Simulation of terrain amplification factors for annual concentration statistics using a Lagrangian particle dispersion model

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1 Introduction

The standard regulatory model in Germany still is a simple Gaussian plume model with no consideration of terrain or building effects or non-stationary situations. Together with the plans to renew the associated technical instruction there is a discussion concerning the definition of a state of the art model type, which is able to take the above mentioned effects into account. Probably, the new standard model will be a combination of a Lagrangian particle dispersion model and a diagnostic flow model. Although this model combination has already been applied to quite a number of cases with complex terrain, only few of these studies deal with the evaluation of terrain effects (e.g. Wichmann-Fiebig, 1999). Moreover, a simple rule is missing in the technical instruction to decide in which cases terrain influence has to be taken into account.

A common method to assess the influence of terrain on atmospheric dispersion is the calculation of terrain amplification factors (TAF; Lawson et al., 1989). The terrain amplification factor is defined as the ratio of the maximum ground level concentrations with terrain and without terrain.

In order to obtain a simple objective criterion concerning the relevance of terrain with respect to annual concentration values, concentration statistics for simple terrain types (a bell shaped mountain and a ridge) have been calculated using LASAT (Janicke Consulting, 2000), which is an implementation of the proposed future model standard. In addition a validation with wind-tunnel data by Lawson et al. (1989) and sensitivity studies have been carried out.

2 The model

The Lagrangian particle dispersion model LASAT is compatible with the German guideline VDI 3945, Sheet 3 (VDI, 2000). It simulates the dispersion of passive trace elements in the boundary layer by means of a Markov process for spatial and velocity components, which allows time steps larger than the Lagrangian correlation time (Janicke, 2000). Time dependent concentration values for a chosen averaging period are calculated from the duration of particle presence in each box of the three-dimensional model grid. The model system contains a diagnostic flow model which includes terrain and building effects. The turbulence module is based on Monin-Obukhov theory profiles. Both, turbulence as well as flow fields may also be prescribed by external flow models. Furthermore, several additional processes as plume rise, sedimentation, deposition and first order chemistry can be handled by LASAT.

3 Neutral and stable flow experiments

A comparison with terrain amplification factors from wind tunnel experiments with neutral flow (Lawson et al. 1989) has been made to test the ability of LASAT to describe flow and dispersion above complex terrain. Figure 1 shows plots of the wind-tunnel experiment results for a single hill and a two-dimensional ridge from Snyder (1990). For source locations upstream of the obstacle terrain amplification factors are dominated by the effect of streamline convergence towards the surface. This effect is more pronounced for the single hill, since parts of the flow are able to pass around the obstacle. The second area with increased TAFs downstream of the hill and the ridge is caused by enhanced vertical turbulent mixing induced by terrain.

