A Quasi-Lagrangian Cell Method for Calculating Long-Distance Transport of Airborne Pollutants

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ABSTRACT

The method of calculating long-distance transport of airborne pollutants presented in this article is based on the idea of following the air flowing into the emission area. The in-flowing air is divided into cells, which are then transported in the actual wind field. The cells are assumed to be able to absorb and give off pollutants and to be deformed. The influence of lateral diffusion, which will be shown to be of minor significance to long-distance pollutant transport, is considered by a smoothing procedure concurrently with the analysis of the concentration field. As examples of application, the results of SO_2 transport calculation over northwestern Europe for two different 3-day periods are presented. The calculated concentration values were found to be in relatively good agreement with the measured values. In studying the sensitivity of the method to changes in the mean parameters, it was deduced that the influence of these changes on the final concentrations is in general relatively easy to estimate.

1. Introduction

A number of models are available for calculating the local spread of air pollutants from individual point sources. For urban areas, also, advanced methods for performing different types of air pollution calculations have been developed, particularly in recent times; however for long-distance transport of pollutants, here defined as transports of the range a few hundred to several thousand kilometers, there are still only a few calculation methods available despite an obvious need. The aim of the present article is to introduce a new alternative method for the numerical calculation of pollutant transport, especially in the long-distance range.

The pollutant transport process can be considered to consist of advective transport, diffusion, and sink processes. Together with the emission, these subprocesses give a transport equation of the form:

$$\frac{\partial C}{\partial t} = -\mathbf{V}_H \cdot \nabla_H C - w\frac{\partial C}{\partial z} + \nabla_H \cdot K_H \nabla_H C + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + Q - S, \quad (1)$$

where the symbols are as follows:

C concentration of pollutant
$\mathbf{V}_H$ horizontal wind vector
w vertical wind
K_H coefficient of lateral diffusion
K_z coefficient of vertical diffusion
Q emission rate
S sink rate
∇_H horizontal del operator.

The terms for vertical transport are written separately in order to bring out the different magnitude of this transport in relation to horizontal transport. Physically, the transport calculation can be regarded as a problem related to solving for the concentration C from (1) as a function of time and space.

2. Review of methods used for calculating long-distance transport of pollutants

The simplest way to make a rough estimate of where a pollutant emitted from a certain area spreads is to calculate forward air parcel trajectories from this area and assume that the pollutants follow the trajectories. Correspondingly, the location of the source area of an observed pollution concentration can be estimated by calculating backward trajectories. In principle, this method, usually combined with statistical data evaluation, has been used in a number of investigations into long-distance transport of pollutants (e.g., Robinson and Robbins, 1969; Rohde, 1971b; Nyberg, 1972; Zeedijk and Velds, 1973; Hall *et al.*, 1973). In the following this method will be referred to, in short, as the "trajectory method."

If the problem is to calculate more accurately the distribution of pollutants from a greater area within which there are a large number of sources, there are two possibilities: first, calculating trajectories for each individual source or group of sources; and second,

including the emission area and the areas over which the transport will probably occur in a grid, and then calculating the pollutant transports through stepwise numerical integration over the whole grid.

The first method is, in principle, a trajectory method. The second method has been used widely for urban area pollution calculations (e.g., Lettau, 1970; Shir and Shieh, 1974) and to some extent for long-distance transports (Reiquam, 1970; Nordoe, 1973). Reiquam's model probably constituted the first attempt to develop a numerical simulation model for calculating long-distance transport of airborne pollutants. Nordoe's model is associated with the relatively extensive model studies carried out in Norway in connection with the O.E.C.D.[1] project, "Long Range Transport of Airborne Pollutants" (Ottar, 1973).

The difficulty with using a model to simulate numerically the long-distance transport of pollutants is to a great extent due to the problem caused by the so-called pseudo-diffusion error, which has been analyzed by Molenkamp (1968) and Egan and Mahoney (1972), among others. It can be shown that this error always occurs with conventional numerical solving of equations of the transport equation type, which are characterized by a combination of source terms varying in space and advection.

To eliminate the pseudo-diffusion error, either some type of quasi-Lagrangian solution must be used or very sophisticated finite difference methods, for example the scheme introduced by Egan and Mahoney for calculating advection. The feasibility of this scheme in calculating long-distance pollutant transport has been shown by Pedersen and Prahm (1974). It can be mentioned that the calculation method presented below is set up so that no real pseudo-diffusion will occur.

