathematical prediction models.

For decisions to be made, the potential adverse effects of pollutants on various receptors, must be known at various levels of concentration, and for various periods of time.

Given, then, that the objectives of air pollution management are defined for a given situation, how can the relevant data, such as meteorological information, for instance, be employed to assure optimum management decisions?

These decisions will take two forms:

1) the specification of source distributions
2) the control of source strength

Both purposes are served best by a mathematical simulation of the source-atmosphere system, because such models permit wide flexibility in varying the parameters of both source distribution and strength, and atmospheric transport and dispersion. Consequently, a preliminary assessment of the consequences of any management decision regarding source controls can be obtained.

Air pollution modelling is indispensable for decisions concerning

- Siting (i.e. admittance of future emitters)
- warning (i.e. pollutant level prediction for a short time period)
- control (i.e. strategy of local-time dependent reduction of emission).

The air quality management system proposed by us consists of:

Data handling system (DH)

which collects, arranges, stores the meteorological and air quality data and the emission inventory of the region under consideration; which selects, rearranges, correlates subsets and prepares the input of the models (PM) and (DM).

Statistical prediction model (PM)

which correlates historical meteorology and air quality data so that a short-range (e.g. 24 hours) receptor-oriented air quality forecast can be given, i.e. weather situations and corresponding air quality data collected in the past will be used to predict air pollution levels in similar structured situations today. These correlations contain the source inventory, physical and chemical reactions, topography etc. implicitly. Such a model deals directly with real air quality situations; each new correspondence "weather situation - air quality", improves the base of the model.[1]

(PM)-input are, besides those historical correspondences, the actual meteorological and air quality situation, and a short-range weather forecast concerning wind- and temperature field, ceiling height etc.

(PM)-output are tables of predicted air pollution levels. Due to this set of correspondences it can be used as a warning system which indicates when the predicted pollution levels exceed anywhere the limits established by the health authority. As soon as a warning occurs, a local and time-dependent reduction of emission has to be activated. An adequate reduction strategy can be based only upon a prevision which results from a simulation.

Dispersion model (DM)

which simulates the transmission between source and receptor either by a

- computer code or by
- tracer experiments, where marked gases or aerosols are released through a chimney, the source strength of which is reducible and where the tracer immissions are measured by a network of control stations. Via (DM) one discovers source modifications which guarantee, that the pollution levels nowhere exceed the prescribed limits, and which influence as little as

possible the industrial production processes. This economic aspect represents evidently the key-point of the reduction strategy. A simultaneous reduction of all sources, e.g. to the half of their strength, would only be an unacceptable superficial solution.

2. Reduction strategy

Under the assumption that

- an improvement of air quality is necessary
- the corresponding reduction of emission solely by the throttling back of one or more single emitters is possible
- these emitters are able and willing to throttle back to the necessary extent

a reasonable, effective and economic control of air quality can be achieved.

The aim of our effort is to develop a technically feasible system of control for an industrialized region, which has available a sufficiently ample set of correspondences: meteorology - air quality, registered continuously at 3-4 control points of the region during, at least, twelve months. For warning we apply a statistical model operating on the following basis:

Multiannual weather observations and emission data are indexed and stored. The corresponding pollutant concentrations observed at the control points are also stored using the above mentioned indices as an addressing system. This data set growing day by day will be fed into a statistical model which gives together with an indexed short-time weather prediction an air quality forecast for the control points by analogue conclusions.

In case of unfavourable pollution levels predicted for one or more control points, a reduction strategy has to be applied to prevent an imminent pollution exceeding the pollution levels tolerated for these control points.

Such a strategy consists in

- picking out all emitters contributing to the pollution levels at the control points,
- calculating reduction coefficients ρ for single emitters, pairs, or groups of three, etc. of emitters, which prevent the imminent pollution excess,
- selecting the most economic reduction from amongst the reducible source combinations.

