A DISPERSION MODEL FOR REGIONAL
AIR POLLUTION PROBLEMS

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1 INTRODUCTION

As a part of a study on oxidant formation in Grenland, Norway,
a dispersion model for regional air pollution problems has
been developed (1). The model has been tested in an area of
16x32 km^2. The results of this study show that larger scale
processes have to be included.

For this purpose a 16x32 grid-points in each of three levels
are proposed. Grid distance is 8 km. A telescoping procedure
is planned for the local area of Grenland where local emissions
are important. The local area of Grenland would then consist of
2x4 gridpoints. In order to separate high and low emissions,
three levels are planned. This separation becomes particularly
important in periods with low vertical exchange. The model
description of local and regional processes follows.

2 GENERAL DESCRIPTION

The dispersion is partly caused by the time variation of the
wind field and partly by turbulent exchange. For each of the
pollution components the following equation is solved:

$$\frac{\partial c_i}{\partial t} = v_h \cdot \nabla_h c_i - \frac{\partial (w'c_i')}{\partial z} - \nabla_h \cdot (v'c_i') + R_i + Q_i \qquad (2.1)$$

$$\begin{array}{ccccc}
\text{Advection} & \text{Turbulent exchange} & \text{Reactions} & \text{Emission} \\
\text{I} & \text{III and IV} & \text{V} & \text{VI}
\end{array}$$

Processes to be included in the model are:

I : horizontal advection, $\mathbf{v}_h \cdot \nabla c_i$

II : vertical advection, $w \dfrac{\partial c_i}{\partial z}$ (assumed to be small and neglected in Eq. (2.1)

III : turbulent exchange horizontally

IV : turbulent exchange vertically

V : chemical reactions (sinks or sources)

VI : emission from natural and anthropogenic sources

The time derivatives caused by advection, turbulent exchange and by emission (Q_i) are calculated separately. Further new values are calculated using the chemical reaction scheme, the values of the time derivatives and the old concentrations. In this way the time integration follows a method proposed by E. Hesstvedt et.al. (2). The calculation of vertical exchange, follows a method proposed by Pasquill (3).

2.1 Boundary conditions

In the vertical, dry deposition is taken into consideration as a lower boundary condition. At the upper boundary a flux of pollution out of the system is made proportional to the concentration in the upper layer. The factor of proportionality may change with time of day.

In the horizontal, the concentrations along the lateral boundaries are determined by long range transport calculations.

For the horizontal advection upwind finite difference methods are used. The pseudo-spectral method, developed by Christensen and Prahm (4), was found time-consuming although numerical diffusion was reduced. For one or only a few components this method can be used and it is included in the model as an option.

Dry deposition is a sink of pollution at the ground. However, pine forests covering parts of the area are a source of hydrocarbons that may influence the chemical reactions.

3   ADVECTION

In the lowest layer wind measurements close to the ground are
used to define a two-dimensional stream function (ψ) along the
lateral boundary of the area. A mass-consistent approximation
of the horizontal windfield is defined by solving

$$\nabla^2 \psi = 0 \tag{3.1}$$

From a dynamical point of view this windfield will change only
as a function of the lateral boundary conditions in the constant
flux layer when the vertical exchange of sensible heat and
momentum are horizontally homogeneous and quasi-stationary.

The dispersion effect of deviations from this horizontal wind-
field is taken into account by the description of horizontal
turbulent exchange.

4   TURBULENT EXCHANGE

4.1 Vertical exchange

A finite difference approach to estimate vertical exchange, based
on K-theory, requires numerical simulation in many atmospheric
layers. To avoid the labour and cost of detailed numerical
solutions, Pasquill (3) has proposed a "local similarity" treat-
ment of vertical spread from a ground source.

The basic principle is to express the rate of dispersion, $\frac{d\bar{z}}{dt}$,
(where $\bar{z}$ is the mean displacement of an ensemble of particles
after a given travel time) in terms of basic parameters of the
turbulent boundary layer. The assumption is made that the
increase in vertical spread, $\bar{z}$, or alternatively z_m (the extreme
vertical displacement), is always determined by two local
properties:

a) σ_w : turbulence intensity, expressed
                as the standard deviation of
                vertical wind velocity, and

b) $\ell(z)$: scale of turbulence prevailing
                at $\bar{z}$ or z_m.