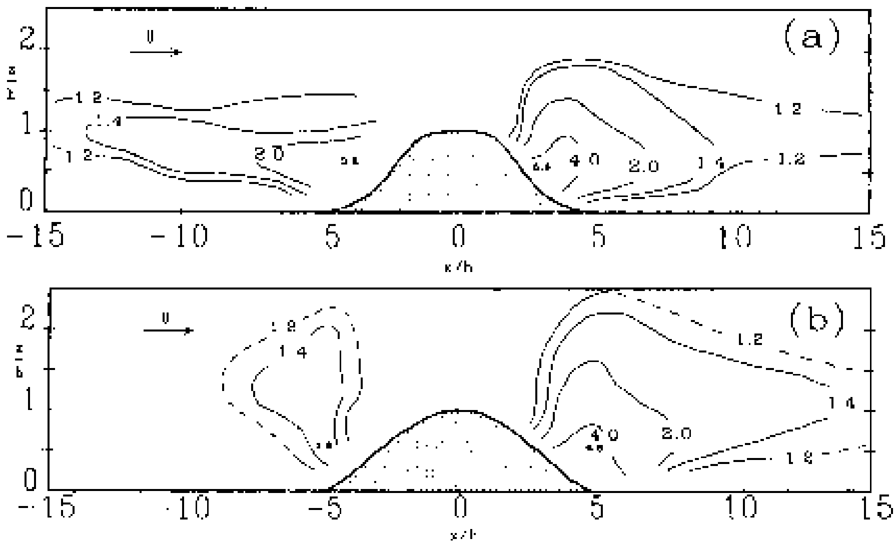

Figure 1 Terrain amplification factors for neutral flow over an axisymmetric hill (a) and a ridge (b) obtained from wind-tunnel experiments (Snyder, 1990). Flow from left to right, source positions (x, z) are scaled with the hill height h, vertical scale exaggerated by a factor of 3.

Model parameters for the simulations with LASAT have been chosen according to the full scale values given in Lawson et al. (1989). The full scale maximum terrain heights are 193.75 m for the hill and 147.5 m for the two-dimensional ridge respectively. The model domain is divided into 16 model layers with 10 m depth near the surface increasing to 100 m at the model top and a horizontal grid box size of 125 m. TAFs are calculated for 135 source locations along the x-z-plane (9 heights and 15 horizontal distances). The LASAT results for the domain corresponding to Fig. 1 are shown in Fig.2.

The simulated pattern of high terrain amplification factors for different stack locations is comparable with experiment values in the upstream area. However, terrain amplification factors in the wake are underestimated due to the flat terrain turbulence which is assumed by the model. Since it is difficult to prescribe wake effect in a diagnostic flow model for arbitrary terrain, similar deviations are found in other models as e.g. in ADMS (Carruthers, 2000). The corresponding simulation for a valley (Fig. 2) shows higher maximum terrain amplification factors than for the terrain types hill and ridge, which is in agreement with findings of other authors (e.g. Snyder, 1990 or Genikhovich and Schiermeier, 1995). In order to quantify the relevance of the downstream underestimation for annual concentration statistics LASAT has been coupled with the prognostic non-hydrostatic flow model FOOT3DK (Flow over orographically structured terrain, Brücher et al. 2000), which contains a 1.5 order turbulence closure scheme. Before applying this model combination to stable situations, the neutral cases have been tested. Resulting TAF values are in better agreement with observations than the original LASAT results (see top of Fig. 3), although downstream terrain amplification factors are still somewhat lower than observed.