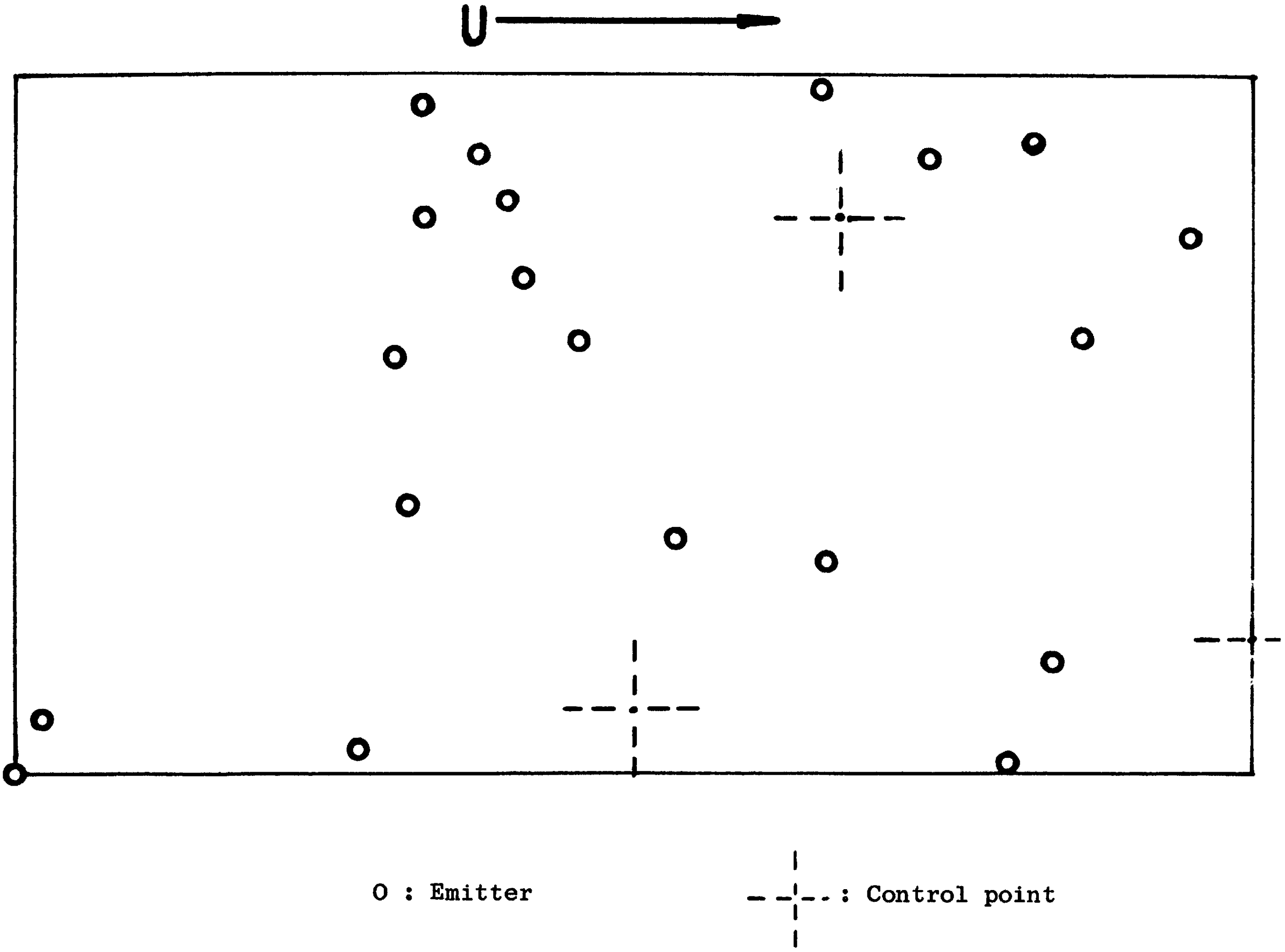
The basic philosophy of this strategy can be illustrated best by an example.

3. Example

In a rectangular region there are 20 single industrial emitters the source strengths of which can be reduced, if required by the air quality control. The corrsponding characteristic data such as position (x,y), effective chimney height z and source strength Q are listed in tab. 1.