If it is further assumed that ℓ is proportional to the spectral scale, λ_m, dimensional analysis gives:

$$\frac{d\bar{z}}{dt} = \sigma_w \ f_1 \ (\frac{\lambda_m}{z}) \bar{z} \qquad\qquad (4.1)$$

$$\frac{dz_m}{dt} = \sigma_w \ f_2 \ (\frac{\lambda_m}{z}) z_m \qquad\qquad (4.2)$$

As a hypothesis, Pasquill (3) proposed the following relations:

$$\frac{d\bar{z}}{dx} = f_3 \ (\frac{K}{uz}) \bar{z} \qquad\qquad (4.3)$$

$$\frac{dz_m}{dx} = f_4 \ (\frac{K}{uz}) z_m \qquad\qquad (4.4)$$

By using detailed numerical dispersion calculations, these universal functions are estimated as simple power functions that apply from unstable conditions (L = -7 m) to moderately stable conditions (L = 4 m):

$$\frac{d\bar{z}}{dx} = a \ (\frac{K}{u\bar{z}})^b \qquad\qquad (4.5)$$

where a = 0.95; b = 1.06

$$\frac{dz_m}{dx} = c\left(\frac{K}{uz}\right)^d \tag{4.6}$$

where $c = 3.56$; $d = 2.7$.

When $\frac{K}{u}$ is constant with height:

$$\bar{z} = \left(a\left(\frac{K}{u}\right)^b (1 + b)x + z_0^{1+b}\right)^{1/(1+b)} \tag{4.7}$$

where z_0 : initial dispersion.

Three layers are considered in the calculations: one layer for the emission of low level sources, and two upper layers for medium height and high level sources (Figure 4.1).
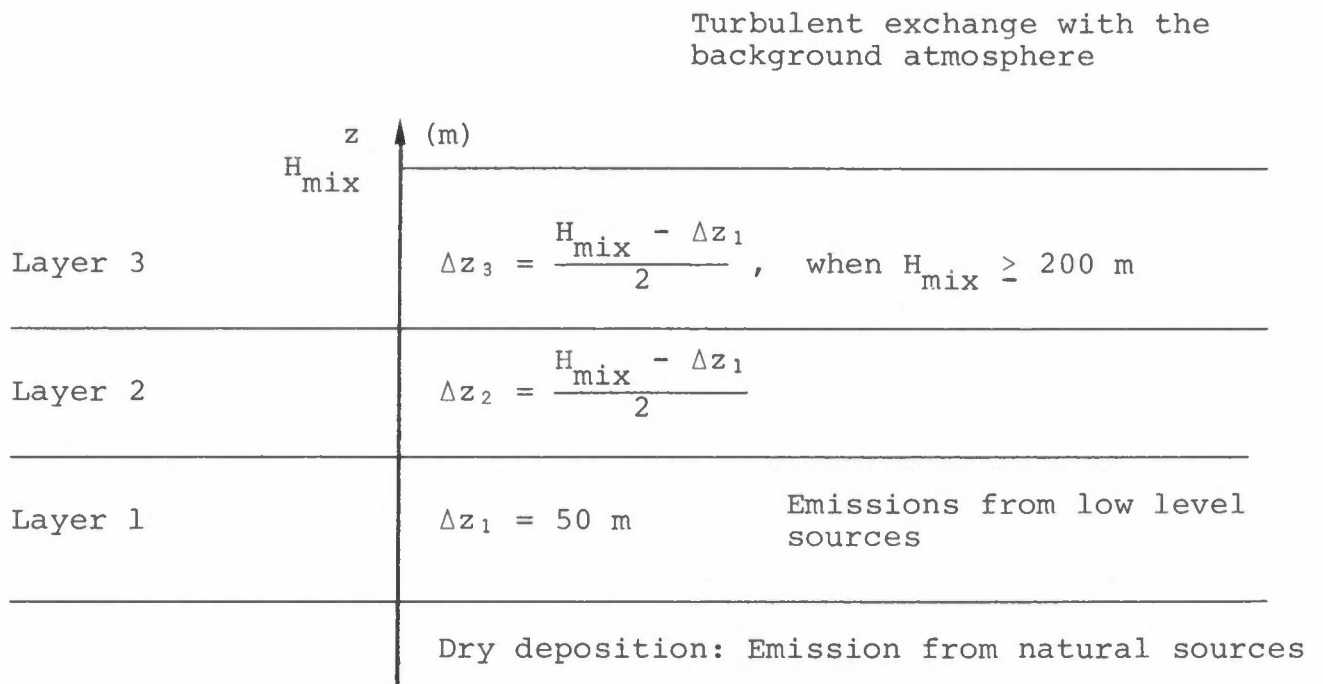
Turbulent exchange with the
background atmosphere

