Estimation of the pollution concentration in the vicinity of a cellulose plant in an Alpine valley using the non-hydrostatic mesoscale model GRAMM

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Abstract

In this paper the application of the non-hydrostatic mesoscale model GRAMM to a mountinous region in the Alps is described. The simulation is used for the estimation of the pollution dispersion of a cellulose plant during selected weather conditions. The GRAMM model solves the conservation equations for mass, momentum, potential temperature and humidity in a terrain-following grid. The time integration scheme is explizit depending on two time levels according to Adams-Bashforth. The discretisation of the model makes use of the Gaussian and the first Green integral theorem without any co-ordinate transformation. The lateral boundary conditions are generalised radiation boundary conditions. On the upper border the boundary conditions damp the vertical velocities and the integral mass flow is kept near zero. The soil temperature is calculated considering the influence of radiation.

The investigated region comprises an area of 13.5 x 13.5 km and the altitudes of the highest peaks are more than 1000 m above ground level. Meteorological conditions were measured at one point during several years. This data have been analysed with special attention to the meteorological conditions during the growth season of the coniferous trees. The concentration of pollutants during the morning hours of spring and summer are important for the rate of growth. The investigated pollutant was SO₂, which will be emitted at a height of 90 m above ground level. The simulations were carried out for three meteorological situations and qualitatively checked. The calculated pollution concentrations were compared to the theoretical values of a Gaussian plume model. The GRAMM concentrations are lower than the maximum values of the results of the Gaussian plume model.
1 Introduction

The pollution burden in forests caused by air pollutants leads to reduced growth and thus to economic losses. In hilly areas with steep slopes, the forest has an important protective function in addition to its economic aspect. It prevents landslides, avalanches and the erosion of the soil. For this reason, the forest in Austria has been protected by a special forest regulation since 1975. The legally necessary steps for setting up or changing an emitting plant involves the assessment of pollution burden caused by \( \text{SO}_2 \) and other pollutants relevant to the forest. This present examination was conducted for the existing cellulose plant in the Austrian city of Pöls. This plant is to be considerably enlarged in the near future. Due to the geographical location of this cellulose plant, which is situated in a deeply cut Alpine valley, a Gauss model cannot be used. For this reason, the non-hydrostatic mesoscale model GRAMM was used in this case to assess the pollution dispersal. The relevant dispersal situations were chosen by a climatologist who has also checked the simulated flow fields.

2 Model description

The GRAMM model [1] solves the conservation equations for mass, momentum, potential temperature, humidity and all types of scalar quantities in a terrain-following grid. For the determinations, the conservation equations are formulated directly for the deformed volumes using a finite volume method. They are not determined with the help of the transformation of coordinates. The derivations of values are determined in the grid with the help of integral equations.

The first and second derivations are mathematically exactly described and can be used for making the conservation equations discrete. The calculated mass fluxes on the surface of each volume are absolutely convergent, except for round-off errors of the computer.

For an undistorted cartesian grid, the conservation equation for a scalar \( \psi \) is

\[
\frac{\partial (\rho \psi)}{\partial t} + \frac{\partial (\rho u \psi)}{\partial x} + \frac{\partial (\rho v \psi)}{\partial y} + \frac{\partial (\rho w \psi)}{\partial z} = R_\psi + Q_\psi
\]

In these equations, the term \( R_\psi \) denote the turbulent diffusion and \( Q_\psi \) denote a source/sink which is dependend on the transported quantity. The implicit non-hydrostatic part of pressure in the momentum equations is determined iteratively using the TDMA (Tri-Diagonal-Matrix Algorithm). The perturbation of density is only considered in the buoyancy term using the virtual potential temperatures with the Boussinesq approximation.

The turbulent diffusion ist determined using the turbulent viscosity principle. This ist done by parameterizing the factor \( k \) with the help of a conservation equation for the turbulent kinetic energy and a mixing length equation. The soil temperature is determined on the basis of a balance of all heat fluxes at the surface. The balance equation takes into account the sensible and latent turbulent
heat fluxes from the atmosphere, the short- and longwave radiation and the heat flux in the soil. The Monin-Obukhov theory is used to determine the sensible and latent heat fluxes. A one-dimensional radiation model is used for the determination of solar and terrestrial radiation. This model considers the effects of shade, reflexion and counter radiation. The divergence of radiation flux in the atmosphere is taken into account by considering emissions in dependence upon the vertical distribution of steam and CO₂ concentrations.

Lateral boundary conditions for momentum, potential temperature and humidity are generalized radiation-boundary conditions. At the upper boundary, a boundary condition is used which enables gravity waves to leave the domain. Both boundary conditions are described in [2]. This keeps the integral mass flux low at the upper boundary and lowers high vertical speeds.