I	x	y	z	Q
1	0	0	10	0.3
2	11	22	24	53
3	722	3	84	87
4	755	85	53	32
5	534	495	20	73
6	354	413	48	7
7	593	155	93	78
8	294	481	84	31
9	373	353	56	73
10	667	442	67	83
11	286	197	55	47
12	275	300	86	68
13	409	311	68	28
14	775	315	18	55
15	854	385	17	54
16	477	174	39	78
17	743	454	11	91
18	296	400	85	81
19	333	446	11	7
20	248	19	77	11

tab. 1



An air quality forecast predicts, for a wind with a speed of U = 5 m/sec blowing in x-direction, at three control points (x_k y_k) the pollution levels χ, which exceed the tolerance levels χ^{tol} by the amount

x_k	y_k	χ^{tol}	χ	$\Delta\chi\%$
450	50	0,91E-3	0,10E-2	10
600	400	0,90E-3	0,94E-3	5
900	100	0,11E-2	0,11E-2	1

tab. 2

These excesses can be suppressed by a reduction of the source strengths of one or more emitters.

Using the dispersion formula

$$\chi(x,y,0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{(y-y_0)^2}{2\sigma_y^2} - \frac{z_0^2}{2\sigma_z^2}\right]$$

$$\sigma_y^2 = \frac{1}{2} C_y^2 x^{2-n} \qquad \sigma_z^2 - \frac{1}{2} C_z^2 x^{2-n}$$

and inserting the dispersion parameters

$C_y = 0{,}41$, $C_z = 0{,}48$, $n = 0{,}33$

corresponding to the predicted weather situation the following pollutant concentrations will be forecast.

I	χ_1	χ_2	χ_3
1	0.449E-05	0.162E-14	0.124E-05
2	0.102E-02	0.146E-11	0.260E-03
3	0.0	0.0	0.298E-08
4	0.0	0.0	0.191E-03
5	0.0	0.0	0.298E-29
6	0.0	0.154E-03	0.144E-10
7	0.0	0.0	0.716E-04
8	0.0	0.104E-04	0.816E-12
9	0.0	0.247E-03	0.174E-07
10	0.0	0.0	0.0
11	0.332E-14	0.514E-10	0.147E-03
12	0.219E-33	0.791E-05	0.289E-05
13	0.0	0.877E-07	0.613E-07
14	0.0	0.0	0.0
15	0.0	0.0	0.0
16	0.0	0.0	0.418E-03
17	0.0	0.0	0.0
18	0.0	0.397E-03	0.314E-08
19	0.0	0.125E-03	0.180E-11
20	0.117E-04	0.889E-25	0.385E-04

tab. 3

Excesses will not occur, if the source strengths Q_i can be reduced to

$$Q_i^{red} = \rho_{ki} Q_i$$

where ρ_{ki} denotes the reduction factor applied to source i to prevent the excess at control point k .

According to tab. 3 we obtain

I	ρ_{1i}	ρ_{2i}	ρ_{3i}	$\rho_i^{eff} = \min\limits_k (\rho_{ki})$
1	0.0	0.0	0.0	$\leq$ 0.0
2	0.90	0.0	0.96	$\leq$ 0.0
6	0.0	0.69	0.0	$\leq$ 0.0
8	0.0	0.0	0.0	$\leq$ 0.0
9	0.0	0.31	0.0	$\leq$ 0.0
11	0.0	0.0	0.92	$\leq$ 0.0
12	0.0	0.0	0.0	$\leq$ 0.0
13	0.0	0.0	0.0	$\leq$ 0.0
18	0.0	0.88	0.0	$\leq$ 0.0
19	0.0	0.62	0.0	$\leq$ 0.0
20	0.0	0.0	0.71	$\leq$ 0.0

tab. 4

Tab. 4 demonstrates that, e.g. a reduction of source strength i = 20 of 29% avoids an excess at control point k = 3; but this reduction is not sufficient to suppress the excess at k = 1 and 2.

Tab. 2 indicates that even a complete shut down of i = 20 cannot prevent the excess at k = 1 (to symbolize this, we wrote $\leq$ 0).