	z (m)	
H_{mix}		
Layer 3	$\Delta z_3 = \dfrac{H_{mix} - \Delta z_1}{2}$,	when $H_{mix} \geq 200$ m
Layer 2	$\Delta z_2 = \dfrac{H_{mix} - \Delta z_1}{2}$	
Layer 1	$\Delta z_1 = 50$ m	Emissions from low level sources
		Dry deposition: Emission from natural sources

Figure 4.1: The vertical structure of the three-level model.
When mixing height (H_{mix}) is larger than 200 m, this
height is used as the upper limit of Layer 3.

Measurements of temperature stratification with height have been used to determine the mixing height H_{mix}.

It is assumed that the air layer between the first and second level grows according to Equations 4.5 and 4.6, causing an exchange of pollution. The exchange will be proportional to the difference in concentration between the levels. The third layer also exchange pollution with the background air above the mixing height.

The following fluxes are calculated:

F_O : Dry deposition to the ground

F_{1-2}: $(\frac{d\bar{z}}{dt})_{1-2} \cdot (C_2 - C_1)$ - from Layer 1 to Layer 2

F_{2-3}: $(\frac{d\bar{z}}{dt})_{2-3} \cdot (C_3 - C_2)$ - from Layer 2 to Layer 3

F_{3-b}: $(\frac{d\bar{z}}{dt})_{3-b} \cdot (C_b - C_3)$ - from Layer 3 to the background atmosphere.

4.2 Horizontal exchange

Measurements of horizontal wind fluctuations are used to estimate horizontal mixing. The standard deviation of these fluctuations (σ_θ) as used with the wind speed and the grid distance to define a horizontal turbulent exchange coefficient, D, describing the dispersion effect of turbulence element smaller than the grid distance, Δx. The following formula as used:

$$\frac{\partial}{\partial x}(u'C_i') + \frac{\partial}{\partial y}(v'C_i') = D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) \tag{4.8}$$

D: horizontal turbulent exchange coefficient

where $D = \sigma_\theta^2 \, u(z) \, \Delta x$

Near point sources the dispersion is described by following
the movements of particles. The horizontal dimension of the puff
increases according to the formula:

$$\sigma_y(t+\Delta t) = \sigma_y(t) + \Delta t \cdot u \cdot \sigma_\theta \cdot B \tag{4.9}$$

$$B = 1.0, \text{ when } \sigma_y < 100 \text{ m}$$
$$B = 0.5, \text{ when } \sigma_y \geq 100 \text{ m}$$

The particles or puffs are growing until their horizontal, σ_y, or
vertical, σ_z, standard deviation is equal to half the grid
distance. The mass of pollution that follows the puff is then
mixed in the area where the particle is. The area is character-
ized by the gridpoint.

5   SIMPLIFIED SET OF EQUATIONS DESCRIBING WIND, TEMPERATURE AND TURBULENCE IN THE FLUX LAYER

The following nomenclature is used:

z : vertical coordinate, meters

z_0 : roughness-parameter, meters

L : Monin-Obukhov length

c_p : specific heat of air at constant pressure

ρ : density of the air

T_0 : air temperature at the ground

u^2_* : $\overline{-u'w'}$, vertical flux of momentum

$u_* \theta_{*0}$: $\overline{w'\theta'} = \dfrac{H_0}{c_p \rho}$, vertical flux of sensible heat

κ : von Karman's constant

ϕ_m : normalized wind gradient $(\kappa z/u_*)\ (\frac{du}{dz}))$

ϕ_h : normalized temperature gradient $((\kappa z/\theta_*)\ \frac{d\theta}{dz})$

To determine the mean air flow close to the ground, the
following "parameter" are important:

1. The horizontal stress, $\frac{\partial \tau}{\partial z}$, has to be known for the horizontal equation of motion:

$$\tau = u_*{}^2/\rho$$

2. The buoyancy force influences the vertical motion. This force is proportional to the Vaisälä-Brundt frequency for small perturbations:

$$\nu_s^2 = \frac{g}{T}\left(\frac{dT}{dz} + \frac{g}{c_p}\right)$$

3. For the thermodynamic energy equation, the vertical flux of heat has to be known:

$$\overline{w'\Theta'} = u_*\Theta_*$$

In Monin-Obukhov similarity theory it is assumed that the vertical fluxes of heat and momentum are the important parameters, together with the height z, and the Vaisälä-Brundt frequency, ν_s.

