A modified diffusion scheme for high-resolution simulations over mountainous terrain

Günther Zängl
Meteorological Institute, University of Munich, Germany
email: guenther@meteo.physik.uni-muenchen.de

1. Introduction

Most numerical models need explicit horizontal diffusion to ensure numerical stability. In mesoscale models based on a terrain-following coordinate system, the diffusion terms may introduce serious errors when they are calculated along the coordinate surfaces. The problem is most evident for atmospheric properties having a strong vertical gradient. Temperature diffusion along the coordinate surfaces, for example, tends to cool valleys and to heat mountains. Likewise, diffusion of the water vapor mixing ratio along the coordinate surfaces tends to dry valleys and to moisten the atmosphere above mountains. To prevent spurious temperature or moisture tendencies, diffusion should be computed truly horizontally. At sufficient distance from the ground, this can be accomplished with vertical interpolation between the coordinate surfaces. However, a special treatment is needed for the model levels close to the ground because a truly horizontal computation may be impossible without intersecting the ground. In the next section, an effective method to minimize diffusion-induced errors in the lower model levels is outlined. A more detailed description is given in Zängl (2002). The modified diffusion scheme has been implemented into the Penn State University/National Center for Atmospheric Research mesoscale model MM5. Test simulations presented in section 3 demonstrate that it greatly improves the model's capability of simulating complex flows in Alpine orography.

2. The modified diffusion scheme

In the modified diffusion scheme, diffusion is computed truly horizontally at all model levels where this is possible without intersecting the topography. For most variables, linear vertical interpolation between the coordinate surfaces appears to be sufficient. For the water vapor mixing ratio, however, exponential interpolation or a higher-order polynomial or spline interpolation should be used.

In the remaining model levels, diffusion is treated differently for momentum, temperature and the moisture variables. For momentum, a simple transition to diffusion along the coordinate surfaces (henceforth referred to as sigma-diffusion) is chosen. For the moisture variables (the mixing ratios of water vapor, cloud water etc.), a combination of one-sided truly horizontal diffusion and orography-adjusted sigma-diffusion is used. One-sided diffusion is discretized using the "half" of the centered difference scheme for the fourth derivative, i.e. $\left(\frac{\partial^4 u}{\partial x^4}\right)_i \approx \frac{3u_i - 4u_{i+1} + u_{i+2}}{\Delta x^4}$, Δx being the grid increment. Orography-adjusted sigma-diffusion follows the idea that sigma-diffusion may be applied along the axis of a valley without inducing spurious tendencies. However, in the direction across the valley axis, sigma-diffusion should be switched off. Details on this procedure are given in Zängl (2002). For temperature, orography-adjusted sigma-diffusion is used without one-sided truly horizontal diffusion because the latter damps slope wind circulations in an unphysical way. The sigma-diffusion for temperature is further improved by a correction involving the leading term appearing in the coordinate-transformed expression of the fourth-order diffusion operator.

3. A test simulation

Idealized numerical simulations of the valley wind system of the Alpine Inn Valley have been performed in order to test the modified diffusion scheme. The Inn valley has been chosen because a large amount of detailed measurements is available for this valley (e.g. Vergeiner and Dreiseitl 1987). Since these measurements show a lot of characteristic features recurring every fine weather day, the simulations could be based on a highly idealized setup, only orography being taken from data.

The test simulations have been computed on five interactively nested model domains, the finest horizontal resolution being 800 m. The innermost model domain covers the lower Inn valley together with its tributaries. In the vertical, 38 sigma levels are used, the lowermost one being located at about 18 m above ground. To keep the setup as simple as possible, the absence of any horizontal pressure and temperature gradients is assumed. This corresponds to vanishing large-scale winds. The simulation starts at a fictitious date of 15 October, 00 UTC (the date being relevant for radiation only) and is carried out for 30 hours. Temperature and moisture are specified according to what is typical for mid-October in the presence of continental air.

Three simulations based on the same initial conditions are considered. Two of them use existing model options. First, actual temperature (T) is used for computing the diffusion along the sigma levels. In the