According to tab. 4 no reduction of <u>one</u> single emitter would be able to avoid the excess at the three control points simultaneously. One, therefore, has to look for pairs of reducible emitters. One finds the following combinations, if

$$X_k = \rho_{kij} \left(Q_i + Q_j \right) ,$$

I	J	ρ_{1ij}	ρ_{2ij}	ρ_{3ij}	ρ_{ij}^{eff}
2	6	0.90	0.69	0.96	0.69
2	9	0.90	0.81	0.96	0.81
2	18	0.90	0.88	0.96	0.88
2	19	0.90	0.62	0.96	0.62

tab. 5

The interpretation of tab. 5 is evident.

It should be added that there are 30 source triplets able to avoid simultaneously the excesses at the three control points. It is obvious, that after the identification of all the reducible emitter pairs, triplets etc. one has to apply criteria to select from all these possibilities the pair or triplet, which bring about the reductions to the required extent. Those are mostly cost-benefit criteria.

4. Transmissions

All weather situations unfavourable to air quality will be indexed, i.e. an index value m will be attached to each of them. The pollution level

$$X_K = Q_i \, p_{ik}^{(m)}$$

caused by the emitter i at the control point k is essentially characterized by the transmission $p_{ik}^{(m)}$ depending upon the weather index m.

The p-values of an emitter can be determined either by a mathematical simulation of the dispersion process or by tracer experiments. A possible tabulation is shown in

	m = 1			m = 2		
i	k = 1	2	3	k = 1	2	3
1						
2						
3	....	.. $p_{32}^{(1)}$ ..	....	....	... $p_{32}^{(2)}$ ..	....
⋮						
20						

tab. 6

The control strategy for an industrialized region can be based upon such a table.

Before putting into operation any new emitter i its transmissions $p_{ik}^{(m)}$ belonging to the existing control points k have to be communicated to the control authority. One could even condition the admittance of construction of a future emitter from an "acceptable" set of p-values.

From a technical point of view there is a certain difficulty to procure a correct set of p-values, because of the current lack of adequate dispersion models.

We stress the fact, that one has to claim a high order of similarity between real pollutant dispersion and mathematical model, since an incorrect set of p-values can create an unjustified obstacle to the production process of an industrial plant. That similarity has to be verified experimentally <u>in situ</u>. Tracer experiments are the most suitable in this case. During such an experiment a tracer gas (e.g. SF_6) released at the emission point of a chimney during unfavourable weather conditions will be caught by a network of control stations. Evaluation of those measurements demands the knowledge of similarity laws which allow a correlation between the tracer dispersion data and the dispersion of industrial air pollutants. [2]

Such tracer experiments not only serve to verify a mathematical model, but their results can also be used instead of a calculated dispersion forecast.

If it is possible, in case of a single source, to inject the tracer gas into the stream of the waste gases and to record the corresponding tracer immission, then a model calculation is superfluous. Due to the variety of unfavourable weather situations the determination of the p-values only by tracer experiments seems to be very uneconomic. One, therefore, will establish the p-tables, in most cases, by model calculations.

5. Models

The plume- and puff-models in almost exclusive use today are basic solutions of the convective diffusion equation

$$\left(\alpha + \frac{\partial}{\partial t} + \vec{u}\cdot\nabla - \nabla\cdot(D\nabla)\right)\chi = S$$

and attribute - because of a simple mathematical formulation - a homogeneous atmosphere to a city, region or even a country; they integrate all the factors characterizing the dispersion behaviour of pollutants in a few dispersion parameters (α,D); they require a flat terrain and a ground-parallel wind vector and moreover a "sufficiently high" wind speed, i.e. situations which occur seldom in industrialized regions and which do not take into account really dangerous situations, such as stagnation. These restrictive assumptions diminuish essentially the domain of applicability of such a model.

One, therefore, looks for a dispersion model which takes into account both the real topography and surface structure, the (measured) micrometeorology in its space-time dependent heterogeneity and physical-chemical reactions occuring in the planetary boundary layer. Such a model has to replace the plume-formula above.