The length parameter, L, and a temperature parameter, Θ_*, are here defined as:

$$L \equiv - \frac{u_*^3}{\kappa g}\frac{T}{u_*\Theta_*}, \quad \Theta_* \equiv \frac{\overline{w'\Theta'}}{u_*}$$

Two non-dimensional products may be defined, and the π theorem used to describe the vertical gradients in wind speed, $\frac{\partial u}{\partial z}$, and potential temperature, $\frac{\partial \Theta}{\partial z}$:

$$\frac{\kappa z}{u_*}\frac{du}{dz} = \phi_m\left(\frac{z}{L}\right)$$

$$\frac{\kappa z}{\Theta_*}\frac{d\theta}{dz} = \phi_h\left(\frac{z}{L}\right)$$

It has been proposed (5) to use Businger's empirically deter-
mined universal functions (6). When these equations are
integrated, with $\zeta = (z + z_o) \cdot L^{-1}$, the following results may
then be written:

When $\zeta < 0$:

$$\frac{u}{u_*} = \frac{1}{\kappa} (\ln \frac{z}{z_o} - \Psi_1) \tag{5.1}$$

where $\Psi_1 = 2 \ln ((1+x)/2) + \ln ((1+x^2)/2) - 2 \tan^{-1} (x+\pi/2)$

and $\quad x = (1 - 15 \zeta)^{1/4} = \phi_m^{-1}$

$$\frac{\bar{\theta} - \theta_o}{\theta_*} = 0.74 (\ln \frac{z}{z_o} - \Psi_2) \tag{5.2}$$

where $\Psi_2 = \ln ((1+y)/2)$
and $\quad y = (1-9\zeta)^{\frac{1}{2}} = 0.74 \phi_m^{-1}$

When $\zeta > 0$:

$$\frac{u}{u_*} = \frac{1}{\kappa} (\ln \frac{z}{z_o} + 4.7 \zeta) \tag{5.3}$$

$$\frac{\bar{\theta} - \theta_o}{\theta_*} = 0.74 \ln \frac{z}{z_o} + 4.7 \zeta \tag{5.4}$$

where $\phi_m = 1 + 4.7 \zeta$

and $\quad \phi_h = 0.74 + 4.7 \zeta$

With measurements of wind and temperature at two levels as
input, Equations 5.1 and 5.2, or 5.3 and 5.4, may be solved
by iteration to find u_*, Θ_*, and L. Only a few iteration
steps are necessary.

The turbulent exchange of pollution, K_z, is estimated by using the turbulent exchange of heat, K_h, and the following formula is used:

$$K_z = K_h = 0.35 \ u_* z/\phi_h \ (z/L) \tag{5.5}$$

6 DRY DEPOSITION

The deposition of a gas to the ground, and in similar way the evaporation of a gas from the ground, are often discussed in terms of the resistance of the boundary layer to diffuse pollution transport. The resistance, r, is the inverse of the velocity of deposition V_g:

$$r = V_g^{-1} = \frac{\text{concentration difference}}{\text{flux}}$$

The total resistance is further divided into three parts:

$$r = r_a + r_b + r_s \tag{6.1}$$

r_a : aerodynamic resistance in free air
r_b : boundary layer resistance
r_s : surface resistance

The Monin-Obukhov similarity theory may be used to clarify the aerodynamic resistance. The surface resistance is dependent on the chemical affinity between the ground and the gas. The boundary resistance is dependent on diffusion processes close to the ground, where the atmospheric surface layer theory does not apply.

For the constant flux layer of the atmosphere, the following equation may be written:

$$c_* u_* = K_z \frac{\partial c}{\partial z} \qquad\qquad (6.2)$$

c   : pollution concentration

c_* : flux of pollution divided by the
        friction velocity.