3. An alternative way of regarding the pollution transport problem

In investigations into pollution transport over longer distances, the relevant question is usually how much pollution is transported from a known emission area to a certain point or area outside this emission area. Furthermore, in nearly all cases of practical interest the emission area is limited. Owing to the continuous motion of the atmosphere, all the air that streams out of the emission area had earlier streamed into this area and the time interval between these two processes is generally not very long. In order to describe the pollution transport from a certain emission area in a certain synoptic situation, it thus suffices to follow the air streaming into the emission area. The spreading of the outgoing polluted air then describes which areas are influenced by the pollutant emissions.

To simplify, it may thus be said that, according to this approach, if the air which has streamed into an emission area Q does not reach a certain point P outside the emission area within a certain time, Q cannot cause pollution at P. Conversely, if air which streams into Q reaches P after a certain time, then emission area Q gives a certain pollution quantity to point P. The magnitude of this pollution quantity at P naturally then depends on a number of factors.

4. A model developed on the basis of the "flow-in" method

According to the above approach, a model for calculation of long-distance pollutant transport may be set up using the following scheme:

(i) Division of the air which flows into the emission area into cells
(ii) Calculation of transport and deformation of the cells in the flow field
(iii) Continuous calculation of the pollutant content of the cells
(iv) Analysis of the concentration field at a desired time.

Calculating this way, the model will appear quasi-Lagrangian. A possible treatment of the different steps of the calculation is presented below.[2]

a. The initial cells

If nothing is known about the actual wind field, a closed circle of air cells[3] must be used at the outset. However, the average wind direction is usually known and thus the initial cells can be located in relation to the emission area, for example, as shown in Fig. 1.

The vertical extension of the cells should correspond to the layer within which the main part of the long-distance transport occurs and within which pollution is fairly homogeneously distributed vertically. In accordance with this the actual "mixing height" for long-distance transport may be taken initially as the upper limit for the cells. Investigations [e.g., Petrenchuk (1971) and Rohde (1971a)] concerning the mean vertical profile of sulfur show that at least for this pollutant most of the long-distance transport occurs below the height of 2000 m and this height can be used as the upper limit if there is no inversion layer below this which prevents the vertical flux. About 100 m could be used as the lower limit, this being the approximate limit over which pollutants must rise in order to participate in the long-distance transport.

[1] Organization for Economic Co-operation and Development. In 1973 the member-countries were the United States, Canada, Australia, New Zealand and 19 western European countries.

[2] The treatment follows the method used in the transport model set up at the Finnish Meteorological Institute.

[3] The definition of a cell used here differs somewhat from that used, for example, by Sklarew *et al.* (1971). In the present model a certain fixed amount of moving air is regarded as a cell.

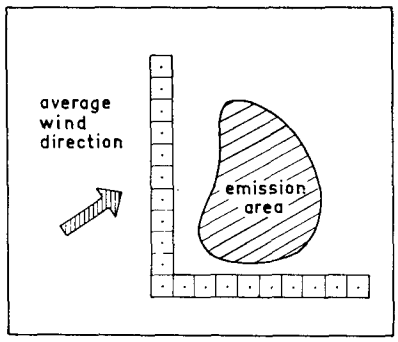

FIG. 1. An example of the initial location of the cells in relation to the emission area and average wind direction.

b. Calculation of transport and deformation of the cells in the flow field

Transport of the cells may be calculated using common trajectory methods. However, if the time step is short, which is necessary to obtain a good estimate of concentration changes due to emission and sink processes, the use of sophisticated trajectory methods for calculating the displacement of the cells for every time step is not required. For instance, mainly for practical reasons, the scheme for the calculation of advective transport introduced by Egan and Mahoney (1972) has been used in the model so far.

As will be shown later, the amount of pollutant absorbed by the cell corresponds to the pollutant sources in the area which is covered by the cell. If a deformation of the cell changes this area it also changes the numbers of the sources which will be taken into account. A stretching deformation, especially, has great influence in this connection and must be considered. This can be done by introducing stretching factors (β and γ) to represent the length of the sides of the rectangular bottom area of the cell. If only terms of the first order are noted, the changes in these factors can be expressed by:

$$\frac{1}{\beta}\frac{d\beta}{dt}=\frac{\partial u}{\partial x}, \tag{2}$$

$$\frac{1}{\gamma}\frac{d\gamma}{dt}=\frac{\partial v}{\partial y}, \tag{3}$$

where the right sides of (2) and (3) are the stretching deformation in the i and j directions of the grid, respectively. It should be noted that the only directions allowed for the axis of shrinking and stretching in this case are the directions of the grid axis.