The temporal discretisation is determined explicitly using the Adams-Bashforth scheme with self-adapting time-steps. Advection terms are implemented using the upwind scheme.

### 3 Geographical Position

The city of Pöls - and thus the cellulose plant - is situated in a side valley of the deeply cut Mur valley in the Austrian part of the Alps. The Mur valley enters the calculation domain at the western border and runs from west to east until it changes its direction southwards. From the northwest, the Pöls valley crosses the whole calculation domain. Over a short distance, both valleys are parallel until they come together. The city of Pöls is situated at a height of 790 meters above sea level. The surrounding mountains within the 13.5 x 13.5 km simulation domain (fig. 1) reach heights of more than 1600 m. The different heights are marked by contour lines at distances of 100 m. The inclination of the slopes partly exceeds 60%. According to the Austrian forest regulation, this forest is being regarded as a so-called protective forest, which means that it must not
be exposed to any additional burdens. Except for the valley ground, the soil in the whole calculation domain is being exploited by coniferous wood.

4 Meteorological Situations

The following assessment of forest-relevant flow situations was gained from a number of measuring campaigns. Part of them were published by the Austrian Federal Institute for Health [3], while other measurements were described in internal reports of the Institute of Geography, department for Climate Geography, of the University of Graz [3]. During situations with slow wind speeds, the flow in an Alpine valley is marked by a mountain and valley wind system which is recurring on a daily basis. The rise in temperature in the Alps during the day causes a mountain wind which, depending on the season, lasts over a shorter period of time in winter and a longer period of time in summer. During the night, the mountains cool off more rapidly and the flow reverses. In fig. 2, the distribution of the winds flowing in and out of the valley during one year (ordinate) is shown over those flowing during one day (abscissa). Therefore, the area in the middle of the figure represents the time period of the winds flowing into the valley, while both areas on the left and on the right side represent the time periods of the winds flowing out of the valley. The areas in between represent the transition periods. The maximum wind velocities in the valley cross section increase during the night from 1 to 2 m/s before midnight to 2-3 m/s during the second half of the night and during the morning. The layering of the flow is stable during wind velocities slower than 2 m/s, and neutral during higher wind velocities. The wind flowing into the valley is influenced by the heating caused by the sun. Depending on the cloudiness, the flow shows a neutral to unstable layering at velocities between 2 - 3 m/s. The flow situations described are only true for the valley cross section up to a height of approx. 500 m above the valley ground. The flow situation above this height separates itself from the mountain-valley wind system.
The pollutant SO₂ has negative influences on the growth of coniferous trees. SO₂ prevents the trees from closing their stomata and thus causes them to dry up. The critical time for this pollution effect during the daytime is in spring and in summer. The pollutant plume emitted from a chimney can either be transported into higher forest regions by anabatic slope winds or, during neutral or stable flow, meet on a wooded slope at the same height. The anabatic slope winds, however, are not very strong, so that the pollutant plume will not be affected by them in most cases. An exception to this situation is the neutrally layered outbound flow of the Mur valley during the morning, which flows over the Pöls ridge and which is directed towards the slopes in the north by the upcoming slope drifts. In this case the pollutant plume transported with the winds hits the wooded slopes at a high concentration. This dispersal situation was simulated as case A. When the sun radiation is very strong, the height of the mixing layer reaches the pollutant plume and reduces its concentration very quickly. Since this situation is only of interest for the valley ground, it was not simulated. When the sky is clouded, the flow remains neutral and transports the pollutant plume towards the Wetzel mountain which is situated in the west. This situation was simulated as case B. In addition to the two situations described above, the neutrally layered outbound flow was simulated as case C.

5 Results of the Simulation

The simulation of the three meteorological situations was carried out in a grid with square cells of 300 x 300 m. The number of cells was 45 x 45 in a horizontal direction. In a vertical direction, the total height of 6000 m was separated into 30 cells with different heights, starting from 20 m near the ground and reaching approx. 400 m at the upper edge. The simulations were carried out for quasi-stationary situations, because the flow in the Mur valley is caused by a system of a much larger scale which therefore could only be considered diagnostically as a boundary condition. The three flow situations described above were carried out with constant-time boundary conditions. In a vertical direction, the inflow was only given up to a height of 600 m above ground. Above this, no wind velocity was assumed. A neutral temperature distribution was assumed for the valley area (up to 600 m above ground), and a stable temperature distribution for the area above it, with a gradient of 3.5 K/km. In the following, the results of the flow and dispersal calculation will be presented and described for the lowest terrain-following calculation level. The pollutants are emitted through a chimney at a height of 90 m above ground. Due to the enormous amount of flue gas (540.000 Nm³/h at 70° C) and the low wind velocities, the effective chimney height is more than 200 m. For this reason, the emissions of 23.8 kg/h SO₂ were calculated at this height as belonging to one cell.
Case A