Together with Equations 5.4 and 5.5, Equation 6.2 may be used
to calculate the variation of concentration with height in
a stable atmosphere:

$$c(z) - c_O = c_*(2.1 \ln \frac{z}{z_O} + 13.4 \; (\frac{(z-z_O)}{L} + \frac{z_O}{L} \ln \frac{z}{z_O})) \qquad (6.3)$$

where: $c_* = (c - c_O)/f(z, z_0, L)$

when $f(z, z_0, L) = (2.1 \ln \frac{z}{z_O} + 13.4 (\frac{z-z_O}{L} + \frac{z_O}{L} \ln \frac{z}{z_O}))$

In correspondance with Equation 6.2:

$$c_* u_* = (c - c_O) u_*/f(z, z_0, L) \qquad\qquad (6.4)$$

where: $r_a = f(z, z_0, L)/u_*$

Further:

$$\frac{c_O}{r_b + r_s} = u_* c_* = (c - c_O) u_*/f(z, z_0, L) \qquad\qquad (6.5)$$

Similar equations may be written for an unstable atmosphere.
In this case vertical exchanges in the atmosphere are most effec-
tive, and the boundary layer and surface resistance often limit
dry deposition ($r_b + r_s \gg r_a$). When the deposition velocity is
of the order of 1 cm/s, the effect becomes important when the
model keeps track of the pollution during several hours.

In mesoscale modelling dry deposition is considered for SO_2, NO, NO_2, O_3, and aerosols. The deposition velocities are determined by measurements. To consider emissions of hydro-carbons from forest areas, Equation (6.5) may also be used. To determine the emissions from a homogeneous area, it is necessary to measure concentrations at two levels, as well as parameters determining the aerodynamic resistance.

The following empirically determined values for dry deposition (8) are used as maximum values for Level 1 in the model:

$$V_{max} = \frac{1}{r_b + r_s} \qquad\qquad (6.6)$$

For O_3 : V_{max} = 0.6 cm/s
For NO   : V_{max} = 0.1   "
For NO_2 : V_{max} = 0.2   "
For PAN   : V_{max} = 0.2   "

When $r_a \gg r_b + r_s$, it is the turbulent flux in the surface layer that determines dry deposition.

Before comparing calculated concentrations for the surface layer (25 m level) with observed values 2 m above the ground, corrections have to be made for the concentration gradient close to the ground.

7   NUMERICAL METHODS FOR CALCULATING HORIZONTAL ADVECTION AND DIFFUSION

7.1   Finite difference methods

To describe the numerical methods that are used the following simplified equation is considered:

$$\frac{\partial c}{\partial t} = - u \frac{\partial c}{\partial x} \qquad\qquad (7.1)$$

For the local time derivative the Euler forward scheme is used:

$$[\frac{\partial c}{\partial t}]^{(n)}_{(j)} \approx \frac{c^{(n+1)}_{(j)} - c^{(n)}_{(j)}}{\Delta t} = - (u \frac{\partial c}{\partial x})^{(n)}_{(j)} \quad \text{Euler Forward scheme}$$

The Adam-Bashforth scheme is more accurate:

$$\frac{c^{(n+1)}_{(j)} - c^{(n)}_{(j)}}{\Delta t} = + \frac{3}{2} (u \frac{\partial c}{\partial x})^{(n)}_{(j)} - \frac{1}{2} (u \frac{\partial c}{\partial x})^{(n-1)}_{(j)} \begin{array}{l} \text{Adam-Bashforth} \\ \text{scheme} \end{array}$$

$$f^{(n)}_{(j)} = f(j\Delta x, n\Delta t)$$

The subscripts denote the value of the function in the grid-point $x = j\Delta x$, at the time $t = n\Delta t$.

For the spatial deviatives the upwind finite diference method is used:

$$[u \frac{\partial c}{\partial x}]^{(n)}_{(j)} \approx u^n_j \cdot \frac{c^{(n)}_{(j)} - c^{(n)}_{(j-1)}}{\Delta x}, \quad \text{when } u^{(n)}_{(j)} > 0$$

$$\approx u^n_j \cdot \frac{c^{(n)}_{j+1} - c^n_j}{\Delta x}, \quad \text{when } u^{(n)}_{(j)} < 0$$

To avoid numerical diffusion, the fact that each Fourier compo-
nent is a solution of Equation (7.1) is favouring the pseudo-
spectral method. The method is described by Christensen and Prahm
(4). According to their results, it is an advantage to use the
scheme of Adam-Bashford for the time intergration (7). In this
work the dispersion of a large number of components had to be
considered, and the scheme of Adam-Bashford would introduce
computer storage problems.