In order to follow the transport more accurately in an area with a strongly difluent wind field, a procedure has been included in the transport model according to which a cell, which due to stretching reaches 3 times its initial length, is divided into three "mini-cells," which are then transported separately.

c. Calculation of changes in pollutant content of the cell due to emission and sink processes

In calculating emission into the cell, the location and degree of stretching are taken into account on the principle that the flux of pollutant into the cell from ground sources is equal to the sum of the emissions from the sources, which are covered by the cell, i.e.,

$$Q_{\text{eff}}=\int_A Q_a da, \tag{4}$$

where the integral represents the total emission from the covered area A and Q_{eff} the effective emission into the cell. The pollutant sources are assumed to be homogeneously distributed inside the grid squares, for which the emission values are given. Therefore, the integral can be calculated so that the parts of the grid squares, which are covered by the cell, are multiplied by the corresponding emissions from the squares; these products are then summed. For example, in the situation shown in Fig. 2 the effective emission would be

$$Q_{\text{eff}}=\frac{1}{\Delta x\Delta y}(a_1Q_1+a_2Q_2+a_3Q_3+a_4Q_4+a_5Q_5+a_6Q_6), \tag{5}$$

where $a_1, \ldots, a_6$ are parts of the cell and $Q_1, \ldots, Q_6$ the total emission values for the corresponding grid squares.

The lack of exact knowledge about the sink processes of most pollutants does not permit a more differentiated treatment of these processes in the transport calculation models. The following simple expressions

$$\left(\frac{\partial C}{\partial t}\right)_{\text{sink}}=-kC, \tag{6}$$

$$\left(\frac{\partial C}{\partial t}\right)_{\text{sink}}=-k_1C-k_2C^2, \tag{7}$$

which usually have been used in transport calculations of SO_2, can be refined by varying the sink coefficients, for example, according to the synoptic situation. The

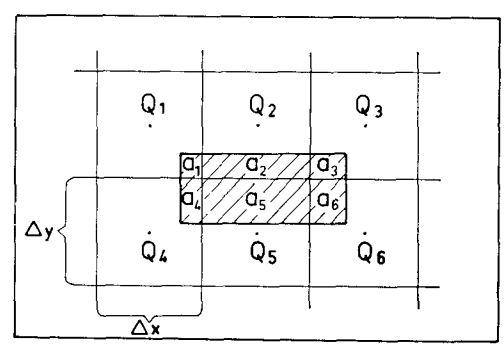

FIG. 2. The cell in the grid and the location of the emissions $Q_1, \ldots, Q_6$ and the parts of the cell $a_1, \ldots, a_6$ in Eq. (5).

form (7), used by Norwegian meteorologists (Groenskei, 1973; Nordoe, 1973) in simulating SO_2 transport, makes it possible to take into account a rapid sink in heavily polluted air.[4]

It may be noted that the vertical transfer of the pollutant is indirectly included in the sink coefficient, since the effectiveness of the vertical transfer has a great influence on the deposition of pollutant on the ground. Changes in the vertical profile of the pollution concentration, which depend primarily on the vertical transfer, also influence the transport directly, but this influence is not taken into account here.

d. Analysis of the pollution field and estimating the effect of lateral diffusion

We first consider the concentration field obtained when following the air which has flowed into the emission area during a short time only, e.g., corresponding to a time step. At each point over which the air divided into cells flows, the pollution concentration of the air is recorded at the moment the air passes over the point. By analyzing the pollution field on the basis of these concentrations, a concentration chart is obtained of the effect of the emission area on its environment. This chart is not, however, synoptic, since it has different times of validity at different places, depending primarily on the distance from the emission area. However, should the wind field, and the transport conditions in other respects, be quite stationary, the pollution field will be synoptically valid, too.

To obtain more generally a synoptic analysis of the concentration field, all the air which streams into the emission area during a longer period should be followed and the location of the individual air quantities and their concentration values analyzed for the required time. This could be achieved with the model by including at each time step an additional new set of cells, corresponding to the air which flows into the emission area at that time step. Most frequently, however, an entirely synoptic analysis is not of such great importance that such a procedure is necessary. For example, in the applications presented in Section 6b a new set of cells was sent out only every sixth hour and, correspondingly, the analysis was carried out so that the location of the cells and their concentration was recorded at every time step within the time interval $T\pm3$ h, where T is the time for which the analysis of the pollutant field was primarily required. The pollution field obtained in this way is thus not quite synoptic, but at every point the concentration in the analysis has been valid for some moment within the time interval $T\pm3$ h. (See also Section 6b.)