Diffusion in meteorology is the exchange of air parcels, called eddies, including their conservative contents and properties, between regions in the atmosphere. Their motions are apparently random motions, much larger in scale than molecular. A dispersion model has, therefore, to be based upon the random walk principle. In the vicinity of chimneys the micro-meteorology is governed by the emission process itself. Released hot gases create a buoyancy zone in which surrounding cold air is drained. This mixing region is the "effective source region" of an emitter. There, the eddies carrying the pollutants start their way through the discharged laminar or turbulent atmosphere. In course of time, the eddies decay and coargulate. The pollutant concentrations are changed by precipitations and chemical reactions in the air and by absorption and reflection along the solid and fluid surfaces. Due to eddy diffusion and convection caused by the local aereodynamics the polluted air will be distributed through an increasing volume, the space-time position of which can be determined by a trajectory analysis.

Our stochastic dispersion model (DM) simulates the trajectories of polluted eddies from source to receptor and, thus, relates source strengths to immission densities. The currently available model-versions have available a submodel for each of the relevant phenomena; e.g. decay of a puff into eddies, interaction of the eddies with the atmosphere, buoyancy, convection, diffusion, friction, absorption, resuspension, re-entrance, washout etc. The submodels chosen up to now are simple and transparent, to study the interaction of the different influences governing the dispersion process.

During the next months, more sophisticated submodels will be used to check their influence on the final results, i.e. the rates of emission and immission. Later decisions can be taken as towhether a more refined submodel has to be inserted into the final version of (DM). Only experiments (e.g. tracers) are able to give a reliable decision here.

Since there is only a finite number of stations in a regional air monitoring network, we interpret the atmosphere of a region as a 3-dimensional system of compartments, each of them with its own homogeneous micrometeorology. All meteorological information belonging to the corresponding compartments is called the "meteorological inventory" of the region. Defective inventories have to be completed either by interpolation or by additional measurements. (DM) is only applicable to a region which has complete inventories of emission and meteorology. It should be mentioned that meteorological phenomena such as heat plume, sea breezes, wind shearing, mountains and valley winds etc. enter the (DM) via the meteorological inventory.

6. Tracer experiments

Since there is at present no satisfactory theory to describe the ventilation of a city, one has nothing but experimental studies. Atmospheric tracers are the obvious indicators for discovering the streams of air ventilating an urban region, because air from the tracer source domain will also have reached the points where tracer substance is noticed. One obtains quantitative results only, when a correlation analysis applied to the space-time dependent concentrations is able to determine one or more transfer functions describing the tracer dispersion. The mathematical structure and the included parameters of those functions characterize, in an integral way, the meteorological and topographic situation of the city and its surroundings.

Instead of deriving one single transfer function for an urban region, one will try - by a correlation analysis of tracer measurements - to discover subregions. Within these subregions the application of mathematically simple structured transfer functions, such as the above plume formula, can be justified. Such a function is characterized by a set of parameters, e.g. (α,D), which can simultaneously be attributed to the corresponding compartment. Thus, one obtains a space distribution of those dispersion parameters and, due to that, finally an "effective" field of air streaming governing the pollutant dispersion. This field however differs from the usual wind data measured near to the ground.

It should be mentioned that architectural modifications within a compartment change its transfer functions. This fact offers a chance to study the air hygienic consequences of such a modification by a computer simulation.

Although the tracer technique represents and extremely effective tool, it has been applied, up to now, very seldom. The reason for this lies partially in the fact that each experiment requires a rather large number of collaborators; about 50 individuals have to stand ready until suitable weather conditions occur and the experiment can be performed. Under such conditions one tries to keep this number as small as possible, in contrast to the requirements of the air quality management which acquires as many experimental data as possible concerning unfavourable weather situations. To overcome this difficulty one will try to build-up a so-called "robot system", i.e. a network of automatic sampling stations. The basic conditions asked from such a system are: simplicity of use, waterproof, robust, reliable, cheap etc. Each city should have its own robot system available in order to be able to make independently all the decisions concerning siting problems which appear day by day in an urban region.