A periodic function, known in a finite number of gridpoints 2N,
may be written as sum of Fourier components, as shown in
Equation (7.2):

$$c_n = \sum_{k=0}^{N} a_k \cos \pi k \frac{n}{N} + \sum_{k=1}^{N} b_k \sin \pi k \frac{n}{N} \qquad (7.2)$$

$$a_k = \frac{2}{2N} \sum_{n=1}^{2N} c_n \cos \left(k\pi \frac{n}{N}\right)$$

$$a_0 = \frac{1}{2N} \sum_{n=1}^{2N} c_n$$

$$b_k = \frac{2}{2N} \sum_{n=1}^{2N} c_n \sin\left(k\pi \frac{n}{N}\right)$$

The discrete function $c(x_n)$, known in 2N points, may be written without error in the form given above. To estimate numerically the derivative of the function $c(x_n)$, the derivative of the corresponding continuous function given below is:

$$c(X) = \sum_{k=0}^{N} a_k \cos\left(\frac{2\pi}{L_k}\right)x + \sum_{k=1}^{N} b_k \sin\left(\frac{2\pi}{L_k}\right)x \qquad (7.3)$$

$$\frac{dc(x)}{dx} = -\sum_{k=1}^{N} \frac{2\pi}{L_k} \cdot a_k \sin\left(\frac{2\pi}{L_k}\right)x + \sum_{k=1}^{N} b_k \cos\left(\frac{2\pi}{L_k}\right)x \qquad (7.4)$$

$$\frac{d^2 c(x)}{dx^2} = -\sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right)^2 a_k \cos\left(\frac{2\pi}{L_k}\right)x - \sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right)^2 b_k \sin\left(\frac{2\pi}{L_k}\right)x \qquad (7.5)$$

$$L_k = \frac{2N\Delta x}{k}$$

The Equations 7.4 and 7.5 are used to estimate the derivatives in the grid points:

$$\left(\frac{dc}{dx}\right)_n = -\sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right) a_k \cdot \sin\left(\frac{2\pi}{L_k} n\Delta x\right) +$$

$$\sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right) \cdot b_k \cdot \cos\left(\frac{2\pi}{L_k} n\Delta x\right) \qquad (7.6)$$

$$\left(\frac{d^2c}{dx^2}\right)_n = -\sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right)^2 \cdot a_k \, \cos\left(\frac{2\pi}{L_k} n\Delta x\right)$$

$$-\sum_{k=1}^{N} \left(\frac{2\pi}{L_k}\right)^2 \cdot b_k \, \sin\left(\frac{2\pi}{L_k} n\Delta x\right) \tag{7.7}$$

7.2 <u>Time integration - numerical stability</u>

To evaluate the numerical stability conditions, the forward time step combined with the pseudo-spectral method are used to solve the equation:

$$\frac{\partial c}{\partial t} = - u \frac{\partial c}{\partial x} + D \frac{\partial^2 c}{\partial x^2} \tag{7.8}$$

    c: pollution concentration

    u: wind speed

    D: turbulent exchange coefficient

A solution of a linear equation can be expressed in the form of a Fourier series where each harmonic component also is a solution. The Equations 7.6 and 7.7 are used in Equation 7.8, and the behaviour of the following numerical solution is studied:

$$c_{(j)}^{(r)} = \omega^r e^{ikx_j} = \omega^r (\cos kx_j + i \sin kx_j)$$

$c_{(j)}^{(r)}$: pollution concentration at a grid point $x_j = j \cdot \Delta x$, at the time $t_r = r\Delta t$

Δx : grid distance

Δt : time step

ω^r : amplification factor raised to the power of r

$i = \sqrt{-1}$: imaginary unit of a complex number

k   : wave number

Using the Euler Forward scheme for time integration the approximation of Equation 7.8 for this numerical solution reads:

$$\frac{(\omega^{r+1} - \omega^r)e^{ikx_j}}{\Delta t} = -u\ ik\omega^r e^{ikx_j} - Dk^2\omega^r e^{ikx_j}$$

Δt: time step

$$\frac{\omega - 1}{\Delta t} = -\ u\ ik - Dk^2$$

$$\omega = 1 - Dk^2\Delta t - uik\Delta t \qquad\qquad (7.9)$$

The condition for a stable scheme is that the amplification factor be less than one. The time step then has to be smaller than a specified value:

$$\Delta t < \frac{2D}{(Dk_m)^2 + u^2} = \frac{2D}{D^2(\frac{\pi}{\Delta x})^2 + u^2} \qquad\qquad (7.10)$$

$k_m = (\frac{\pi}{\Delta x}) = $ the maximum wave number that may be resolved in the grid system.