For the pollution distribution caused by long-distance transport from area sources, the effect of turbulent lateral diffusion is primarily one of smoothing. If, when the point-source models are used, the horizontal spread of the plume is described by means of standard deviations (σ_y), then this smoothing can be roughly estimated. By extrapolating the σ_y values used for Gaussian plumes (see, e.g., Gifford, 1961), for instance, for a distance of 1000 km in a neutral atmosphere, a value for σ_y of the magnitude of 20 km is obtained. The turbulent diffusion proper, corresponding to a sampling time of the same length as the time step (<1 h) thus results primarily in a mixing of the pollution within the cell.

More important than the turbulent lateral diffusion is the spatial variation in wind values, which cannot be observed in the relatively low-resolution grid used for the wind analysis. A method of taking into account the effect of similar variations in numerical calculations is presented by Smagorinsky (1963). Adapting this method, an "effective" diffusion coefficient corresponding to the grid used and the flow patterns has been calculated in the model version developed so far. For example, with a 150 km grid, the magnitude of the coefficient is of the order of 5×10^4 m^2 s^{-1}.

Using this diffusion value, the pollution field was smoothed taking into consideration the different transport times for pollutant at different distances from the source area. However, it should be noted that the influence of this smoothing is relatively marginal, which can be seen by comparing Figs. 8d and 9b. The latter figure shows the calculated concentrations for the same situation as Fig. 8d, but without the final smoothing.

5. Brief discussion of the model

In the specific model based on the "flow-in" principle which is described above, two over-simplifications occur: deformation of the cells is limited to stretching and shrinking, and lateral diffusion is represented by rough average values. These simplifications naturally cause some degree of uncertainty in the final result. However, unquestionably the greatest source of error is in the estimation of the sink rate. This sink rate, which obviously varies greatly both in time and space, depends primarily on chemical processes, on the absorption properties of the ground, and on the effectiveness of the turbulent flux close to the ground. Knowledge of these three processes affecting sink rate is still scant and it is therefore also impossible to take the sink rank into account accurately in the transport models. Consequently, there was no motivation to set up a model which is very sophisticated in other respects, e.g., regarding deformation and diffusion.

[4] Nordoe (1973) has shown that the coefficient values $k_1=10^{-6}$ s^{-1}, $k_2=0.25\times10^{-6}$ m^3 s^{-1} μg^{-1}, give mean residence times for SO_2 which agree well with the values observed for both strongly polluted air (100 μg SO_2 m^{-3}) in which the residence time has been observed to be about 10 h (Meetham, 1950), and relatively clean air in which the residence time is several days (Junge, 1960).

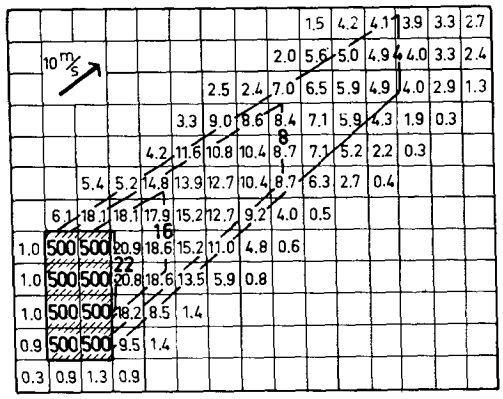

FIG. 3. Application of the model to a simple test situation. The solid lines are the analytically calculated concentrations and the values in the grid squares denote the concentrations ($\mu g\ m^{-3}$) calculated with the present model. The bold face numbers in the framed area are the assumed emission rates in 1000 tons per year and the arrow in the upper left hand corner shows the assumed wind direction. The grid distance is 150 km.

6. Applications

a. To a test situation

In order to show that the numerical errors in the present model are small, especially when compared with models where pseudo-diffusion is not eliminated, the concentration distribution of a simple analytically soluble situation was calculated using both methods.

An emission area covering eight squares with an emission rate of 5×10^5 tons per year was assumed for the test situation (see Fig. 3). Furthermore, it was assumed that the wind was constant and the components in the i and j directions of the grid were 8 and 6 m s^{-1}, respectively. Mixing height was taken as 1000 m and the sink rate as 10^{-5} s^{-1}. Fig. 3 shows both the concentration distribution analytically calculated and that calculated using the present model. As can be observed, the differences are small. The slightly unrealistic spread in the crosswind direction comes from the analysis technique used.