During the last months we have developed a series of robots which fulfill the above requirements. [2]

7. Control equipment

The control system for an industrialized urban region needs, because of the statistical prediction model integrated in it, a

(1) short time weather forecast

and a complete set of

(2) correspondences: weather-air quality

registered continuously (averaged over one hour) during, at least, the preceding 12 months at one weather station and three air hygienic stations. Furthermore an instrumental equipment for monitoring is required which should consist, at least, of

(3) one weather station for wind speed and direction, temperature, inversion height etc. and the further operation of the already-used

(4) 3 air hygienic stations for SO_2, NO_x, CO_x etc. by which a continuous extension and updating of the set of correspondences (2) can be performed.

The

(5) statistical prediction tables

derived from the correspondences (2) should be calculated and updated - on behalf of the urban health authority - by a computer center. The reduction strategy requires in addition to the

(6) emission inventory of the region, also an instrumental equipment for tracer experiments consisting of a

(7) robot system with about 20 units and - for the evaluation of the air samples withdrawn by the robots - an

(8) analysis instrument (e.g. gaschromatograph).

This instrumentation serves both for supporting decisions concerning the siting problems of the region arising day by day and for completing and checking the

(9) tables of transmissions $p_{ik}^{(m)}$

which, in general, are calculated via a mathematical simulation by an institute equipped with suitable dispersion models.

Remark: The best possible air quality control system is useless, if there is no

(10) legal base

by which an emitter can be forced to reduce its pollutant emission.

8. Statistical prediction model

It correlates historical meteorology and air quality data in such a way that a short-range (e.g. 24 hour) receptor-oriented air quality forecasting system can be produced; it creates a set of prediction tables. The system may be updated as often as changes in source emissions or distribution indicate the need.

```
                                              TABULATION PREDICTION TECHNIQUE
   FRANKFURT     (RPU)    STATION 3 = ACKERMANSCHULE        STATION        3    PERIOD OF DATA    MARCH,APRIL,MAY 1969
----------------------------------------------------------------------------------------------------------------------------------
WIND DIR  CLDHT1    WIND SP   TEMP     HOUR                  PERCENTILE VALUES OF SO2(PPB) CONCENTRATIONS              MEAN   ST DEV  FREQ
DEGREES   METERS    M/SEC     DEG C    CST      MIN    25     50    75    90    95    98    99   MAX  75-25 95-75
----------------------------------------------------------------------------------------------------------------------------------

 BAND 1   0- 650    0- 1    -5- 12   BAND 1    15.   34.   65.   87.  100.  114.  114.  114.  114.   53.   27.   62.     29.    13
 BAND 1   0- 650    0- 1    12- 30   BAND 1    21.   21.   21.   21.   21.   21.   21.   21.   21.    0.    0.   21.      0.     1
 BAND 1   0- 650    1- 3    -5- 12   BAND 1    10.   42.   53.   67.   80.   89.   97.   97.   97.   25.   22.   53.     21.    88
 BAND 1   0- 650    1- 3    12- 30   BAND 1    41.   41.   52.   62.   98.   98.   98.   98.   98.   21.   36.   52.     22.     4
 BAND 1   0- 650    3- 8    -5- 12   BAND 1    11.   31.   45.   65.   75.   83.   88.   88.   88.   33.   18.   47.     20.   100
 BAND 1   0- 650    3- 8    12- 30   BAND 1     7.    7.   10.   21.   26.   26.   26.   26.   26.   14.    5.   13.      8.     4
 BAND 2   0- 650    0- 1    -5- 12   BAND 1    52.   57.   62.   77.   81.   82.   82.   82.   82.   21.    4.   57.     15.     2
 BAND 2   0- 650    1- 3    -5- 12   BAND 1     8.   28.   44.   54.   85.   85.   85.   85.   85.   26.   31.   43.     22.     7
 BAND 2   0- 650    1- 3    12- 30   BAND 1    23.   25.   29.   39.  139.  142.  143.  143.  143.   14.  103.   49.     47.     5
 BAND 2   0- 650    3- 8    -5- 12   BAND 1    33.   41.   46.   52.   67.   67.   67.   67.   67.   10.   15.   48.     12.     4
 BAND 3   0- 650    0- 1    -5- 12   BAND 1    19.   25.   32.   40.   48.   52.   89.   90.   90.   15.   12.   34.     15.    20
 BAND 3   0- 650    0- 1    12- 30   BAND 1     5.   10.   21.   57.   63.   63.   63.   63.   63.   46.    6.   32.     22.     8
 BAND 3   0- 650    1- 3    -5- 12   BAND 1     4.   14.   25.   39.   50.   74.   79.   81.   82.   25.   35.   28.     19.    48
 BAND 3   0- 650    1- 3    12- 30   BAND 1     4.    9.   21.   33.   53.   74.   85.   87.   87.   24.   41.   24.     20.    37
 BAND 3   0- 650    3- 8    -5- 12   BAND 1     4.    8.   17.   29.   40.   46.   54.   58.   62.   21.   17.   19.     14.    80
 BAND 3   0- 650    3- 8    12- 30   BAND 1     4.    5.   13.   23.   38.   55.   59.   61.   62.   17.   33.   17.     16.    51
 BAND 4   0- 650    0- 1    -5- 12   BAND 1     6.   24.   36.   70.   81.  104.  104.  104.  104.   46.   34.   46.     28.    13
 BAND 4   0- 650    0- 1    12- 30   BAND 1    55.   55.   55.   55.   55.   55.   55.   55.   55.    0.    0.   55.      0.     1
 BAND 4   0- 650    1- 3    -5- 12   BAND 1     4.    8.   19.   47.   54.   58.   60.   61.   62.   38.   12.   26.     19.    22
 BAND 4   0- 650    1- 3    12- 30   BAND 1    30.   30.   31.   36.   39.   40.   40.   40.   40.    6.    4.   35.      5.     2
 BAND 4   0- 650    3- 8    -5- 12   BAND 1     4.    5.    9.   15.   19.   22.   26.   26.   26.   11.    6.   11.      7.    18
```