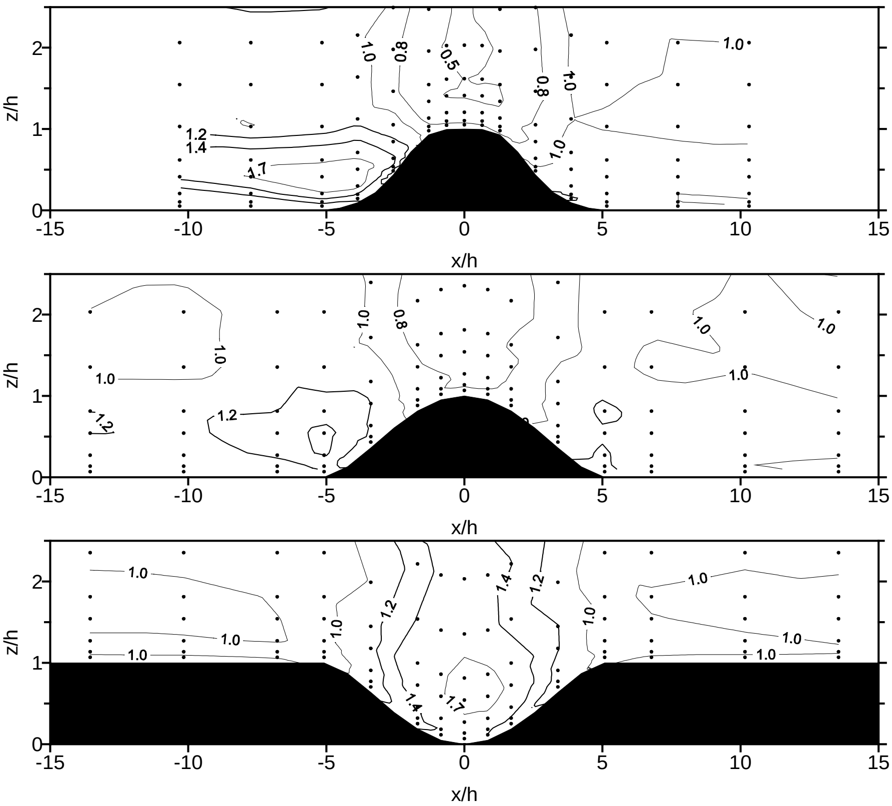

Figure 2 Terrain amplification factors for neutral flow over an axisymmetric hill (top), a two-dimensional ridge (middle) and a valley (inverted ridge, bottom) based on dispersion simulations with LASAT. Source positions are marked with dots. Scaling is identical to Fig. 1 but the number of contours is increased.

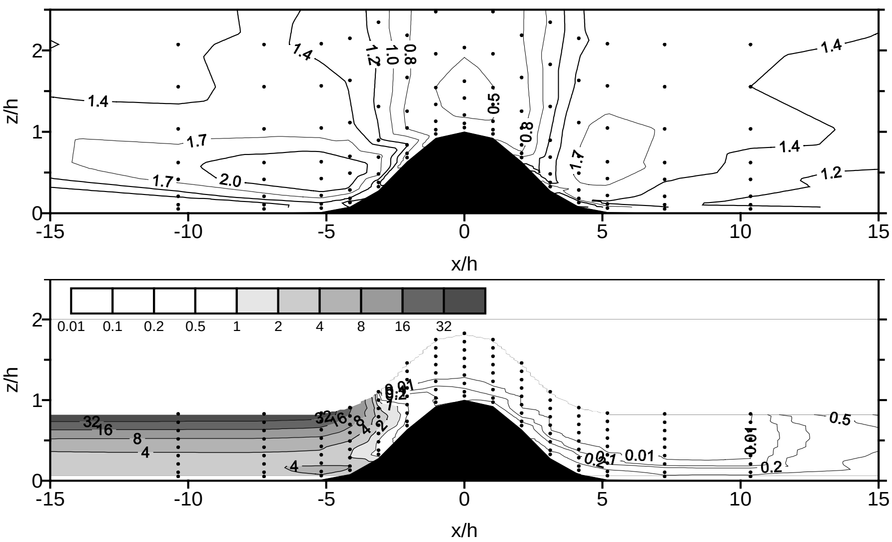

Figure 3 Terrain amplification factors for neutral flow (top) and for stable stratification (standard atmosphere, bottom) over an axisymmetric hill based on dispersion simulations with LASAT coupled with FOOT3DK. Vertical scaling as in Fig. 2, source positions are marked with dots.

TAF values for a stable stratification (standard atmosphere) simulated with FOOT3DK/LASAT are given in Fig. 3 (bottom). In this case maximum ground level concentrations for high stacks occur at long distances from the source outside the grid. Hence, no TAFs for elevated stacks are simulated.

Upstream TAF values for stable stratification are higher than for the neutral case the plume centerline converge nearer to the ground than in the neutral case. On the other hand the downstream terrain amplification factors are lower than 1, which is due to two effects. First the flow is accelerated downhill and second the flow is horizontally converging downstream which is leading to a plume lift. The latter effect is not found in combination with the ridge (not shown) but downstream values are lower than 1 too. Hence, the upstream terrain effect is much more important than the downstream effect with respect to annual mean concentrations.

4 Annual concentration statistics

9 annual simulations sets with LASAT for a bell shaped (Gaussian) mountain have been performed. Each set consists of simulations for 49 source locations and 1944 atmospheric situations (6 dispersion categories, 9 velocities and 36 directions, according to the current technical instruction TA Luft, 1986). Annual mean concentration statistics are calculated from the combination of all simulations with a dispersion category statistic. In order to obtain terrain amplification factors with respect to local site dispersion statistics, no adjustment of the forcing statistic to terrain has been made. Instead, the same (German) statistic, averaged with respect to direction, was used at all source positions for flat and for hilly terrain.