Fig. 4 shows the calculated solution of the same transport situation when upstream finite differences are used. The large error in this solution depends mainly on the pseudo-diffusion effect of that scheme. (It can easily be seen that other conventional finite-difference schemes would also give large errors.) A corresponding test situation has been studied more extensively by Pedersen and Prahm (1974).

In a situation as simple as the above, where the transport process consists only of emission, horizontal advection and a constant sink, the present quasi-Lagrangian method gives results which are almost correct. However, in real situations the transport processes are more complex and the error correspondingly greater.

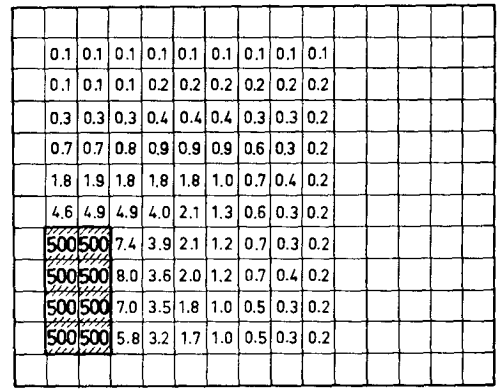

FIG. 4. As in Fig. 3 except when upstream finite differences are used for solving the advective transport.

b. Two real situations

In calculating the pollutant transport in the two situations presented below, a 150 km grid was used extending over the whole of Europe and the eastern part of the Atlantic. For western Europe the emissions were estimated according to O.E.C.D. reports (O.E.C.D., 1973) on sulfur emissions in member countries. For the Soviet Union, and to some extent for other eastern European countries, the values were estimated subjectively without any information from the countries themselves. Fig. 5 shows the emissions for the areas which had the greatest influence on pollution concentrations in northwestern Europe during the episodes.

A front of grid squares were used as initial cells, which lay in a north–south direction west of Great Britain down toward Spain, and from there eastward along the Pyrenees and straight across Italy. The number of initial cells and their exact position varied somewhat depending on the synoptic situation. 1000 m was estimated to be the average mixing height in the episode 30 November to 2 December, 1972, and 800 m in the episode 23–25 March 1973, and these values were then used throughout the calculations.

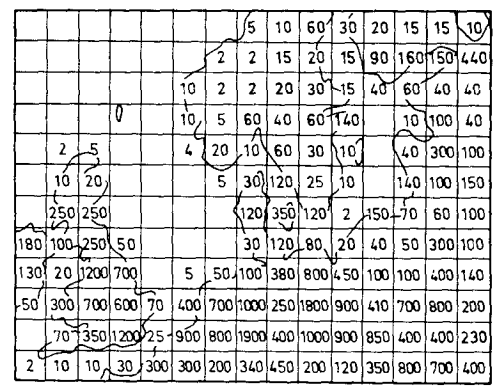

FIG. 5. The emission values used in calculating the transport of SO_2 in two actual pollution episodes. Units for the emission in the 150 km×150 km squares is 1000 tons of SO_2 per year.