It is seen that the turbulent exchange coefficient has to be larger than zero for the numerical scheme to be stable.

The stability conditions of other finite difference schemes may be evaluated by the same method.

8   CONCLUDING REMARKS

The model has been programmed by defining subroutines for each of the processes described in the previous section (9). When applying the model in certain areas, a better description is needed for some of the processes. For instance, in complex terrain a better model, based on dynamical principles, is needed to describe inhomogeneous wind and dispersion conditions.
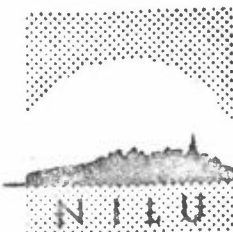
The model has further been developed to include a telescoping procedure using a Lagrangian procedure close to the large sources.

A finite difference approximation is suitable for the mesoscale, and quasi-Lagrangian approach may be used for long range transport calculations.

9   REFERENCES

(1)   Gram, F.,   Fotokjemiske oksydanter i
      Grønskei, K.E.,   Grenland. Modellberegninger.
      Horntveth, K.,   Lillestrøm 1980 (NILU OR 1/80).
      Hov, Ø.,
      Isaksen, I.S.A.,
      Schjoldager, J.

(2)   Hesstvedt, E.,   Quasi-steady state approximations
      Hov, Ø.,   in air pollution modelling:
      Isaksen, I.,   Comparison of two numerical
                             schemes for oxidant prediction.
                             Oslo, Institutt for Geofysikk,
                             Universitetet i Oslo, 1977.
                             (Institute Report Series Report
                             No 25.)

(3)   Pasquill, F.,   Some topic relating to modelling of
                             dispersion in boundary layer.
                             Washington D.C. 1975.
                             (EPA-650/4-75-015.)

(4)   Christensen, O.,   A pseudospectral model for disper-
      Prahm, L.P.,   sion of atmospheric pollutants.
                             J.Appl.Meteor., 15 (1976) 1284-1294.

(5)   Busch, N.E.,   A multi-level model for the plane-
      Chang, S.W.,   tary boundary layer suitable for
      Anthes, R.A.,   use with mesoscale dynamic models.
                             J.Appl.Meteor., 15 (1976) 909-919.

(6)   Businger, J.A.   Turbulent transfer in the atmos-
                             pheric surface layer.
                             In: *Workshop on Micrometeorology*,
                             D.A. Haugen, ed., Boston Amer. Meteor.
                             Soc., 1973, pp. 67-98.

(7) Prahm, L.P.   Long range transmission of pollutants
     Christensen, O.   simulated by a two-dimensional
                           pseudospectral dispersion model.
                           J. Appl. Met. 16, 896-910 (1977).

(8) McMahon, T.A.,   Review paper. Empirical atmospheric
     Denison, P.J.   deposition parameters. A survey.
                           Atmos.Environ., 13, 571-585 (1979).

(9) Gram, F.,   Program "TFKJEMI". Modellbereg-
     Grønskei, K.E.,   ninger av fotokjemiske oksydanter
                           i Grenland.
                           Lillestrøm 1980 (NILU TN 15/79).

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3 STIKKORD (á maks.20 anslag)		
Regional	Dispersion	Model

REFERAT (maks. 300 anslag, 5-10 linjer)

Tidsvariasjonen i konsentrasjonen i tre nivå beskrives ved numeriske metoder for: a) adveksjon, b) vertikalutveksling, c) horisontaldiffusjon, d) kjemiske reaksjoner, e) utslipp fra naturlige og antropogene bilder.
Tørravsetning og utveksling med omgivelsene er innarbeidet som grensebetingelser. På grunnlag av beskrivelsen er det utarbeidet et programsystem hvor hver av prosessene er subrutiner.

TITLE   En regional spredningsmodell

ABSTRACT (max. 300 characters, 5-10 lines)

The time variation in concentration in three levels is considered by describing: a) advection, b) vertical exchange, c) horizontal diffusion, d) chemical reactions, e) emission from natural and antropogenic sources.
Dry deposition and exchange with the surroundings are taken into consideration as boundary conditions. Based on the description a program system is developed favouring a tele-scoping procedure.

**Kategorier: Åpen - kan bestilles fra NILU   A
Må bestilles gjennom oppdragsgiver B
Kan ikke utleveres   C