The simulation for case A was calculated for a cloudless day in mid April as of 8:00 LST. After a simulation period of three hours, the calculation shows an incoming flow from the west through the Mur valley and from northwest through the Pöls valley at velocities of approx. 2.5 m/s. The flow from the Mur valley is being separated into two parts by the Falken mountain. Those two parts pass the mountain in the south and in the north. The northern part flows over the Pöls ridge near the plant. Due to the increasing temperature of the earth surface, it changes directly into a slope updrift. Therefore, the pollutant plume is transported to these slopes. The maximum concentrations near ground are approx. 10.5 µg/m³. The flows in the whole area are meanwhile marked by slope updrifts. Since the slope updrifts remove all the warm air, no major mixing layer can build up.

Case B

The simulation for case B was also carried out for a day in mid April during cloudy weather. The simulation started at 10:00 LST with a flow coming from the east and lasted until 13:00 LST. The situation shows the inflow
into the area from the east with low velocities. Due to the reduction of the flow cross section, the velocity of the flow increases at both sides of the Falken mountain to up to 3 m/s. The pollutant plume is transported along with this flow towards the Wetzel mountain, where it hits the wooded areas with a maximum concentration of 4.7 µg/m³.

**Case C**

The simulation for case C was calculated for the morning hours of a day in April. Similar to case A, the flow enters the calculation domain from the west and northwest via the two valleys. Due to the fact that the valleys are smaller at the north and the south of the Falken mountain, the flow velocities are increased and reach speeds of up to 2.5 m/s. The pollutant plume is transported by the flow towards the southeast, where it hits an exposed mountain which reaches far into the Pöls valley and which acts as a natural barrier. This mountain reaches a height of more than 200 m above ground, which, therefore, corresponds to the height of the pollutant plume. The maximum concentrations are 3.7 µg/m³.

The limiting value provided in the forest regulation is 70 µg/m³, which has not been reached in any of the three cases. The presented complex flow cases could not be compared with values gained from meteorological measurements. The measurements were performed over a number of years on the existing chimney of the plant, and they were used for analysing the relevant flow situations. The time distribution of the winds flowing into and out of the valley was derived from these measurements. The season distribution of the wind directions showed a share of 85% in flows parallel to the valley with a major share in winds flowing out of the valley. The rest is made up of flows from the southwest to the south. These typical flows were considered in the three cases.

**Comparison with the results from the Gauss Model**

In order to check the results of the pollutant concentrations, the three cases described above were compared to the Austrian version of the Gauss model [4].
The results were calculated on the basis of the unrealistic assumption that the pollutant plume would penetrate the mountain. The resultant concentrations must in any case be higher than the results from the simulation. The comparison shown in table 1 was carried out for the concentration on the ground and, for Gauss, also at the height of the plume.

<table>
<thead>
<tr>
<th>Ground (distance)</th>
<th>Gauss: ground</th>
<th>Gauss: height: 170m</th>
<th>GRAMM: ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A (1500 m)</td>
<td>10.9 µg/m$^3$</td>
<td>11.0 µg/m$^3$</td>
<td>10.3 µg/m$^3$</td>
</tr>
<tr>
<td>Case B (3500 m)</td>
<td>6.5 µg/m$^3$</td>
<td>8.1 µg/m$^3$</td>
<td>4.7 µg/m$^3$</td>
</tr>
<tr>
<td>Case C (3500 m)</td>
<td>0.0 µg/m$^3$</td>
<td>73.1 µg/m$^3$</td>
<td>3.7 µg/m$^3$</td>
</tr>
</tbody>
</table>

Table 1: Comparison of the maximum ground concentrations GRAMM - Gauss

Here it shows that the results of GRAMM are considerably lower than those of Gauss. The factor, however, is less than a power of ten. For checking the individual situations, tracer examinations with SF$_6$ will be carried out in the future.

6 Conclusions

In order to assess the pollution burden in the vicinity of a cellulose plant, the non-hydrostatic mesoscale model GRAMM was used. The calculation domain is situated in a deeply cut Alpine valley in Austria. Because of the orography, it is not possible to use a simple Gauss dispersal model. The three-dimensional simulation was carried out for three chosen quasi-stationary situations and leads to plausible meteorological results. Together with the meteorological quantities, the dispersal of the pollutant SO$_2$ was calculated. Finally, the ground concentrations were compared with the theoretical values of the Austrian Gauss model. Due to the unrealistic assumptions, the comparison shows higher pollutant concentrations for the Gauss model.

7 References

4. ÖNorm 9440,“ÖNorm 9440: Dispersion of pollutants in the atmosphere - Calculation of ambient air concentrations and determination of stack heights,” Fachnormenausschuß 139 Luftreinhaltung, Österreichisches Normungsinstitut, Wien, Austria, 1992