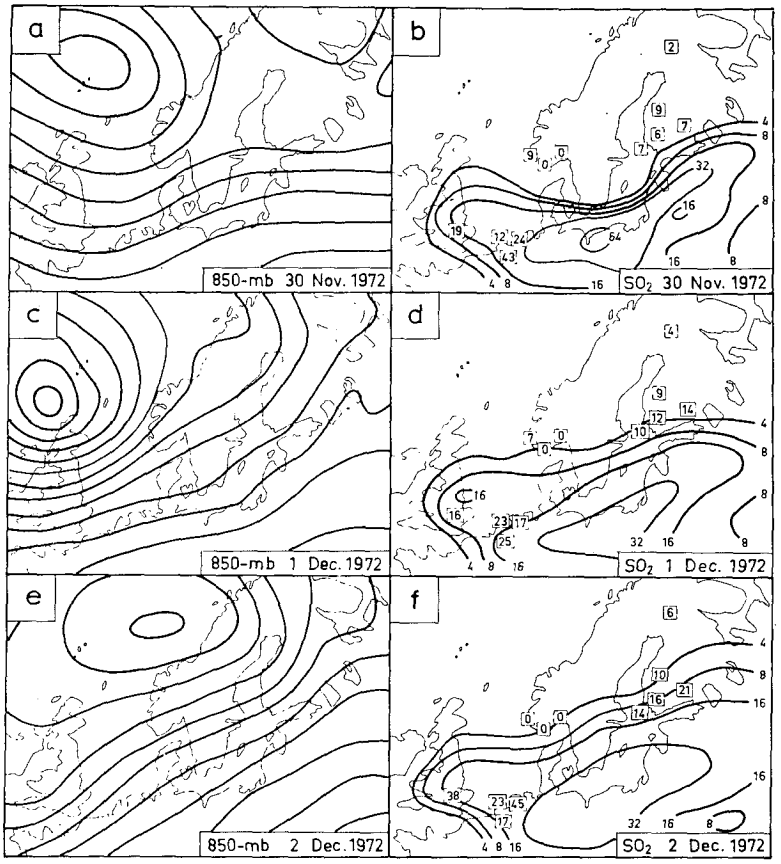

FIG. 6. The episode of 30 November to 2 December 1972. The absolute topographies for the 850 mb pressure level at 1200 GMT (contour interval 40 m) are presented on the left. The calculated isopleths for the SO_2 concentrations and the observed SO_2 values (in squares) are presented on the right: Units: $\mu g\ m^{-3}$.

The geostrophic wind obtained from numerical analyses at the 850 mb pressure level was used as wind data. Such wind analyses were performed every 12 h. The winds for the intervening time steps (the length of the time step was 30 min) were calculated using second-order interpolation.

Since no precipitation occurred during the March episode, the same value ($10^{-5}\ s^{-1}$) was used throughout for the sink. This value corresponds to a mean residence time of 28 h, a value which has been found realistic for dry deposition in moderately polluted air according to several episodic studies made on long-distance transport.

During the December episode precipitation occurred, and thus in this episode, when cells were situated in a precipitation area, a more rapid sink of $10^{-4}\ s^{-1}$ was used, which according to Bolin and Granat (1973) is realistic for precipitation scavenging of SO_2. Otherwise the value $10^{-5}\ s^{-1}$ was used for this episode as well, corresponding to dry deposition.

According to the analysis technique used, the calculated concentration values correspond to values for the analysis at the given valid time, within 3 h accuracy. The calculated value for a certain point thus corresponds to the concentration value at that point at some moment within the time interval $T\pm3$ h, when T is the given valid time.

The episode of 30 November to 2 December 1972, is presented in Fig. 6. The most characteristic feature of this episode was the high SO_2 concentrations in Finland beginning on 1 December, which considerably exceeded normal. By calculating long-distance transports of SO_2 for this episode, using the model presented in this article, it could be shown that the high concentrations were probably caused by Central European sources. Conversely, it may be said that the simulation model caught the strong transport of SO_2 to Finland during the first days in December. In other respects, too, the measured and calculated SO_2 concentrations agree fairly well. However, it should be noted that the measured concentrations are mean values for a 24 h period (0600–0600 GMT), while the calculated concentrations apply specifically to the time 1800 GMT$\pm$3 h. Because of this, no more accurate verification can be carried out. However, with regard to the two situations presented here, the discrepancy is not so significant since, fortunately, the synoptic situation changed

relatively slowly and, furthermore, the changes were well synchronized with the measurement periods.

The effect of precipitation scavenging was greatest in England and western Scandinavia. For example, the calculated pollution distribution on 1 December should have been as shown in Fig. 7, if no scavenging had been taken into account. In general, better agreement with the measured concentrations was achieved when scavenging was considered.

The episode of 23–25 March 1973, presented in Fig. 8, is included partly because no precipitation occurred during this period and partly because the December episode alone would not have given a representative view of the results obtained with the model so far. The characteristic features for this episode were the high concentrations in southern Norway on 24 March, the high concentrations in Finland on 25 March, and the steady decrease in the SO_2 values measured in the Netherlands. As can be seen in Fig. 8, the first two features are relatively well explained by the model. The third, the decrease in the concentrations in the Netherlands, was not at all noticeable in the calculated concentrations. This probably is due to the fact that the wind near the surface was slight and came from the sea, bringing in clean air over land in the lowest atmospheric layer.

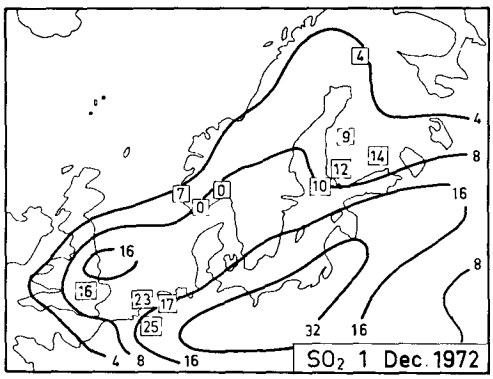

FIG. 7. The calculated SO_2 concentrations ($\mu g\ m^{-3}$) for 1 December 1972, when no precipitation scavenging is taken into account.