Tab. 7 - Prediction Table

Wind direction	4 groups
Cloud height	1
Wind speed	3
Temperature	2
Hour	1

The relation between meteorological variables and pollutant concentrations may be displayed by arranging combinations of significant meteorological variables in an ordered sequence and presenting the associated probability distribution for each entry, as shown in tab. 7. The method is based on hourly readings. For each combination of meteorological variables the minimum value, 10, 25, 50, 75, 90, 95, 98, 99, percentiles and maximum value of SO_2 concentrations are shown. Also presented are the interquartile range i.e., the difference in SO_2 concentration between the 75th and 25th percentiles, and that of the 95th and 75th percentiles. The number of cases observed for each combination of meteorological variables is shown in the last column.

The interquartile range is a measure of the spread of the data for each combination of meteorological measurements. The amount of noise or uncertainty in the prediction is shown by the magnitude of the interquartile range. Similarly, the difference between the 95th and 75th percentile values represents the amount of skewness present. Since the percentile distributions approximate the log-normal function, one would expect appreciable skewness.

The meteorological variables recommended for the construction of a Tabulation Prediction Scheme are: wind direction, ceiling height, wind speed, temperature, hour of the day etc.

The significance of atmospheric stability has been noted, but such data are usually unavailable. A substitute is provided by the choice of the variables: ceiling height, hour of the day, and wind speed. Combinations of these are closely related to stability.

The order of the variables in the columns are arranged so that the last column represents the variable which influences the SO_2 concentrations the least and the first column the most. Further, wind speed and temperature are presented in descending order since lowest values of each correspond to highest SO_2 concentrations. Thus, the tabular arrangement shows a general increase in values of SO_2 concentration as one reads down from the top of the table. [1]

Literature

[1] Croke E.J., Moses,H. et al., "Chicago Air Pollution Systems Analysis Program", ANL-ES CC 006, 1970

[2] Müller K.-H., "Meteorologische Tracer in der Regionalplanung", EUR-Report 1974, in press