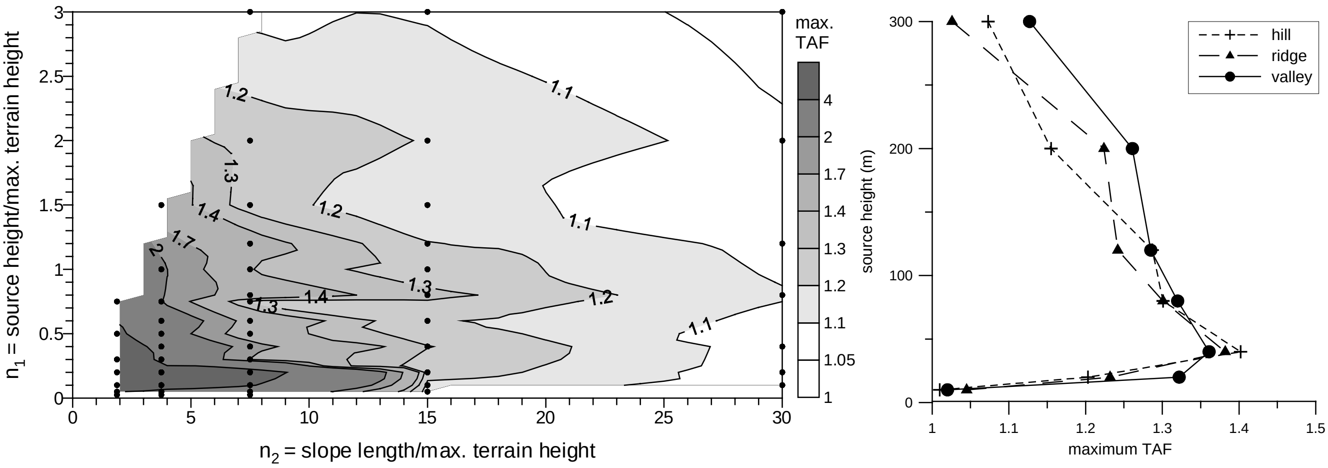

Figure 4 Maximum terrain amplification factors for annual mean concentrations obtained from 9 LASAT simulation sets with a bell shaped mountain and an extrapolation to the valley terrain type (left, see text for details) and maximum TAFs simulated for 3 terrain types (h_{max} =200 m , σ=1000 m).

The 9 simulations sets originate from combinations of 3 hill heights and 3 hill widths. Maximum terrain amplification factors for all combinations of the dimensionless parameters n_1 (source height/terrain height) and n_2 (slope length/terrain height) according to Genikhovich and Schiermeier (1995) are extracted. Finally, the results are scaled with ratios between single hill TAFs and valley TAFs from Genikhovich and Schiermeier (1995) to get a conservative estimate of terrain amplification factors in arbitrary terrain. The resulting distribution of maximum TAFs depending on n_1 and n_2 is presented is presented in Fig 4 (left). The ratios, which are used for the extrapolation of terrain amplification factors of annual mean concentrations from the single hill case towards the (worst case) valley terrain type are not proven to be valid for annual statistics. Nevertheless, a sensitivity study with a maximum terrain height of 200 m and a σ of 1000 m for all three terrain types shows the same trend with highest TAF values for the valley type at most source heights (Fig. 4, right).

5 Conclusions

The Lagrangian particle dispersion model LASAT has been validated with wind-tunnel data for neutral flow over a hill and a ridge. There are some deficits in the downstream area, but sensitivity studies with a more complex model show the minor importance compared to the upstream area with respect to annual mean concentrations. Simulations of annual mean concentrations for a number of hill shapes are combined with hill to valley ratios for maximum TAFs. The resulting figure may be used as a estimate to decide whether terrain has to be taken into account or not. Nevertheless it should be noted that these results are only based on annual mean concentrations and a simplified German dispersion category statistic. Further simulations would be necessary to obtain a similar scheme for high quantiles or exceedances of concentration thresholds.

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