Moreover, the grid distance used (150 km) was definitely too large for calculating pollutant concentrations at places which are as close to major sources as the observation stations in the Netherlands are.

7. Brief discussion of the applications

No definite conclusions should be drawn concerning the calculation method on the basis of the results of the episode investigations described above. It should, for instance, be taken into account that the concentra-

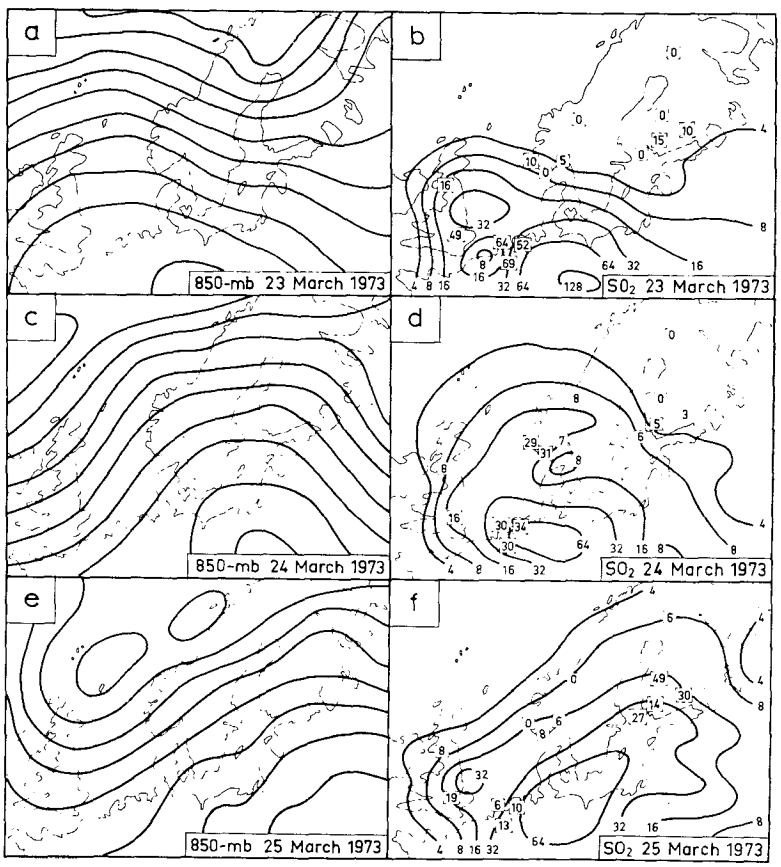

FIG. 8. As in Fig. 6 except for the episode of 23–25 March 1973.

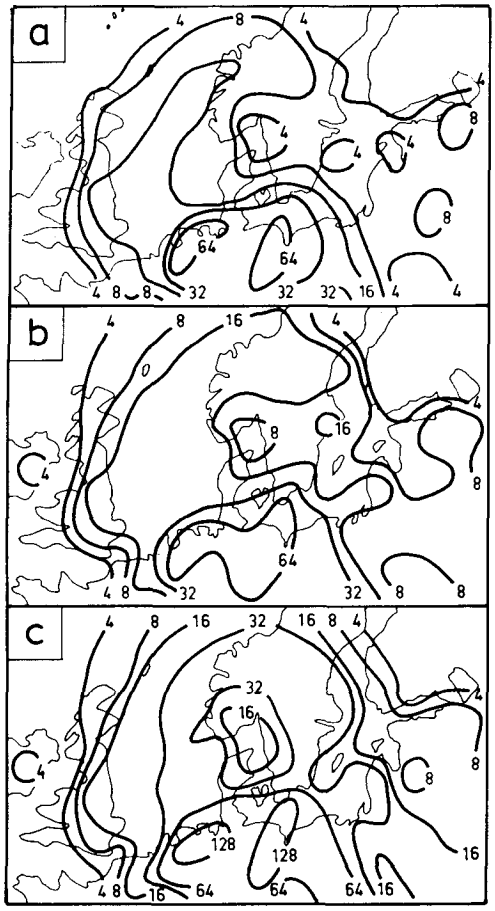

FIG. 9. The calculated SO_2 concentrations ($\mu g\ m^{-3}$) for 24 March using different sink factors: (a) $2\times10^{-5}\ s^{-1}$, (b) $10^{-5}\ s^{-1}$, (c) $10^{-6}\ s^{-1}$. No smoothing is performed.

tion values which were measured at ground level are not quite representative of the whole layer for which the calculated values stand. It could even be said that the calculated concentrations represent the quantity of transported pollutants originating in remote sources better than an observation made near the ground. This to some extent confirms the preliminary results from aircraft samplings carried out over the North Sea. The episode investigations are included primarily to show that even with a relatively rough model, based on the "flow-in" principle, acceptable pollutant concentrations caused by long-distance transport can be calculated. Corresponding quantitative results would be difficult to obtain using trajectories only and, at least due to numerical errors, the results would be less accurate if they were obtained using an unsophisticated Eulerian calculating method.