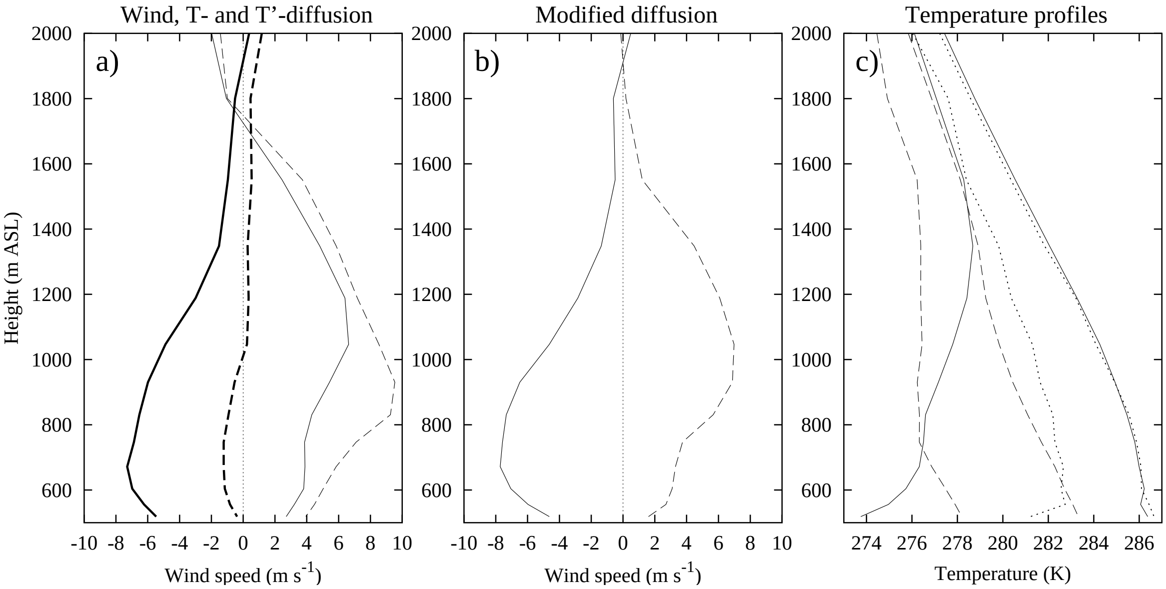

Figure 1: (a) Simulated wind profiles, $t = 16$h (solid lines) and $t = 30$h (dashed lines). Positive (negative) values denote downvalley (upvalley) wind. Simulations are performed with T-diffusion (thin lines) and T'-diffusion (bold lines). (b) Same as (a), but for simulation with the modified diffusion scheme. (c) Simulated temperature profiles for modified diffusion (solid lines), T-diffusion (dashed lines) and T'-diffusion (dotted lines). In each case, the colder (warmer) profile refers to $t = 30$h ($t = 16$h).

second simulation, the so-called perturbation temperature (T') is used for computing the diffusion. T' the difference between the actual temperature and a model reference temperature profile that usually has a vertical gradient around $-6\,\mathrm{K\,km^{-1}}$ in the lower troposphere. In the following, these two versions of sigma-diffusion will be referred to as T-diffusion and T'-diffusion, respectively. In the third simulation, the modified scheme described in section 2 is used.

Simulated vertical wind profiles at a location in the lower part of the Inn Valley are displayed in Figs. 1a and 1b for $t = 16$ h (solid lines) and $t = 30$ h (dashed lines). In each case, negative (positive) values denote upvalley (downvalley) wind. From the measurements, we expect upvalley wind in the afternoon and downvalley wind in the night. At the location considered here, the upvalley wind maximum is observed significantly closer to the ground than the downvalley wind maximum (see Zängl 2002 for more details).

It is obvious that the model fails to reproduce the observed valley wind circulation with the original sigma-diffusion scheme (Fig. 1a). With T-diffusion, downvalley wind is simulated throughout the day. It is only slightly weaker in the afternoon than during the night. On the other hand, permanent upvalley wind is obtained with T'-diffusion. It is rather weak at the end of the night and of realistic strength in the afternoon. With the modified diffusion scheme, however, the simulated valley wind circulation is rather close to reality (Fig. 1b). The wind maxima of both the upvalley wind and the downvalley wind are well within the observed range of values. Moreover, the observed day-night asymmetry of the height of the wind maximum is captured well by the simulation.

To explain the differences between sigma-diffusion and the modified diffusion scheme, vertical temperature profiles of the valley atmosphere are considered (Fig. 3). With the modified scheme (solid lines), a realistic diurnal temperature range is obtained. In particular, enhanced nocturnal cooling is evident up to a height of 1000 m above ground. Such a nocturnal temperature profile is rather typical for the Inn Valley (e.g. Vergeiner and Dreiseitl 1987). However, with sigma-diffusion, a realistic simulation of the diurnal temperature range is impossible. In both cases, the day-night difference of the surface temperature is several times too weak. Comparing the profiles for T-diffusion (dashed lines) and T'-diffusion (dotted lines), it becomes clear why the direction of the valley wind is opposite for these two options. With T-diffusion, the whole valley atmosphere is several degrees colder than with T'-diffusion.

References

Vergeiner, I., and E. Dreiseitl, 1987: Valley winds and slope winds – Observations and elementary thoughts. *Meteorol. Atmos. Phys.*, **36**, 264–286.

Zängl, G., 2002: An improved method for computing horizontal diffusion in a sigma-coordinate model and its application to simulations over mountainous topography. *Mon. Wea. Rev,* in press.