8. The sensitivity of the model to changes in the main parameters

There are four parameters which basically control the pollutant concentration in a downwind direction from a source area: the pollutant emission from the area, the mixing height of the transport layer, the effectiveness of the sink mechanism, and the wind velocity. The following subsections concern changes in these parameters and how they are reflected in the calculated concentration values when the version of the model presented in Section 4 is used.

a. Changes in the emission

When the emission of a certain area changes by a certain percentage, the pollution mass absorbed by a cell changes by the same percentage according to Eq. (4). If the sink is assumed to be proportional to the concentration, i.e., only a first-order term of the sink is taken into account, the changed concentration of the cell will prevail during the transport and the percentage change of the final concentration will be equal to the percentage increase or decrease in the emission value. This applies both to an overall change and to a change in the emission value of a small area. However, in the latter case the influence area is correspondingly smaller.

b. Changes in the mixing height

Since emission into the cell is assumed to be distributed homogeneously in the cell, a change in the mixing height, which determines the height of the cell, influences the cell concentration in the same way as a change in the emission value. A change in the overall mixing height by a certain percentage consequently changes the final concentrations by the same percentage. This applies to the present version of the model, for which a constant sink factor is assumed, but not to the real atmosphere since a change in the mixing height will also influence the sink factor.

c. Changes in the sink factor

If only a first-order sink term is taken into account, the time it will take to reduce the amount of pollutant by 50% is

$$T_{\frac{1}{2}}=\frac{\ln 2}{k},$$

where k is the sink factor. From this formula alone it is somewhat difficult to see how a change in the sink factor influences the final results. This influence is therefore illustrated in Fig. 9, which shows the results of transport calculations of the same situation when different sink factors are used. The sample day was 24 March, which is one of the days in the March episode presented in Section 6b. However, with regard to the calculations here, no final smoothing of the concentration field is carried out in order to determine the influence of the changes in the sink factor alone.

It can be seen from Fig. 9 that if the sink factor grows from $10^{-5}\ s^{-1}$ (used as reference value) to $2\times10^{-5}\ s^{-1}$

this gives a strong decrease in the concentration values. On the other hand, a decrease in the sink factor to 10% of its original value, i.e., from 10^{-5} s^{-1} to 10^{-6} s^{-1}, does not give a correspondingly large change in the concentration field. It can also be noticed that in areas with large sources and light wind (e.g., in Germany), or in areas far from the large sources, the influence of a change in the sink factor is greater than in areas with strong wind (e.g., in the United Kingdom).

d. Changes in the wind velocity

It is difficult to determine the influence of changes or errors in the wind values. However, if no attention is paid to effects due wind direction, the influence of changes in wind speed consists of two parts: the concentration at the downwind boundary of the emission area is, if the sink factor is relatively small, about inversely proportional to the wind speed; and the "stretching" of the concentration isopleths in the downwind direction is directly proportional to the wind speed. The first effect depends on the fact that the time during which a cell moves over an emission area and absorbs pollutants from it is inversely proportional to the wind speed. The second effect is explained by the proportionality between wind speed and transport distance of a cell during the time before the concentration of the cell has dropped to a certain value.

9. Concluding remarks

An alternative model for calculating airborne pollutant transport has been presented. Although the model aims at taking into account all the processes which influence the transport, it is best applied to transport calculations where horizontal advection is the most important process. This is especially true of long-distance transport for which the model was designed.

A couple of transport calculations for specific synoptic situations are presented, such calculations representing the most likely application. If, however, the frequency of different transport situations over a longer period is known, the model may be used for budget calculations, which are of particular interest for long-distance transport.

Concerning further development of the transport model, the greatest improvement could probably be achieved through developing a two-layer version. The processes in the lowest layer of the atmosphere could then be calculated separately so that a quantitative estimate could be made of the extent to which the emitted pollutants will participate in the long-distance transport. However, it must be pointed out that if such a sophisticated model is to achieve a corresponding improvement in results, a better understanding of the processes of deposition and vertical transport is required.

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